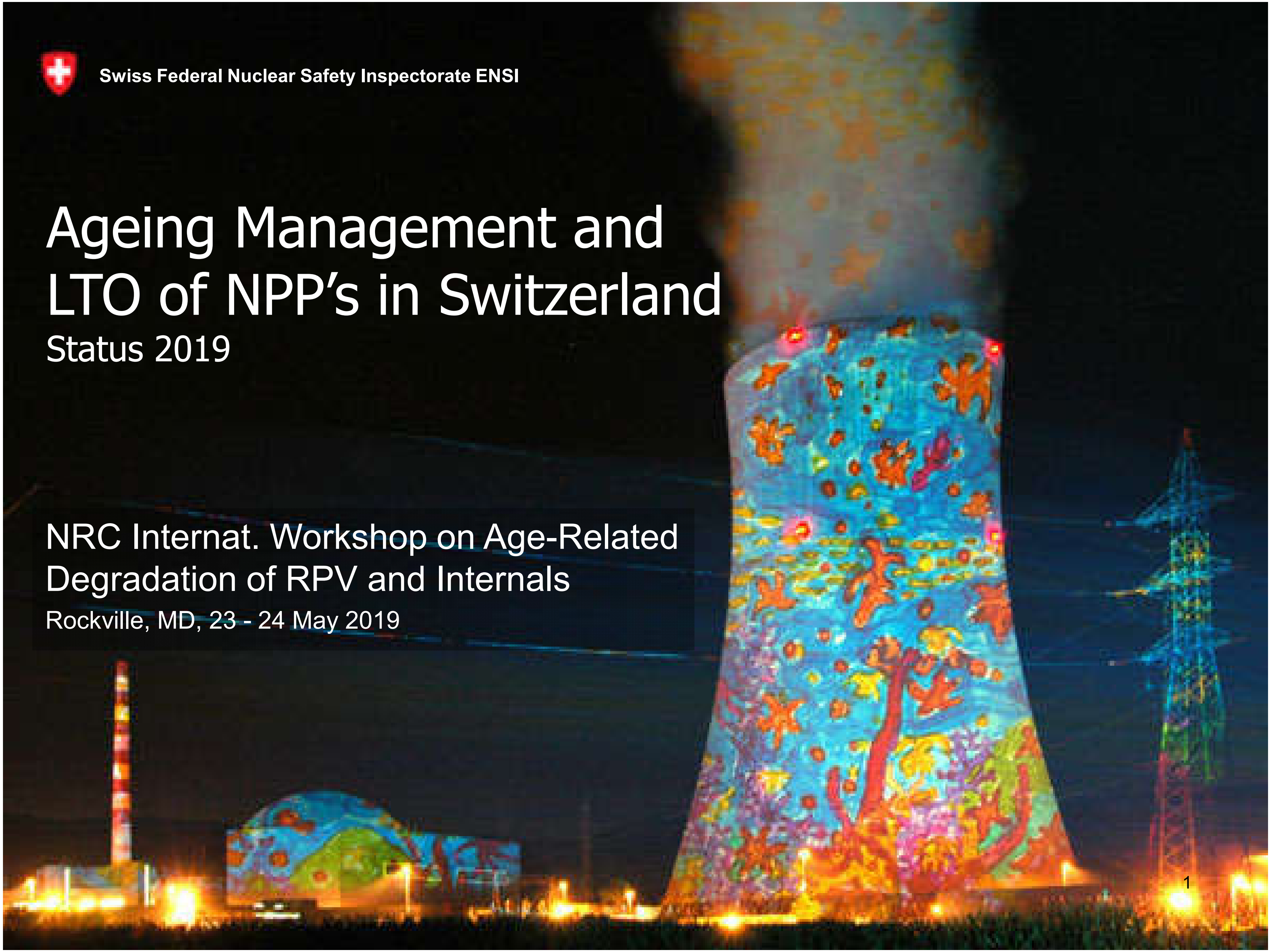
Swiss Federal Nuclear Safety Inspectorate ENSI

Ageing Management and LTO of NPP’s in Switzerland

Status 2019

NRC Internat. Workshop on Age-Related Degradation of RPV and Internals

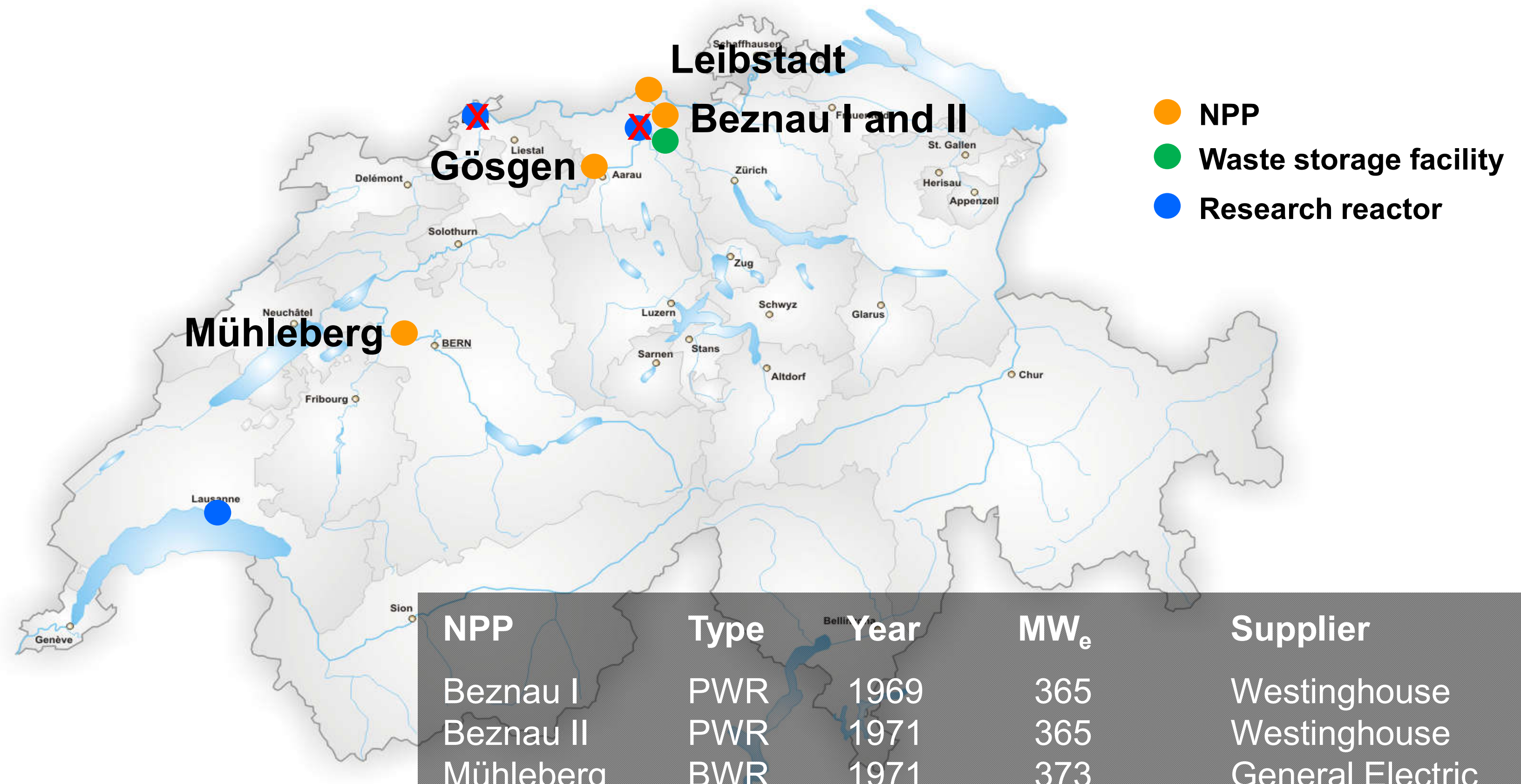
Rockville, MD, 23 - 24 May 2019



Presentation outline

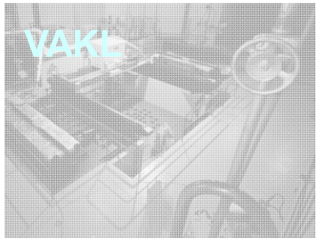
- Nuclear power plants in Switzerland
- Regulatory framework related to Ageing & LTO
- OpEx: Fatigue & Embrittlement
- OpEx: NPP Beznau & Safety Case (RPV Inclusions)
- OpEx: NPP Mühleberg, Core Shroud Cracking
- Research activities
- Summary
- *OpEx: NPP Leibstadt (to be presented by J. Heldt)*

Nuclear facilities in Switzerland



NPP	Type	Year	MW_e	Supplier
Beznau I	PWR	1969	365	Westinghouse
Beznau II	PWR	1971	365	Westinghouse
Mühleberg	BWR	1971	373	General Electric
Gösgen	PWR	1979	985	Siemens-KWU
Leibstadt	BWR	1984	1165	General Electric

Nuclear Power Plants in Switzerland



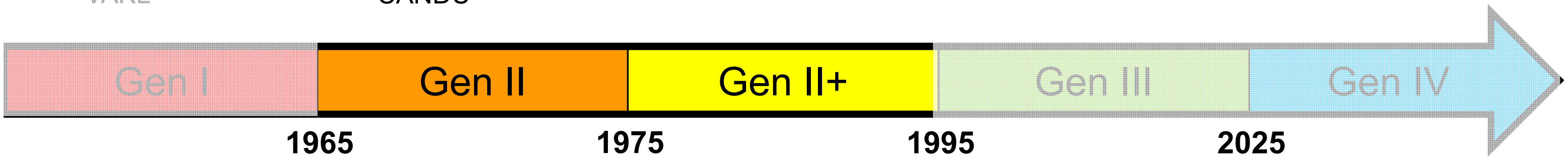
Early Prototypes:
- Magnox
- Dresden
- VAKL

Commercial Power:
- 2L Westinghouse
- BWR 3
- AGR
- CANDU

General Design Criteria:
- 4L Westinghouse
- BWR 6
- KWU Konvoi

Evolutionary Designs:
- AP1000
- ABWR
- EPR
- CANDU 6

Revolutionary Designs:
- Sustainable
- Physically secure
- Proliferation resistant



Nuclear Power Plants in Switzerland

	KKB 1	KKB 2	KKG	KKL	KKM
Thermal output [MW]	1130	1130	3002	3600	1097
Net electric output [MW] (2017)	365	365	1010	1220	373
Reactor supplier	WE	WE	KWU	GE	GE
Reactor type	PWR	PWR	PWR	BWR	BWR
Reactor model	1st Gen. 2 loop	1st Gen. 2 loop	2nd Gen. 3 loop (Pre-Konvoi)	BWR-6 GE-5	BWR-4 GE-3
Main heat sink	River water	River water	Cooling tower	Cooling tower	River water
Commenced com-mercial operation	1969	1972	1979	1984	1972
Final shutdown (assumption)	(2029 ... 2031)	(2029 ... 2031)	(≥ 2039)	(≥ 2044)	2019
Expected lifetime	(≈ 60)	(≈ 60)	(≥ 60)	(≥ 60)	48

Current LTO Status, 2019

Unlimited operating life time for NPP's but **conditions for preliminary taking out of service, Periodic Safety Review + LTO safety evaluation (10 year interval)**

1st generation NPPs in Switzerland

- Beznau-1 (1969), LTO approved for the period 2008 until 2018
  Beznau-2 (1971), LTO approved for the period 2010 until 2020
  second LTO (Unit 1&2) project submitted to ENSI in 2018 for the next 10 year period
- Mühleberg (1972), LTO approved until shut down in 2019

2nd generation NPPs in Switzerland

- Gösgen (1979), LTO project submitted to ENSI end of 2018
- Leibstadt (1984), LTO project in 2023 / 2024

LTO Requirements

After 40 years of operation:

- Unlimited operating life time for NPP's but **conditions for preliminary taking out of service**
- **Continued backfitting measures** to improve nuclear safety or reduce nuclear risks
- Periodic Safety Review + **LTO safety evaluation based on licensees' safety cases**

  2010, Report on Life Management for LTO NPP Beznau
  2012, Report on Life Management for LTO NPP Mühleberg

Time Limited Ageing Analysis (TLAA) & Safety Analyses

- RPV Integrity (irradiation surveillance program, neutron fluence assessment, PTS analyses)

  (ENSI-B01, Reg.-Guide 1.99 Rev. 2, KTA 3203)

- Pressure vessels and piping, mechanical and thermo-mechanical fatigue analysis

  (ENSI-B01,10 CFR 50.54, NUREG-1800, NUREG-6909)

- Pressure vessels and piping, leak before break analysis

  (NUREG 0800 SRP 3.6.3, NUREG-1061, Reg.-Guide 1.45 KTA3206)

- Safety Analyses for NSSS
- Steel containment, corrosion monitoring and corrosion assessment
- Structural analysis of the concrete parts of the containment

Regulatory Timeline of AMP in Switzerland

- 1991 HSK enforced requirement for AMP
- 2001 RegGuide HSK-R-48 – Periodic Safety Review (PSR)
- 2004 RegGuide HSK-R-51 – Ageing Management (AMP)
- 2005 Nuclear Energy Act, Nuclear Energy Ordinance
- 2008 DETEC Ordinance "Preliminary shut down of NPP"
- 2008 RegGuide ENSI-B02 – Periodic Reporting
- 2009 IAEA NS-G-2.12, Safety Guide for AMP
- 2011 RegGuide ENSI-B01 – Ageing Management
- 2012 IAEA OSART Mission (with LTO module) Mühleberg NPP, 2014 OSART follow-up visit
- 2014 RegGuide ENSI-A03 – PSR for NPP (incl. LTO),
- 2017 Swiss Participation on ENSREG Topical Peer Review 2017,
- 2018 IAEA SSG-48, New Safety Guide for AMP -> Review of RegG B01
- 2018 ENSI guide manual for AM of storage tanks

Key legal documents and guidelines, NEA, NEO

- Nuclear Energy Act
  - ✓ Art. 22: Maintenance, PSR, AMP and Backfitting

- Nuclear Energy Ordinance
  - ✓ Art. 32 Maintenance, in-service inspection and functional testing,
  - ✓ Art. 33 Systematic safety and security assessments
  - ✓ Art. 34 Comprehensive safety review for nuclear power plants
  - ✓ Art. 35 Ageing management
  - ✓ Art. 36 Monitoring the state of the art in science and technology and the operating experience in comparable installations
  - ✓ Art. 44 Conditions for the taking out of service and backfitting of nuclear power plants

Key legal documents and guidelines, Ordinances

- Ordinance for safety classified vessels and piping
  - ✓ During design, fabrication and construction of mechanical components materials with highest quality shall be used to minimize the impact of ageing effects
- DETEC Ordinance "Preliminary shut down of NPP"

A NPP has to shut down if the integrity of the physical barriers is compromised by ageing mechanisms (definition of acceptance criteria)

- ✓ RPV embrittlement: - adjusted reference temperature > 93 °C
  - upper shell Charpy energy < 68 J
- ✓ Wall thickness of primary piping < original design thickness
- ✓ Cracking of primary piping < allowable limits (fracture mechanics)
- ✓ Wall thickness of primary containment < original design thickness

For LTO: Demonstrate compliance with these criteria for ageing over the expected operation time by TLAA

Key legal documents and guidance, RegG ENSI-B01

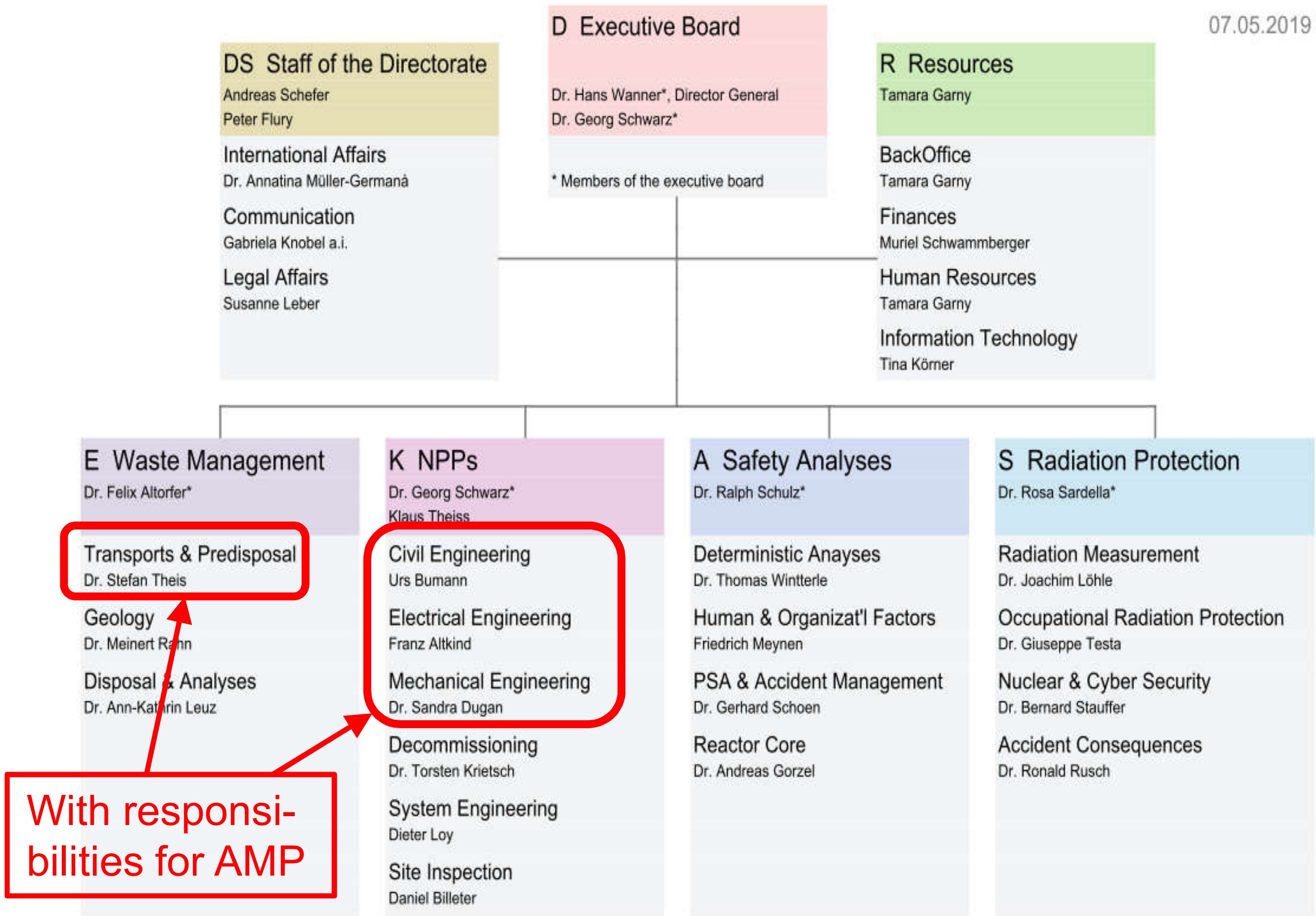
- Guideline ENSI-B01 (specific requirements for AMP)
  - Scope of the SSCs to be covered in the AMP
    - ✓ All safety classified structures and electrical components
    - ✓ All safety class 1-3 vessels and piping and related mechanical components (e.g. pumps, valves, supports and attachments)
  - Methods used for the verification of the embrittlement resistance of the RPV (Mandatory TLAA, Appendix 5)
  - Scope of the components to be covered in the fatigue monitoring and assessment program (Mandatory TLAA, Appendix 6)
- AMP basic documents (to prepare by licensees)
  - Plant-specific or generic guidelines (GSKL, Swiss NPP owners group),
  - KATAM (since 1991, periodical update): compendium of potential materials ageing mechanisms for mechanical Equipment in NPP (GSKL),
  - Fact sheets (“Steckbriefe”): basic data, tables of ageing mechanisms relating to the affected components, component history, periodical update (licensee),

Key legal documents and guidance, RegG ENSI-B02, -A03

- Guideline ENSI-B02 (annual reporting)
  - Overview of changes performed in the AM-documents
  - Results of the fatigue surveillance program
  - Results of the review of the operating experience and the follow-up of the current state of science and technology
  - Description of the consequences of these results on the AMP
  - Evaluation of the efficiency of the AMP based on failure statistics and maintenance indications

- Guideline ENSI-A03 (additional reporting within the PSR)
  - Review of the qualification status of the in-scope SSCs
  - Assessment of technological obsolescence
  - Review of existing time limited ageing analyses with respect to LTO

The regulatory body ENSI (2019)



Swiss Federal Safety Inspectorate ENSI at all has around 150 employees

Mechanical Engineering Group 8 (6) employees

Supported by SVTI (TSO)

with 26 employees

SVTI reviews and supervising In-service inspections, manufacturing, installation and repair activities.

NDT Qualification body

Main degradation mechanisms

- Fatigue (LCF, HCF, TF, TMF, EAF)
- Irradiation Embrittlement
- Stress Corrosion Cracking (SCC)
- FAC
- Other (corrosion, wear, erosion, thermal ageing, …

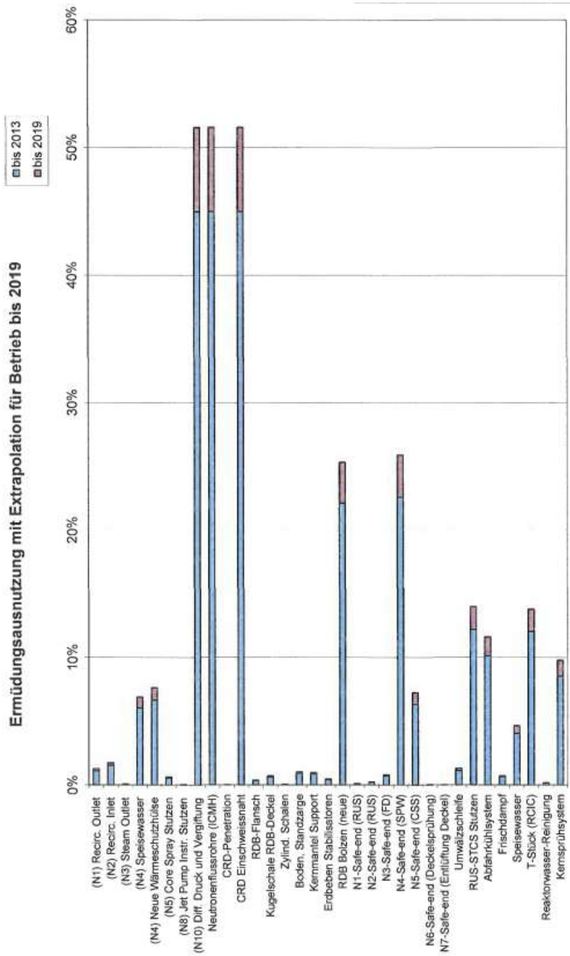
Fatigue Monitoring in Swiss NPP (1)

- 3 of 4 Swiss NPP using fatigue monitoring systems
  - KKL: “Fatigue Pro”, since 2007 (installed 2003), EPRI / Structural Integrity
  - KKG: “FAMOSi”, since 2014, Framatome
  - KKB: “WESTEMS”, since 2002, Westinghouse
  - KKM: Manual recording and assessment of fatigue
- Selection of monitoring positions based on recommendations and experience of manufacturer
- Typically around 25 - 30 positions are permanently monitored, including nozzles of RPV, steam generators and pressurizer and some piping like main cooling line and surge line.

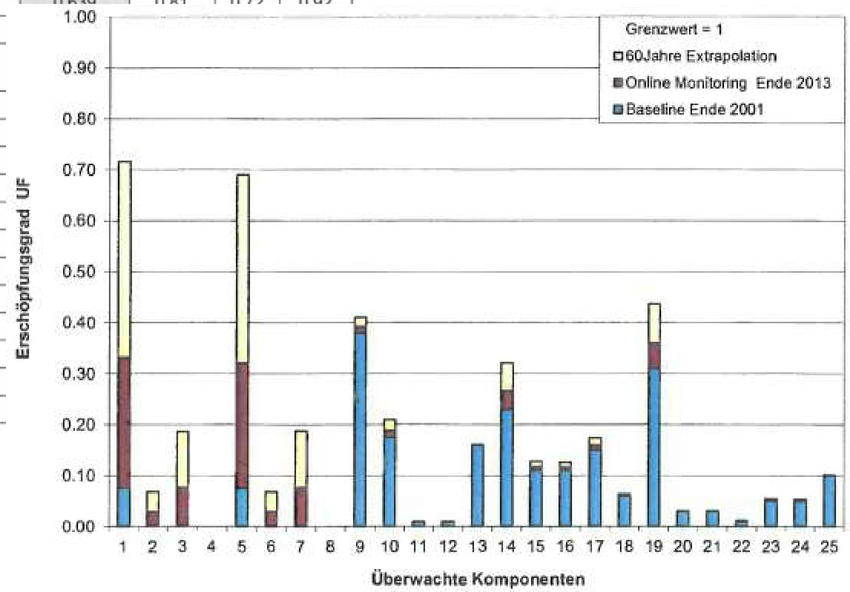
Fatigue Monitoring in Swiss NPP (2)

- Measurement of temperature-time histories to identify transients (stress based approach)
- Baseline fatigue (before installing monitoring systems) is estimated from counted transients based on design specification (cycle based approach)
- Environmental effects on fatigue have to be considered according to ENSI-B01 and NUREG/CR-6909
- Annual fatigue report submitted to regulator about the current and extrapolated fatigue usage factors for 60 operation years (or EOL).

Fatigue Monitoring, annual reporting



onente	AK.-Nr.	Ist: Änderung 2016	Ist: Stand 31.12.2016	Spezifikation: 40 Jahre	Extrapolation: 2025, 40 Jahre	Extrapolation: 2045, 60 Jahre
EHÄLTER						
	YC	0.005	0.179	0.67	0.23	0.33
	YC	0.002	0.261	0.75	0.30	0.39
stützring	YC	0.002	0.407	0.86	0.47	0.62
ehäuse	YC	0.001	0.601	0.91	0.63	0.68
sgehäuse	YC	0.004	0.633	0.87	0.73	0.95
zen	YC	0.000	0.185	0.90	0.19	0.19
STEME						
RHR-T-	YB	0.007	0.639	0.81	0.72	0.92
	YB	0.005				
utzen,	YB	0.001				
	YB	0.001				
	YB	0.000				
em	YB	0.001				
jungssystem	TC	0.002				
jungssystem	TC	0.001				
jungssystem	TC	0.000				
stem	TH	0.003				
stem	TH	0.002				
tem	TM	0.000				
ısystem	TJ	0.000				
ısystem	TJ	0.000				
	TW	0.015				



Fatigue Monitoring, backfittings & modifications

- KKM
  - 1995 to 1996, the RPV head bolts were replaced, replacement bolts having rolled threads and optimized thread geometry (calculated fatigue life 90 Y, bolts are the leading position for RPV)
  - In 1997, based on results from the fatigue monitoring measures, the RPV nozzles were modified by the installation of double thermo-sleeves.
  - A blind flange was fixed on RPV nozzle N9 in 2004. This modification largely eliminated fatigue loadings on this nozzle.
- KKG
  - 2005 PISA-project (TMI follow-up action), backfitting of primary pressure relief system, reduction of fatigue usage factors on surge line and pressurizer nozzles due to these system modifications and replacements of some pipe-sections
- KKB
  - 2013 New shafts for primary reactor water pumps (new material, optimized geometry, modified seal water flow)

Fatigue Monitoring, conclusions

- The results of the fatigue monitoring in the form of current fatigue usage factors and the corresponding levels extrapolated to 60 years of operation are submitted to ENSI in an annual report.
- The existing results show that the long-term operation of the Swiss NPP is not subject to any limitations as a result of RPV material fatigue.
- Potential future challenges:
  - Prevention of fatigue damages caused by vibrations (small piping, rotating equipment),
  - Load flexible operation

Program for assessment of irradiation embrittlement

- Neutron fluence assessment (Reducing of fluence by low leakage core configuration)
- Testing of surveillance specimens
- Determination of ART based on requirements of Guideline ENSI-B01 (U.S.-NRC 1.99 Rev. 2 / ASTM E 1921 Master Curve Concept)
- Embrittlement have to comply with "DETEC Criteria" (ART < 93°C in ¼ wall depth, Charpy energy ≥ 68 J)
- PTS analyses by deterministic FM (PWR)
- P-T limiting curves

Background of "DETEC Criteria" for RPV embrittlement

U.S. NUCLEAR REGULATORY COMMISSION

Revision 2
May 1988

REGULATORY GUIDE

OFFICE OF NUCLEAR REGULATORY RES

REGULATORY GUIDE 1.99
(Task ME 305-4)

3. REQUIREMENT FOR NEW PLANTS

For beltline materials in the reactor vessel for a
content of residual elements such as copper, phos
and vanadium should be controlled to low levels.* T
tent should be such that the calculated adjusted referer
at the 1/4T position in the vessel wall at end of li
200°F. In selecting the optimum amount of nickel
deleterious effect on radiation embrittlement shoul
against its beneficial metallurgical effects and its ten
the initial RT_{NDT}.

NB-2330 TEST REQUIREMENTS AND ACCEPTANCE STANDARDS[2]

NB-2331 Material for Vessels

Pressure-retaining material for vessels, other than bolting, shall be tested as follows:

(a) Establish a reference temperature RT_{NDT}; this shall be done as follows:

(1) Determine a temperature T_{NDT} that is at or above the nil-ductility transition temperature by drop weight tests.

(2) At a temperature not greater than T_{NDT} + 60°F (T_{NDT} + 33°C), each specimen of the C_v test (NB-2321.2) shall exhibit at least 35 mils (0.89 mm) lateral expansion and not less than 50 ft-lb (68 J) absorbed energy. Retesting in accordance with NB-2350 is permitted. When these requirements are met, T_{NDT} is the reference temperature RT_{NDT}.

Status of surveillance programmes, March 2019

4 reactors have finished the surveillance programmes.
Continued in Leibstadt NPP, 3th capsule will be removed in 2020.

	KKB1	KKB2	KKG	KKL	KKM
Tested specim.	6	5	3	2	3*
last removed	2010	2010	2006	2008	2002
Coverage by tested specim.	> 60 Y	> 60 Y	> 100 EFPY	> 24 Y	> 30 Y (BM, v3) 78 EFPY (weld v2)
Remaining spec. in RPV	-	1	-	5	1* (reinstalled in 2004)
coverage 2019	-	> 80 Y	-	> 35 Y	≈ 50 Y (BM, v3)

* All specimens provided to PSI for future research activities.

Adjusted reference temperatures for 54 EFPY / 60 Y

	KKB1	KKB2	KKG	KKL	KKM
ART [°C] Method I inner wall / 1/4T	104 / 98	76 / 70	33 / 28	9	61 (V2) 17 (BM)
RT_{ref} [°C] Meth. IIA inner wall / 1/4T	80 / 74	51 / 46	-16 / -18		
Min. upper shelf Charpy energy [J]	137	120	118	> 119	125
Material	BM Ring C	BM Ring C	BM II	BM	Weld V2 BM

(KKG has installed ex-vessel dosimetry.
It allows a more precise fluence calculation.)

Swiss Regulatory Guide ENSI-B01, Appendix 5

Alternative assessment methods for RT_{ref} :

- Method I (US NRC Regulatory Guide 1.99 Rev. 2):
  $RT_{ref} = ART$

- Method II-A:

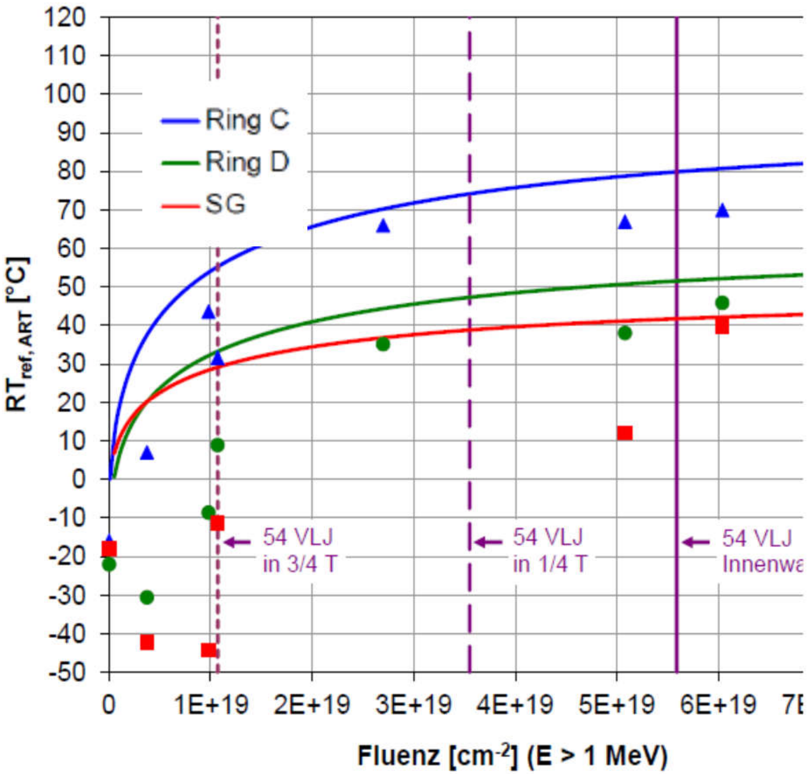
$$RT_{ref} = T_0 + 14.4K + \Delta T_S + \sqrt{324/n + 16 + \Delta T_M^2 + \Delta T_T^2}$$

T_o	reference temperature acc. to ASTM E 1921 (Master curve approach)
n	number of valid tests
ΔT_s	=0 for 1T-C(T) specimens; =10K for 0.4T-SEN(B) specimens
ΔT_M	=0 for base material; =6K for weld material
ΔT_T	=0 for 1T-C(T) specimens; =5K for 0.4T-SEN(B) specimens

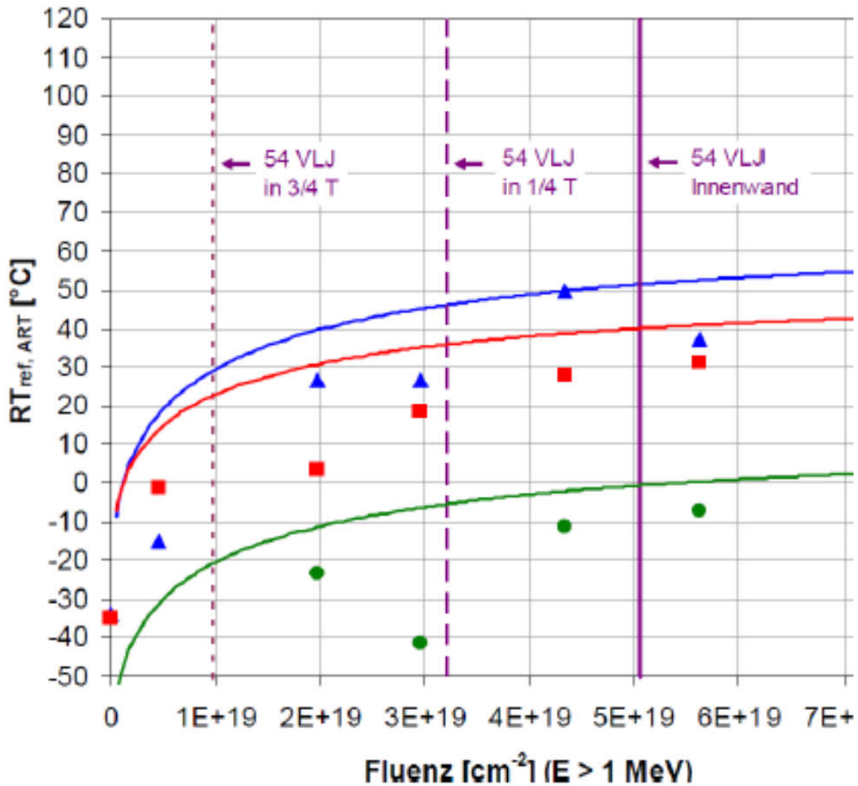
- Method II-B:
  $RT_{ref} = RT_{ref}^{(o)} + \Delta T_j$

$RT_{ref}^{(o)}$	reference temp. acc. to equation of method II-A for unirradiated material
ΔT_j	temperature shift according to NRC Regulatory Guide 1.99 Rev. 2

Embrittlement KKB 1&2, ENSI-B01 Method-IIA (MC)



KKB, Unit 1

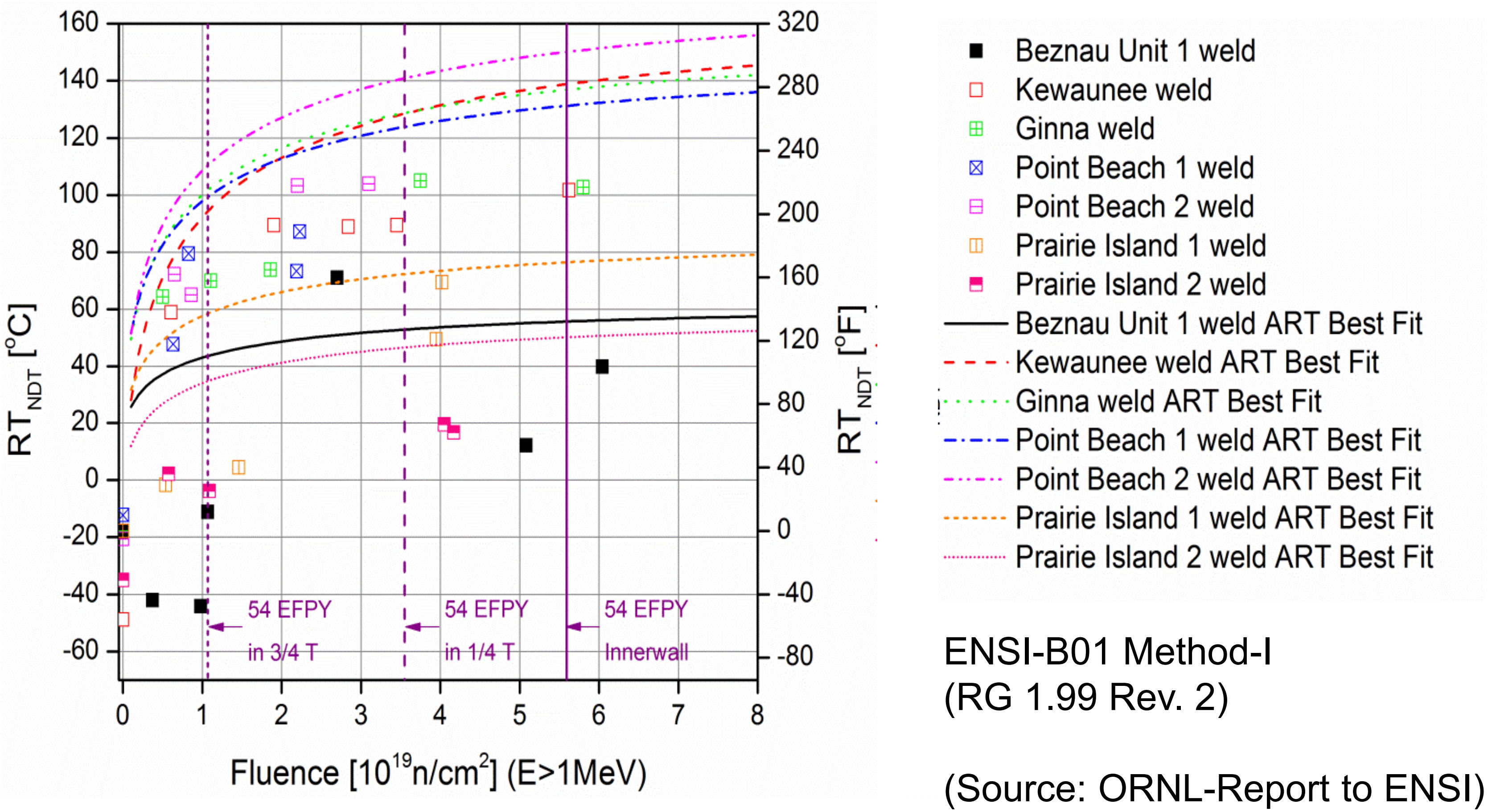


KKB, Unit 2

Embrittlement KKB 1, Ring C, ENSI-B01, 54 EFPY / 60 Y

Material	RPV position	Neutron fluence [cm^{-2}]	RT_{ref} [°C]	
Method I Charpy	surface	5.59E+19	104	
	¼ wall thickness	3.55E+19	98	
Method II-A Master Curve	surface	5.59E+19	80	
	¼ wall thickness	3.55E+19	74	DETEC ≤ 93°C
Method II-B T_0+Charpy-shift	surface	5.59E+19	89	
	¼ wall thickness	3.55E+19	83	DETEC ≤ 93°C

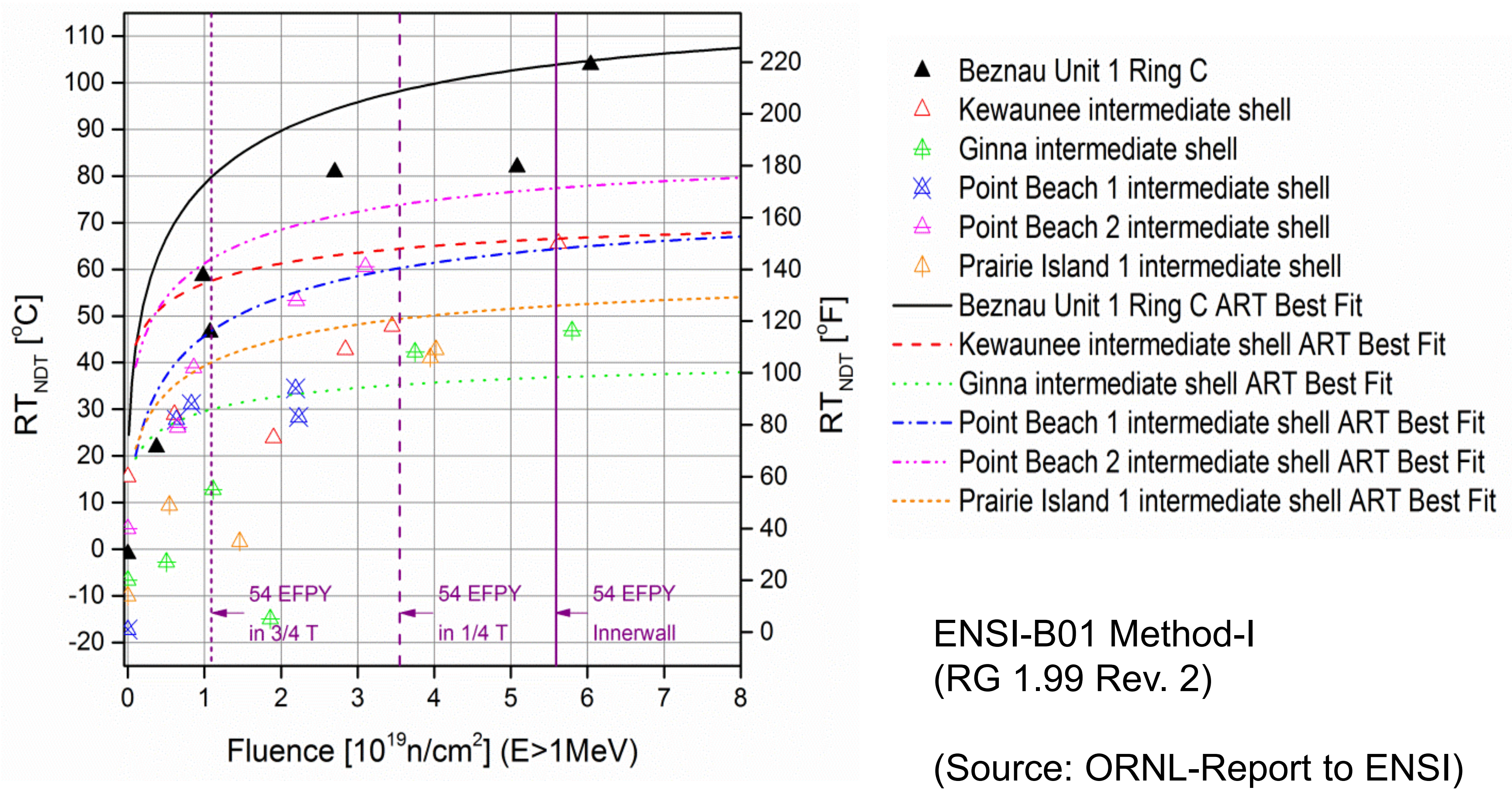
RT_{NDT} and the ART best fit curves for Beznau Unit 1 core weld, compared to Westinghouse US PWRs of same design



ENSI-B01 Method-I
(RG 1.99 Rev. 2)

(Source: ORNL-Report to ENSI)

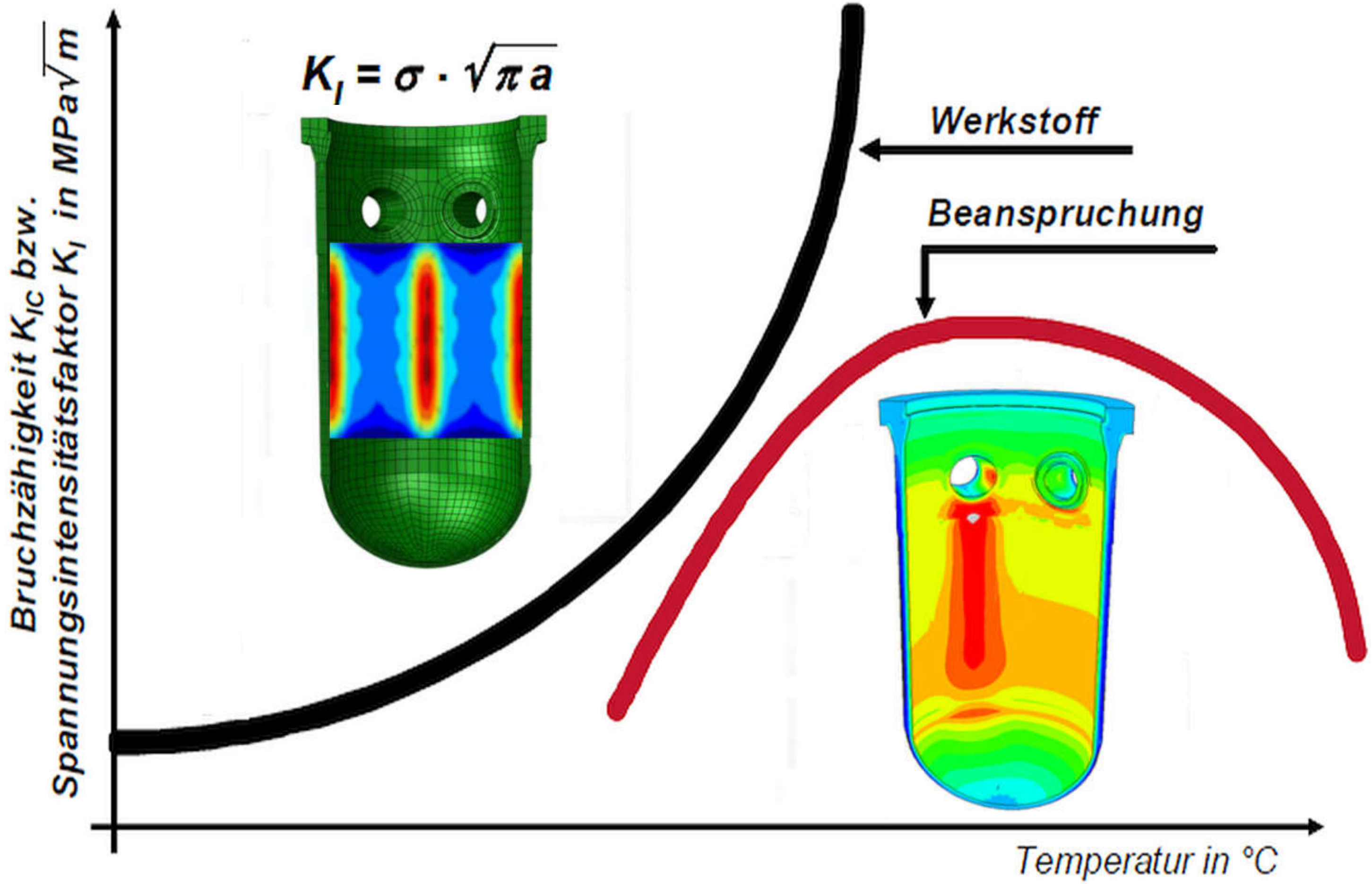
RT_{NDT} and the ART best fit curves for Beznau Unit 1 Ring C, compared to Westinghouse US PWRs of same design



ENSI-B01 Method-I
(RG 1.99 Rev. 2)

(Source: ORNL-Report to ENSI)

PTS-Analyses based on deterministic FM



PTS-Analyses based on deterministic FM

For PWR's a PTS-Analysis is required which include following tasks:

- Thermo-hydraulic Analyses (RELAP5, KWU-Mix, optional CFD) for a comprehensive load case matrix:
  - different leak sizes from 3 cm^2 up to 2F-break,
  - leak locations in hot and cold leg, different injection temperatures,

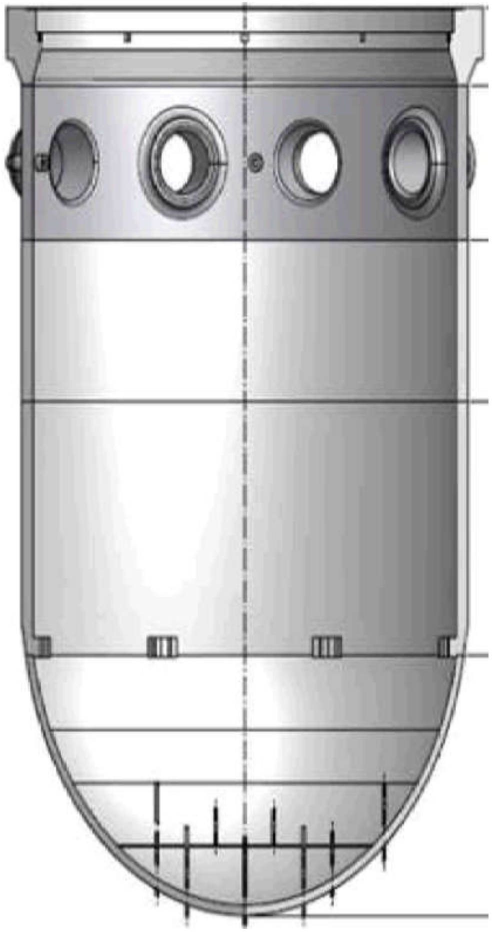
  (For Swiss NPP the medium size LOCA's are leading.)
- Fracture Mechanics Analyses for:
  - Different crack locations (Nozzle corner, **core region**),
  - Different crack orientations (axial / **circumferential**),
  - Different crack types (surface / undercladding),
  - Different crack depths, aspect ratio is given by code (1/5 or 1/6)
  - Possible options with/without WPS,
  - Additional options, but not used for Swiss NPP PTS analyses: constraint effects, crack arrest, PFM to demonstrate conservatisms

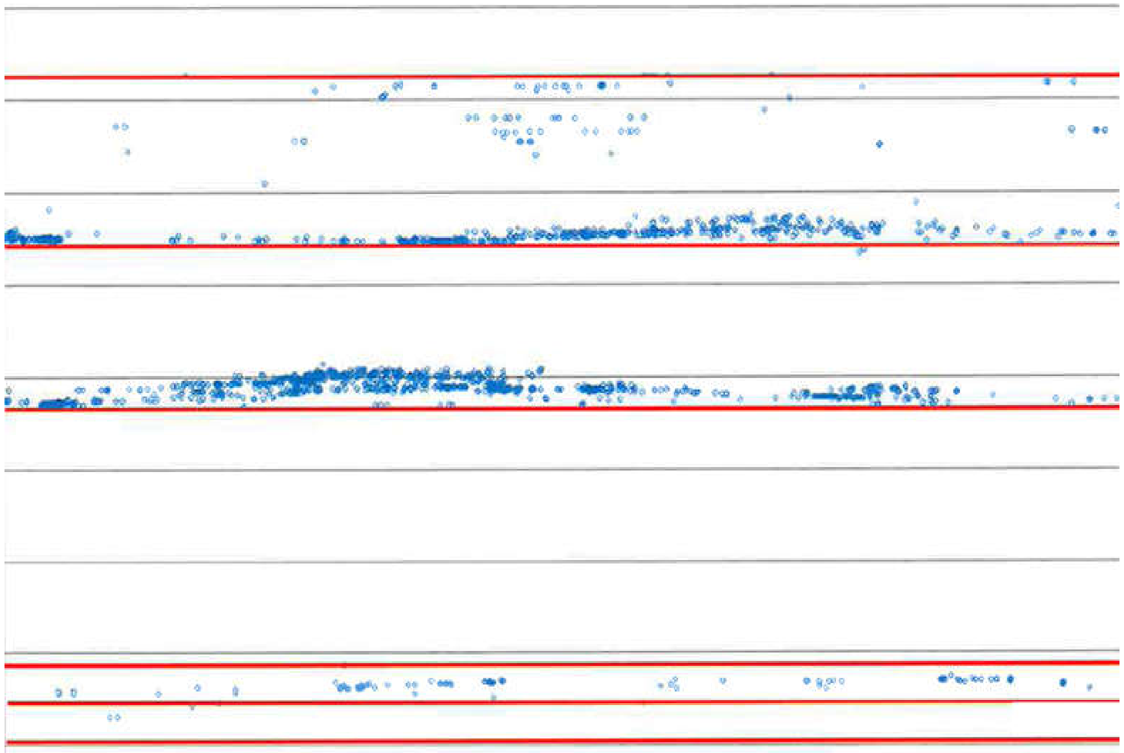
PTS-Analyses for Beznau and Gösgen NPP based on KTA 3203 methology.

Irradiation embrittlement, conclusion

- The results of the surveillance programs in the form of fluence calculations and the corresponding levels of irradiation embrittlement extrapolated to 60 years of operation are submitted to ENSI.
- Highest embrittlement of all Swiss Reactors have the Base Material of Ring C in Beznau unit 1. It fulfils the requirements of 93°C shut down criteria of the DETEC Ordinance.
- The existing results show that the long-term operation of the Swiss NPP is not subject to any limitations as a result of RPV irradiation embrittlement.
- PTS-Analyses showed for all Swiss PWR that the allowable $RT_{,PTS}$ (with consideration of WPS effect) is higher than the 93°C DETEC shut down criteria.

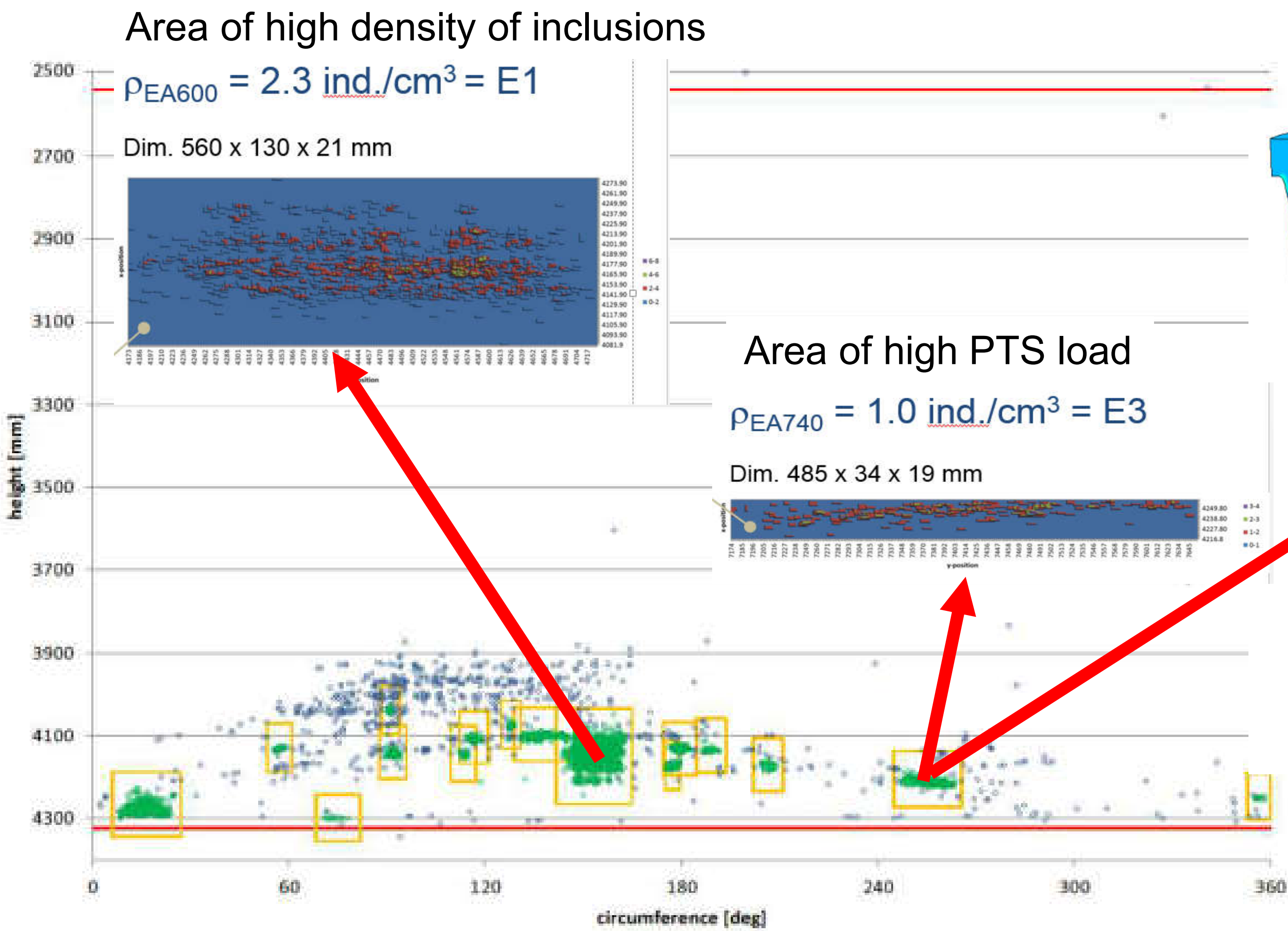
KKB 1, UT Indications in 2015

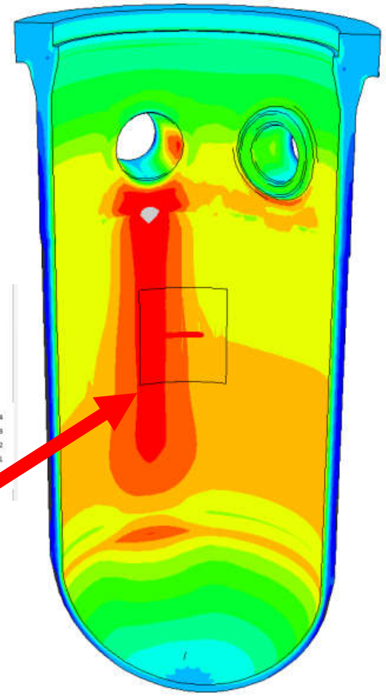




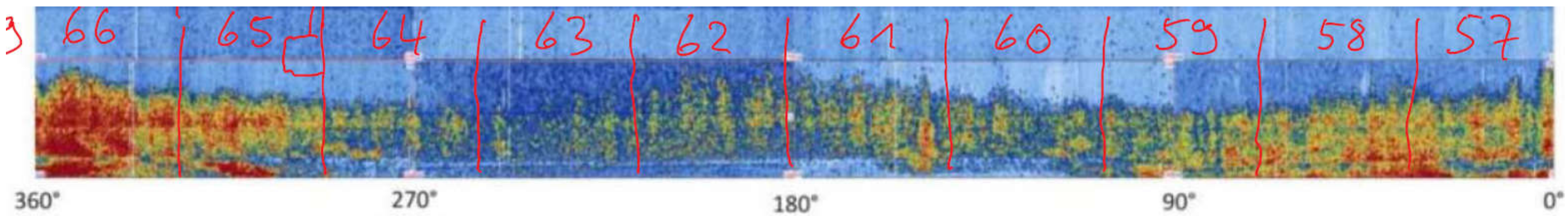
- Indications identified as Al2O3-Inclusions
- Not Ageing, manufacturing problem (insufficient discard rate from ingot)

KKB 1, Safety Case

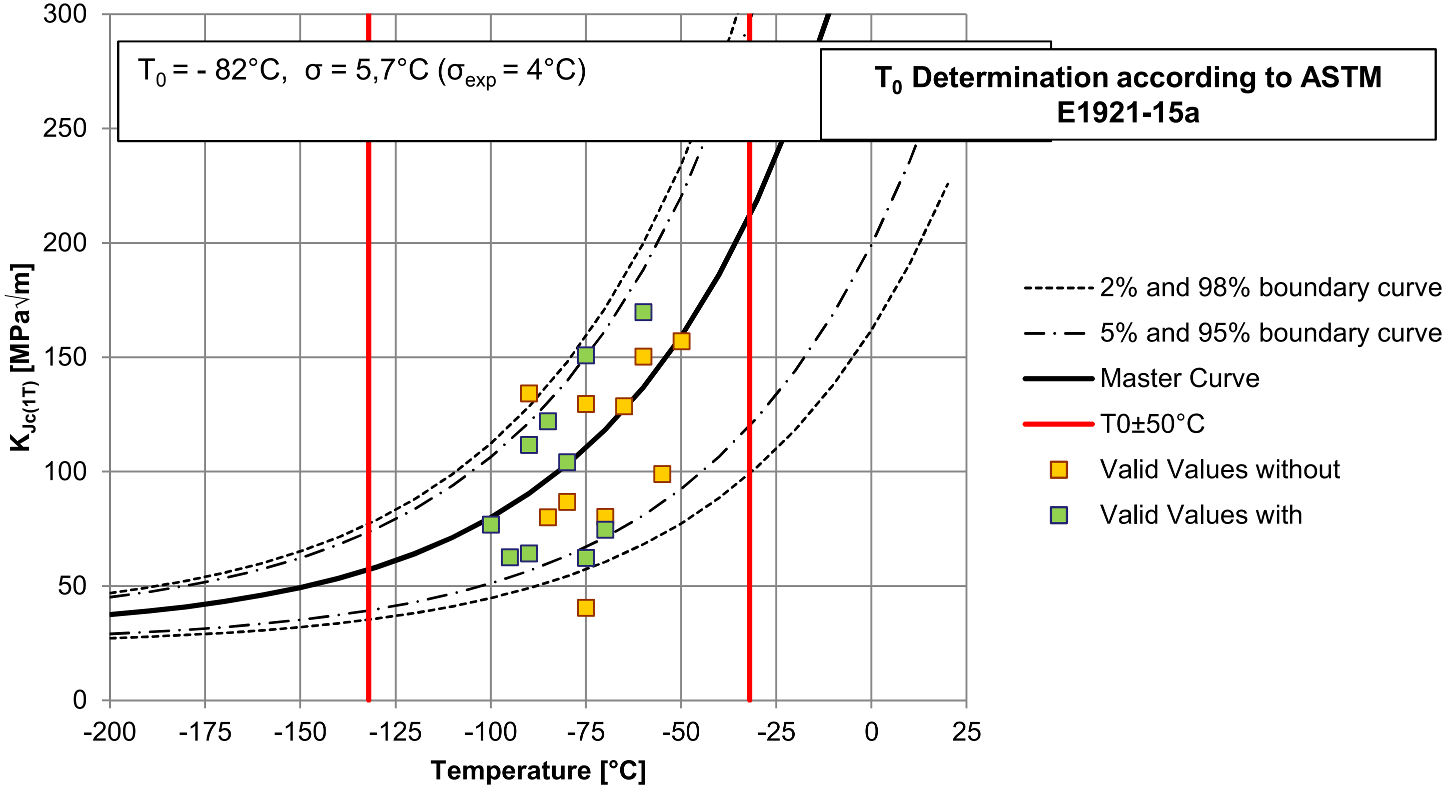




KKB 1, Replica of Ring C based on manufacturing records



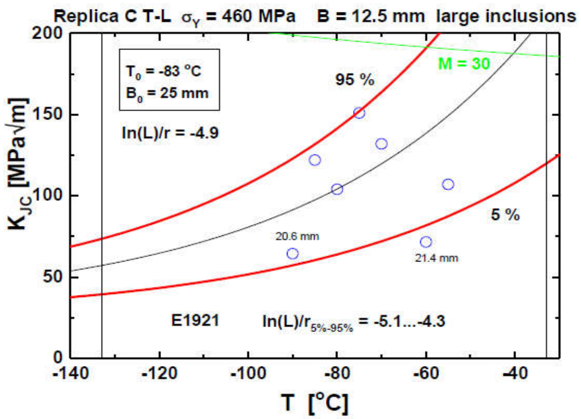
KKB 1, Master Curve by 1 CT-Specimen from Replica



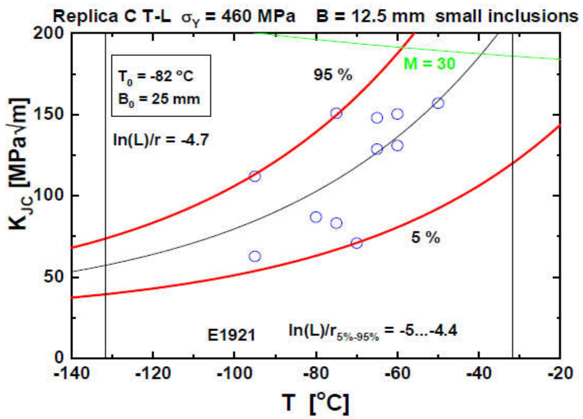
Master Curve Testing of the replica shell C material: Specimens with inclusions show no difference to specimens without inclusions

KKB 1, Master Curve by 0.5 CT-Specimen from Replica

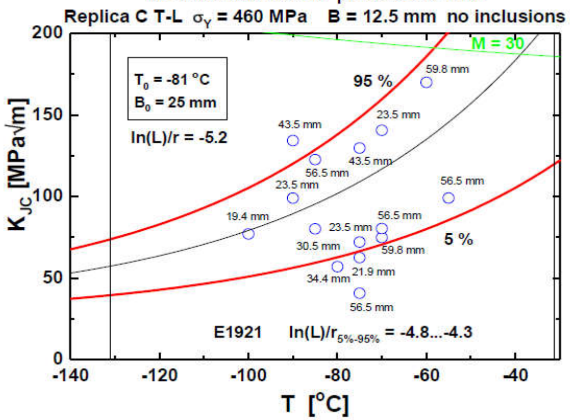
large inclusions of 2mm on process zone



inclusions < 2mm on process zone



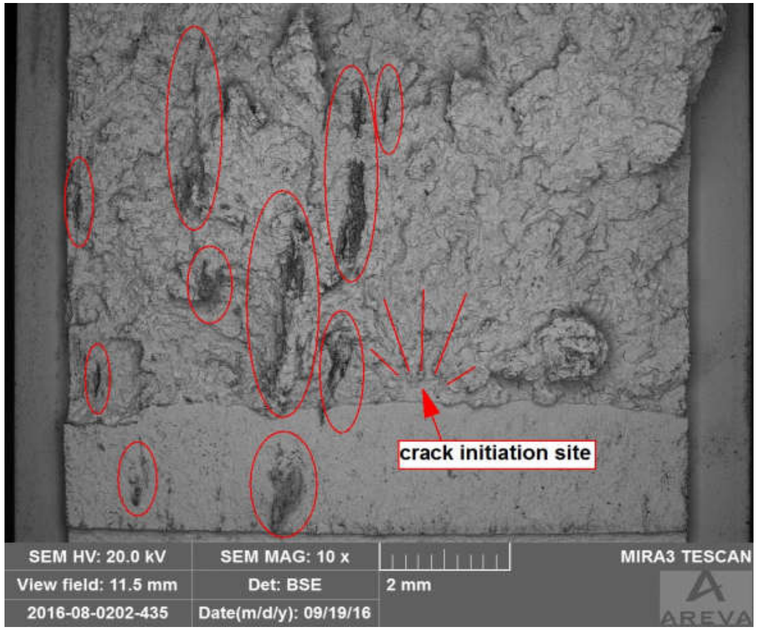
no inclusions on process zone

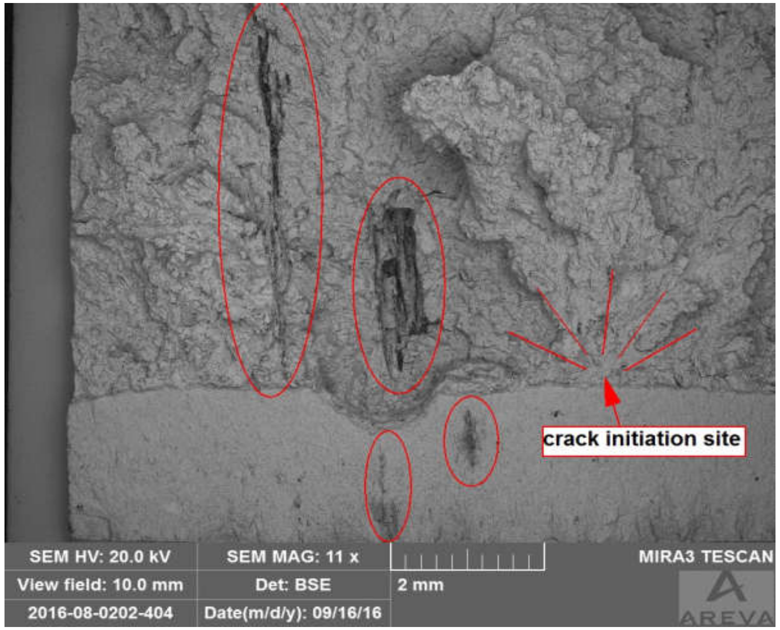


A standard MC analysis indicate that specimens with large or small inclusions in the fracture process zone are homogeneous based on the log-likelihood criterion.

Only the specimens without inclusions show an indication of inhomogeneity.

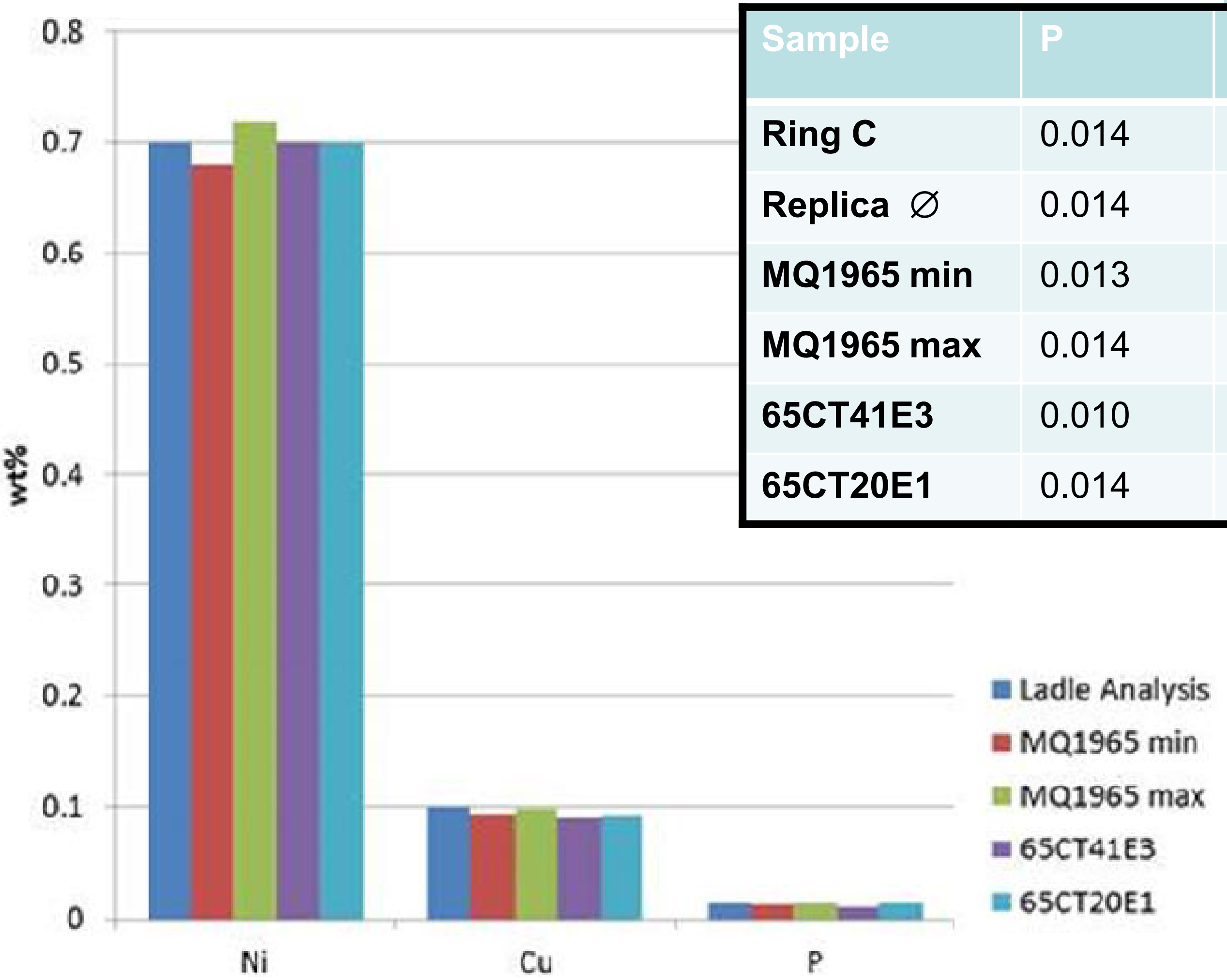
KKB 1, Fractography of Replica Material





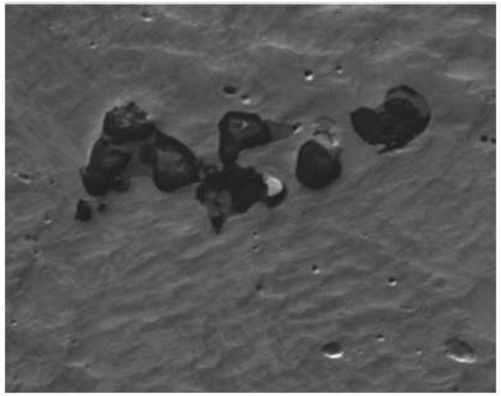
Fracture surface (SEM) of broken CT-specimens, replica C material
Result: No influence of Al_2O_3 inclusions on crack initiation

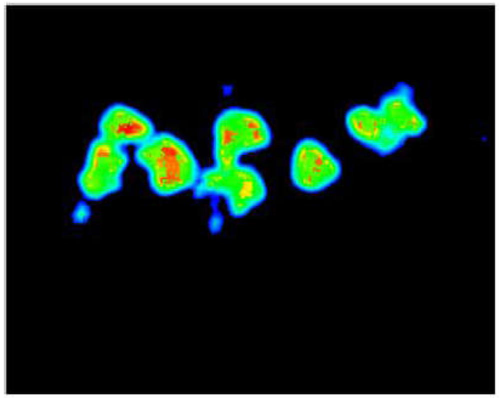
KKB 1, Comparison of Chemical Composition

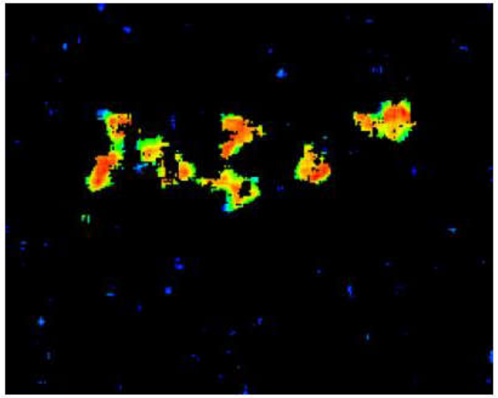


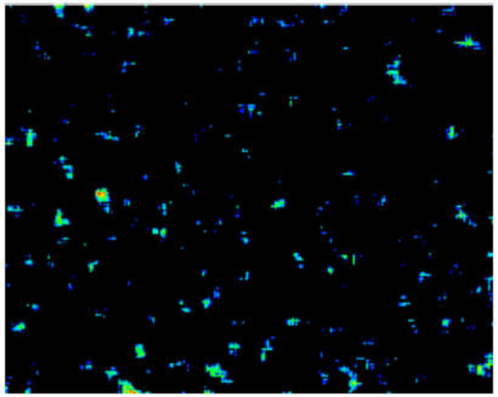
Sample	P	Ni	Cu
Ring C	0.014	0.71	0.092
Replica ∅	0.014	0.70	0.100
MQ1965 min	0.013	0.68	0.093
MQ1965 max	0.014	0.72	0.099
65CT41E3	0.010	0.70	0.090
65CT20E1	0.014	0.70	0.092

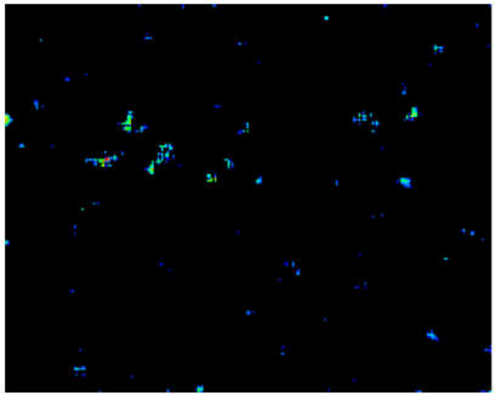
KKB 1, Local Chemical Composition near Inclusions

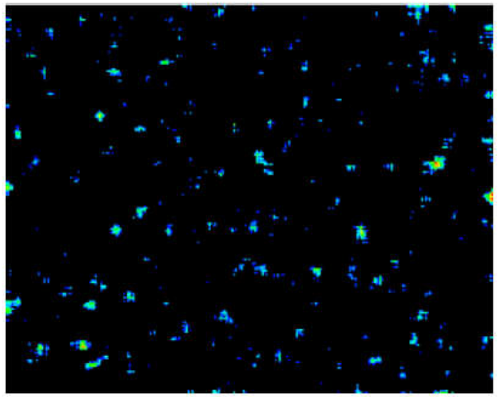

C7-B154 Inclusion 1, BSE


Al Kα, element distribution


O Kα, element distribution


Cu Kα, element distribution


P Kα, element distribution

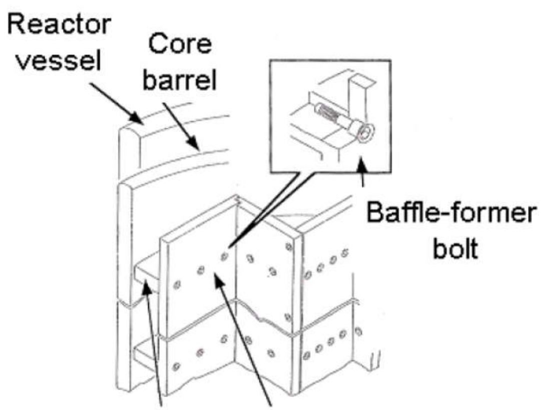

Ni Kα, element distribution

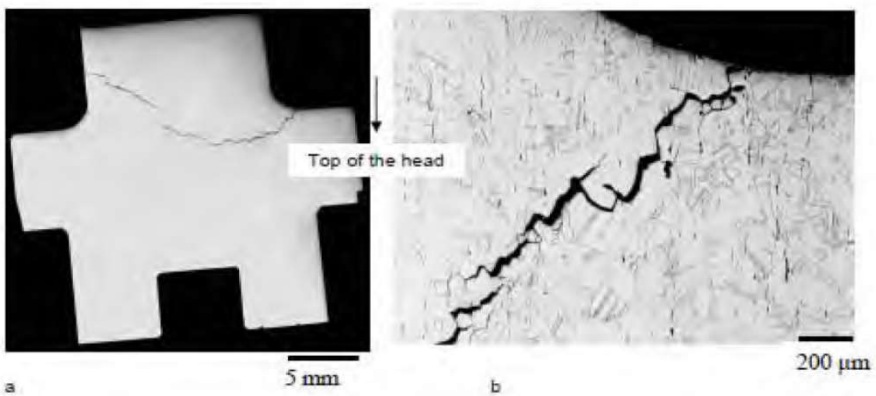
KKB 1, Safety Case Summary and Conclusions

- UT indications found in 2015 in RPV Base material were identified as non-metallic aluminium oxide inclusions.
- Fracture mechanics testing on specimen from replica ring C did not show an influence of these inclusions.
- Fractographic analyses never showed crack initiation at Al_2O_3-Inclusions.
- Inclusions do not have a negative effect on fracture toughness.
- According to chemical analyses, Inclusions do not influence irradiation embrittlement behaviour.
- Large inclusions or inclusion clusters, so called “high amplitude indications”, were conservatively assumed as flaws. These assumed flaws are covered by the ASME XI, IWB-3000 acceptance standards as well by the postulated cracks for PTS analyses.
- An alternative multiple flaw combination rule was proposed, now Code Case N-877. Acceptance criteria met with CC N-877 as well with standard rules according to Section XI, IWA-3000.

Examples of IASCC Incidents in LWRs

Baffle Former Bolts in PWR





Pokor et al., Fontevraud 6, A154-T02, 2006

- Replacement of baffle former bolts at Beznau unit 1&2 in 2009 and 2010
- 192 bolts (unit 2)
- 195 bolts (unit 1)
- Replacement in an optimized pattern
- new material (AISI 316 CW)
- Optimized notch con-tour to reduce stresses

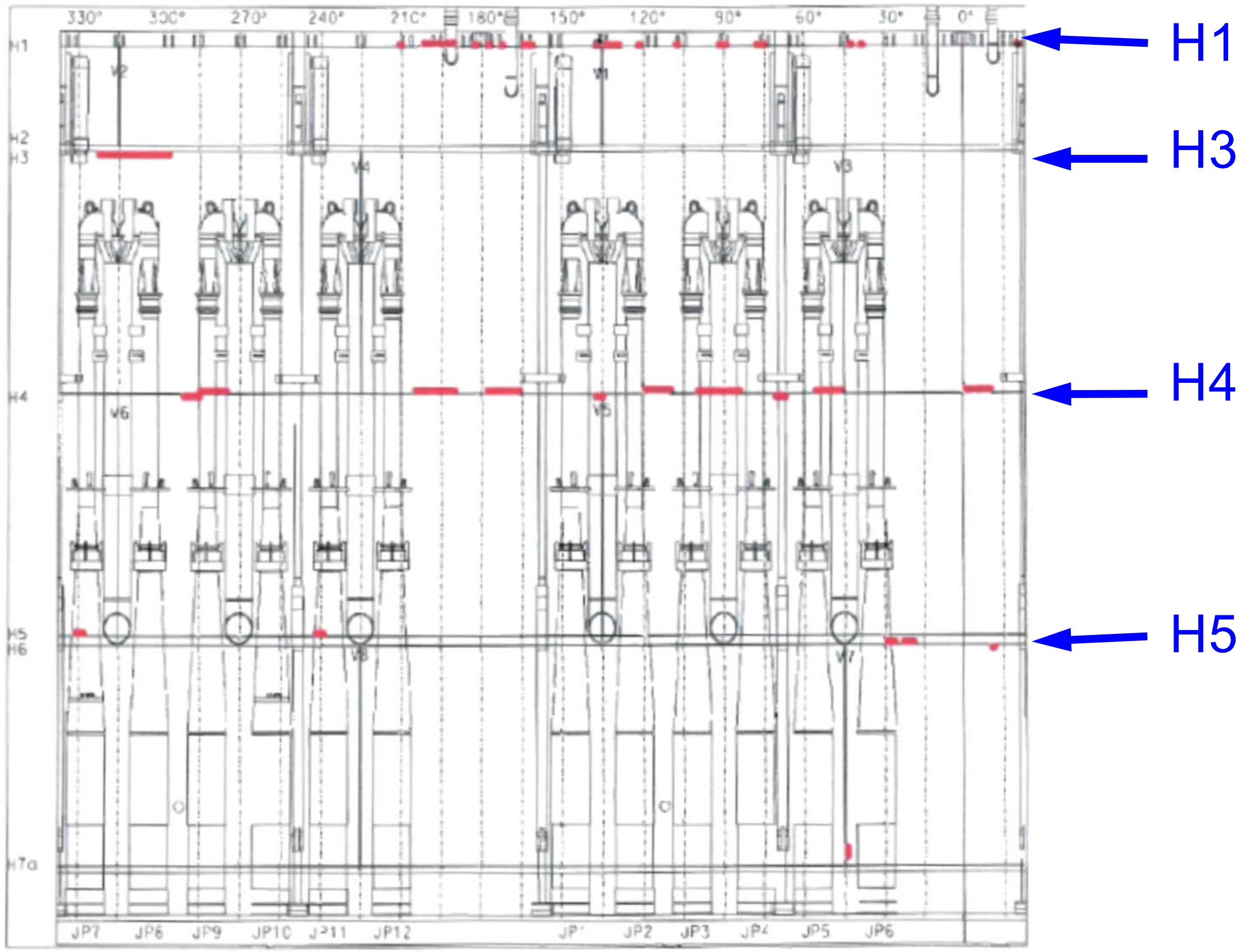
KKB, (HERA) 2015/16 RPV Head Replacement

- New RPV closure heads with a series of small improvements
- Inconel 600 replaced by Inconel 690 and 52 (head penetration seal welds),
- No control rod thermal sleeve wear issue (no thermal sleeve),
- A small boric acid cavity at unit 1 removed.

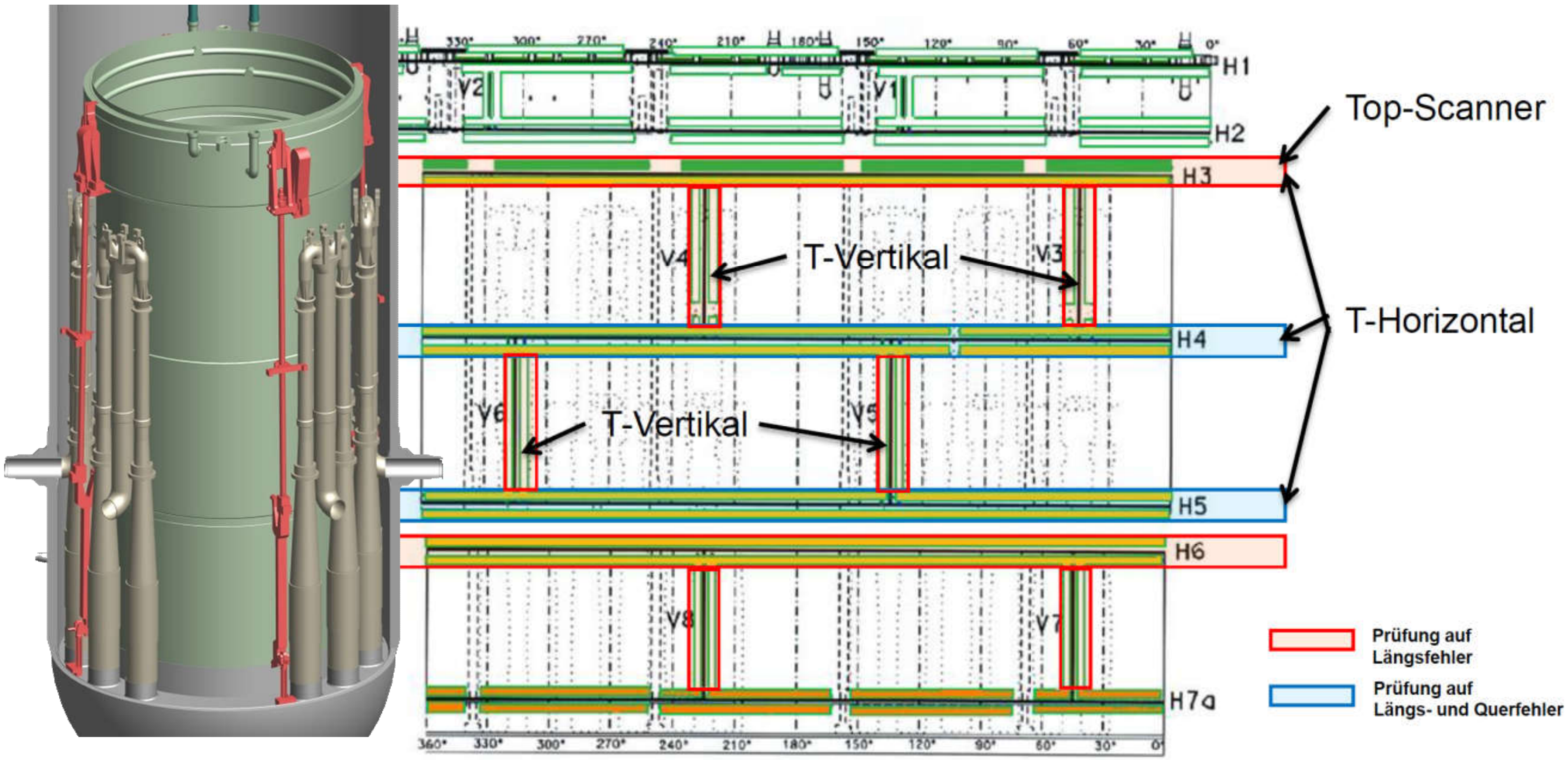
KKM, Overview core shroud cracking

- 1990 cracks in HAZ of H4 weld discovered by VT inspections, 1991 UT on H4, IGSCC driven by weld residual stresses, starting from inner surface
- 1992/93 conductivity of reactor water optimized (to around 0.1 µS/cm), 2" Plug sample removed
- 1993 on HSK request, start of qualified systematic (1 or 2-year) VT and UT (GE from ID)
- 1994 Simplified FM-model (screening criteria)
- 1996 installation of pull rods and radial stabilizers at 4 positions, precautionary safety action against unexpected fast crack growth. VT of rods
- 2000 HWC & NobleChem, 2005 OLNC (platinum injection),
- 2011 3D FE-model for FM analyses to LTO
- 2011 New UT-System (WE, from OD with measurement of depth), enhanced coverage
- 2013 New FE-model with circumferential cracks, 60 % wall thickness, acoustic loads, further optimization of Pt feed-in strategy
- 2014 replacement of pull rods planned, 6 rods new design, cancelled because of shut down
- 2014 first detection of transversal cracks (off-axis flaws), FE-model adapted
- 2015 & 2016 inspections H4 (UT, VT)
- 2018 last inspection (VT, H4 and the off axis cracks), no propagation

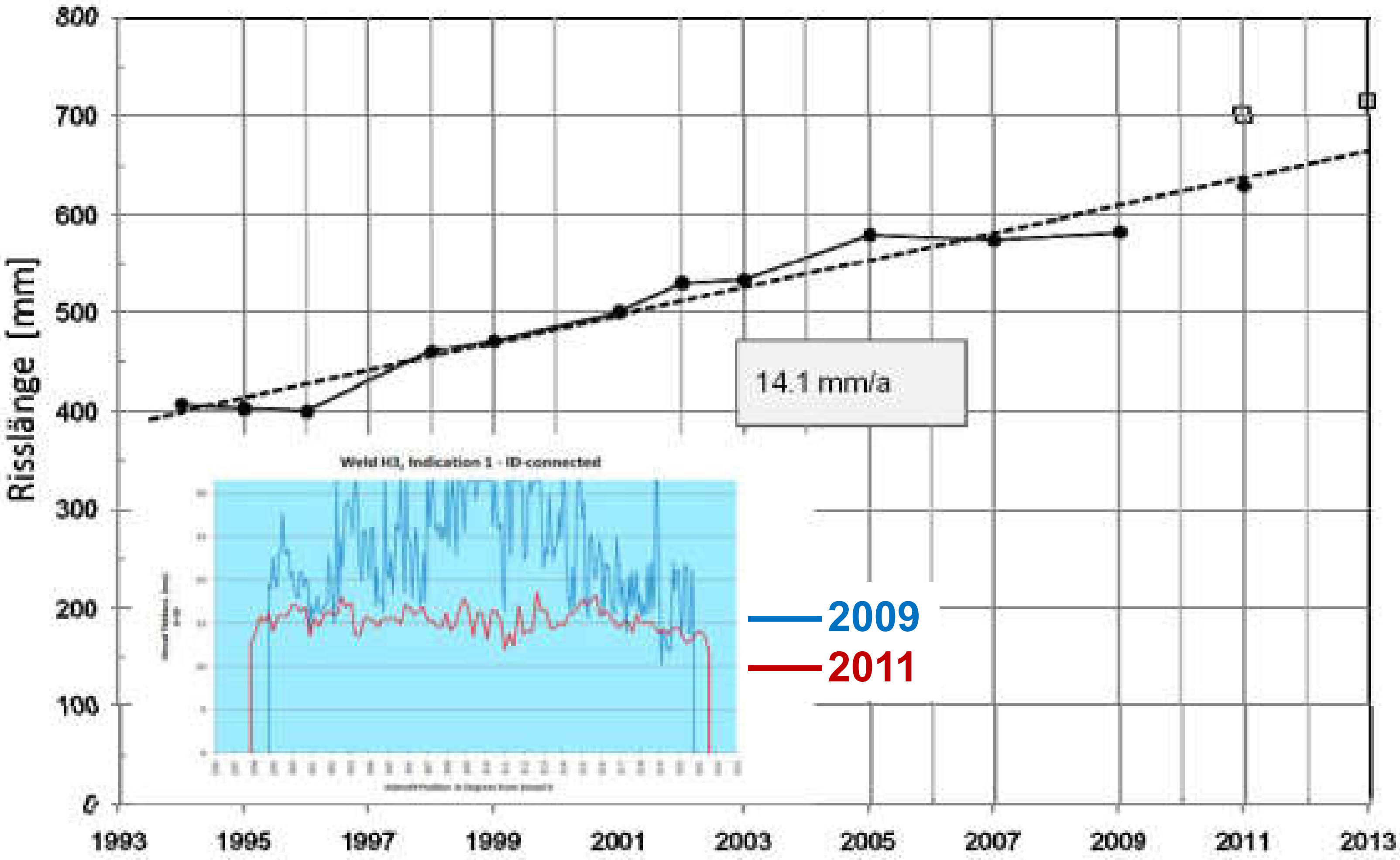
KKM, Core Shroud Cracks, 2011



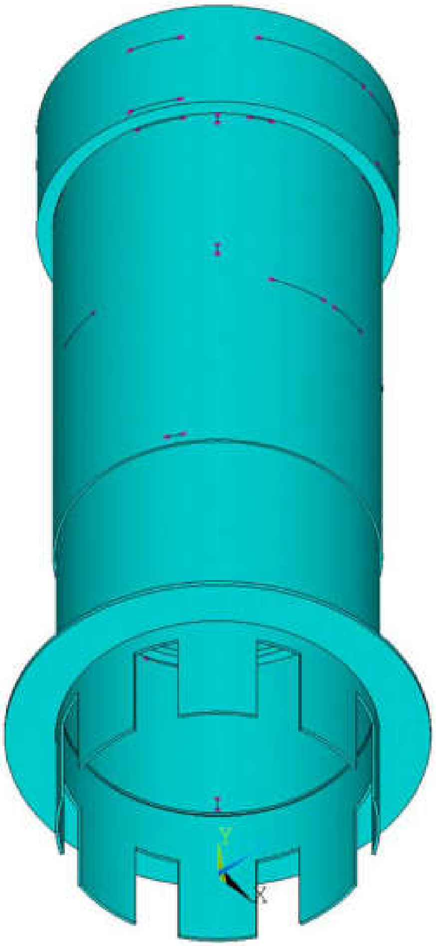
KKM, systematic Core Shroud measurements since 1993

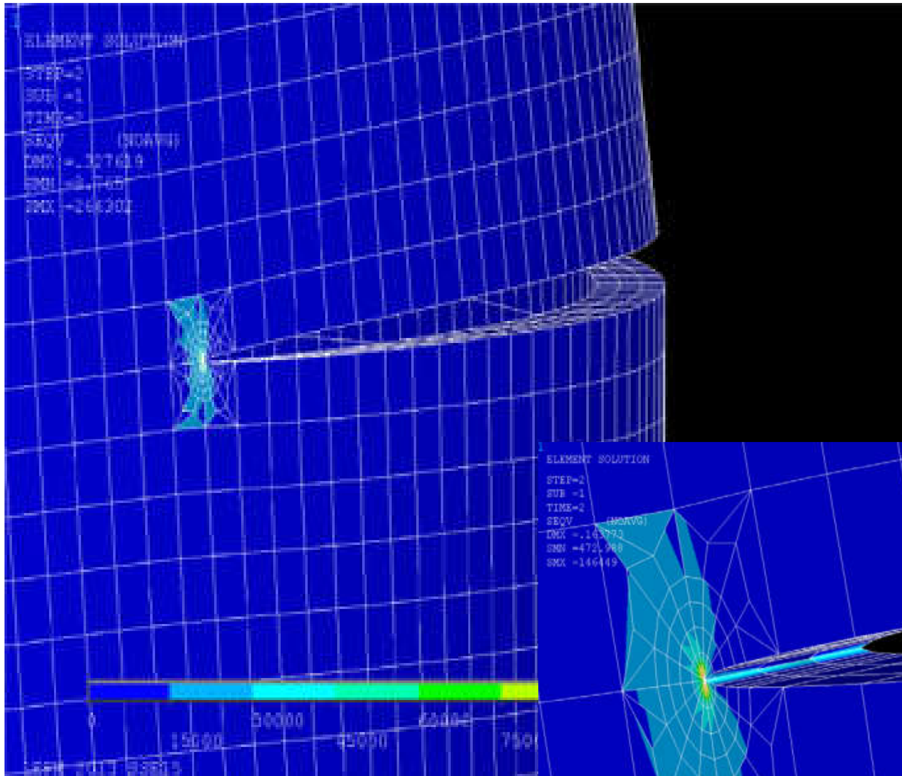


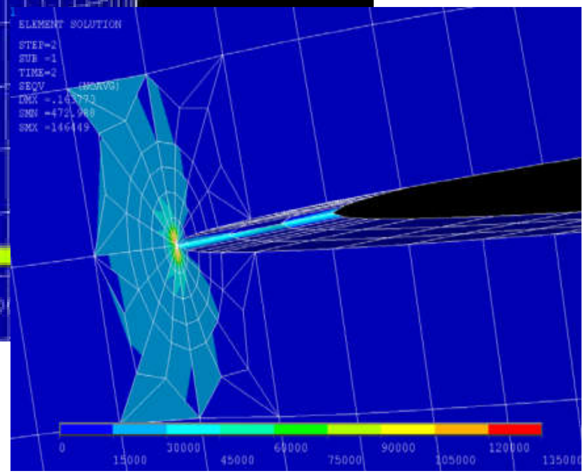
KKM, Core Shroud Crack, Indication 1, Weld H3



KKM, Core Shroud Model with through wall cracks, 2011







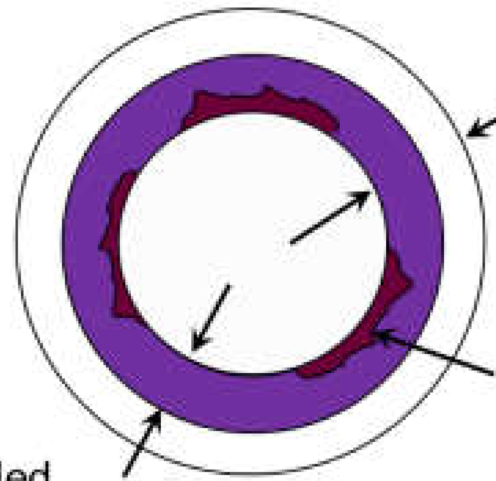
KKM, Results of FM analyses of core shroud cracks

LC 6.3.1: SSE von 102°, 3 Zuganker, Δp Recirc-Bruch, Eigengewicht, ΔT

	$K_{I\,max}$ [MPa√m]	$K_{I\,c}$ [MPa√m]	SF_{erf}	SF	Marge
H1	15.8	165	1.39	10.4	> 3 x
H2	33.9	165	1.39	4.9	> 3 x
H3	41.4	165	1.39	4.0	2.9 x
H4	39.5	123	1.39	3.1	2.2 x
H5	---	165	1.39	---	---
H6	24.7	165	1.39	6.7	> 3 x
V3	15.1	123	1.50	8.1	> 3 x
V4	3.9	123	1.50	> 15	> 3 x
V7	25.7	165	1.50	6.4	> 3 x

SSE according to “PEGASOS” (increased seismic hazards), 2013 acoustic loads added

KKM, Core Shroud Model with circumferential cracks, 2013

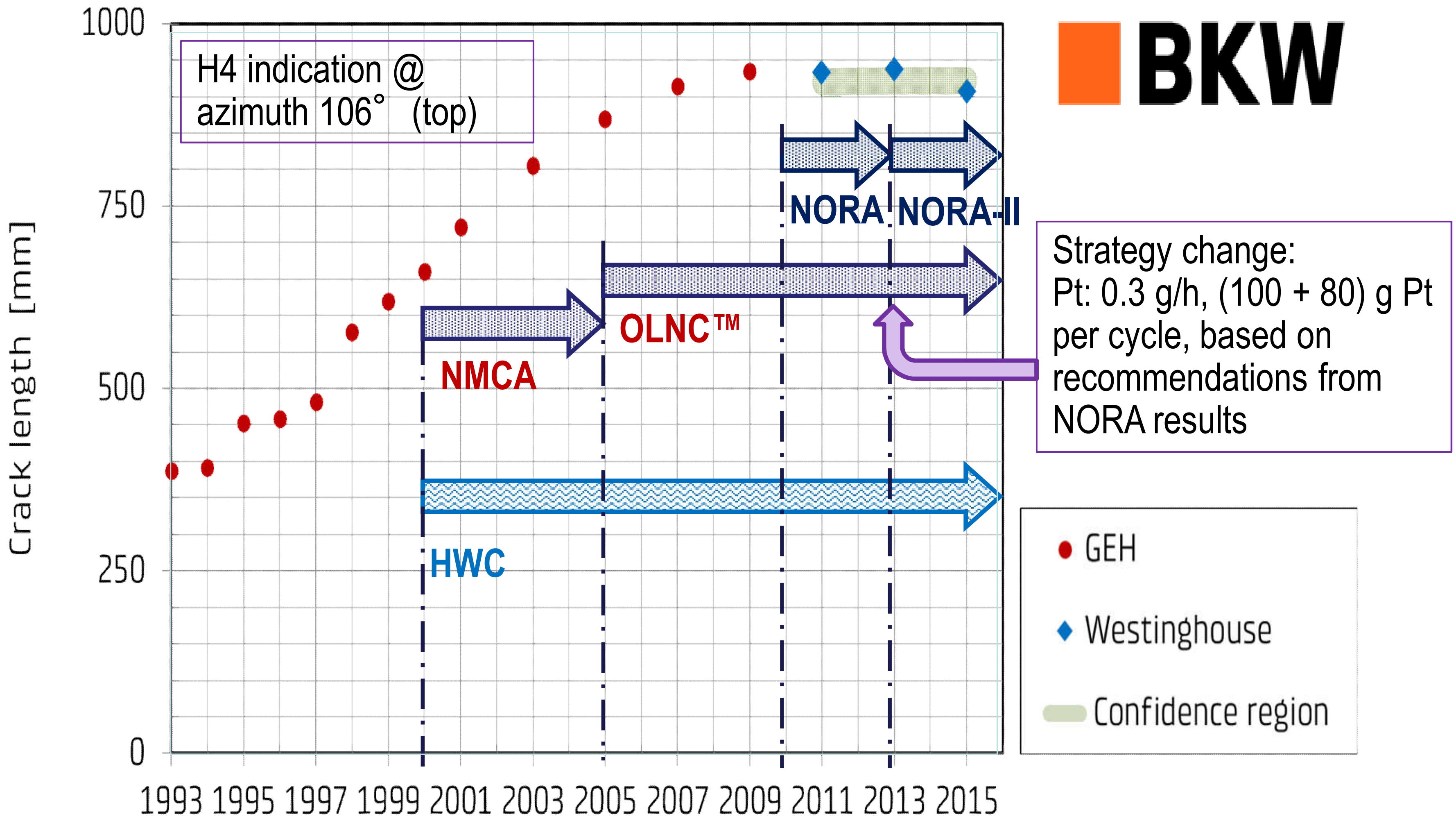


Modelling:
3D-Finite Element Modeling of whole Core Shroud:
Enveloping 360° cracks at H3 and H4 with crack depth of 75% resp. 66% of wall thickness.

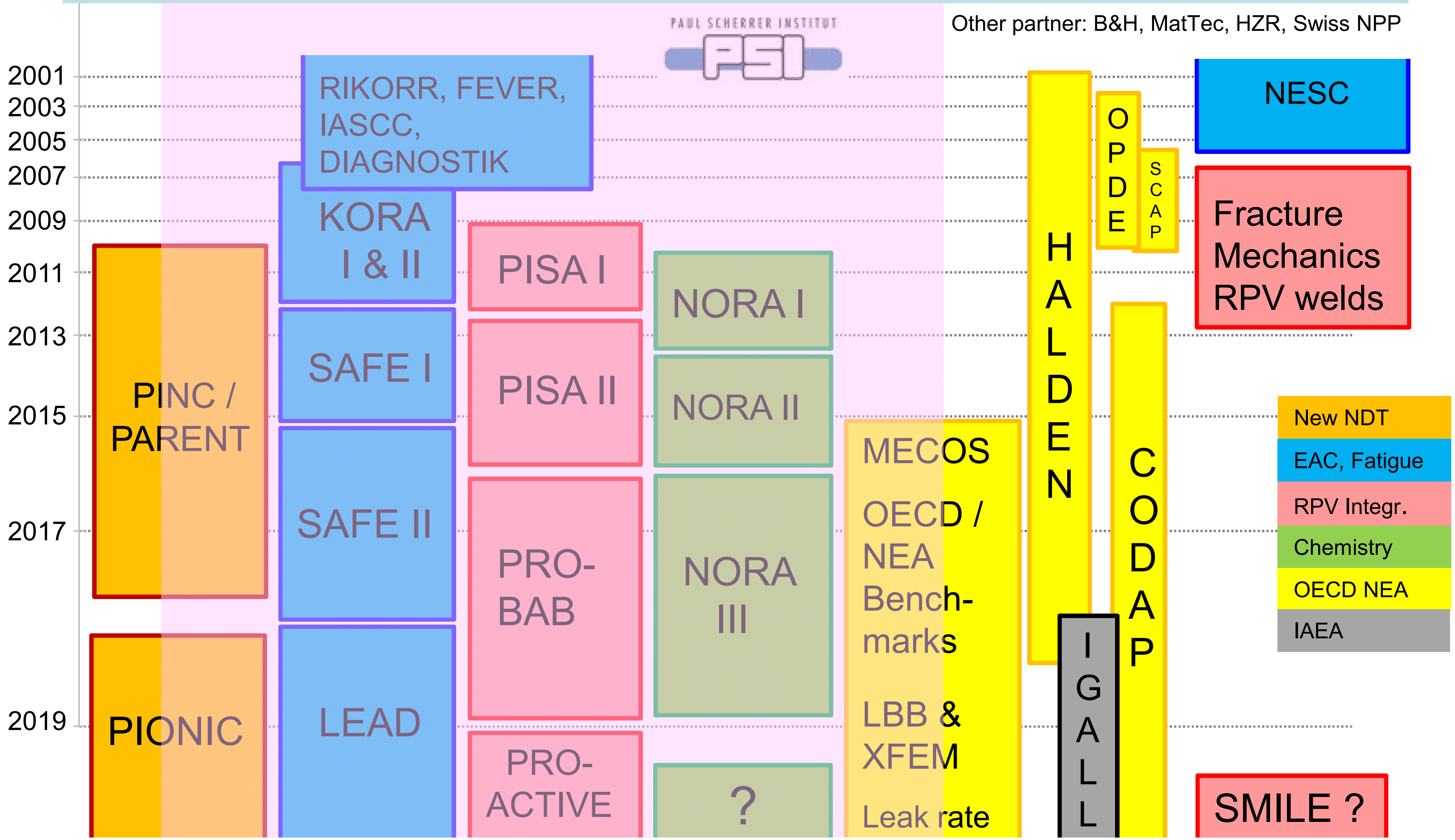
Acceptance Criteria based on LEFM: (defined by ENSI (Swiss regulator) for the specific KKM situation considering PCO 2019)

- KI max < 75 MPa√m (transversal cracks);
- ℓ transversal through-wall cracks < 320 mm

KKM Core Shroud - UT inspection results 1993 - 2015



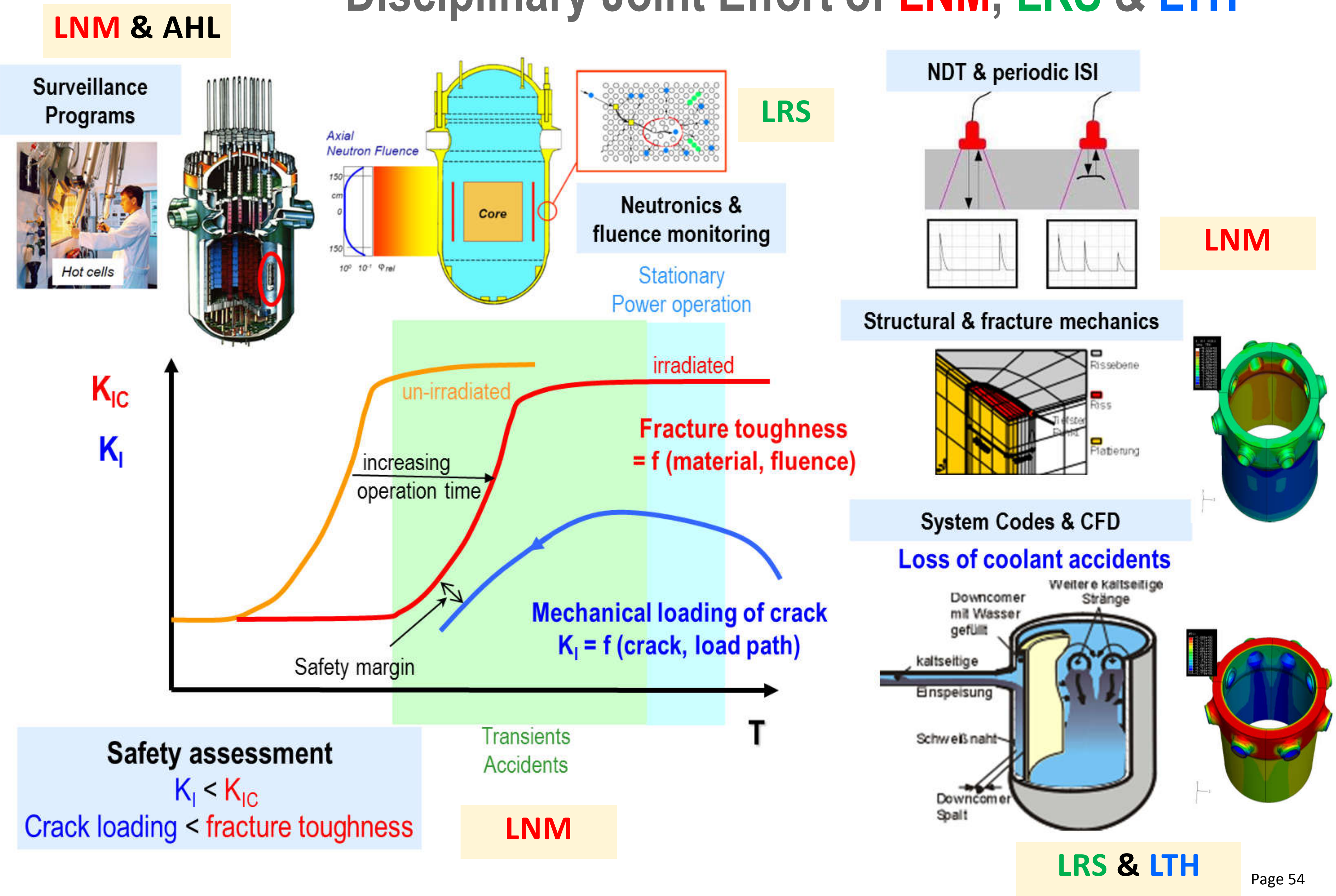
ENSI research and related activities, overview



PROBAB (2016-18, ENSI): RPV Structural Integrity

- **SP-I (25 %): Systematic LOCA transients study by LTH and LRS**
  - Analysis of various LOCA scenarios (T, p, dm/dt, h) with system (LRS) and CFD codes (LTH)
  - Evaluation of cooling for various TH regimes (single & two-phase, plume & stripe cooling)
  - Uncertainties of transients & critical evaluation of transient matrix
- **SP-II (50 %): Probabilistic & deterministic PFM PTS analysis of a reference RPV by LNM**
  - Various LOCA and other transients (LTOP, …)
  - Consideration of plume & stripe cooling by engineering models
  - Material inhomogeneity's (segregation, inclusion bands) and hydrogen flakes
  - Effect of cladding & residual stress (cladding, welds)
  - 3D FEM & XFEM analysis for various crack configurations, validation of XFEM
- **SP-III (25 %): Probabilistic integrity, lifetime & LBB assessment for material ageing by LNM**
  - Literature survey for active ageing mechanism (SCC, EAF, TMF) → state-of-the-art
  - Evaluation of potential codes (PRO-LOCA, X-LPRM, …) and selection of code → POR-LOCA
  - Application of code to a selected specific case (e.g., KKL feedwater nozzle) in a first pre-study
  - Participation in OECD XFEM & LBB benchmarks / round robins study & in PARTRIDGE project

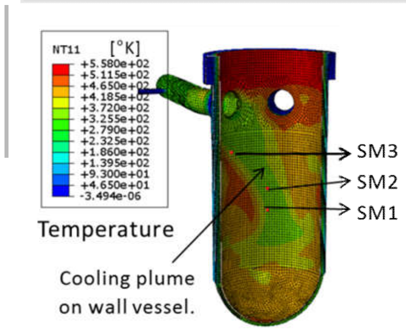
PROBAB: RPV Integrity Assessment as Multi-Disciplinary Joint Effort of LNM, LRS & LTH

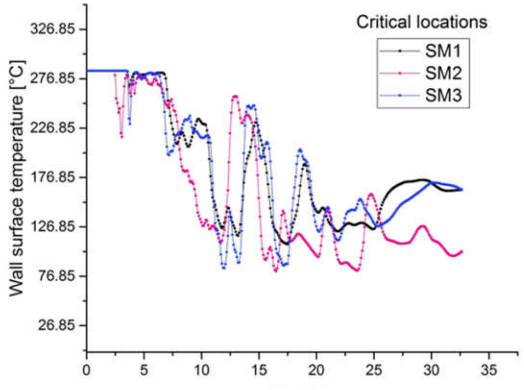


3D SM & FM Simulations of LOCAs by LNM

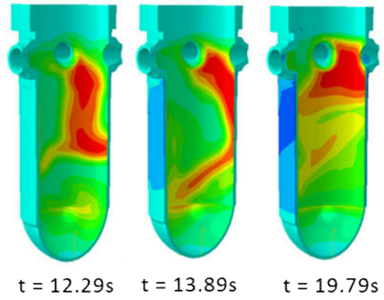
LBLOCA

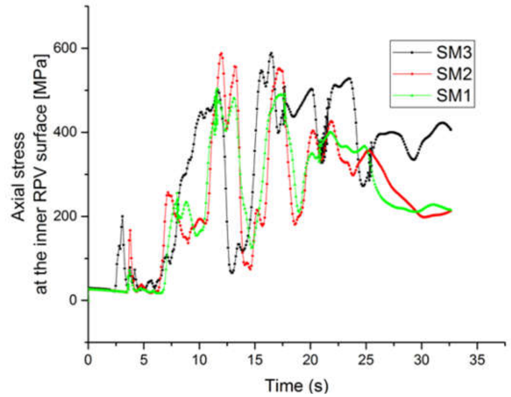
Wall temperature distribution

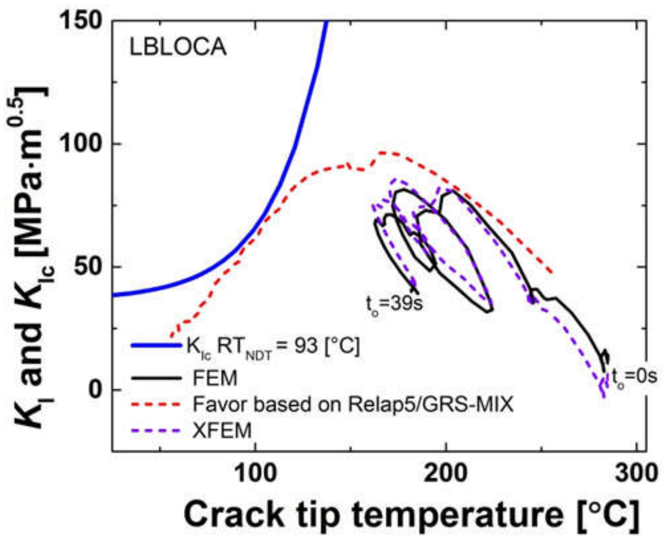


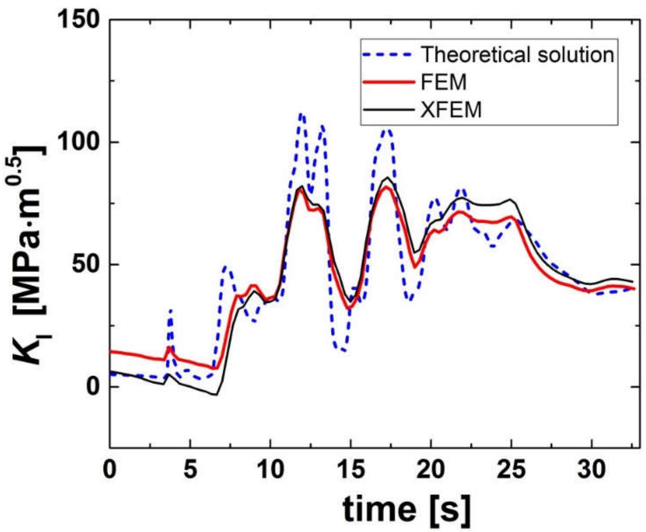


Axial stress distribution









Peak K_I at crack-tip in plume may be higher than in simplified 1D-models

Complex time course with significant reloading → WPS may be challenged

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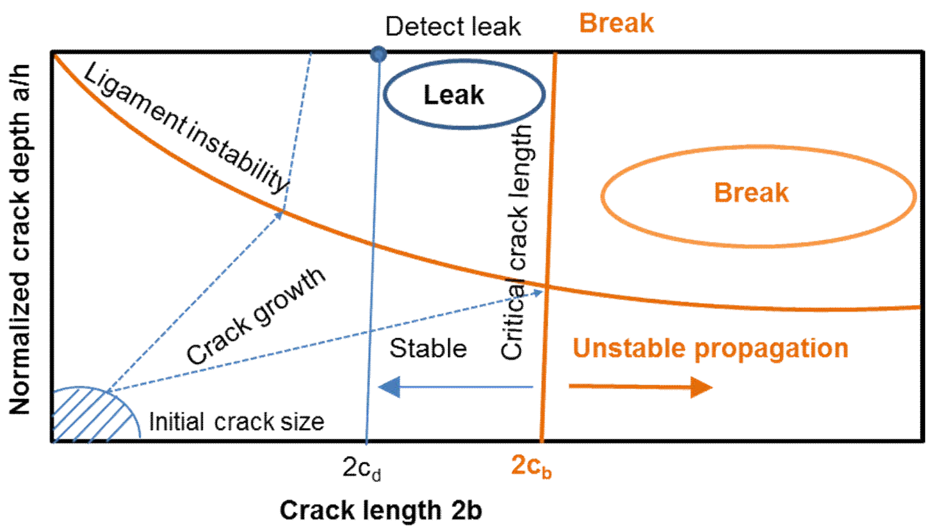
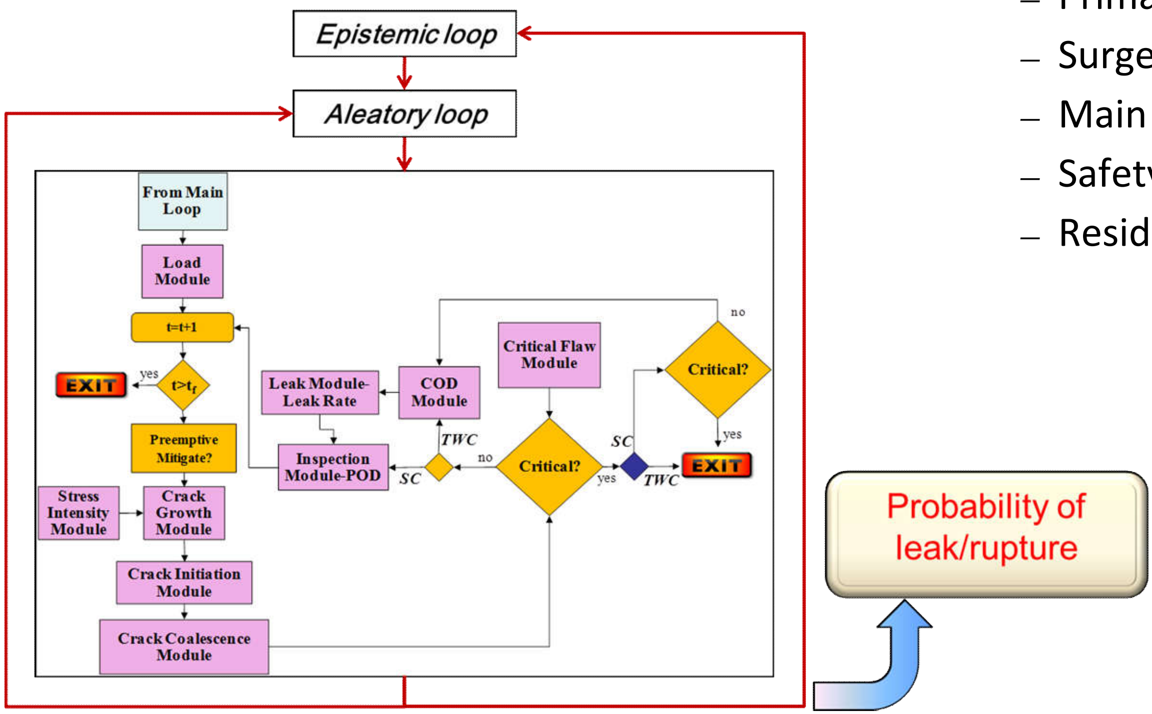
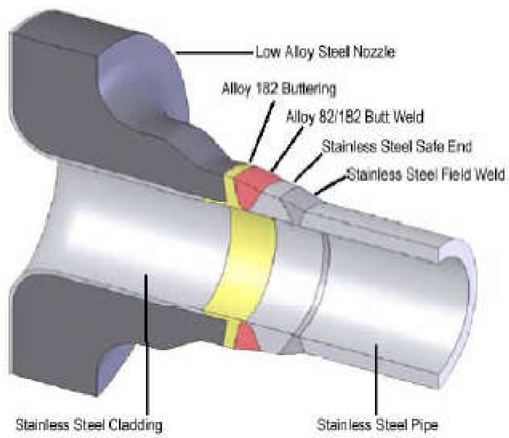
PRO-LOCA - Probabilistic LBB Analysis





- PRO-LOCA code is used for **Leak-Before-Break (LBB)** analysis (criteria: $2c_d < 2c_b$)
- Demonstration that LBLOCA is an extremely rare event
- Active degradation mechanisms:
  - PWSCC for PWR & IGSCC for BWR
  - TMF
- The scope of the LBB analysis includes
  - Primary coolant loop
  - Surge line
  - Main steam line
  - Safety injection line
  - Residual heat removal line



PROACTIVE 2019 - 2021

PROACTIVE is the follow-up project of PROBAB

part	topics	effort
TP-I	Probabilistic Integrity Assessments at critical RPV locations and piping under consideration of active degradation mechanisms (PARTRIDGE, PRO-LOCA, OECD-Benchmark „LBB“)	40 %
TP-II	Experimental Validation of Extended Finite Element Method (XFEM) with respect to application to crack growth simulations. (Experiments and participation at OECD-Benchmark „XFEM“)	40 %
TP-III	Fracture toughness evaluation of RPV-steels by using of small specimen (mini-CT?) (literature study to identify knowledge gaps + definition and start for a PhD-thesis)	20 %

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SAFE-II (ENSI, 2015 - 2017)

SP-I: SCC Initiation in Austenitic SS & Ni-Alloys

- PhD thesis of J. Bai: Effect of H_2 on SCC initiation in Alloy 182 under BWR/HWC conditions @ 274 °C
- International MICRIN+ / NUGENIA+ project with 9 partners: Accelerated screening–SSR-Tests (tapered specimens) on SCC initiation (critical strains & stresses) in CW & high Si SS and Alloy 182
- ICG-EAC Round Robin on SCC initiation (constant load tests)
- ECG-COMON Round Robin on ECN & EIS measurements in high-temperature water

SP-II: Environmental Effects on Fracture

- Systematic study & quantification of environmental & hydrogen effects on the fracture behaviour in the upper shelf & brittle to ductile transition region in different RPV steels.
  - DBTT shifts and reduction of resistance to brittle failure due to H and HTW?
  - Major factors of influence & critical system conditions
  - Underlying mechanism, synergies/interactions with other mechanism (EAC, DSA, …)
- PhD thesis (Z. Que) on high-temperature water effects & Post-Doc project (S. Rao) on H effects in air

SP-III: Environmental Effects on Fatigue

- International EU HORIZON2020 INCEFA+ collaborative project, 2015 to 2020 (5 y), 14 partners
  - Effect of mean stress, long static load hold times & surface conditions on fatigue of SS in HTW
  - Development of European EAF analysis procedure, EAF data base (MATDB, JRC)
- PhD thesis (W. Chen) with focus to basic aspects of EAF (mean stress, stress state & mechanism)

LEAD Project (ENSI, 2018 - 2020)

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SP-I: SCC Initiation in Austenitic Ni-Alloys & SS (30 %)

- Effect of surface conditions on SCC initiation & surface modification for SCC mitigation, LBB
- New PhD thesis (A. Treichel), 5/2018-4/2022
- H2020 MEACTOS project, 2017- 2020
- ICG-EAC Round Robin on SCC initiation (constant load tests) – phase II

SP-II: Environmental Effects on Fracture (20 %)

- PhD thesis (Z. Que), RPV steels (DSA, S, TE, HAZ), 2/2019

SP-III: Environmental Effects on Fatigue (20 %)

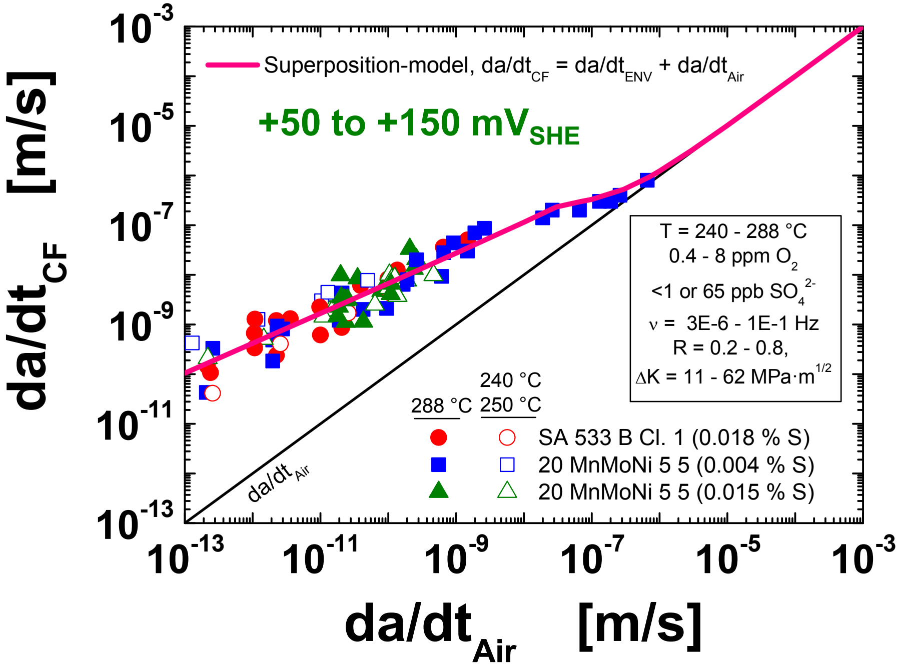
- International EU HORIZON2020 INCEFA+ collaborative project, 2015 to 2020 (5 y), 14 partners
  - Effect of mean stress, long static load hold times & surface conditions on fatigue of SS in HTW
  - Development of European EAF analysis procedure, EAF data base (MATDB, JRC)
- PhD thesis (W. Chen), 3/2020

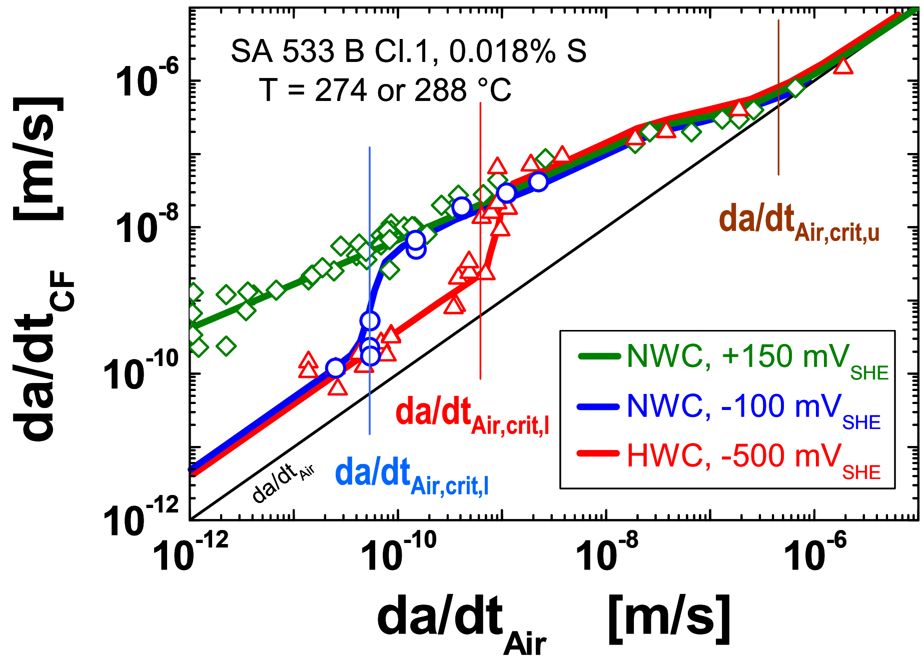
SP-IV: Synergies & Superposition of Ageing Mechanisms (25 %)

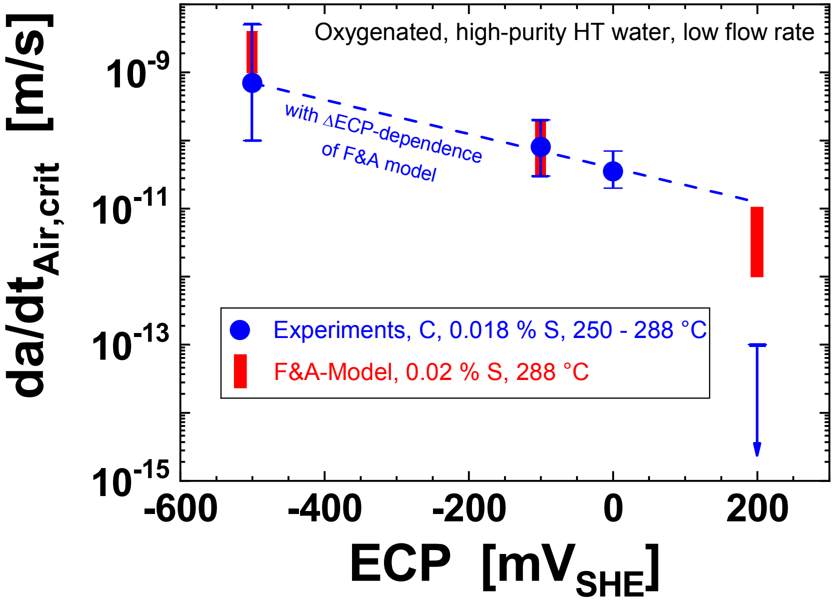
Part-I: Environmental fracture & (IA)SCC of irradiated RPV steels (JRQ)

Part-II: Environmental fracture & SCC of thermally-aged Alloy 182 weld metal ($\rightarrow$short range ordering)

PSI Corrosion Fatigue Crack Growth Model







$da/dt_{CF} = da/dt_{ENV} + da/dt_{Air}$

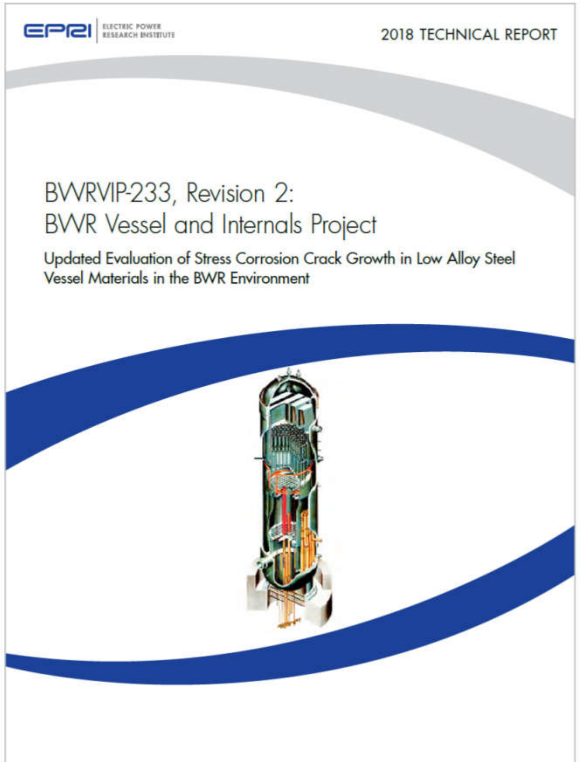
$da/dt_{Air} = f(\Delta K, R, \Delta t_R)$
$= (7.87E\text{-}11/\Delta t_R) \cdot (\Delta K/(2.88-R))^{3.07}$

$da/dt_{Air} < da/dt_{Air,crit} = f(ECP)$:	$da/dt_{ENV} = 3 \cdot da/dt_{Air}$
$da/dt_{Air,\,crit} \leq da/dt_{Air} < 3.7E\text{-}8$ m/s:	$da/dt_{ENV} = 6.6E\text{-}3 \cdot (da/dt_{Air})^{0.6}$
$da/dt_{Air} \geq 3.7E\text{-}8$ m/s:	$da/dt_{ENV} = 2.3E\text{-}7$ m/s

$da/dt_{Air,crit}$ for high-sulphur steel and low-flow conditions

ECP = -500 mV_{SHE}:	$da/dt_{Air,crit} \approx 7E\text{-}10$ m/s
ECP = -100 mV_{SHE}:	$da/dt_{Air,crit} \approx 8E\text{-}11$ m/s
ECP = +200 mV_{SHE}:	$da/dt_{Air,crit} < 1E\text{-}13$ m/s

BWRVIP-233 R.2 SCC Disposition Lines

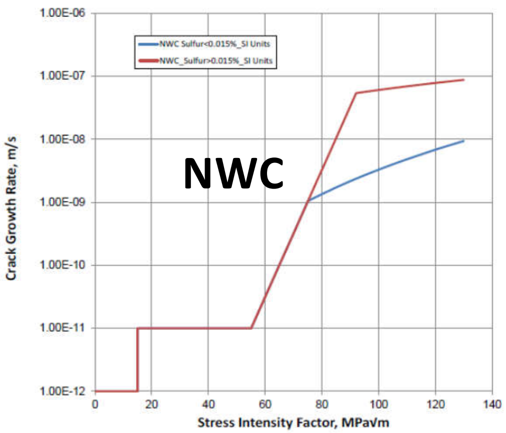


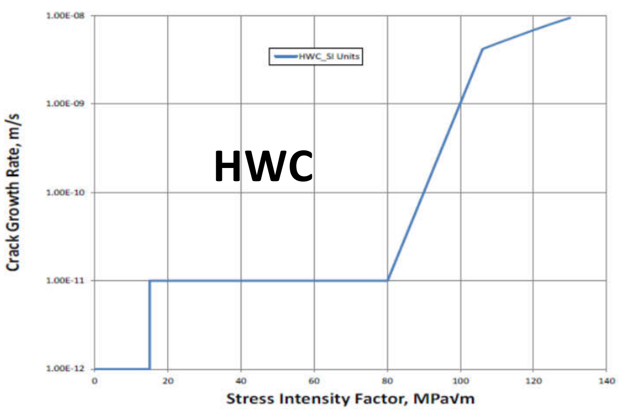
- New SCC disposition lines for RPV steels for BWR/NWC, HWC & chloride transients
- ASME BPV Code Case, positive feedback from all code (sub-) committees, response to US NRC feedback done, final approval expected in May 2019
- Largely based on PSI results and suggestions
- Adjustment of AL 1 of EPRI BWR WC Guidelines for chloride to 3 ppb in 2016

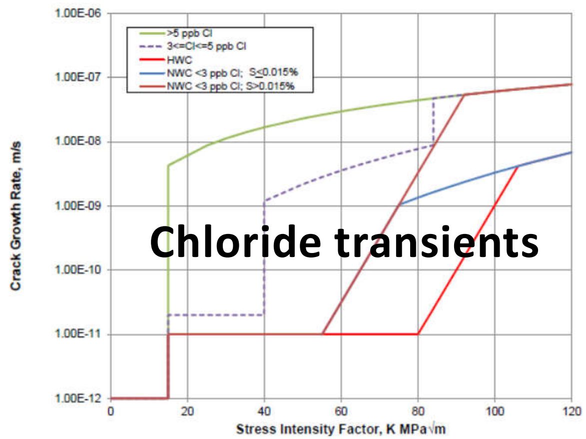
Reference Crack Growth Rate Curves for Stress Corrosion Cracking of Low Alloy Steels in Boiling Water Reactor Environments

Inquiry: When performing a flaw growth analysis under IWB-3600 of Section XI, what reference crack growth rate curve(s) may be used for Stress Corrosion Cracking of Low Alloy Steels in Boiling Water Reactor Environments?

Reply: It is the opinion of the Committee that the stress corrosion crack (SCC) growth rate







PSI support to new ASME Code Cases for EAC

- Code Case N-XXX
  "Reference Crack Growth Rate Curves for SCC of Low Alloy Steels in BWR Environments"
  Draft close to final approval,
  (C&S Connect Record # 17-3016)
- Two new Code Cases for BWR Fatigue Crack Growth Rates are under preparation
  - for Low Alloy Steel (i.e., BWR Version of N-643-2) expected to use data provided by PSI
    (C&S Connect Record # 19-5)
  - for Stainless Steel (i.e., BWR Version of N-809)
    (C&S Connect Record # 19-6)

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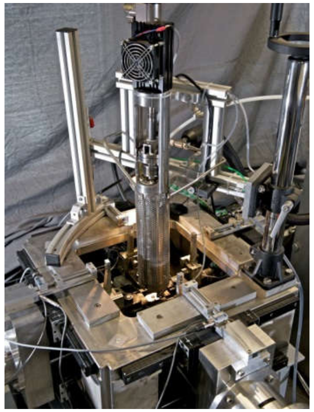
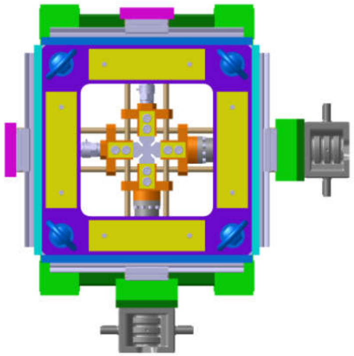
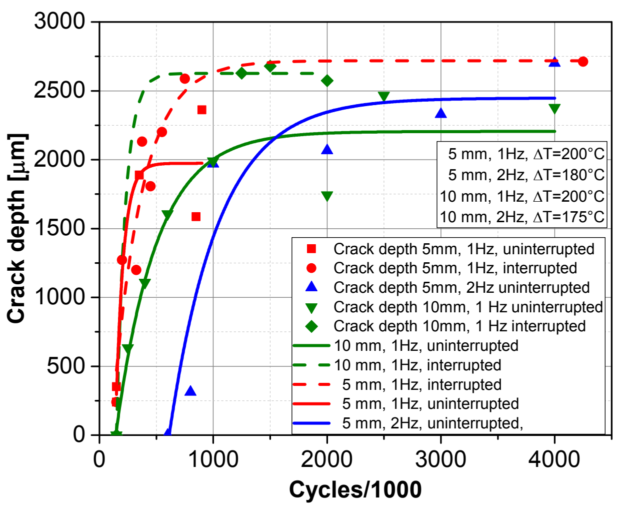
Non-Standard Fatigue Tests for Model Validation & Development

(supported by swissnuclear)

TMF
with biaxial pre-loading

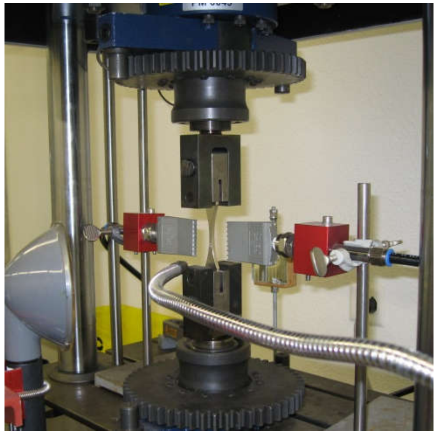


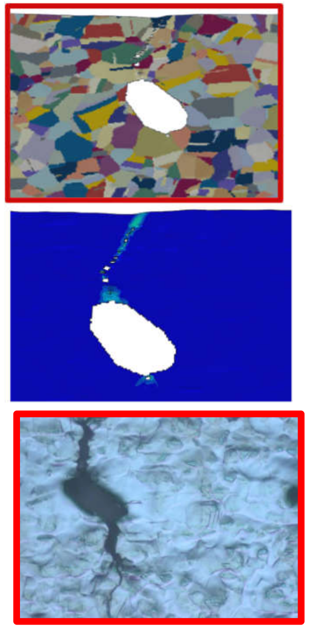




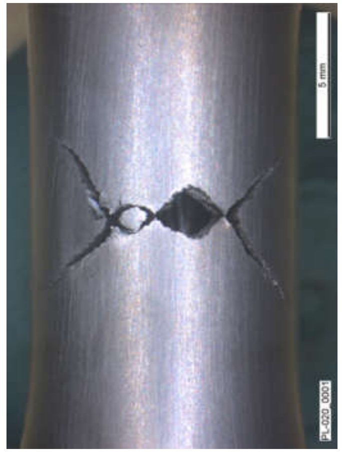
- Crack arrest at 2 to 2.5 mm = f (frequency)
- Strong effect of surface conditions on initiation

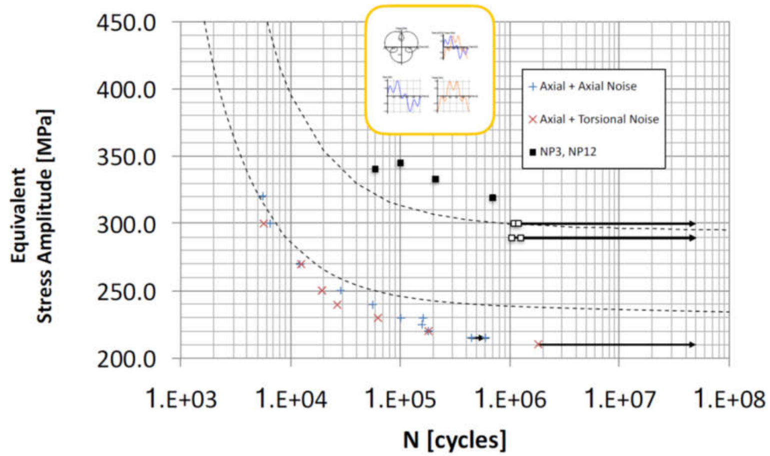
HCF
with micro notch (FIB)





Multiaxial HCF
tension-torsion, proportional & non-proportional

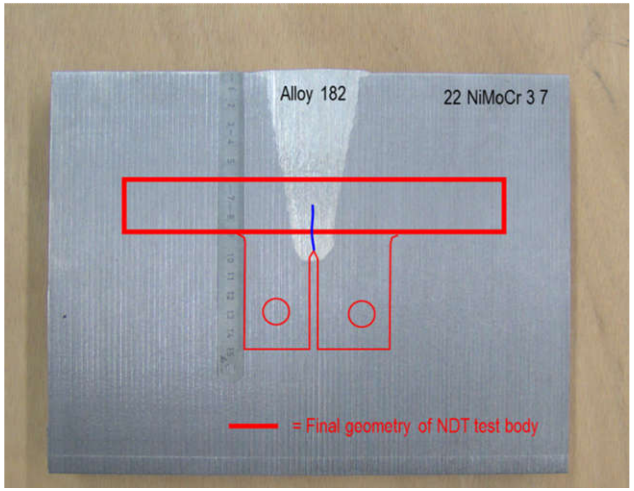


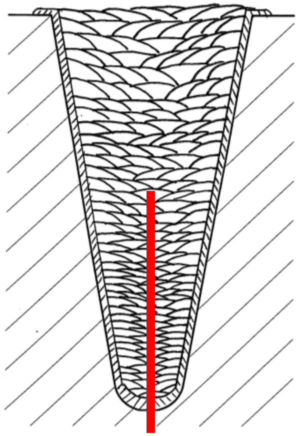


Significant effect of small non-proportional noise on fatigue life!

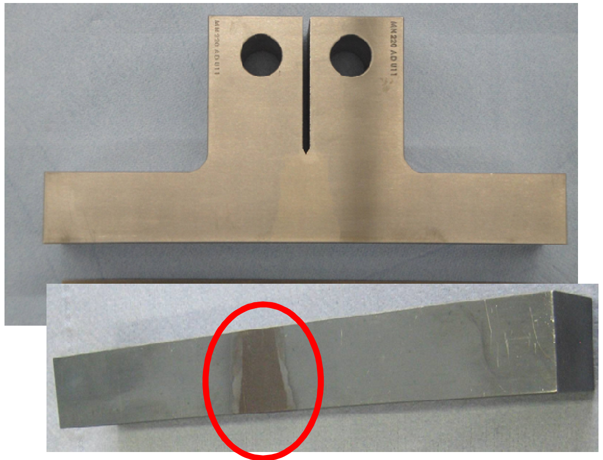
PAUL SCHERRER INSTITUT

Swiss contribution to PARENT, PIONIC

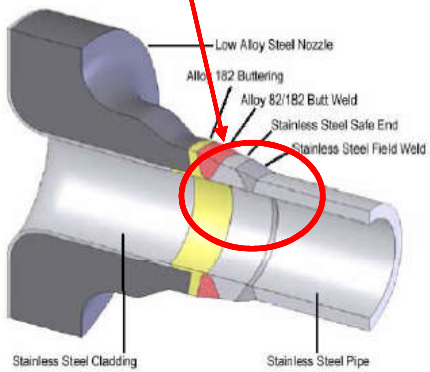




1. IG SCC crack (BWR/NWC) in middle of bulk weld metal ~ 20 % of wall thickness



2. Detailed UT characterization by SVTI
3. Cutting of weld segment & insert of segment in weld mock-up by minimally invasive welding

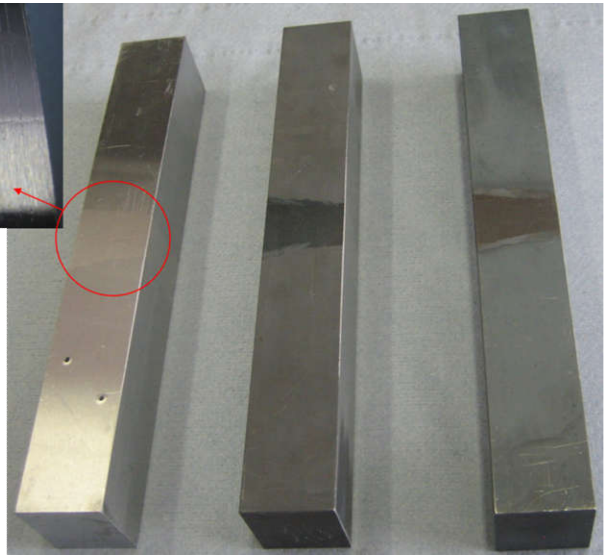


PARENT (2012-16): NDT Test Bodies with SCC Cracks

Detection and, in particular, sizing of SCC defects in DMWs represents a challenge and is related to relevant uncertainties. Crack depth is often significantly underestimated by NDT!

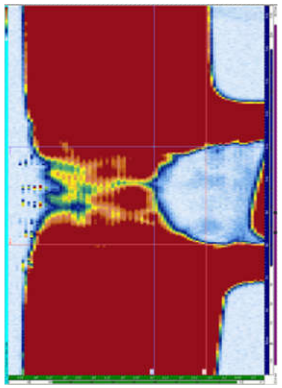
PARENT: Program to Assess the Reliability of Emerging Nondestructive Techniques
follow-on project to **PINC: Program for the Inspection of Nickel Alloy Components**

- Participation of Swiss consortium (ENSI, PSI, ALSTOM, SVTI, EMPA) in PARENT-Project
- International program including regulators, industrial groups and research institutions
- Assessment & quantification of established & new promising NDE techniques
- NDT tests bodies with well characterized SCC cracks for open round robin as PSI contribution
- Participation in open and closed round robin programs (ALSTOM, SVTI)



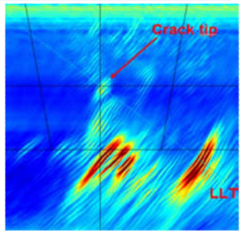
- Real SCC cracks
- PWR & BWR/NWC
- a/W ~ 0.1 to 0.8
- Bulk weld metal & weld butter interface
- 8 specimens plus 1 verification specimen

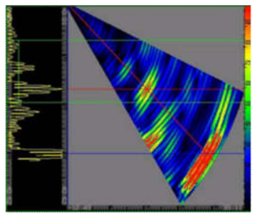
UT immersion
Alstom



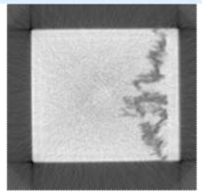
BWR/NWC SCC Crack

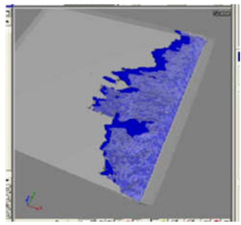
UT phased array
SVTI, Alstom





X-ray radiography & tomography
EMPA





PIONIC

Background:

- Optimization of NDT methods for SCC detection in DMW and Ni-alloys
- Follow-up project of PARENT & PINC

Administrative issues:

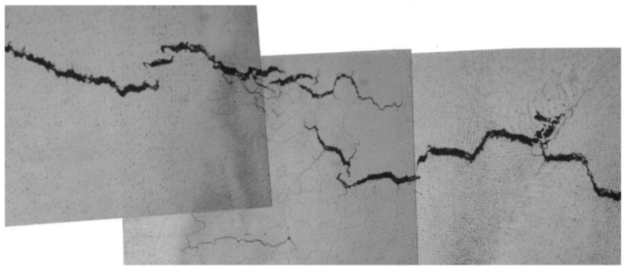
- Contract of ENSI with US NRC (in-kind contributions), contract of PSI with ENSI

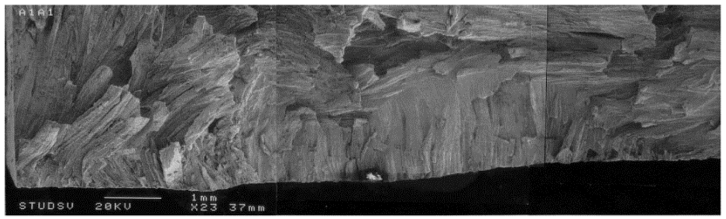
PSI Tasks:

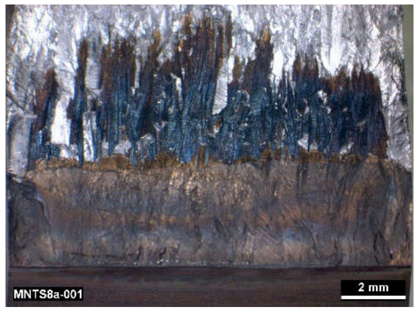
- 2 (or 3) NDT specimens with real IG/ID SCC with short cracks (~ 20 % of wall thickness), NWC with chloride and high-purity water in final phase, interrupted with UT at Alstom & SVTI?
- 2 x 1T C(T) specimens for quantitative crack configuration characterizations: Crack openings, branching, un-cracked ligaments, surface roughness in loaded and unloaded conditions
- ~ 1 year of total testing time

Status:

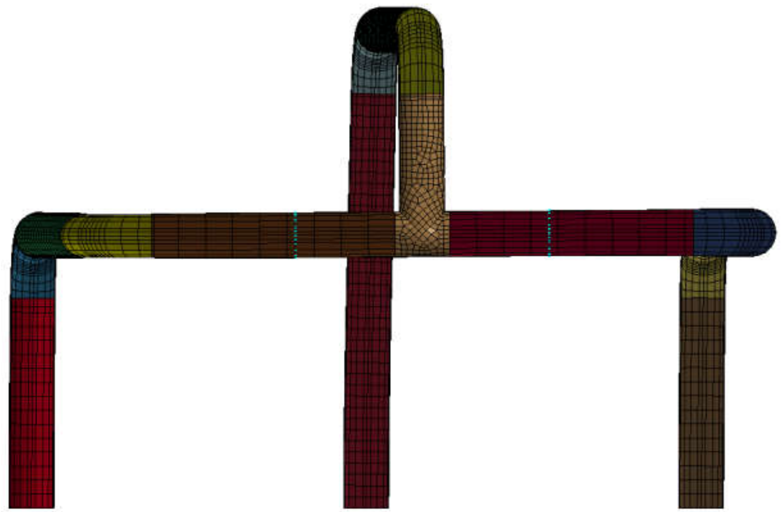
- Specimens fabricated and pre-cracked, 3rd test is running,
- NDT pre-characterization of initial conditions at SVTI in December 2018







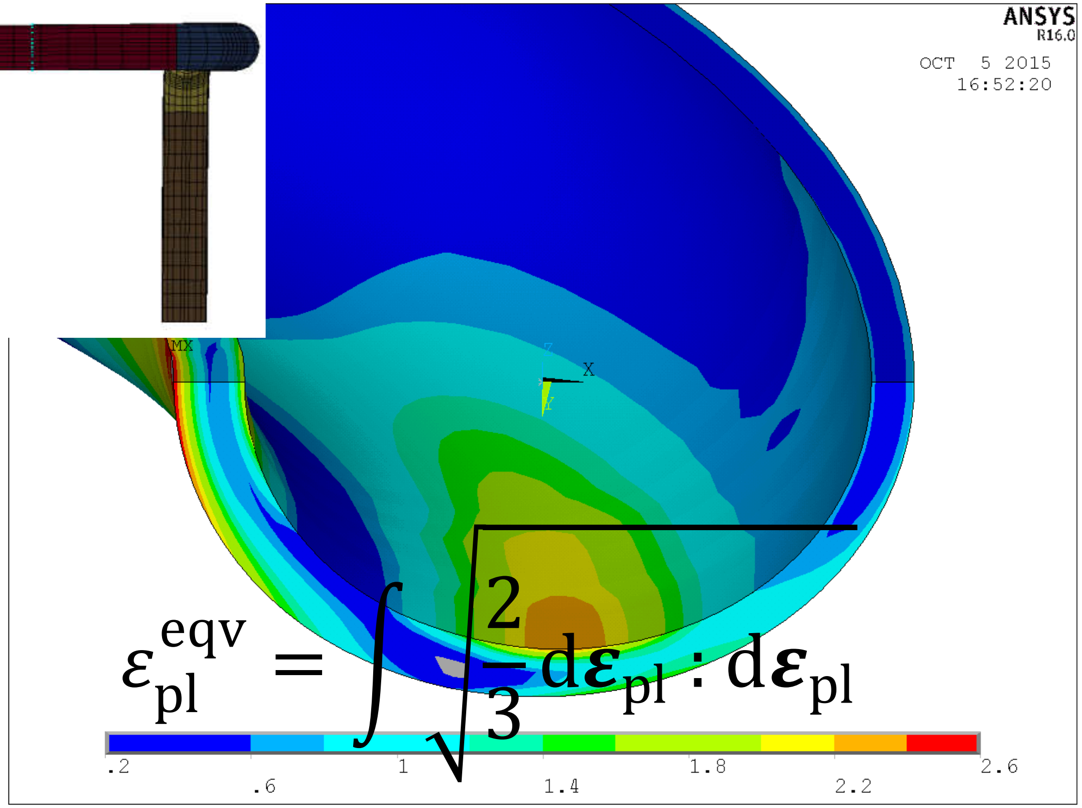
Research activities, OECD/NEA MECOS Benchmark



Mode 2, f = 5.9 Hz

(Structural Dynamic Analyses by B&H)

(Cyclic Quasi-static calculations on Elbow by ENSI)



$$\varepsilon_{\mathrm{pl}}^{\mathrm{eqv}} = \int \sqrt{\frac{2}{3} \mathrm{d}\boldsymbol{\varepsilon}_{\mathrm{pl}} : \mathrm{d}\boldsymbol{\varepsilon}_{\mathrm{pl}}}$$

Results of Fracture Mechanics RPV weld project

- Inclusion of MC-Concept to the RegGuide ENSI-B01, App. 5
- An Equation to convert T_0 (ASTM E-1921) to RT_{ref} was developed, which have to be used instead ASME CC-N-629 or N-631
- ENSI-B01, Method II:

$$RT_{ref} = T_0 + 14.4K + \Delta T_S + \sqrt{324/n + 16 + \Delta T_M^2 + \Delta T_T^2}$$

T_o	reference temperature acc. to ASTM E 1921 (MC approach)
n	number of valid tests
ΔT_s	=0 for 1T-C(T) specimens; =10K for 0.4T-SEN(B) specimens
ΔT_M	=0 for base material; =6K for weld material
ΔT_T	=0 for 1T-C(T) specimens; =5K for 0.4T-SEN(B) specimens

- ASME CC-N-629, N-631:

$RT_{T0(}$°C) = T_0 + 19.4K

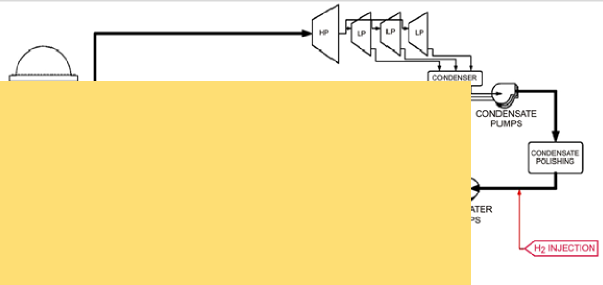
$$RT_{To}(°F) = [T_o + 35](°F)$$

NORA: Noble metal deposition behaviour in boiling water reactors

Objective: Investigation of the Pt deposition behaviour in boiling water reactors and its possible impact on structural materials and fuel element performance.

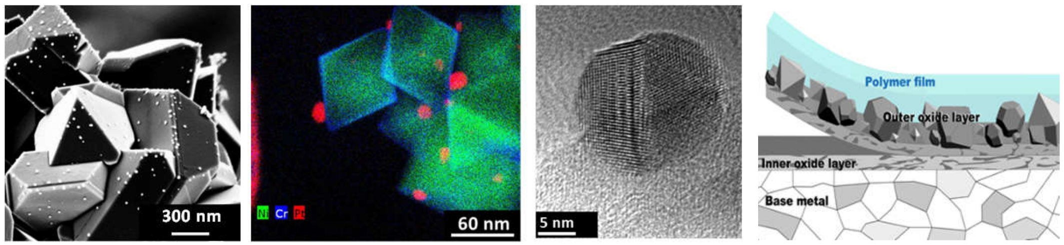
Systematic Pt deposition tests in sophisticated high-temperature water loop with steel specimens and simulated fuel rods.

Exposure of steel specimens in the reactor system at nuclear power plant Leibstadt.

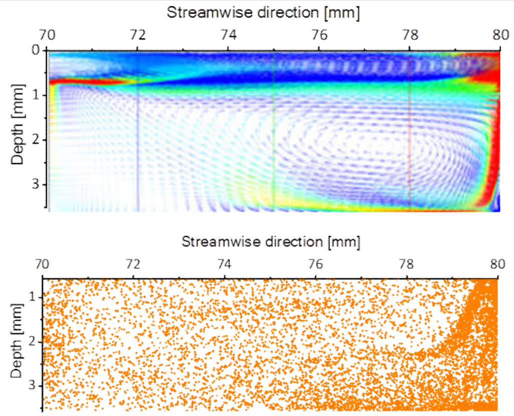


- **NORA-I to NORA-III from 2010 to 2019**
- **Project partners: PSI, ENSI, KKL, KKM**
- **Independent expertise and world-wide unique capabilities**
- **Results of direct practical use (optimized OLNC procedure)**
- **Several additional small industry R&D and service projects acquired**
- **Cooperation between several labs at PSI (LNM, AHL, LTH, & others)**

Characterization by high-resolution SEM, (S)TEM/EDS & LA-ICP-MS and development of non-destructive technique for radioactive components.



Modelling of Pt deposition (with LTH).

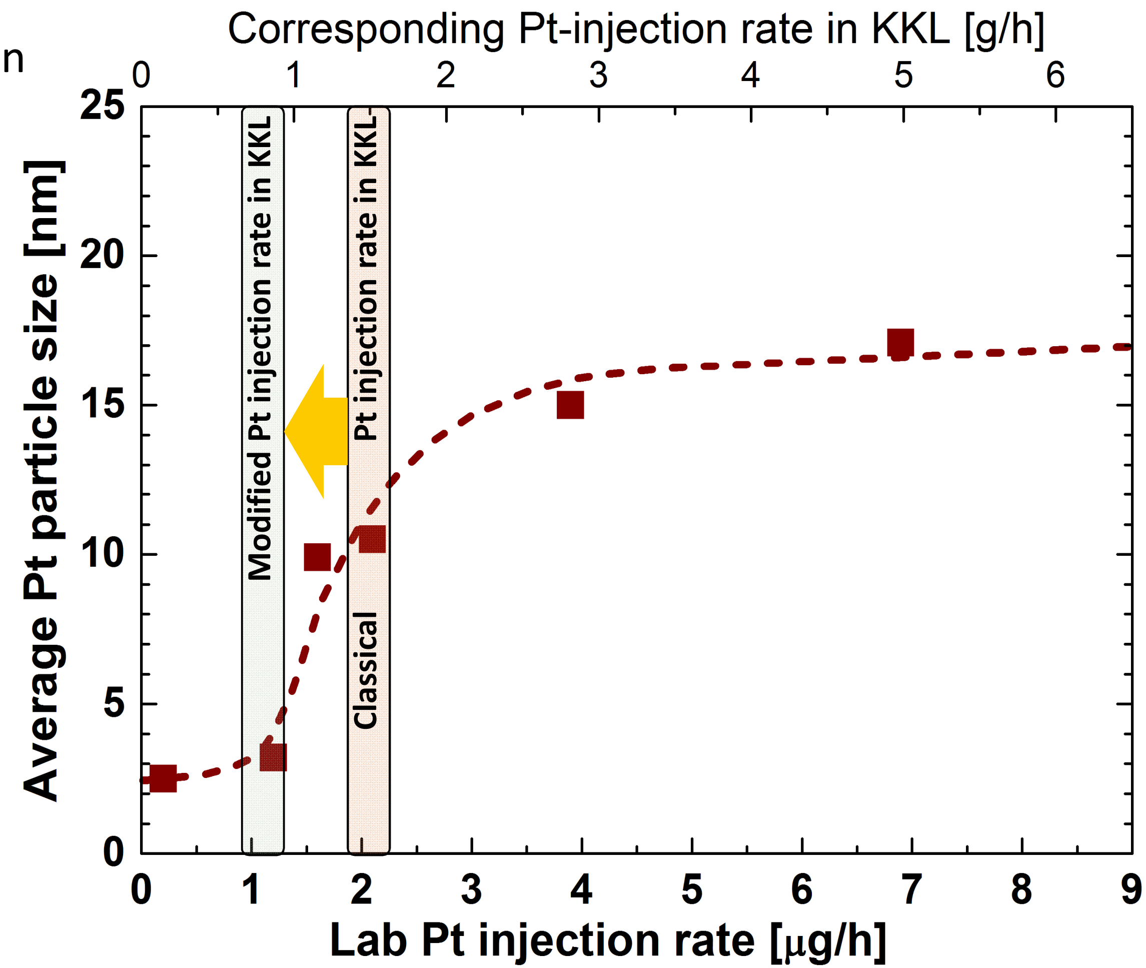


Effect of Pt injection rate on the Pt particle size

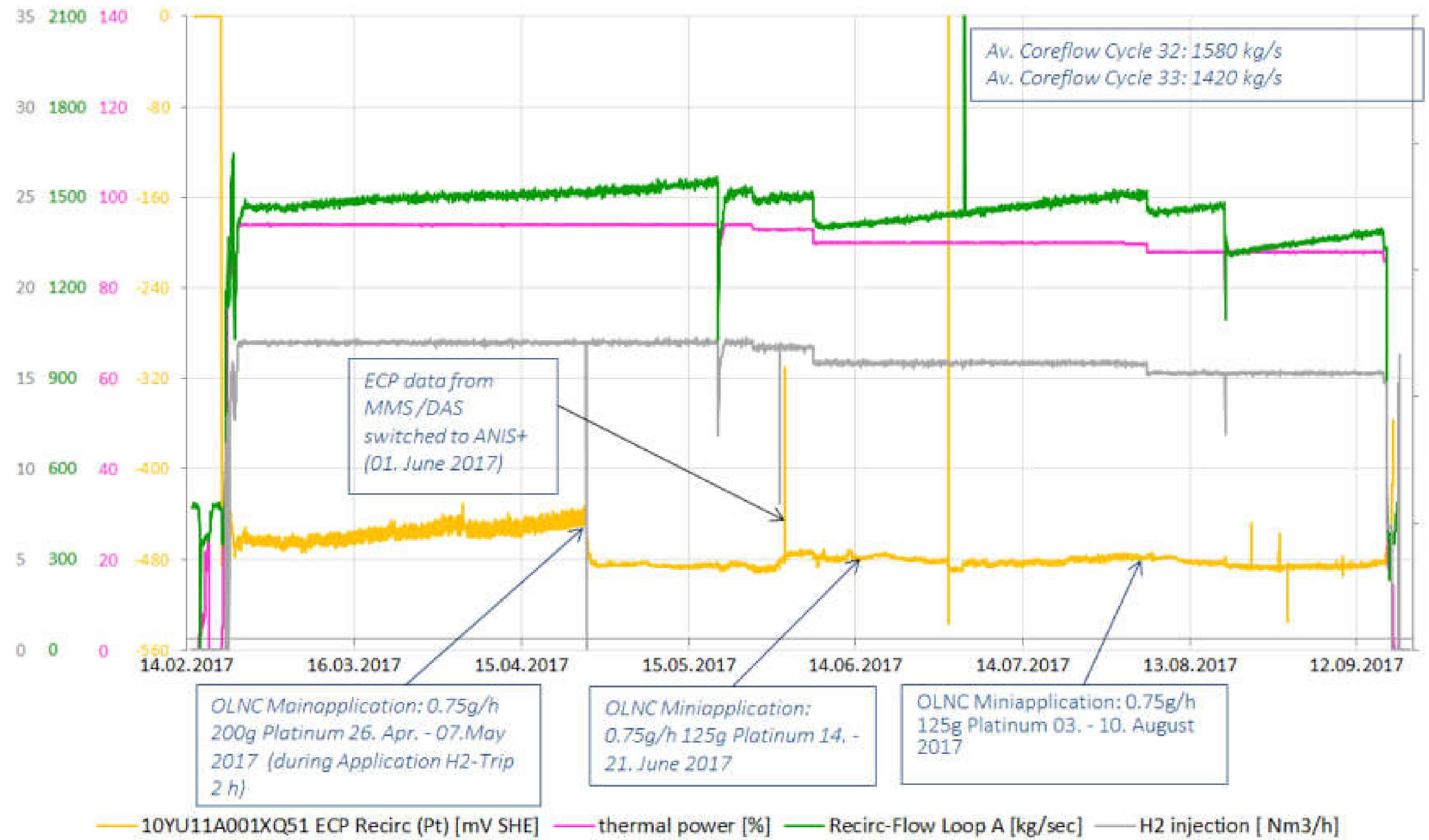
Experiments at PSI revealed that the Pt injection rate has an impact on the Pt particle size, whereas smaller particles are beneficial (more homogenous coverage with a low total amount of injected Pt).

These results were directly applied at KKL (as well as at KKM):

The Pt injection rate was reduced from 1.50 to 0.75 g/h to generate and deposit smaller and therefore more nanoparticles.



HWC/OLNC: ECP-run Cycle 33



Kernkraftwerk Leibstadt

Summary

- In Switzerland the establishing of a systematic ageing management started in 1991
- From ENSI`s perspective, a comprehensive and effective ageing management is implemented for the RPVs in the Swiss nuclear power plants, with which relevant ageing effects are detected at an early stage and effective corrective actions are initiated.
- Within the AMP all relevant ageing mechanisms for the RPV components are identified and evaluated according to the current state-of-the-art of science and technology.
- Based on results of the extensive inspection programmes, specific corrective actions have been taken for identified ageing-related damage and degradation.
- With the existing AMP for the RPVs, safe long-term operation for an operating period of 60 years, or for KKM until the final shutdown in 2019, is ensured.

Acknowledgement

Special thanks to

Hans-Peter Seifert and colleagues (PSI)
Jens Heldt (KKL)
and to all colleagues from ENSI
supported this presentation

and for providing material.

Thank You for your kind attention.