PROBABILISTIC STRUCTURAL INTEGRITY OF A PWR REACTOR PRESSURE VESSEL : PROSIR ROUND ROBIN

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ABSTRACT

In the framework of Committee on the Safety of Nuclear Installations of the OCDE/ NEA, the Working Group on the Integrity of Components and Structures is in charge of studies and information exchanges on ageing of nuclear power plant components and structures.

One of the key issue of ageing of nuclear power plants is the radiation effect on the reactor pressure vessel that leads to material embrittlement and can reduce the safety margins in case of pressurized thermal shock .

The analysis of these pressurized thermal shocks needs a large number of data with their uncertainties: transients, material properties and flaw distribution.

Consequently, the deterministic approach is too much conservative and probabilistic are used or under development in many countries (USA, Japan, France and Korea).

Following an OCDE round robin proposal, 9 countries (USA, Japan, Korea, Sweden, Germany, Czech Republic, Spain, EC and France) has been involved in the round robin defined in 2 phases:

- deterministic approach
- probabilistic approach

This paper presents the major hypothesis, the results of the two phases and the complementary actions needed.

INTRODUCTION

The US pressurized thermal shock (PTS) screening Criteria on RT_{NDT} of Reactor Pressure Vessel (RPV) of PWR [1] is based on a probabilistic fracture mechanic approach. In the other hand, if a plant is supposed to over-pass the screening criteria the Regulatory Guide RG 1.154 [2] define the requirements based on a justification through a probabilistic approach.

The objective of these Round Robins (RRs) is to issue some recommendation of best practices in this area and to assure an understanding of the key parameters of this type of approach, like transient description and frequency, material properties, defect type and distribution, fracture mechanic methodology… An other possible result will be to identify the consequences of different parameter uncertainties on the probability of failure of a RPV.

It's a complementary step to FALSIRE [3] and ICAS [4] program on RPV integrity.

You will find enclosed a general description of RPV Probabilistic Fracture Mechanic scheme with all the basic data for the different Round Robin's.

A pre-requisite set of deterministic approaches has been proposed and discussed with the different partners before moving to probabilistic approaches.

Different sensitivity studies around the base case (longitudinal weld) has been done and discussed.

The final recommendations of phase 1 and 2 have been developed round a workshop in September 2006.

PROBLEM DEFINITION

The proposal plans to cover step by step the problems of RPV probabilistic structural integrity procedure. Major RR's will be done independently, using published results of previous step.

The next table precise the major common data for the different Round Robin:

<u>If no distribution law are specified in the text, use normal distribution (standard deviation: SD)</u>

RPV geometry	PWR 3-loop type	• inner surface radius: 1994mm • cladding thickness: 7.5mm • base metal thickness: 200mm • outer surface radius : 2201.5mm
Properties of base metal, weld and cladding	Thermal	See table 1
	Tensile- Stress-strain curves	See tables 2-a and 2-b
	Toughness : - K_{IC} versus temperature - K_{Ia} versus temperature	See table 3
	Chemical composition	See table 4

Irradiation effects	Fluence on the inner surface in n/m^2 Y= year	- 1Y=1.10^{23}, 10Y=3. 10^{23}, 20Y=5. 10^{23}, 40Y=7.5. 10^{23}, 60Y=10. 10^{23} - 2 SD value: 20%
	Irradiation shift formula	See table 5
	Irradiation decrease through the RPV wall	- $F = F_0\, e^{-0.125x}$ for 0<x<0.75t and x in 10^{-2}m
	Irradiated tensile properties	- effect is not considered
Defect	Orientation: longitudinal or circumferential	- longitudinal in the base case - see table 9
	Location: surface, underclad or embedded	- surface / underclad crack - see table 9
	Size: depth and length Shape	- 12mm depth x 72mm length for elliptical underclad crack (model 3) - 19.5mm depth x 117mm length for semi-elliptical through clad crack (model 2) - see table 9
	Size distribution Density	- Marshall/ PNNL distribution - See appendix 1 - 1 crack is considered
Transient loads	- Tr1: SBLOCA - Tr2: SLB - Tr3: PTS (with re-pressurisation)	- pressure, temperature and heat exchange coefficient versus time - see table 6, 7 and 8
Other loads	- residual stresses	- not considered in the base case - nevertheless, the free stress temperature of the vessel is: 300°C - no consideration of hydroproof test
Fracture mechanic model	elastic K evaluation compare to K_{IC} or K_{Ia} for the corresponding crack tip temperature and irradiation level	- without plasticity correction for all cracks except for underclad cracks - see appendix 2

If no distribution law are specified in the text, use normal distribution (standard deviation SD)

	Temperature °C	Base metal and welds	Cladding
Thermal expansion in $10^{-6}.°C^{-1}$ (mean value between 20°C and temperature)	20	10.9	16.4
	300	12.9	17.7
Conductivity λ in $W.m^{-1}.°C^{-1}$	20	54.6	14.7
	300	45.8	18.6
Diffusivity $\mu=\lambda/\rho C$ in $10^{-6}.m^2.s^{-1}$	20	14.7	4.1
	300	10.6	4.3
Density ρ	20-300	7.6	7.6

Table 1: Thermal material properties

Unit : MPa	Temperature °C	Base metal	2 SD for Base metal	Welds	2 SD for Welds	Cladding
Yield strength: S_y ($R_{p0.002}$)	20	588	60	646	80	380
	300	517	60	563	80	270
Young modulus: E	20	204000	10000	204000	10000	197000
	300	185000	10000	185000	10000	176500
ν	20 - 300	0.3	-	0.3	-	0.3

Table 2-a: Mechanical material properties – General

Total strain ε		0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
σ/S_y for base metal	**20°C**	1.02	1.11	1.19	1.25	1.29	1.33	1.36	1.38	1.40	1.42
	300°C	1.11	1.21	1.28	1.33	1.37	1.41	1.43	1.45	1.47	
σ/S_y for weld	**20°C**	1.00	1.05	1.10	1.15	1.19	1.22	1.24	1.26	1.28	1.29
	300°C	1.07	1.15	1.21	1.26	1.30	1.34	1.36	1.39	1.41	1.43
σ/S_y for cladding	**20°C**	1.06	1.10	1.13	1.16	1.19	1.22	1.25	1.27	1.30	1.32
	300°C	1.07	1.11	1.14	1.17	1.20	1.23	1.26	1.29	1.31	1.34

Table 2-b: Mechanical material properties – Stress-strain curves

Mean values - 2 standard deviation (SD) = ASME curves - K_{Ia} has to remain lower or equal than K_{IC} - K_{Ia} has to remain greater than 0.	Crack initiation	$K_{IC} = 36.5 + 3.1 \exp[0,036 (T-RT_{NDT} + 55.5)]$ $K_{IC\ max}$= 220 MPa.m$^{0.5}$
	Crack arrest	$K_{Ia} = 29.4 + 1.4 \exp[0,026 (T-RT_{NDT} + 88.9)]$ $K_{Ia\ max}$= 220 MPa.m$^{0.5}$
1 SD	Crack initiation	On K_{IC} 15% On $K_{IC\ max}$ = 15 MPa.m$^{0.5}$
	Crack arrest	On K_{Ia} 10% On $K_{Ia\ max}$ = 15 MPa.m$^{0.5}$
K_{IC} and K_{Ia} normal distribution truncated between +3SD and –3SD		

Table 3: Toughness curve and uncertainties for un-irradiated weld and base metal

	Initial RT_{NDT}	1 SD uncertainties	% copper (Cu)	2 SD uncertainties
Base metal	-20°C	9°C	0.086	0.02
Welds	-30°C	16°C	0.120	0.02
	% phosphorus (P)	**2 SD uncertainties**	**% nickel (Ni)**	**2 SD uncertainties**
Base metal	0.0137	0.002	0.72	0.1
Welds	0.0180	0.002	0.17	0.1

Table 4: Chemical composition and initial RT_{NDT}

Base metal	mean	ΔRT_{NDT} = [17.3+1537*(P-0.008)+238*(Cu-0.08)+191*Ni^{2}Cu]*$\varphi^{0.35}$
	1SD	10°C
Weld	mean	ΔRT_{NDT} = [18+823*(P-0.008)+148*(Cu-0.08)+157*Ni^{2}Cu]*$\varphi^{0.45}$
	1SD	6°C
ΔRT_{NDT} normal distribution truncated between +3SD and –3SD		

φ: fluence in n/m^2 divided by 10^{23}; P, Cu, Ni % of phosphorus, copper and nickel

Table 5: Shift formula and corresponding uncertainties

Time in second	Pressure in MPa	Fluid temperature	Heat Exchange coefficient in W/m^2.°C
0	15.5	286	174000
50	11.8	283	174000
100	8	280	43600
300	7	266	21200
520	6.4	250	2700
600	5.5	227	3200
700	5	202	3200
740	4.8	192	3200
800	4.5	170	3200
1000	3.5	114	3000
1300	2	64	2500
1800	2	27	1900
2800	2	10	1400
3800	2	7	1200
4800	2	7	1000
6300	2	7	800

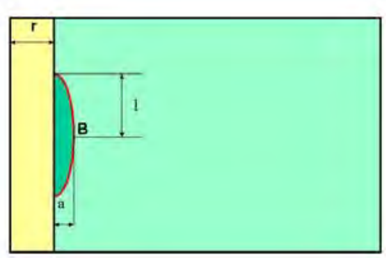
Table 6: Tr1 transient description (typical SBLOCA)

Time in second	Pressure in MPa	Fluid temperature	Heat Exchange coefficient in W/m^2.°C
0	15.5	286	60000
50	10.9	226	60000
125	4	200	60000
240	3.6	178	60000
300	3.7	171	60000
310	3.7	170	3100
340	3.8	166	3100
480	4	112	2500
670	5.6	90	2300
720	6	90	2300
960	11	90	2300
1180	16.8	90	2300
7200	16.8	90	2300
8500	16.8	70	2300

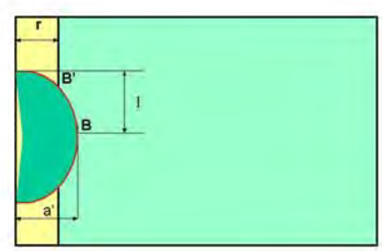
Table 7: Tr2 transient description (typical SLB)

Time in second	Pressure in MPa	Fluid temperature	Heat Exchange coefficient in $W/m^2.°C$
0	15,3	295	24125
45	7,8	287	24696
165	7,0	276	3453
255	7,3	279	1054
300	5,7	268	6232
375	5,5	261	1757
615	5,1	251	4834
1515	4,0	206	1581
2865	2,9	152	1838
4695	2,0	59	1147
6015	1,5	37	992
7125	2,5	48	877
7185	16,8	49	790
8970	17,1	69	602
13290	17,0	96	710
14025	17,1	106	1229
14985	17,1	115	1057

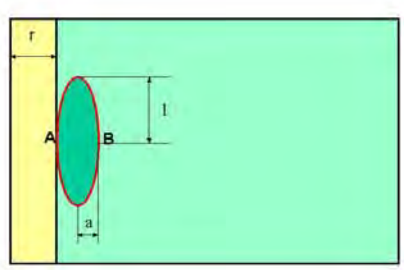
Table 8: Tr3 transient description (typical PTS with re-pressurization)



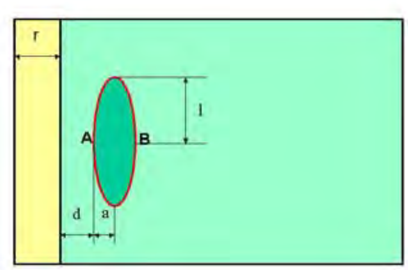
Model 1: - base metal surface defect
- a = 12mm ; 2l = 72mm
- cladding only considered for crack tip temperature and fluence evaluation, not for stress and K computation



Model 2: - surface breaking crack; a’=19.5mm
- a’ = 19.5mm ; 2l = 117mm



Model 3: - underclad crack
- a = 6mm ; l = 36mm



Model 4: - embedded crack
- d = 12mm ; a = 6mm ; l = 36mm

Table 9: Locations and shapes of defects

PHASE 1 – DEFINITION AND RESULT PRESENTATION

A deterministic approach based of mean value of each random parameters has to be done as a pre-requisite to assure a perfect fitting at this level of all interesting participants [5]. The crack will be located in a longitudinal weld, 2 types of cracks will be considered surface and underclad cracks.

PHASE 1 RESULTS

The first results are confirmed:

- good agreement on temperature, except participant2 and some that take 300°c at 0 second (see figure 1)
- some differences between material property temperature (fixed or connected to the temperature variations)
- large differences in K computation of surface crack that can be connected mainly to the K estimation scheme (see figure 2)
- large differences in K computation of underclad crack that can be connected to the stress evaluation, to the K estimation scheme or the plastic zone size correction (see figure 3)
- large difference between surface crack and underclad crack for initiation time or crack tip temperature at crack initiation. (compare figure 2 and 3)
- some difficulties with the RT_{NDT} evaluation at the crack tip due to the problem statement that is not completely clear

The second level of comparison through some detailed analysis confirm :

- a perfect agreement between 1 and 7 on underclad crack estimation for TR2
- some differences of K estimation between 1, 2 and 6 on surface crack estimation for TR1 mainly due to K estimation scheme: using a global stress fitting without any consideration of stress discontinuity at the clad-base metal interface like 2, and with a specific consideration of this discontinuity in a similar manner between 1 and 6.

PHASE 2 – DEFINITION AND RESULT PRESENTATION

RR1 : Toughness property distribution versus aging

RR1-a : data and results
RR1-b : data and results

RR2: Probability of crack initiation versus time for a given transient

RR2-a : Surface crack initiation versus time for a given transients
RR2-b : Probability of underclad crack initiation versus time for a given transient

RR3: probability of arrest of a surface crack for 2 given transients

RR4: probability of crack initiation for 1 crack in a crack size distribution

RR5 : Parametric studies

Consideration of: other transients, crack type, crack location, base metal / welds, plasticity correction, residual stress, master curve or other random variable are welcome. Some discussion of more interesting cases has been done.

PHASE 2 RESULTS ANALYSIS

Some phase 1 conclusions have been included in phase 2:

- all the material property have to be function of temperature
- the free stress state is obtained at 300°C (time before 0 second in the transient), at 0 second all the cylinder temperature is 286°C
- K estimation scheme has to be computed with the PROSIR statement attachment, through an elastic K computation + a plastic zone size correction Kβ (reference results from participant 1 and 7)
- Concerning the K_{IC} estimation the decrease formulae of fluence is in the PROSIR statement: $F = F_0 . e^{-0.0125x}$ mm, with x the distance of the crack tip to the base metal / clad interface and the unit for x is mm

The major results comparisons are presented from figure 1 to 5.

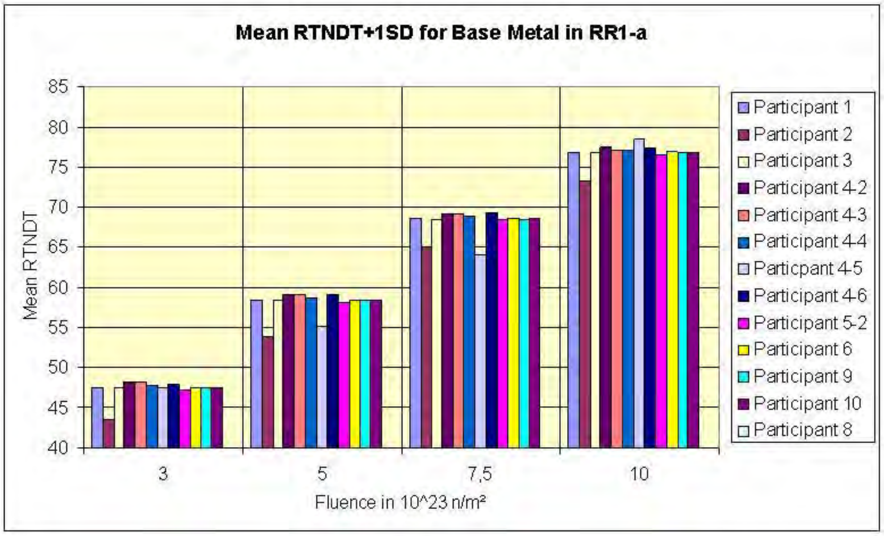


Figure 1 : RTNDT distribution result comparisons

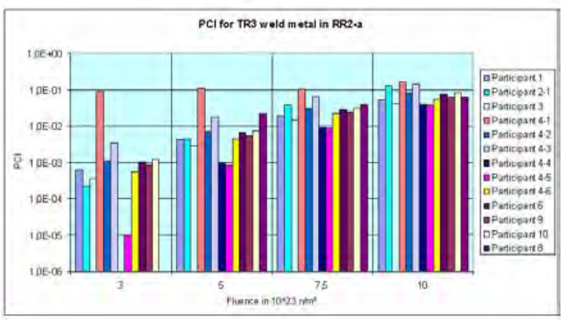


Figure 2 : Probability of crack initiation for surface crack and transient TR3

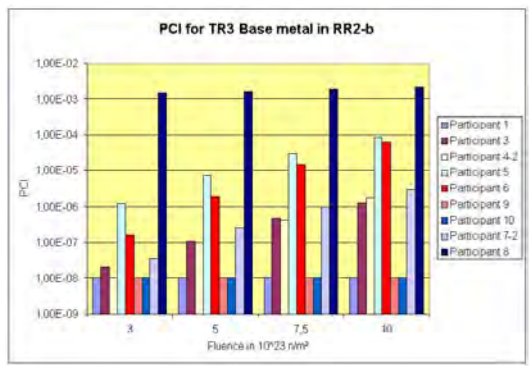


Figure 3 : Probability of crack initiation for underclad crack and transient TR3

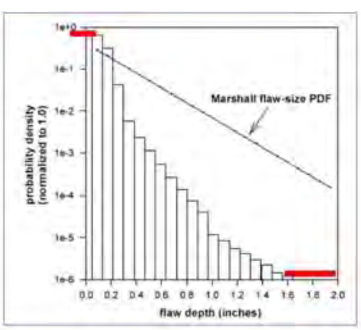


Figure 4 : Flaw distribution from PNNL

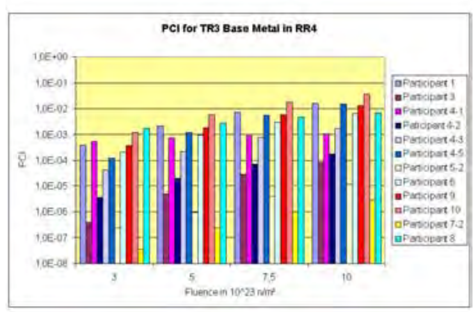


Figure 5 : Probability of 1 crack initiation for a flaw distribution for TR3

CONCLUSIONS

The phase 1 (deterministic approach) conclusions are :

- good agreement on temperature, except participant 2 and some that take wrong initial temperature
- some differences between material property variation with temperature (fixed or connected to the temperature variations)
- some differences in K computation of surface crack that is connected mainly to the K estimation scheme
- some differences in K computation of underclad crack that is connected to the K estimation scheme or the plastic zone size correction
- some difficulties with the RTNDT evaluation at the crack tip due to the problem statement not completely clear

All the difficulties have been discussed and finalized before the secong phase of PROSIR Round Robin.

The phase 2 (probabilistic approach) conclusions are :

- for RTNDT estimation :
  - very good agreement for toughness uncertainties propagation with vessel age (10, 20, 40, 60 years) : les than few degree on RTNDT
  - No major influence of the fluence uncertainties on RTNDT estimation, in our case
- for crack initiation for 1 defect (PCI) :
  - Less than 1 decade on PCI of SC
    including all the differences in participant models (see phase 1 results)
  - Around 2 decade in PCI of UCC due to criteria : with / without plasticity effects
- for crack initiation for a flaw distribution (PCI) :
  - Larger scatter in the results : up to 3 decade difference
  - Different uses of the flaw distribution

A simple thermal chock evaluation needs a large number of very precise data and method definitions.
For similar data and similar methods the results can be strongly different.
The type of initial defect (surface crack or embedded crack) is an important hypothesis.
The need of determinist approaches based on mean value of each parameters is a key issue to compare probabilistic methods and results.

REFERENCES

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