International Atomic Energy Agency

RPV Integrity Assessment: Coordinated Research Projects

Ludovit Kupca

Nuclear Power Division

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International Atomic Energy Agency

Part 1 : **Results of the IAEA Coordinated Research Projects on Irradiation Effects on RPV Steels**

Part 2 : **Review and Benchmark of Calculation Methods for Structural Integrity of RPVs during PTS in PWR**

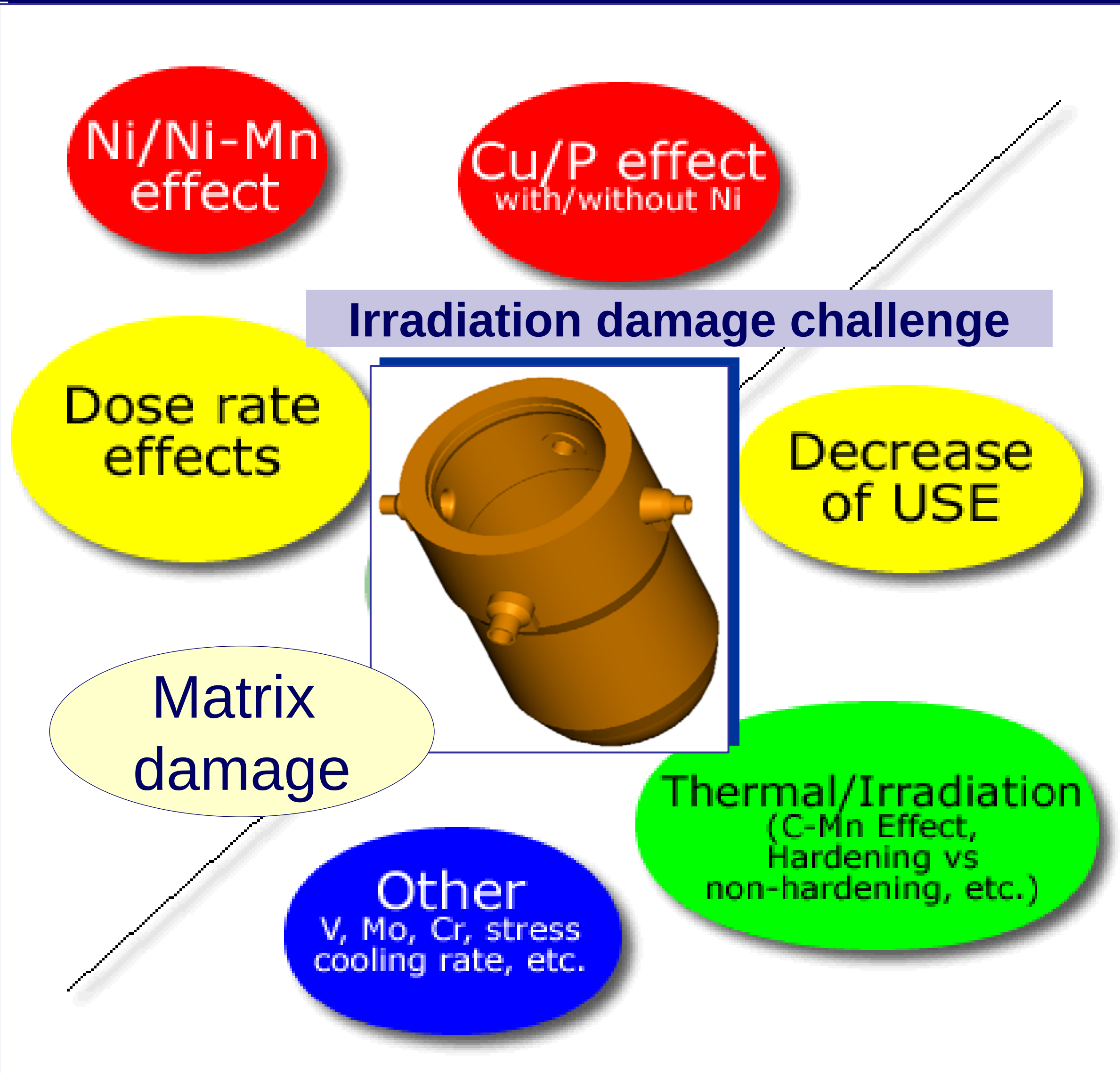
IAEA CRP History on RPV steels under neutron irradiation

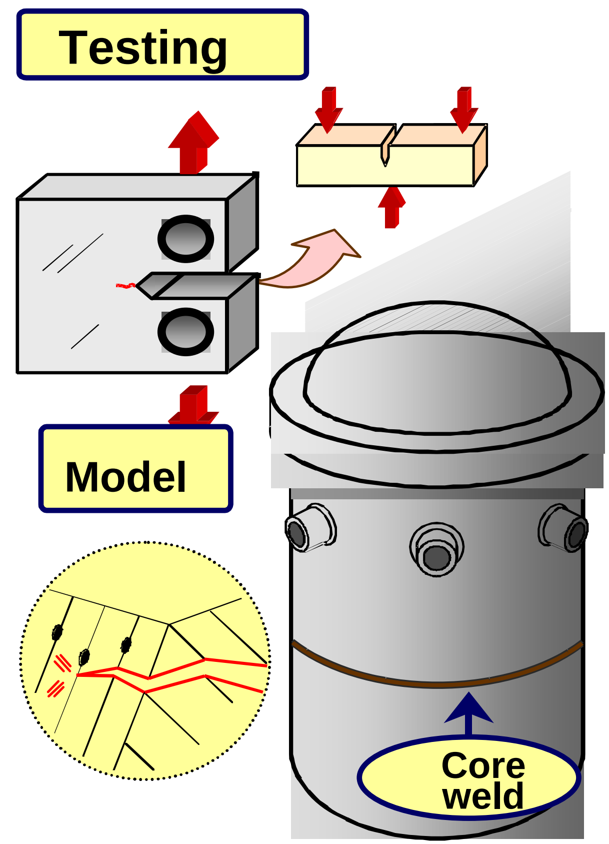
- IAEA has supported neutron radiation effects on RPV steel information exchanges since the mid of 1960s
  - Consultants' meeting,
  - Specialist meetings,
  - Conference and
  - Coordinated research projects

- In 1972, 25 countries operated water cooled type reactor.
  - Individual studies on the basic phenomenon of radiation hardening and embrittlement
    - Increases in the strength,
    - A shift upward of the brittle to ductile transitions temperature,
  - Applied the different test conditions and different steels using different test samples.

➡ It was the intent to develop a correlative comparison to test the uniformity of results through coordinate research project.

RPV integrity under irradiation damage





IAEA CRP History on RPV Structural integrity

- Phase 1 : Irradiation Embrittlement of RPV Steels (1975): 9 Org. from 8 MS.

- Phase 2 : Analysis of the Behavior of RPV Steels under Neutron Irradiation (1986) : 10 Org from 9 MS.

- Phase 3 : Optimizing RPV Surveillance Programmes and Analyses (2001) 24 Org from 18 MS.

- Phase 4 : Assuring Structural Integrity of RPV (2002) : 24 Org. from 19 MS.

- Phase 5 : Surveillance Programme Results Application to RPV Integrity Assessment (1999-2003) : 24 Org. from 15 MS.

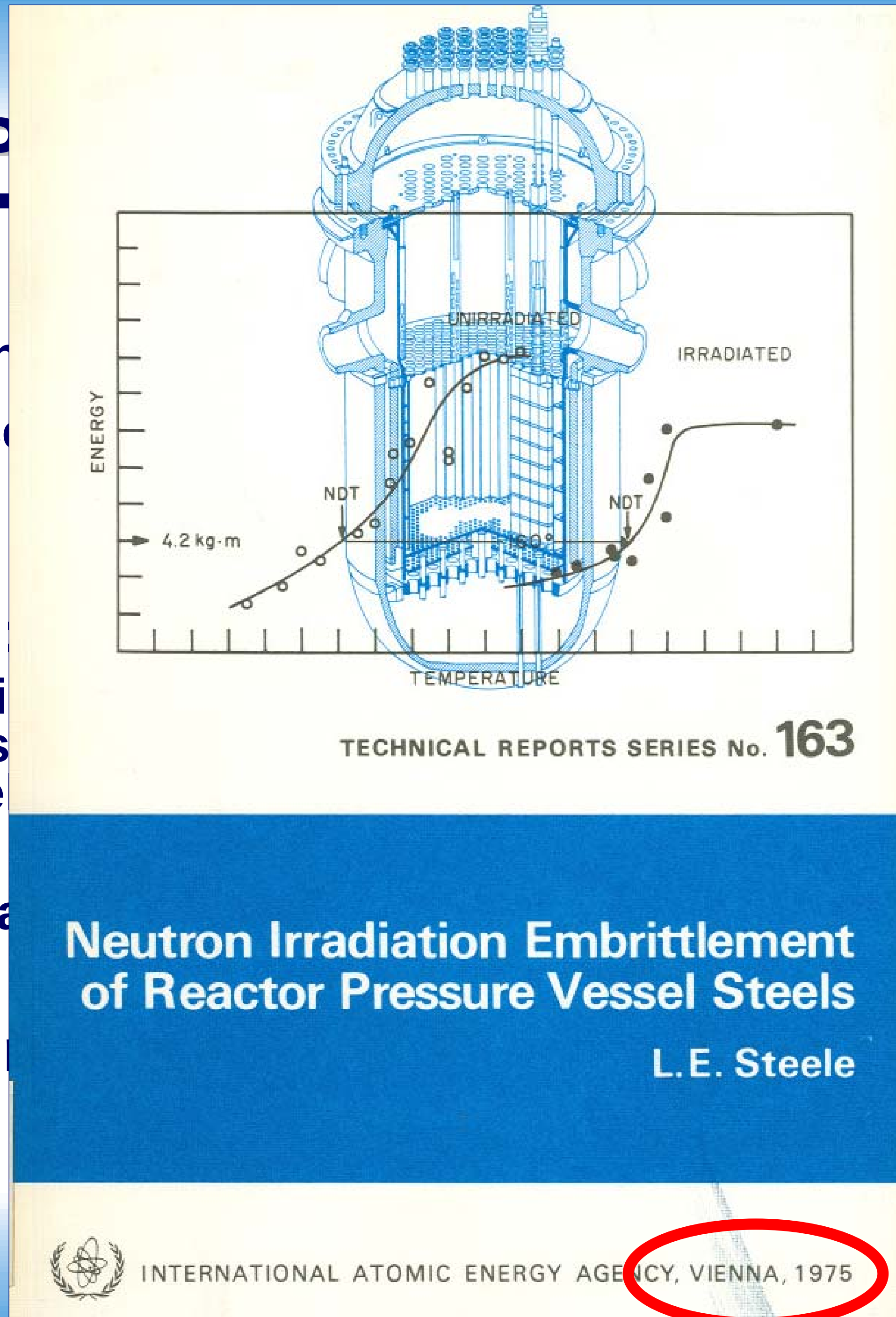
IAEA CRP History on RPV Structural integrity

- **Phase 6 : Mechanism of Ni effect on radiation embrittlement of RPV materials (1999-2003), 11 Org. from 10 MS**
- **Phase 7 : Evaluation of Radiation damage on WWER-440 RPV materials using IAEA DB (2001 - 2004), 8 Org. from 7 MS**
- **Phase 8 : Master Curve Approach to monitor the Fracture Toughness of RPV (2004 - 2007), 15 Org. from 11 MS**
- **Phase 9 : Review and Benchmark of calculation methods for structural integrity assessment of RPVs during PTS (2005 - 2007), 10 Org. from 10 MS**

More than 120 research organizations from 20 countries since 1975

Phase 1 ent of
P

- **Duration :**
- **Nine organ ates**
  - **Referenc te 03)**
    provided)
- **Main goal :**
  - **to establi rect inter-**
    comparis diation of
    RPV stee
  - **To compa ional steels**
    with that
- **Technical**



Phase 2 : Analysis of the behavior of advanced RPV steels under neutron irradiation

- **Duration : 1979 ~ 1983**
- **Purpose :**
  - **To undertake a comparative study of the irradiation embrittlement behavior of improved (advanced) steels produced in various countries**
  - **To demonstrate that careful specification of the steel for RPV can eliminate the problem of potential failure including that caused by neutron irradiation**
- **Nine organizations : Same organizations as Phase 1**

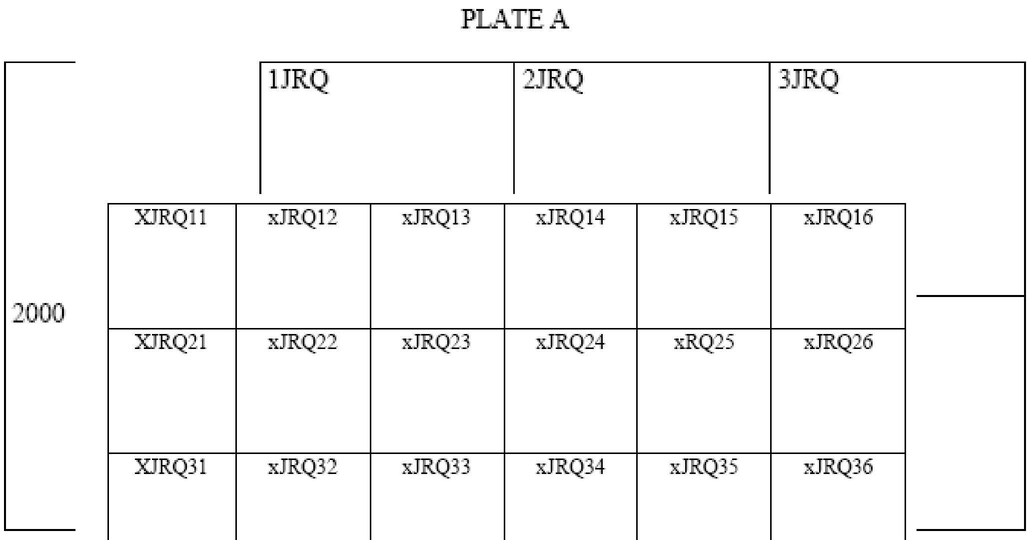
Phase 2 Main Conclusions

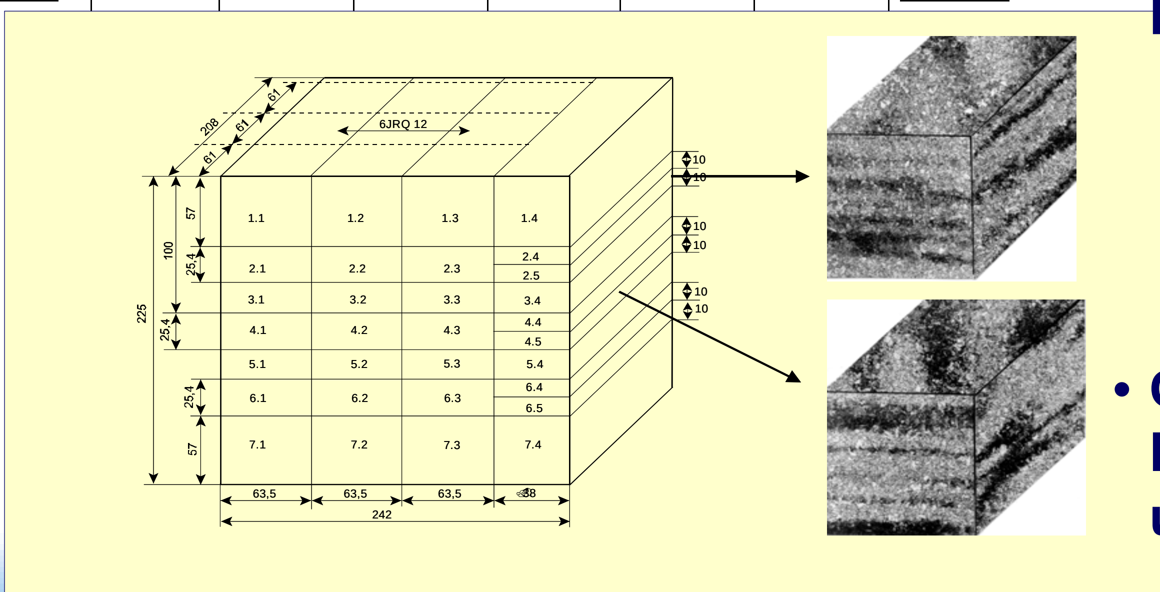
- **Modern RPV material possess high resistance to neutron irradiation damage.**
- **Reducing the copper content of steels has led to an improvement in their irradiation resistance.**
- **Changes in tensile yield strength and hardness followed the Charpy transition temperature changes**
- **There was no systematic variation of Charpy upper shelf energy change (decrease) with neutron fluence**
- **The results of fracture toughness test showed that modern steel are more resistance to neutron irradiation than older RPV steels.**

Phase 3 : Optimizing RPV Surveillance Programmes and Analyses

- Duration : 1986 ~ 2001
- 25 organizations from 15 Member states
- 16 based material and 6 weld material : tested under irradiated condition.
- Reference material : ASTM A 533 grade B Class 1: JRQ
  - Supported by Atomic Energy Research Committee of Japan.
- Objective :
  - Consolidate the growing body of data and knowledge of embrittlement,
  - Establish a guidelines for surveillance testing which could be used internationally
    - Optimization of the means for measuring fracture resistance
    - Establishment of correlative methods for measuring irradiation response
    - Understand the mechanisms responsible for embrittlement

JRQ Reference Material





- **Large sample of 25 ton steel manufactured Kawasaki Steel Corporation.**
- **Cutting diagram of test block with 1 M* 1M**
- **150 mm* 150 mm – test plate**
  - **Chemical composition**
  - **Tensile properties**
  - **Impact properties**
  - **Fracture properties**
- **Comparatively homogenous and can used as reference steel**

Phase 4 : Assuring Structural Integrity of RPV

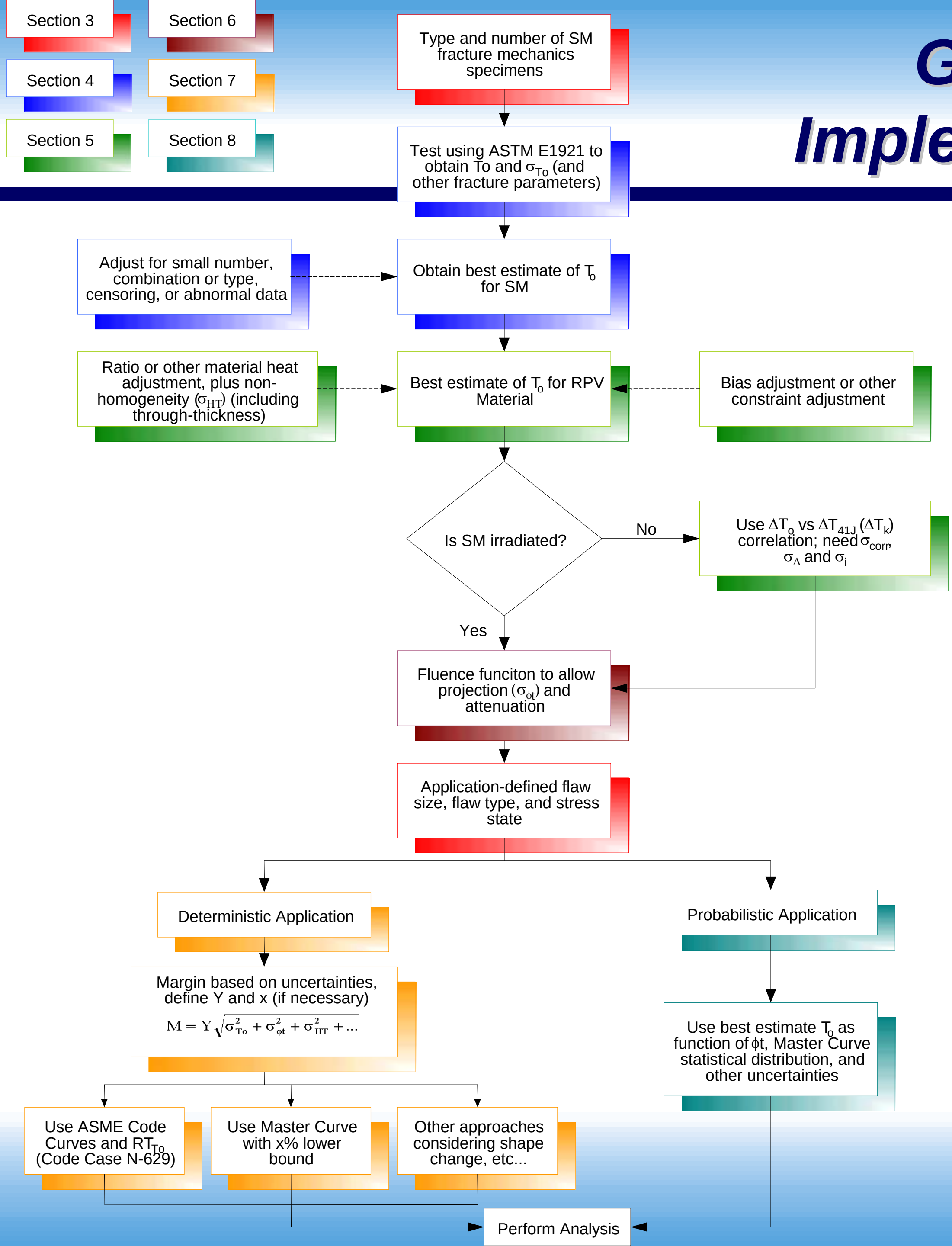
- Duration 1995~2001
- Collected a large amount of experimental data
  - To check the ASTM “ Master curve” approach using the IAEA reference steel JRQ as well as other national material
  - To verify the application of the MC using small precracked Charpy size specimens

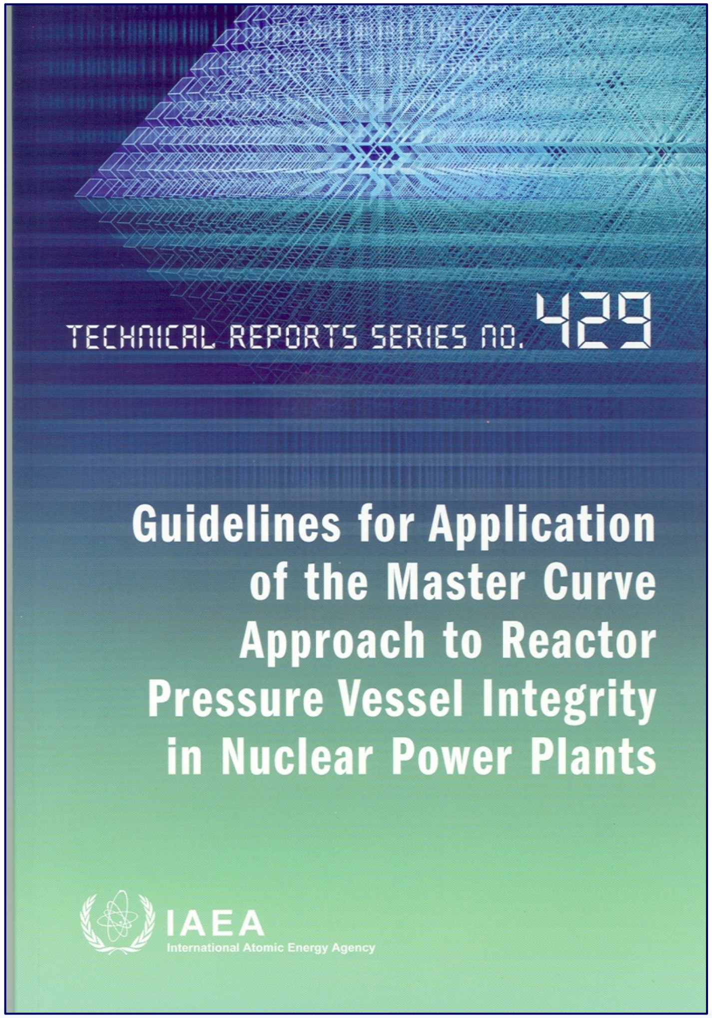
- Conclusions :
  - MC approach can be applied to wide set of national RPV type material of LWR as well as WWER type reactor
  - Demonstrated that small size specimens can be used for determination of valid values of fracture toughness of RPV steels in the transition temperature region

Phase 5 : Surveillance Programme Results Application to RPV Integrity Assessment

- **Duration : 2002~ 2004**
- **24 Organizations represen**
- **Goal :**
  - **Develop a large database of** **a** **using the Master Curve metl** **precracked Charpy size and**
  - **Develop international guidel** **applying Master Curve fractu** **for RPV integrity assessmer**

Guidelines for Implementation of MC





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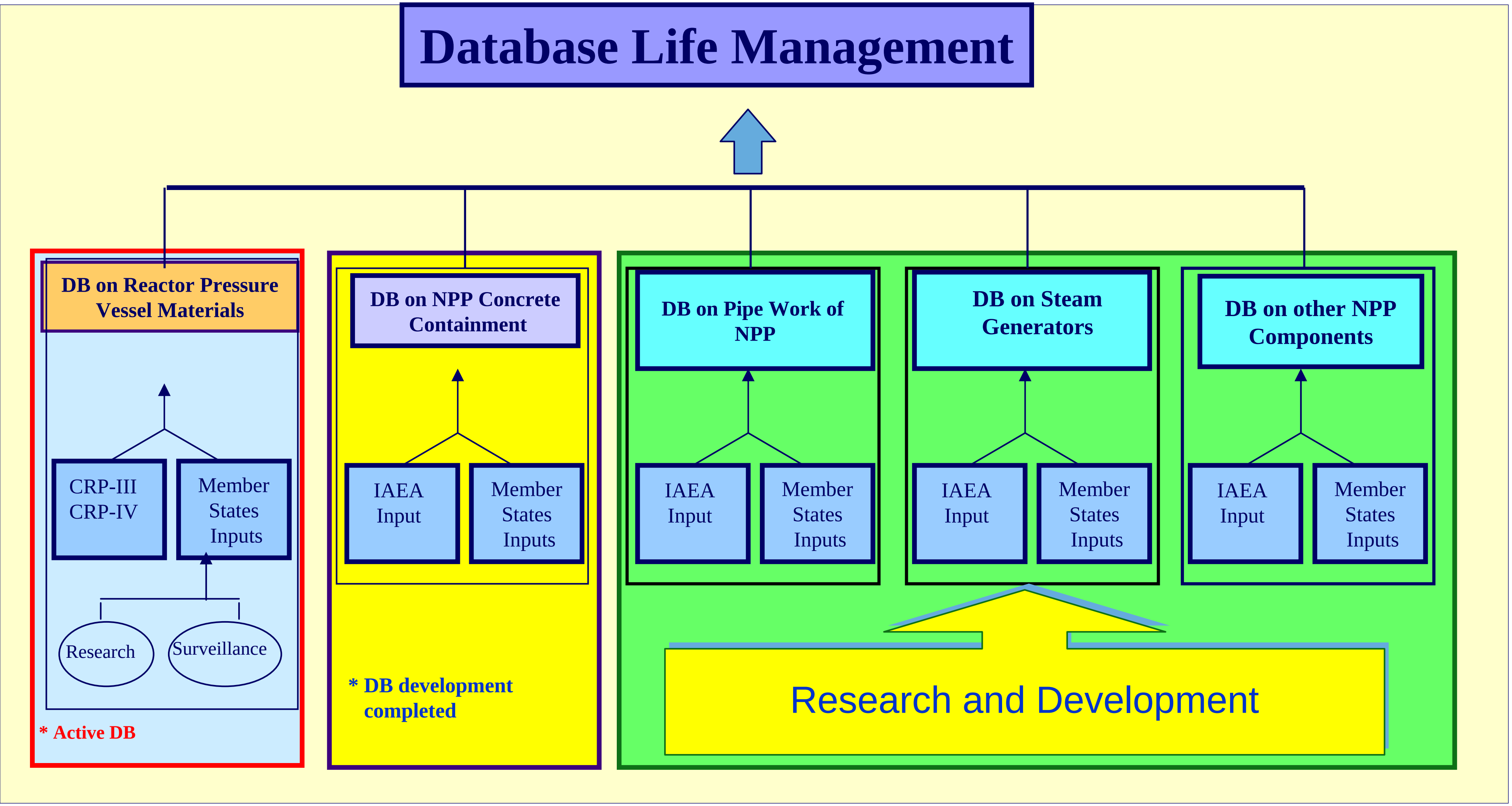
Database on NPP Life Management



Database on NPP Life Management

- All data, including text, tables, diagrams, images, received from the contributors are considered as raw data:
  - organization information
  - reactor information
  - reactor pressure vessel information
  - material properties
  - irradiation conditions
  - test conditions and results;

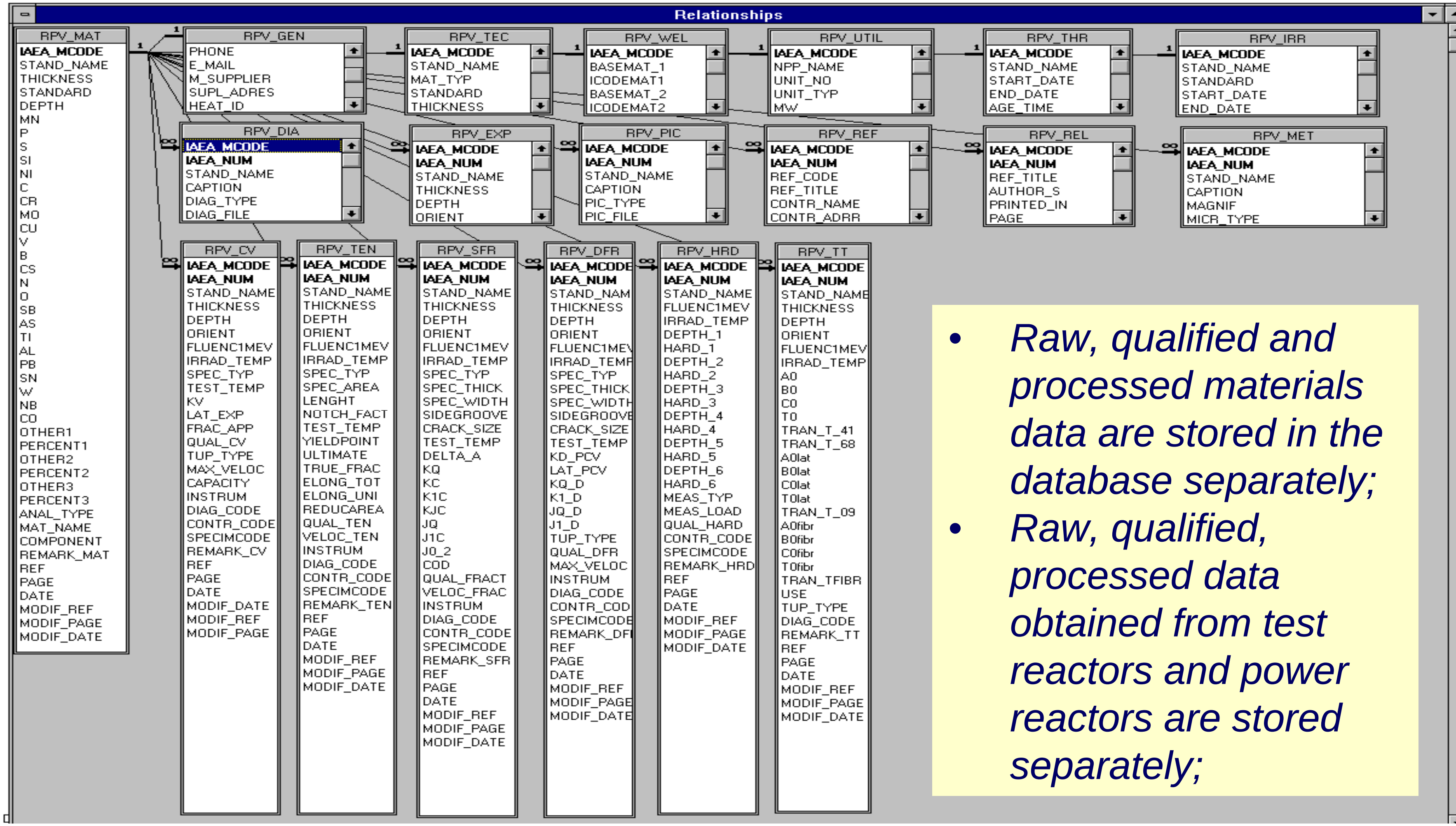
- Qualified data
- Processed materials data

- Fourteen countries supplied of surveillance data and research data through CRP-3,4, 5 and Round-Robin test on WWER 440 weldment

Structure of RPV Main Base Database

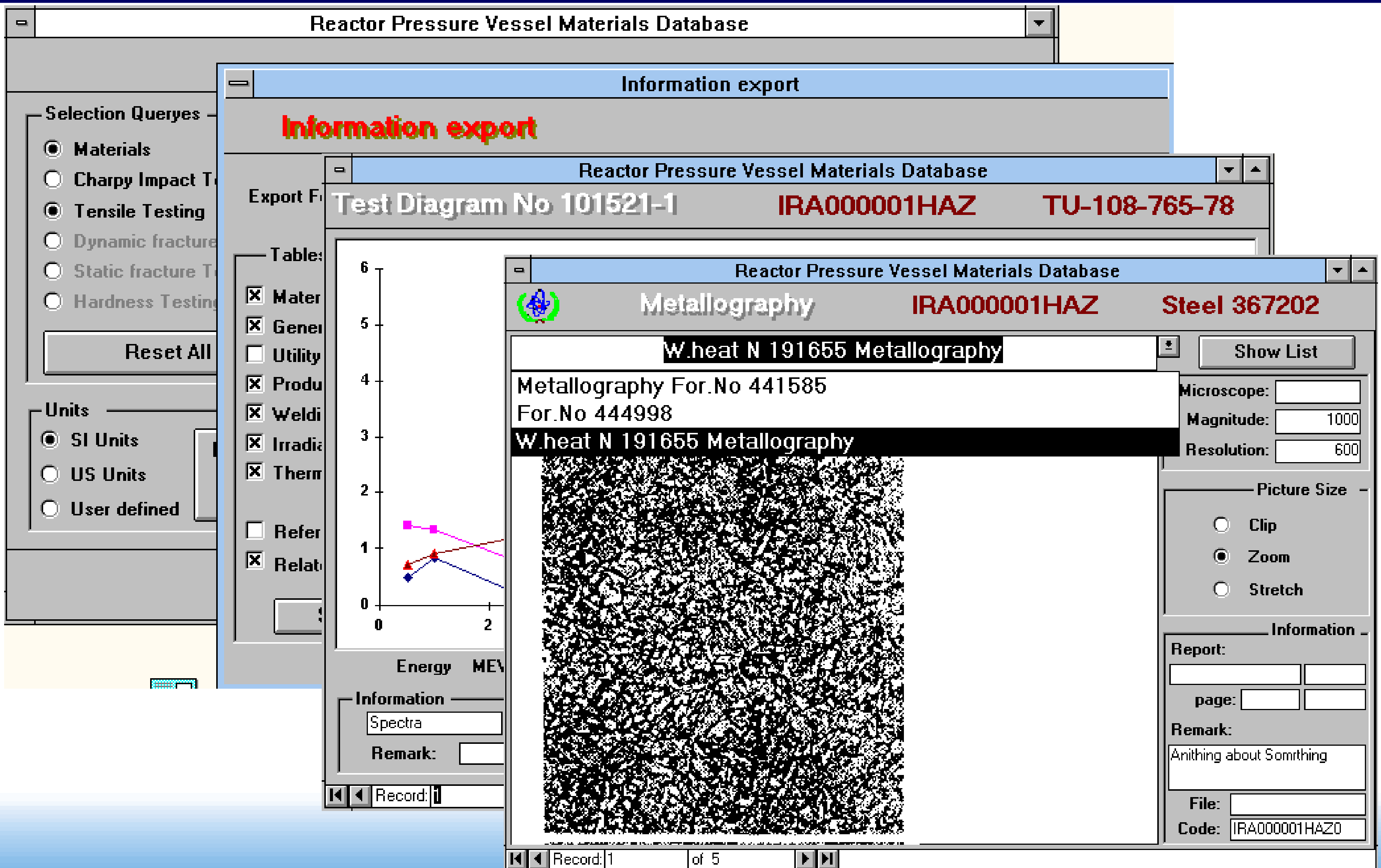
NO	Table	Comment
1	RPV_CV	Charpy V Impact Testing results
30	RPV_DFR	Dynamic fracture toughness testing results
65	RPV_DIA	Illustrative diagramms collection
89	RPV_EXP	Exponential curve collection
111	RPV_GEN	General information and address of the contributor, material supplier, rpv manufacturer
135	RPV_HRD	Hardness testing results
165	RPV_IRR	Description of the irradiation conditions
204	RPV_MAT	Material catalog and chemistry composition
249	RPV_MET	Metyallography images collection
266	RPV_PIC	Illustrative picturess collection
279	RPV_REF	References on the contributor reports
290	RPV_REL	References on the open reports
301	RPV_SFR	Static fracture toughness testing results
338	RPV_TEC	Production technology of the base material
385	RPV_TEN	Tensile testing results
418	RPV_THR	Description of the termal ageing conditions
438	RPV_TT	Transition temperatures and tangeht hyperbolic coefficients
473	RPV_UTIL	Identification of the utility which is the donor of the data
488	RPV_WEL	Welding technology information

Main relationships of developed software



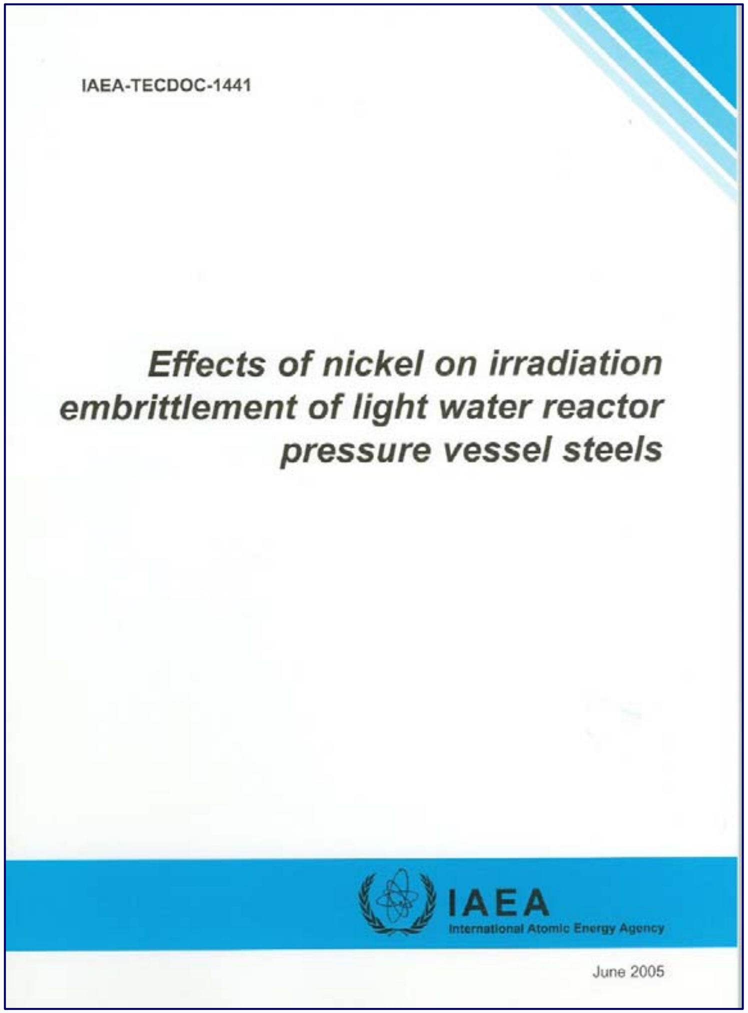
- *Raw, qualified and processed materials data are stored in the database separately;*
- *Raw, qualified, processed data obtained from test reactors and power reactors are stored separately;*

Database on Int. RPV materials



Phase 6 : Effects of Nickel on Irradiation Embrittlement of RPV Steels

- **2001~ 2004**
- **Eleven institutes from eight different countries and the European Union participated in this research and six institutes conducted the irradiation experiments of the materials.**
- **In addition to the irradiation and testing of those materials, irradiation experiments of various national steels were also conducted.**



Phase 6 : Effects of Nickel on Irradiation Embrittlement of RPV Steels

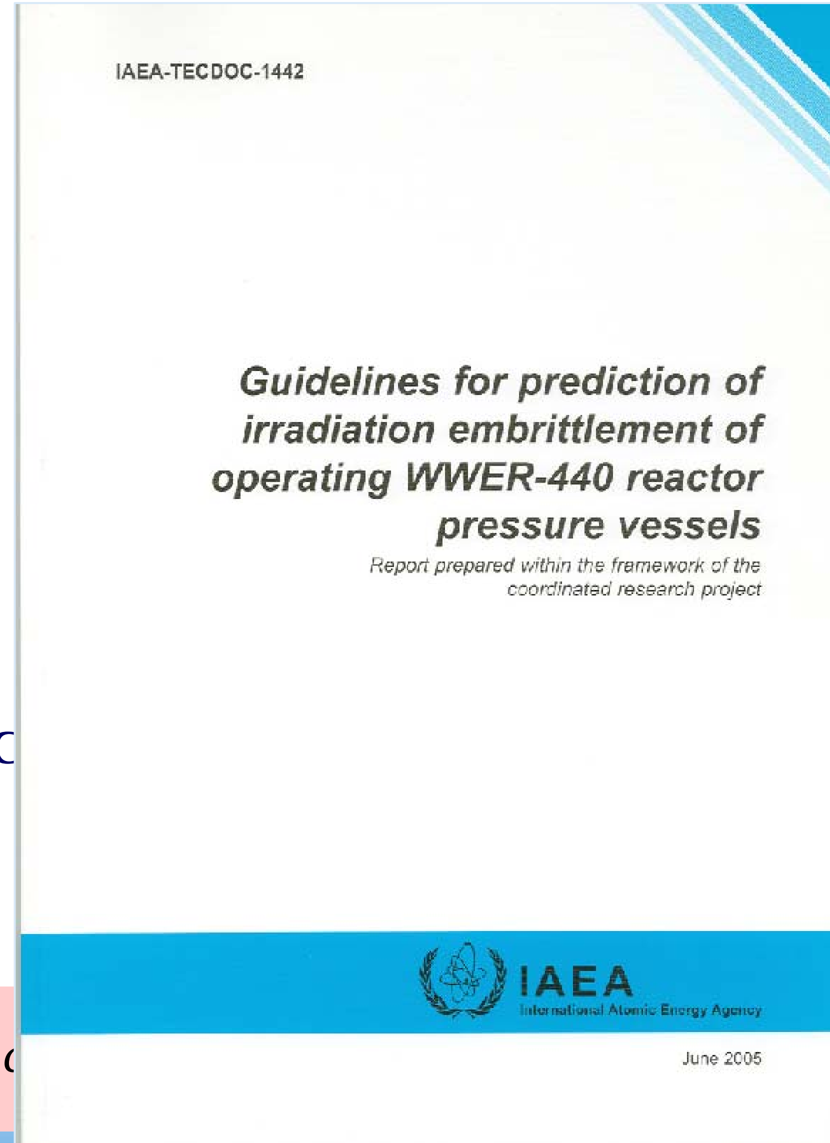
- Charpy test results in WWER -1000 base metal exhibited significantly greater scatter in the unirradiated conditions than weld metal.
- Showing higher radiation sensitivity of the high nickel weld metal compared with the lower Ni based metal.
- High Mn content leads to much greater irradiation-induced embrittlement than low Mn content
- High NI when not combined with Copper and moderate Mn, is not serious embrittling agent.

Phase 7 : Guidelines for Prediction of Radiation Embrittlement of Operating WWER-440 RPVs

- **2001~ 2005**
- **Collection of complete WWER-440 surveillance data**
- **Analysis of radiation embrittlement data of WWER-440 RPV materials**
- **Evaluation of predictive formulae depending on material chemical composition, neutron fluence and neutron flux,**
- **Development of the guidelines including methodology for evaluation of surveillance data for prediction of radiation embrittlement of NPPs**

C

$$\Delta T = a * F^{n} + b1 * \left[1 - e(^{-F/F_{sat}}) \right] + c$$


IAEA-TECDOC-1442

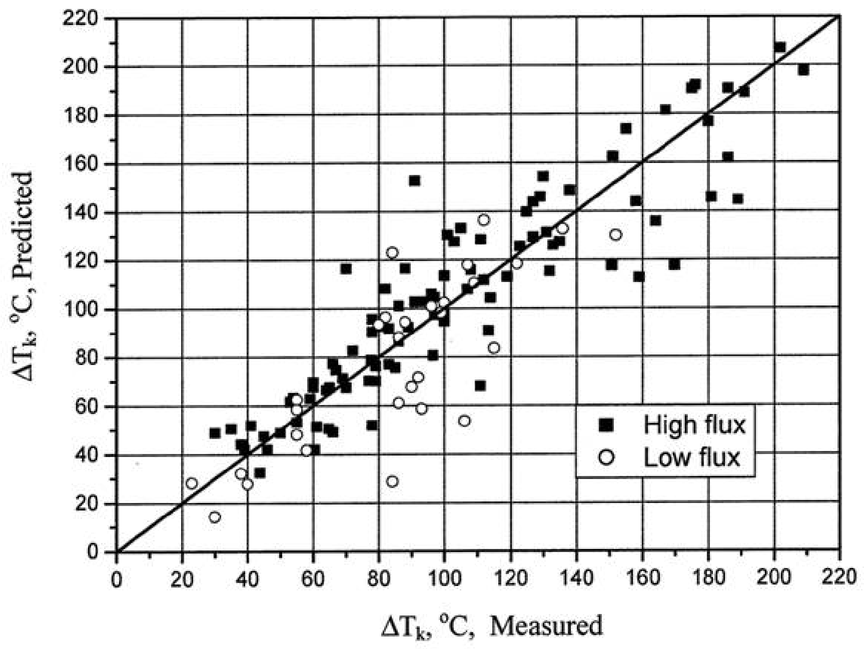
Guidelines for prediction of irradiation embrittlement of operating WWER-440 reactor pressure vessels

Report prepared within the framework of the coordinated research project

IAEA
International Atomic Energy Agency

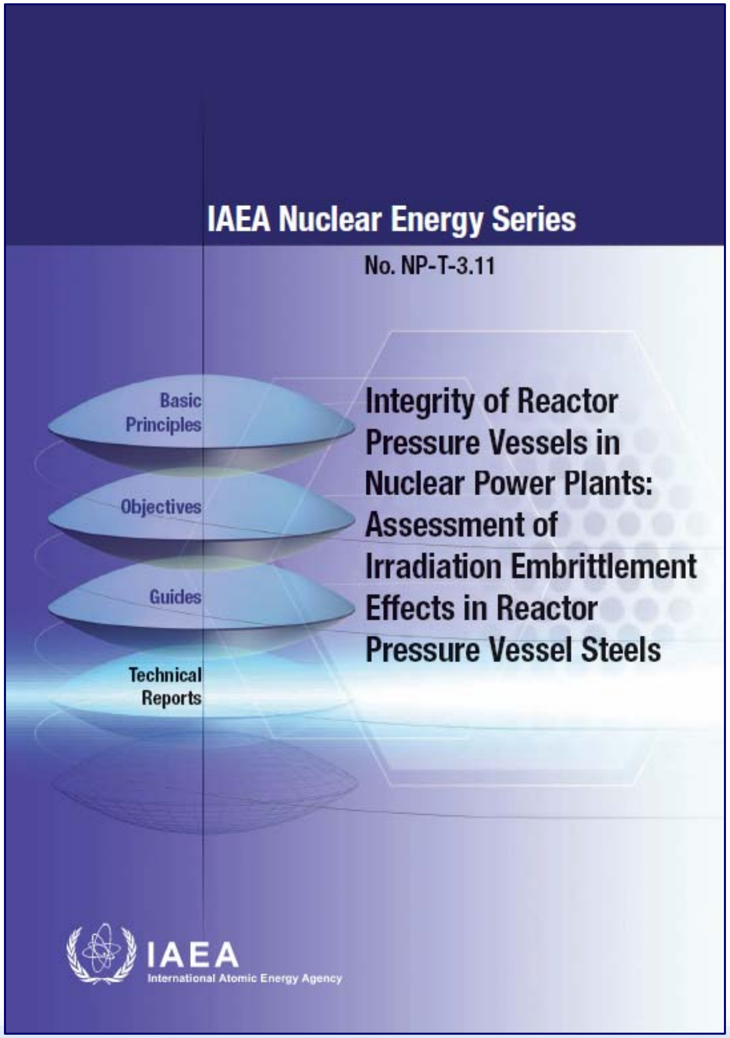
June 2005

Comparison of Experimental Data with Predictions for WWER-440 Steels



Metal	Formula	Standard Deviation
Weld Metal	$\Delta T = [884\times P + 51.3\times Cu]\Phi^{0.29}$ $= 800\times(1.11\times P + 0.064\times Cu)\ \Phi^{0.29}$	22.6°C
Base Metal	$\Delta T = 8.37\times\Phi^{0.43}$	21.7°C

Integrity of Reactor Pressure Vessel In NPPs



- **Description of reactor pressure vessels**
- **Effect of irradiation of mechanical properties**
- **Mechanisms governing the irradiation induced embrittlement of LWR RPV**
- **Assessment of the mechanical properties of operating RPVs**
- **Effects of irradiation on RPV Operation**

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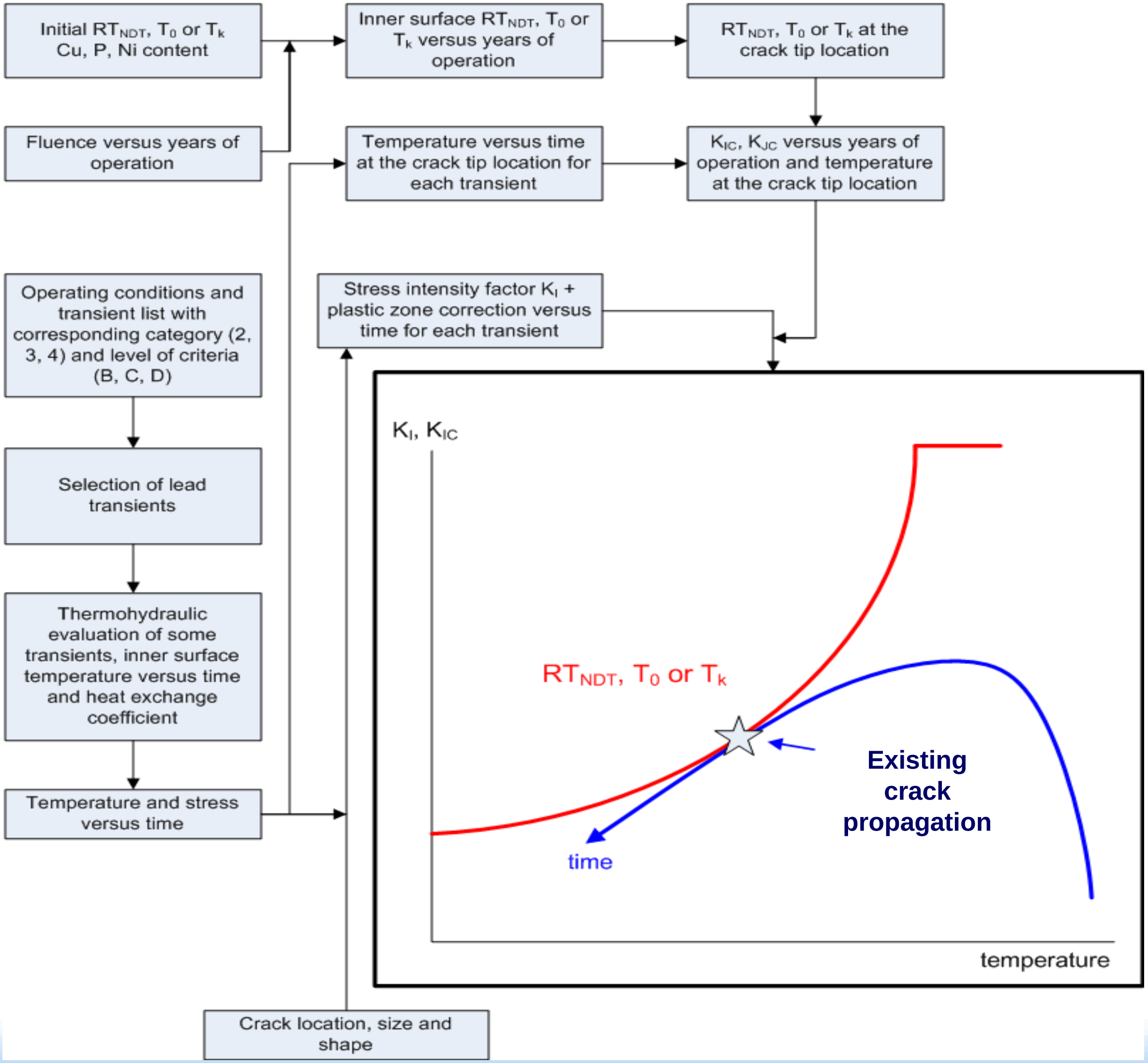
Part 2 :

Review and Benchmark of Calculation Methods for Structural Integrity of RPVs during PTS in PWR

Review and benchmark calculation methods for structural integrity assessment of RPVs during PTS

- **Benchmark calculations**
  - **WWER-440**
  - **PWR-900**
- **Participations**
  - **AREVA NP GmbH, Germany (AREVA)**
  - **CEA, Saclay, France (CEA)**
  - **EdF, BPI/SEPTEN, France, (EDF)**
  - **Fortum Nuclear Services, Finland (FNS)**
  - **KFKI, Hungary, (KFKI)**
  - **Nuclear Research Institute Rez, plc, Czech Republic (NRI)**
  - **OKB Gidropress, Russia (OKB)**
  - **Shanghai Nuclear Engineering Research & Design Institute, China (SNERDI)**
  - **VÚJE, Slovakia (VUJE)**
  - **Korea Institute of Nuclear Safety, Korea, (KINS)**

Typical RPV integrity assessment process



Approach to the PTS evaluation (1)

- Review all the possible design basis transients of a given plant, in accordance with the plant safety analysis report. Establish criteria for transient selection in term of PTS margins.
- Select the more significant transients, and corresponding criteria (e.g. level A, B, C or D) [1]
- Perform thermal hydraulic evaluation of the fluid temperature distribution in the RPV in the nozzles and down comer, the corresponding heat transfer coefficient with the RPV inner surface.
- Define the crack location, size and shape in accordance with fabrication, end of fabrication non destructive examination, previous in service inspection or conventional values.
- Evaluate the residual stress level in cladding, under the cladding and in the circumferential welds.

[1] A : normal conditions; B: upset conditions;
C: Emergency conditions; D: Faulted conditions

Approach to the PTS evaluation (2)

- **Evaluate the stress intensity factor K_I (SIF) through elastic or elasto-plastic approaches, through finite elements or engineering methods, for all the major transients.**
- **Evaluate the crack tip area temperature and fluence level, the toughness level and its increase through the wall.**
- **Evaluate K_{IC} (fracture toughness) taking into account radiation embrittlement.**
- **Compare K_I (stress intensity factor) with K_{IC} for crack initiation with corresponding safety factors; at this level different aspects can be considered, like warm pre-stress (WPS) effects, constraint effects or crack front length effects, crack arrest.**
- **Analyse the results and consider safety margins, if necessary.**

Crack initiation criteria

- The crack initiation criteria, all along the crack front in the ferritic material, with safety factor (SF), is based on:

  K_I (+ plasticity effects) $<$ K_{IC} (or K_{JC}) / SF

  This criteria can be expanded to consider other aspects such as WPS effect or crack arrest.

  For cracks totally or partially in the cladding, some specific criteria have to be consolidated.

Other considerations

In parallel with these evaluations, some checks are needed to confirm the validity of the data used:

- Fluence measurements
- Fracture toughness or Charpy specimens from surveillance programme
- Non accessible locations for in-service inspection have to be considered in the assessment
- Qualification level of the ISI has to be consistent with the analysis.

Coordinated research project -9

The overall focus was concerned fracture mechanics issues, such as the representation of the material fracture toughness (*RT_{NDT}*, *RT_{T0}* or integral Master Curve type approaches), as well as looking in detail at issues such as:

- **Postulated defect shape, size and location,**
- **Local thermo-mechanical loads (inner and outer surface in some cases) and through thickness stress distributions,**
- **Residual stresses in welds and in cladding,**
- **Cladding behaviour,**
- **WPS effect,**
- **Constraint effects due to shallow cracks, biaxial loading and crack length.**

CRP-9: technical activities (1)

Phase 1: “Benchmark analyses for generic PWR and WWER design”

- Definition of the benchmarks for generic WWER-440/213 and PWR-900 (3 Loop) designs, considering the participants own experience and the results previous international studies.
- Basic analysis of the benchmark problems and application of national code approaches i.e. including safety factors.
- Sensitivity studies to assess the impact of individual parameters.

CRP-9: technical activities (2)

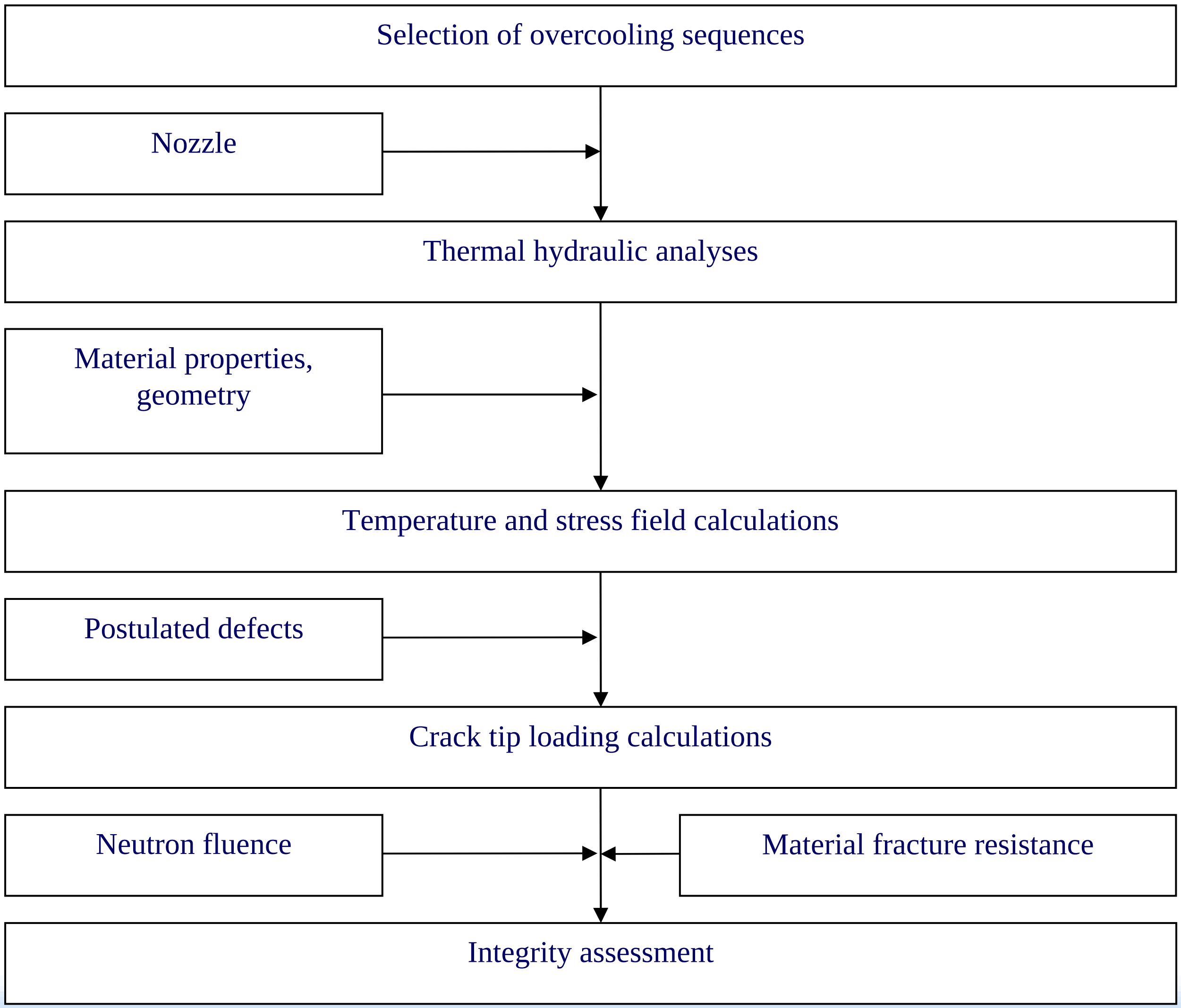
Phase 2: “Practice handbook for RPV deterministic integrity evaluation during PTS”.

- The results of Phase 1 have been used to define the present best practices guidelines, taking into account also the knowledge of the project participants and existing data from other projects and the literature.

Phase 3: Overview on PTS assessment for the IAEA technical report series

- A review of the state-of-the-art for PTS assessment technology has been performed and is published as an independent document.

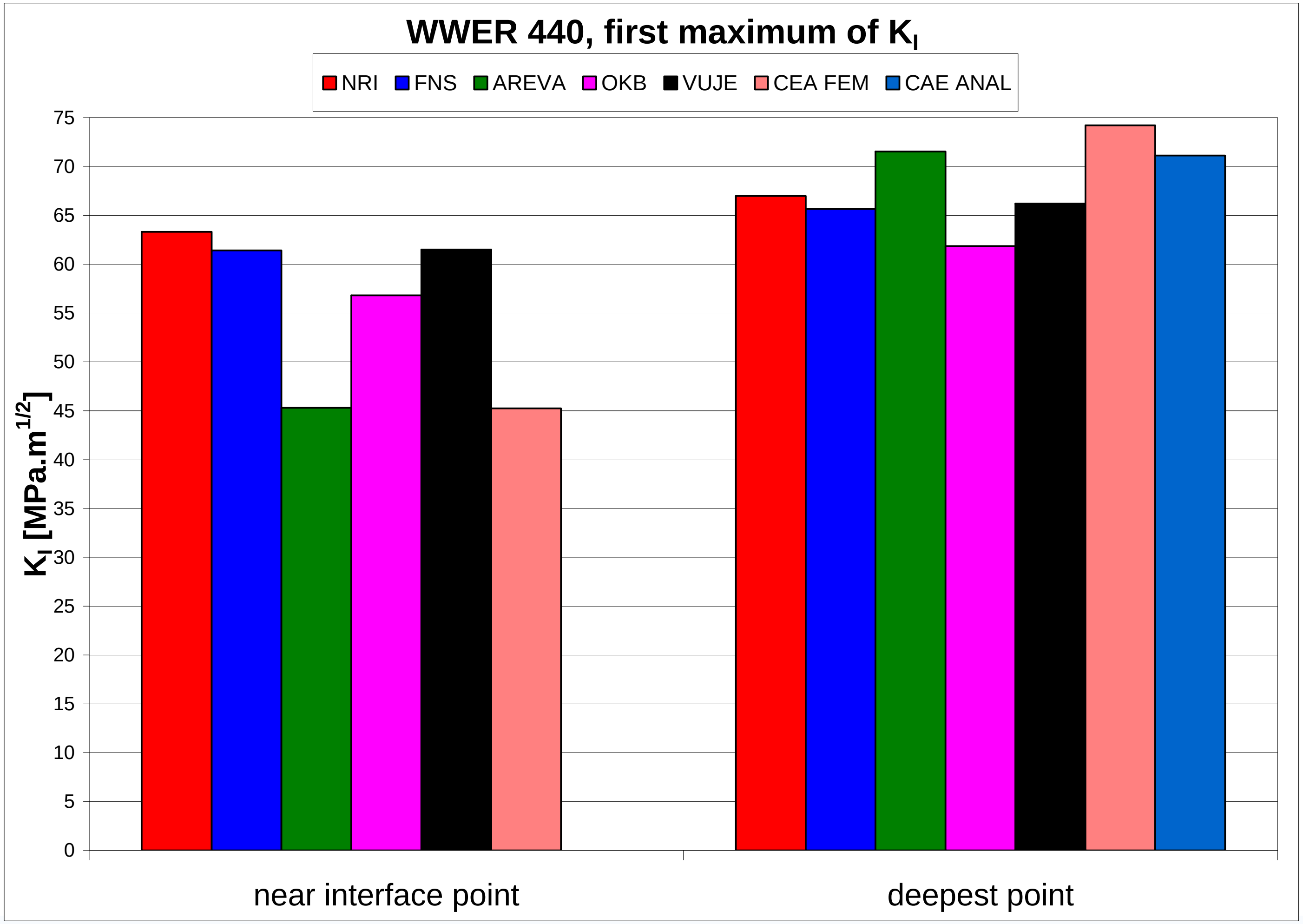
Basic evaluation scheme for PTS analysis



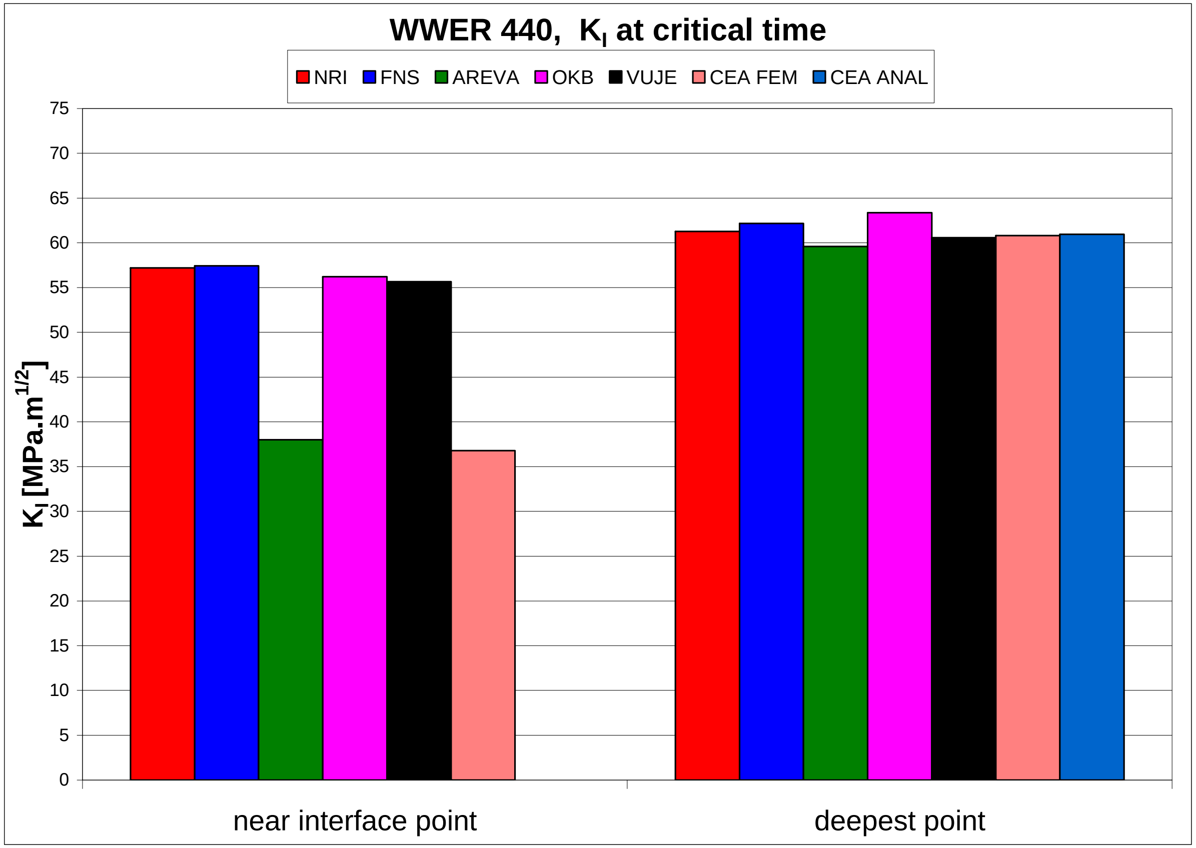
COMPUTER CODES AND METHODS USED FOR TEMPERATURE AND STRESS ANALYSIS

Participant	Computer code name	Method	Model	Type of thermal analysis	Type of mech. analysis (for nat. codes)
VUJE	ADINA	FEM	3-D	nonlinear	elastic-plastic
NRI	SYSTUS	FEM	3-D	nonlinear	elastic-plastic
AREVA	Company code ABAQUS	Semianalytical FEM	1-D 3-D	nonlinear	elastic elastic-plastic
FNS	ABAQUS	FEM	3-D	nonlinear	elastic elastic-plastic
OKB GP	MSC. Marc	FEM	3-D	nonlinear	elastic-plastic
SNERDI	MSC. Marc	FEM	3-D	nonlinear	elastic-plastic
Korea	Analytical	Analytical	1-D	linear	elastic
EdF	CUVE-ID	FEM	1-D	nonlinear	plasticity correction
KFKI	MSC. Marc	FEM	3-D	nonlinear	
CEA	Own code	Analytical	1D	linear	Elastic + plastic correction

WWER case, first maximum of K_I



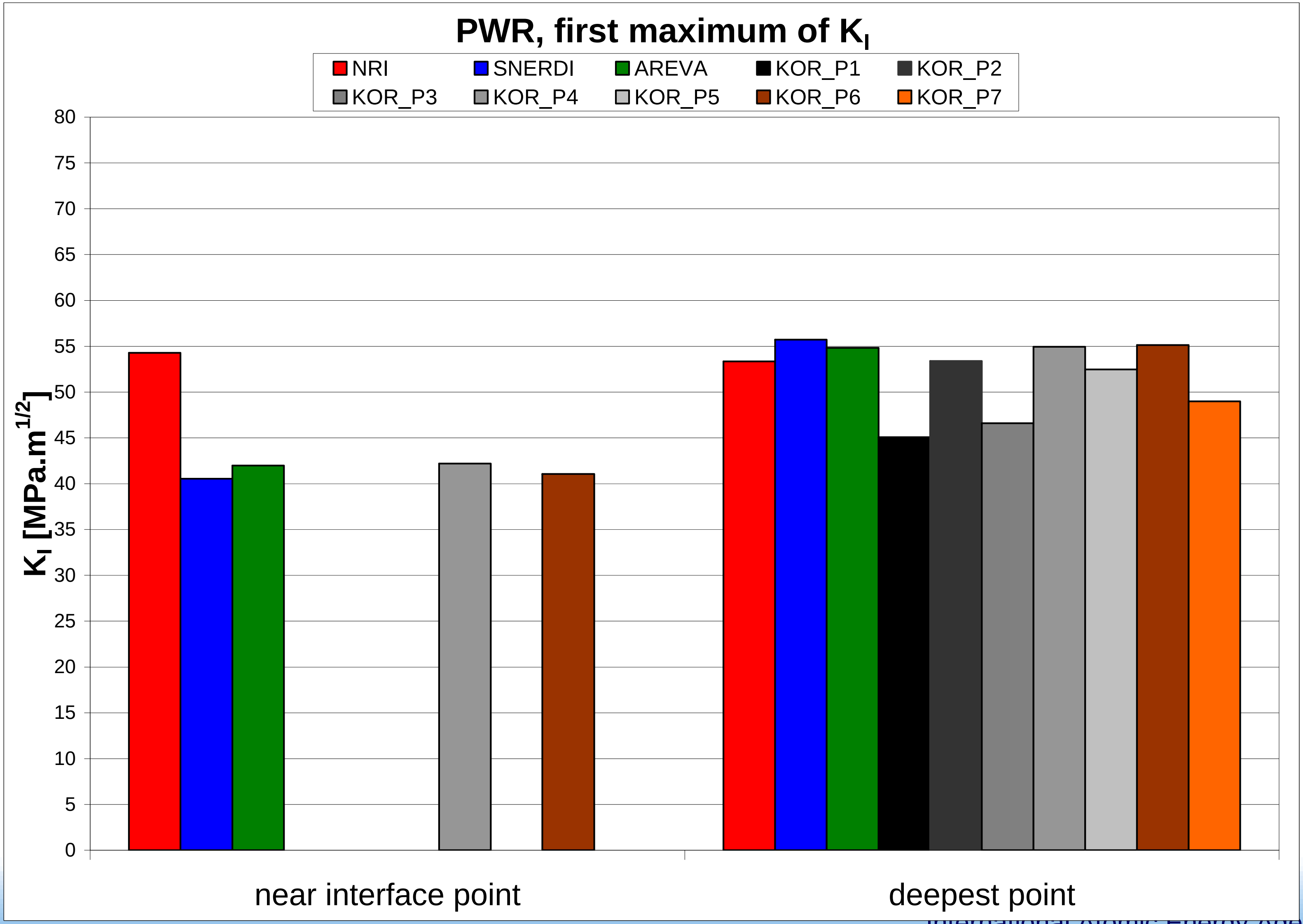
WWER case, K_I at critical time



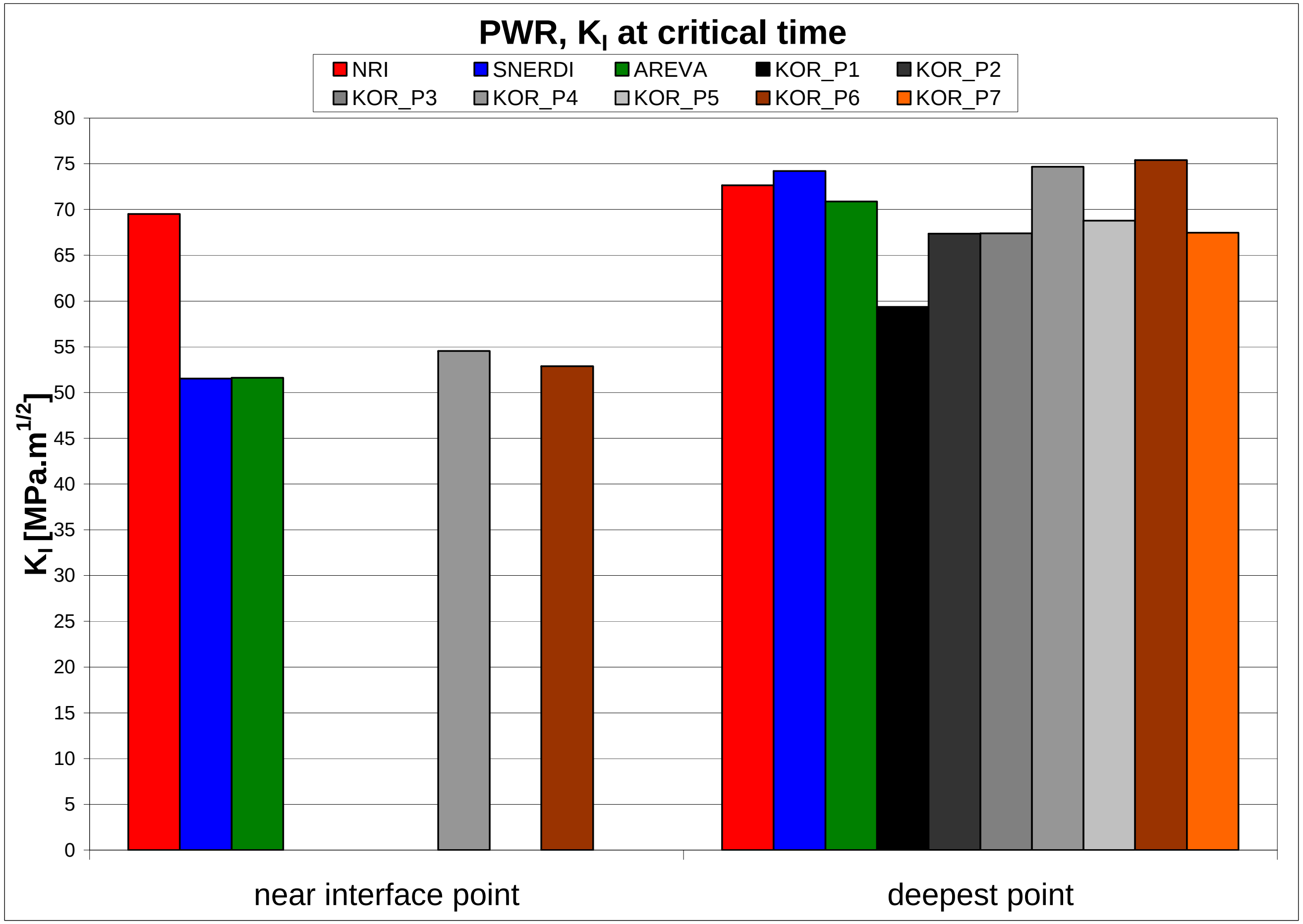
Comments to the results

- For the first maximum of K_I and the deepest point of the crack the scatter in K_I values is up to 12 MPa.m$^{1/2}$.
- The highest deviation is observed for CEA and AREVA solutions. Both used the 1D calculations for temperature and stress fields and then analytical formulae for K_I calculations.
- The approach does not take into account the effect of cold plume, which is not negligible for the time interval close to K_I maximum.

PWR case, first maximum of K_I



PWR case, K_I at critical time

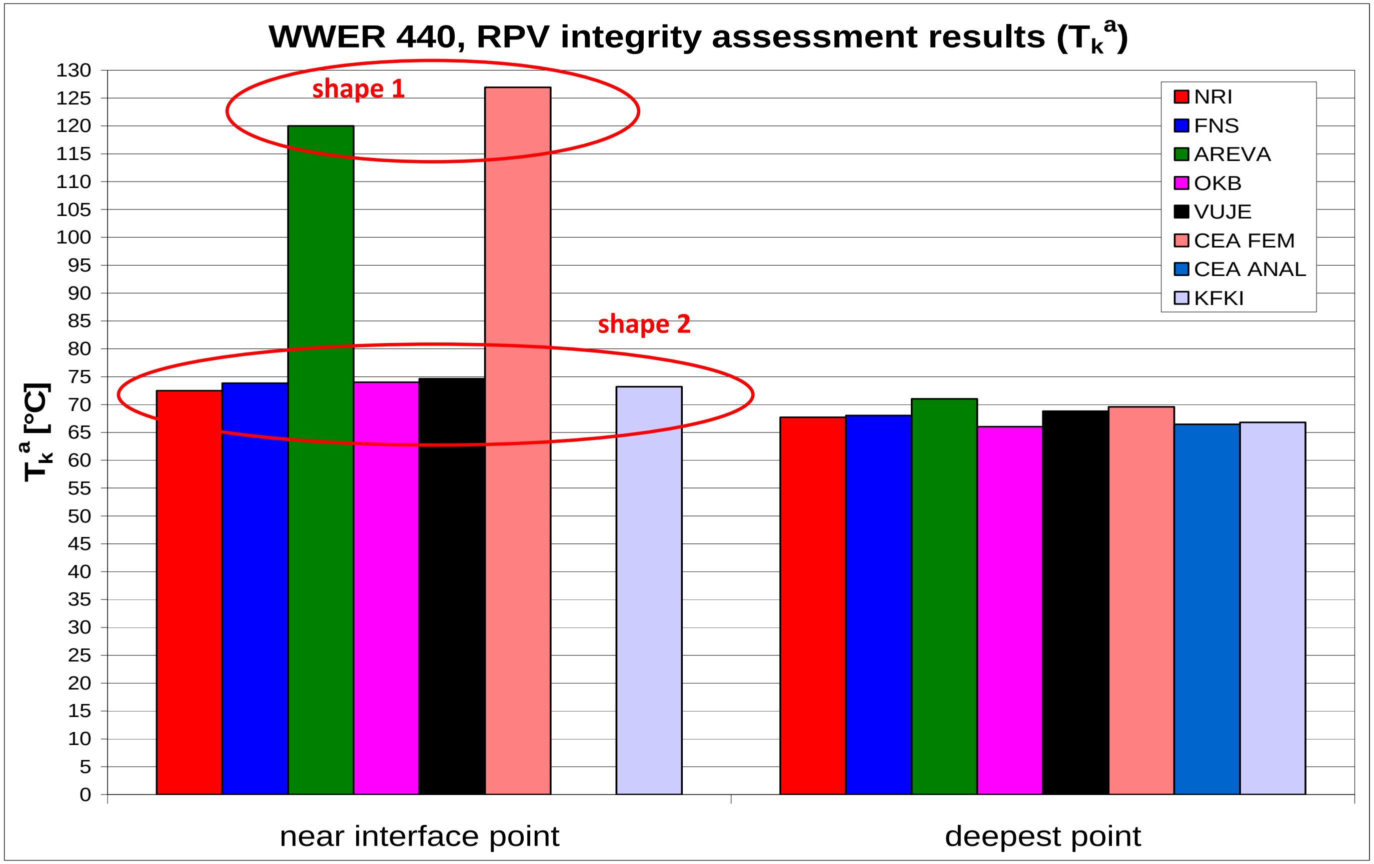


Comments to the results

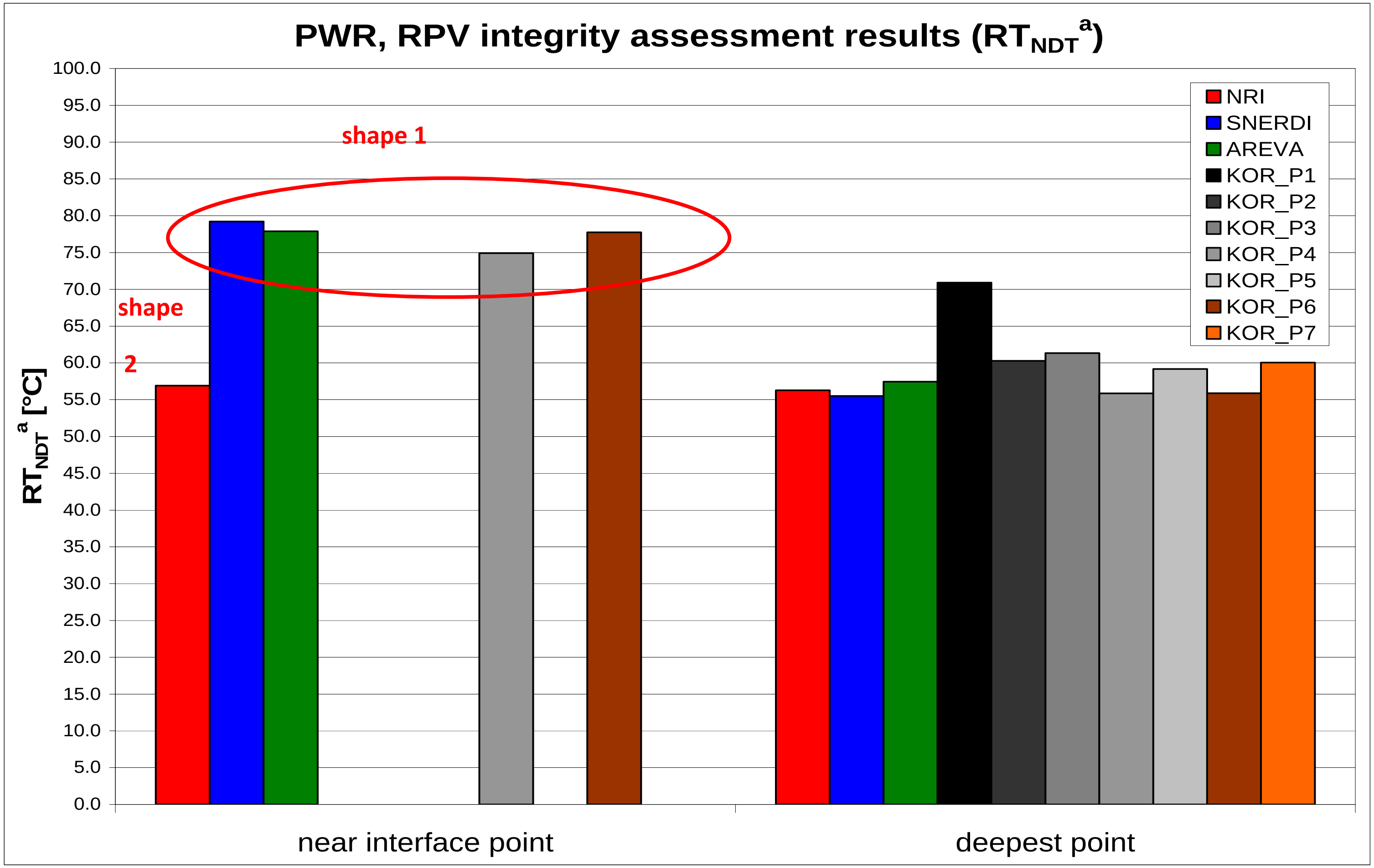
- **For PWR case we see some scatter mainly in cladding and close to the interface, caused by different shape of the crack.**

- **For corresponding shape of the crack, the accordance of the results in the base material is good.**

WWER case, maximum allowable critical temperature of brittleness T_k^a



PWR case, maximum allowable reference temperature for nil ductility transition RT_{NDT}^{a}



Comments to the results

- For the WWER case, the scatter in resulting T_k^a values for the deepest point (which is the worst one along the crack front) is 5 °C, which is very good result, having in mind the complexity of the problem and different FEM codes and tools used for J (or G) calculations. The critical time was found in range 3650s to 4200s.

- For the PWR case, the scatter in resulting RT_{NDT}^a values for the deepest point after excluding too simplified P1 solution is 5 °C, which is very good result. The critical time was found in range 7185 s to 7273 s. The time 7185 s is the time just after sudden re-pressurization.

CRP-9: Conclusions

- Benchmark calculations were performed to improve the user qualification and to reduce the user effect on the results of the analysis. This addressed generic PWR and WWER reactor vessels types, as well as sensitivity analyses to check several points. For well-defined boundary conditions (vessel geometry, transient parameters, material properties, postulated flaw) the participating organizations produced very consistent results.

The complementary sensitivity analyses showed that the following factors significantly influenced the assessment:

- flaw size,
- flaw shape,
- flaw location and orientation,
- thermal hydraulic assumptions,
- material fracture toughness.

CRP-9: Conclusions

- Applying national codes and procedures to the benchmark cases produced significantly different results in terms of allowable material transition temperature. This is mainly related to the safety factors used and approaches to postulated defects, postulated transients and representation of material toughness.
- For estimating crack driving force for flaws on clad vessels, estimates from advanced handbook methods provided equivalent results to 3-D finite element calculations.
- For symmetrical cooling of the core weld with 1-D temperature distributions, simplified fracture mechanics assessment methods can be applied.

CRP-9 recommendations: Identified priorities

- Continue in development of international consensus on good practices for PTS assessment and associated safety margins.
- Improve consistency between PTS assessment, flaw evaluation, P-T curves, screening criteria and ISI performance.
- Development of associated training material, in particular benchmarks, recognising the multi-disciplinary nature of PTS assessment and the part it plays in the overall plant life management programme.

CRP-9 recommendations: Identified priorities

- Future studies should focus on thermal hydraulic aspects, transient selection and on nozzle assessment.
- Improve use of harmonised probabilistic methods (transient selection, safety factors etc.) in the context of the assessment procedure.
- Need to have common approach to efficient selection of transients.

Challenges Still Remain

- IAEA has contributed significantly to dissemination of knowledge regarding RPV structural integrity though nine CRPs, sponsored meetings, and associated publications.

- Other advances in technology exist that still need further integration; e.g.:
  - Elastic-plastic fracture mechanics using even smaller test specimens
  - Large databases of surveillance data from various types of reactors to assess uncertainties associated with predictive embrittlement correlations/models
  - Enhanced microstructural tools, such as atom probe tomography and SANS, for obtaining better understanding of radiation damage mechanisms
  - Computational sciences that provide ability to rapidly perform modeling studies, such as molecular dynamics