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Probabilistic Structural Integrity of a Pressurised Water Reactor Pressure Vessel

Final Report

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes;
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The committee's purpose is to foster international co-operation in nuclear safety among NEA member countries. The main tasks of the CSNI are to exchange technical information and to promote collaboration between research, development, engineering and regulatory organisations; to review operating experience and the state of knowledge on selected topics of nuclear safety technology and safety assessment; to initiate and conduct programmes to overcome discrepancies, develop improvements and reach consensus on technical issues; and to promote the co-ordination of work that serves to maintain competence in nuclear safety matters, including the establishment of joint undertakings.

The priority of the CSNI is on the safety of nuclear installations and the design and construction of new reactors and installations. For advanced reactor designs, the committee provides a forum for improving safety-related knowledge and a vehicle for joint research.

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EXECUTIVE SUMMARY

PROSIR - Probabilistic Structural Integrity of a Pressurised Water Reactor (PWR) Pressure Vessel, was a round robin exercise with the primary objective to issue some recommendations of best practices when performing probabilistic analysis of a reactor pressure vessel (RPV). Another objective was to try to understand what the key parameters are in this type of approach. Following an NEA CSNI round robin activity proposal, 16 participants from 9 countries (the United States, Japan, Korea with 5 participants, Sweden, Germany, the Czech Republic, Spain, France with 4 participants and the European Commission) were involved in the round robin.

The project was divided into four steps, starting with a definition of the different parameters that should be considered when performing a probabilistic analysis of RPV. In the next step, several deterministic analyses to predict stress intensity factors and analyse crack initiation were performed to ensure that all the participants understood the problem definition from the previous step. Then the probabilistic part of the project was performed with the initial goal to predict the probability of initiation of crack growth for a given surface crack and an underclad crack. The next step considered a surface defect distribution. Finally, a probabilistic analysis of crack arrest for a given surface crack was performed.

In this report, the PROSIR project is summarised in a structured way and additional remarks are included to emphasise some parts of the project. Also included is a sensitivity analysis, which provides an understanding of the key driving parameters in the analysis and also discusses the effect of the assumed fracture toughness representation within PROSIR. Finally, the report provides some suggestions and recommendations regarding future probabilistic benchmarking.

The results of the probabilistic benchmark evaluations show large differences between participants in certain cases. The reasons for this wide difference are in most cases related to unclear problem definitions, differences in treatment of stresses in K-solutions, and user errors. Some of the biggest differences were provided by participants with the least experience in conducting deterministic and probabilistic fracture mechanics analyses.

Within the project, the following conclusions are made regarding key parameters for the probabilistic results:

- The parameter that contributes the most to the calculated conditional initiation probability is the 15% standard deviation on fracture toughness K_{Ic} (the ASME curve). There are also quite large contributions from the shift curve of nil-ductility reference temperature (RT_{NDT}) and the initial value of RT_{NDT}.
- The change of the mean value of the Phosphorus content (used in the definition of the RT_{NDT} shift curve) has the most influence on calculated conditional initiation probability. The change of mean value of copper content (also used in the definition of the RT_{NDT} shift curve) has the next most influence on the calculated conditional initiation probability.

For best practice it is recommended to use temperature dependent material properties in the analysis of the temperature distribution and stress analysis. This is particularly important for high amplitude thermal shock stress analysis and consequently for fracture mechanics parameter evaluation (K or J). Further it is recommended to use only verified and well-established K-solutions when performing the analyses. The chosen K-solution is an important part of fracture mechanics analysis for different stress distributions and different defect locations, especially in the vicinity of the cladding.

A necessary prerequisite for successful benchmarking of probabilistic fracture mechanics analyses is to have a consensus deterministic solution to a well-defined problem, i.e. participants must achieve a very tight band with respect to results for temperature (T), stress and stress intensity (K_I) versus time for the given defect.

Only after reaching such a deterministic consensus should participants focus on the probabilistic methodology that involves determining:

- variables to be treated probabilistically;
- how each of the uncertainties are propagated through the probabilistic methodology; and
- how they impact the probabilistic solutions, i.e. the conditional probability of crack initiation.

In order to perform probabilistic crack initiation analysis within a benchmark a few general recommendations are made:

- Use a well-defined and verified deterministic fracture mechanics model.
- Use clear specifications in the problem statement and assumptions, for example specify whether cracks originate from inner surface or from base metal/cladding interface.
- Particular attention should be devoted to the cladding transition to base metal regarding stresses, *K*-solutions, fracture toughness and defect definition.
- Probabilistic fracture mechanics evaluations require a lot of sensitivity studies, associated with a large number of deterministic analyses in order to confirm the effects of different data or models.
- A formal validation-verification program should be developed/performed for each computer program containing the probabilistic models.

The lessons learnt from PROSIR offer some suggestions regarding future probabilistic benchmarking in area of fracture mechanics analysis. The probabilistic problem statement for the exercise should have a solution, which should be properly defined, verified and documented by the responsible organisation before distributed for launching the benchmark. The problem statement should prescribe deterministic solutions for benchmarking cases in adequate detail, e.g. definition of base cases with examples of deterministic solutions for T(t) and KI(t) at the appropriate crack tip.

In addition a successful benchmark should include steps for verifying results of participants for the initial calculation problem and for guiding them to the complicated probabilistic solutions for increasing levels of complexity. In more complex problem statements the incorporation of correlation(s) that are a function of neutron fluency and chemistry to generate values of ΔRT_{NDT}, rather than sampling each value of RT_{NDT} from a distribution, could be used. Furthermore with respect to recent crack indications in individual RPVs, multiple flaws in RPV regions having different chemistries and fluencies could be investigated.

LIST OF ABBREVIATIONS AND ACRONYMS

AFCEN	French Association for Design, Construction and Surveillance Rules of Nuclear Power Plant Components
ASME	American Society of Mechanical Engineers
CEA	French Alternative Energies and Atomic Energy Commission
CSNI	Committee on the Safety of Nuclear Installations
EC	European Commission
EDF	Électricité de France
FINAS	IAEA/NEA Fuel Incident and Notification and Analyses System
IAEA	International Atomic Energy Agency
IRSN	French Institute for Radiological Protection and Nuclear Safety
ISA	Integrated safety analysis
JAEA	Japan Atomic Energy Agency
KAERI	Korea Atomic Energy Research Institute
KINS	Korea Institute of Nuclear Safety
MCS	Monte Carlo simulation
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission
NRI	Czech Nuclear Research Institute
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
PCI	Probability of crack initiation
PCA	Probability of crack arrest
PFM	Probabilistic fracture mechanics
PNNL	Pacific Northwest Laboratory
PROSIR	Pressurised Water Reactor Probabilistic Structural Integrity
PTS	Pressurised thermal shock
PWR	Pressurised water reactor
RCCM-RSEM	A code for in-service-inspection, surveillance, monitoring, maintenance and flaw evaluations, written by AFCEN
RPV	Reactor pressure vessel
SBLOCA	Small-break loss-of-coolant accident
SD	Standard deviation (sta. dev.)
SLB	Steam line break
WGIAGE	Working Group on Integrity and Ageing of Components and Structures

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1. INTRODUCTION

PROSIR (Probabilistic Structural Integrity of a PWR Reactor Pressure Vessel) was a round robin exercise with the primary objective to issue some recommendations of best practices when performing probabilistic analysis of a RPV. Another objective was to try to understand what the key parameters are in this type of probabilistic approach.

One motivation for carrying out this round robin exercise is related to probabilistic analysis of PTS (Pressurised Thermal Shock) transients or cold over-pressure transients that are important potential transients that can affect the RPV (Reactor Pressure Vessel) safety margins. This type of transient experiences all five of the following conditions:

1. rapid cooling of the primary system,
2. continuation of that cooling to a low temperature,
3. maintenance of high primary system pressure, or re-pressurisation,
4. presence of a crack near the vessel inner surface,
5. significant irradiation embrittlement of the vessel material at the crack's location, which can substantially decrease the material fracture toughness against brittle fracture.

The US pressurised thermal shock (PTS) screening Criteria on RT_{NDT} of RPV of PWR [1] is based on a generic probabilistic fracture mechanics approach. On the other hand, if a plant is supposed to over-pass the screening criteria, the Regulatory Guide RG 1.174 [2] defines the requirements based on a justification through a probabilistic approach.

Following an OECD NEA round robin proposal, 16 participants from 9 countries (USA, Japan, Korea 5 participants, Sweden, Germany, Czech Republic, Spain, EC and France 4 participants) was involved in the round robin. The PROSIR project then started in 2003 and the analyses were finalised in 2007. A final draft version of the main report of the project was sent out in 2011. However, the draft report was never finalised.

Table 1.1 List of the original PROSIR participants

Number	Participant	Country
1	ORNL	USA
2	AREVA-Gmbh	Germany
3	NRI	Czech Republic
4.2	KOPEC2	Korea
4.3	KAERI3	Korea
4.4	KAERI4	Korea
4.5	KINS5	Korea
4.6	KINS6	Korea
5.1	CEA-Saclay	France
5.2	CEA-Cadarache	France
6	JAEA/JAERI	Japan
7.1	EDF Eng	France
7.2	EDF R&D	France
8	Inspecta	Sweden
9	IE-JRC	EC (Netherlands)
10	TECNATOM	Spain

In this report the PROSIR round robin is presented together with additional remarks from Inspecta (participant number 8) in order to meet the project objectives with regard to the key parameters in this type of approach. Also, some remarks are given by ORNL (participant number 1) to get an updated perspective on the PROSIR project.

The project was divided into four steps (phases) starting with a definition of the different parameters that should be considered when performing a probabilistic analysis of RPV. In the next step several deterministic analyses were performed to ensure that all the participants had understood the problem definition from the previous step. Then the probabilistic part of the project, related to initiation of crack growth, was performed. Finally one tried to perform a probabilistic analysis of crack arrest.

2. PHASE 0 – GENERAL PROBLEM DEFINITION

2.1 RPV geometry and material data

For the baseline case a PWR Reactor Pressure Vessel was chosen for the analysis, it had an internal radius of 1994 mm, a total wall thickness of 207.5 mm (with a cladding thickness of 7.5 mm). All the relevant material data were defined (for the base metal, weld metal and the cladding). Typical data for thermal expansion coefficient, conductivity, diffusivity and density are given in Table 2.1. Data for yield strength, Young modulus, Poisson's ratio and stress-strain curve are given in Tables 2.2-2.3. Fracture toughness data K_{Ic} and K_{Ia} (ASME curve or upper shelf toughness) can be found in Table 2.4. Also relevant for this analysis are data for initial RT_{NDT} (the Reference Temperature for Nil Ductility Transition), copper content, nickel content and phosphorus content that can be found in Table 2.5. Fluence φ on the inner surface (as a function of time) are given in Table 2.6. Finally, the definitions of the shift of the ASME curve as a function of fluence are given in Table 2.7.

Table 2.1 Thermal material properties

	Temperature [°C]	Base metal and welds	Cladding
Thermal expansion in [10^{-6}.°C^{-1}]	20	10.9	16.4
	300	12.9	17.7
Conductivity λ [Wm^{-1}°C^{-1}]	20	54.6	14.7
	300	45.8	18.6
Diffusivity μ [$10^{-6}m^2s^{-1}$]	20	14.7	4.1
	300	10.6	4.3
Density ρ [kg/m^3]	20-300	7600	7600

Table 2.2 Mechanical material properties – General

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

Table 2.3 Mechanical material properties – Stress-strain curves

Total strain		0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
σ/S_y 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 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 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 2.4 Toughness curve and uncertainties for un-irradiated weld and base metal

Note 1: Mean values - 2 SD = ASME curves Note 2: K_{Ia} has to remain lower or equal than K_{IC} Note 3: K_{Ia} has to remain greater than 0.	Crack initiation	$K_{Ic} = 36.5 + 3.1\exp\left(0.036\left(T - RT_{NDT} + 55.5\right)\right)$ $K_{Ic,\max} = 220\,\text{MPa}\sqrt{\text{m}}$
	Crack arrest	$K_{Ia} = 29.4 + 1.4\exp\left(0.026\left(T - RT_{NDT} + 88.9\right)\right)$ $K_{Ia,\max} = 220\,\text{MPa}\sqrt{\text{m}}$
1 SD (Standard deviation)	For crack initiation	15% on K_{Ic} 15 MPa√m on $K_{Ic,max}$
	For crack arrest	10% on K_{Ia} 15 MPa√m on $K_{Ia,max}$
Note 4: K_{Ic} and K_{Ia} follows a normal distribution that is truncated between +3SD and –3SD.		

The fracture toughness (in the transition region), the fracture toughness (at the upper shelf), the fracture toughness at arrest and the RT_{NDT} shift curve are truncated between -3 sta.dev. and +3 sta.dev. Using truncation in the parameter distributions lead to difference in the results compared to not using truncation. Inspecta did a test and treating these parameters as not being truncated may give a difference of 1-2 decades (using simple Monte Carlo simulation). Also there is the possibility of incorrect treatment of the transition from upper shelf toughness to toughness in the transition region.

Table 2.5 Chemical composition and initial RT_{NDT}

	Initial RT_{NDT}	1 SD	% copper (Cu)	2 SD
Base metal	-20°C	9°C	0.086	0.02
Welds	-30°C	16°C	0.120	0.02

	% phosphorus (P)	2 SD	% nickel (Ni)	2 SD
Base metal	0.0137	0.002	0.72	0.1
Welds	0.0180	0.002	0.17	0.1

Table 2.6 Fluence □ on the inner surface (as a function of time)

Time [year]	1	10	20	40	60
Fluence φ [n/m^2]	$1{\cdot}10^{23}$	$3{\cdot}10^{23}$	$5{\cdot}10^{23}$	$7.5{\cdot}10^{23}$	$10{\cdot}10^{23}$

Note: 2 SD value is 20% on φ.

The irradiation decrease through the RPV wall is given by $F = F_0\ e^{-0.125x}$ (for $0 < x < 0.75t$), where x is given as 10^{-2} m from the crack tip to the base metal / clad interface.

Table 2.7 The shift of the ASME curve (□RT_{NDT}) as a function of fluence

Base metal	Mean	$\Delta RT_{NDT} = \left[17.3 + 1537\cdot(P-0.008) + 238\cdot(Cu-0.08) + 191\cdot Ni^2\cdot Cu\right]\varphi^{0.35}$
	1 SD	10°C
Weld	Mean	$\Delta RT_{NDT} = \left[18 + 823\cdot(P-0.008) + 148\cdot(Cu-0.08) + 157\cdot Ni^2\cdot Cu\right]\varphi^{0.45}$
	1 SD	6°C

Note 1: ΔRT_{NDT} follows a normal distribution that is truncated between +3SD and –3SD.

Note 2: Fluence is given in n/m^2 divided by 10^{23}; *P, Cu, Ni*: is % of phosphorus, copper and nickel.

2.2 Defect assumptions

For the baseline case, surface and internal (underclad) defects oriented in the axial direction are included in the analysis. Three different defect assumptions are used in the probabilistic analysis:

1. A semi-elliptical surface defect with a fixed size according to Figure 2.1 (depth = 19.5 mm, total length = 117 mm).
2. An elliptical internal defect with a fixed size according to Figure 2.2 (total depth = 12 mm, total length = 72 mm). This defect is also called an underclad defect because it touches the interface between the cladding and the base/weld material.
3. A semi-elliptical surface defect depth distribution. It is assumed that this defect is only present in base/weld material (and not in the cladding). This defect distribution is (within PROSIR) called the Marshall/PNNL-distribution and can be found in Figure 2.3.

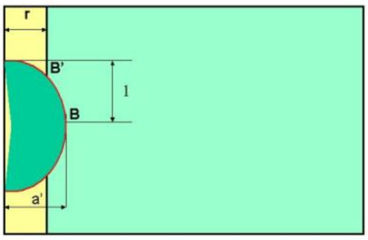

Figure 2.1 A semi-elliptical surface defect (a' = 19.5 mm, $2l$ = 117 mm)

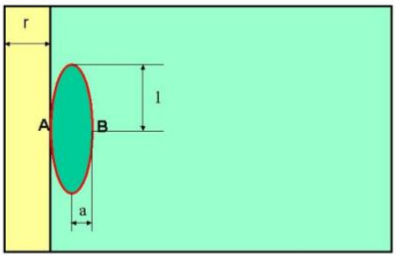

Figure 2.2 An elliptical internal defect (a = 6 mm, l = 36 mm)

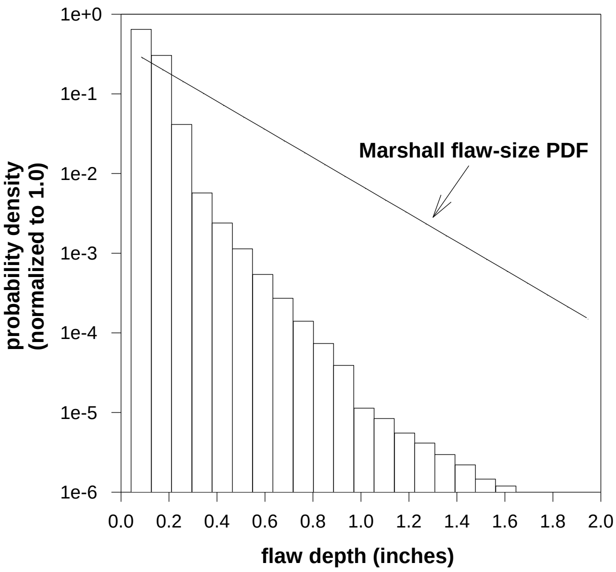

Figure 2.3 The Marshall/PNNL defect depth distribution compared with the original Marshall distribution.

In Figure 2.3 the semi-elliptical surface defect depth distribution is illustrated. When implementing this distribution, some participants considered the inner surface as the start of the distribution and other started the distribution at the base metal/cladding interface. Another difference was that some used both an upper and a lower truncation of the distribution. And finally some used a bi-linear approximation (see Figure 2.4) while other used tabulated values (see Figure 2.3) or a linear approximation of the bi-linear curve. Inspecta did a test and this could give a difference of approximately 1 decade (larger if upper shelf toughness dominates the analysis).

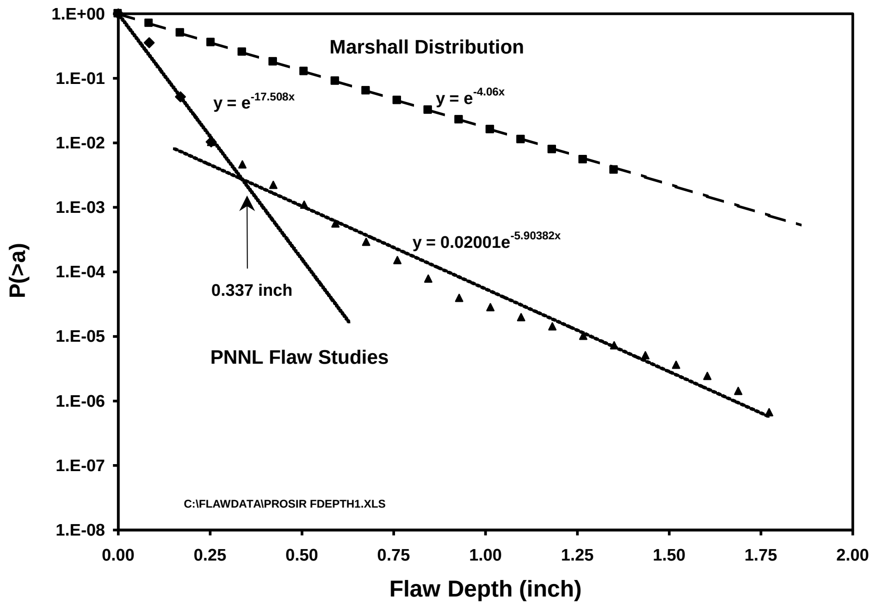

Figure 2.4 The PNNL defect depth distribution (used in PROSIR) compared with the original Marshall distribution

2.3 Transients and other assumptions regarding loads and stresses

For the baseline cases, three different transients were considered:

Tr1 Close to a typical SBLOCA (Small-Break Loss-Of-Coolant Accident).
Tr2 Close to a typical SLB (Steam Line Break).
Tr3 Close to a typical PTS (Pressurised Thermal Shock) with re-pressurisation.

The temperature variation as a function of time in the transients is found in Figure 2.5. The pressure variation as a function of time in the transients is found in Figure 2.6. More details are found in Tables 2.8-2.10.

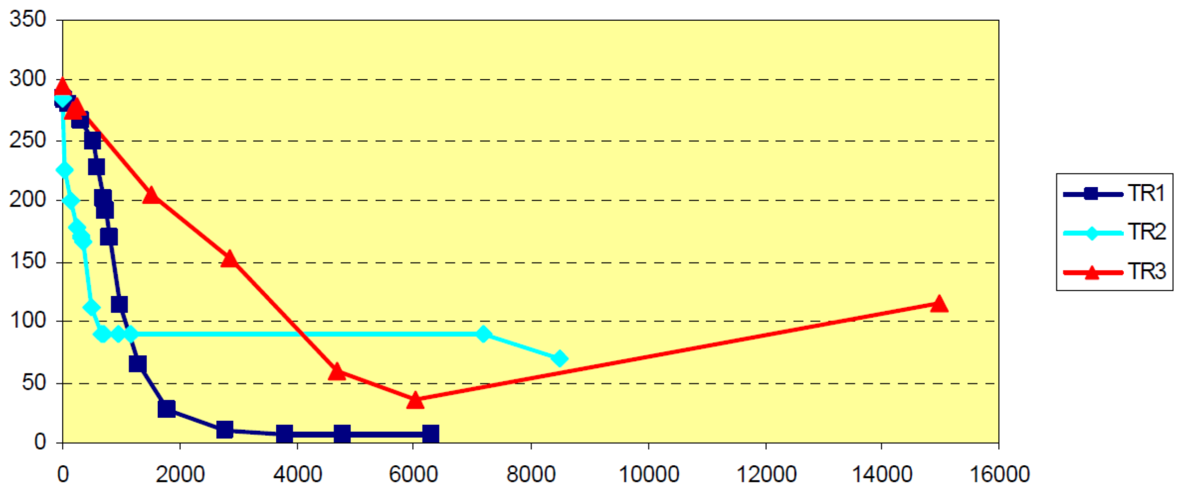

Figure 2.5 The temperature variation as a function of time

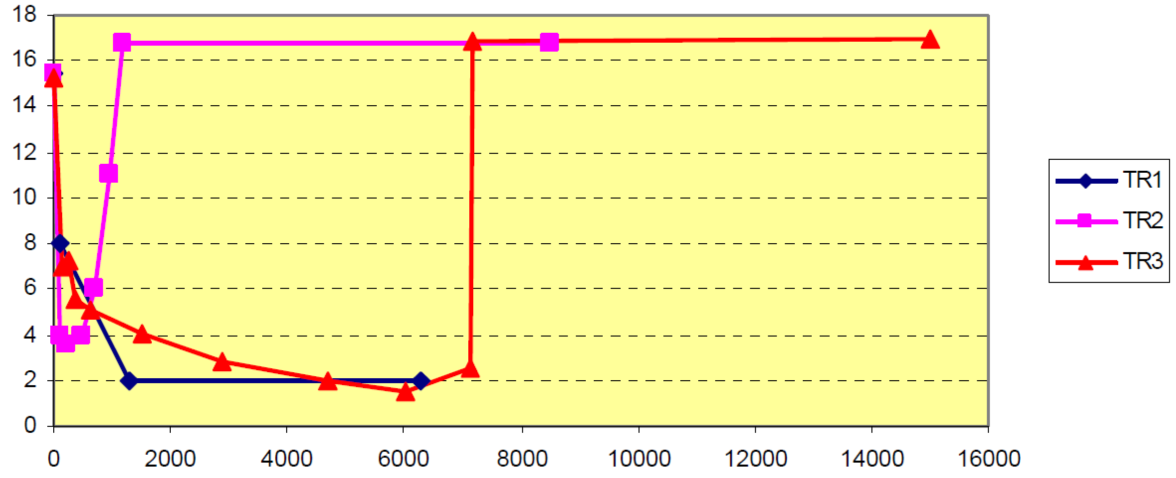

Figure 2.6 The pressure variation as a function of time

Table 2.8 TR1 transient description (a typical SBLOCA)

Time [s]	Pressure [MPa]	Water temperature [°C]	Heat exchange coefficient [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 2.9 Tr2 transient description (a typical SLB)

Time [s]	Pressure [MPa]	Water temperature [°C]	Heat exchange coefficient [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 2.10 Tr3 transient description (a typical PTS with re-pressurisation)

Time [s]	Pressure [MPa]	Water temperature [°C]	Heat Exchange coefficient [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

For the baseline case, no residual stresses were included in the analysis.

2.4 Assumptions regarding parameters that are considered to be probabilistic

Below is a short description regarding the parameters that are considered to be probabilistic (for the baseline cases). Please note that there are 20 probabilistic parameters in the analysis. All parameters follow a normal distribution except the defect depth that follows an exponential distribution.

- The mean value of the fluence (on the inner surface) is given as a function of time. The standard deviation is 10% of the mean value (see Table 2.6).
- The defect depth distribution is given in Figure. 2.3.
- The mean value of the yield strength is given as a function of temperature (for the base and weld material). The standard deviation is 30 MPa for the base material or 40 MPa for the weld material (see Table 2.2).
- The mean value of the Young modulus is given as a function of temperature (for the base and weld material). The standard deviation is 10 GPa (base/weld material, see Table 2.2).
- The mean value of the fracture toughness (in the transition region) is given by the ASME initiation curve (see Table 2.4). The standard deviation is 15% of the mean value. The fracture toughness distribution is truncated between -3 sta.dev and +3 sta.dev (see Table 2.4).
- The mean value of the fracture toughness (at the upper shelf) is 220 MPa$\sqrt{\text{m}}$. The standard deviation is 15 MPa$\sqrt{\text{m}}$. The fracture toughness distribution is truncated between -3 sta.dev and +3 sta.dev (see Table 2.4).
- Similar data are given for the fracture toughness at arrest (ASME arrest curve etc., see Table 2.4).
- The mean value of the initial RT_{NDT} is -20°C (base material) or -30°C (weld material). The standard deviation is 9°C for the base material or 16°C for the weld material (see Table 2.5).
- The mean value of the copper content is 0.086 (base material) or 0.120 (weld material). The standard deviation is 0.01 (base/weld material, see Table 2.5).
- The mean value of the nickel content is 0.72 (base material) or 0.17 (weld material). The standard deviation is 0.05 (base/weld material, see Table 2.5).
- The mean value of the phosphorus content is 0.0137 (base material) or 0.0180 (weld material). The standard deviation is 0.001 (base/weld material, see Table 2.5).
- The mean value of the RT_{NDT} shift is given by the shift curve (see Table 2.7, for the base material). The standard deviation is 10°C. The shift distribution is truncated between -3 sta.dev and +3 sta.dev. How the implementation of the truncation should be handled in a probabilistic way was not given in the problem definition.
- Similar data are given for the RT_{NDT} shift for the weld material (see Table 2.7).

To conduct analyses with this many probabilistic parameters is a challenge, especially if you wish to take into account the dependency between the input parameters. The latter is not included in this project.

3. PHASE 1 – DETERMINISTIC ANALYSIS

A deterministic approach based of mean value of each random parameter has been done as a prerequisite to assure a perfect fitting at this level of all the methods used by all the participants. The defect is considered axial, located in a longitudinal weld, 2 types of defects are considered (surface and internal (underclad), see Figure 2.1-2.2).

The reference solutions that were recommended in the PROSIR project and against which all other benchmark solutions were compared were:

- For elastic approaches (*K*-solutions): finite element method from NRI, FAVOR from ORNL, ProSACC from Inspecta, EDF using RCCM-RSEM values and CEA for surface breaking cladding defects.
- For *J* approach or elastic approach with plasticity correction: finite element method from NRI, EDF-CEA using RCCM-RSEM values.

3.1 Analysis of the thermal transients

First an analysis of all the transients was performed and temperatures and stresses through the thickness were calculated. In Figure 3.1-3.3 the temperature distributions are shown.

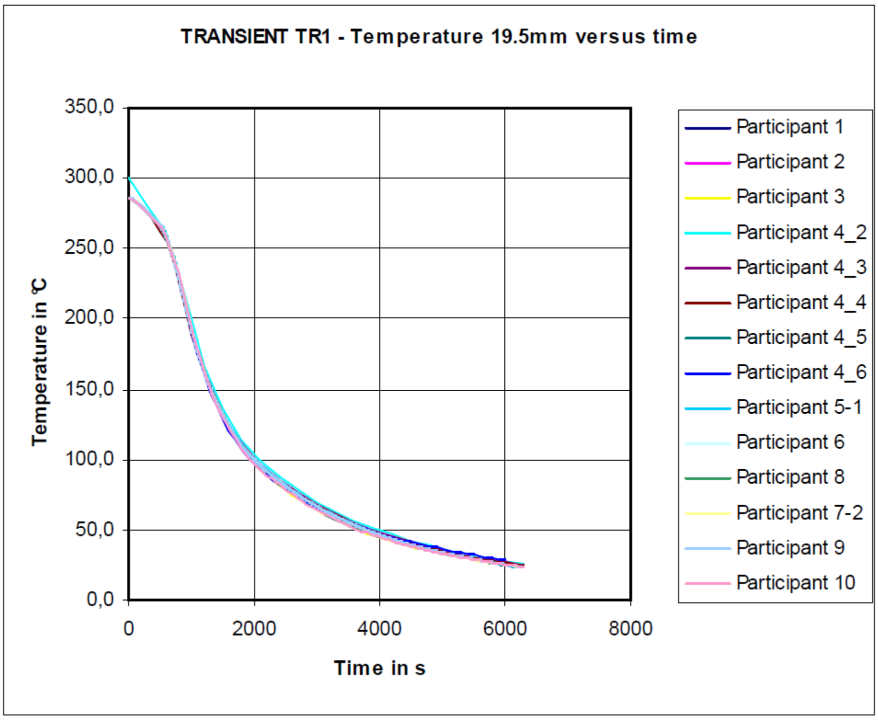

Figure 3.1 Temperature as a function of time in transient Tr1 (at a position equal to the crack tip)

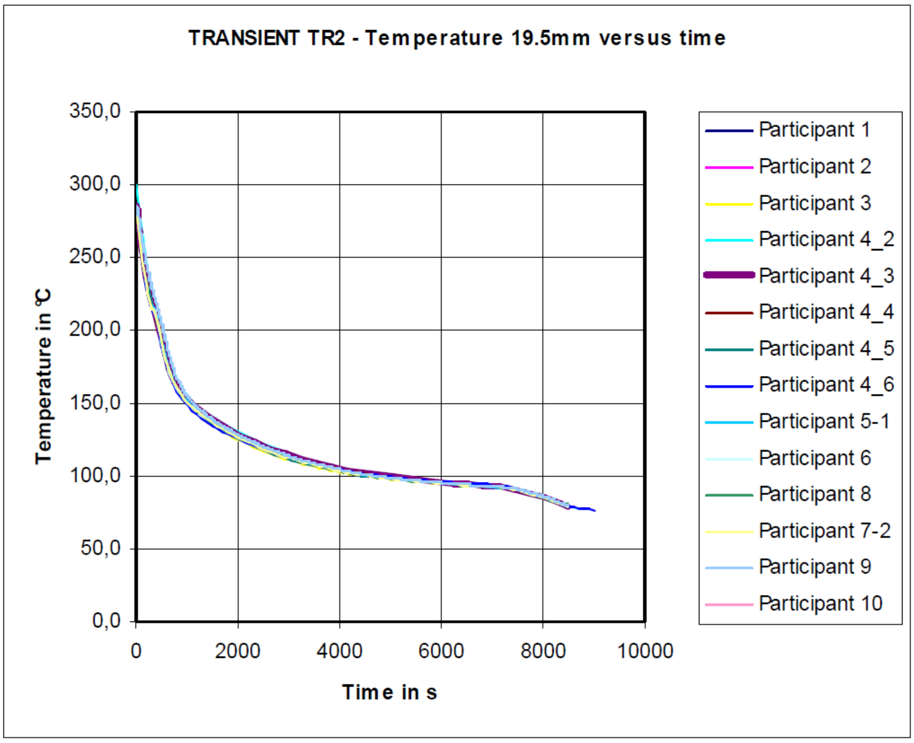

Figure 3.2 Temperature as a function of time in transient Tr2 (at a position equal to the crack tip)

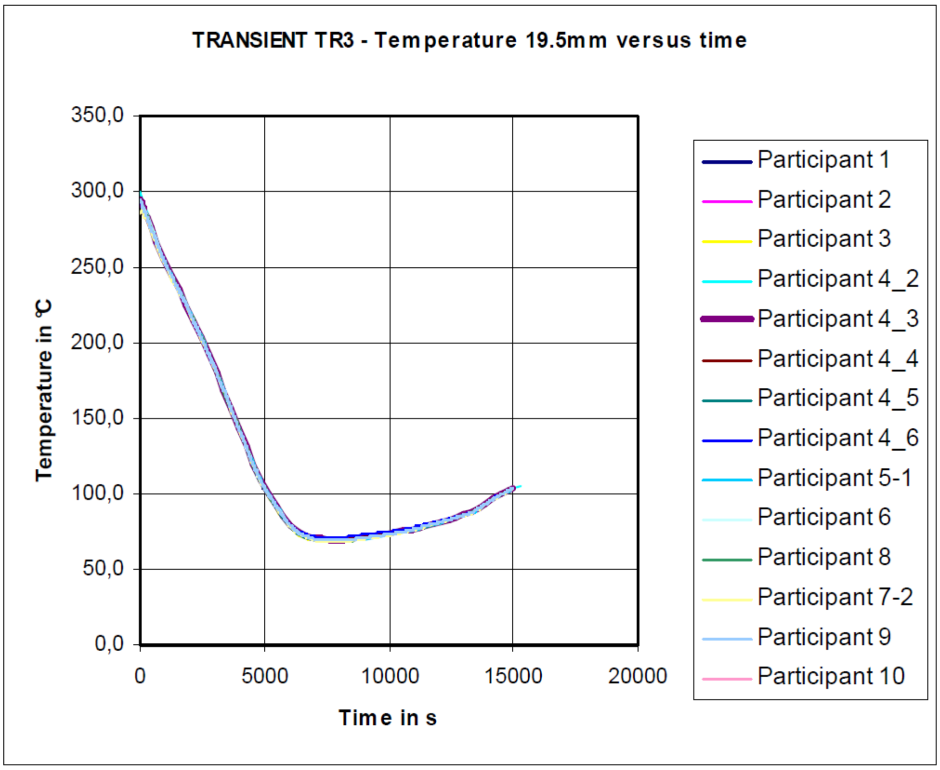

Figure 3.3 Temperature as a function of time in transient Tr3 (at a position equal to the crack tip)

In general there were a good agreement regarding temperature and stresses between all the participants. Some differences that could be found, see participant 4_2 in Figure 3.1, were mainly related to the handling of the stress free temperature or the handling of the temperature dependence of the material data.

3.2 Calculation of the stress intensity factor for a surface defect

Then, all the participants calculated the stress intensity factor (K_I) for a surface defect (see Figure 3.4-3.6).

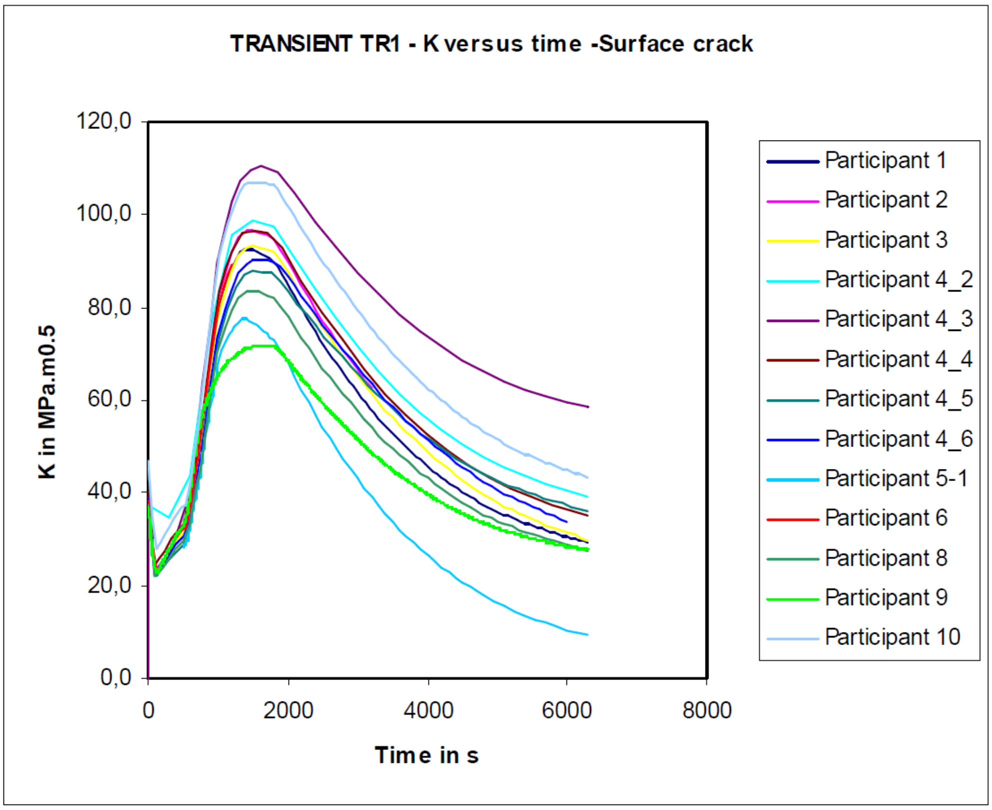

Figure 3.4 K_I as a function of time in transient Tr1 (a surface defect)

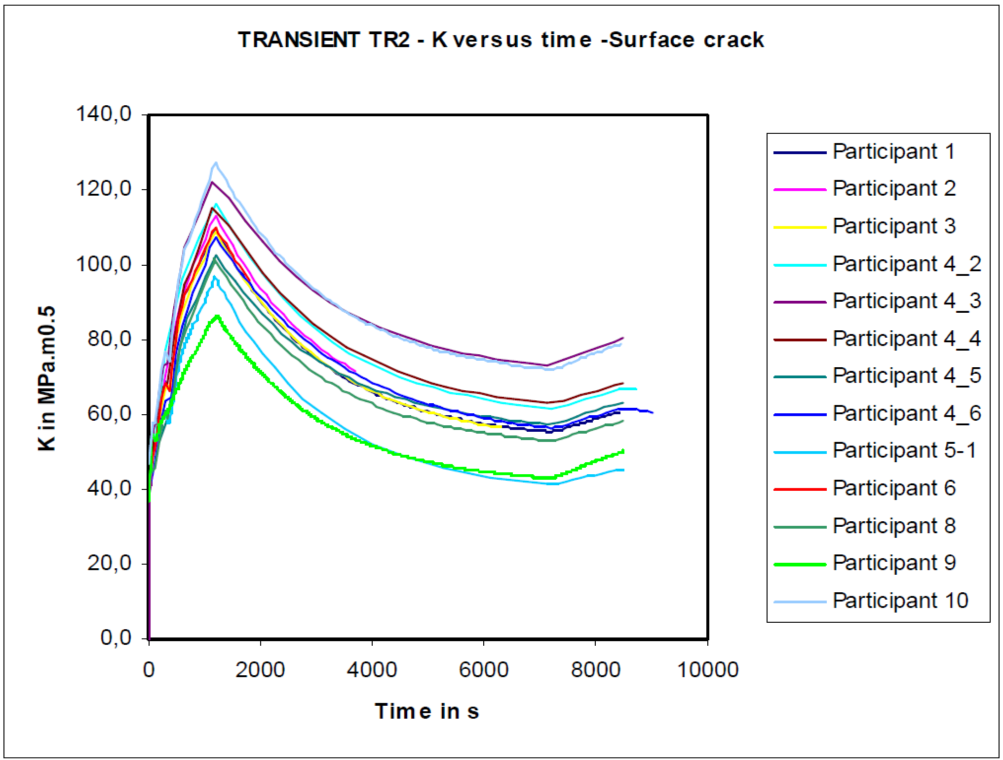

Figure 3.5 KI as a function of time in transient Tr2 (a surface defect)

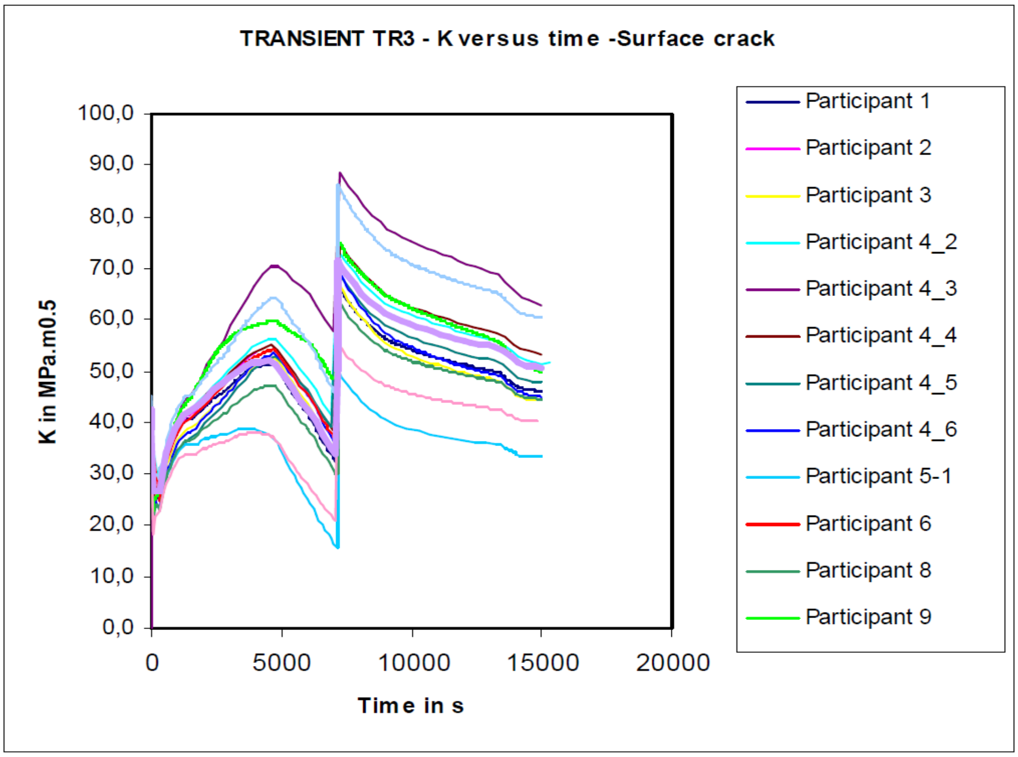

Figure 3.6 KI as a function of time in transient Tr3 (a surface defect)

For a surface defect, there were large differences in the calculation of K_I (see the examples in Figure 3.4-3.6). According to draft PROSIR report in 2010, this difference was mainly related to the chosen K_I-solution, especially how the different solutions handle the discontinuity found in the transition between the cladding and the base material. Inspecta investigated this further and noticed that this was perhaps more related to error in the implementation of the K_I-solutions (and not the chosen K_I-solution) from the different Korean participants (4-2 to 4-6). With error in implementation is meant when two or more participants use the same K_I-solution, they still get different results. Also a quite large difference in how the cladding induced stresses (with a discontinuity at the clad/base metal interface) were transferred to the K_I-solutions was found.

3.3 Calculation of the stress intensity factor for an internal defect

Then, all the participants calculated the stress intensity factor (K_I) for an internal defect (see Figure 3.7-3.9).

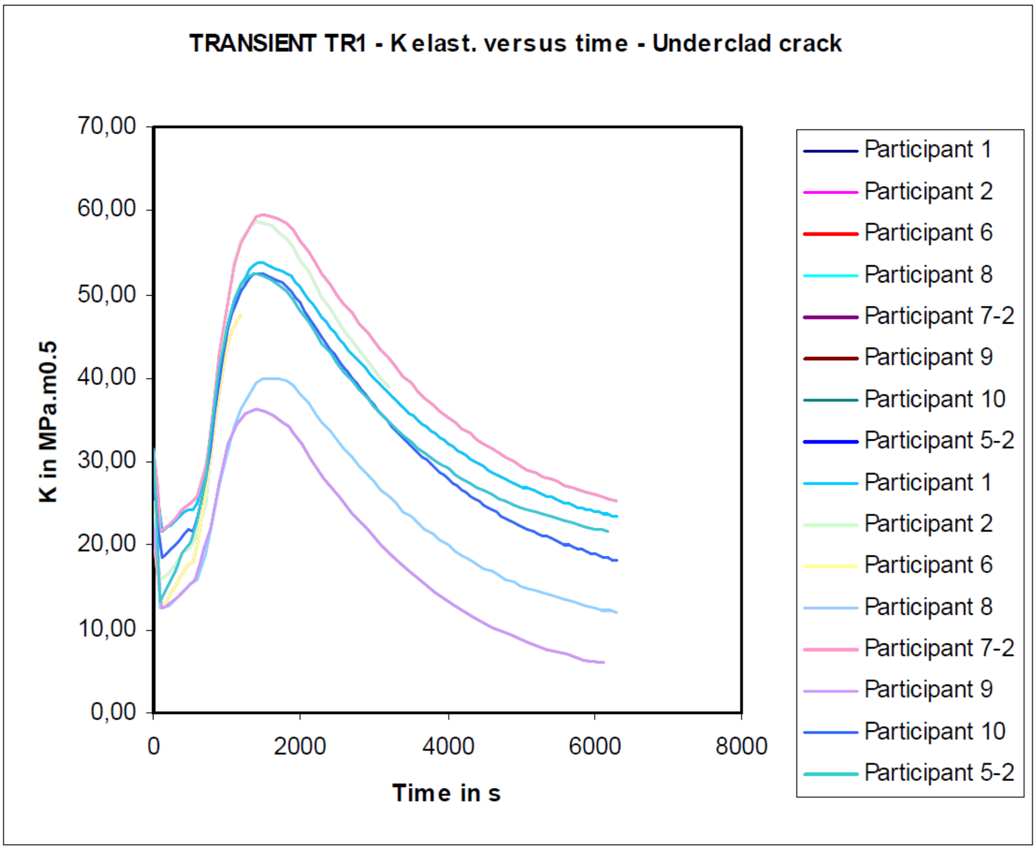

Figure 3.7 K_I as a function of time in transient Tr1 (an internal defect)

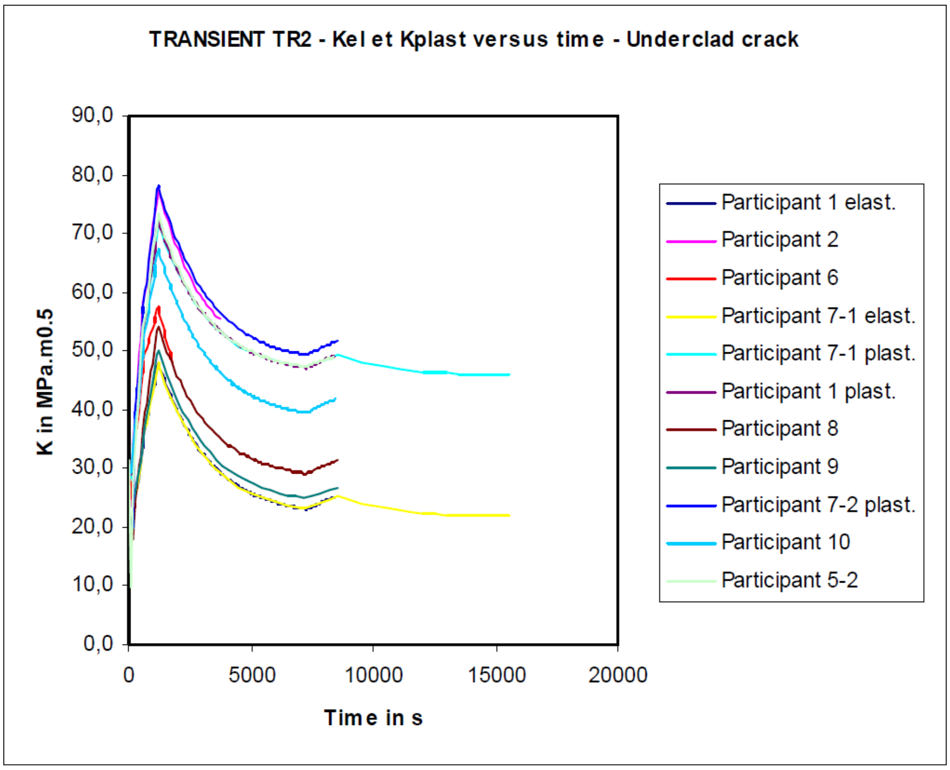

Figure 3.8 KI as a function of time in transient Tr2 (an internal defect)

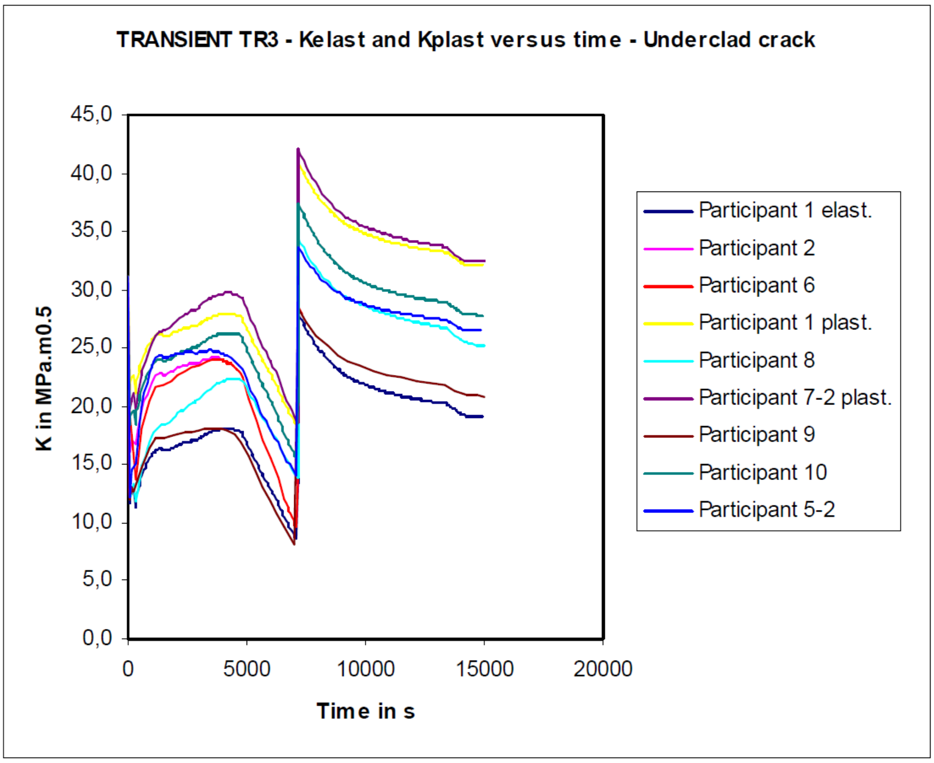

Figure 3.9 KI as a function of time in transient Tr3 (an internal defect)

For an internal defect (i.e. an underclad defect, evaluated at the deepest point B), there were also large differences in the calculation of K_I (see the examples in Figure 3.7-3.9). This difference was mainly related to the chosen K_I-solution, how the stresses were evaluated and if a plastic zone correction were used (see the example in Figure 3.9, which shows that the highest K_I-values corresponds to the participants who included a plastic zone correction). Inspecta investigated this further and came to the same conclusion (and noticed that the participants 4-2 to 4-6 were unable to get satisfactory results). The plasticity correction can increase the K_I-values up to 60% for the maximum K_I-value.

3.4 Calculation of crack initiation as a function of aging for a surface defect

Then, all the participants did a direct comparison between the stress intensity factor (K_I) and the calculated fracture toughness for a surface defect (see Figure 3.10-3.12). This comparison was made with an increasing amount of aging (i.e. increasing amount of irradiation embrittlement).

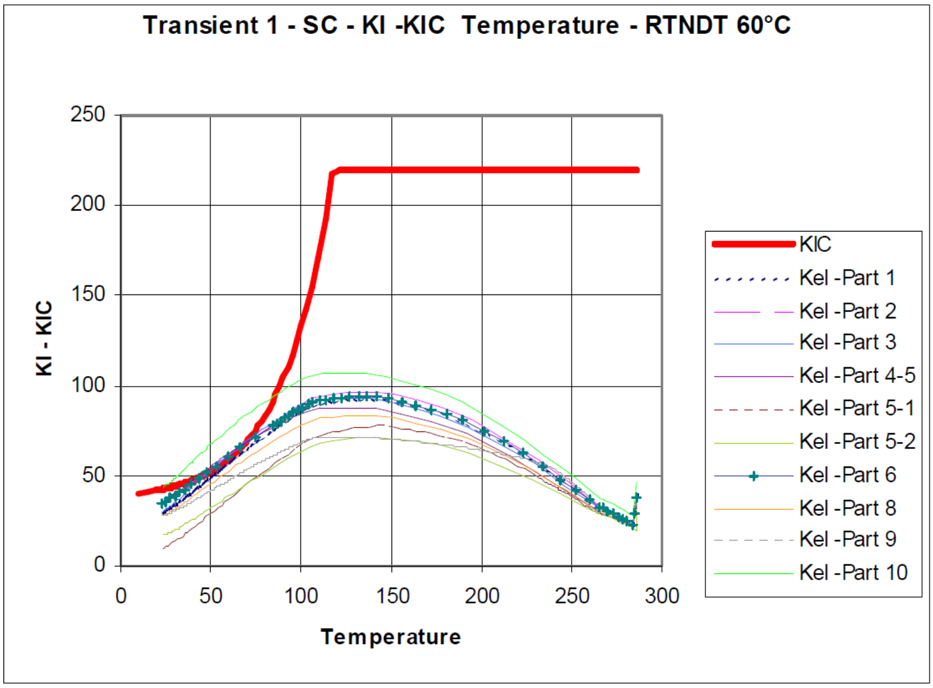

Figure 3.10 Comparison between the stress intensity factor (K_I) and the calculated fracture toughness for a surface defect (transient Tr1).

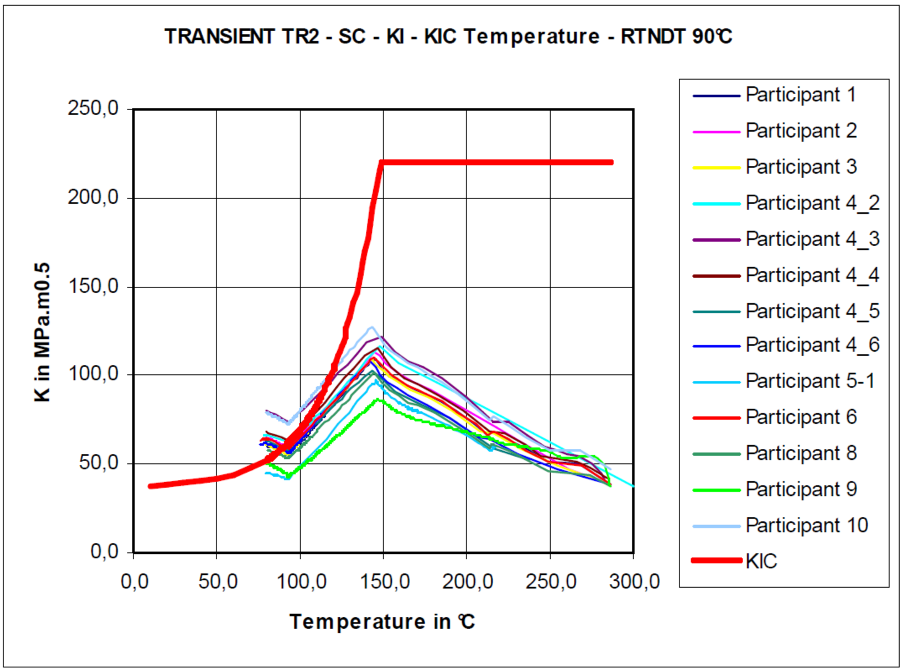

Figure 3.11 Comparison between the stress intensity factor (KI) and the calculated fracture toughness for a surface defect (transient Tr2).

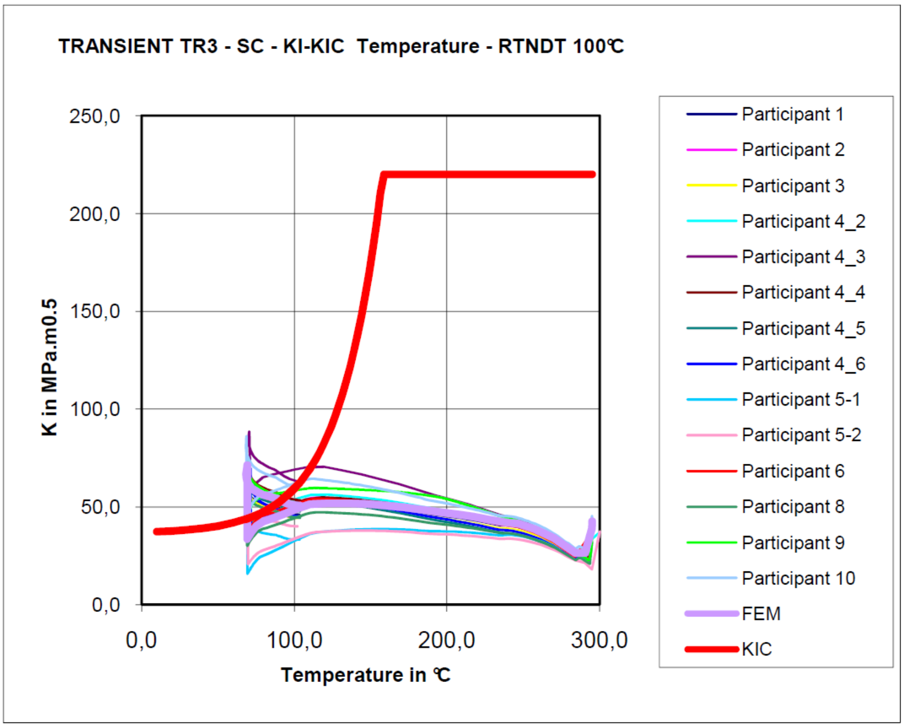

Figure 3.12 Comparison between the stress intensity factor (KI) and the calculated fracture toughness for a surface defect (transient Tr3).

Because of the large differences in the calculation of K_I (see the examples in Figure 3.4-3.6) there was also a large difference in the estimation of initiation of crack growth (when it should occur). For the transient Tr1 crack initiation occurred for a crack tip temperature between 35°C and 90°C or without initiation for some participants (dependent of aging, see an example in Figure 3.10). Also, several participants had misunderstood how to evaluate RT_{NDT} at the crack tip (because the problem statement was unclear).

3.4 Calculation of crack initiation as a function of aging for an internal defect

Then, all the participants did a direct comparison between the stress intensity factor (K_I) and the calculated fracture toughness for an internal defect. The results and the conclusions were similar to the case with a surface defect and therefore not repeated in this section.

4. PHASE 2 – PROBABILISTIC ANALYSIS

4.1 Toughness property distribution versus aging

First, a check was made to see if the different participants have understood the definition of toughness property distribution versus aging (checked the mean value of RT_{NDT}). In this analysis the initial RT_{NDT}, chemical composition (Cu, Ni, P), shift curve, fluence level (fixed or probabilistic) was considered to be probabilistic parameters.

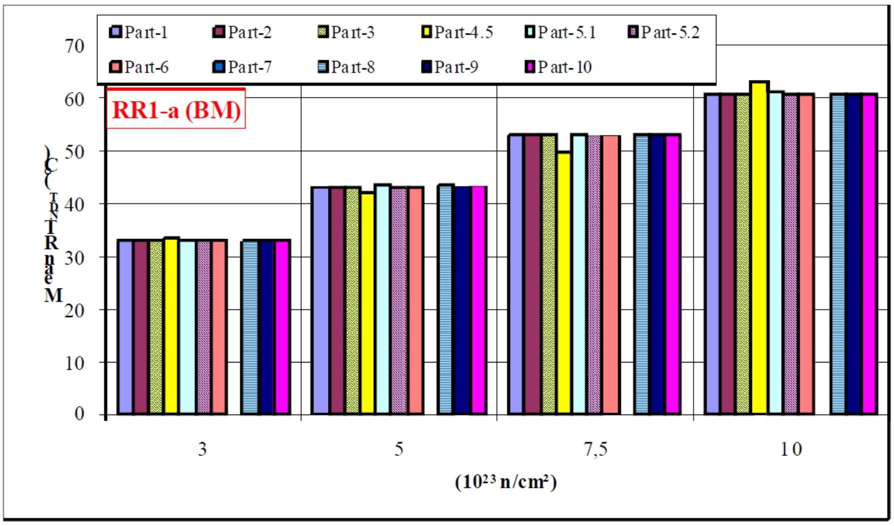

Figure 4.1 The mean value of RT_{NDT} versus aging (for the base metal material)

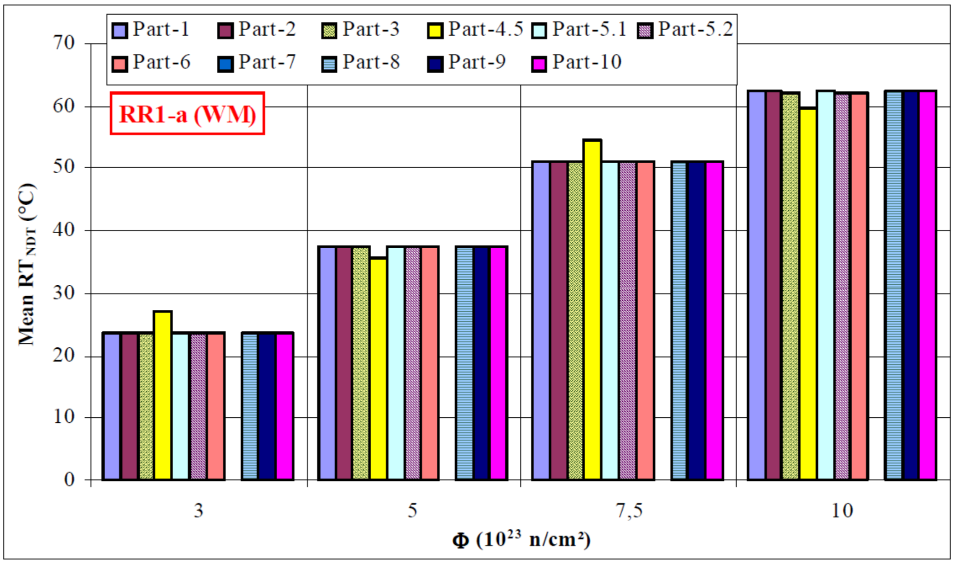

Figure 4.2 The mean value of RTNDT versus aging (for the weld material)

As can be seen in Figure 4.1-4.2 there where an excellent agreement between the different participants (except two participants). This comparison was made without consideration of the irradiation decrease through the RPV wall; this was unfortunate because a contributor to the errors seen in the probabilistic analysis could be related to the definition of origin when evaluating the irradiation decrease, i.e. if the irradiation decrease starts at the inner surface or at the clad/base metal interface.

4.2 Probability of crack initiation for a surface defect with a given size

Then, the probability of crack initiation for a surface defect (with a given size) was evaluated. Typical results can be found in Figure 4.3-4.4 (using transient Tr3).

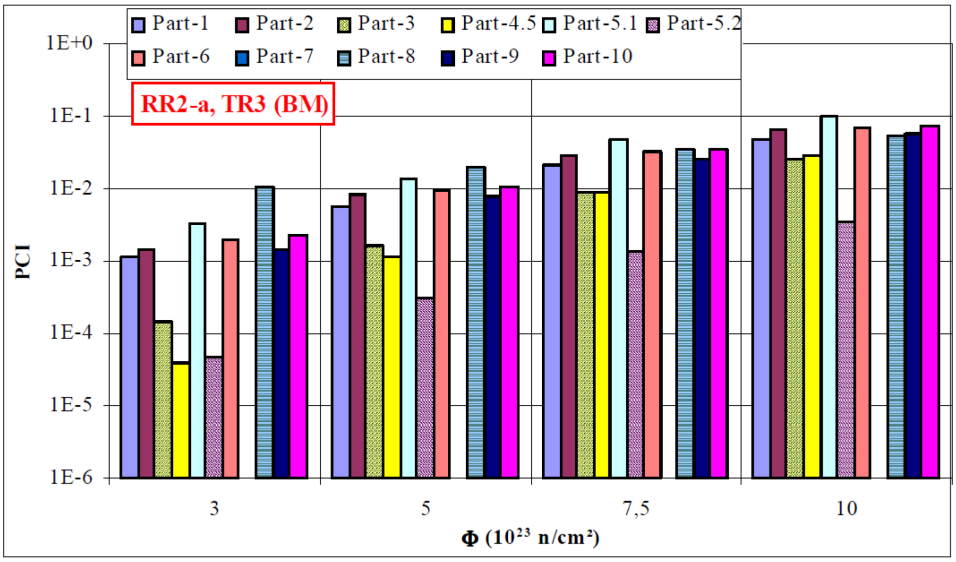

Figure 4.3 Conditional probability of crack initiation (PCI) versus aging (surface defect, transient Tr3 and base material).

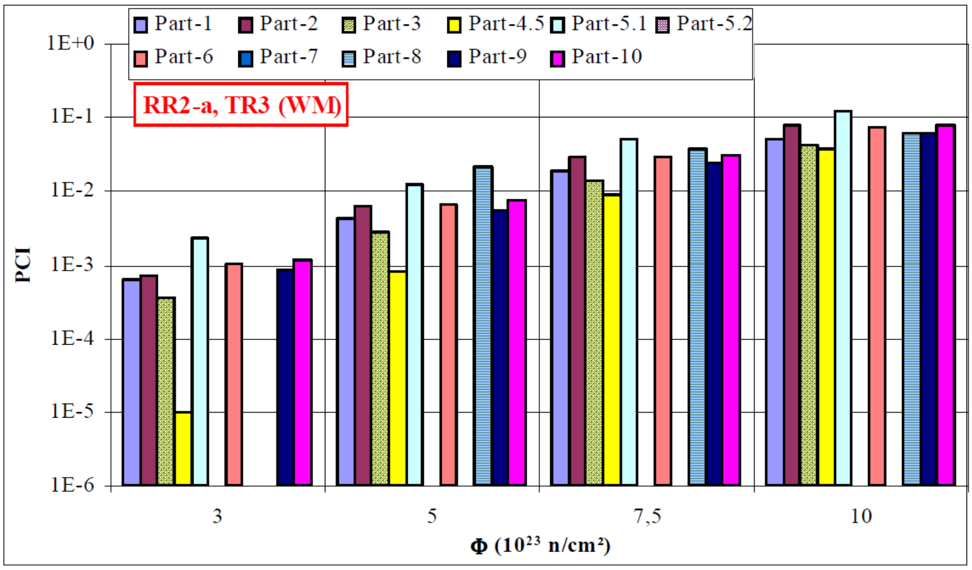

Figure 4.4 Conditional probability of crack initiation (PCI) versus aging (surface defect, transient Tr3 and weld material)

Figures 4.3-4.4 shows that there are quite good agreement between the different participants except for some participants that are one or two decades in difference (mainly related to differences in the calculation of K_I). The agreement seems better for high RT_{NDT} level (or fluence level) or for higher probability of crack initiation level. However, if one includes all the participants from Korea (which is not included in the draft report the difference is much larger (see Figure 4.5).

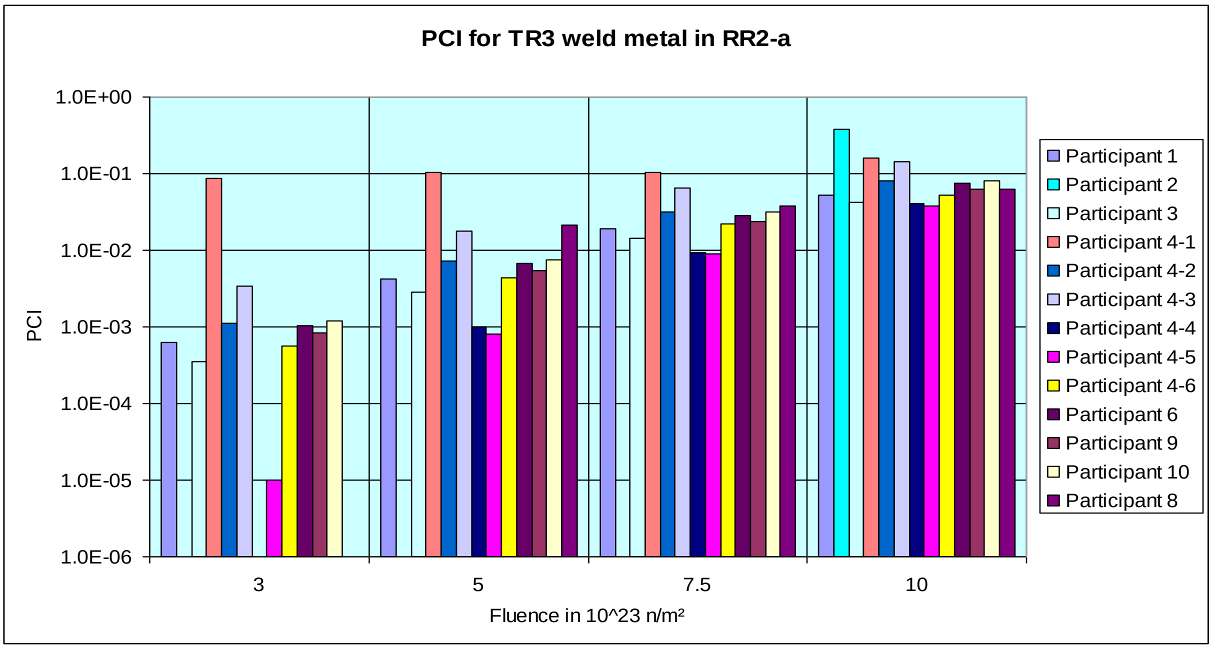

Figure 4.5 Conditional probability of crack initiation (PCI) versus aging (surface defect, transient Tr3 and weld material). This is not the final results, since the comparison was made early in the project

Participant 8 (Inspecta) investigated the transition from upper shelf toughness to toughness in the transition region; this is shown in Figure 4.6-4.8. Firstly the conditional probability of crack initiation versus time in the transient is plotted in Figure 4.6 (without consideration of upper shelf toughness).

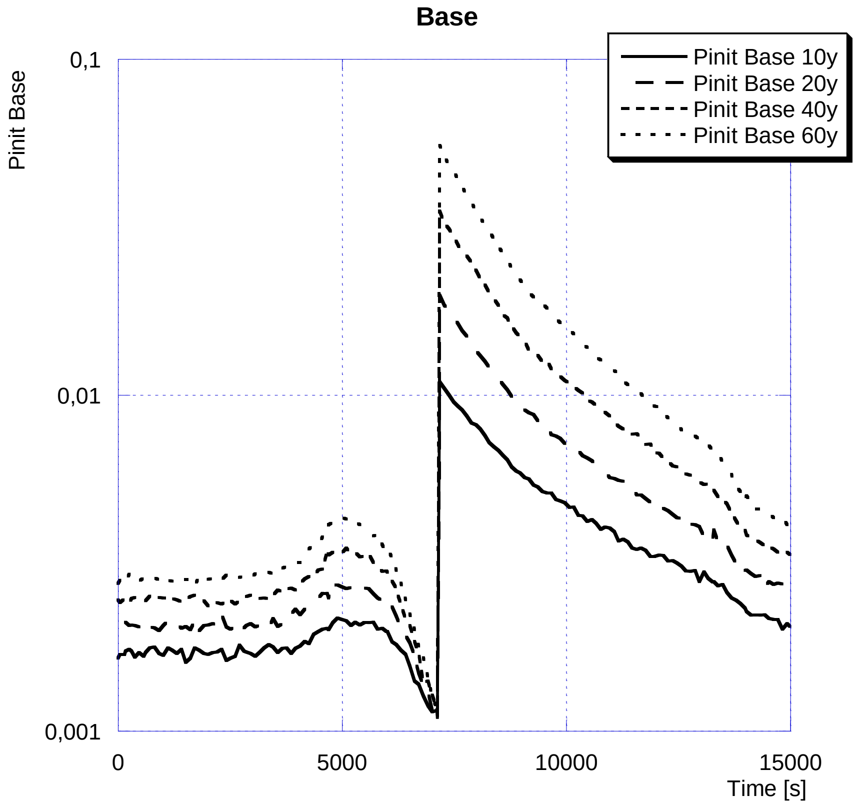

Figure 4.6 Conditional probability of crack initiation versus time in the transient
(surface defect, transient Tr3 and base material)

As can be seen in Figure 4.6, there is a maximum after 7185 seconds in the transient (related to re-pressurisation that occurs in the PTS transient).

When we compare the mean K_I-values and the mean fracture toughness during the transient (see Figure 4.7) we notice that the maximum K_I and the minimum fracture toughness coincide in time. This comparison must be made using the mean values from the probabilistic analysis; since the mean values from a deterministic analysis are different (the difference could be very large, up to 40 MPa $\sqrt{m}$ at the end of transient Tr3).

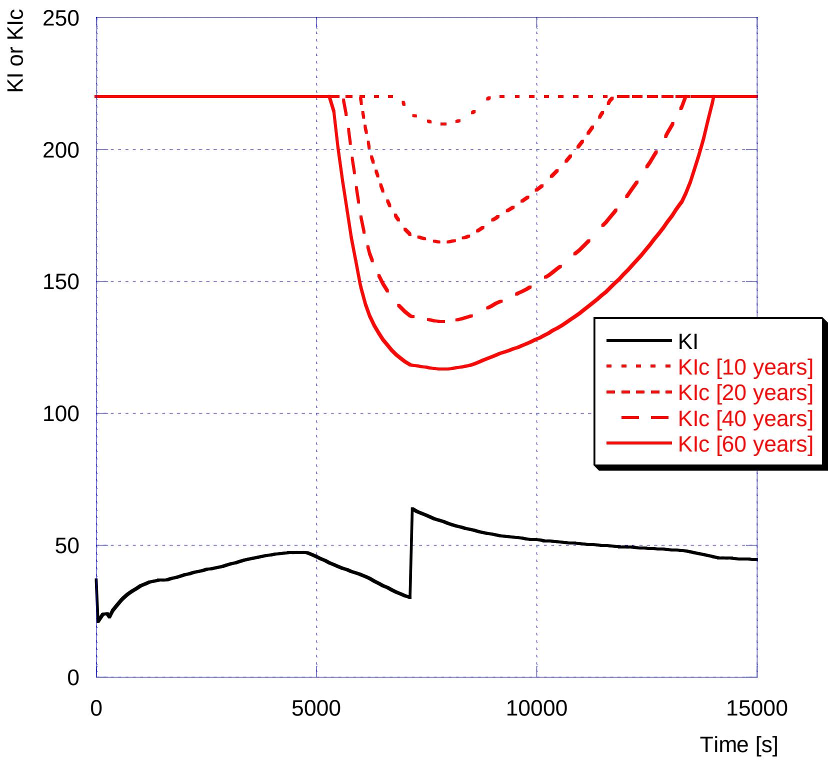

Figure 4.7 Comparison between the mean KI-values and the mean fracture toughness during the transient Tr3 (surface defect and base material)

Now the conditional probability of crack initiation versus time in the transient can be plotted in Figure 4.8 (with consideration of the upper shelf toughness). Some participants did this incorrectly, without proper consideration of the upper shelf toughness, which could give very conservative results.

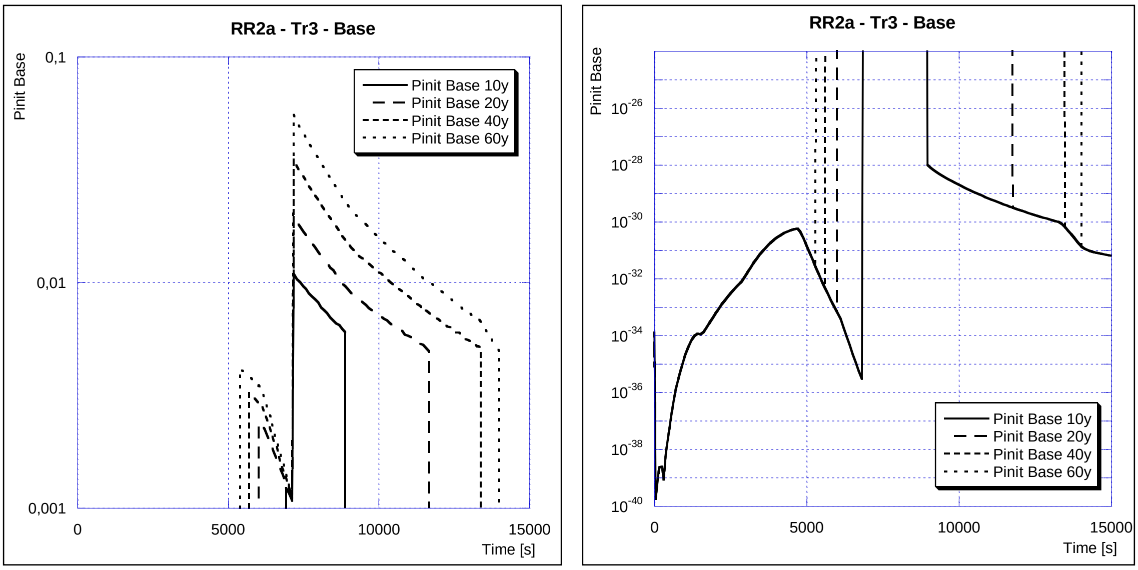

Figure 4.8 Conditional probability of crack initiation versus time in the transient (surface defect, transient Tr3 and base material). In this plot, with the upper shelf toughness included

4.3 Probability of crack initiation for an internal defect with a given size

Then, the probability of crack initiation for an internal defect (with a given size) was evaluated. A typical result can be found in Figure 4.9 (using transient Tr3 and base material).

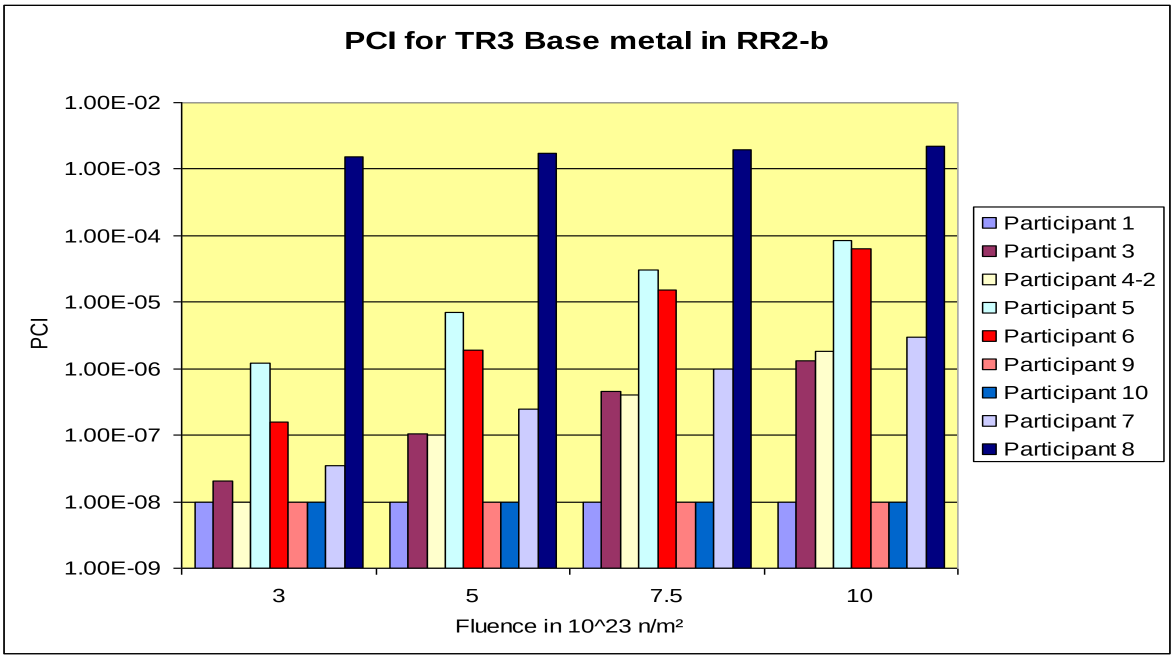

Figure 4.9 Conditional probability of crack initiation (PCI) versus years of operation (internal defect, transient Tr3 and base material)

The figure above shows quite good agreement between some participants. One of the participants has larger values independent of the number of years in operation, the reason being that this participant evaluated the results at point A instead of point B (larger K_I closer to the surface and also more irradiation embrittlement). Three participants has smaller values independent of the number of years in operation, the reason being that these participants presents cut-off values = 1.0E-8 (similar trends for the Tr1 and Tr2 transients). As mentioned earlier in Sect. 3.3, several participants had difficulties treating the case with an internal defect close to the cladding interface. Because of this, there were several projects started to develop new K_I-solutions for an internal defect [4, 5].

4.4 Probability of crack initiation using a surface defect distribution

Then, the probability of crack initiation for a surface defect (using a surface defect distribution) was evaluated. Some results can be found in Figure 4.10-4.12 (using transient Tr3 and base material).

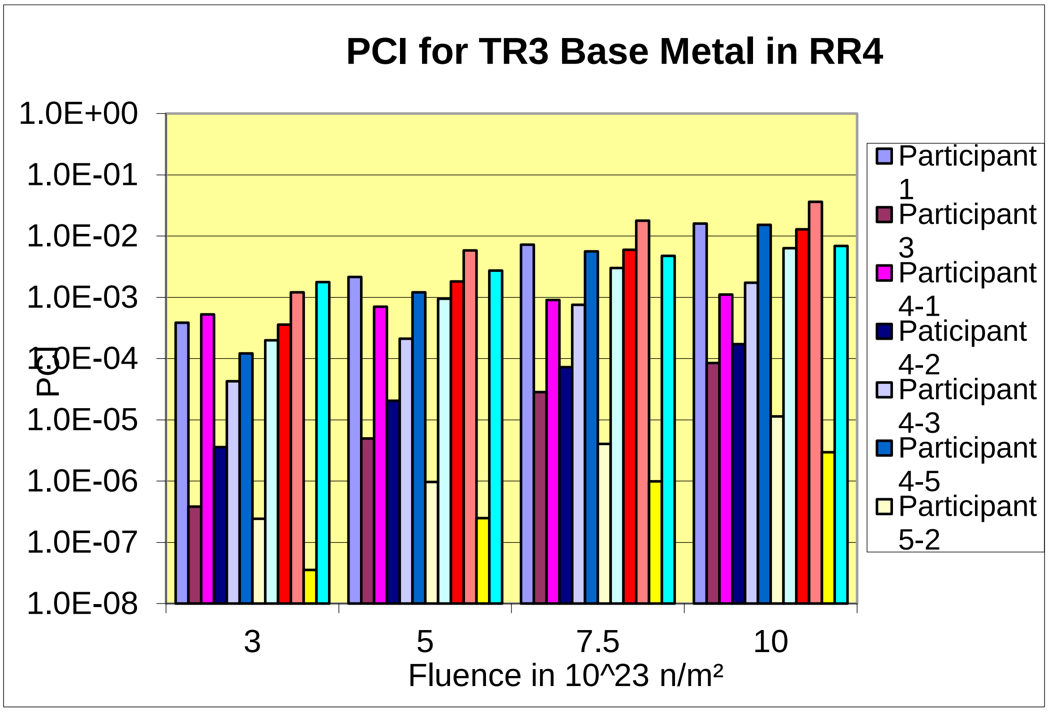

Figure 4.10 Conditional probability of crack initiation (PCI) versus aging (surface defect distribution, transient Tr3, base material)

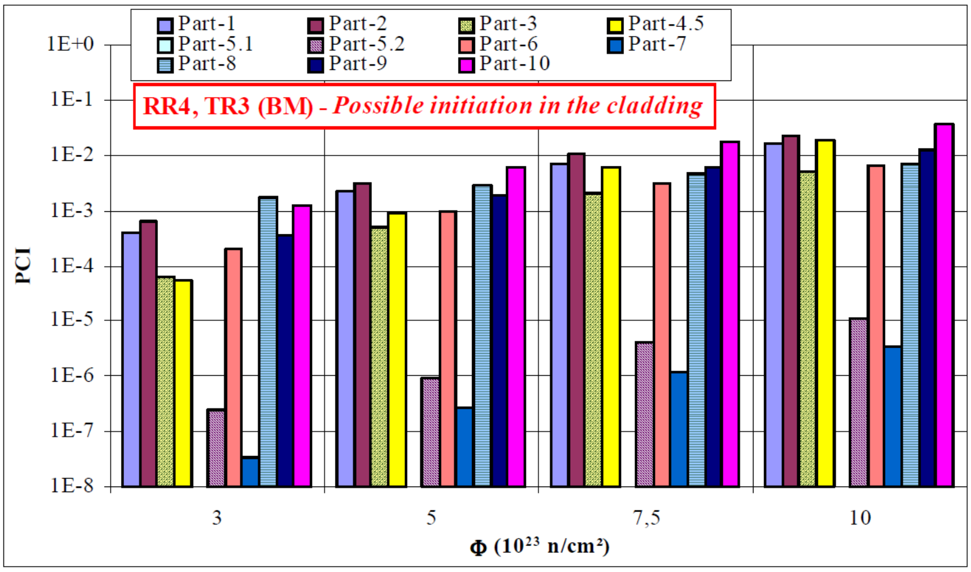

Figure 4.11 Conditional probability of crack initiation (PCI) versus aging (surface defect distribution, transient Tr3, base material and crack initiation in the cladding)

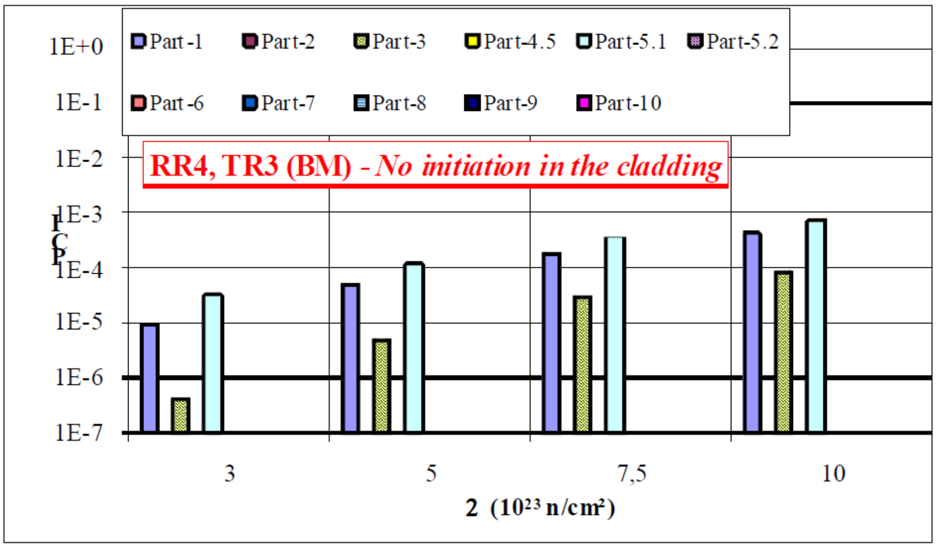

Figure 4.12 Conditional probability of crack initiation (PCI) versus aging (surface defect distribution, transient Tr3, base material and no crack initiation in the cladding)

Figure 4.11-4.12 shows that there is a large difference between the participants related to crack initiation using a defect distribution. A particular difference is connected to the defect distribution origin: some consider the inner surface (with small defects in the cladding), some others consider the defect distribution at the base metal/cladding interface (with no small defects in the cladding). The difference can be greater than one decade.

5. PHASE 3 – CRACK ARREST

5.1 Probability of crack arrest for a surface defect with a given size

A few participants analysed the probability of crack arrest after initiation. The procedure used is generally the ASME Code procedure. Some results can be found in Figure 5.1.

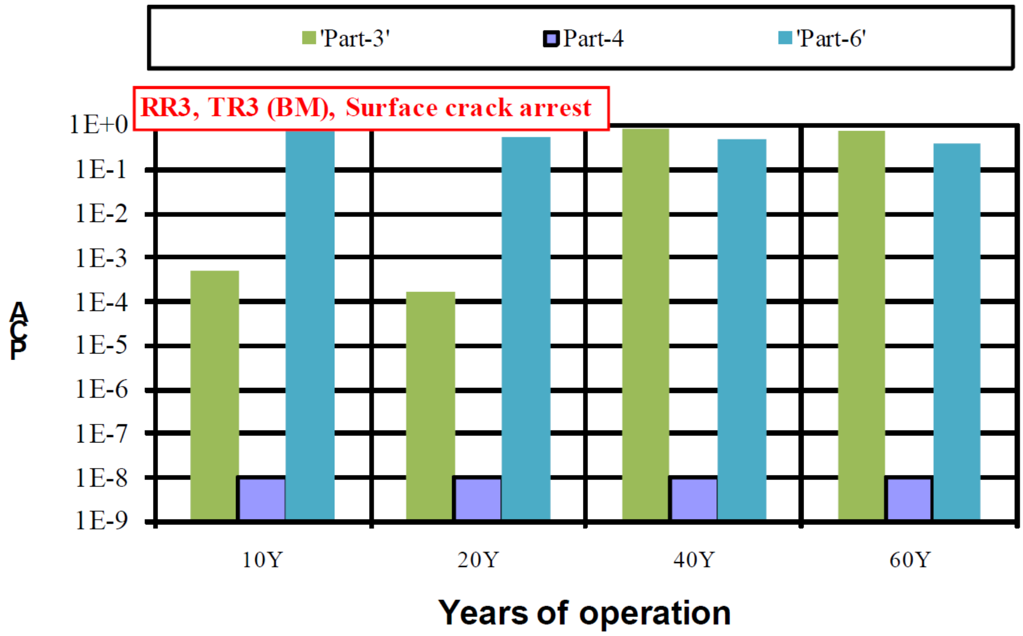

Figure 5.1 Probability of crack arrest (PCA) versus aging (surface defect, transient Tr3 and base material)

Due to large misunderstanding of the round robin definition by different participants, big scatter in the results was observed and the round robin was cancelled. This can be further seen in Figure 5.2, where the probability of crack arrest (PCA) is plotted as a function of time in transient Tr3. Because of the weak definition, the maximum (and minimum) PCA-value occurred at different times in the transient. Also, the probability of re-initiation of crack growth together with the probability of a new arrest was not defined in the round robin.

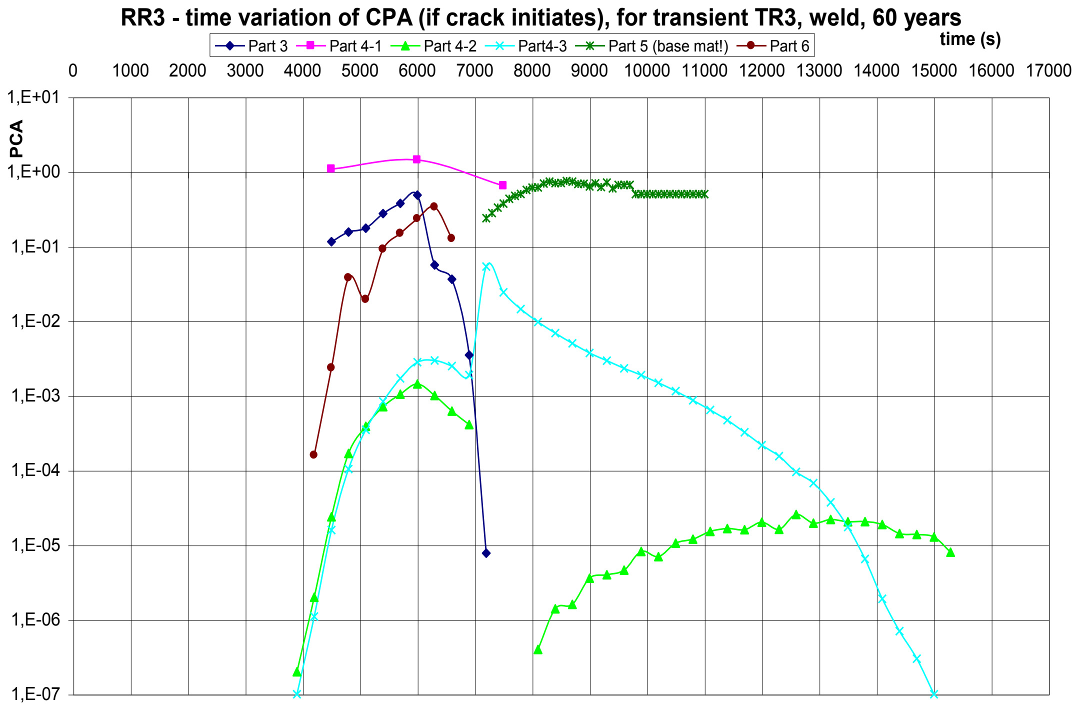

Figure 5.2 Probability of crack arrest (PCA) versus time in the transient (surface defect, transient Tr3 and weld material)

6. IDENTIFICATION OF KEY PARAMETERS AND THEIR INFLUENCE ON THE RESULTING PROBABILITIES

One of the major objectives in the PROSIR project was to try to understand what the key parameters are in this type of approach. Inspecta (participant 8) and EDF (participant 7.1/7.2) did several analyses to identify the key parameters. The results from Inspecta are presented below:

6.1 Identification of key parameters in the analysis

Firstly, we try to identify what parameter that contributes the most to the calculated conditional initiation probability. To do this, we use a simple approach to investigate on the relative importance of the basic standard normal random variables that is given in a FORM analysis, see for example [8]. These can be given be means of the vector α^* defined as:

$$\alpha^* = \frac{y^*}{\|y^*\|} \tag{6.1}$$

where y^* denotes the co-ordinates of the design point in the standard normal space. The ordering of the elements in α^* indicates the relative importance of the random variables in the standard normal space.

Since y^* is the co-ordinate of the design point (or the most probable point of fracture), then $\|y^*\|$ is equivalent to the design point β and related to the conditional probability of initiation via $Pi = \Phi(-\beta)$ (when using a FORM approximation). This means that there is nonlinear relation between the importance factors given below and how they contribute to the calculated conditional fracture probability. These importance factors should therefore be used to get a qualitative understanding of the different parameters/variables relative importance in a probabilistic analysis.

The study below therefore shows the importance factors, i.e. what parameter that contributes the most to the calculated conditional initiation probability.

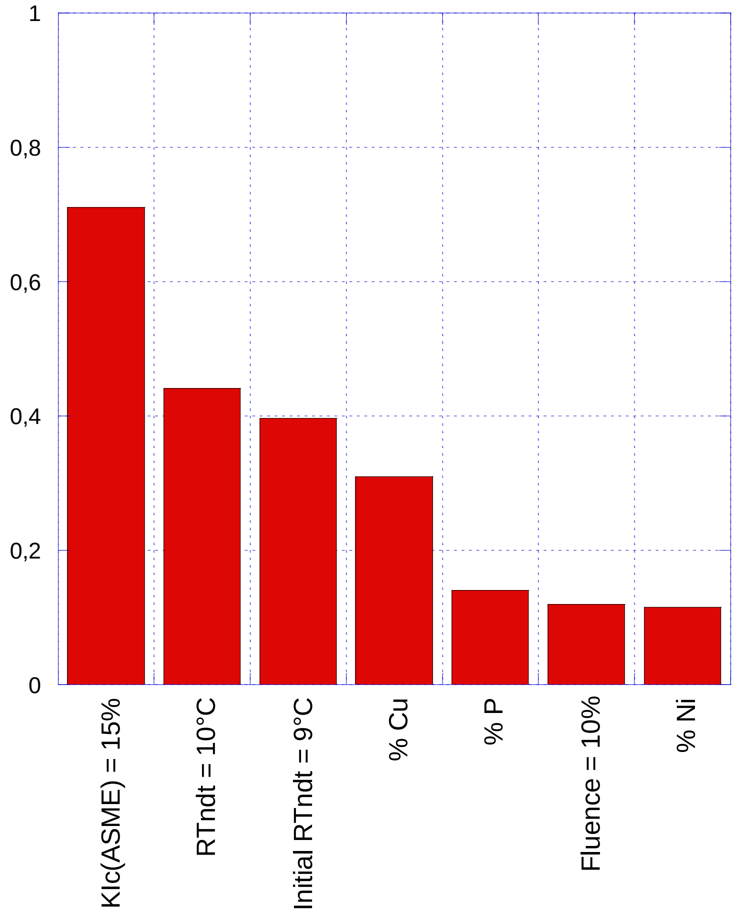

Figure 6.1 Importance factors for the case with a surface defect, transient Tr3, base material and 60 years of operation.

As can be seen in Figure 6.1, the 15% standard deviation on K_{Ic} (the ASME curve) is the largest contributor to the probability of crack initiation. There are also quite large contributions from the RT_{NDT} shift curve and the initial value of RT_{NDT}. A similar analysis was performed by EDF for the case with an internal defect transient Tr3, weld material and 60 years of operation. They reported the same three parameteras as having the largest importance factors. An analysis performed by EDF for the case with a surface defect distribution showed that the crack depth had the largest importance factor (then came the same three parameters as given above).

Above, the importance factors were given for one of the baseline cases. The purpose was to show what parameter that contributes the most to the calculated conditional initiation probability. Another aspect of a probabilistic analysis is to define what happens to the calculated conditional initiation probability if we introduce a small change in the input data, i.e. what parameter change has the most influence on the calculated conditional initiation probability.

Of interest is therefore the sensitivity of the reliability index β with respect to parameters θ entering the definition of the limit state function g . The sensitivity of β is given by:

$$\frac{d\beta}{d\theta} = \frac{1}{\|\nabla G\|} \frac{dg}{d\theta} \quad . \tag{6.2}$$

When doing a FORM analysis, the probability of initiation is given as $P_i = \Phi(-\beta)$ and differentiated with respect to θ:

$$\frac{dP_i}{d\theta} = \frac{d}{d\theta}\Phi(-\beta) = \frac{d}{d\theta}\big(1-\Phi(\beta)\big) = -\frac{d\beta}{d\theta}\frac{d}{d\beta}\Phi(\beta) = -\frac{d\beta}{d\theta}\varphi(\beta) \ . \tag{6.3}$$

The sensitivity of the probability of initiation P_i with respect to parameters θ is then given by:

$$\frac{dP_i}{d\theta} = -\varphi(\beta)\frac{1}{\|\nabla G\|}\frac{dg}{d\theta} \ , \tag{6.4}$$

where $\|\nabla G\|$ and $dg/d\theta$ is easily computed in any FORM analysis.

The study below then tries to answer the question: What parameter change has the most influence on the calculated conditional initiation probability? Here we investigate a change in the given mean values (same analysis could be done to check the given standard deviation values). The results are normalised (against the conditional initiation probability) to get a better understanding of the interaction between the calculated sensitivities.

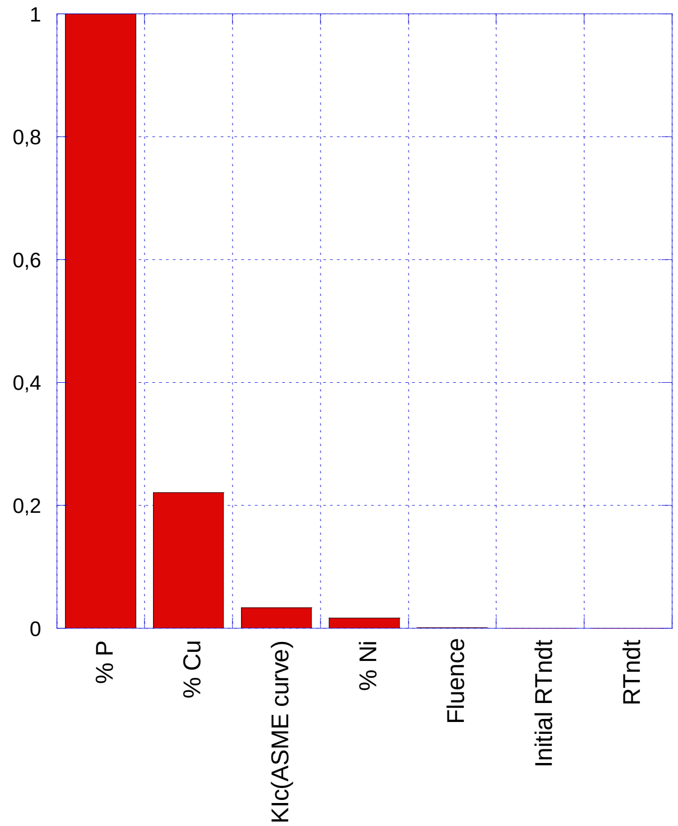

Figure 6.2 Check regarding what parameter change has the most influence on the calculated conditional initiation probability (for the case with a surface defect, transient Tr3, base material and 60 years of operation).

As can be seen in Figure 6.2, the change of the mean value of the parameter Phosphorus content (used in the definition of the RT_{NDT} shift curve) has the most influence on calculated conditional initiation probability. The next parameter is the change of mean value of copper content (also used in the definition of the RT_{NDT} shift curve). That these parameters are so dominating in the analysis is not easy to see just by looking at the problem definition in PROSIR.

Several PROSIR participants also did different sensitivity analyses in order to understand the contribution from different parameters in this type of approach. The results from Inspecta (participant 8) are presented below:

6.2 Sensitivity study – defect size

The baseline case, when calculating the probability of crack initiation for a surface defect with a given size, is a defect with a depth = 19.5 mm and length/depth = 6. To check this assumption Inspecta did a sensitivity study with a defect depth that varied between 2 mm up to 100 mm, the results are given in Figure 6.3 (with explanations as given in the figure).

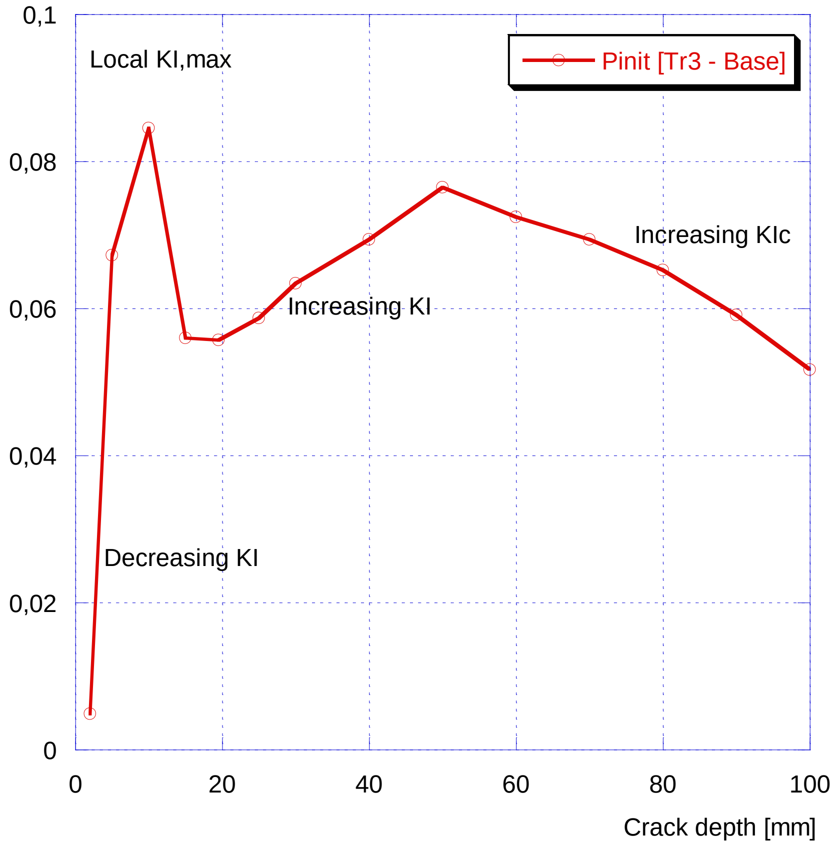

Figure 6.3 Sensitivity study for PCI with a defect depth that varied between 2 mm up to 100 mm (for the case with a surface defect, transient Tr3).

Given the results in Figure 6.3, it would be interesting to check the influence of the main contributors to the probability of crack initiation. This could be done by changing the given data with a factor of ±20%. This sensitivity study is presented in Figure 6.4.

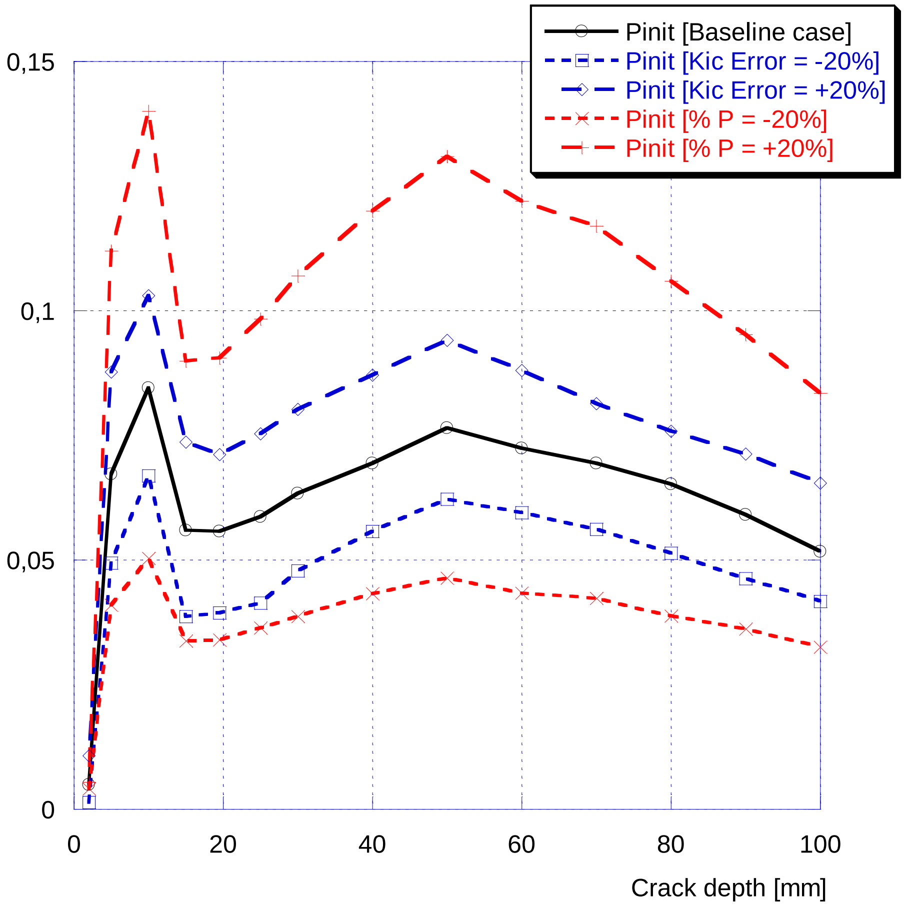

Figure 6.4 Sensitivity study for PCI for the main contributors to the probability of crack initiation.

In Figure 6.4, the blue lines represent the parameter that contributes the most to the calculated conditional initiation probability (given all the chosen combinations of mean values and standard deviations for all parameters). This is the 15% standard deviation on K_{Ic} (the ASME curve). The red lines represent the parameter with the maximum mean value contribution. This is the parameter Phosphorus content (used in the definition of the RT_{NDT} shift curve).

6.3 Sensitivity study – defect orientation

The baseline case, when calculating the probability of crack initiation for a surface defect with a given size, is a defect with a depth = 19.5 mm and length/depth = 6 and oriented in the axial direction. To check this assumption Inspecta did a sensitivity study with a defect depth that varied between 2 mm up to 100 mm and oriented in the circumferential direction, the results are given in Figure 6.5.

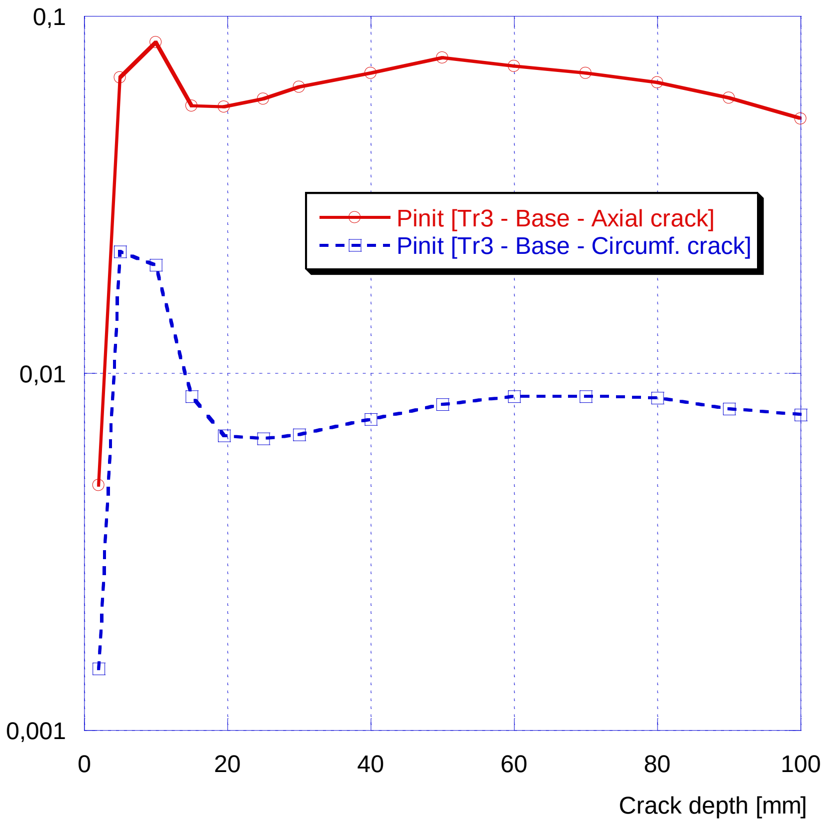

Figure 6.5 Sensitivity study for PCI with different defect orientation.

As can be seen in Figure 6.5, the resulting probabilities are of the same order (the maximum value), i.e. the stresses from the transient are dominating (together with the cladding induced stresses) over the stresses from the internal pressure.

6.4 Sensitivity study – residual stresses

The baseline case, when calculating the probability of crack initiation for a surface defect with a given size, is a defect with a depth = 19.5 mm and length/depth = 6 and without weld residual stresses. To check this assumption Inspecta did a sensitivity study with a defect depth that varied between 2 mm up to 100 mm and this time using a constant weld residual stresses equal to 15% of the yield strength (equivalent to a stress relieved weld), the results are given in Figure 6.6.

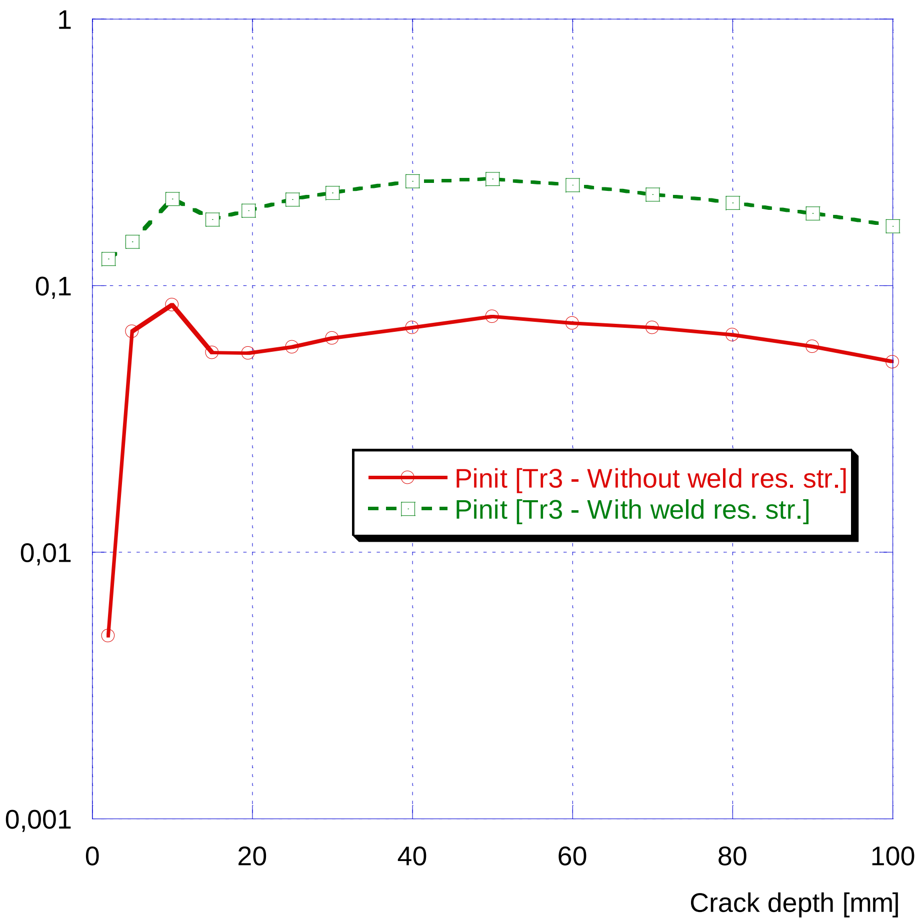

Figure 6.6 Sensitivity study for PCI with/without weld residual stresses.

As can be seen in Figure 6.6, the resulting probabilities are of the same order (the maximum value), i.e. the stresses from the transient are dominating (together with the cladding induced stresses) over the stresses from the internal pressure.

6.5 Sensitivity study – fracture toughness representation

The fracture toughness representation in PROSIR uses the "mean value" version of the ASME reference curve. It would be interesting to compare the results using a Master Curve representation of the fracture toughness. Then the analysis should compare the following curves:

- The ASME Curve (mean value) which is equal to the reference curve divided by 0.7.
- The Master Curve that has been developed by doing a Master Curve analysis of the original data for the ASME reference curve (done by Kim Wallin at VTT).

The fracture toughness curves are summarised in Figure 6.7 and the results from the sensitivity study is given in Figure 6.8.

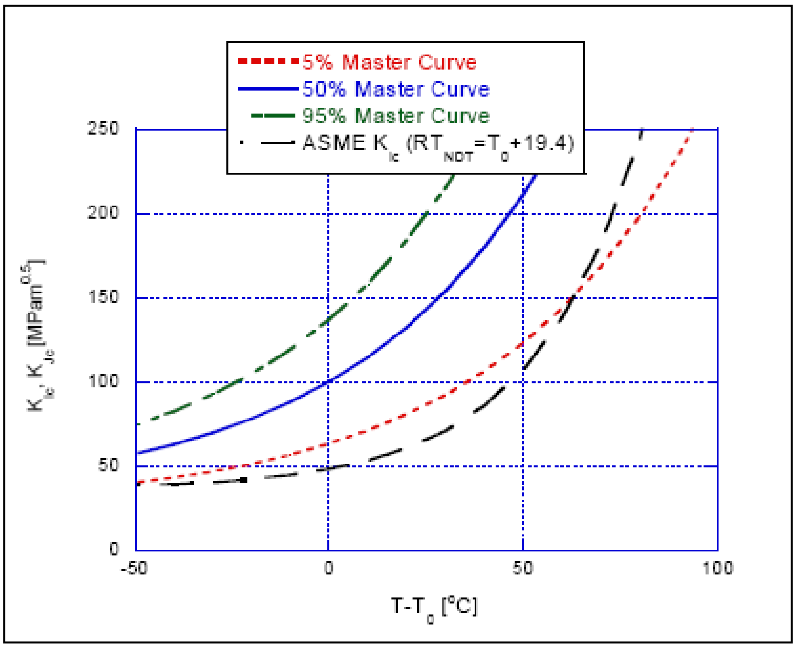

Figure 6.7 Different fracture toughness curves to be used in this sensitivity study.

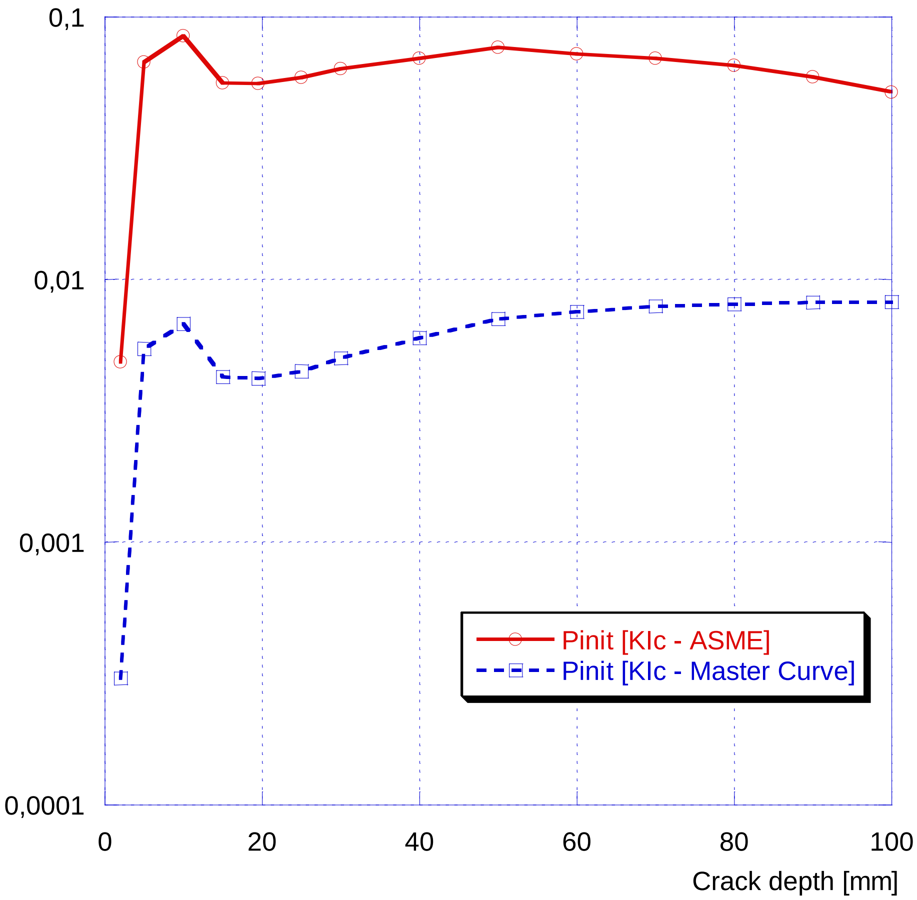

Figure 6.8 Sensitivity study for PCI using different fracture toughness representation

As can be seen in Figure 6.8, there are a difference in the resulting probabilities when using different fracture toughness representation. Obviously, using the “mean value” version of the ASME reference curve gives values that are 1 decade larger than using a Master Curve representation of the fracture toughness. This difference is not present in the data, but in the representation of the data. It is possible that the ASME reference curve has dependencies between different parameters that are not implemented in the methods used (to calculate probabilities) within the PROSIR project. Also, by using this model a greater spread of the calculated fracture toughness values are obtained. Therefore, using a Master Curve representation of the fracture toughness is perhaps a better choice than using the “mean value” version of the ASME reference curve.

6.6 Sensitivity study – method to calculate probabilities

Inspecta (participant 8) and EDF (participant 7.1/7.2) did a comparison between different methods when doing the probabilistic analysis. The methods were FORM, SORM, simple Monte Carlo simulation (MCS) and MCS with importance sampling. The differences in the results were quite small (less than half decade).

7. PROJECT OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS

7.1 Observations and conclusions

Below are some of the major conclusions as stated in the draft PROSIR report in 2010:

- The link between deterministic sensitivity studies and different probabilistic analysis is essential.
- Intermediate validation of the PFM analysis is important for verification of the result validity.
- Using the same data and the same models and criteria the results are in a good agreement for crack initiation of a single crack, but not perfect for a flaw distribution.
- User error or un-precise specification can lead to major final result errors.

The third item above is not altogether true. From the results a maximum of 7 decades difference can be found. But this difference is actually related to a cut-off used when compiling all the results in an Excel table. The maximum difference without the cut-off was much larger. The reasons for this wide difference are in most cases connected to

- unclear problem definitions;
- differences in treatment of stresses in K-solutions; and
- user errors and sometimes inexperienced users.

During the PROSIR project, several participants had difficulties treating the case with an internal defect close to the cladding interface. Also, there were discussions regarding the correct treatment of the plasticity correction. Because of this, there were several projects started to develop new *K*-solutions for an internal defect [5], [6].

One of the major objectives in the PROSIR project was to try to understand what the key parameters are in this type of approach. Within the project, the following conclusions are made regarding this aspect:

- The parameter that contributes the most to the calculated conditional initiation probability is the 15% standard deviation on K_{Ic} (the ASME curve). There are also quite large contributions from the RT_{NDT} shift curve and the initial value of RT_{NDT}.
- The change of the mean value of the parameter Phosphorus content (used in the definition of the RT_{NDT} shift curve) has the most influence on calculated conditional initiation probability. The next parameter is the change of mean value of copper content (also used in the definition of the RT_{NDT} shift curve). That these parameters are so dominating in the analysis is not easy to see just by looking at the problem definition in PROSIR.

Although the analysis results are more than eight years old they are still relevant to the scientific community because under the conditions given in the past the results would be nearly the same today. The recommendations for best practice given in chapter 7.2 are up-to-date because they have been drawn with respect to the interim knowledge growth.

7.2 Recommendations for best practice

Recommendations regarding temperature and stress analysis

Use temperature dependent material properties in the analysis of the temperature distribution and stress analysis. Comparison made within the project confirms that this is a recommended practice, in particular for high amplitude thermal shock stress analysis and consequently for fracture mechanics parameter evaluation (*K* or *J*).

Recommendations regarding K-solutions

It is recommended only to use verified and well-established K-solutions when performing the probabilistic analyses. The chosen *K*-solution is an important part of fracture mechanics analysis for different stress distributions and different defect locations, especially in the vicinity of the cladding: through clad surface defect, no clad surface defect, internal (underclad) defect and internal (embedded) defect.

Special care should be used to handle the stress profile in the cladding area with a discontinuity due to thermal expansion coefficients. This needs a specific development for the influence function method to generate K-solutions.

Recommendations regarding the analysis of probabilistic crack initiation

In order to perform probabilistic crack initiation analysis a few recommendations are made:

- Use a well-defined and verified deterministic fracture mechanics model.
- Use clear specifications in all the data, for example originating from inner surface or from base metal/cladding interface.
- Particular attention should be devoted to the cladding transition to base metal regarding stresses, *K*-solutions, fracture toughness and defect definition.
- Probabilistic fracture mechanics tools needs a lot of sensitivity studies, associated with a large number of deterministic analysis in order to confirm the effects of different data or models.
- A formal validation-verification programme should be developed/performed for each computer program containing the probabilistic models.

8. ACKNOWLEDGEMENT

The completion of this report was funded by the Swedish Radiation Safety Authority (SSM). This support is greatly appreciated. The report is based on the draft report written by Claude Faidy (EDF), Stephane Chapuliot (CEA), Terry Dickson (ORNL), Vladislav Pistora (NRI) and Kunio Onazawa (JAEA). https://www.oecd-nea.org/download/iage/metals/documents/13Prosir_Final_Feb2012-Ind4-5.pdf (draft report is available only to the members of NEA CSNI WGIAGE group.

Some remarks are also given by Terry Dickson (ORNL) to get an updated perspective on the PROSIR project.

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10. APPENDIX A, UPDATED PERSPECTIVE ON THE PROSIR PROJECT - OBSERVATIONS FROM ORNL

10.1 Introduction

The foregoing chapters provide a narrative developed by Inspecta that summarises major elements of the PROSIR Project, and also include observations and sensitivity analyses prepared by Inspecta; the latter material draws from the 2010 PROSIR draft report. In this appendix, ORNL (participant number 1) offers its own observations regarding results and conclusions from PROSIR as represented in this report, all viewed from a perspective of nearly a decade having transpired since completion of the computational work in 2007.

10.2 Revised PROSIR Report

The PROSIR Project was a traditional round robin exercise with

- organisation precipitated by an OECD action;
- technical support provided by16 participating organisations drawn from 9 countries (chairman provided by EDF-Septen);
- primary objectives:
  - to issue recommendations of best practices when performing probabilistic analyses of an RPV;
  - to understand the key parameters involved in the probabilistic analysis approach;
- issuance of a final report in 2010.

In this current report, Inspecta provides closure to the 2010 draft final report of PROSIR by focusing on three elements:

1. a summary of the results included in that PROSIR draft final report, with the objective of taking the "partially unstructured and unclear" original draft and summarising it in a more structured presentation
2. a critique of both the general problem statement of PROSIR as well as specific tasks attempted by the project
3. sensitivity analyses performed with the objective of determining influences of various factors on probabilistic results, including key parameters, defect size/orientation, residual stresses, fracture toughness representation, etc.

The discussion by Inspecta and included herein in Chapters 2-7:

- gives clarity and structure to the analysis results and conclusions of the project;
- identifies technical contributions (and short-comings) of the original draft;
- augments the original draft material by providing additional data on tasks that were not completed (or were performed inadequately or not at all) by the original PROSIR participants.

10.3 ORNL observations

The collection of analysis results originally generated by participants in the PROSIR project is unaltered as a result of the revised and amended Inspecta presentation. Notable tasks executed in that PROSIR work scope that had a less-than-satisfactory outcome (in the opinion of ORNL) include the following:

- Comparative deterministic analyses show wide disagreement of K_I versus time solutions for an inner surface breaking flaw and an underclad (embedded) flaw; see Figures. 3.4-3.6 and 3.7-3.9 in Sect. 3 of this report.
- Calculations for the probability of crack initiation when using the defect depth distribution given in the problem statement (see Figure 2.3) show large differences among participants; see Figures. 4.10-4.12 in Sect. 4.

Explanations provided herein in Sect. 4 for those large differences in solutions among participants include

- technical modeling issues (for example, not properly accounting for clad loading due to differential thermal expansion);
- differences in interpretation of the problem statement;
- large disagreement in K_I versus time solutions leading to large disagreement for probabilistic results, i.e. the probability of crack initiation;
- wide disparity in levels of experience among the participants in addressing probabilistic analyses of RPVs.

It has been ORNL's experience (extending over three decades) that, in a round robin exercise, a wide range in computed $T(t)$ and / or $K_I(t)$ results will produce a wide range in the probabilistic analysis results. Thus, a necessary prerequisite for successful benchmarking of probabilistic analyses is to have a consensus deterministic solution to a well-defined problem, i.e. participants must achieve a very tight band with respect to results for temperature, stress and K_I versus time for the given defect. Only after reaching such a deterministic consensus should participants focus on the probabilistic methodology that involves determining

- variables to be treated probabilistically;
- how each of the uncertainties are propagated through the probabilistic methodology; and
- how they impact the probabilistic solutions, i.e. the conditional probability of crack initiation.

More generally, ORNL is concerned that an updated presentation of the PROSIR Project should be presented in a proper context that recognises more recent advances in analysis capabilities.

- Taken as a whole, analysis results from PROSIR provide a snapshot of capabilities that were assessed nearly a decade ago; thus, PROSIR results cannot reflect the current level of expertise that is available and being applied by the international nuclear technology community.
- The disparity of results encountered in PROSIR, dated as they are, should not be allowed to promote a negative connotation (regarding application of the current probabilistic approach) among readers of the report who are not experienced in that discipline, but who may be influential in the regulatory arena.

To address the foregoing concern, ORNL presents a recently completed example to illustrate that a simple bi-lateral collaboration between organisations [5] can be an effective strategy for verifying the capabilities of computational tools:

- Figures. 10.1-10.3 below illustrate comparisons of computed conditions at tip B of an underclad defect (see Figure 10.1) in an RPV subjected to pressure/temperature transient loading on the inner surface.
- Figures. 10.2 and 10.3 compare the temperature $T(t)$ and stress intensity factor $K_I(t)$ deterministic solutions generated by the ORNL FAVOR code and by the EDF-Septen ASTER code.
- In this case, participants are experienced analysts using computer codes that have undergone extensive verification while in the development stage.
- The deterministic solutions are observed to be nearly identical for comparisons of elastic K_I, as well as for plasticity-corrected K_I; a French plasticity correction routine was implemented into the FAVOR code for this exercise.

Consequently, there is a reasonable expectation that the two organisations could successfully extend the benchmarking exercise to include probabilistic analyses, assuming a well-defined problem statement is employed for that study.

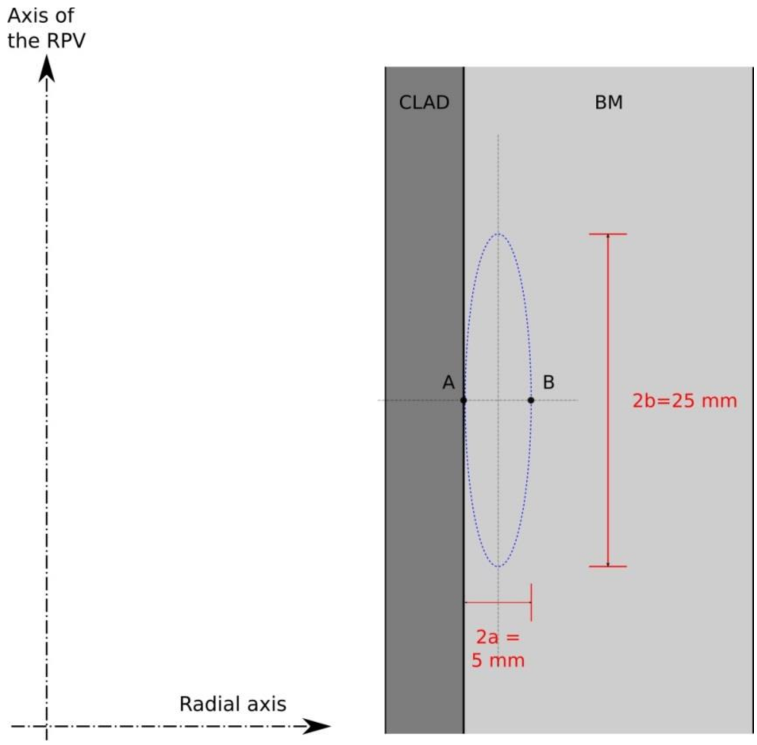

Figure 10.1 Geometry of the axially oriented underclad defect

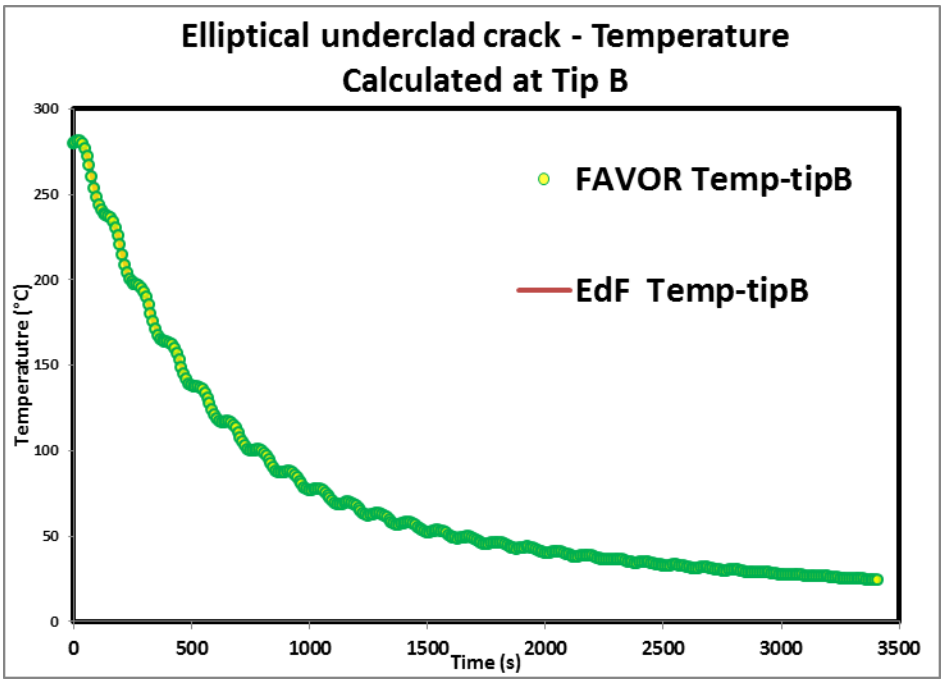

Figure 10.2 Illustration of agreement between FAVOR and ASTER code for deterministic thermal $T(t)$ solution at crack tip. The results are almost identical and the curves overlap.

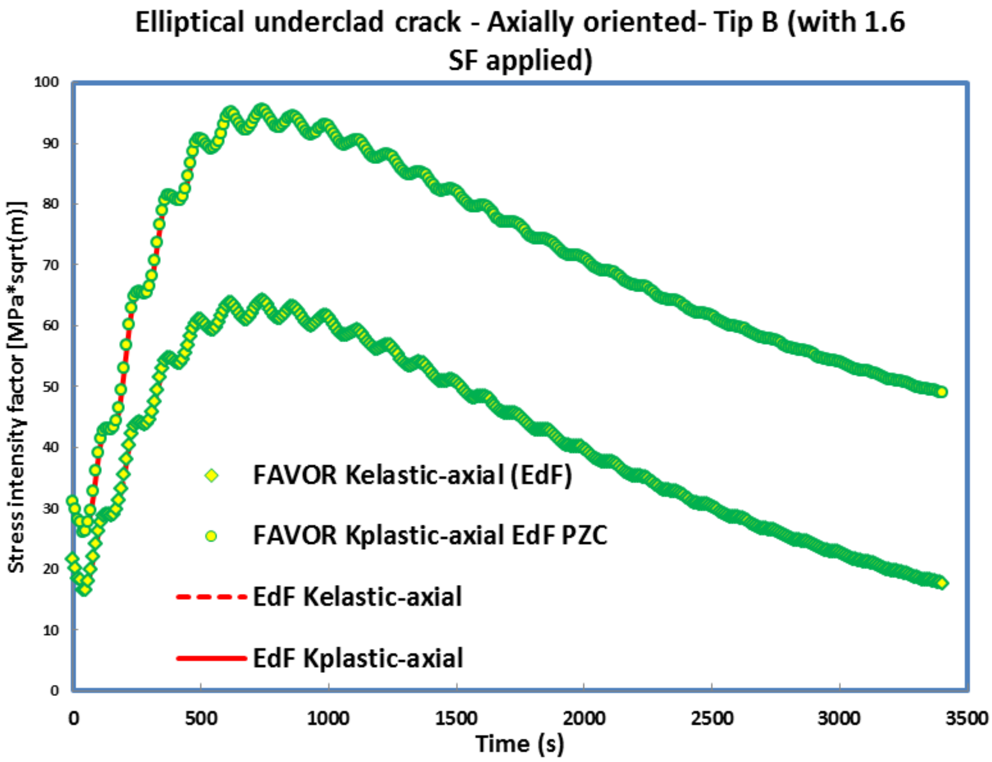

Figure 10.3 Illustration of agreement between FAVOR and ASTER code for deterministic $K_I(t)$ solution. The results are almost identical and the curves overlap

Also there has been a previous probabilistic benchmark study of a RPV involving EDF and ORNL which is reported in [7]. This study gives additional insights of how to perform probabilistic evaluations of a RPV.

10.4 Template for future PFM benchmarking

Based on past experience and on lessons learnt from PROSIR, ORNL offers some suggestions regarding future probabilistic benchmarking:

- The organisation responsible for the exercise should provide a problem statement that prescribes deterministic solutions for $T(t)$ and $K_I(t)$ at the appropriate crack tip. Thus, the probabilistic benchmarking will not be dependent on participants generating identical deterministic solutions at the crack tip.
- The probabilistic problem statement for the exercise should be properly defined by the responsible organisation such that it has a documented, verified solution.
- The recommended approach to the probabilistic exercise is to begin with the simplest problem specification and to add complexity incrementally. The initial problem could be:
  - a single flaw geometry subjected to a specified $T(t)$, $K_I(t)$, RT_{NDT} (defined distribution, including mean and standard deviation), and $K_{Ic}(T(t), RT_{NDT})$; the latter problem definition is sufficient to generate a probabilistic solution;
  - for each RPV containing exactly one flaw, the only required operation during the Monte Carlo process is to sample a value of RT_{NDT} from the prescribed distribution, and then to step thru transient time comparing $K_I(t)$ with $K_{Ic}(T(t), RT_{NDT})$.
- Each participant must successfully solve the initial problem before attempting solutions for increasing levels of complexity.
- More complex problem statements could include
  1. incorporation of correlation(s) that are a function of neutron fluence and chemistry to generate values of ΔRT_{NDT}, rather than sampling each value of RT_{NDT} from a distribution as specified above in the simplified initial problem;
  2. multiple flaw types and geometries;
  3. multiple RPV regions that have different chemistries and fluences;
  4. combinations of multiple regions and multiple flaws.

The above template is based on insights gained during the USNRC sponsored verification of the FAVOR code [6].

11. APPENDIX B, SUMMARY OF THE RESULTS FROM THE PROBABILISTIC ANALYSIS

This Appendix presents the results of the probabilistic analysis for those participants who reported the results in tabulated form (taken from App. 4 of the draft PROSIR report).

Table 11.1 Probabilistic results given by ORNL (participant 1)

Surface crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	4.61E-04	3.09E-03	1.41E-02	4.01E-02
	BM	8.36E-04	4.30E-03	1.50E-02	3.50E-02
Tr2	WM	2.20E-05	2.64E-04	1.84E-03	7.05E-03
	BM	3.40E-05	2.97E-04	1.69E-03	5.17E-03
Tr3	WM	6.16E-04	4.20E-03	1.88E-02	5.16E-02
	BM	1.12E-03	5.86E-03	2.05E-02	4.63E-02

Underclad crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
	BM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
Tr2	WM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
	BM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
Tr3	WM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
	BM	1.00E-08	1.00E-08	1.00E-08	1.00E-08

Surface crack initiation for 1 crack in a crack size distribution					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	4.61E-04	3.09E-03	1.41E-02	4.01E-02
	BM	8.36E-04	4.30E-03	1.50E-02	3.50E-02
Tr2	WM	1.00E-05	1.17E-04	8.37E-04	3.13E-03
	BM	1.40E-06	1.12E-04	6.12E-04	1.93E-03
Tr3	WM	2.59E-04	1.78E-03	8.07E-03	2.13E-02
	BM	3.83E-04	2.15E-03	7.24E-03	1.59E-02

Table 11.2 Probabilistic results given by AREVA-Gmbh (participant 2)

Surface crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	6.35E-04	4.25E-03	1.97E-02	5.48E-02
	BM	1.70E-03	7.59E-03	2.43E-02	5.35E-02
Tr3	WM	7.32E-04	6.31E-03	2.92E-02	7.65E-02
	BM	1.46E-03	8.05E-03	2.92E-02	6.58E-02

Surface crack initiation for 1 crack in a crack size distribution					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	3.17E-04	2.43E-03	1.07E-02	2.71E-02
	BM	6.21E-04	3.19E-03	1.03E-02	2.17E-02

Table 11.3 Probabilistic results given by NRI (participant 3)

Surface crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	3.57E-04	2.83E-03	1.43E-02	4.18E-02
	BM	1.45E-04	1.66E-03	9.03E-03	2.61E-02

Underclad crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	2.35E-08	1.43E-07	7.35E-07	2.57E-06
	BM	2.04E-08	1.05E-07	4.50E-07	1.29E-06

Surface crack initiation for 1 crack in a crack size distribution					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	1.07E-06	9.38E-06	4.87E-05	1.51E-04
	BM	3.84E-07	4.98E-06	2.84E-05	8.50E-05

Probability of crack arrest for an initiated surface crack					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	1.46E-04	0.451	1.139	0.487
	BM	5.26E-04	1.75E-04	0.836	0.800

Table 11.4 Probabilistic results given by KINS5 (participant 4.5)

Surface crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	1.00E-05	8.02E-04	8.89E-03	3.75E-02
	BM	4.00E-05	1.16E-03	8.57E-03	2.86E-02

Surface crack initiation for 1 crack in a crack size distribution					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	5.50E-05	9.30E-04	6.21E-03	1.91E-02
	BM	1.21E-04	1.21E-03	5.65E-03	1.52E-02

Probability of crack arrest for an initiated surface crack					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	2.00E-06	8.20E-05	1.34E-03	7.02E-03
	BM	3.00E-06	7.40E-05	7.55E-04	3.18E-03
Tr3	WM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
	BM	1.00E-08	1.00E-08	1.00E-08	1.00E-08

Table 11.5 Probabilistic results given by CEA-Cadarache (participant 5.2)

Surface crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	BM	4.60E-05	3.02E-04	1.33E-03	3.56E-03

Underclad crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	BM	1.19E-06	7.14E-06	3.10E-05	8.59E-05

Surface crack initiation for 1 crack in a crack size distribution					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	BM	2.43E-07	9.71E-07	4.04E-06	1.14E-05

Table 11.6 Probabilistic results given by JAEA / JAERI (participant 6)

Surface crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	1.05E-03	6.69E-03	2.85E-02	7.44E-02
	BM	1.95E-03	9.62E-03	3.16E-02	6.83E-02

Underclad crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	1.70E-07	2.08E-06	2.09E-05	1.03E-04
	BM	1.60E-07	1.92E-06	1.50E-05	6.27E-05

Surface crack initiation for 1 crack in a crack size distribution					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	1.15E-04	7.43E-04	3.10E-03	7.87E-03
	BM	1.99E-04	9.49E-04	3.02E-03	6.35E-03

Probability of crack arrest for an initiated surface crack					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	1.09E-03	4.17E-03	1.97E-02	4.13E-02
	BM	8.81E-04	4.89E-03	1.77E-02	4.13E-02
Tr3	WM	1.00E+00	5.80E-01	3.89E-01	3.37E-01
	BM	1.00E+00	5.58E-01	4.78E-01	4.01E-01

Table 11.7 Probabilistic results given by EDF (participant 7)

Underclad crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	BM	3.32E-07	5.86E-06	4.89E-05	2.18E-04

Surface crack initiation for 1 crack in a crack size distribution					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	BM	3.53E-08	2.47E-07	9.87E-07	2.96E-06

Table 11.8 Probabilistic results given by Inspecta (participant 8)

Surface crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	1.01E-02	1.71E-02	2.84E-02	4.59E-02
	BM	8.48E-03	1.44E-02	2.45E-02	3.81E-02
Tr2	WM	1.00E-08	1.00E-08	1.80E-02	2.71E-02
	BM	1.00E-08	8.59E-03	1.39E-02	2.08E-02
Tr3	WM	1.00E-08	2.16E-02	3.82E-02	6.34E-02
	BM	1.09E-02	1.98E-02	3.50E-02	5.53E-02

Underclad crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	1.67E-03	2.44E-03	3.35E-03	4.54E-03
	BM	9.56E-04	1.41E-03	1.92E-03	2.58E-03
Tr2	WM	1.00E-08	1.00E-08	3.08E-03	2.90E-03
	BM	1.00E-08	1.39E-03	1.52E-03	1.73E-03
Tr3	WM	1.00E-08	3.68E-03	3.65E-03	3.53E-03
	BM	1.53E-03	1.71E-03	1.97E-03	2.19E-03

Surface crack initiation for 1 crack in a crack size distribution					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	3.18E-03	3.81E-03	5.64E-03	8.68E-03
	BM	1.78E-03	2.73E-03	4.76E-03	6.89E-03

Table 11.9 Probabilistic results given by JRC (participant 9)

Surface crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	5.99E-04	3.82E-03	1.69E-02	4.68E-02
	BM	1.11E-03	5.39E-03	1.82E-02	4.13E-02
Tr2	WM	4.58E-05	4.74E-04	3.06E-03	1.10E-02
	BM	6.26E-05	5.60E-04	2.83E-03	8.36E-03
Tr3	WM	8.31E-04	5.39E-03	2.38E-02	6.34E-02
	BM	1.50E-03	7.62E-03	2.60E-02	5.74E-02

Underclad crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
	BM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
Tr2	WM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
	BM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
Tr3	WM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
	BM	1.00E-08	1.00E-08	1.00E-08	1.00E-08

Surface crack initiation for 1 crack in a crack size distribution					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	4.73E-03	1.45E-02	3.53E-02	6.39E-02
	BM	8.24E-03	1.93E-02	3.72E-02	5.80E-02
Tr2	WM	1.02E-05	1.08E-04	6.97E-04	2.50E-03
	BM	1.29E-05	1.12E-04	5.56E-04	1.61E-03
Tr3	WM	2.06E-04	1.43E-03	6.25E-03	1.62E-02
	BM	3.57E-04	1.81E-03	5.94E-03	1.28E-02

Table 11.10 Probabilistic results given by TECNATOM (participant 10)

Surface crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	2.15E-04	1.52E-03	7.27E-03	2.16E-02
	BM	3.87E-04	2.07E-03	7.59E-03	1.83E-02
Tr2	WM	6.86E-05	6.64E-04	4.21E-03	1.49E-02
	BM	9.40E-05	8.12E-04	3.99E-03	1.15E-02
Tr3	WM	1.19E-03	7.42E-03	3.12E-02	8.03E-02
	BM	2.22E-03	1.07E-02	3.47E-02	7.42E-02

Underclad crack initiation versus time for a given transient					
Transient	Material	10 years	20 years	40 years	60 years
Tr1	WM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
	BM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
Tr2	WM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
	BM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
Tr3	WM	1.00E-08	1.00E-08	1.00E-08	1.00E-08
	BM	1.00E-08	1.00E-08	1.00E-08	1.00E-08

Surface crack initiation for 1 crack in a crack size distribution					
Transient	Material	10 years	20 years	40 years	60 years
Tr3	WM	7.24E-04	4.62E-03	1.88E-02	4.58E-02
	BM	1.21E-03	5.82E-03	1.78E-02	3.62E-02