Laboratory for Nuclear Materials (LNM)

- Overview & selected highlights with focus to material ageing -

H.P. Seifert, J. Bertsch, M. Pouchon
Paul Scherrer Institute
5232 Villigen PSI, Switzerland

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Outline

- **Overview on LNM**
  - Mission & organizational structure
  - R&D portfolio, lab infrastructure & modeling tools
  - Education & teaching activities
  - Scientific services
  - National & international collaborations

see electronic version!

- **Examples of current material ageing related activities & highlights**
  - INTEGER research program
  - Material ageing & degradation (characterization, mechanisms, mitigation)
  - Structural integrity (modeling of ageing, integrity & lifetime assessment)
  - ND diagnostics (early detection & monitoring of ageing & degradation)

Overview on LNM

http://www.psi.ch/lnm/

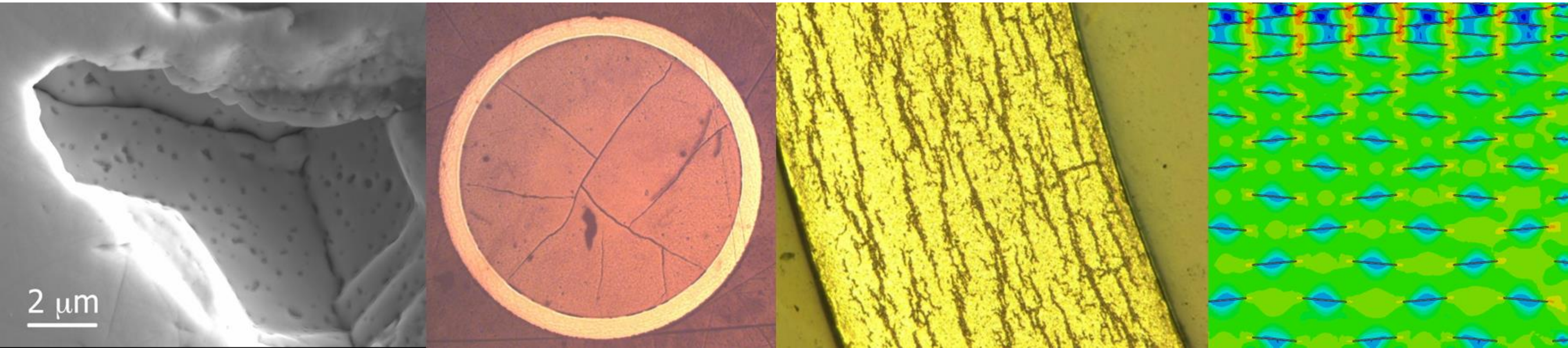
Swiss Centre of Excellence for Nuclear Materials Science

- Safe & efficient LTO
- Advanced fission reactors MS
- Spallation & fusion MS

- Education & teaching
- Knowledge transfer & management

- Independent expertise
- Expertise & consulting (TSO)
- Failure analysis & PIE

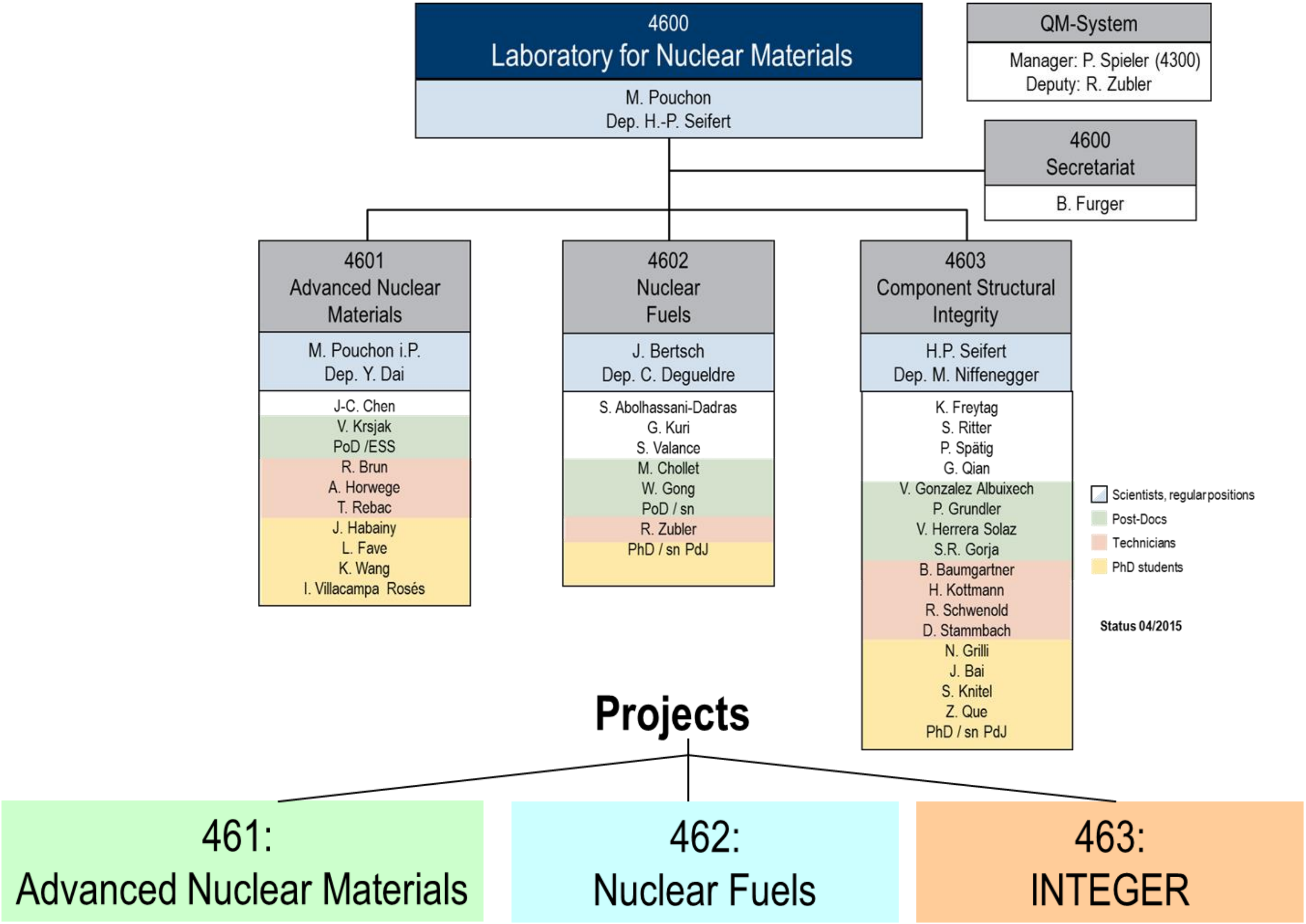
- Radioactive material characterization
- Materials irradiation (STIP)



Mission of LNM

- The LNM is the principal research unit and national centre of excellence in Switzerland in the domains of (radioactive) **materials behaviour** and **ageing** in **nuclear installations**.
- It provides material-related academic R&D contributions and scientific services to the **sustainability** of **current** and **future nuclear installations** for electricity & heat generation or waste reduction as well as to the performance of **nuclear research facilities**. A special emphasis is placed to the **safety** & **safe long-term operation** of the CH NPPs.
  - **Material ageing** in the primary circuit and its impact on **integrity, safety** & **lifetime**
  - **Performance** and **safety** of **LWR core materials** in **service** and storage
  - **Radiation damage** in structural and core/target materials of advanced nuclear and accelerator systems.
  - **Material irradiation program at SINQ** in co-operation with the Spallation Neutron Source Division.
  - **Post-irradiation examinations** and **failure analysis** in close cooperation with the Hotlab Division AHL.
- LNM is engaged in academic **teaching** and **education** as well as in **knowledge transfer** in its activity fields contributing to the education of the future nuclear specialists and preservation of expertise & excellence.
- Its **independent expertise** and **excellence** are always available to the **Swiss safety authority**, e.g. for expertise's and consulting (TSO), and for the **industry**, e.g., for material examinations and failure analysis.
- It operates a state-of-the-art **lab & computing infrastructure** and **modelling tools** for the **characterization** of **(radioactive) materials** (strongly benefiting from PSI's unique large scale facilities: hotlab, SLS, SINQ, SwissFEL) and for the **analysis & prediction** of the **material behaviour, integrity, safety & lifetime.**

Current Organisation of LNM by 4 /2015



4600
Laboratory for Nuclear Materials
M. Pouchon
Dep. H.-P. Seifert

QM-System
Manager: P. Spieler (4300)
Deputy: R. Zubler

4600
Secretariat
B. Furger

4601
Advanced Nuclear Materials
M. Pouchon i.P.
Dep. Y. Dai
J-C. Chen
V. Krsjak
PoD /ESS
R. Brun
A. Horwege
T. Rebac
J. Habainy
L. Fave
K. Wang
I. Villacampa Rosés

4602
Nuclear Fuels
J. Bertsch
Dep. C. Degueldre
S. Abolhassani-Dadras
G. Kuri
S. Valance
M. Chollet
W. Gong
PoD / sn
R. Zubler
PhD / sn PdJ

4603
Component Structural Integrity
H.P. Seifert
Dep. M. Niffenegger
K. Freytag
S. Ritter
P. Spätig
G. Qian
V. Gonzalez Albuixech
P. Grundler
V. Herrera Solaz
S.R. Gorja
B. Baumgartner
H. Kottmann
R. Schwenold
D. Stammbach
N. Grilli
J. Bai
S. Knitel
Z. Que
PhD / sn PdJ

☐ Scientists, regular positions
🟩 Post-Docs
🟥 Technicians
🟨 PhD students

Status 04/2015

Projects

461:
Advanced Nuclear Materials

462:
Nuclear Fuels

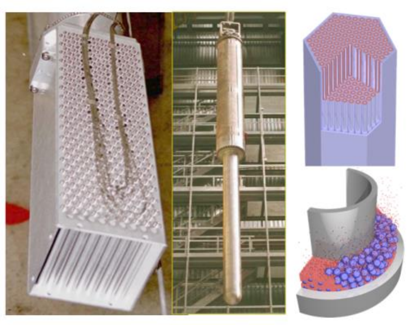
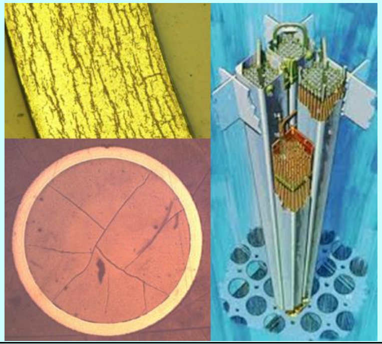
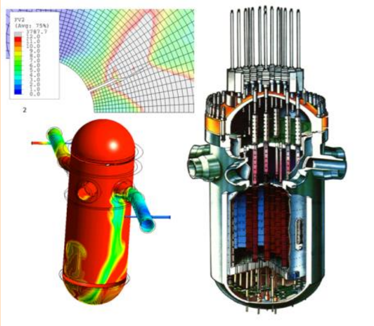
463:
INTEGER

~ 70 % externally funded & ~ 45 % permanent positions, PhD & Pos-Doc / Scientist ratio: ~ 1.5

New LNM Lab Head by 4/2015: Dr. M. Pouchon

- Swiss, 45 years old
- Physicist, ETHZ
- PhD in Natural Science, Uni Geneva / PSI
- ANM group and project leader since 2012
- German, French, English
- 2 years at JNC (now JAEA) in Japan
- Editorial Advisory Board member of Nuclear Materials and Energy (Elsevier)
- Active member in various international working groups & organizations (EERA, ESNI, GIF VHTR & GFR, OECD/NEA, IAEA, …)
- Responsible for Nuclear Materials Course in the NE Master Course of ETHZ/EPFL
- MER at EPFL since 2015
- 15 years of experience in (advanced) nuclear fuels and structural materials (experimental & modeling) R&D
- Radiation protection and Pu lab responsible in hotlab & extensive experience in radioactive materials handling

LNM Research Portfolio

	Advanced Nuclear Materials 	Nuclear Fuels 	INTEGER 
Project leader	**M. Pouchon**	**J. Bertsch**	**H.P. Seifert**
Topic	SNS/GEN-IV candidate materials Fuel element development	Performance of fuel & integrity of cladding	Material ageing & structural integrity
Components	Target & structures (SNS) Fuel element (GEN-IV/ADS)	Core materials (fuel, cladding)	Pressure boundary comp. & reactor internals
Key words	Performance (SNS) Sustainability (GEN-IV/ADS)	Performance, safety	Safety, lifetime (extension), performance
Systems	Spallation Neutron Sources GEN-IV / ADS, LWR-III++	LWR (GEN-II, III & III+)	LWR (GEN-II & III)

LNM Research Portfolio

	Advanced Nuclear Materials	Nuclear Fuels	INTEGER
Project leader	**M. Pouchon**	**J. Bertsch**	**H.P. Seifert**
Topic	SNS/GEN-IV candidate materials radiation damage at high T & dose	Performance of fuel & integrity of cladding	Material ageing & structural integrity
Components	Target & structures (SNS) Fuel element (GEN-IV/ADS)	Core materials (fuel, cladding)	Pressure boundary comp. & reactor internals
Key words	Performance (SNS) Sustainability (GEN-IV/ADS)	Performance, safety	Safety, lifetime (extension), performance
Systems	Spallation Neutron Sources GEN-IV / ADS, LWR-III++	LWR (GEN-II & III)	LWR (GEN-II & III)
Extern. funding Main source	40 % EU, STIP, CCEM	50 % swissnuclear, industry	60 % ENSI, swissnuclear
Indispensable for	PSI (SINQ/accelerators) Education	Radioactive material know how	Independent expertise (TSO)

R & D share:	65 % applied & 35 % basic 70 % GEN-II & 30 % GEN-IV/SNS	75 % experimental & 25 % modeling 55 % CH, 35 % international, 20 % PSI
Lab capacity:	10 % for teaching & education	10 - 15 % for expertise & service work

Contract-Projects in LNM (incomplete list)

- **ENSI:** PISA, NORA, SAFE, PIE Halden, SAFE-II, PISA-II, PARENT, NORA-II
- **Swissnuclear (FW contract):** PLiM-V, H-Uptake, Mech. Behaviour of Cladding & H, NFIR-VI, Doped Fuel, PLiM-VI, H-Uptake-II, Mech. Behaviour of Cladding & H-II, Doped Fuel-II
- **Swissnuclear (free competition)**: SiC, PWR-CRUD, He/IASCC, DF-PAS, ATF
- **ETH Competence Centres CCEM & CCMX:** PhiTEM, PINE, TMF, In-situ-Testing, MeAWaT

sole nulcear project in CCMX/CCEM

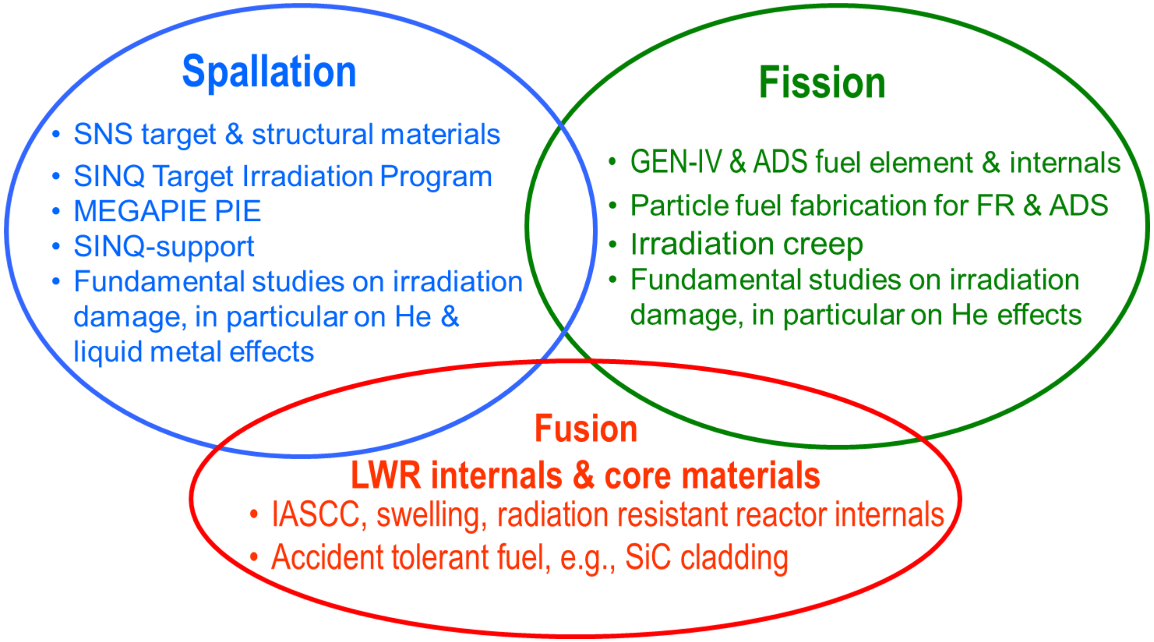
- **SNF/DFG:** Nanomagnetism, Fatigue (CPFEM), Helium FM (Fusion/STIP-V), FIB (Requip)
- **EU-6, EU-7 & H2020:** EXTREMAT, RAPHAEL, GETMAT, F-BRIDGE, NUGENIA/MICRIN, ARCHER, MATTER, ASGAARD, PELGRIM, *SOTERIA, INCEFA+, MICRIN+, DEF-PROSAFE*
- **GIF:** GEN-IV Materials Project
- **Industry:** SCIP, Crud-PhD (Westinghouse & KKL), Doped Fuel PhD (AREVA), LAS-BWRVIP, NFIR, PIE, Crud & Pt analysis (KKL, GE, …), Fuel (SLS/TEM) for AREVA & Westinghouse, FA of valve, NDT test bodies, OLNC (EPRI/BWRVIP), YUMOD (KKL), OLNC (EPRI), Pt-analysis (Spanish BWR)
- **KTI:** Brass music instruments
- **PSI-FOKO, PSI or CH:** In-Situ Testing, PSI ESS, 3 x PSI-Fellow, ESS-CH
- **International:** IAEA CRP DHC, MUCIZ-III, STIP-V to VIII, MEGAPIE, IFA 638 (Halden), ESS target (ESS)

- **Broad diversity** of **funding sources**
- **LNM holds largest share in ENSI & swissnuclear R&D funding**

Red colour: new projects *Blue colour: terminated projects 13/14*

Advanced Nuclear Materials

Performance of **SNS** & **sustainability** of **nuclear energy production** (GEN-IV, ADS)



Spallation

- SNS target & structural materials
- SINQ Target Irradiation Program
- MEGAPIE PIE
- SINQ-support
- Fundamental studies on irradiation damage, in particular on He & liquid metal effects

Fission

- GEN-IV & ADS fuel element & internals
- Particle fuel fabrication for FR & ADS
- Irradiation creep
- Fundamental studies on irradiation damage, in particular on He effects

Fusion

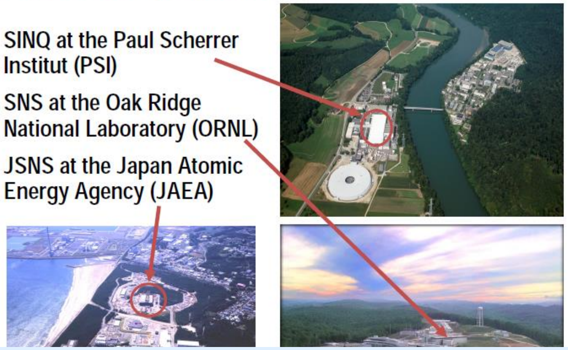
LWR internals & core materials

- IASCC, swelling, radiation resistant reactor internals
- Accident tolerant fuel, e.g., SiC cladding

Spallation Neutron Sources ↔ ADS ↔ GEN-IV Nuclear Systems

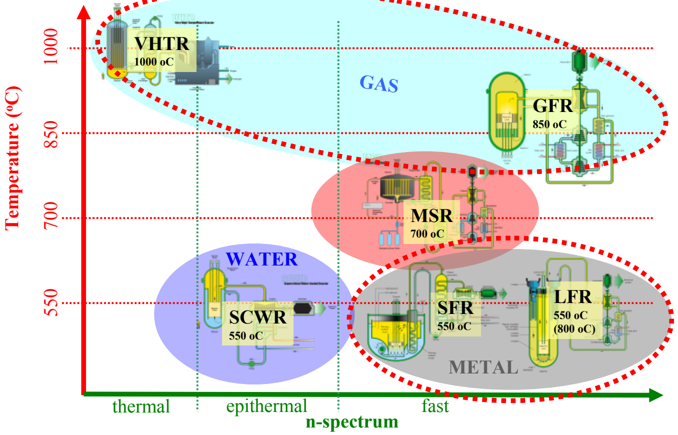
MW-Class Spallation Targets

- SINQ at the Paul Scherrer Institut (PSI)
- SNS at the Oak Ridge National Laboratory (ORNL)
- JSNS at the Japan Atomic Energy Agency (JAEA)



+ European Spallation Source (ESS)

same candidate materials
(ODS, FM steels, …)
and similar problems
(He, radiation creep, LME, …)



Current Activities in ANM

- **Particle fuel** (containing MA) **production** feasibility studies **by internal μ-wave gelation technology** for fast reactor (FR) & acceleration-driven systems (ADS)
- Characterization of **radiation damage and mechanical behaviour** in candidate structural and core/target materials in advanced nuclear and accelerator systems (He, displacement damage, irradiation creep)
- Characterization of the **behaviour** of candidate structural and core/target materials in the **service environment** in advanced nuclear and accelerator systems (liquid metal embrittlement & corrosion, creep & irradiation creep, phase stability)
- **Material irradiation program at SINQ** (STIP) in co-operation with ASQ/NUM.
- **PIE** of MEGAPIE and **SINQ targets**

STIP - SINQ Target Irradiation Program

Main purposes:

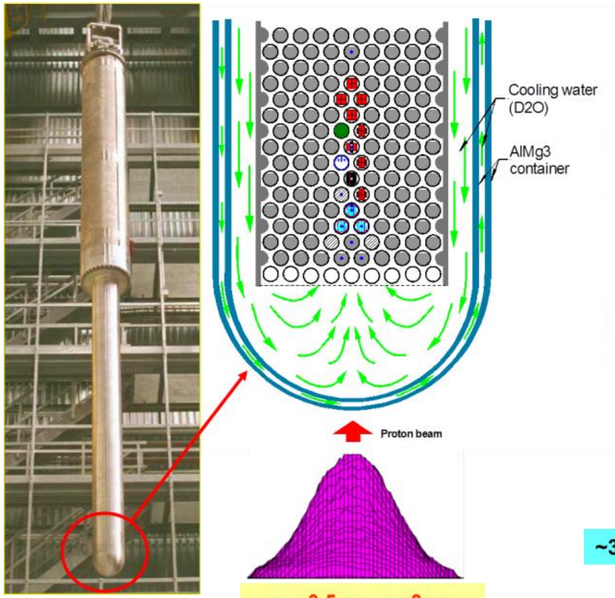
1) to provide necessary materials data for developing advanced spallation targets;
2) to understand radiation, He and H effects in different structural materials;
3) to study liquid metal effects on structural materials in intensive irradiation environments.

The main STIP partners are from sp
(e.g. CEA, FZJ, CIAE, IMP, JAEA, L

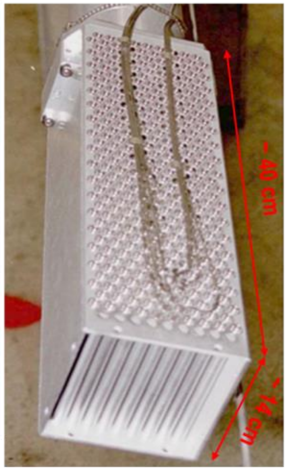
More then 7000 samples from 60+ c
(C/SiC, SiC/SiC…) were irradiated in first six experiments (STIP-1 to -6) up to 28 dpa / 2000 appm
He (in steels) at temperatures up to ~800° C.

Very strong link to China through

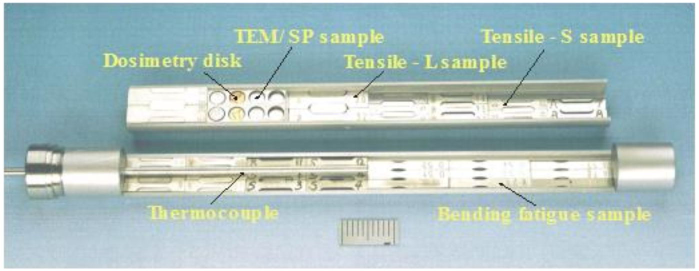
- STIP & MEAWAT
- Y. Dai & J. Chen as Visiting Professors in CAS institutes



σ_x~3.5cm, σ_y~2cm



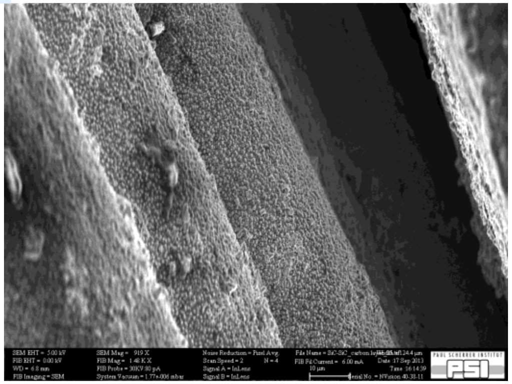
~360 Pb rods with SS / Zy-2 tubes



Advanced Claddings – PhD Thesis of L. Fave / CCEM

Piece of potential cladding tube (SiC/SiC with Ta)

PyC layer on SiC fibers



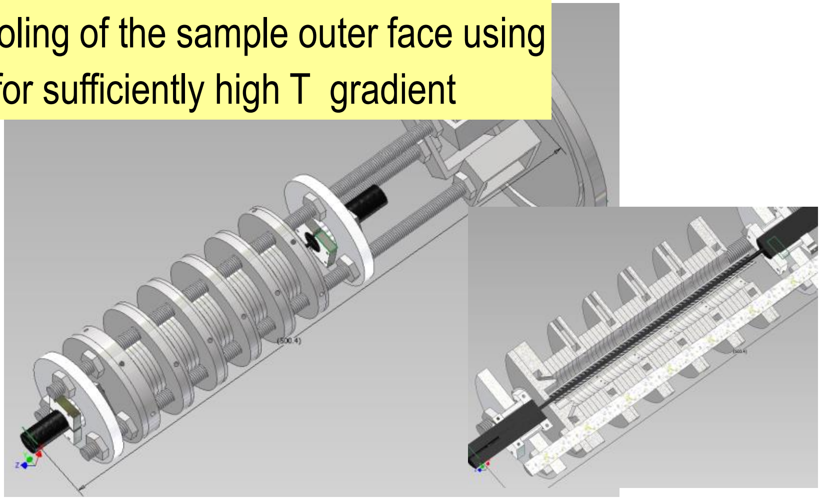
Investigation of SiC based composite tubes as potential cladding materials (e.g., in ATF):

- Microstructure & irradiation-induced changes
- Thermal conductivity λ
- Interaction between μ-structure & λ
- Design of λ measurement facility

Thermal conductivity measurement using radial heat flow

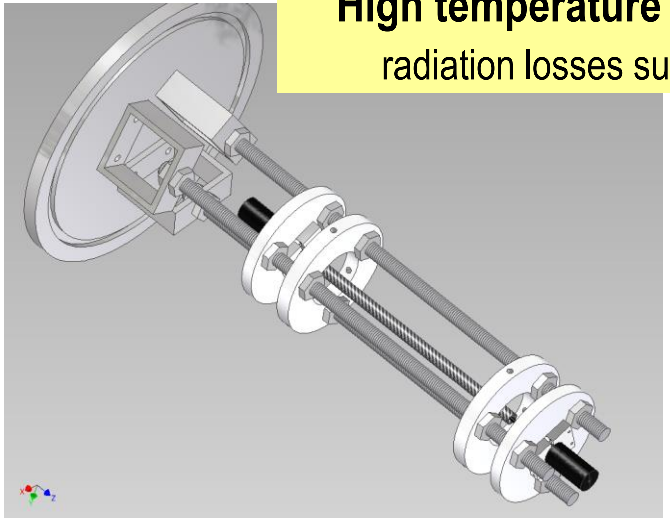
Low temperature setup

forced cooling of the sample outer face using N_2 for sufficiently high T gradient



High temperature setup

radiation losses sufficient



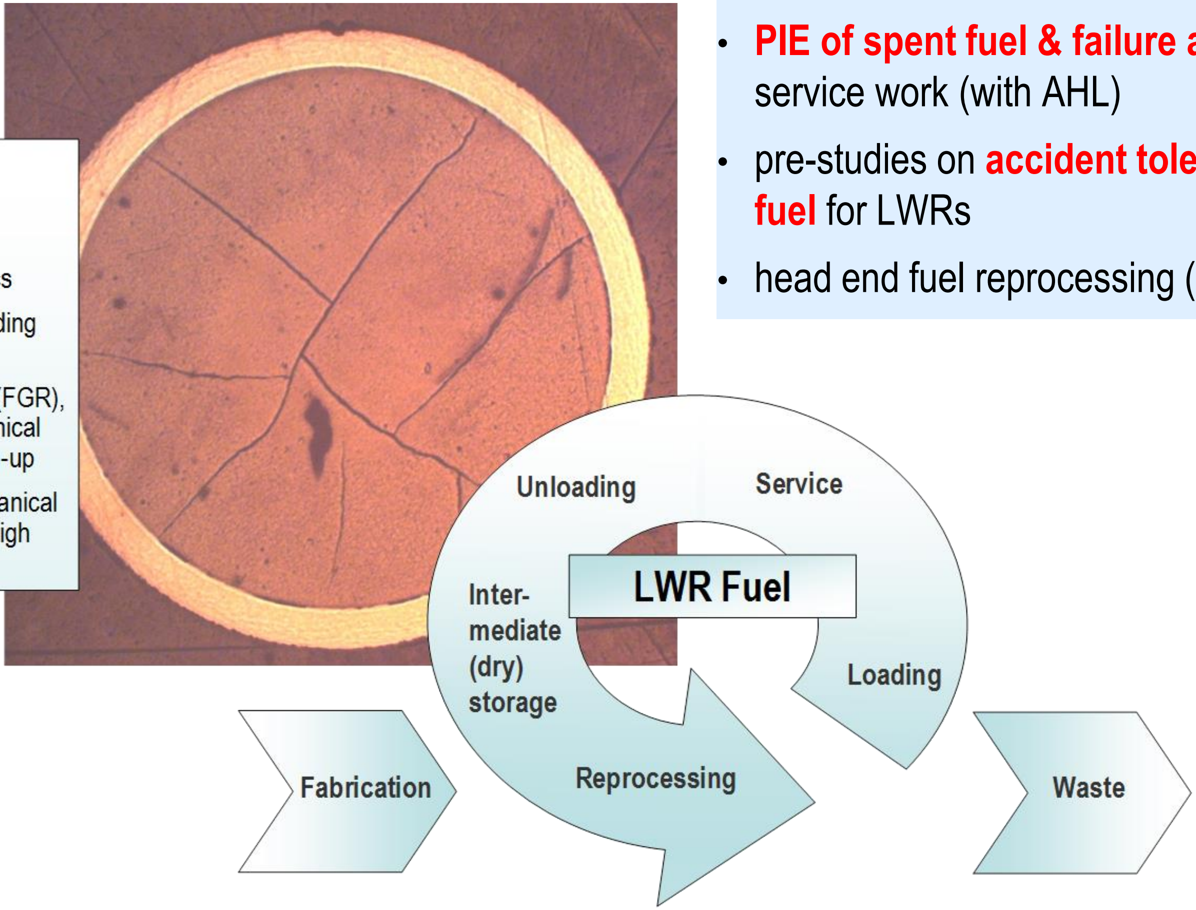
Nucelar Fuels

Fuel life & integrity → core materials issues with respect to **safety & performance**

close collaboration with Swiss utilities (KKL, KKG) & fuel vendors (AREVA, Westinghouse) or international programs (NFIR, SCIP, MUCIZ, …)

- **corrosion & mechanical behaviour** of **cladding** in service & storage
- **fuel element behaviour in service**
- **PIE of spent fuel & failure analysis** as scientific service work (with AHL)
- pre-studies on **accident tolerant fuel** and **Th fuel** for LWRs
- head end fuel reprocessing (in AHL)

• CRUD:	Magnetic properties
• Oxide:	Corrosion, hydrogen uptake
• Cladding:	Hydrogen, mechanics
• Gap:	Isotopes, pellet cladding interaction (PCI)
• Rim:	Fission gas release (FGR), physical and mechanical properties, high burn-up
• Pellet:	FGR, physical/mechanical properties, doping, high burn-up



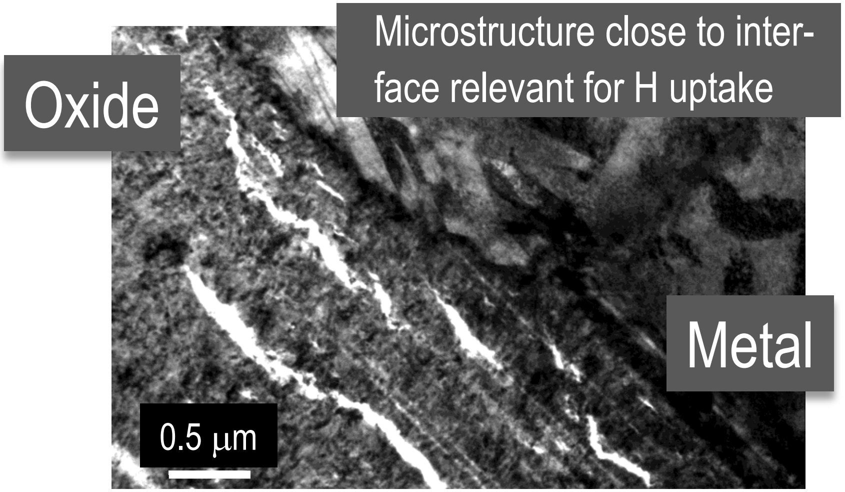
Current Activities in NF

- experimental characterization & modelling of **corrosion & mechanical behaviour** of **cladding** in service, (dry) storage and transport (H uptake, hydride formation, mechanical behaviour, DHC, SPP,…).
- experimental characterization by PIE and modelling of **fuel element behaviour in service** (HBU, doped fuel, crud, PCI, fission gas retention, transport & release, …).
- **PIE of spent fuel & failure analysis** as scientific service work in close collaboration with AHL
- experimental investigations on **head end fuel reprocessing** by thermo-chemical treatment for removal of actinides and fission products by advanced analytical methods and support by kinetic/thermodynamic modelling
- pre-studies on **accident tolerant fuel/cladding** and **Th fuel** for LWRs

Fuel Cladding Projects – Hydrogen Uptake

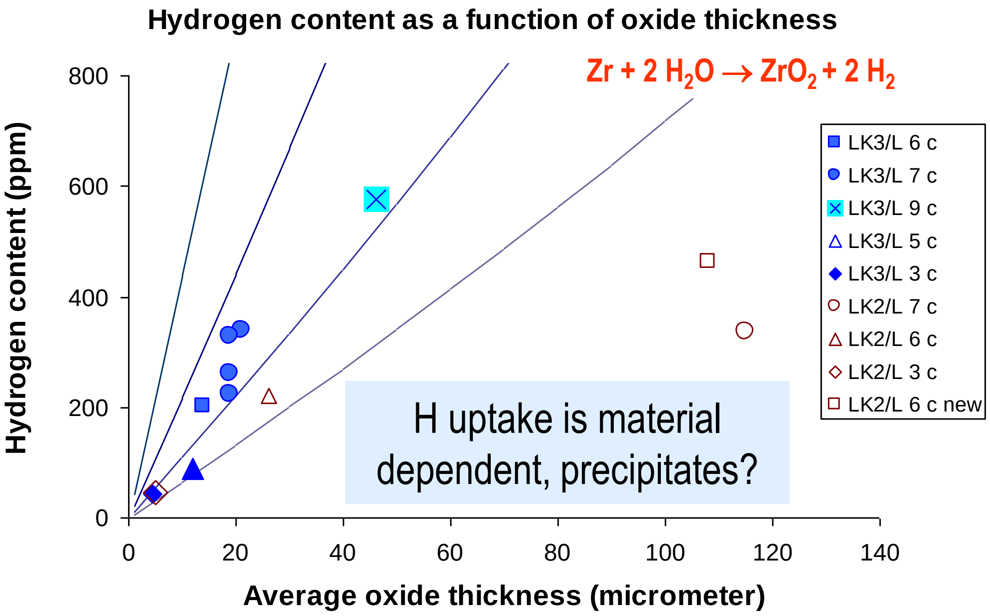
- **Corrosion & mechanical behaviour** of **cladding** in service, (dry) storage and transport
- Hydrogen uptake, hydride formation, mechanical behaviour, DHC, SPP,….

- Nuclear Fuels project investigates H uptake in **irradiated** cladding.
- H affects the **mechanical behaviour** and integrity during transients & transport & in storage
- H uptake as as a function of alloy, elevation, burn-up, number of cycle, oxide thickness, …
- Methods: hotgas extraction, EPMA, SIMS, TEM, metallography, SLS
- Collaboration with **swissnuclear**, **KKL**, **Westinghouse**



Microstructure close to inter-face relevant for H uptake

TEM bright field contrast of metal-oxide interface, LK3/L cladding, 7 cycles (BWR / Leibstadt)



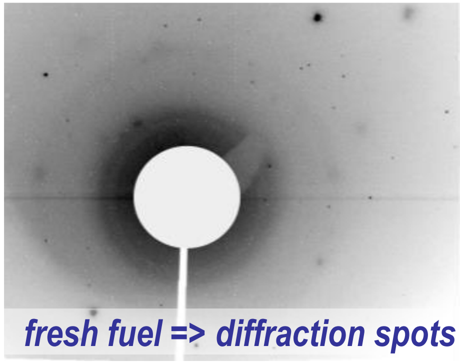
$Zr + 2\,H_2O \rightarrow ZrO_2 + 2\,H_2$

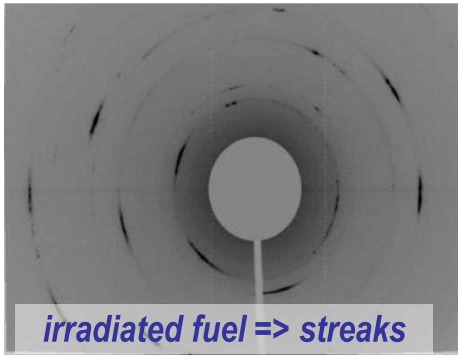
H uptake is material dependent, precipitates?

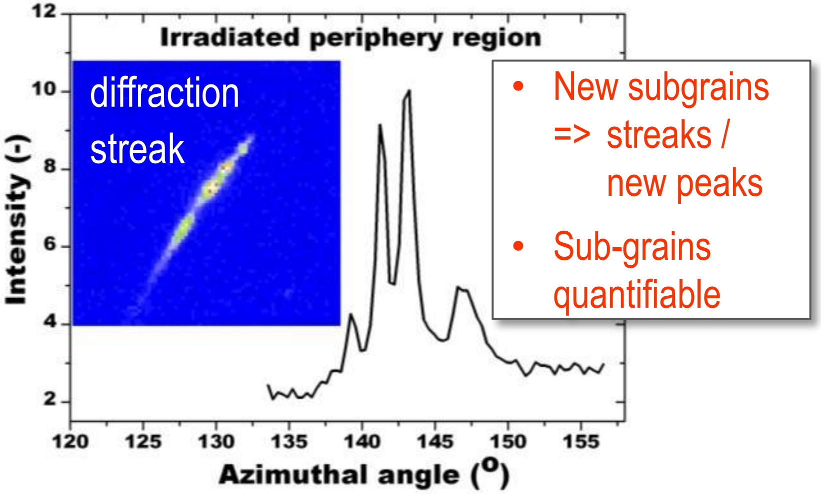
Nuclear Fuels Projects – Material Characterization at SLS

- Characterization by PIE and modelling of fuel element behaviour in service
- HBU, doped fuel, crud, PCI, fission gas retention, transport & release, …
- Pre-studies on accident tolerant fuel/cladding and Th fuel for LWRs

- Performance & safety of nuclear fuel depends on microstructure & crystallography.
- During irradiation fuel changes its structure. Break up of fuel crystallites with increasing burn-up => impact on thermal, physical, mechanical properties.
- For very tiny fuel particles: **crystallographic changes observed at SLS and quantified**.
- Collaboration with hotlab (AHL/NES), μXAS beam line (SLS), industry (swissnuclear, Areva), Université Paris-Sud


fresh fuel => diffraction spots


irradiated fuel => streaks



- New subgrains => streaks / new peaks
- Sub-grains quantifiable

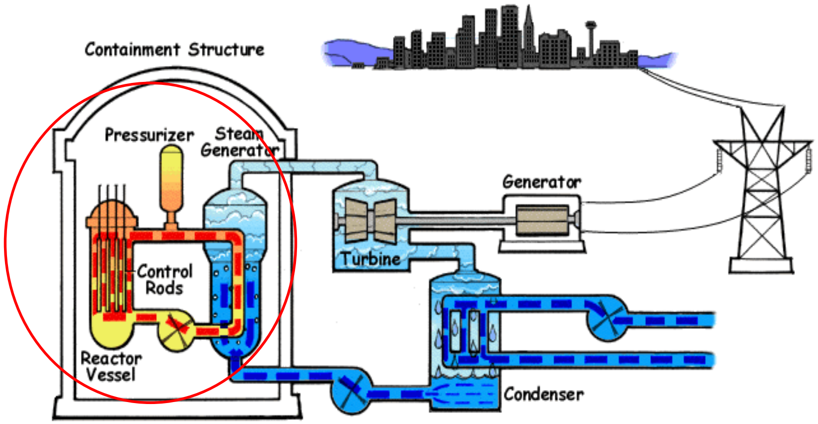
- Practically relevant nuclear material questions with PSI's large-scale facilities
- Leading position with highly radioactive fuel/cladding materials

INTEGER

Scientific contributions to & maintenance of independent expertise in the field of

Safe & efficient LTO of Swiss NPPs in the context of material ageing

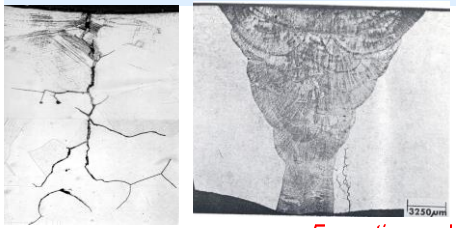
Primary pressure boundary components & reactor internals



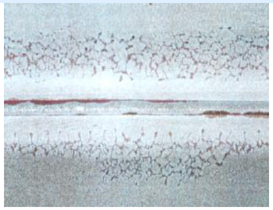
- Critical systems with regard to safety and lifetime (extension)
- Assurance of structural integrity in the context of material ageing a key task

Ageing & degradation mechanism’s

Stress Corrosion Cracking



Thermal Fatigue



→ Formation and growth of cracks

Flow-Accelerated Corrosion

→Wall thinning

→CS (and LAS) with less than 0.2 % Cr

Irradiation Embrittlement

→ Reduction of toughness & ductility

→ Increase of DBTT & brittle fracture risk

- **Ageing & degradation** → characterization & mechanism, mitigation
- **Integrity** → deterministic & probabilistic structural integrity & lifetime assessment
- **Diagnostic** → ND early detection of damage and monitoring of ageing conditions

Current Activities in INTEGER

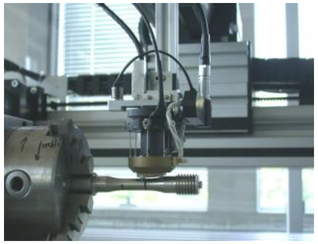
- the quantitative experimental characterization of **critical ageing mechanism** (SCC/IASCC, TMF, irradiation embrittlement) for the **safe long-term operation** and the validation of their potential **mitigation actions** (OLNC/NMCA, HWC)
- the identification of the underlying **degradation mechanism** (fatigue, TMF) and **mechanistic modeling** (CPFEM, meso-scale crystalline plasticity) of the **damage evolution** and their **validation** by **in-situ mechanical testing** at SLS & SINQ (μ-Laue, POLDI) and electron microscopy (ECCI, EBSD, TEM)
- the reliable **prediction of ageing and degradation** (RPV irradiation embrittlement, TMF) with deterministic and probabilistic engineering structural, fracture and damage mechanics methods and their experimental **validation** under simulated **realistic operational conditions** to further reduce undue conservatism or uncertainties in lifetime prediction and safety assessments and better estimation of **safety margins**.
- the development and evaluation of **advanced in-service inspection** and continuous **monitoring techniques** (magnetic, thermoelectric, ECN) for the detection, characterization and evaluation of **degradation and ageing** (SCC, TMF, irradiation embrittlement), in particular in the technical pre-crack stage and in aged components.

Tools operated, co-operated or used by LNM

Microscopy

- FEG-SEM / EBSD& EDX, SEM/EDX
- TEM, FIB, *shielded FIB/SEM*
- LM & SM, metallography

ND Diagnostics



- Magnetic methods (EC, 3 MA, GMR, SQUID, Ferromaster)
- Electric & thermoelectric methods

Beam Line Techniques

- **SLS:** EXAFS, XAS, XRD, in-situ testing with μ-LD, …
- **SINQ:** STIP, ND, residual stress,

Broad spectrum of tools for chemical & microstructural or mechanical & physical properties characterization of in-active and highly radioactive specimens(bulk, surface, local)

Corrosion Testing

- 9 HT-water loops with autoclaves with loading systems. Static autoclaves.
- Crack initiation & growth monitoring
- HT electrochemistry (ECN, IS, RE).

Mechanical Testing

- **Inactive:** TMF, HCF, LCF, impact, tensile, creep, hardness, μ-hardness, furnaces, hydrogenation facility, DIC.
- **Active:** Tensile, LCF, n-intender, small punch, drop tower, in-situ irradiation creep.

Hot Laboratory (AHL)

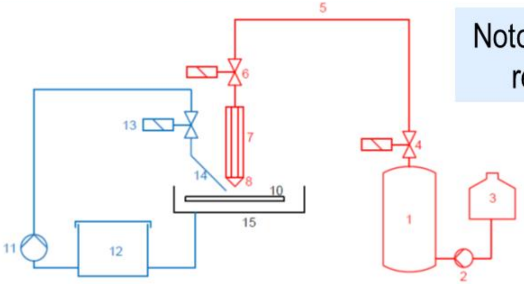
- **LA ICP-MS, EPMA, SIMS**
- **Active metallography & sample preparation**
- **γ-spectrometry, fission gas analyzer**

Examples of Unique Facilities

Cyclic TMF Facility with Biaxial Pre-Loading (INTEGER)

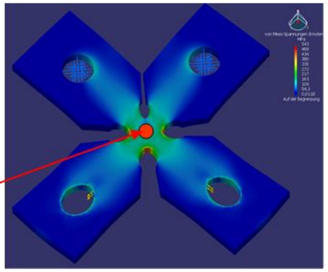
Cyclic thermal shocks by hot steam & cold water with specimen heating option

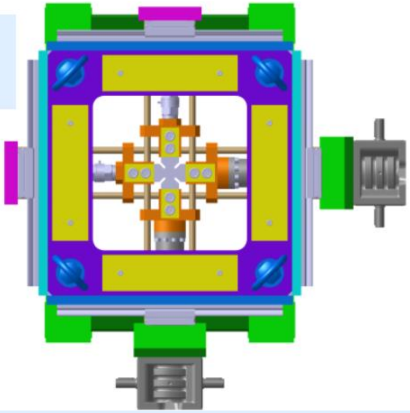
Controlled indepdendent biaxial pre-loading



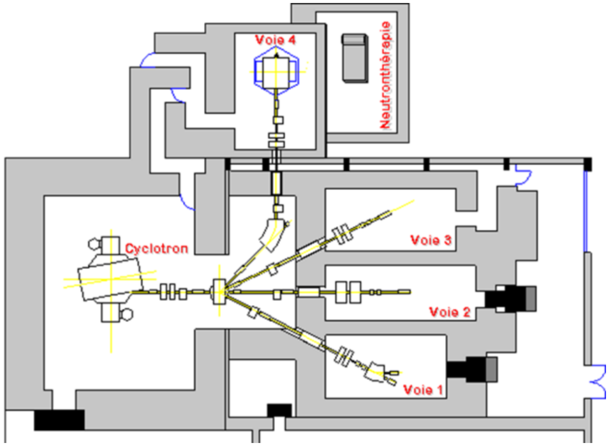
location with thermal shocks

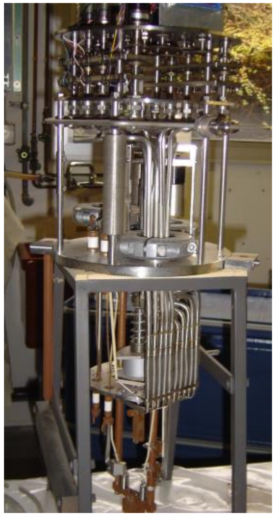
Notched cruciform specimen with reduced thickness in center

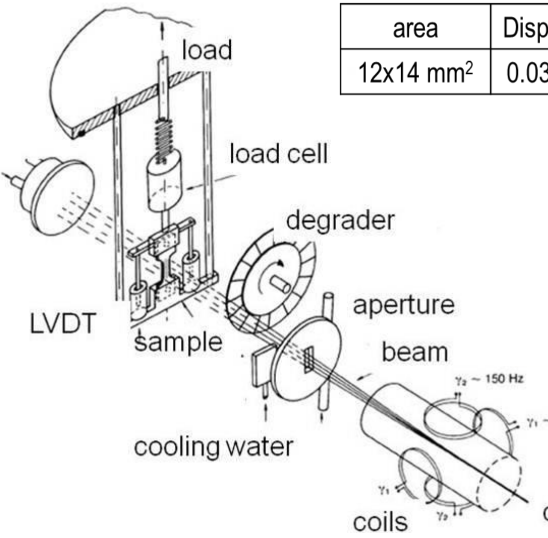




Facility for In-Situ Creep under Irradiation at CRNS / CEMHTI (ANM)







area	Dispal. rate	Impl. rate	T (° C)
12x14 mm^2	0.03 dpa/h	150 appm-He/h	150-1000

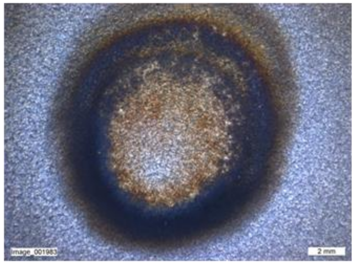
Ions	Energy (MeV)	Intensity (µA)	Range (µm)
p	5--38	15	2800
H_2^+	5--25	13	380
d	5--25	40	760
α	10--50	15	380
^{3}He	10--50	15	470

- $\Delta\varepsilon \sim 10^{-5}$
- $\Delta T = \pm 2°$ C

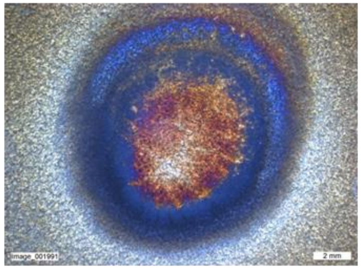
Crack Network Formation due to Cyclic Thermal Shocks

Crack network formation due to cyclic thermal shocks (ΔT=160 °C, 1Hz, H_2O)

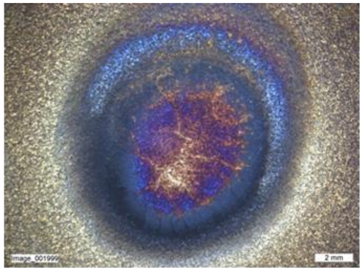
0 cycles



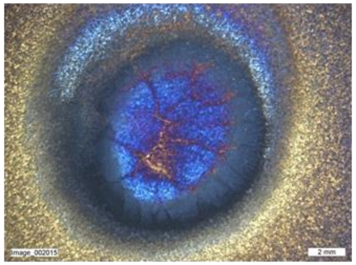
150 kc



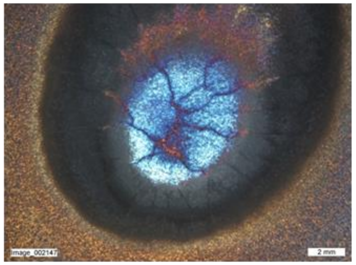
400 kc



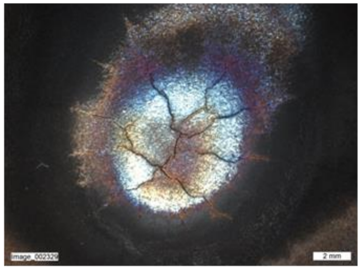
1050 kc



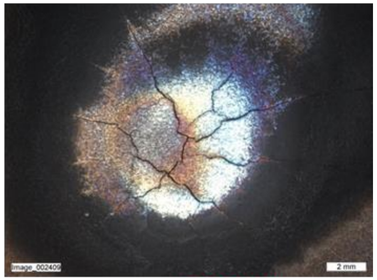
1950 kc



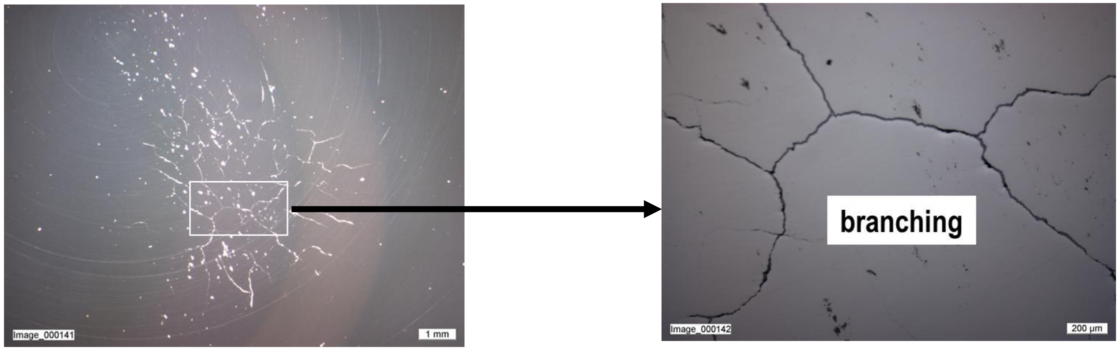
2450



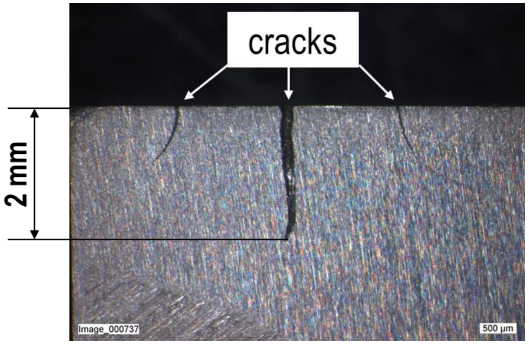
3000 kc



3300 kc



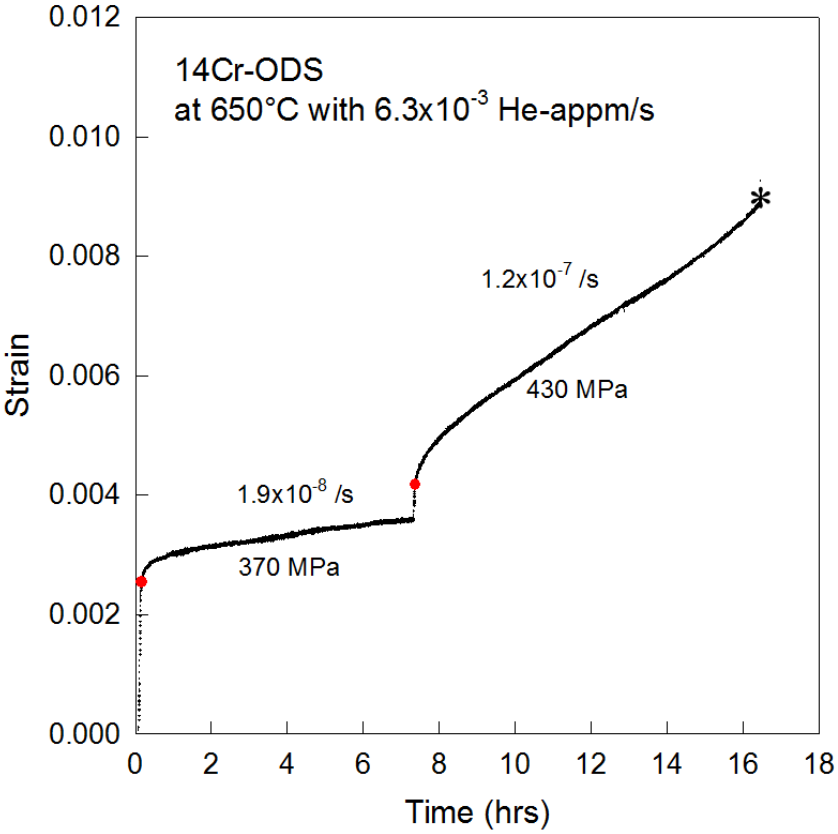
branching



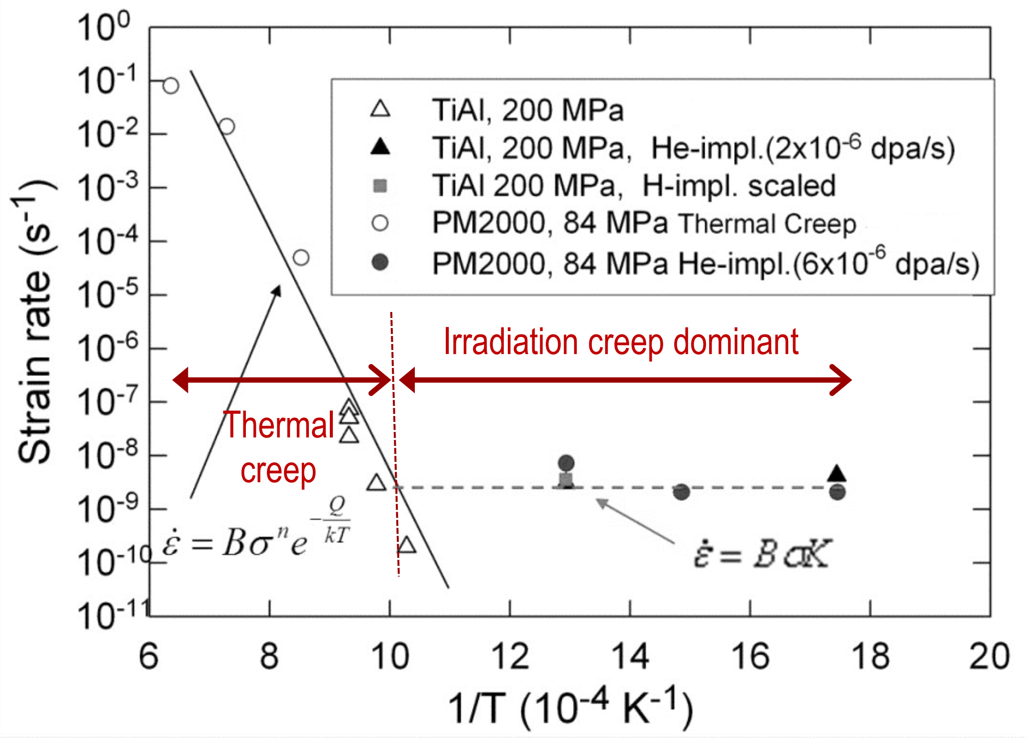
cracks

Irradiation Creep of GEN-IV Candidate Materials

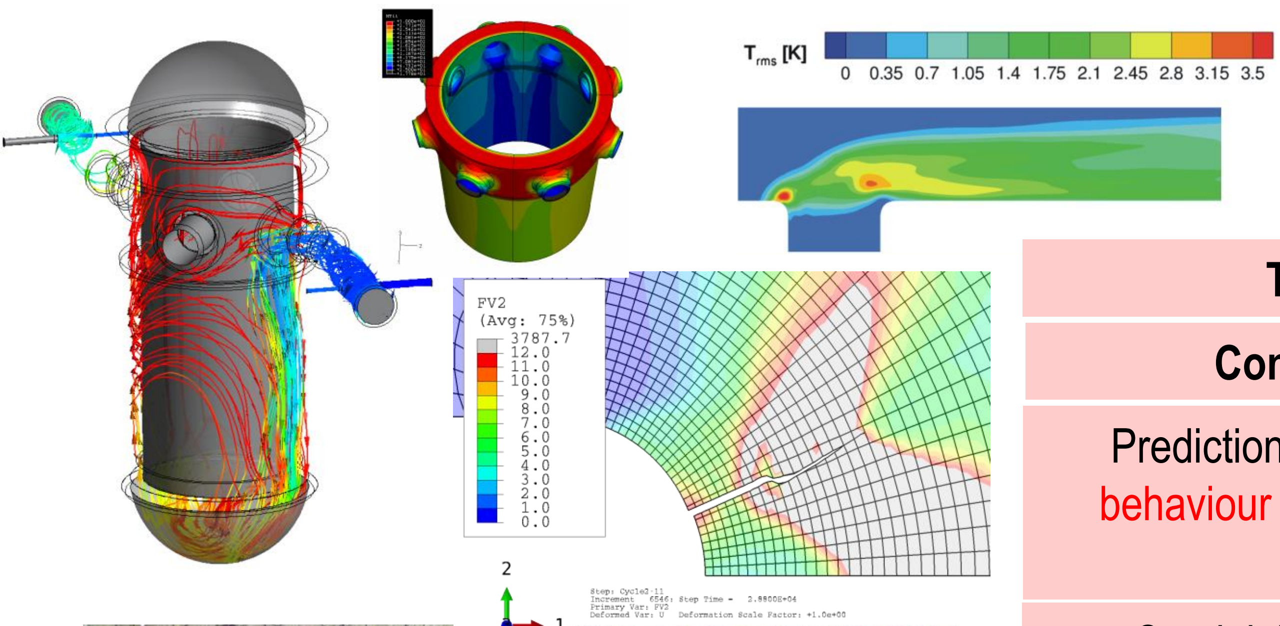
Creep strain of 14Cr ODS during He-implantation at 650°C

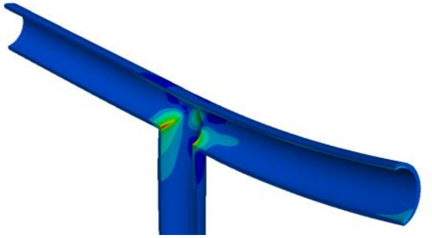


Thermal & irradiation Creep in TiAl and ODS



Modeling Activities and Tools in LNM



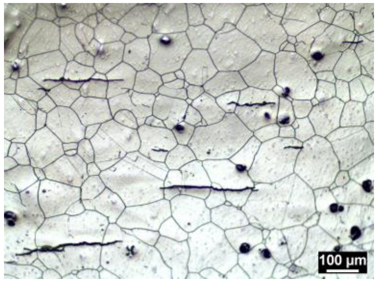


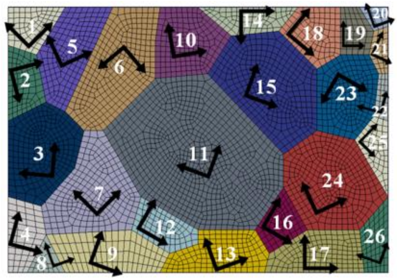
Top-down approach

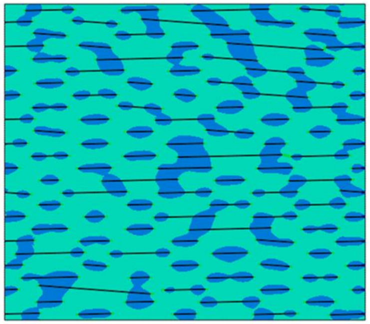
Continuum to meso scale

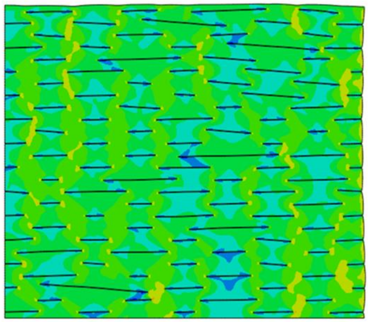
Prediction & assessment of mechanical behaviour and of integrity and lifetime on component level

Crack initiation & growth, fracture, …
RPV irradiation embrittlement, TMF, hydride in Zr-alloy,…









- FEM & X-FEM
- Deterministic & probabilistic methods
- Meso-Scale Field Dislocation Mechanics (MFDM)
- Cristal plasticity (CPFEM)
- Coupling of TH / CFD & SM

- *ABAQUS, FAVOR (ORNL), PASCAL (JAERI)*
- *CFX, FLUENT*
- *CP-FEM (MPI-E), PMFDM (U-Illinois)*

Crystal Plasticity FE Modeling of Fatigue

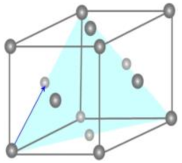
PhD thesis of N. Grilli (SNF-DFG, 2012-15), Supervisor: Dr. K.Janssens , Prof. H. Van Swygenhoven (EPFL/PSI)

Goal

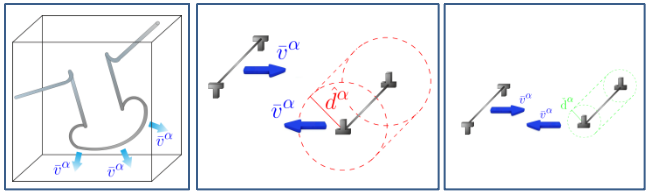
- Development & validation of new **dislocation-based constitutive equations** for **cyclic plasticity** within the **DAMASK** Crystal Plasticity FE code of MPI-E
- Description of the material behavior at a length scale smaller than dislocation structures under cyclic fatigue.

Continuum crystal plasticity model with consideration of different dislocation types & processes

Slip system dynamics



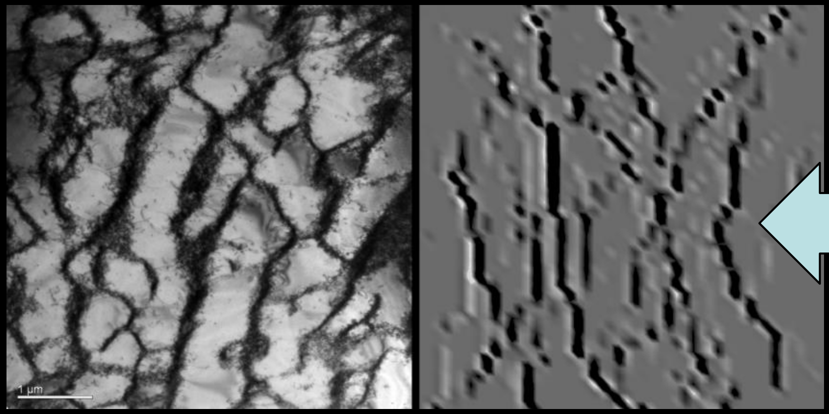
Dislocation processes



Simulation of cyclic shear test of single crystal (small volume: 10 μm, elements: 100 nm)

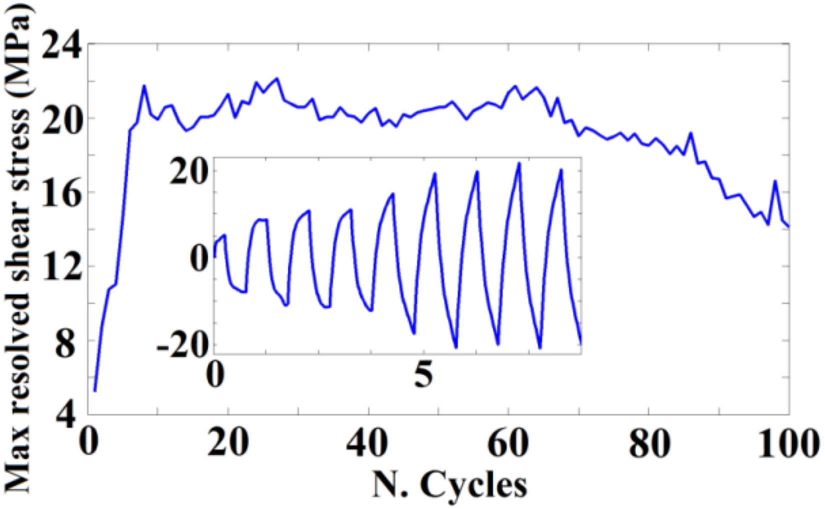
Capability to reproduce nucleation & growth of vein & channel structures from random dislocation distributions

Prediction of cyclic hardening and subsequent softening (owing to deformation localization in the softer channels)



Vein and Channel Dislocation Structures in Austenitic Stainless Steel as observed in Transmission Electron Microscopy and as Simulated using Crystal Plasticity Finite Elements - G Facheris - M-S Pham - N Grilli - K G F Janssens

1 : 1

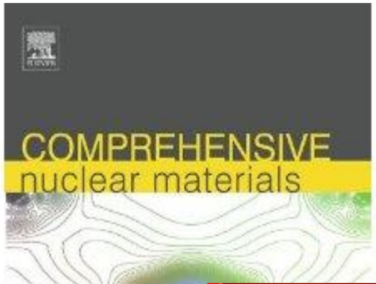


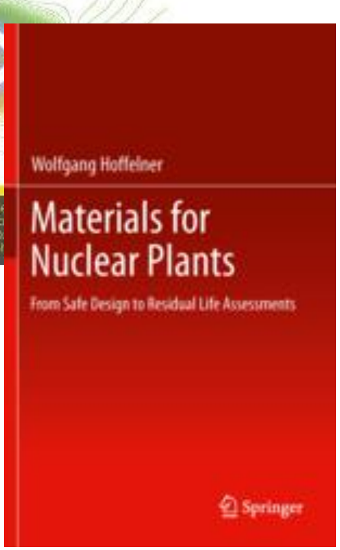
Education & Teaching Activities

- **10 PhD** and **8 PoD running projects** in LNM
- Contribtuion to **ETHZ/EPFL NE Master** by lectures & master projects
- **EPFL Doctoral School in MS & E and Physics** by lectures
- Contribution to **swissnucelar/PSI education course Kerntechnik**
- Other university teaching (Uni Geneva, …), summer schools, tutorials
- Textbooks and reference books on nulcear materials

Nuclear Materials Workshop

EPFL Doctoral School in MS & E, Course MSE-600, Effects of Radiation on Materials **by LNM**



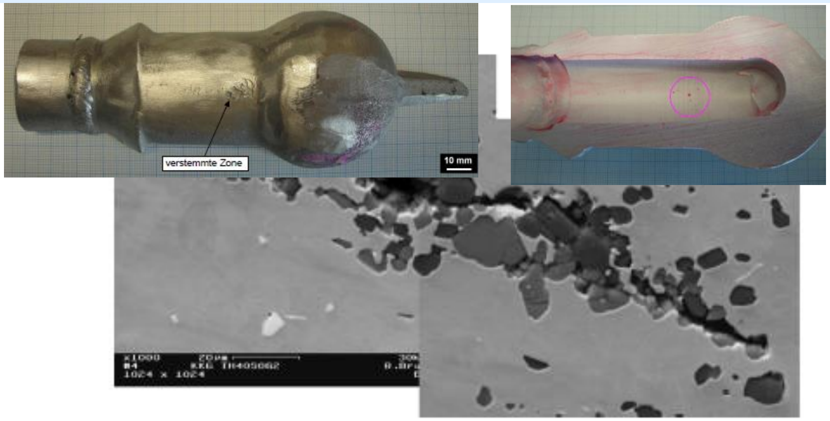


Staudinger-Durrer Medaille 2012 of MS Department of ETHZ for **W. Hoffelner**

Examples of External Services

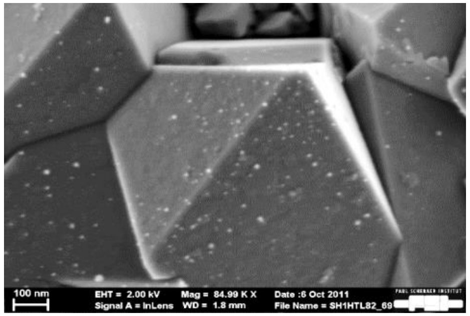
- Expertise on KATAM (basic document of ageing management) for ENSI
- Expertise on SCC of SS for ENSI
- Consulting for CH NPPs (e.g., Overlay repair welding of SCC in feedwater nozzle in KKL)

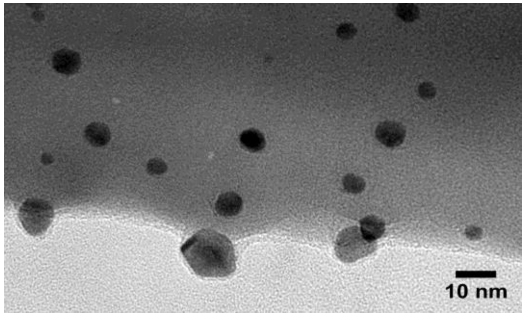
Failure analysis of leaking valve for KKG

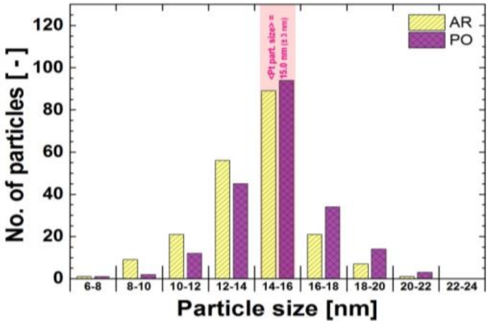


NDT test bodies with fatigue cracks in SS welds for KKG

Pt particle analysis for KKL, KKM, Cofrentes & EPRI, YUMOD







Scientific support of PIE & failure analysis in hotlab

Major National Collaborations

- **PSI:** MSS/NUM (STIP, in-situ-mechanical testing), NUM, BIO, SYN, ENE (joint operation of facilities: EMF, SEM; SLS), NES (AHL, LTH, LRS)
- **ENSI**

  Mainly through research projects (SAFE, PISA, NORA, …) and to a lesser extent through expertise/consulting work
- **CH-NPPs**

  Mainly through swissnuclear research projects (BGM, BGB) and scientific service work (PIE of fuel, failure analysis, expertise, consulting, …)
- **ETH Domain (ETHZ, EPFL, EMPA)**

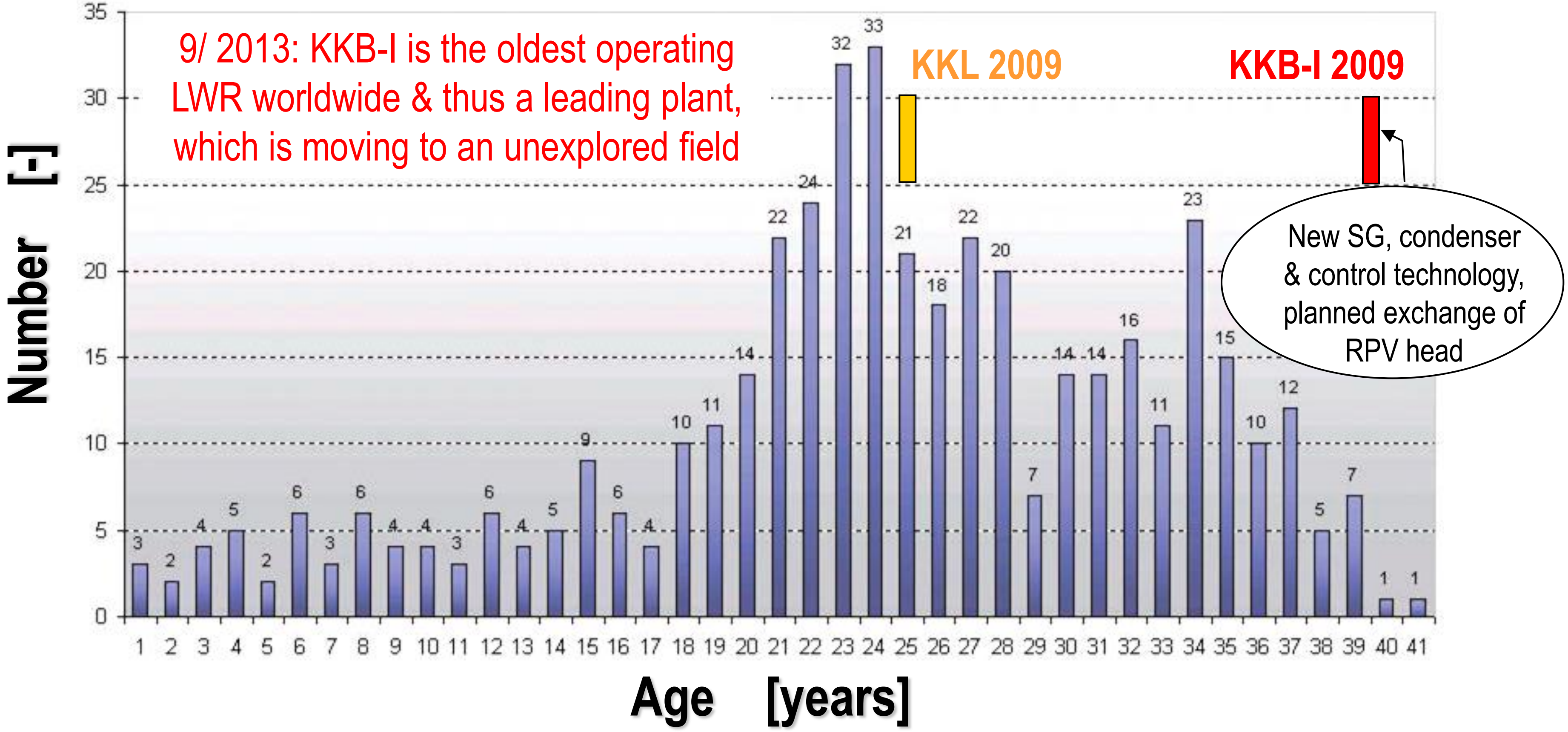
  Mainly through PhD & master thesis‘s, the NE Master Course and the Competence Centres for Energy & Mobility (CCEM) and Materials Science & Technology (CCMX) (& *National Competence Centers in Research (NCCR)?)*

Examples of International Collaborations

- **Networks & international organizations:** NUGENIA, ETSON, ESNII, GIF, EERA ICG-EAC, IGRDM, ECG-COMON, IFRAM, EFC-WP4, OECD/CSNI/NEA, IAEA, ASME, …
- **EU-7 & Horizon 2020:** ARCHER, MATTER, ASGAARD, PELGRIM, GETMAT, MATISSE, *INCEFA+, SOTERIA, FALSTAFF, …*
- **Universities:** Tohoku, Erlangen, Glasgow, INSA de Lyon, Carnegie Mellon, Wupperthal, Grenoble, Valencia, UCSB, …
- **Institutes:** VTT, ORNL, SNL, MPI, CEA, Halden, FZK, CRNS Orleans, Charkow, Kurtschatow, MPI, KIT, …
- **Authorities:** JNES, US NRC, SKI
- **Industry:** EPRI (NFIR, BWRVIP), Westinghouse, STUDSVIK, AMEC, SIMPELKAMP, IPS, …
- **STIP & MEGAPIE:** CEA, JAEA, LANL, ORNL, KAERI, ENEA, SCK, ESS, IMP/CAS, …

Selected examples of current material ageing related activities & highlights

Number of Operating LWRs by Age (January 2008)



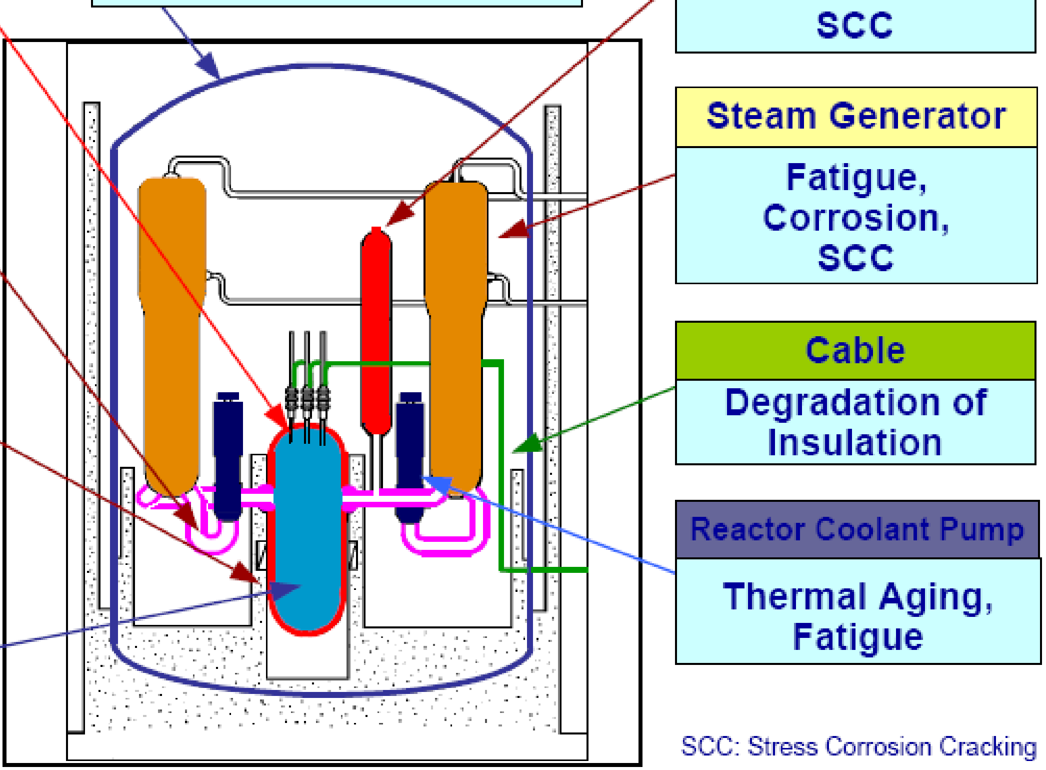
9/ 2013: KKB-I is the oldest operating LWR worldwide & thus a leading plant, which is moving to an unexplored field

New SG, condenser & control technology, planned exchange of RPV head

- Original design lifetime of Gen-II LWRs was 30 to 40 y (rather legally than technically motivated, related to maximum insurance period in USA at that time). No legal limitation of lifetime in CH.
- Lifetime extension up to 50 to 60 y, 80 year lifetime under discussion in the USA
- Besides the design lifetime, there is also a license, technical and economical lifetime

Major Ageing & Degradation Mechanism in PWRs

Major Aging Phenomena of Major Components and Structures (PWR)



Reactor Vessel
Irradiation Embrittlement, Fatigue, SCC

Primary Containment Vessel
General Corrosion

Pressurizer
Fatigue, SCC

Main Coolant Piping
Fatigue, Thermal Embrittlement

Steam Generator
Fatigue, Corrosion, SCC

Concrete Structures
Strength Degradation and Shielding Performance degradation

Cable
Degradation of Insulation

Reactor Internals
Irradiation Assisted SCC, Irradiation Embrittlement

Reactor Coolant Pump
Thermal Aging, Fatigue

SCC: Stress Corrosion Cracking

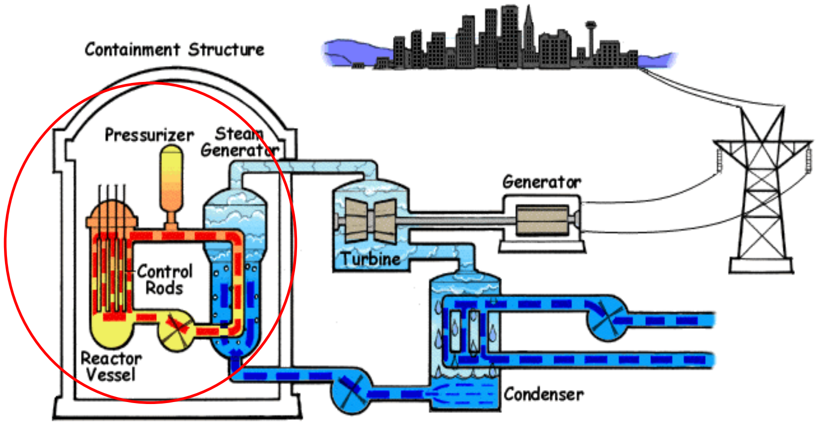
Material ageing in mechanical components, buildings and control & process technology!

INTEGER

Scientific contributions to & maintenance of independent expertise in the field of

Safe & efficient LTO of Swiss NPPs in the context of material ageing

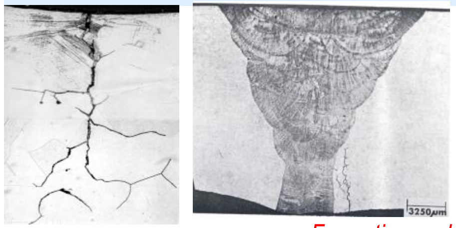
Primary pressure boundary components & reactor internals



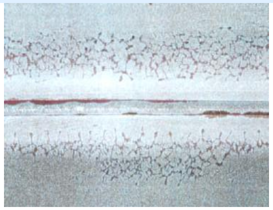
- Critical systems with regard to safety and lifetime (extension)
- Assurance of structural integrity in the context of material ageing a key task

Ageing & degradation mechanism’s

Stress Corrosion Cracking



Thermal Fatigue



→ Formation and growth of cracks

Flow-Accelerated Corrosion

→Wall thinning

→CS (and LAS) with less than 0.2 % Cr

Irradiation Embrittlement

→ Reduction of toughness & ductility

→ Increase of DBTT & brittle fracture risk

- **Ageing & degradation** → characterization & mechanism, mitigation
- **Integrity** → deterministic & probabilistic structural integrity & lifetime assessment
- **Diagnostic** → ND early detection of damage and monitoring of ageing conditions

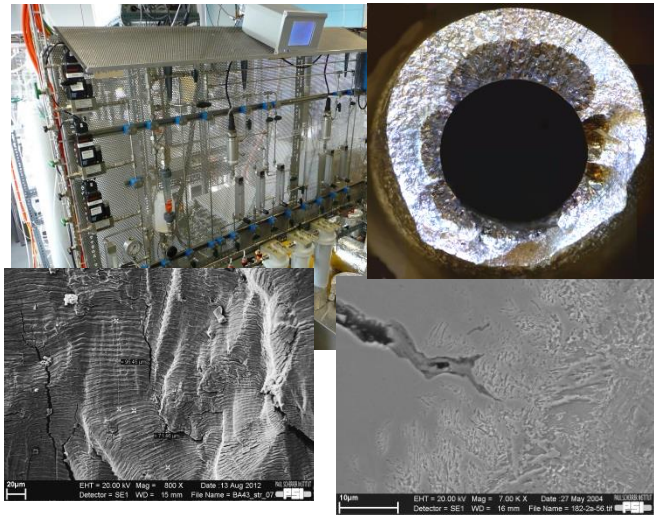
Major Activities in INTEGER Research Program

Material Ageing

Characterization, Mechanism's

- Environmentally-assisted cracking
- Thermal fatigue
- Irradiation embrittlement

- *Basic understanding, mechanisms*
- *Quantitative data for engineering integrity & lifetime assessment*
- *Model validation*
- *Evaluation of mitigation actions*

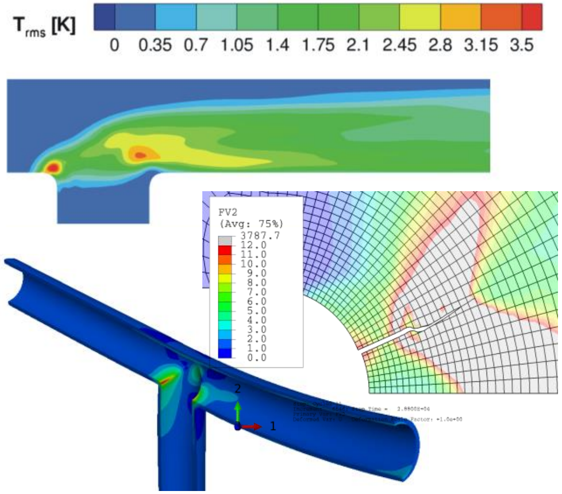


Structural Integrity

Modeling, Assessment

- RPV integrity & safety
- Thermal fatigue

- *Development of advanced mechanistic material ageing models*
- *Deterministic & probabilistic integrity assessments & lifetime prediction*
- *Elimination of uncertainties and undue conservatism*
- *Quantification of safety margins*

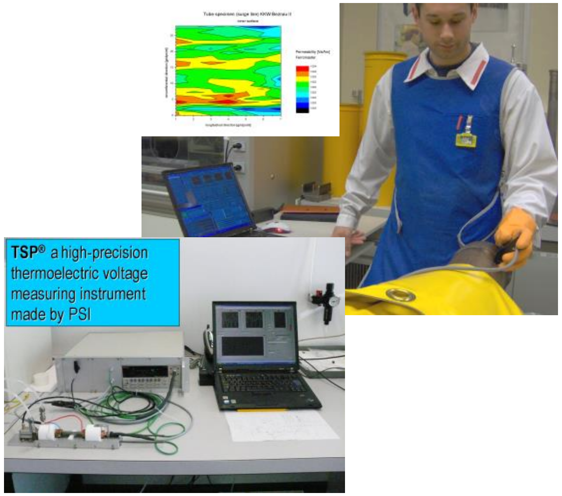


ND Diagnostic

Early Detection, Monitoring

- Irradiation embrittlement
- Stress corrosion cracking
- Thermal fatigue

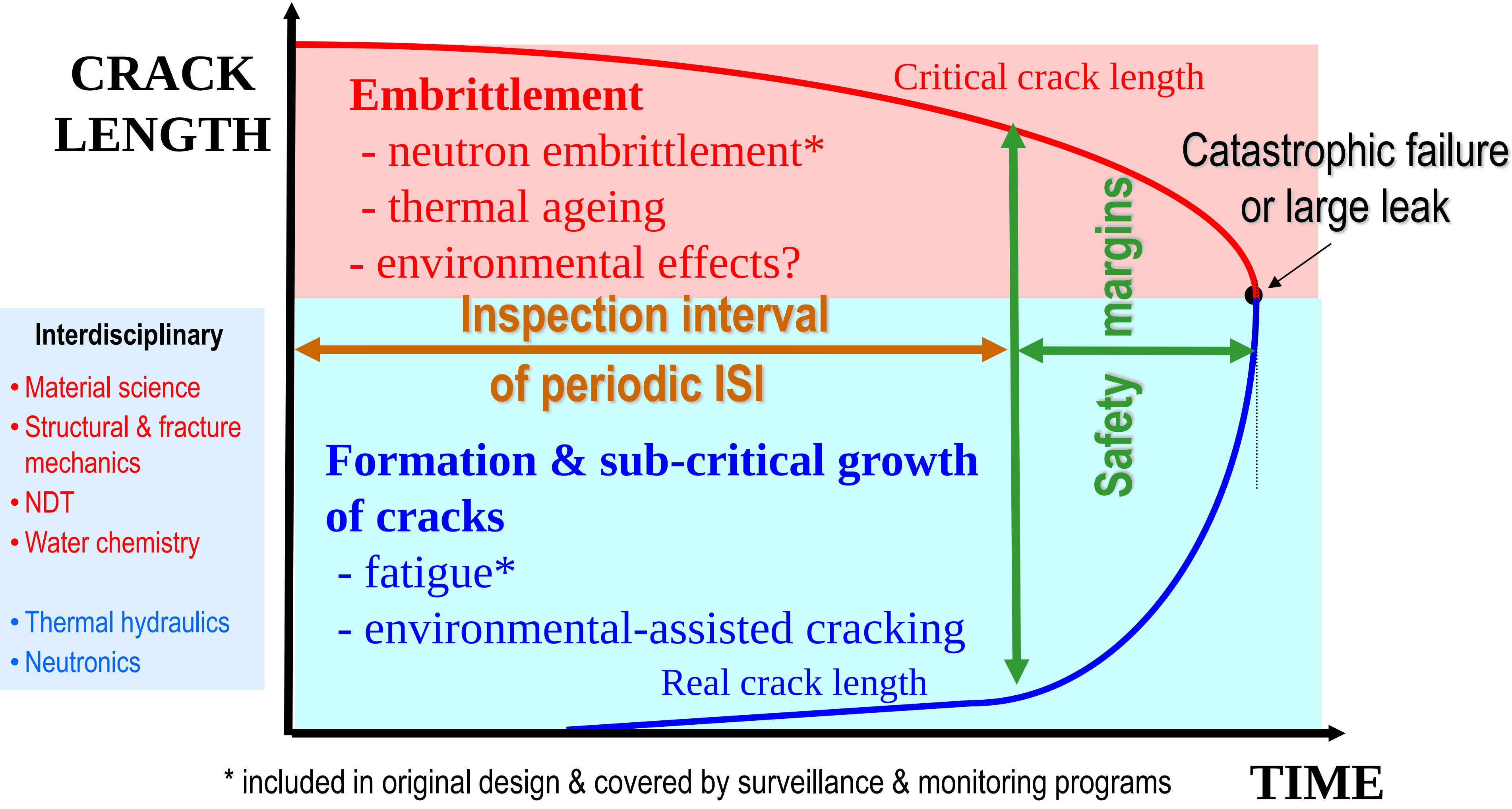
- *Evaluation of advanced ND in-service inspection & monitoring techniques for material ageing*
- *Early detection of SCC & TMF in technical pre-crack stage*
- *ND characterization of degree of irradiation & thermal embrittlement*


TSP® a high-precision thermoelectric voltage measuring instrument made by PSI

Current Activities in INTEGER

- the quantitative experimental characterization of **critical ageing mechanism** (SCC/IASCC, TMF, irradiation embrittlement) for the **safe long-term operation** and the validation of their potential **mitigation actions** (OLNC/NMCA, HWC)
- the identification of the underlying **degradation mechanism** (fatigue, TMF) and **mechanistic modeling** (CPFEM, meso-scale crystalline plasticity) of the **damage evolution** and their **validation** by **in-situ mechanical testing** at SLS & SINQ (μ-Laue, POLDI) and electron microscopy (ECCI, EBSD, TEM)
- the reliable **prediction of ageing and degradation** (RPV irradiation embrittlement, TMF) with deterministic and probabilistic engineering structural, fracture and damage mechanics methods and their experimental **validation** under simulated **realistic operational conditions** to further reduce undue conservatism or uncertainties in lifetime prediction and safety assessments and better estimation of **safety margins**.
- the development and evaluation of **advanced in-service inspection** and continuous **monitoring techniques** (magnetic, thermoelectric, ECN) for the detection, characterization and evaluation of **degradation and ageing** (SCC, TMF, irradiation embrittlement), in particular in the technical pre-crack stage and in aged components.

Structural Integrity of Primary Pressure Boundary Components



* included in original design & covered by surveillance & monitoring programs

→ Ageing and lifetime management to assure adequate margins over whole lifetime

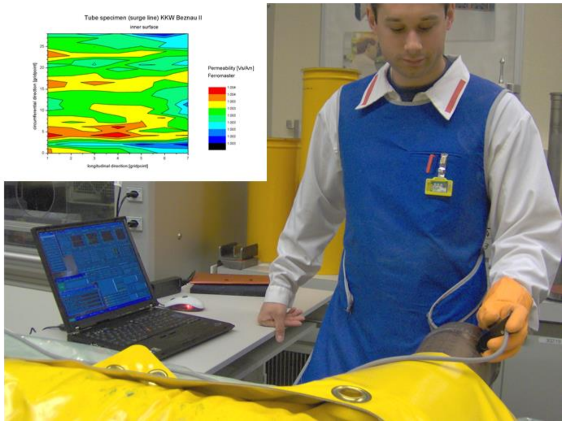
INTEGER/BTS Activities in Hotlab

- Active NobleChem samples from KKL in the frame of the NORA project
- He effects on IASCC of SS (swissnuclear PhD thesis)
- Effects on radiadation damage & He on fracture (SNF PhD thesis)
- NDT & diagnostic of ageing
- Failure analysis

EPFM & mechanical tests with non-standard samples

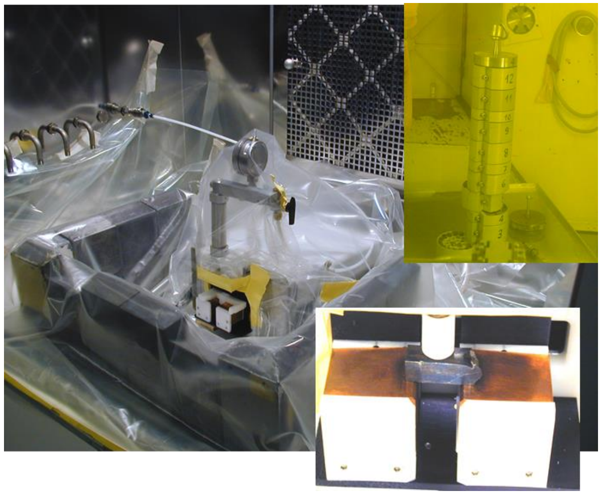
- STIP-V samples
- EUROFER, ODS

Magnetic measurements on exchanged NPP components with TF



- Pressurizer spray line, surge line
- Thermal sleeve / CRD nozzle

TEP measurements on irradiated surveillance specimens

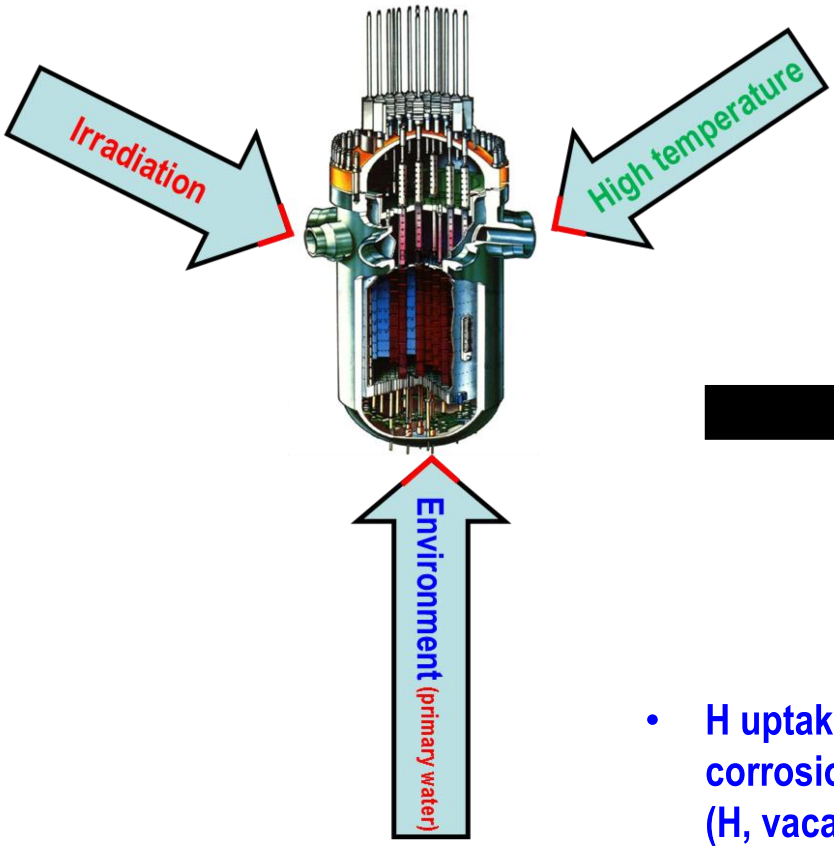


- Surveillance specimens
- JRQ material from IAEA CRP's

Material Ageing

Characterization, Mechanism‘s & Mitigation

RPV Integrity & Material Ageing



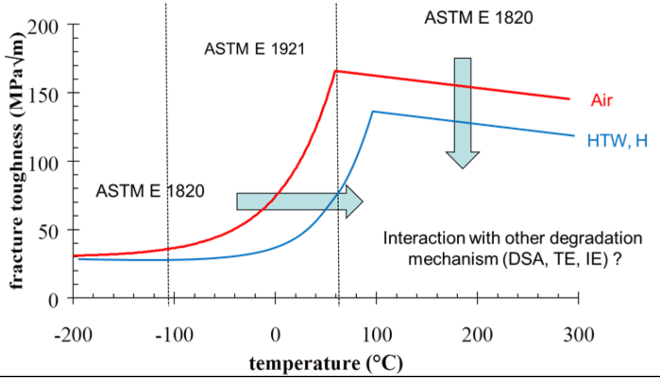
- Surveillance programs
- PTS analysis

→ *PISA*

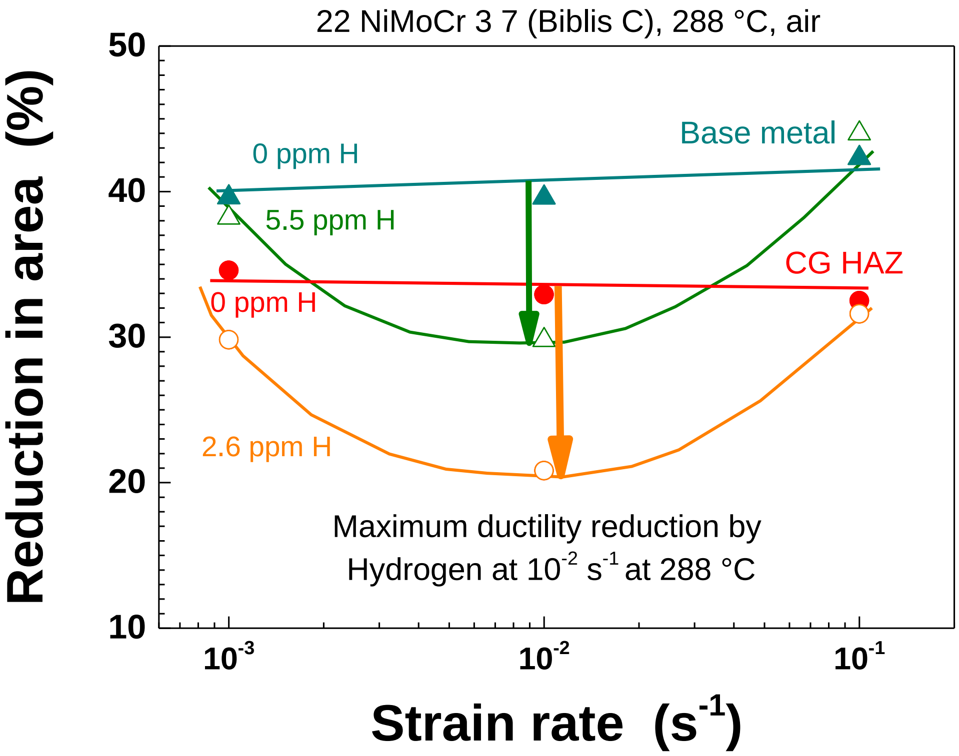
- Irradiation embrittlement
- Thermal aging, DSA
- Environmental effects

- H uptake (corrosion, environment) & corrosion-deformation interactions (H, vacancies)
- Loss in fracture toughness & tearing resistance → *SAFE-I & II*
- Reduction in resistance to unstable brittle failue (DBTT-shift)? → *SAFE-II*
- Synergies with irradiation embrittlement, DSA or TE?

- Sub-critical crack growth: SICC, CF, SCC → *RIKORR, KORA & SAFE*
- Boric acid corrosion, FAC

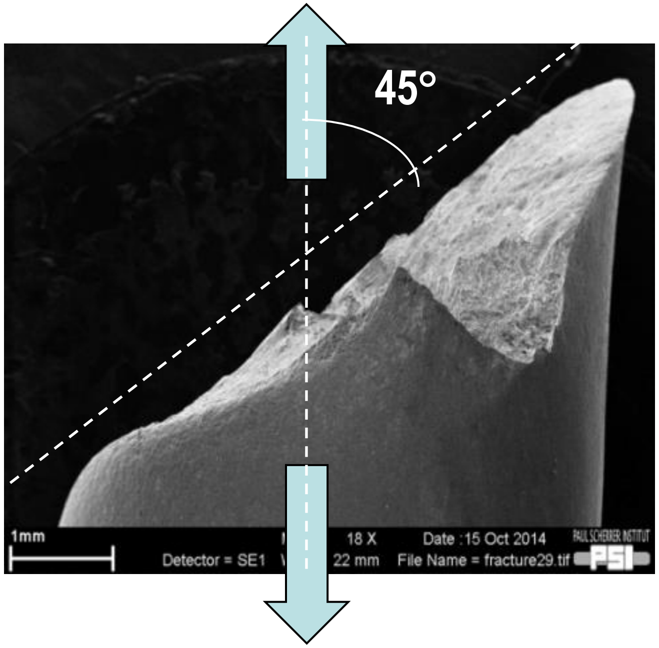


Effect of H on Mechanical Behaviour in Tensile Tests



Maximum ductility reduction by Hydrogen at 10^{-2} s^{-1} at 288 °C

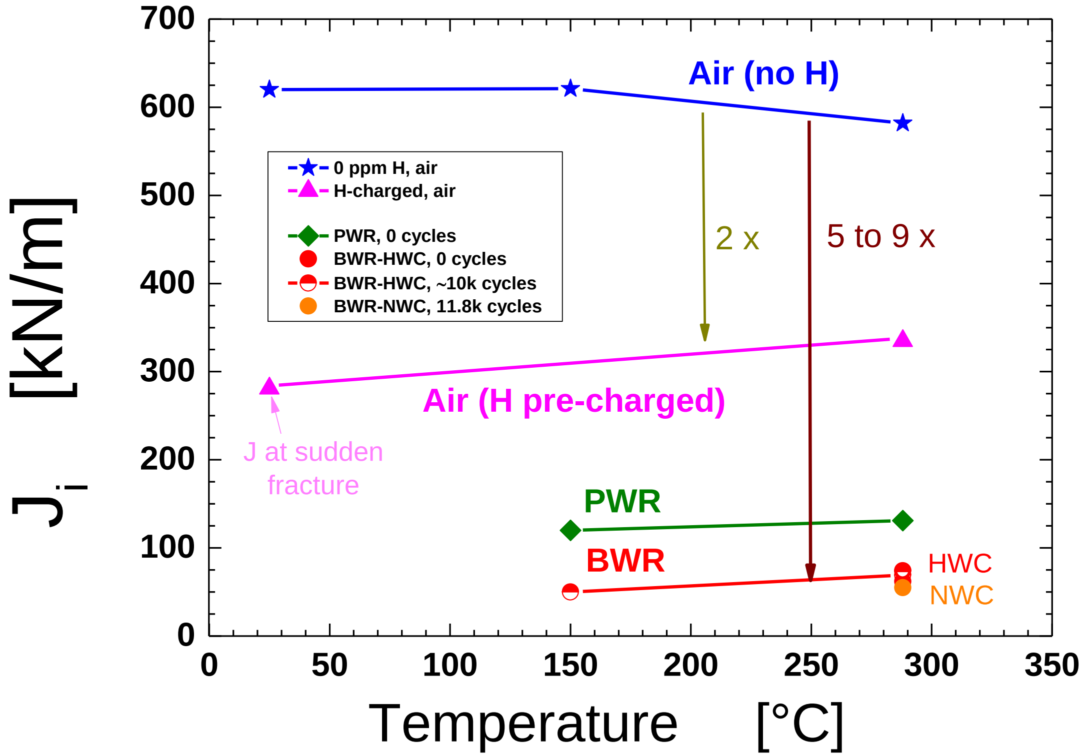
Ductile shear fracture in presence of H



- 1.5 to 5 ppm H in RPV steel resulted in embrittlement in tensile tests in air both at 25 and 288 °C
- Embrittlement was more significant at 25 °C and at higher H concentrations
- Maximum effects were observed at strain rates of 10^{-5} to 10^{-4} s^{-1} at 25 °C and 10^{-3} to 10^{-2} s^{-1} at 288 °C
- CG HAZ is more susceptible than the base metal.

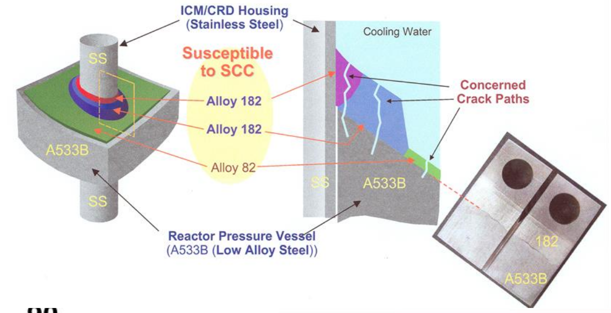
Effect of H & HT Water on Fracture in EPFM Tests

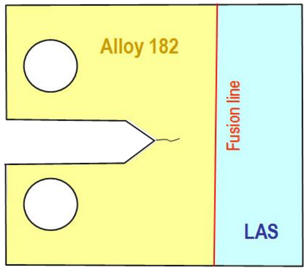
22 NiMoCr 3 7, base metal, (Biblis C) $dCOD_{LL}/dt$ = 0.25 to 0.35 mm/min



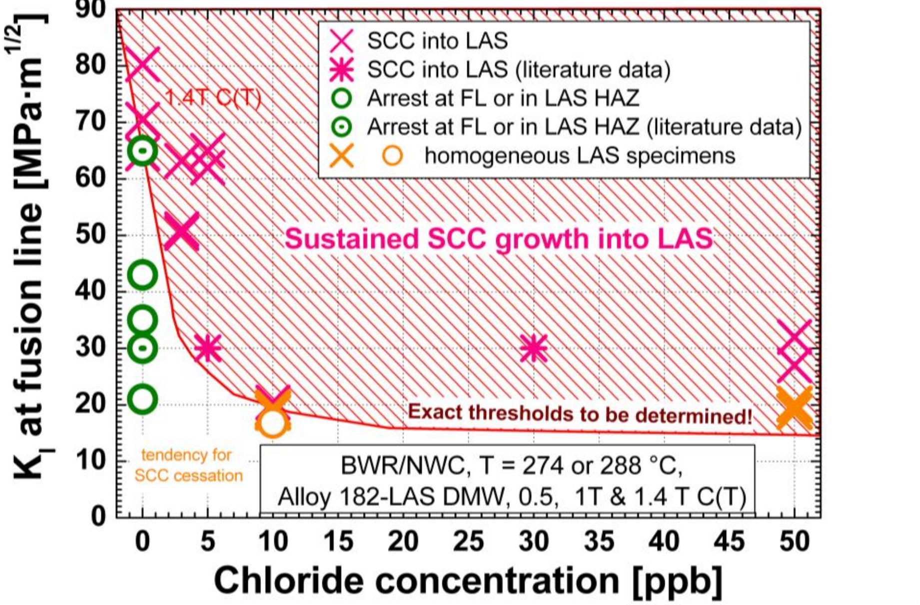
- Moderate reduction of upper shelf initiation fracture toughness by H in air at 288 °C
- Exposure to HTW at 150 and 288 °C resulted in a significant toughness reduction
- Similar toughness reduction in oxygenated, hydrogenated & nitrogenated high-temperature water → dominant effect of corrosion H uptake?
- At 150 & 288 °C, fracture occurred by stable "ductile" crack growth. So far, rapid, unstable crack growth in CGHAZ only.

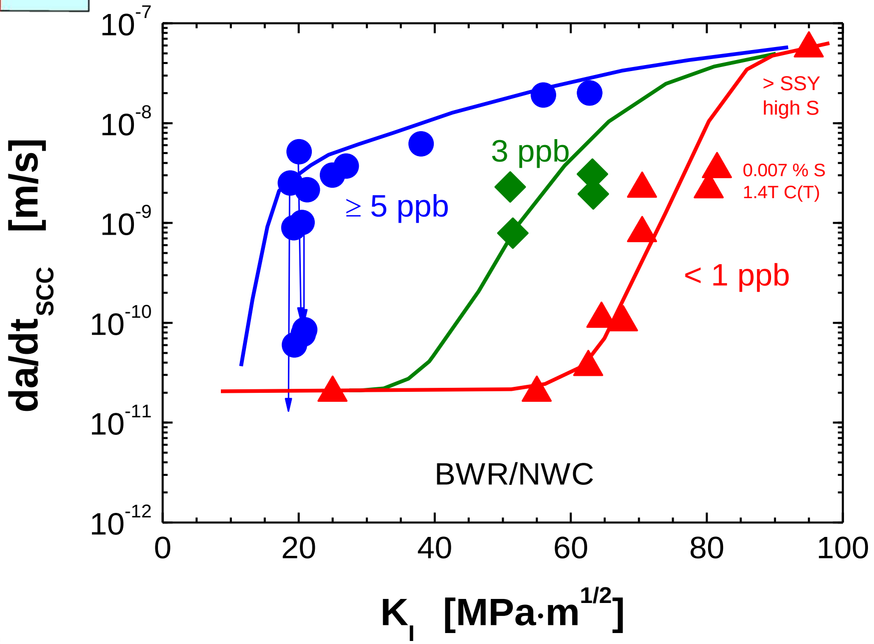
SCC in Alloy 182-RPV Steel DMWs in LWRs





recent SCC incidents in feedwater nozzle DMW in KKL (93 % of wall thickness) & core shroud support DMW of Swedish BWR



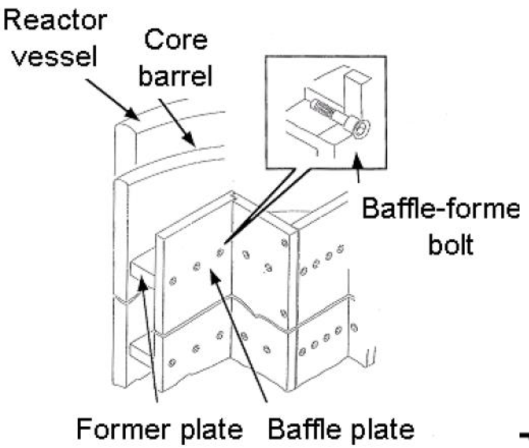


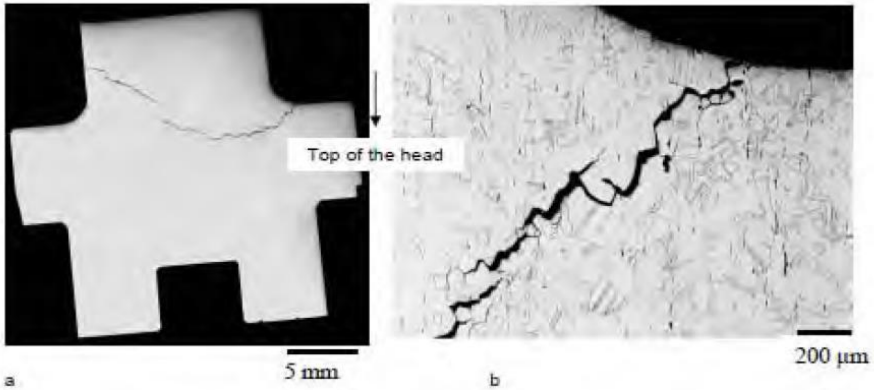
- SCC into the LAS cannot be excluded in high-purity BWR/NWC water at > 60-70 MPa·m$^{1/2}$
- For 3, 5 & 10 ppb of Cl$^-$, fast SCC into LAS is possible down to at least 50, 30 & 20 MPa·m$^{1/2}$, respectively.
- In PWR & BWR/HWC water SCC into the LAS might be possible at > 80-100 MPa·m$^{1/2}$.
- Accurate prediction of residual stress profile in DMW (& resulting K_I at fusion boundary) is crucial!
- Termination of JNES project due to Fukushima → no weld residual stress simulations & measurements

Examples of IASCC Incidents in LWRs

Baffle Former Bolts in PWR

e.g., KKB



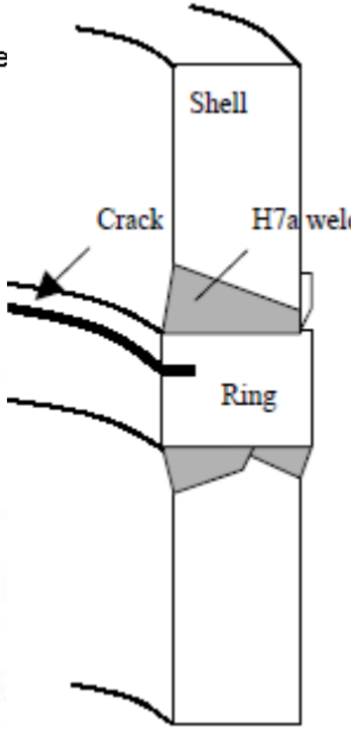


Pokor et al., Fontevraud 6, A154-T02, 2006

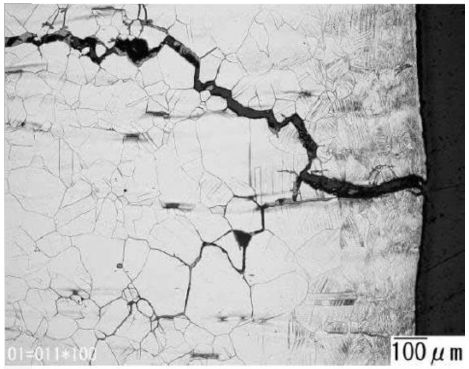
Core Shroud in BWR

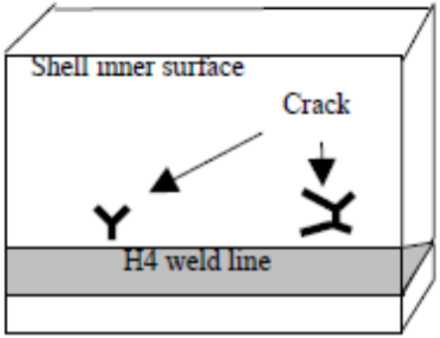
e.g., KKM

Most cracks in "low dose" region



[Straight circumferential type]

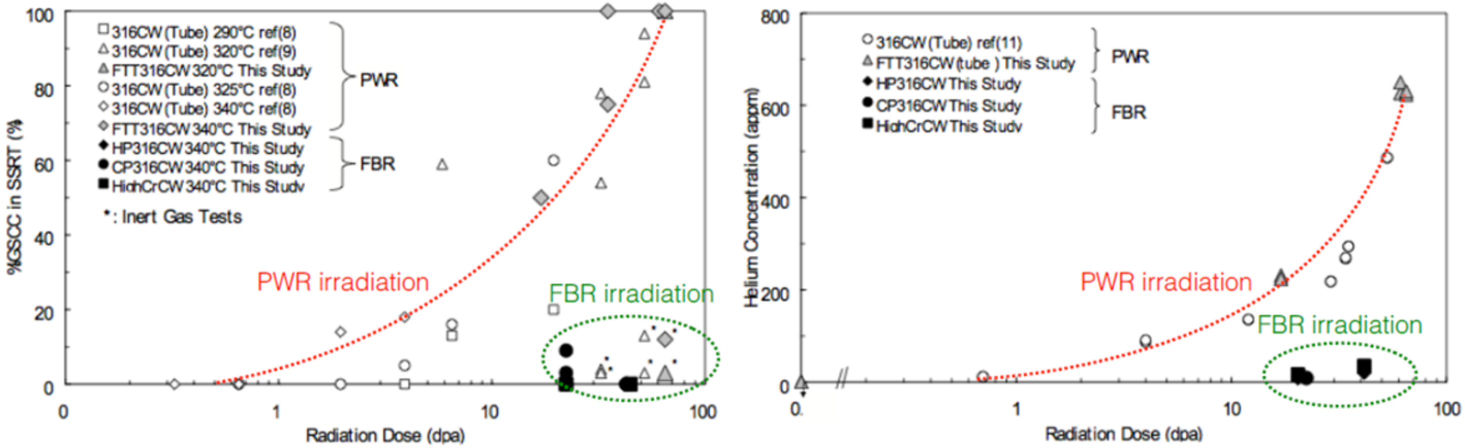




[Radial type]

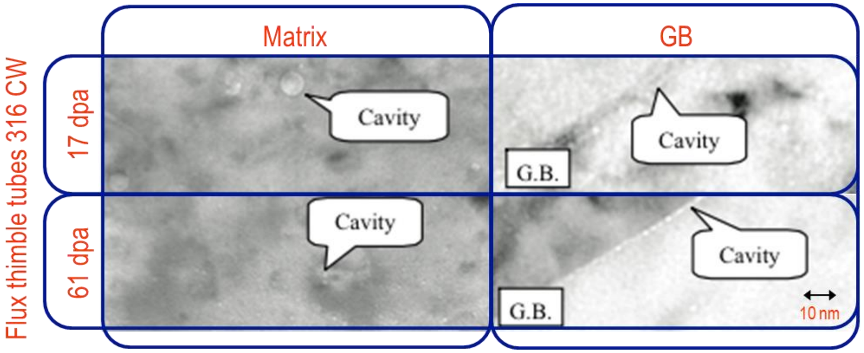
Potential He Effects on IASCC

- PWR reactor internals can reach up to 100 – 150 dpa & high levels of several 100 ppm of He after 50+ operation years. He from (n,α) reactions of B-10 and Ni-58 (at high fluence) by thermal n.



K.Fujimoto. Proc.of the 12th Int. Conf. on EDMaterials in NPS, 299-310, 2005.

- Higher IASCC susceptibility at high dose for PWR (~10 ppm He/dpa) than for fast n MTR irradiation (~ 0.1 ppm He/dpa) in spite of similar microstructures, hardening/yield stress levels or grain boundary segregation. Good correlation of IASCC susceptibility with the measured He contents in PWR



He Effects on IASCC, PhD Thesis (swissnuclear 1/14 - 12/17)

Goals:

- Clarification of the role of He on the mechanical properties and in IASCC in the LWR regime.
- Identification of the critical helium concentration for the onset of significant effects on IASCC and mechanical properties for SS in the solution annealed & cold worked conditions

Approach:

- SSRT tests with He implanted small-size SA & CW SS specimens in air and simulated PWR water
- Separation of He from displacement damage effects
- He-levels from 100 ppm to 1000 ppm, $T_{imp} = 300\ °C$
- Implanted & post-implantation annealed (simulated He bubble configurations) conditions
- He implantation: Short irradiation time, little displacement damage (< 0.5 dpa) and only slight activation → handling of specimens in C- or A-lab, reasonable costs
- Metallographical & metallurgical post-test evaluation by SEM & TEM

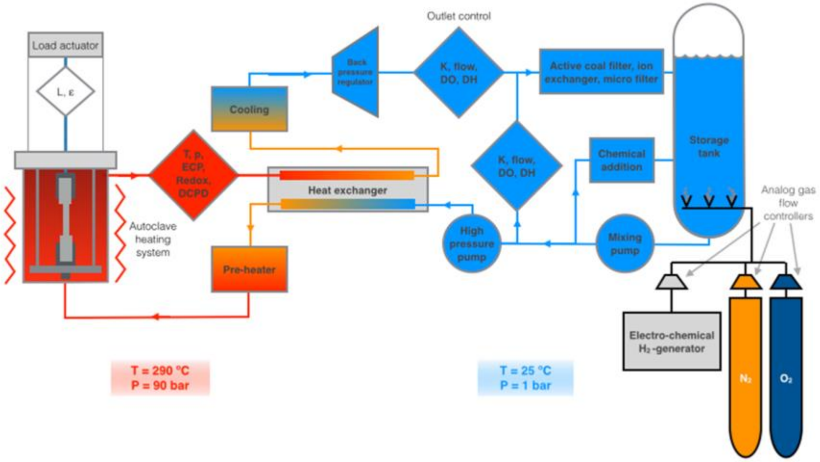
- **Joint effort of BTS & ANM group**
- **Example of cross fertilization of GEN-IV expertise for LWRs**

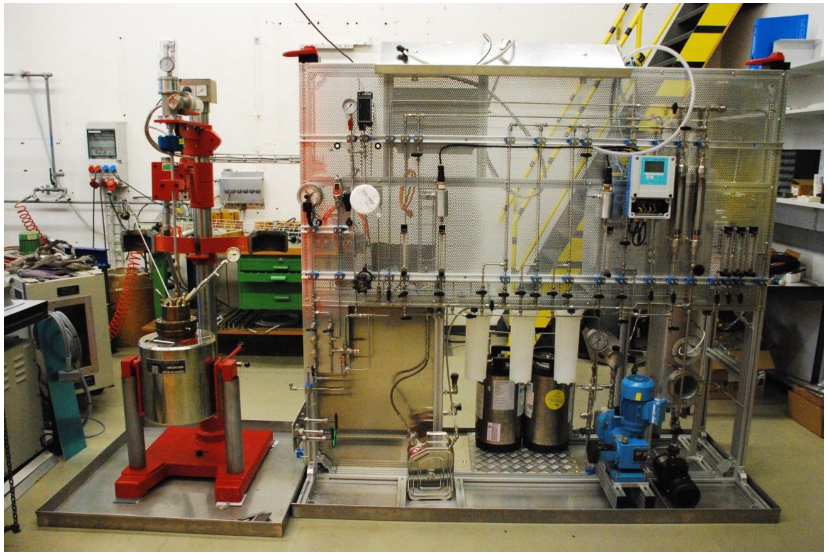
Team:

- PhD student: I. Villacampa
- Dr. J. Chen (ANM/LNM); Supervisor, irradiation damage, He effects, TEM
- Dr. P. Spätig (BTS/LNM): Thesis director (MER/EPFL), fracture mechanics, small size sp.
- H.P. Seifert (BTS/LNM): Manager of INTEGER, SCC testing, IASCC

Status after First Year

HTW loop autoclave system for IASCC tests on miniaturized specimens in hotlab & DCPD for on-line monitoring of cracking



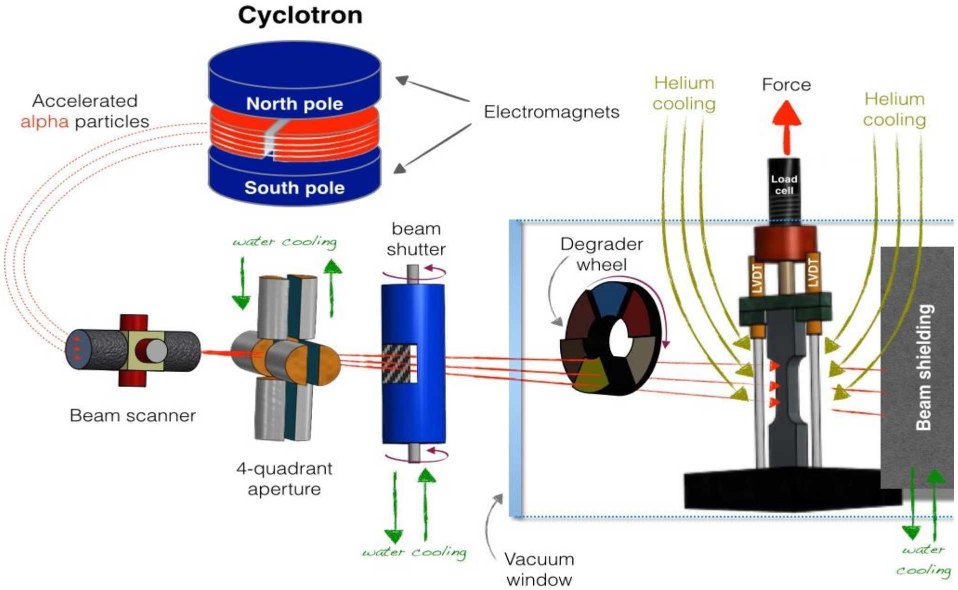


Validation of miniaturized specimens

D = 500 µm
~ 10 x mean grain size
homogeneous He implantation

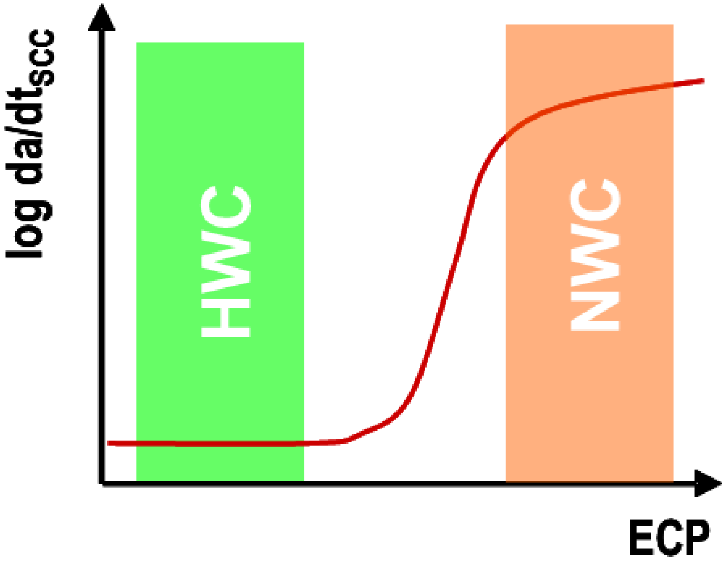
Sample	dε/dt (1/s)	YS (MPa)	UTS (MPa)	R (%)
Standard	10^{-6}	279	566	81%
Mini	10^{-6}	276	562	83%
Mini	10^{-6}	285	561	85%

He implantation in LNM in-situ irradiation creep facility at cyclotron at CRNS / CEMHTI (France)



SCC Mitigation in BWRs by HWC & NMCA

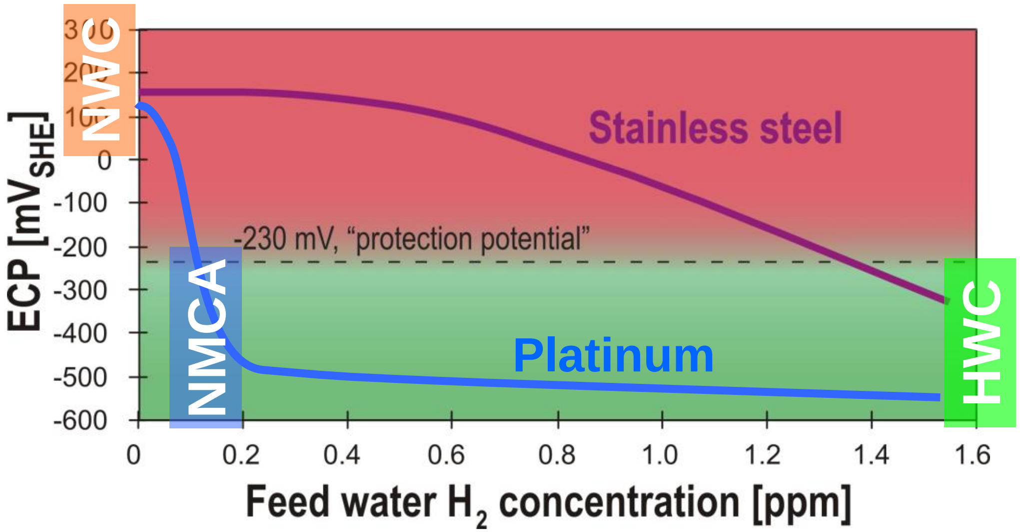
SCC mitigation by ECP reduction

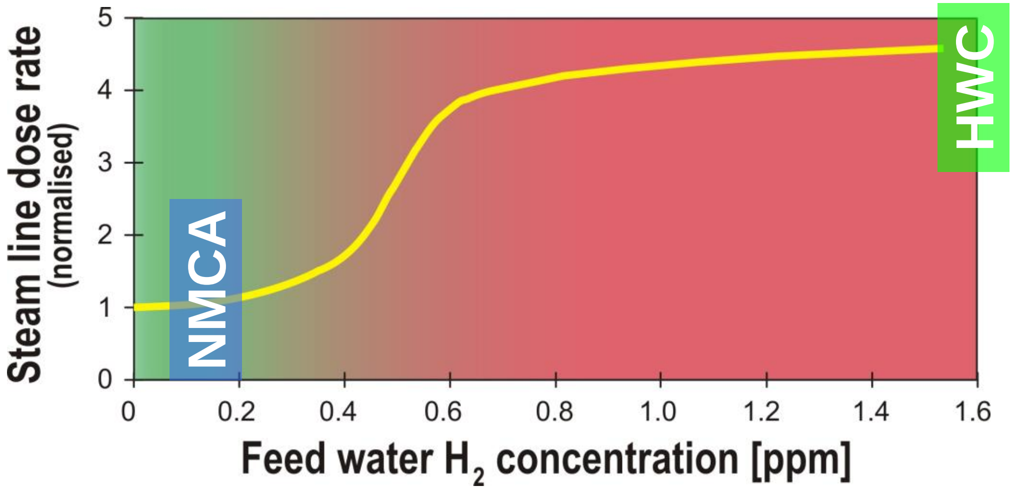


→ H_2 injection into feedwater (HWC)

But some negative side effects like an increase in steam line dose rate

→ Noble metal injection (NMCA, OLNC)

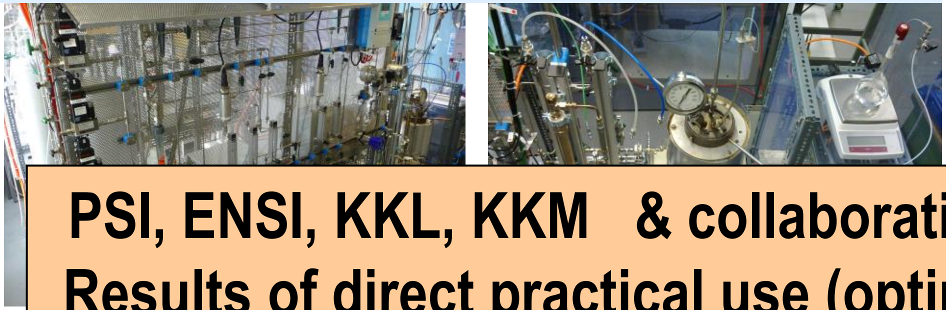




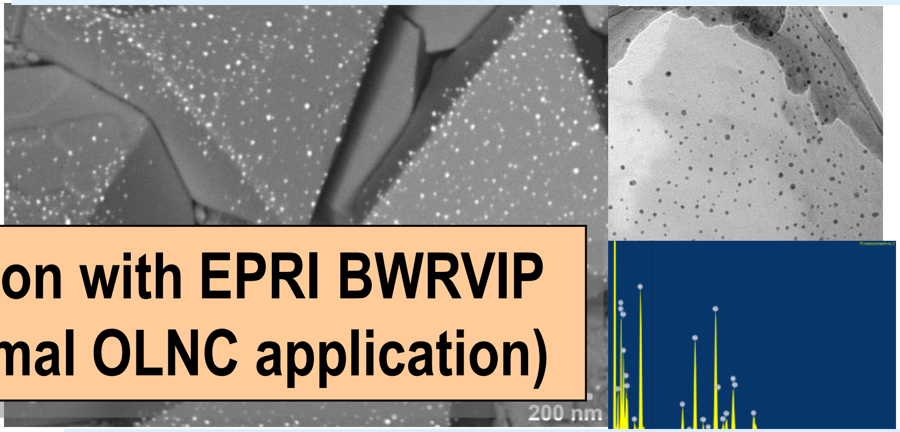
Noble metal deposition & redistribution behaviour in BWRs? → NORA

NORA-I & -II - On-line Noblechem in BWRs

Systematic Pt deposition tests in loops & autoclaves with flat & pre-cracked specimens and simulated fuel rods

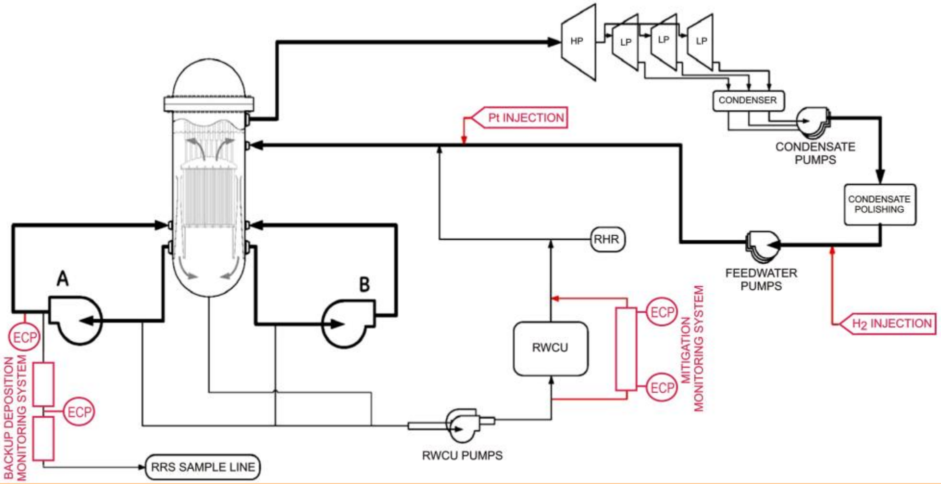


Characterization (size, distribution,conc.) by LA-ICP-MS, FEG-SEM/EDX & TEM/EDX/EELS

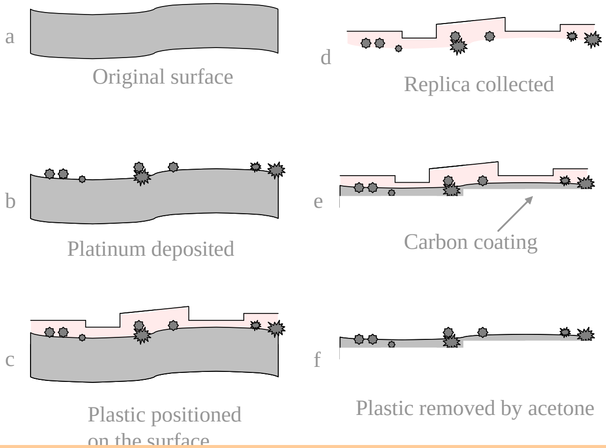


PSI, ENSI, KKL, KKM & collaboration with EPRI BWRVIP
Results of direct practical use (optimal OLNC application)

Exposure of specimens in Mitigation Monitoring System & Reactor Water Sample Line at KKL



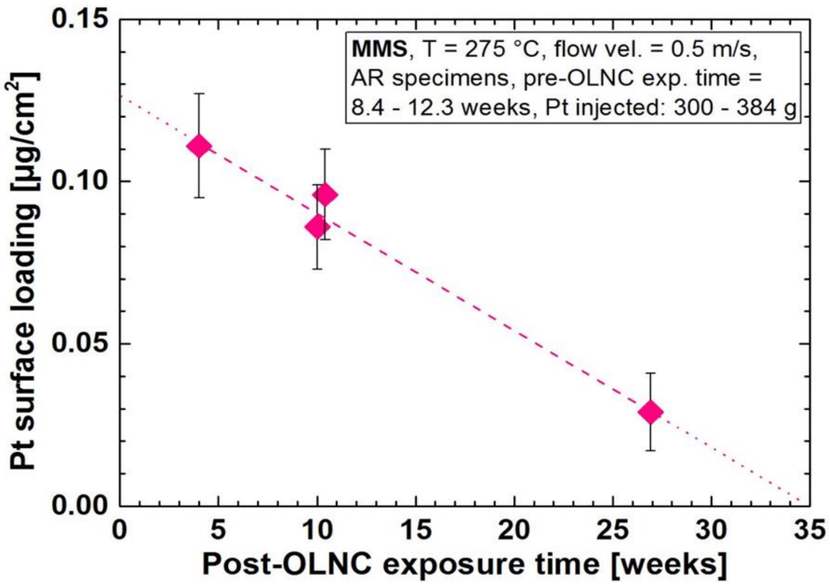
Development of a replica-based ND technique for radioactive components



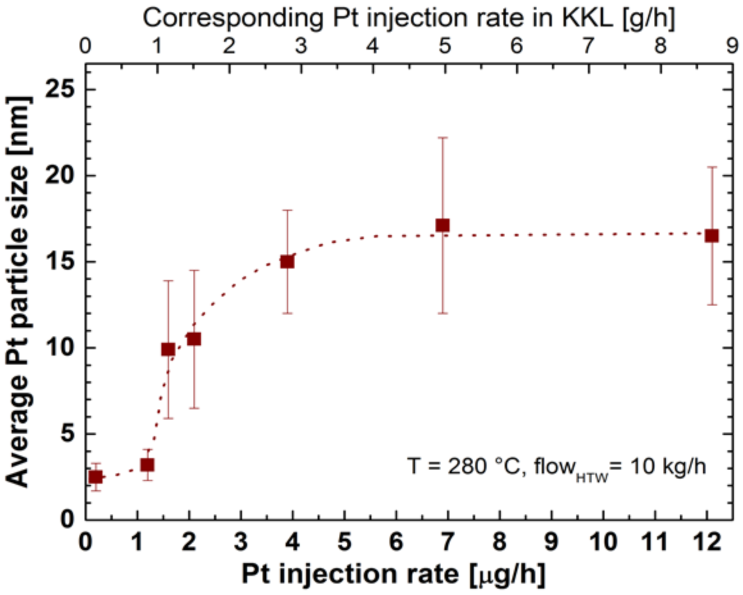
Several additional side projects: YUMOD (KKL), optimization of OLNC injection system (KKL), Pt-analysis on dry tubes (EPRI/KKL), crud (KKL), monitors (Spanish BWR), crevice monitors (KKM), EPRI/PSI OLNC projects, …

Selected Results of NORA Project

Example of plant data



Example of lab data



- Erosion of Pt particles with time after OLNC application.
- Most of the released Pt does not re-deposit on steel surfaces, but possibly becomes trapped on CRUD, fuel or in the water clean-up system & is thus lost for protection
- Repeated or even continuous OLNC applications could compensate for the erosion of Pt from the surfaces

- → smaller Pt-particle size (catalytic surface area↑, surface coverage, transport into cracks, …)
- For an optimal protection, the Pt solution should be injected at low rates over extended periods of time & under reducing water chemistry conditions
- Adjustment of injection procedure at KKM & KKL

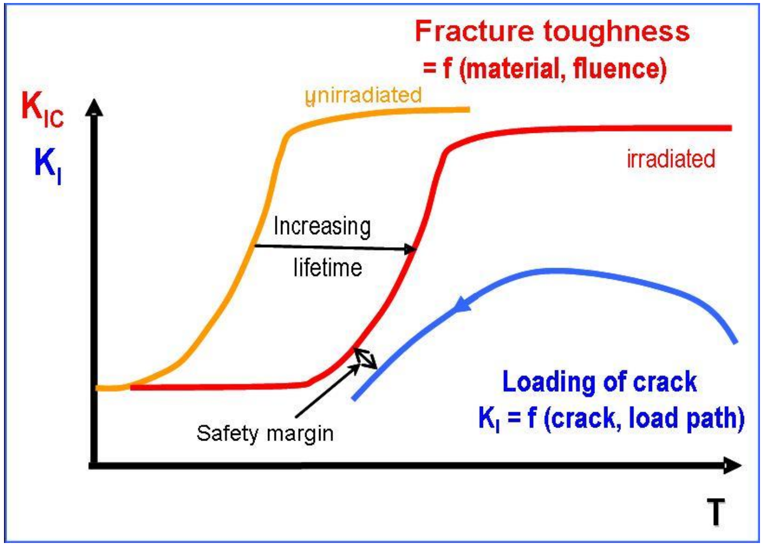
Structural Integrity

Integrity Assessment

Modeling of degradation

PISA: Deterministic & Probabilistic RPV Integrity Assessment

Deterministic



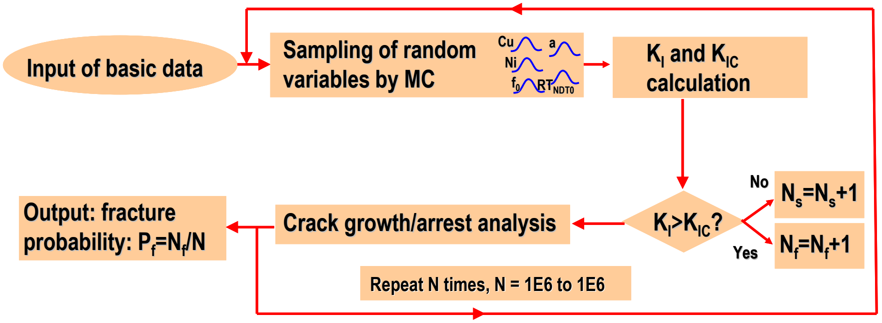
For postulated cracks & all operating & selected bounding accident (e.g., PTS) conditions

$$K_I = f(a, \text{load}) < K_{IC} \text{ or } K_{Ia}$$

Operating conditions → a = ¼ of wall thickness

Accident conditions → a = 2 x NDT resolution limit

Probabilistic



Input of basic data

Sampling of random variables by MC

K_I and K_{IC} calculation

$K_I > K_{IC}$?

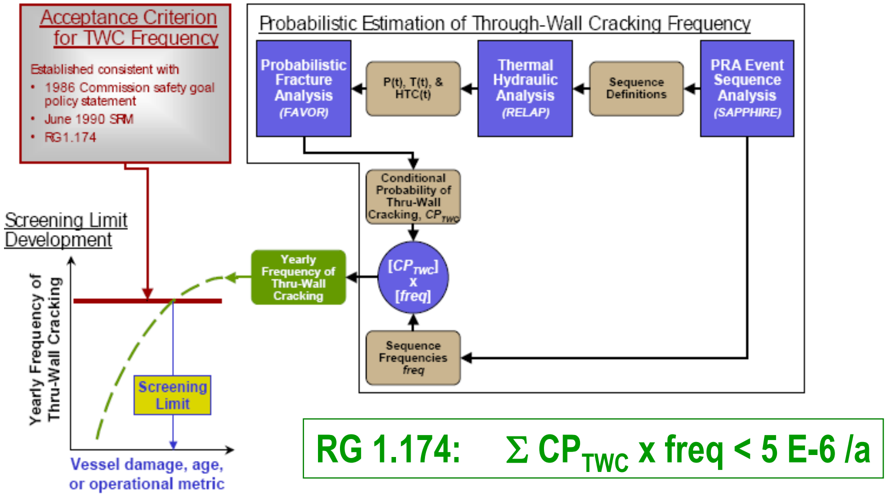
No: $N_s = N_s + 1$

Yes: $N_f = N_f + 1$

Crack growth/arrest analysis

Output: fracture probability: $P_f = N_f/N$

Repeat N times, N = 1E6 to 1E6



Acceptance Criterion for TWC Frequency

Established consistent with
- 1986 Commission safety goal policy statement
- June 1990 SRM
- RG1.174

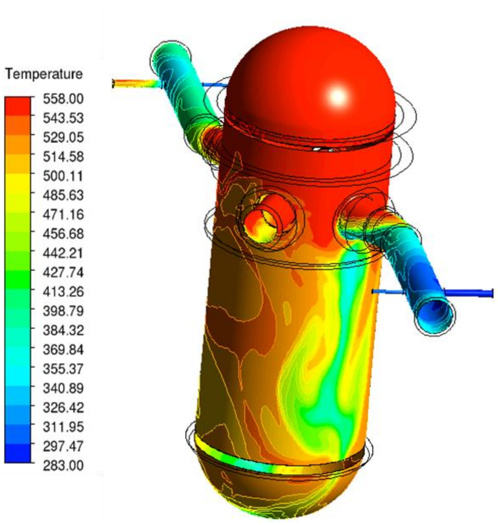
Probabilistic Estimation of Through-Wall Cracking Frequency

RG 1.174: $\Sigma\, CP_{TWC}$ x freq < 5 E-6 /a

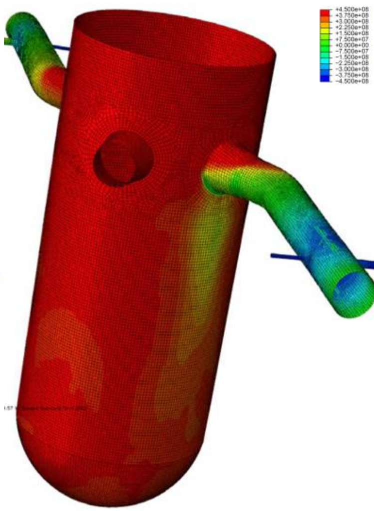
- Identify accident scenarios & estimate their frequencies
- Estimate RPV failure probability for different transients
- Estimate total RPV failure frequency
- Consideration of random & lack of knowledge uncertainties
- Better estimation of safety margins

3D-LEFM Analysis with T from 3D-CFD Simulation

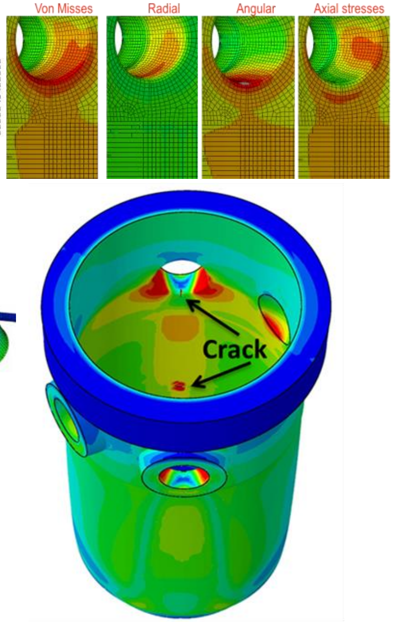
Fluid T



Wall T

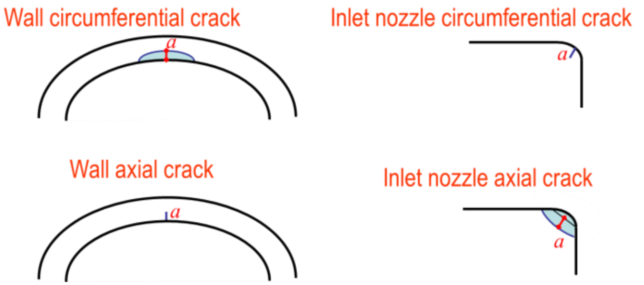


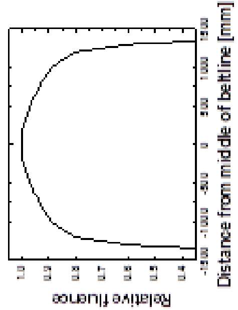
Stress σ

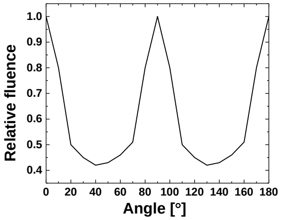


Crack configurations

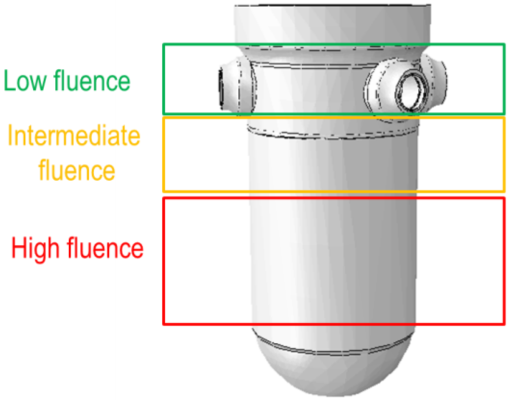
- axial & cirmumferential cracks
- at nozzle corner & cylindrical shell
- inside & outside the plume region
- surface & underclad cracks
- base metal or weld





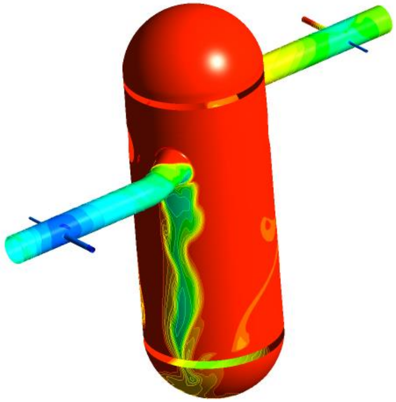


Fluence
= f(location, operation time)



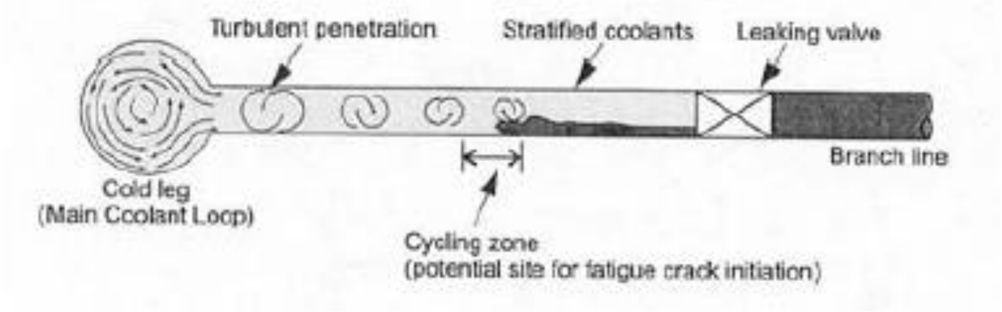
LOCA and transient scenarios

- SLOCA
- MLOCA
- LLOCA
- Size of leak
- Boundary conditions
- Other transients

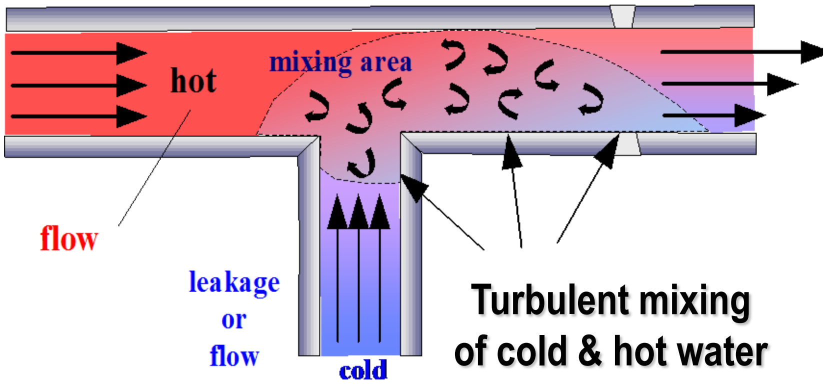


Thermal Fatigue Cracking Incidents

Vortex penetrations at tees or dead legs with leaking valves → HCF

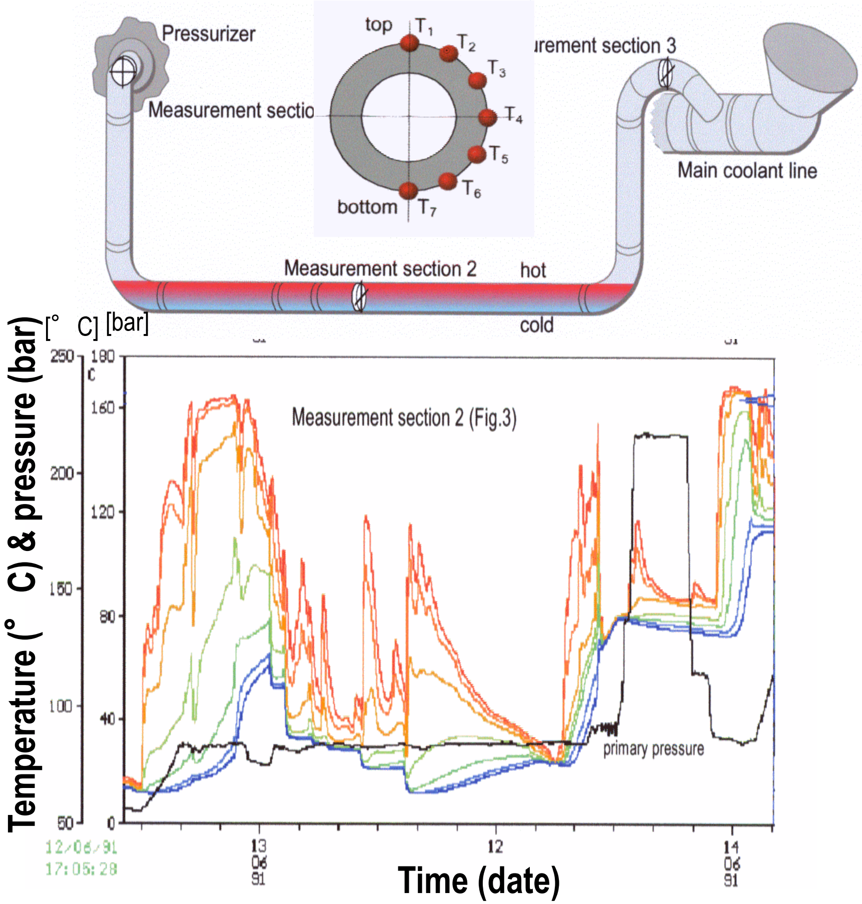


Turbulent mixing at tee joints → HCF



Turbulent mixing of cold & hot water

Thermal stratification → LCF



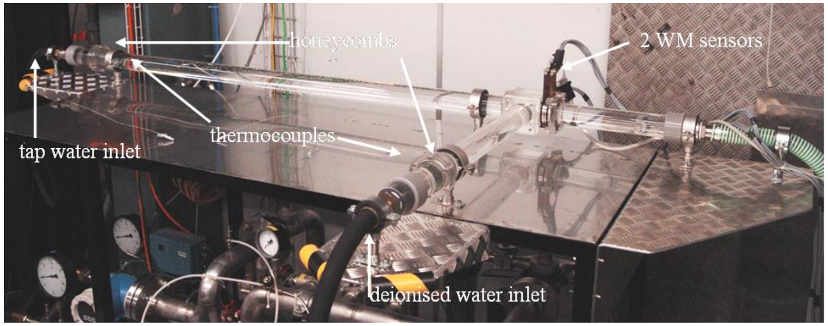
Moderate environmental effects possible!

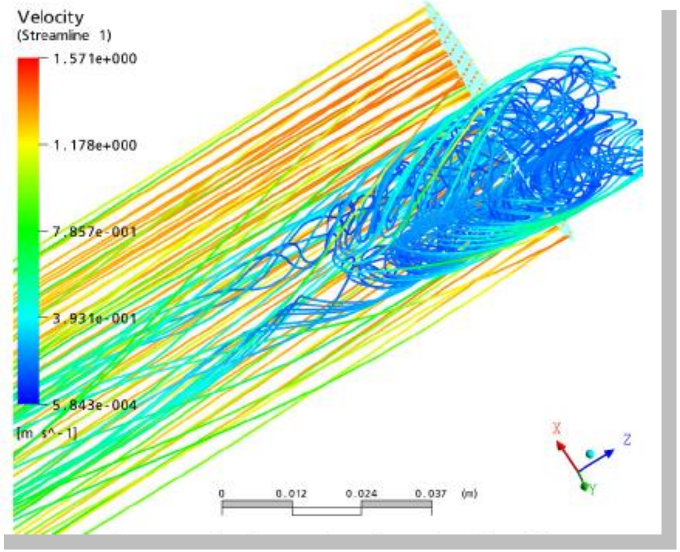
Strong environmental effects possible!

PLiM-V & VI (swissnculear, 2012-16): TMF

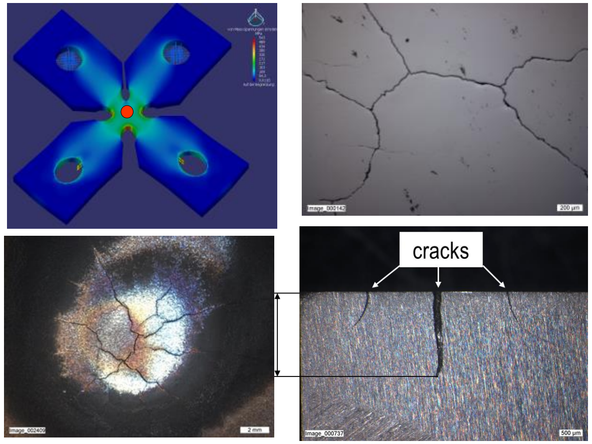
Modeling & Characterization of TMF Initiation & Growth under Turbulent Mixing Conditions in T-Joints

CFD Modeling & Validation (by LTH)

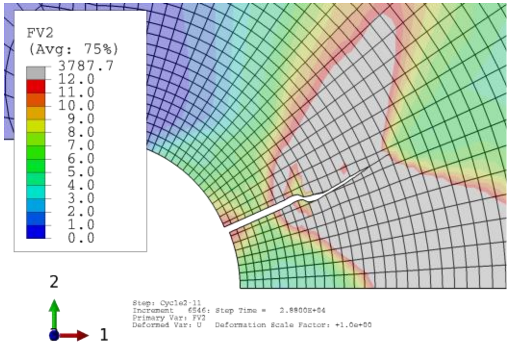




Structural Mechanics Modeling & Validation

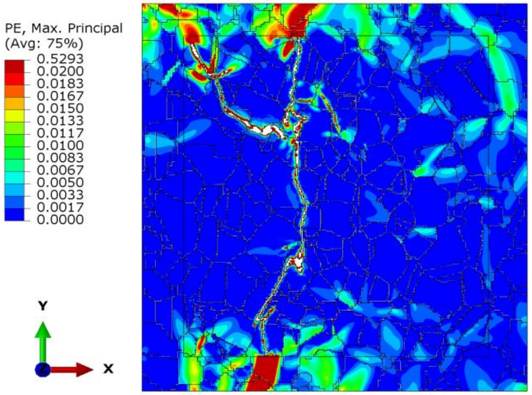


continuum-scale

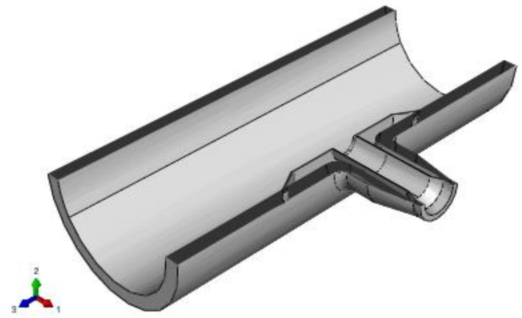


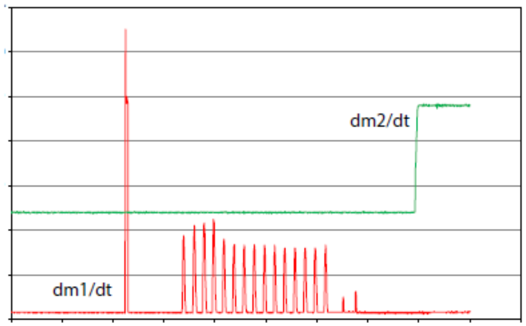
Step: Cycle2-11
Increment 6546: Step Time = 2.8800E+04
Primary Var: FV2
Deformed Var: U Deformation Scale Factor: +1.0e+00

meso-scale



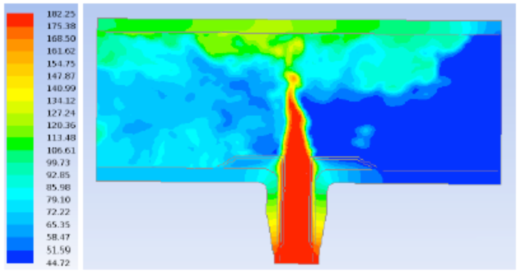
Lifetime Assessment of Mixing T-Joint in KKM

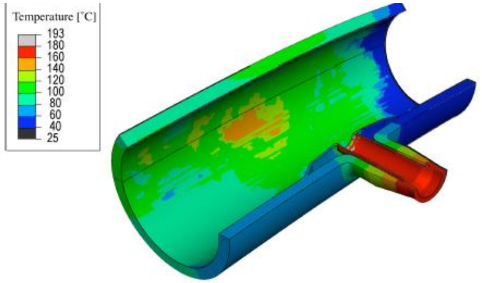


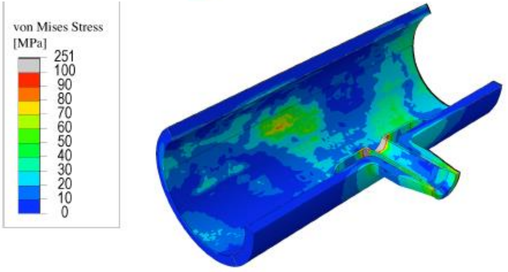


Load Case 1

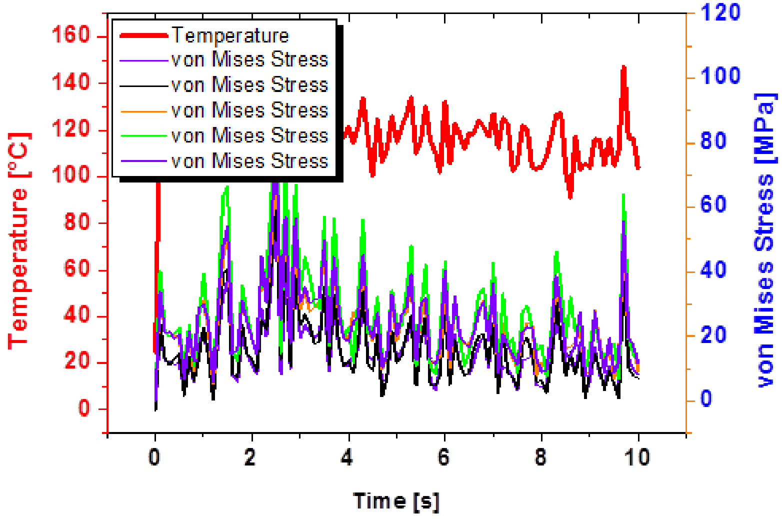
	Flow Rate [t/h]	Inlet Temperature [°C]	Coolant Pressure [bar]	Reynolds No.
Main	32	48	25	7.4×10^4
Branch	12	180	25	4.1×10^5



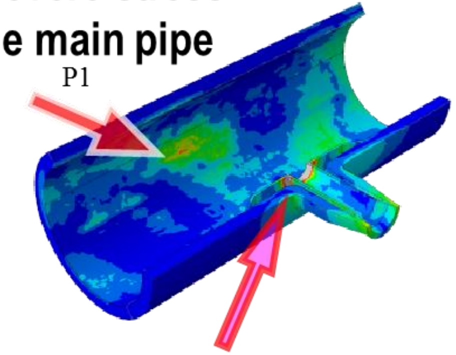




Stress & temperature at P1 vs time



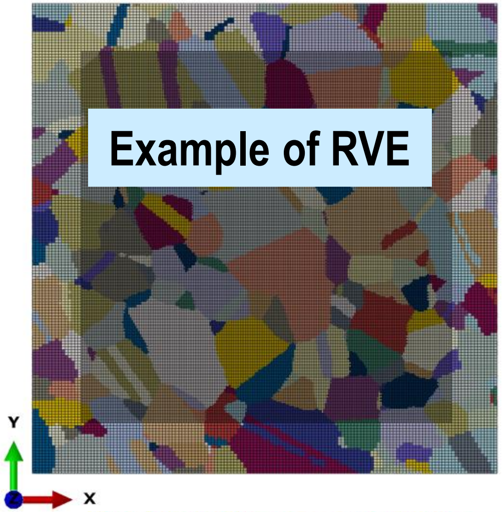
Areas of most severe stress transients in the main pipe



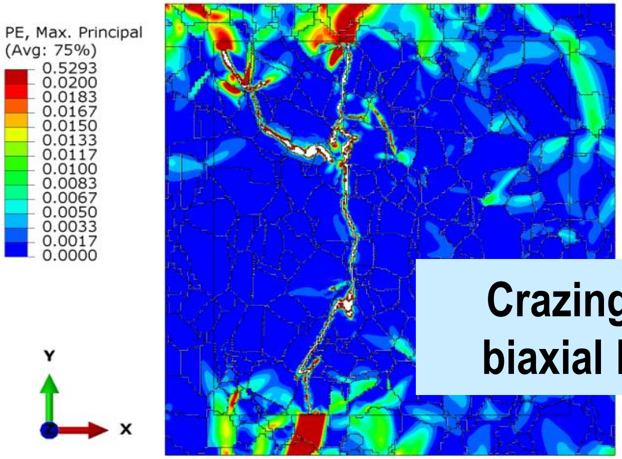
- Surface crazing not excluded for certain load cases
- Challenging evaluation of complex combined high & low frequency, multi-axial, variable amplitude fatigue load

Microstructural Modeling of Fatigue Life in FE Context

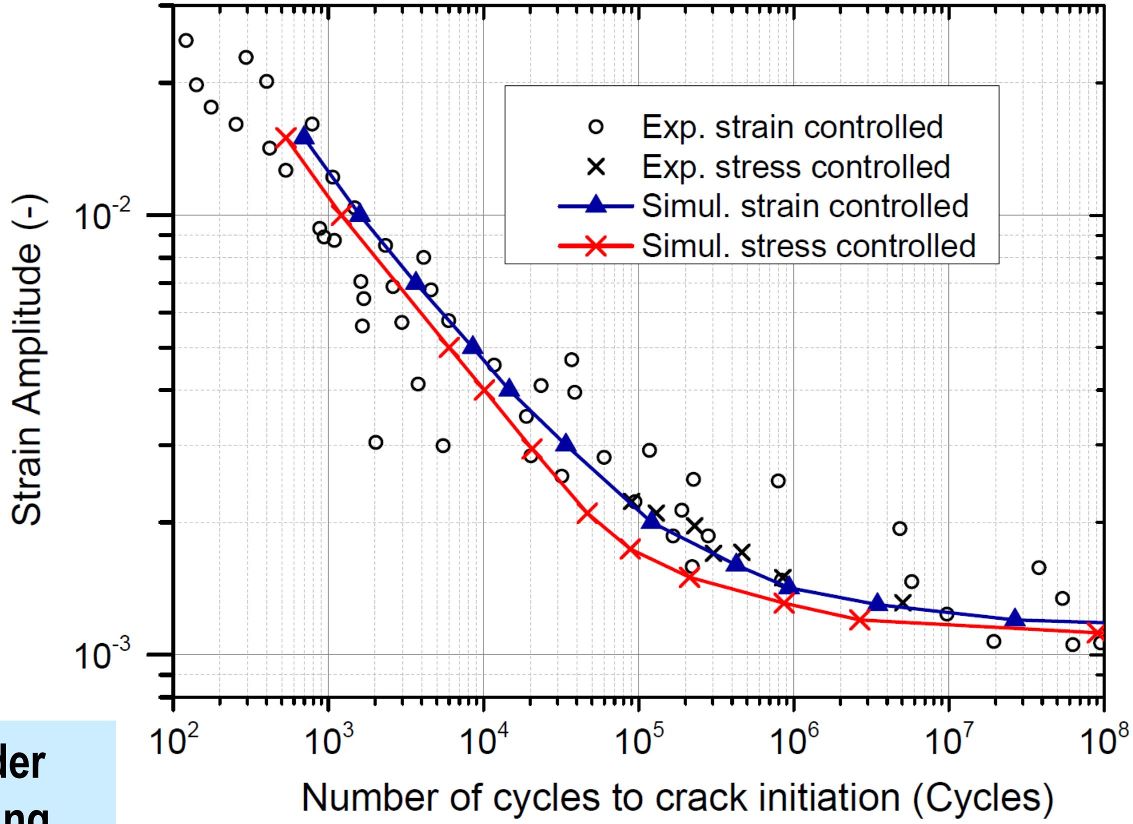
- Consideration of grain structure & crystallographic orientation by representative volume element (RVE)
- Microscale-based modelling of plastic deformation (crystallographic slip systems)
- Continuum damage model for fatigue, which is related to plastic hysteresis energy. Damage criteria fitted to macroscopic fatigue data.



Example of RVE



Crazing under biaxial loading



PoD M. Sistaninia

ND Diagnostic

Early Detection, Monitoring, NDT

NDT & DIAGNOSTICS Activities in INTEGER

Stress Corrosion Cracking

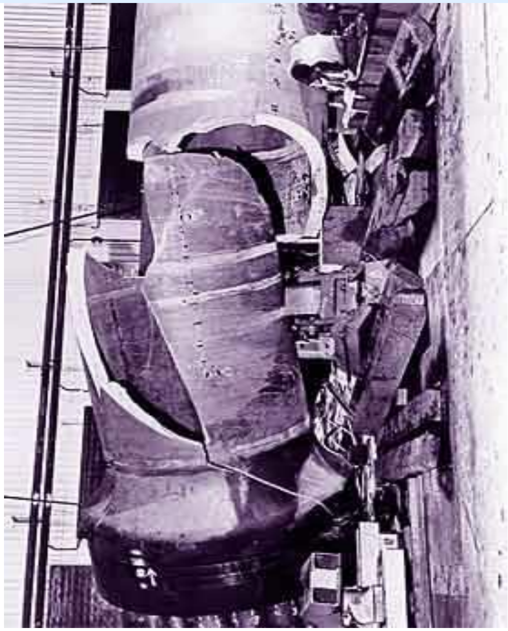
- Electrochemical noise
- DCPD
- Replica (Pt distribution)
- NDT test bodies

KORA-II, SAFE & PARENT

Fatigue & TMF

- Magnetic methods
- Thermoelectric methods

Irradiation Embrittlement & Thermal Ageing



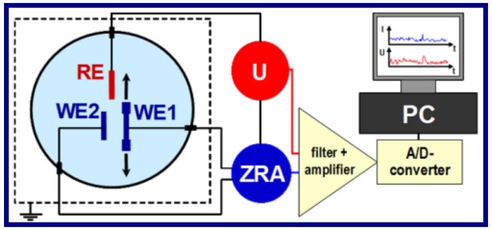
- Thermoelectric methods
- Magnetic methods

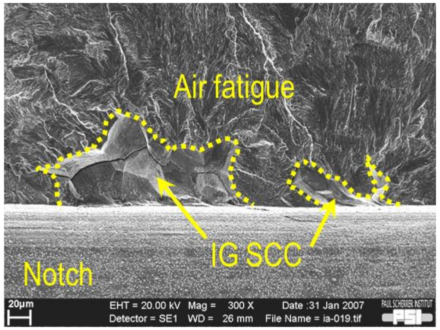
DIAGNOSTIK-I & II & PISA-I

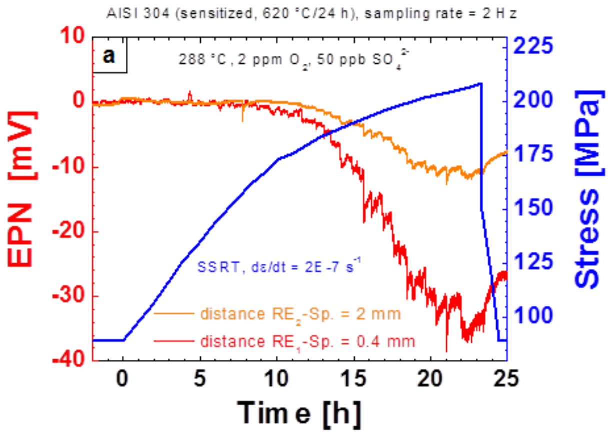
- *Significant reduction of activities in 2012 (→ funding as filter & limited practical applicability)*
- *Currently running at low level (by internships, new PhD project)*

Examples of Past Activities

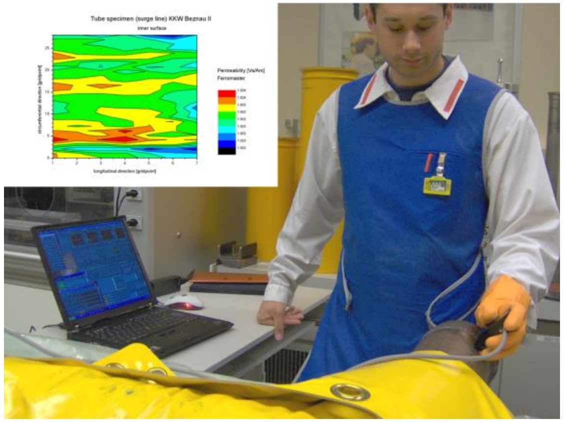
SCC initiation detection by ECN

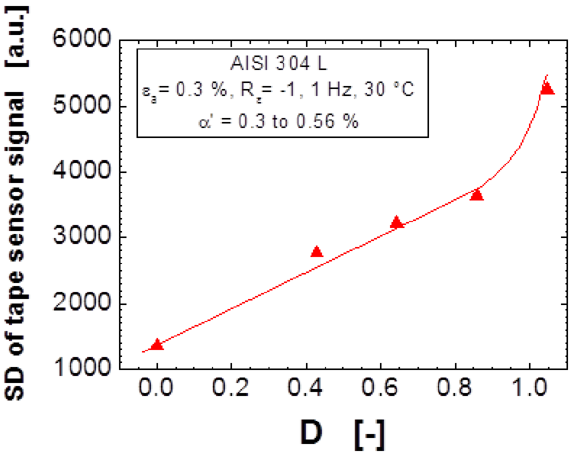




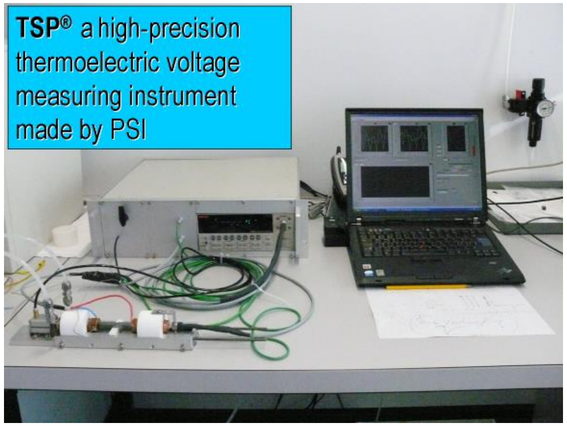


Fatigue monitoring by magnetic methods

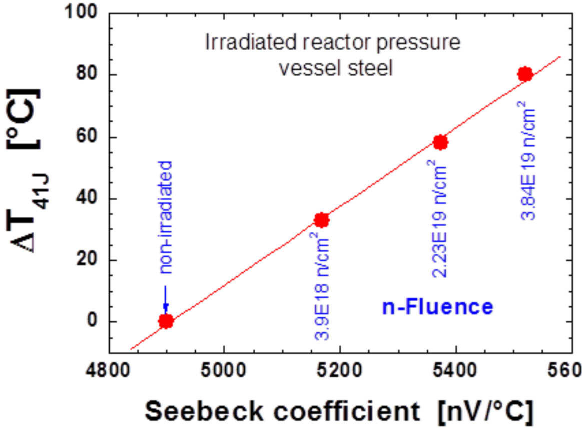




RPV irradiation embrittlement monitoring by TEP



TSP® a high-precision thermoelectric voltage measuring instrument made by PSI



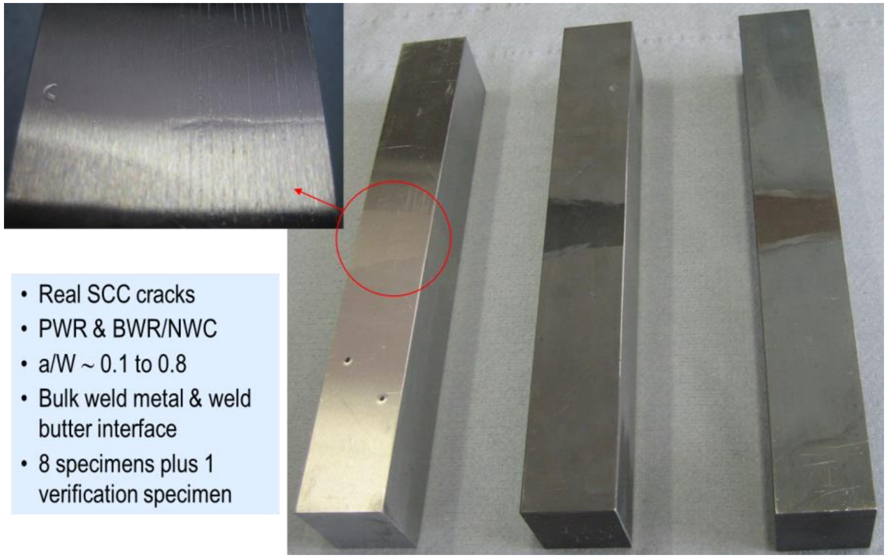
PARENT (2012-16): NDT Test Bodies with SCC Cracks

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

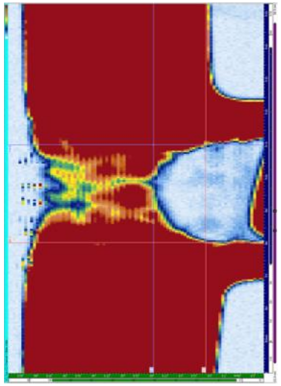
- International program including regulators, industrial groups and research institutions
- Assessment & quantification of established & new promising NDE techniques
- NDT tests bodies with well characterized SCC cracks for open round robin as PSI contribution
- Participation in open and closed round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



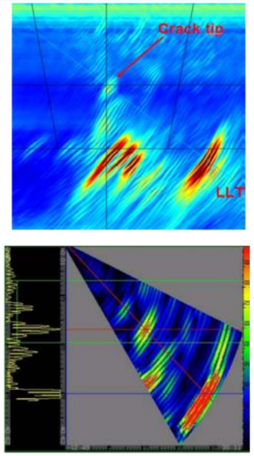
- Real SCC cracks
- PWR & BWR/NWC
- a/W ~ 0.1 to 0.8
- Bulk weld metal & weld butter interface
- 8 specimens plus 1 verification specimen

BWR/NWC SCC Crack

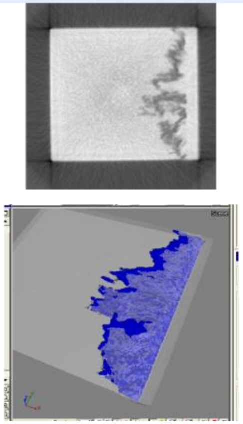
UT immersion
Alstom



UT phased array
SVTI, Alstom

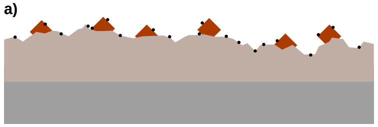
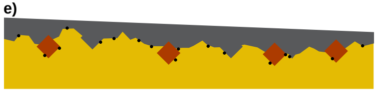
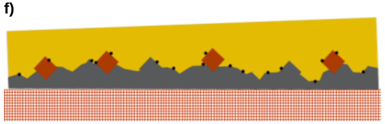
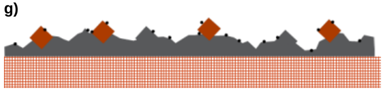


X-ray radiography & tomography
EMPA

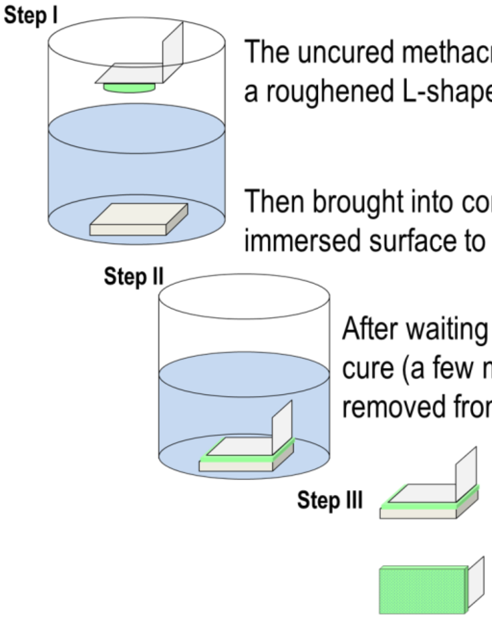


Replica Technique for Radioactive Components

NDT characterisation of Pt-particle distribution & Pt surface concentration on highly radioactive components

a) 	Outer oxide layer and Pt particles Inner oxide layer Steel
b) 	After application of the cellulose acetate adhesive film
c) 	Peeling off the adhesive film with oxide crystals and Pt particles adhering to the film
d) 	Replica
e) 	Replica is carbon coated
f) 	Carbon coated replica is placed on a TEM copper grid
g) 	Cellulose acetate is removed with acetone, leaving the carbon film with oxide crystals and Pt particles on the grid

Under water technique



The uncured methacrylate is applied to a roughened L-shaped metal piece.

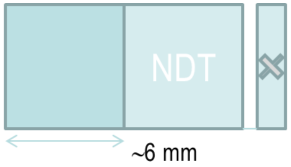
Then brought into contact with the immersed surface to be sampled

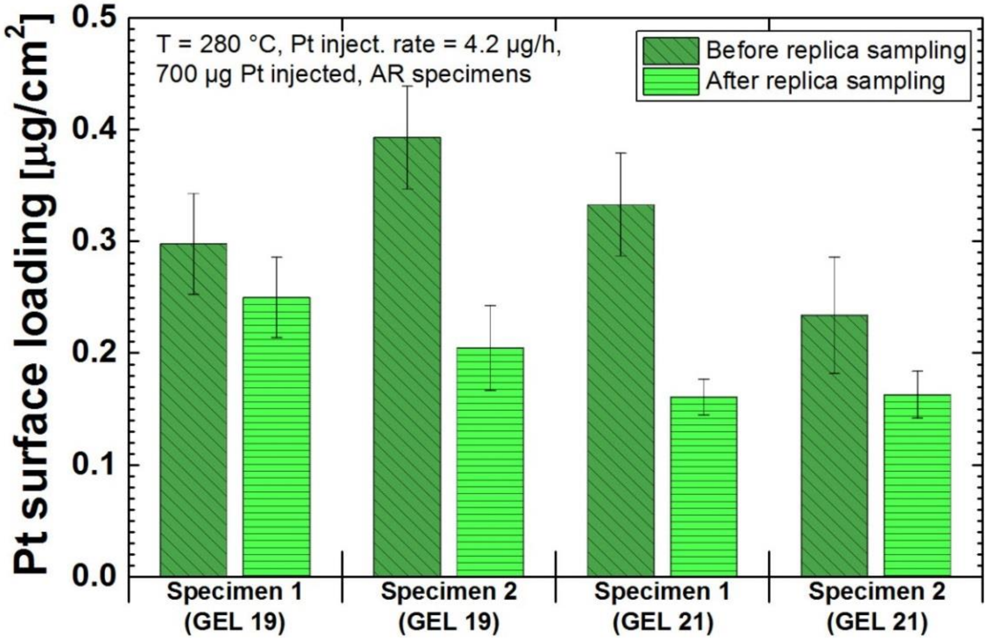
After waiting for the methacrylate to cure (a few minutes), the assembly is removed from the water.

The hardened methacrylate is broken away from the specimen.

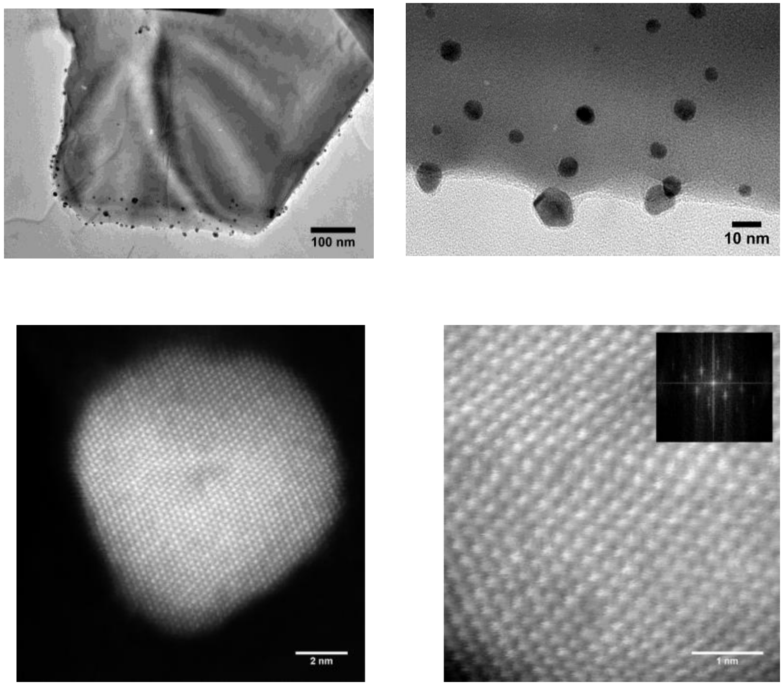
Replica Technique for Radioactive Components

Pt surface loadings before and after replica sampling





TEM, High-Resolution TEM & STEM (Tomography)



- Replica removes up to 50 % of the Pt present on specimens
- Provides useful results, but further qualification necessary
- Nature & structure of individual particles (important for catalysis efficiency)