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

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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) are now involved in the round robin defined in 2 phases:

- deterministic approach
- probabilistic approach

This paper presents the major hypothesis, the results of the first phase and the definition of the second phase that will start mid of 2005.

Keywords: structural integrity, probalistic fracture mechanic, reactor pressure vessel

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 are proposed and will be discussed with the different partners before moving to probabilistic approaches.

Any sensitivity studies around the base case (longitudinal weld) are welcome and will be discussed during meetings in 2003- 2004.

The final recommendations of phase 2 have to be available for June 2005, in order to prepare a workshop before end of 2005, or beginning of 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:

Table 1: Thermal material properties

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

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 2-a: Mechanical material properties – General

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-b: Mechanical material properties – Stress-strain curves

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

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 4: Chemical composition and initial RT_{NDT}

	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 5: Shift formula and corresponding uncertainties

Base metal	mean	$\Delta RT_{NDT} = [17.3+1537*(P-0.008)+238*(Cu-0.08)+191*Ni^2Cu]*\varphi^{0.35}$
	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 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	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

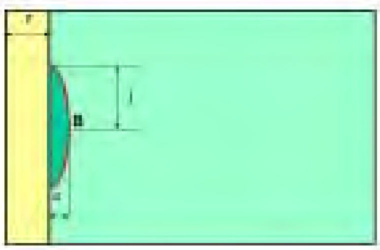
Table 7: Tr2 transient description (typical SLB)

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

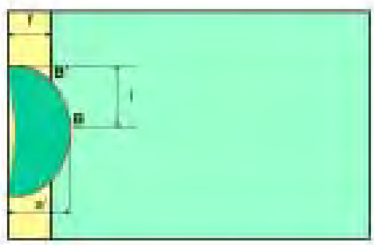
Table 8: Tr3 transient description (typical PTS with re-pressurization)

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

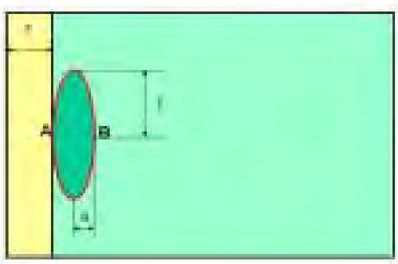
Table 9: Locations and shapes of defects



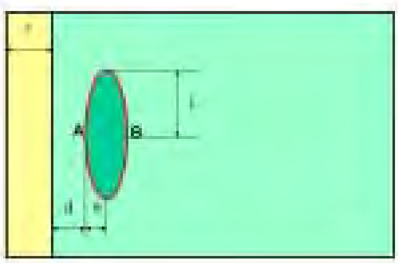
Model 1: - base metal surface defect
- a = 12mm ; 2l = 72mm
- cladding only considered for crack tip temperature and fluence evaluation, not for stress and K computation



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

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. The crack will be located in a longitudinal weld, 2 types of cracks will be considered surface and underclad cracks.

PR1: Crack initiation of surface crack in RPV

PR1-a: surface crack (model 2) and transient Tr1, Tr2 and Tr3

by direct comparison of K_I and K_{IC}

outputs: crack initiation time in the transient; crack tip temperature, toughness at this time; K_I, K_{IC} versus temperature plot for different base metal inner surface RT_{NDT} (50; 100; 150; 200°C)

PR1-b: underclad crack (model 3) and transient Tr1, Tr2 and Tr3

by direct comparison of K_I and K_{IC}

outputs: crack initiation time in the transient; crack tip temperature, toughness at this time; K_I, K_{IC} versus temperature plot for different base metal inner surface RT_{NDT} (50; 100; 150; 200°C)

5.2. PR2: Crack arrest of an initial surface crack

Transient Tr1 and Tr3

Initial crack: surface crack, longitudinal, 19;5 mm x 117mm (model 2)

following the ASME procedure, at initiation time the crack has immediately an infinite aspect ratio

outputs: crack initiation time, crack arrest time in the transient, crack size at this time, crack front temperature, irradiation level and toughness at this time for different inner surface RTNDT (50, 100, 150 and 200°C), for base metal and weld metal

RR1 : Toughness property distribution versus aging

RR1-a : data and results

random parameters: initial RT_{NDT}, copper, phosphorus and nickel contents, RT_{NDT} shift

non-random parameters: fluence

RT_{NDT} distribution: mean value and SD for different level of fluence

RR1-b : data and results

random parameters: initial RT_{NDT}, copper, phosphorus and nickel contents, RT_{NDT} shift, fluence in 10^{23} n/m^2

non-random parameters: none

RT_{NDT} distribution: mean value and SD for different level of RPV age

Corresponding plots on EXCEL sheet

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

RR2-a : Surface crack initiation versus time for a given transients

random parameters: toughness distribution from RR1

non-random parameters:

vessel geometry

defect : longitudinal, model 2, in base metal or weld (weld as base case)

1 transient for the base case : Tr3

fluence decrease through the thickness (IS value = inner surface of RPV value)

thermal and mechanical material properties

Fracture mechanic model

Elastic K computation for surface crack with no plasticity correction (see appendix 2.1)

Crack initiation only at the deepest point B (for base case)

No residual stress, except the free stress temperature of 300°C

Results:

for Tr3 transient, PCI: probability of crack initiation (K_I>K_{IC}) for one defect in weld or in base metal versus vessel age : 10; 20; 40; 60 years of operation corresponding to 3; 5; 7.5 and 10. 10^{23} n/m^2 fluence (mean inner surface value)

Time in the transient of the maximum PCI

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

Data:

random parameters:

same as RR2-a

non-random parameters:

same as RR2-a

except defect : longitudinal, model 3, in base metal or weld (weld as base case)

Fracture mechanic model

Elastic K computation for underclad crack with plasticity correction (d=0); see appendix 2.2

Crack initiation only at the deepest point B

No residual stress, except the free stress temperature of 300°C, same as RR2-a

Results:

same as RR2-a

for Tr3 transient, PCI: probability of crack initiation (KI>KIC) for one defect in weld or in base metal versus vessel age : 10; 20; 40; 60 years of operation corresponding to 3; 5; 7.5 and 10. 1023 n/m2 fluence (mean inner surface value)

Time in the transient of the maximum PCI

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

Data:

random parameters:

same as RR2-a

non-random parameters:

same as RR2-a

Fracture mechanic model

Elastic K computation for surface crack, same as RR2-a

ASME methodology for crack arrest: at crack initiation time the crack length will be immediately infinite

Crack initiation only at the deepest point B

No residual stress, except the free stress temperature of 300°C, as RR2-a

Results:

for Tr1 and Tr3 transient, PCI: probability of crack initiation (K_I>K_{IC}) and crack arrest (PCA) for the defect versus vessel age : 10; 20; 40; 60 years of operation corresponding to 3; 5; 7.5 and 10. 10^{23} n/m^2 fluence (mean inner surface value)

Time in the transient of the minimum PCA and corresponding crack size

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

Data:

random parameters:

as RR2-a

defect aspect ration a/2l = 1/6

flaw size distribution: PNLL as base case ; see appendix 1

non-random parameters:

as RR2-a

Fracture mechanic model

As RR2-a

Results:

for Tr3 transient, PCI: probability of crack initiation (K_I>K_{IC}) for one defect in weld or in base metal versus vessel age : 10; 20; 40; 60 years of operation corresponding to 3; 5; 7.5 and 10. 10^{23} n/m^2 fluence (mean inner surface value)

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 will be done.

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.

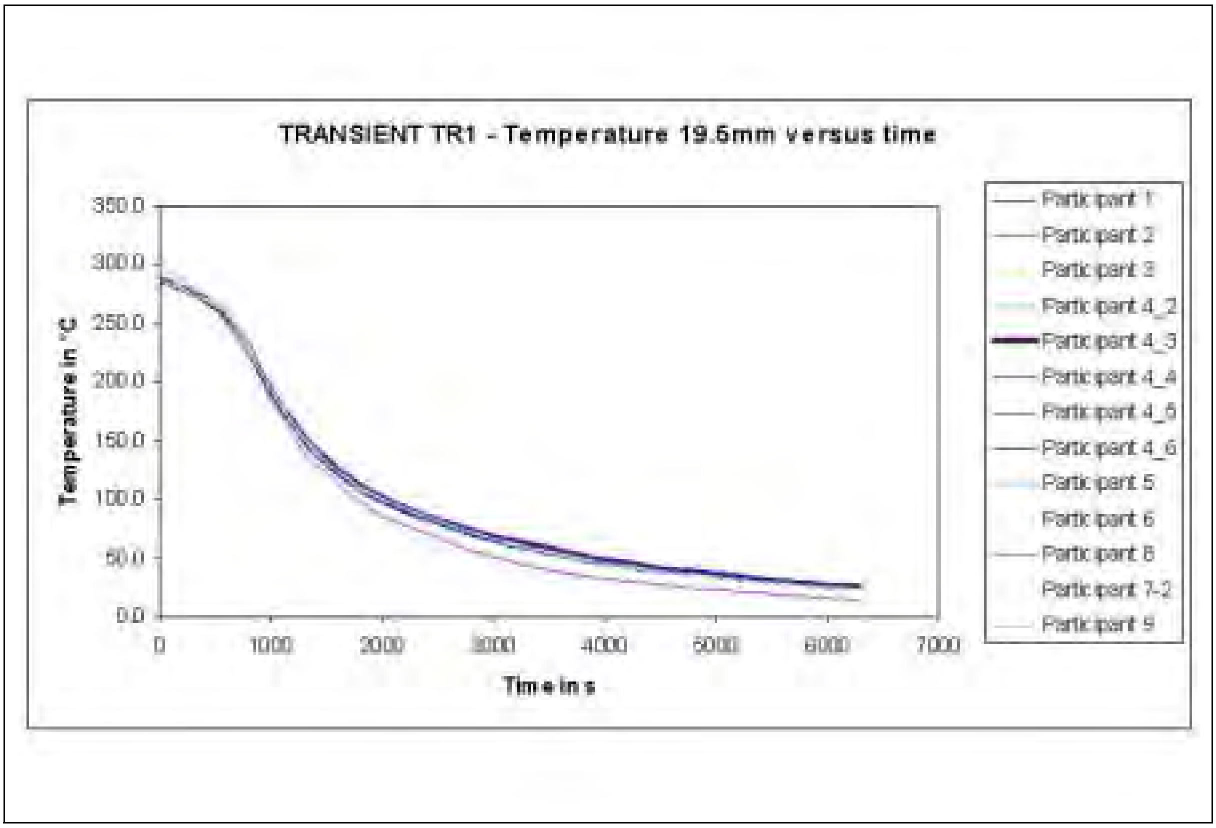


Figure 1 : Temperature variation at the crack tip versus time in transient TR1

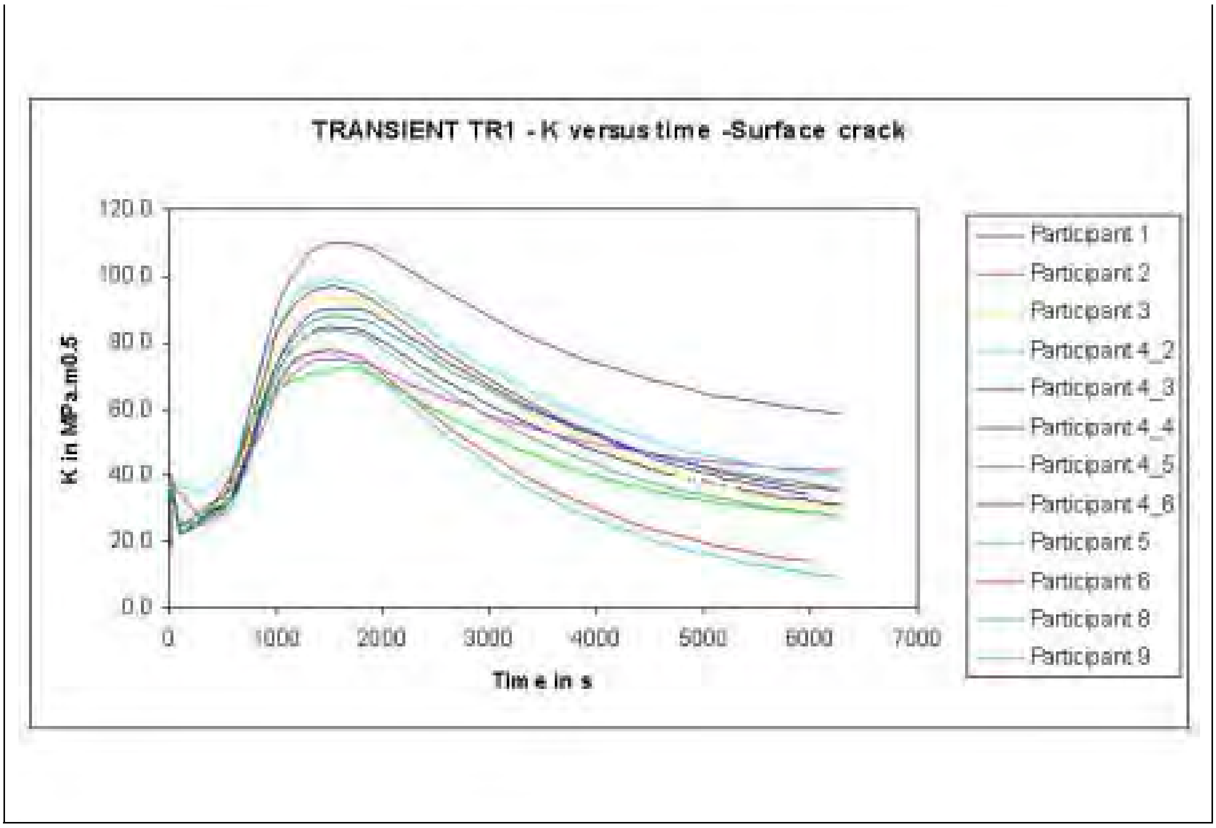


Figure 2 : K versus time for transient 1 and surface crack

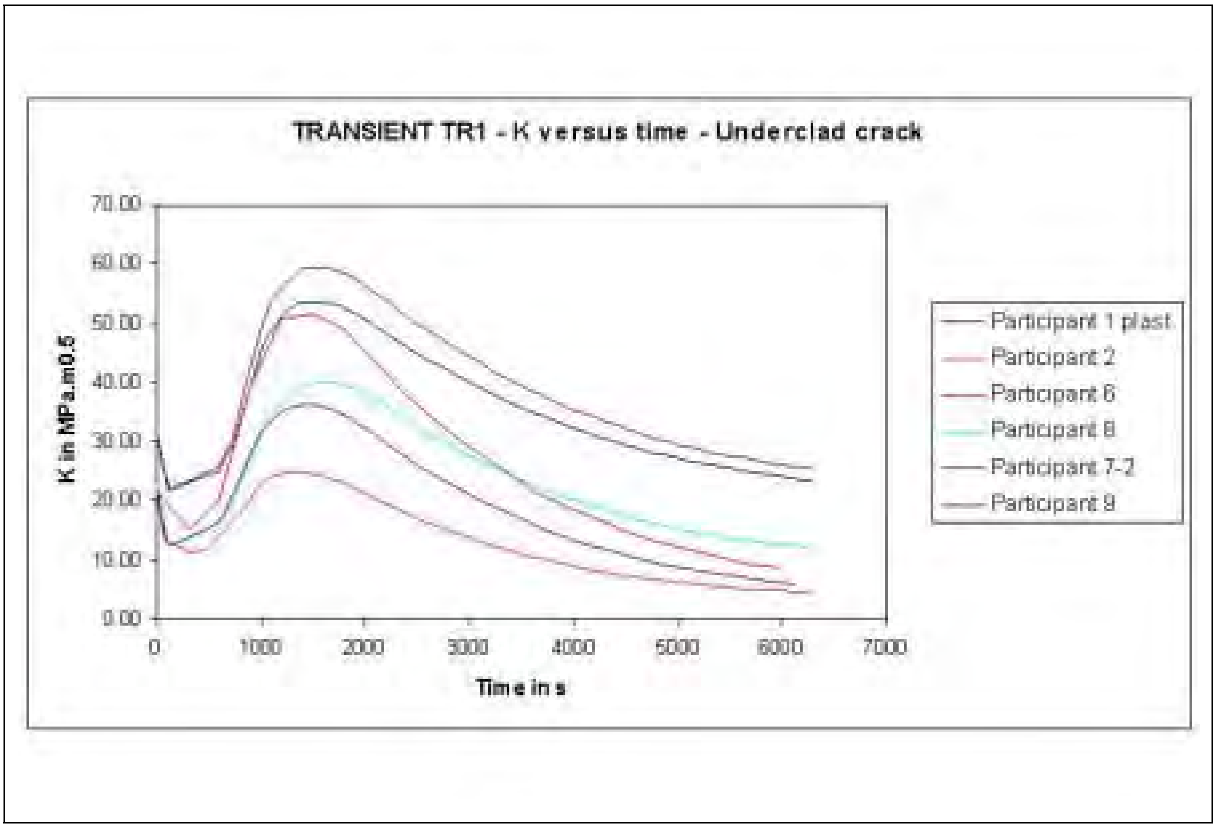


Figure 3 : K versus time for transient 1 and underclad crack

PHASE 2 REQUIREMENTS

Some phase 1 conclusions have to be 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

Finally phase 2 will be launched beginning of 2005 for RR 1 to 4.

CONCLUSIONS

It seems that a simple thermal chock evaluation needs 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

USNRC- 10CFR50-61 : "Fracture toughness requirements for protection against pressurized thermal shock events"

RG 1. 174 "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis", Revision 1 November 2002

FALSIRE : CSNI project for Fracture Analyses of Large- Scale International Reference Experiments, 1996

ICAS : Comparison Report of RPV Pressurised Thermal Shock International Comparative Assessment Study - PTS ICAS