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Wir schaffen Wissen – heute für morgen

Laboratory for Nuclear Materials (LNM)

- Overview, activities & selected highlights -

H.P. Seifert, J. Bertsch, M. Pouchon

Nuclear Energy and Safety

Paul Scherrer Institute

5232 Villigen PSI, Switzerland

NES Info Event 2014, PSI, OSGA/EG06, March 27, 2014.

Certified System swiss TS ISO 9001

Outline

- **Overview on LNM**
  - Mission
  - Organisational structure
  - Research & project portfolio, core expertise's
  - Lab infrastructure & modeling tools
  - Education & teaching activities
  - Scientific services
- **Selected examples of current activities & highlights**
  - Advanced Nuclear Materials
  - Nuclear Fuels
  - INTEGER

Overview on LNM

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

4600 Laboratory for Nuclear Materials

H-P. Seifert a.i.
Dep. J. Bertsch

QM-System
Manager: M. Streit (4300)
Deputy: R. Zubler

4600 Secretariat
B. Furger

4601 Advanced Nuclear Materials

M. Pouchon
Dep. Y. Dai

- J-C. Chen
- V. Krsjak
- PoD ESS
- R. Brun
- T. Rebac
- Tech. MEAWAT
- W. Wu
- L. Fave
- C. Vieh
- K. Wang
- I. Villacampa Rosés
- PhD ESS

4602 Nuclear Fuels

J. Bertsch
Dep. C. Degueldre

- S. Abolhassani-Dadras
- G. Kuri
- S. Valance
- M. Chollet
- PoD (sn)
- R. Zubler
- C. Mieszczynski
- PhD sn PdJ
- PhD Fuel

4603 Component Structural Integrity

H.P. Seifert
Dep. M. Niffenegger

- K. Freytag
- K. Reichlin
- S. Ritter
- P. Spätig
- G. Qian
- V. Gonzalez
- P. Grundler
- S. Roychowdhury
- M. Sistaninia
- B. Baumgartner
- H. Kottmann
- L. Nue
- R. Schwenold
- N. Grilli
- J. Bai
- S. Knitel
- PhD sn PDJ

Scientists, regular positions
Post-Docs
Technicians
PhD students

Status 03/2014

Projects

461: Advanced Nuclear Materials	462: Nuclear Fuels	463: INTEGER

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 — 75 % experimental & 25 % modeling
70 % GEN-II & 30 % GEN-IV/SNS — 55 % CH, 35 % international, 20 % PSI

Lab capacity: 10 % for teaching & education — 10 - 15 % for expertise & service work

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

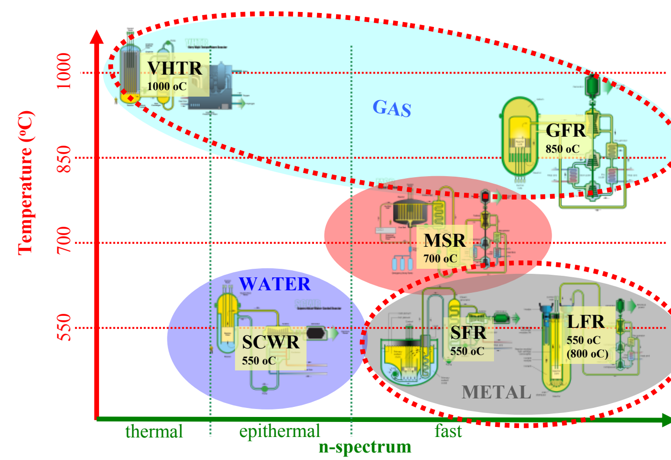
Spallation Neutron Sources ↔ ADS ↔ GEN-IV Nuclear Systems

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, …)



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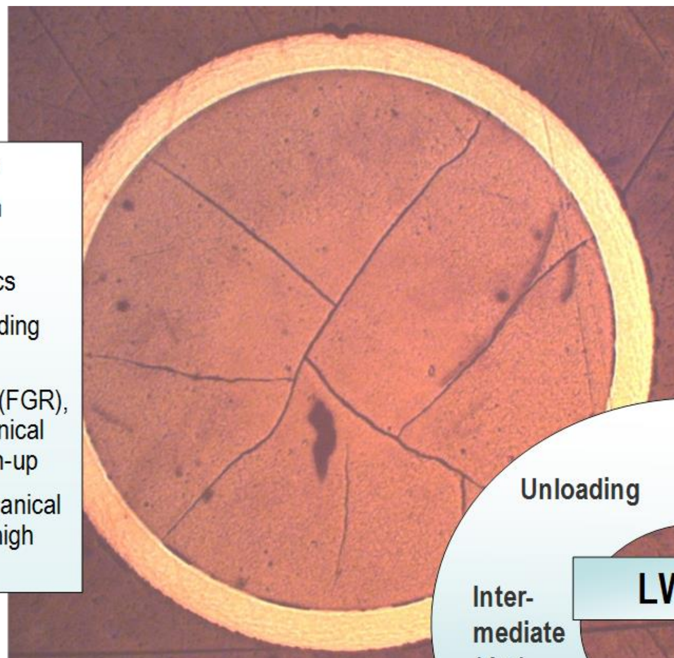
Nucelar Fuels

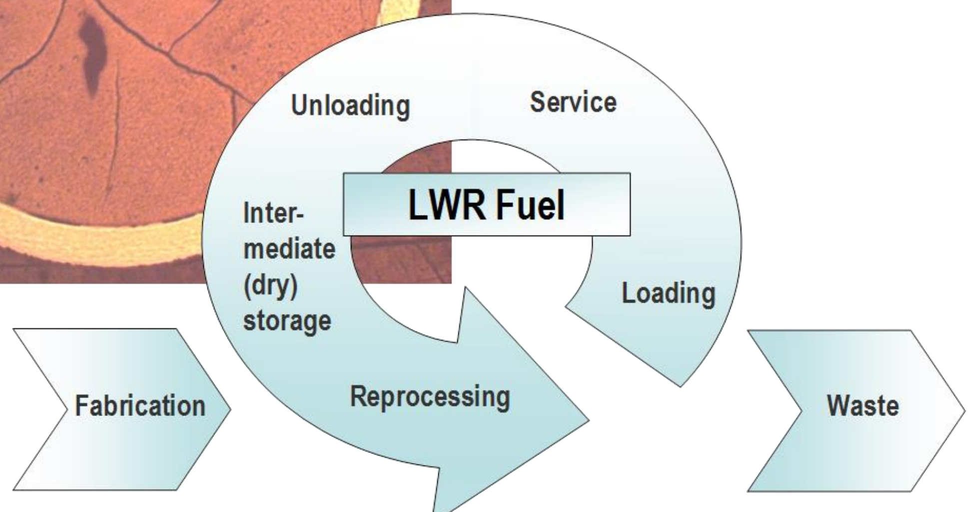
Fuel life & integrity → core materials issues with respect to **safety & performance**

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

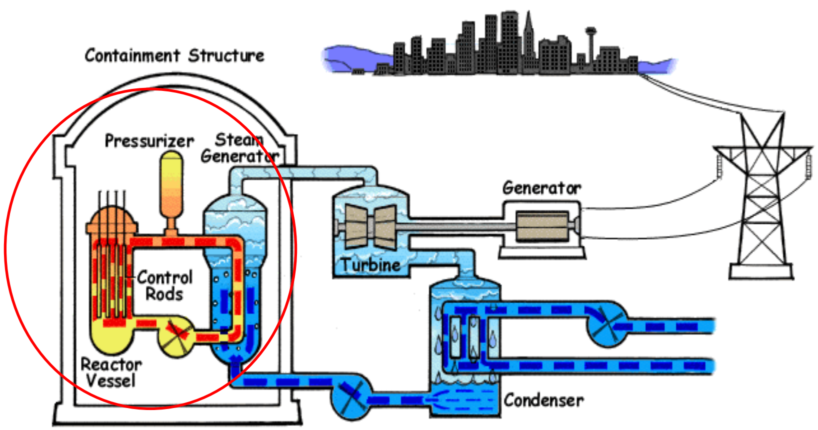


INTEGER

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

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

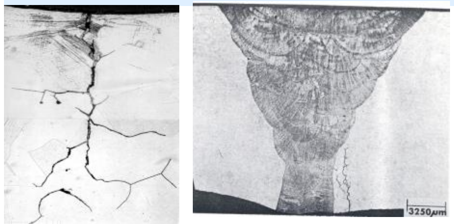
Primary pressure boundary components & reactor internals



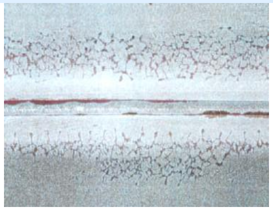
- Critical systems with regard to safety and lifetime (extension)
- Assurance of structural integrity in the context of material ageing a key task

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

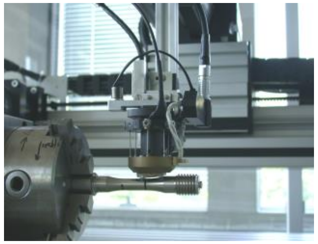
- **Ageing & degradation** → characterization & mechanism, mitigation
- **Integrity** → deterministic & probabilistic structural integrity & lifetime assessment
- **Diagnostic** → ND early detection of damage and monitoring of ageing conditions

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)

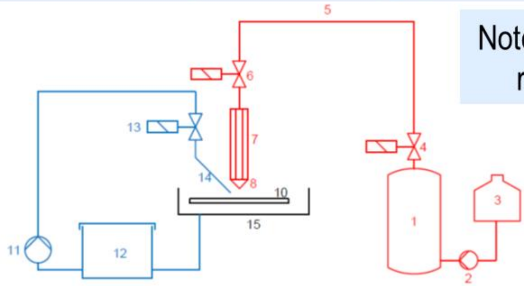
- **LA ICP-MS, EPMA, SIMS**
- **Active metallography & sample preparation**
- **γ-spectrometry, fission gas analyzer**

Examples of Unique Facilities

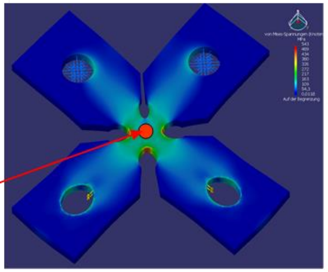
Cyclic TMF Facility with Biaxial Pre-Loading (INTEGER)

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

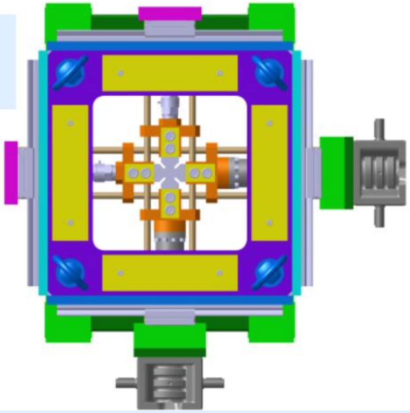
Controlled indepdendent biaxial pre-loading



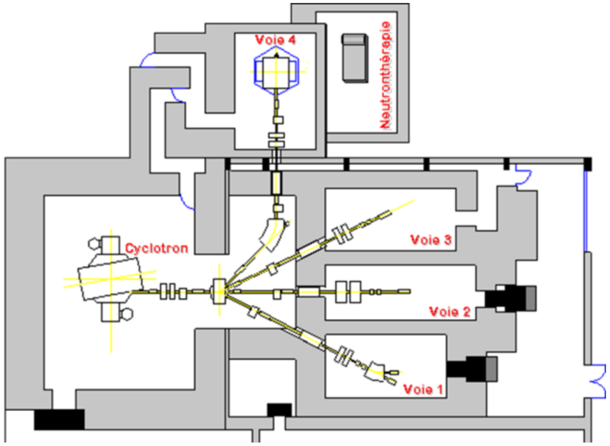
Notched cruciform specimen with reduced thickness in center

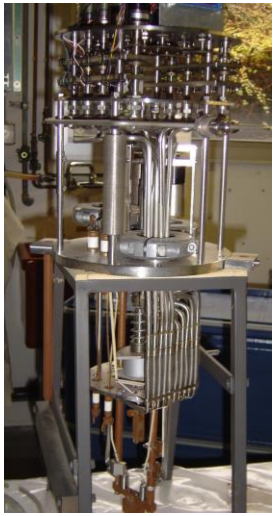


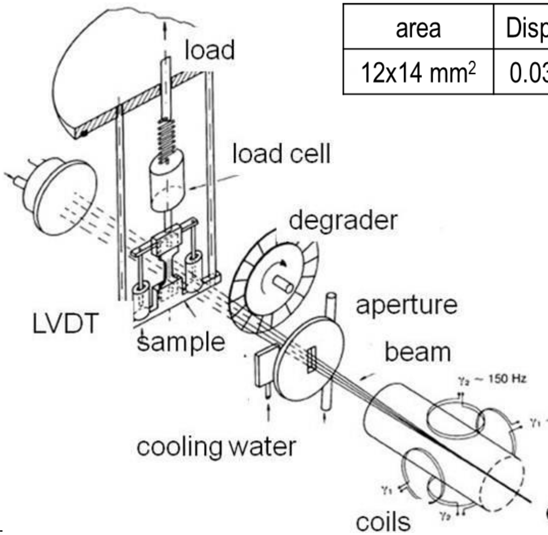
location with thermal shocks



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







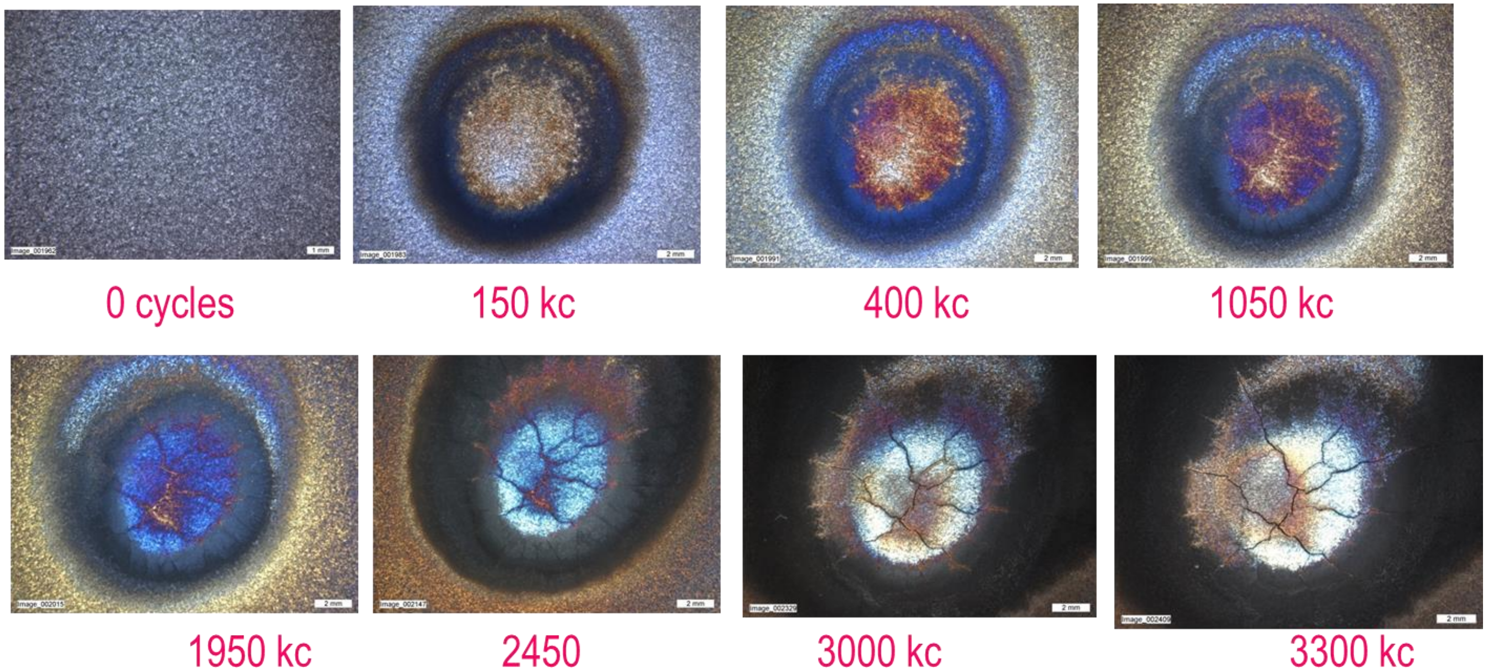
area	Dispal. rate	Impl. rate	T (°C)
12x14 mm²	0.03 dpa/h	150 appm-He/h	150-1000

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
^3He	10--50	15	470

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

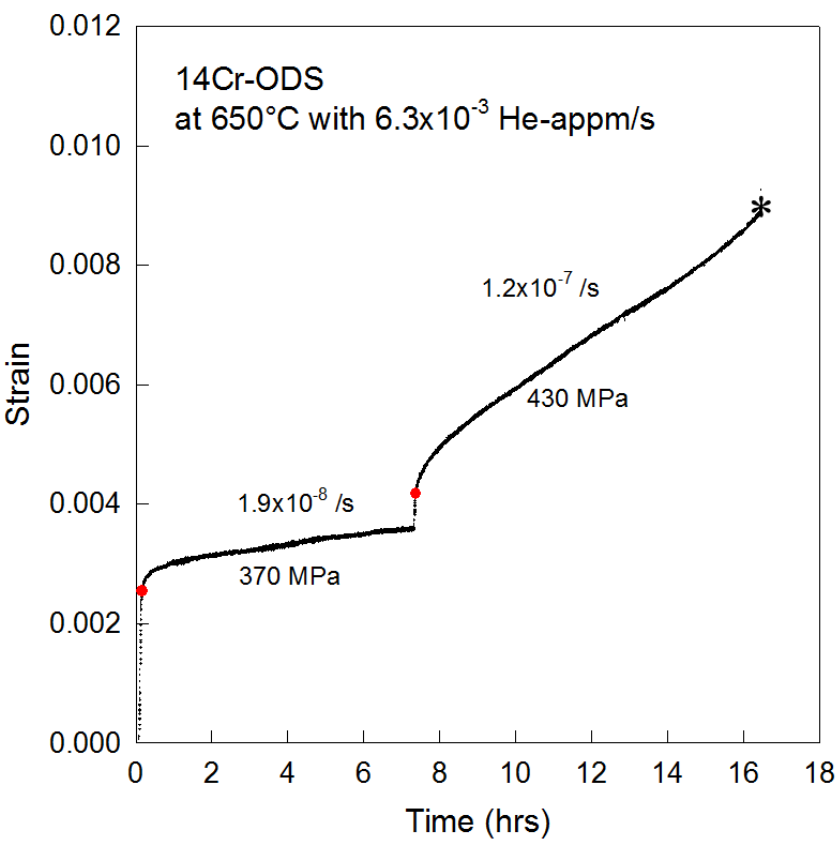
Crack Network Formation due to Cyclic Thermal Shocks

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

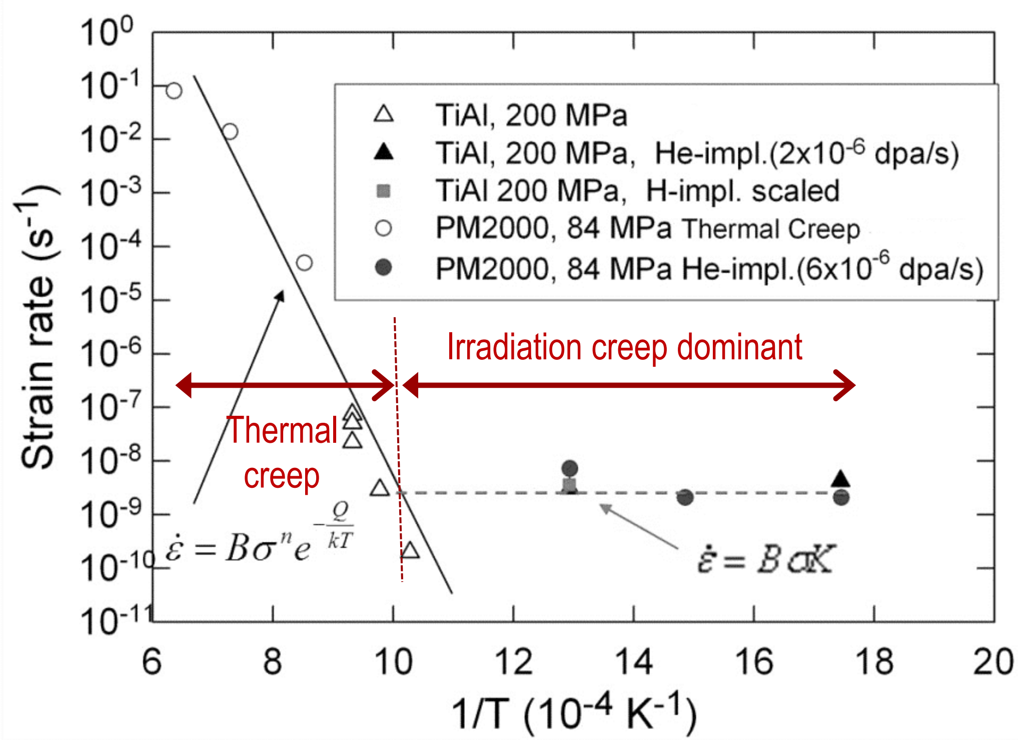


Irradiation Creep of GEN-IV Candidate Materials

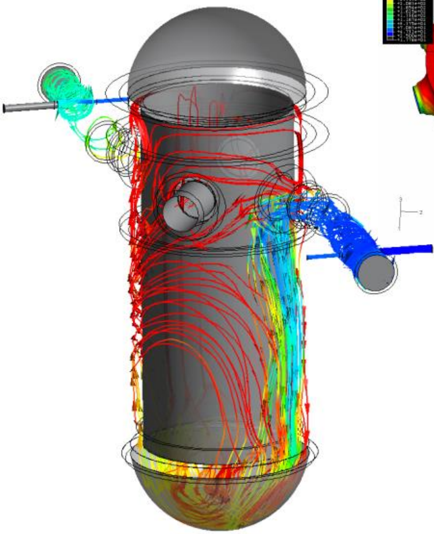
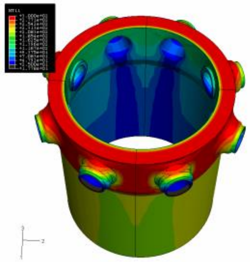
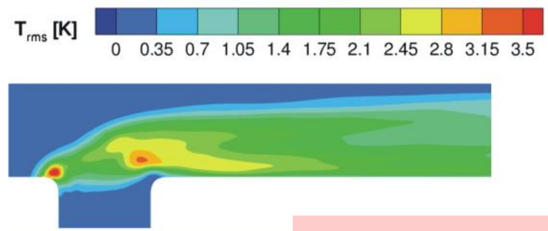
Creep strain of 14Cr ODS during He-implantation at 650°C

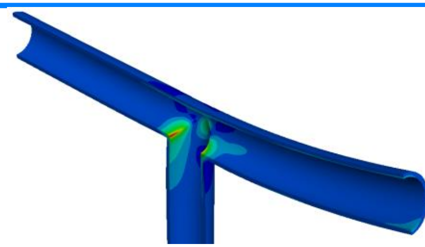
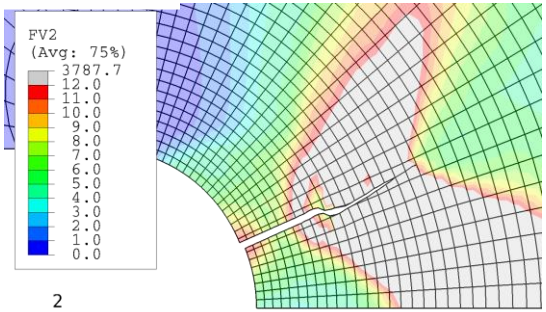


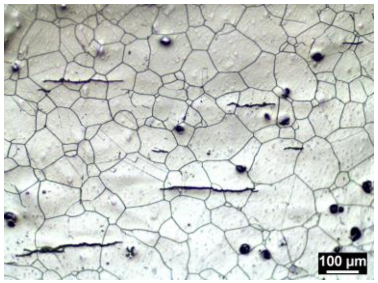
Thermal & irradiation Creep in TiAl and ODS

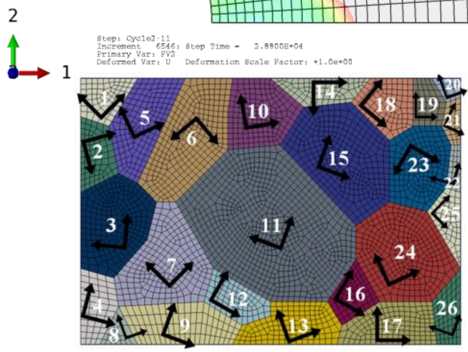


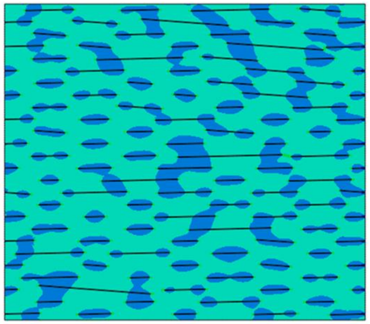
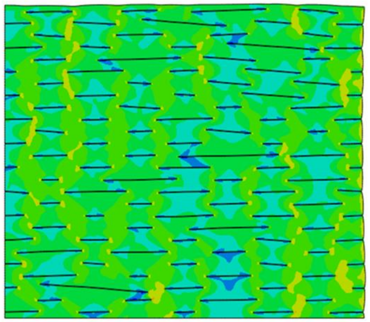
Modeling Activities and Tools in LNM





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,…

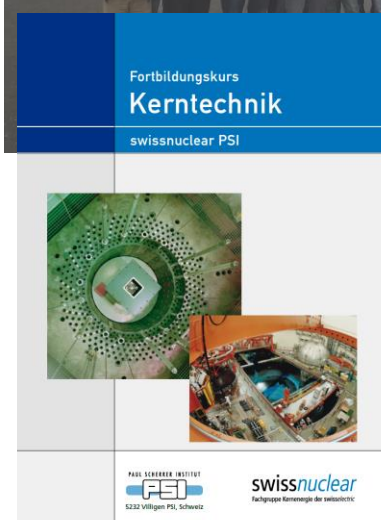
- FEM & X-FEM
- Deterministic & probabilistic methods
- Meso-Scale Field Dislocation Mechanics (MFDM)
- Cristal plasticity (CPFEM)
- Coupling of TH / CFD & SM

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

Education & Teaching Activities

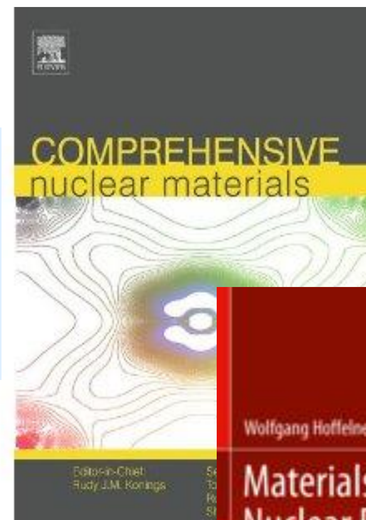
- **10 PhD** and **8 PoD running projects** in LNM
- Contribtuion to **ETHZ/EPFL NE Master** by lectures & master projects
- **EPFL Doctoral School in MS & E and Physics** by lectures
- Contribution to **swissnucelar/PSI education course Kerntechnik**
- Other university teaching (Uni Geneva, …), summer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

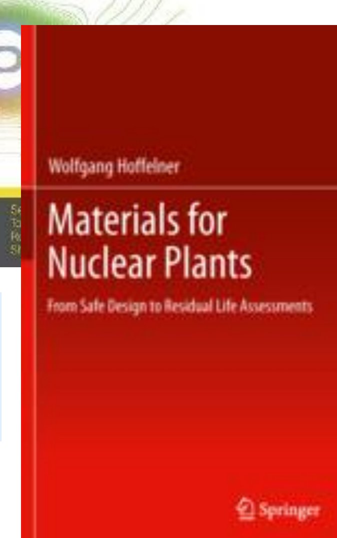
Nuclear Materials Workshop



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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**

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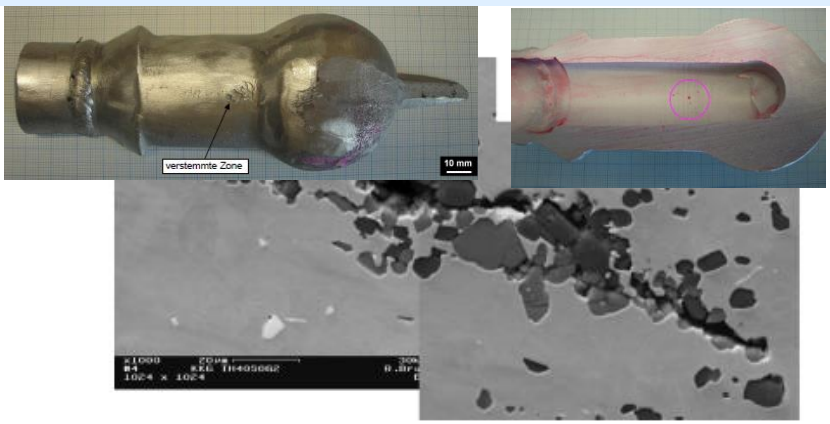
Examples of External Services

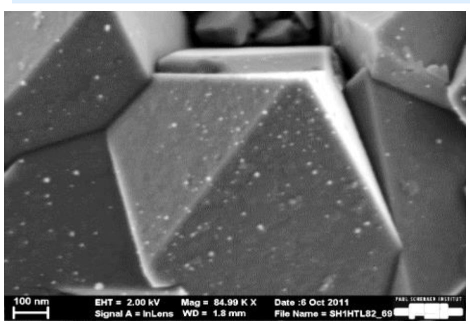
- Expertise on KATAM (basic document of ageing management) for ENSI
- Expertise on SCC of SS for ENSI
- Consulting for CH NPPs (e.g., Overlay repair welding of SCC in feedwater nozzle in KKL)

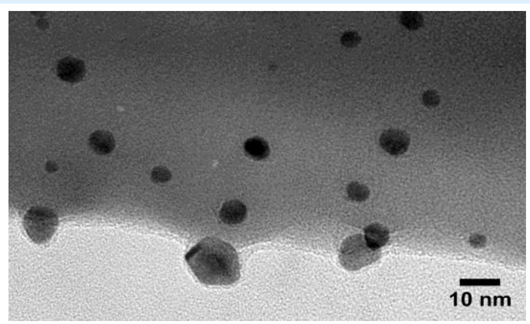
Failure analysis of leaking valve for KKG

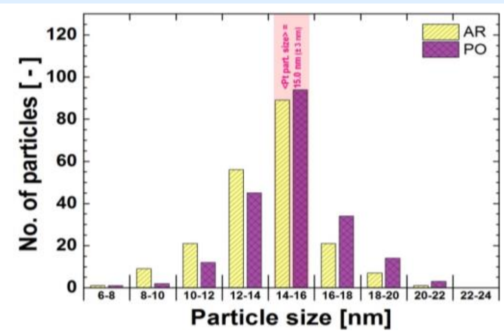


NDT test bodies with fatigue cracks in SS welds for KKG

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







Scientific support of PIE & failure analysis in hotlab

Selected examples of current activities & highlights

Advanced Nuclear Materials

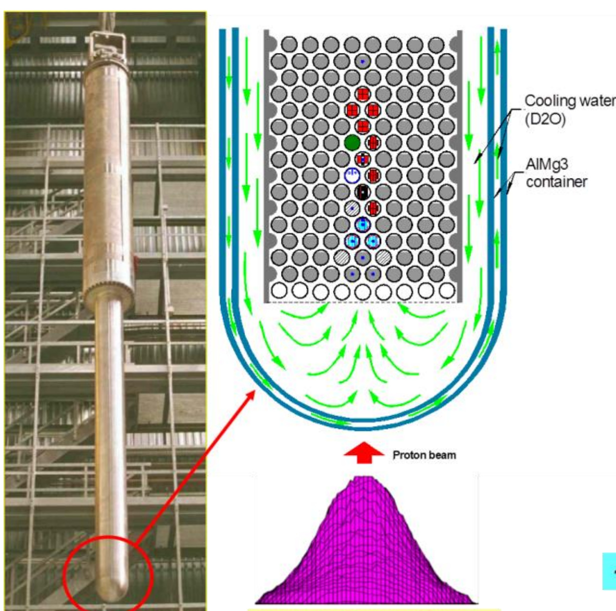
STIP - SINQ Target Irradiation Program

Main purposes:

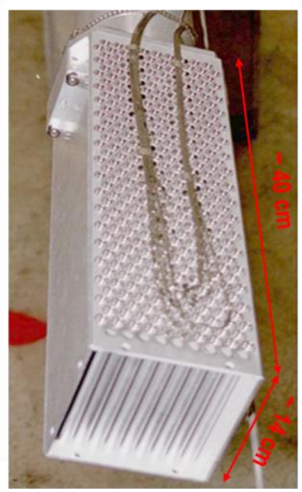
1) to provide necessary materials data for developing advanced spallation targets;
2) to understand radiation, He and H effects in different structural materials;
3) to study liquid metal effects on structural materials in intensive irradiation environments.

The main STIP partners are from spallation, fusion and ADS communities in Europe, Asia and USA (e.g. CEA, FZJ, CIAE, IMP, JAEA, LANL, ORNL, UCSB)

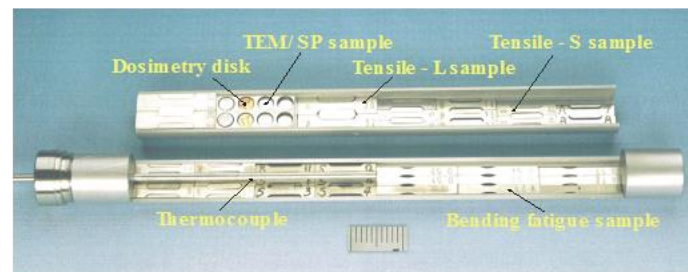
More then 7000 samples from 60+ different materials of Fe-, Al-, Ti- Ni-, Mo- W-alloys, ceramics (C/SiC, SiC/SiC…) were irradiated in first six experiments (STIP-1 to -6) up to **28 dpa / 2000 appm** He (in steels) at temperatures **up to ~800° C**.



σ_x~3.5cm, σ_y~2cm

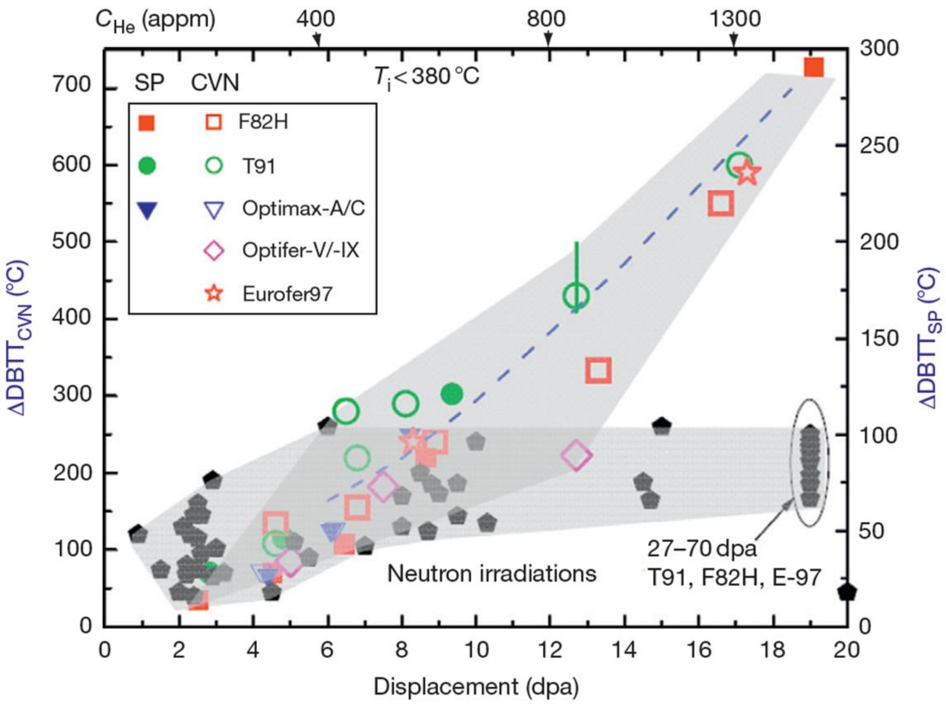


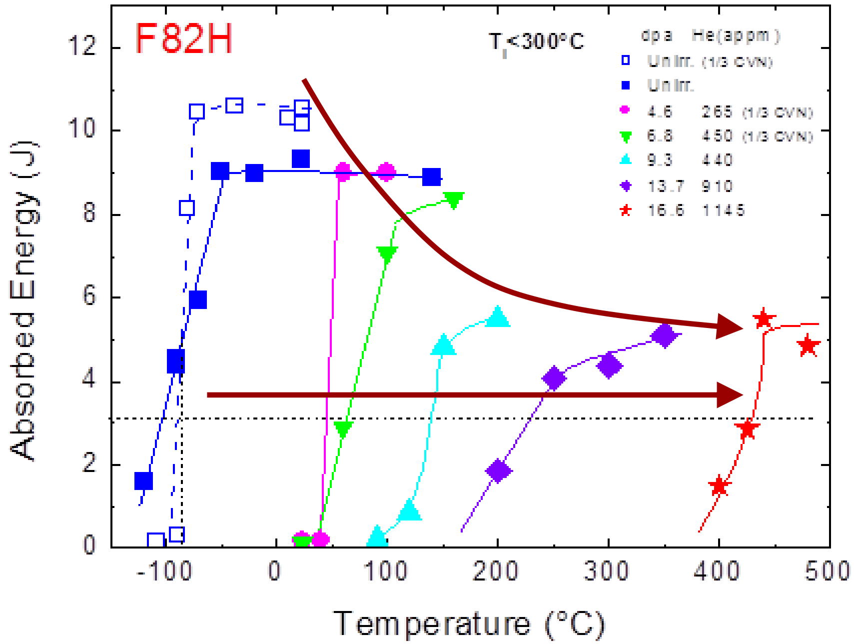
~360 Pb rods with SS / Zy-2 tubes



Examples of STIP Results

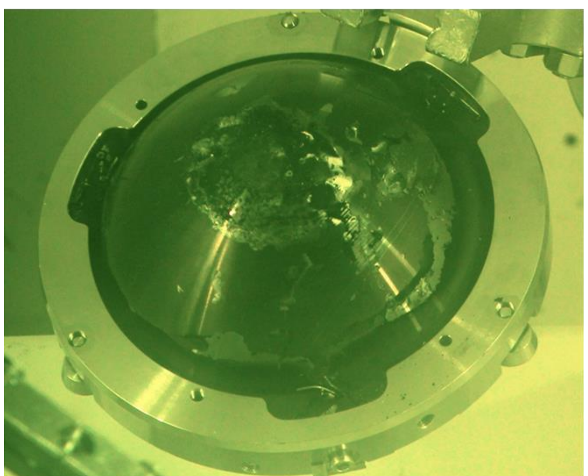
Embrittlement of FM Steels

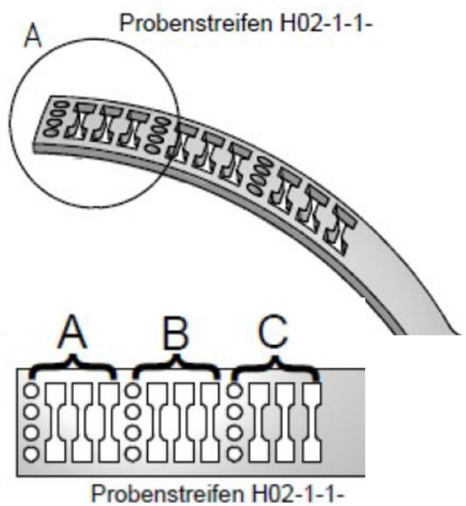


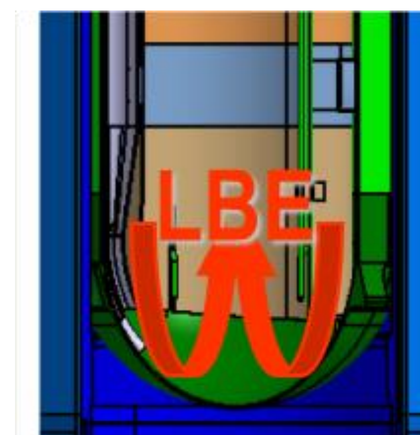


PIE of MEGAPIE (Megawatt Pilot Experiment)

- MEGAPIE is a joint initiative by six European research institutions, the EU, JAEA (Japan), DOE (USA), and KAERI (Korea). Essential Element of EU-/ GERMAT project.
- Design, operate & explore **a liquid PbBi (LBE) spallation target for 1 MW of beam power**.
- The irradiation of the target was done at **PSI in 2006**.
- About **800 samples** were extracted from the lower part of the target for PIE:
  - changes in mechanical properties and microstructure of structural materials
  - radionuclide inventory produced in LBE and their precipitation behavior





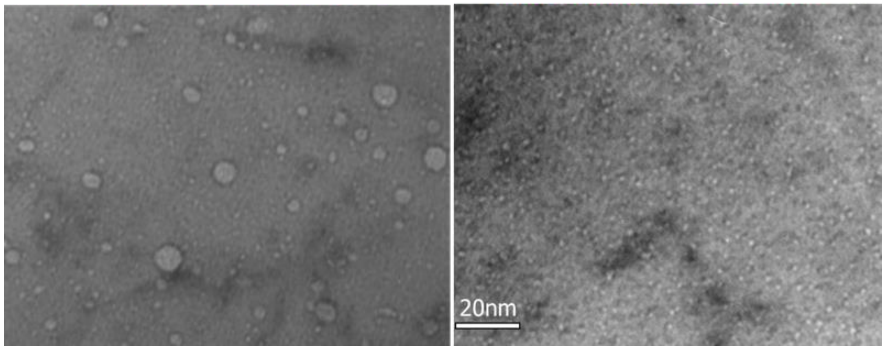


highly activated and α-contaminated samples

Basic Studies on Irradiation Damage & LME

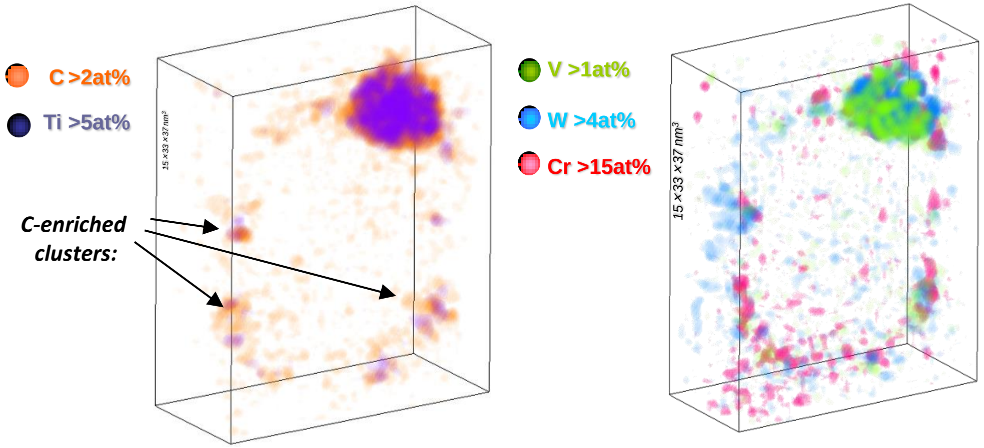
He bubble formation by TEM

F82H	SS 316LN
20.3 dpa, 1800 appm He, 400±50° C	19.6 dpa, 1800 appm He, 420±55° C

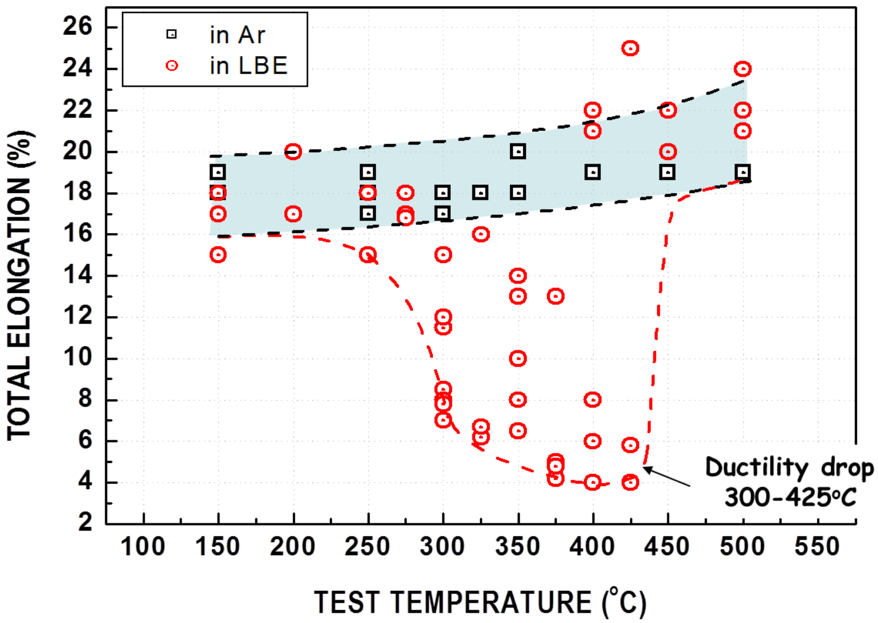


Atom Probe Tomography (ATP)

First time observation of the behaviour of solid spallation products (e.g., Ti) in steels



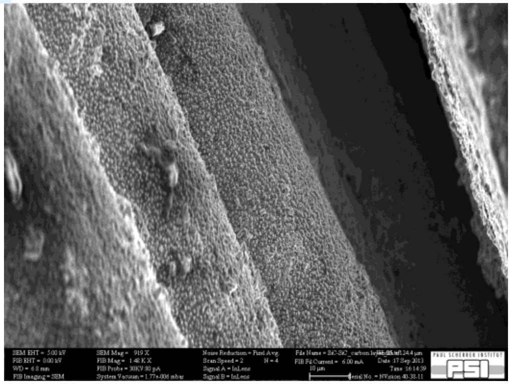
Lead-Bismuth Eutectic (LBE) Embrittlement of FM Steel



Advanced Claddings – PhD Thesis of L. Fave / CCEM

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

PyC layer on SiC fibers



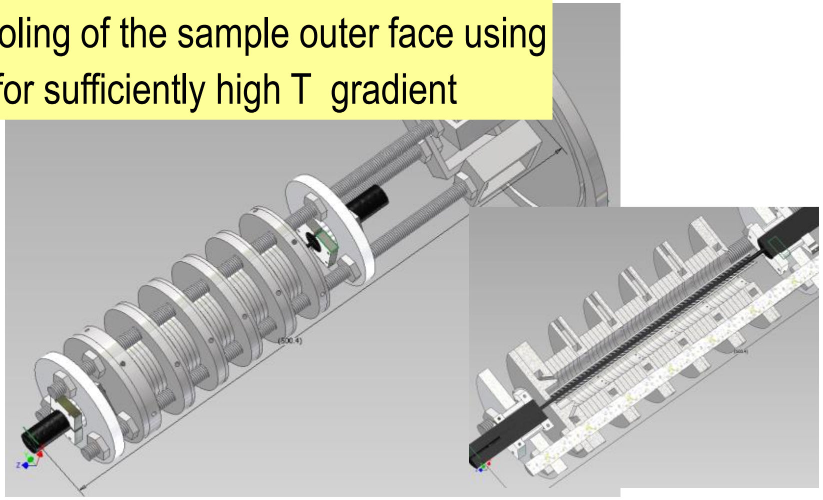
Investigation of SiC based composite tubes as potential cladding materials (e.g., in ATF):

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

Thermal conductivity measurement using radial heat flow

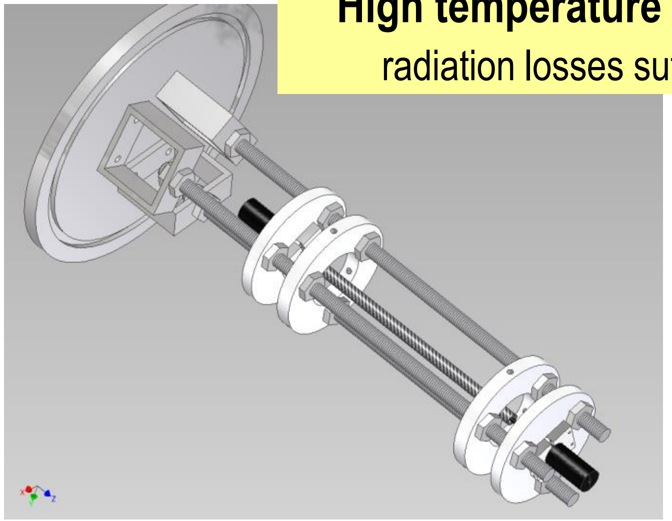
Low temperature setup

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



High temperature setup

radiation losses sufficient

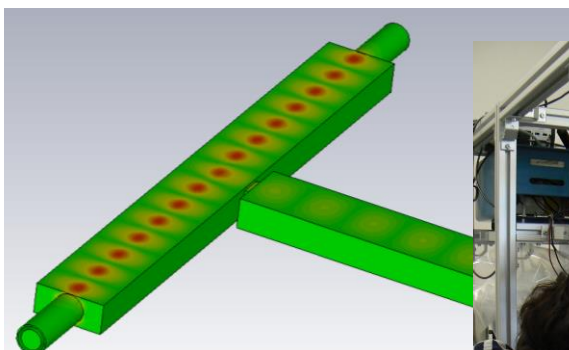


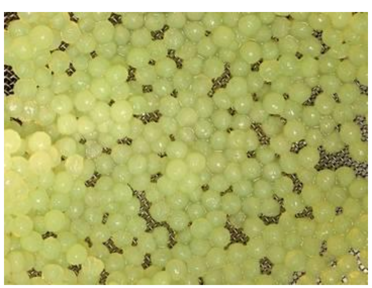
Advanced Fuel & Cladding Concepts (CCEM-/MEAWAT)

CCEM-Project **MeAWaT**: Methods for Adanced Waste Treatment

- Particle fuel (containing MA) production feasibility studies by internal μ-wave gelation technology for fast reactor (FR) & acceleration-driven systems (ADS)
- Collaboration with Chinese ADS project (IMP/CAS) and EMPA, EPFL, LNM, AHL, LTH & LRS

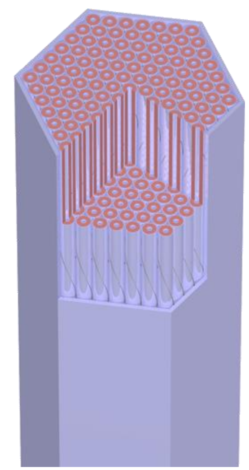
Microwave internal gelation for remote nuclear fuel production → transmutation targets



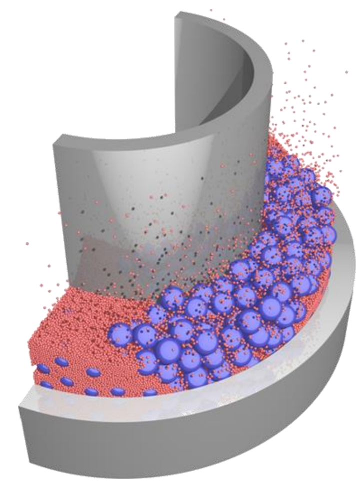


Sphere-pac in annular pin for better heat transfer

Neutronic & thermal-hydrualic analysis by LRS & LTH



FR bundle with annular pins



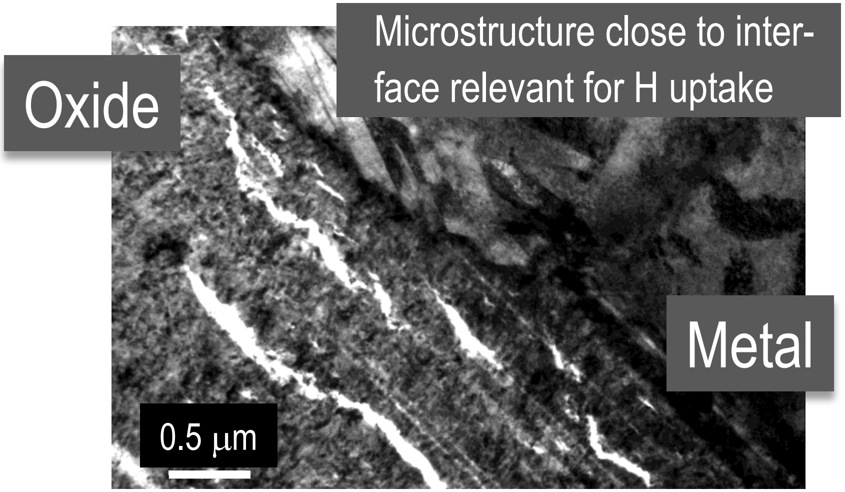
Annular pins with inner and outer cooling

Nuclear Fuels

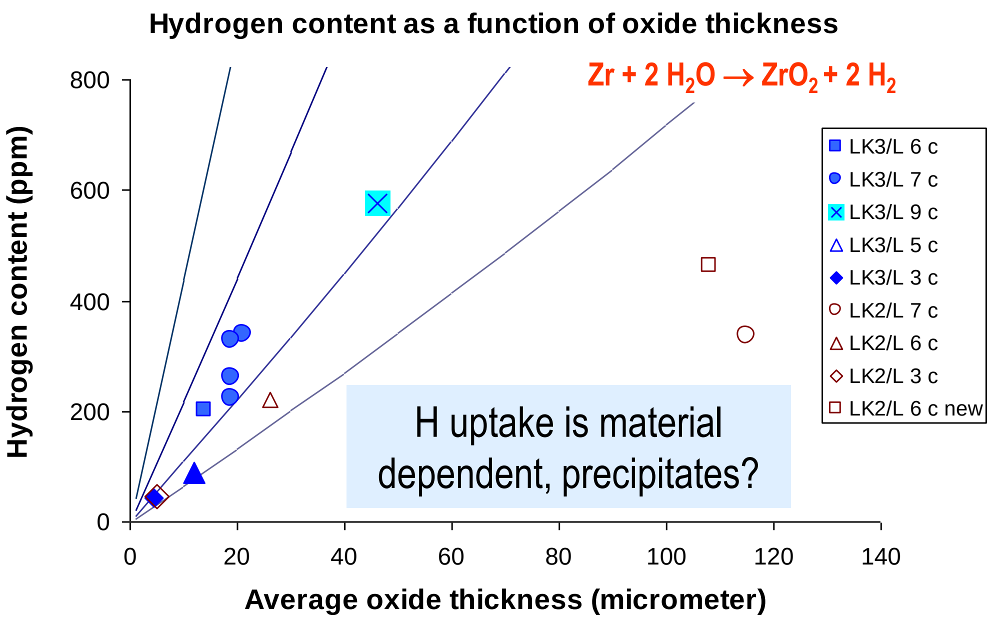
Fuel Cladding Projects – Hydrogen Uptake

- **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**

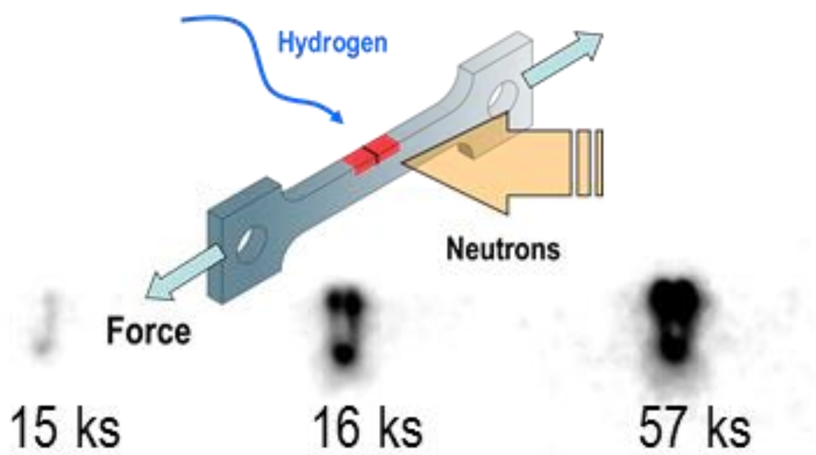


TEM bright field contrast of metal-oxide interface, LK3/L cladding, 7 cycles (BWR / Leibstadt)

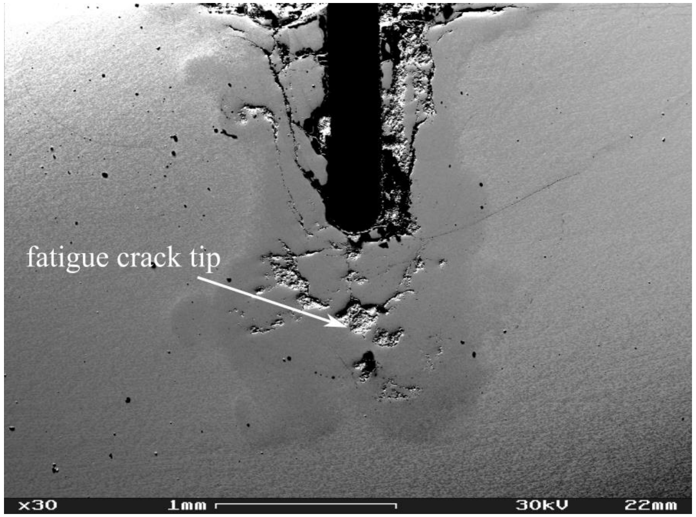


Hydrides in Claddings – In-situ Mechanical Testing

Neutron Tomo- **& Radiography** at **SINQ / NEUTRA**



Heavy hydriding at notch root
BSE SEM image

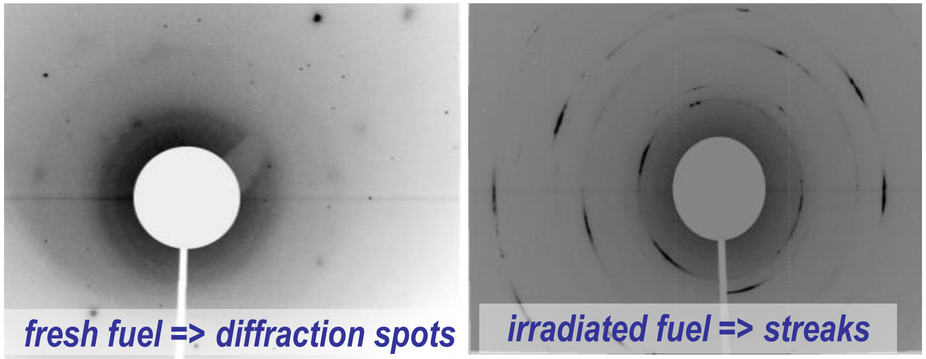


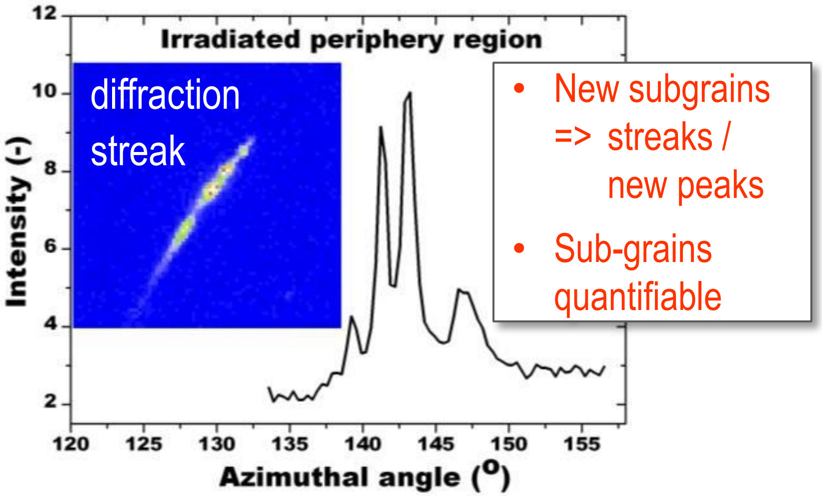
- Hydrogen uptake & distribution in cladding under mechanical stress
- Collaboration with ASQ & KIT,
- Cofund / PSI Fellow project proposal in 2014

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

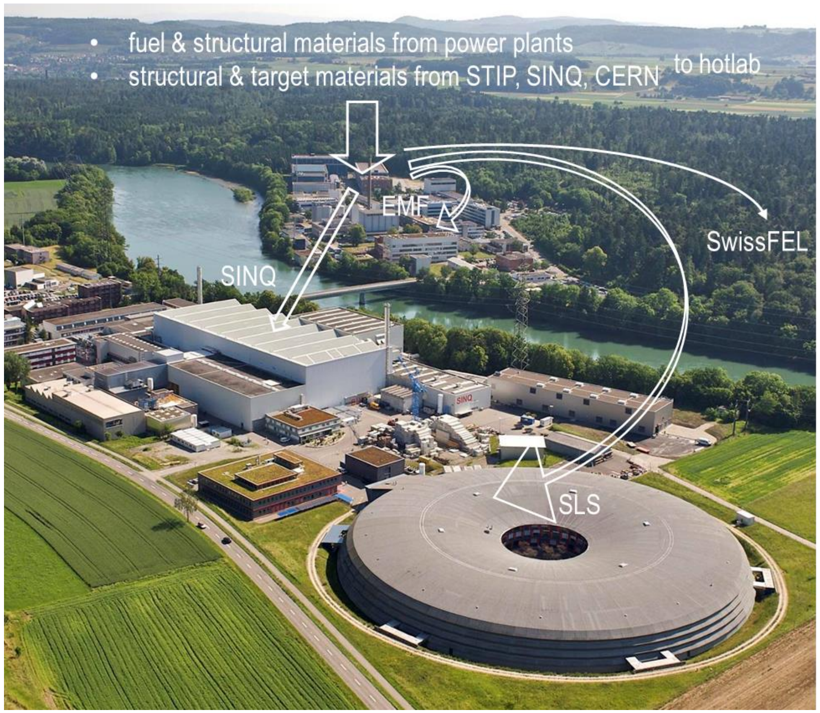
- Performance & safety of nuclear fuel depends on microstructure & crystallography.
- During irradiation fuel changes its structure. Break up of fuel crystallites with increasing burn-up => impact on thermal, physical, mechanical properties.
- For very tiny fuel particles: **crystallographic changes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



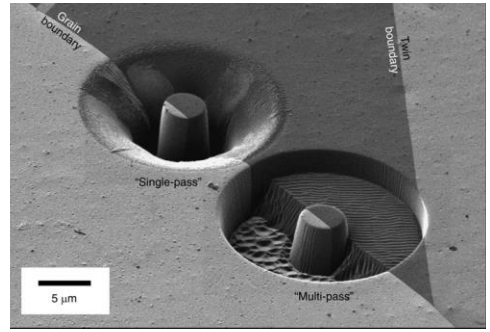


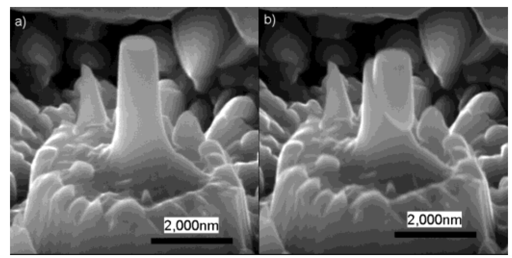
- Practically relevant nuclear material questions with PSI's large-scale facilities
- Leading position with highly radioactive fuel/cladding materials

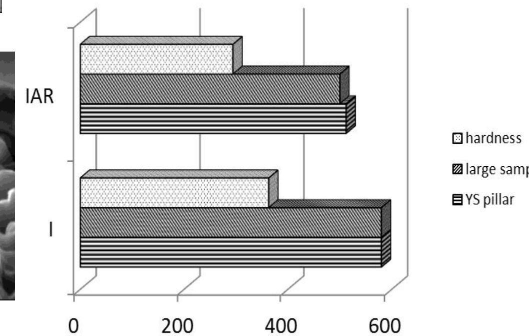
Shielded FIB/SEM – A Key Investment of LNM & AHL



µ-chemical & µ-mechanical characterization (e.g., GB segregation & strength)





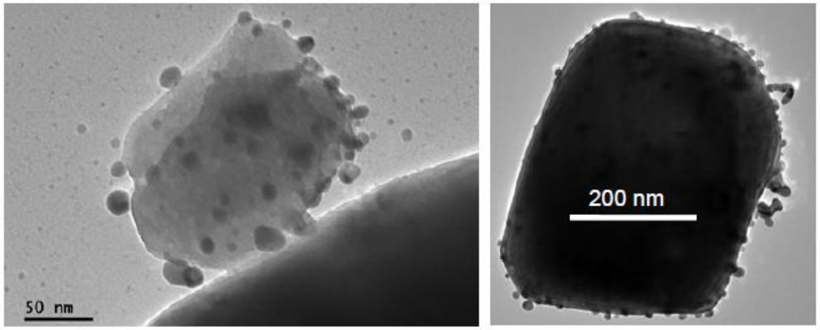


- Joint investment of LNM & AHL of ~ 2 MCHF, SNF-R'equip proposal in 5/2014
- Replacement of 20 y old SEM. Indispensable workhorse for service work, e.g., failure analysis
- Targeted & efficient sub-size sample preparation of highly radioactive materials (LWR fuel & reactor internals, spallation & acclerators) for µ-chemical, -microstructural, & -mechanical characterizations
- Cost reduction, significant efficiency, productivity & capacity increase
- Crucial for the optimal exploitation of PSI's unique research infrastructure (hotlab, SLS, SINQ, EMF), the acquisition of additional competitive second part (e.g., SNF) and international funding (e.g., industry), but also for the attraction of young talents and foreign scientists and for visibility.

Examples of Scientific Services in Nuclear Fuels Project

Scientific support of PIE of spent fuel & failure analysis in hotlab (AHL)

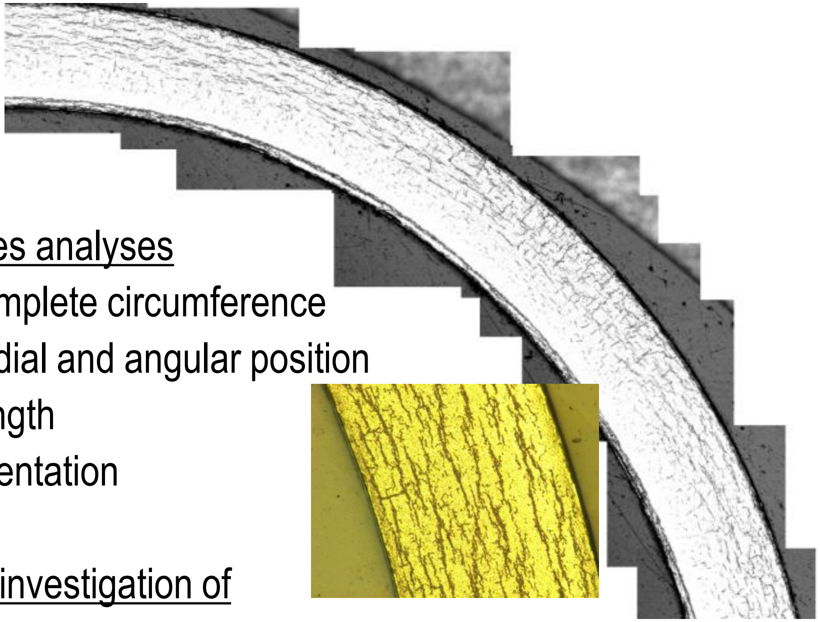
Analysis of fuel crud particles



TEM bright field contrast of CRUD particles decorated with small Pt particles

⇨ Analysis of possible impact of Pt addition on the fuel rods (e.g., on accelerated H uptake or corrosion, increased Crud formation, …)

Quantitative hydride analysis



<u>Hydrides analyses</u>

- Complete circumference
- Radial and angular position
- Length
- Orientation

<u>Allows investigation of</u>

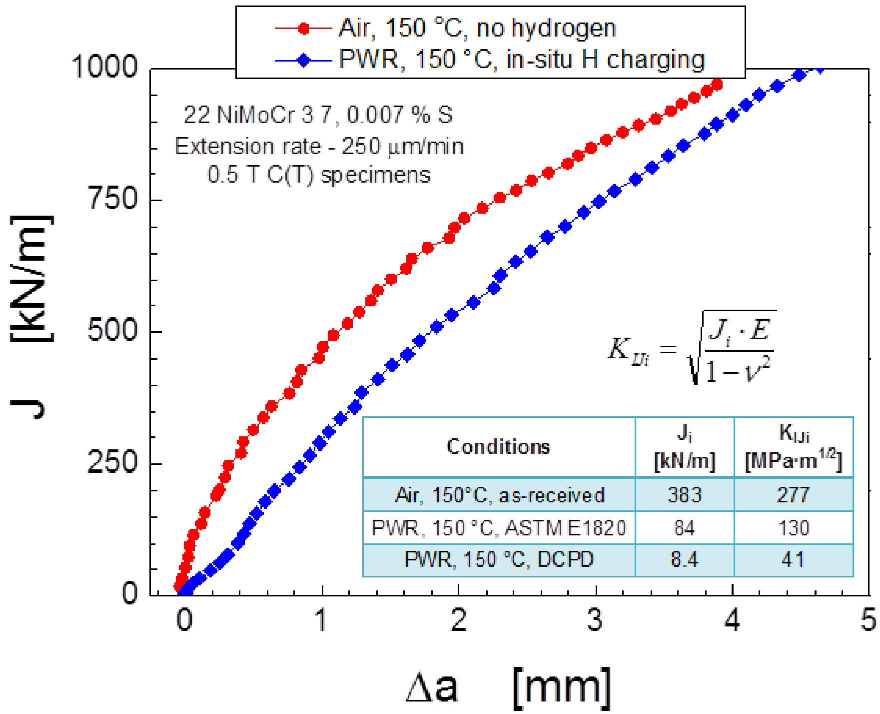
- hydrides reorientation
- Influence of uneven stress distributions (of interest in case of, e.g., soft versus standard pellets, pellet cracks or oxide layer damage)
- Influence of temperature and fluence (axial position, rod position in bundle)

INTEGER

SAFE (2012-14, ENSI): Environmental Assisted Fracture

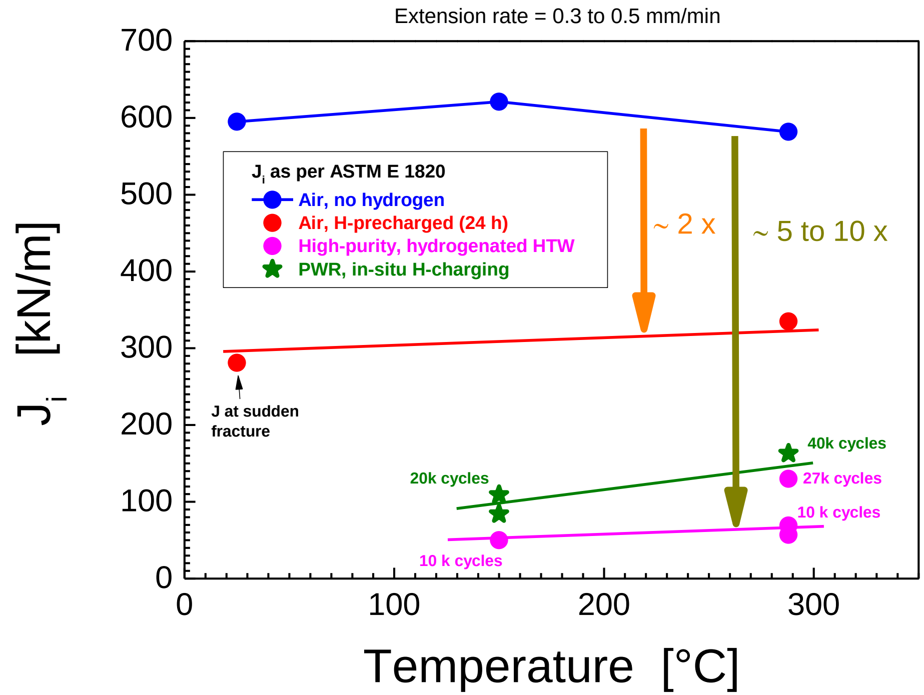
SAFE project: SCC initiation & growth and environmental effects on fatigue & fracture

Results of first screening EPFM tests in hydrogenated high-temperature water



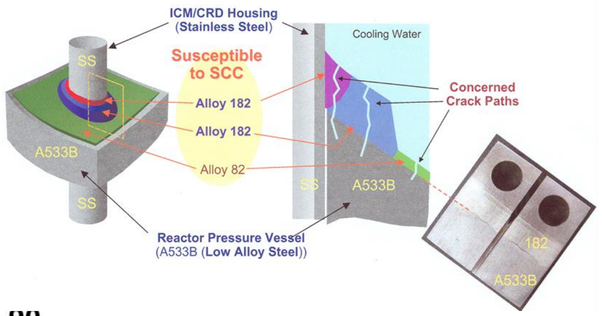
$$K_{IJi} = \sqrt{\frac{J_i \cdot E}{1-\nu^2}}$$

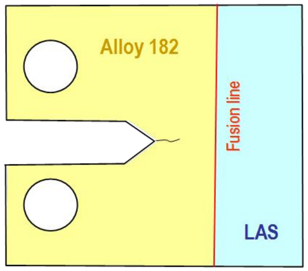
Conditions	J_i [kN/m]	K_{IJi} [MPa·m$^{1/2}$]
Air, 150°C, as-received	383	277
PWR, 150 °C, ASTM E1820	84	130
PWR, 150 °C, DCPD	8.4	41



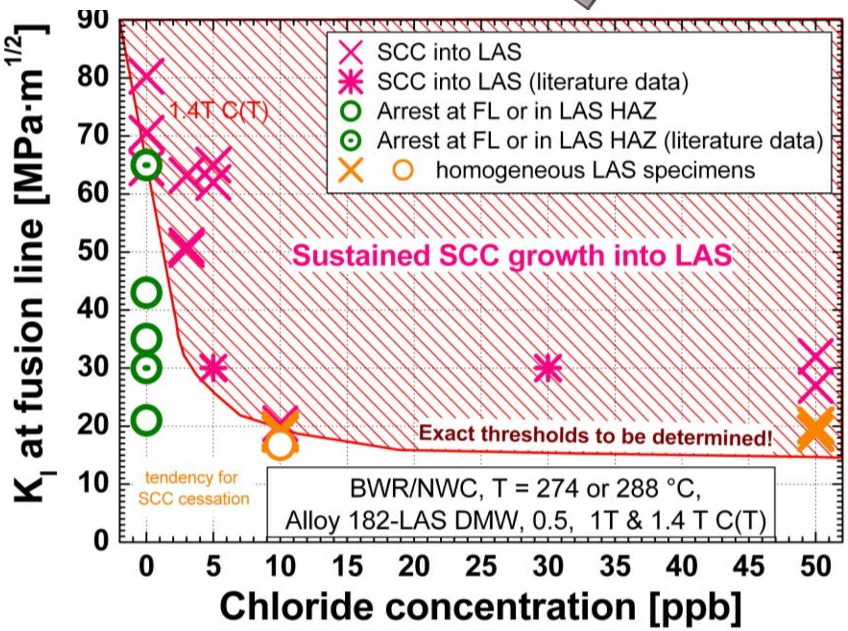
- Significant reduction in initiation toughness (& tearing resistance) in RPV base metal in BWR/HWC & PWR environment compared to fracture toughness tests in air without H
- J_i by DCPD is a factor of ~ 3 lower than J_{ic} by ASTM E1820
- Systematic tests with variation of T, loading rate, environment, pre-exposure time, etc. including simulated peak hardness coarse grain RPV HAZ materials.

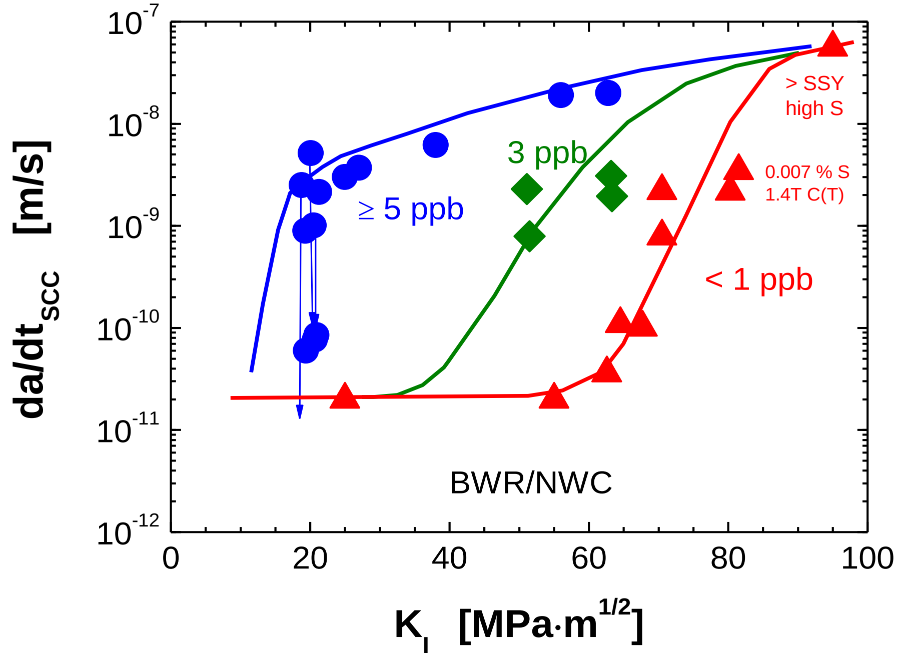
SAFE: SCC in Alloy 182-RPV Steel DMWs in LWRs





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 $MPa{\cdot}m^{1/2}$
- For 3, 5 & 10 ppb of Cl^-, fast SCC into LAS is possible down to at least 50, 30 & 20 $MPa{\cdot}m^{1/2}$, respectively.
- 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

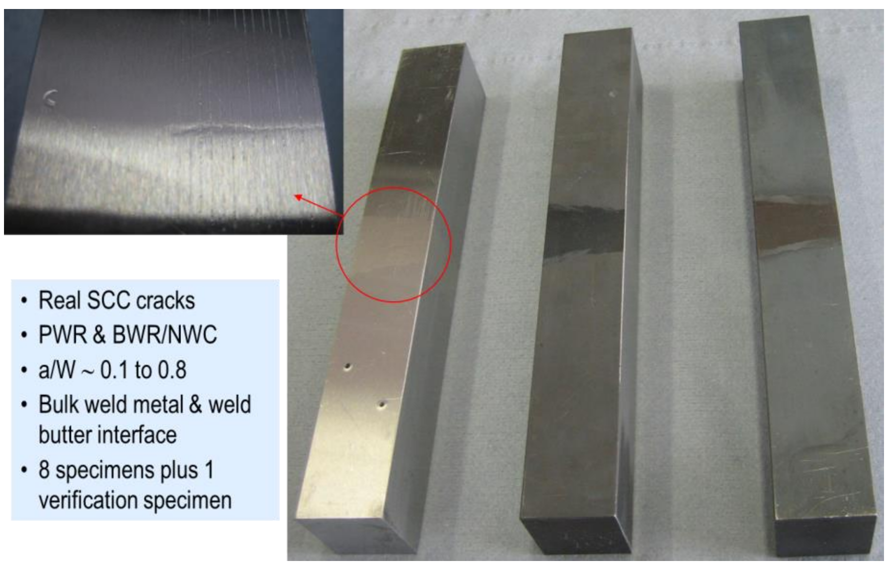
PARENT (2012-15): NDT Test Bodies with SCC Cracks

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

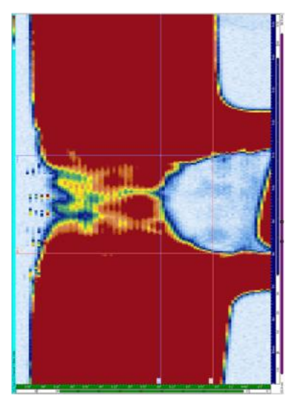
- International program including regulators, industrial groups and research institutions
- Assessment & quantification of established & new promising NDE techniques
- NDT tests bodies with well characterized SCC cracks for open round robin as PSI contribution
- Participation in open and closed round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



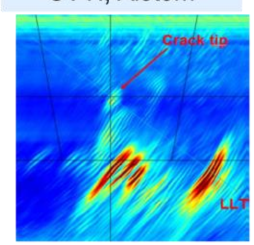
- Real SCC cracks
- PWR & BWR/NWC
- a/W ~ 0.1 to 0.8
- Bulk weld metal & weld butter interface
- 8 specimens plus 1 verification specimen

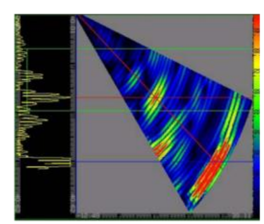
BWR/NWC SCC Crack

UT immersion
Alstom

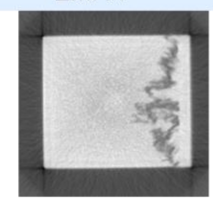


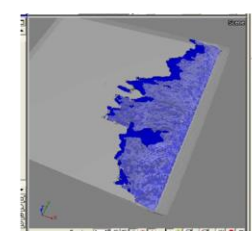
UT phased array
SVTI, Alstom





X-ray radiography & tomography
EMPA

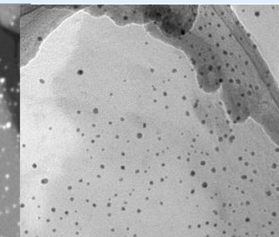


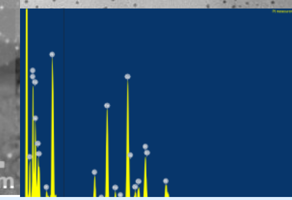


NORA-I & -II - On-line Noblechem in BWRs

Systematic Pt deposition tests in loops & autoclaves with flat & pre-cracked specimens

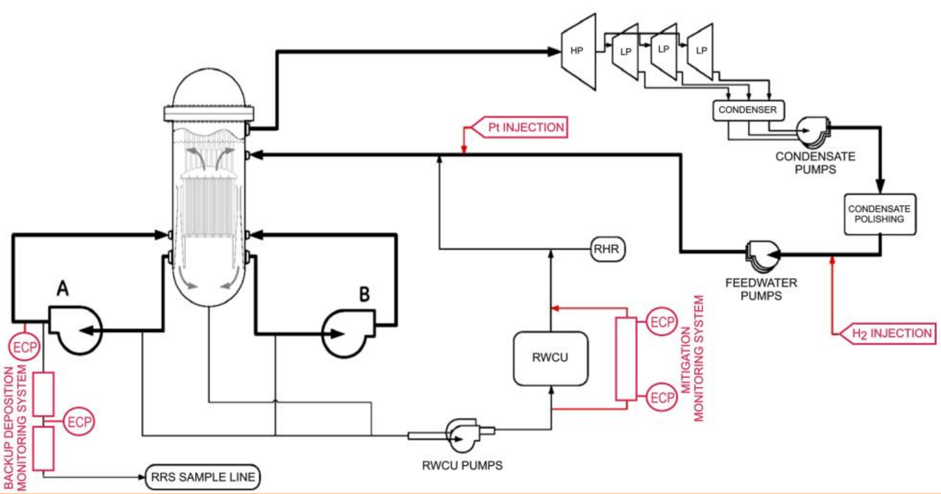
Characterization (size, distribution,conc.) by LA-ICP-MS, FEG-SEM/EDX & TEM/EDX/EELS



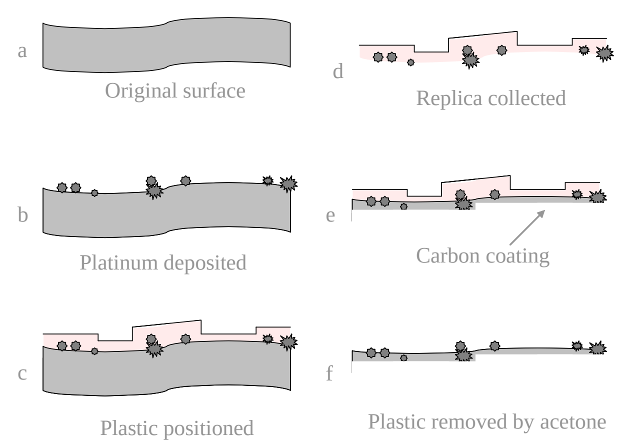


PSI, ENSI, KKL, KKM & collaboration with EPRI BWRVIP
Results of direct practical use (optimal OLNC application)

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



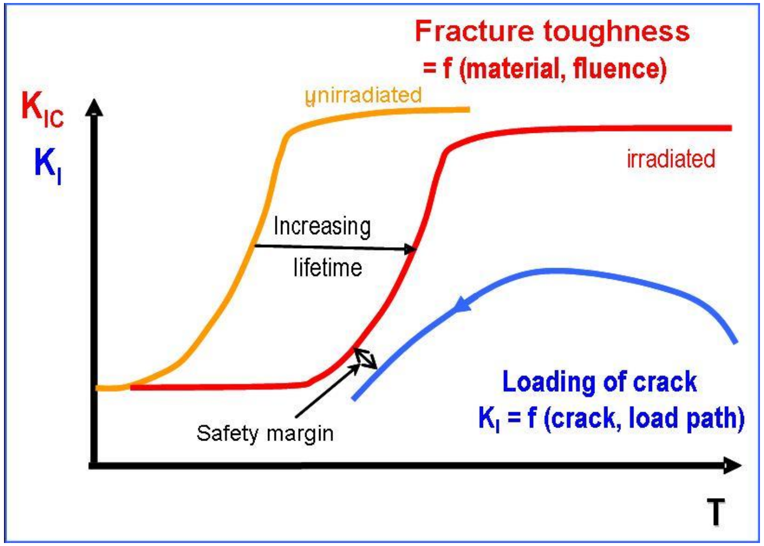
Development of a replica-based ND technique for radioactive components



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, …

PISA: Deterministic & Probabilistic RPV Integrity Assessment

Deterministic



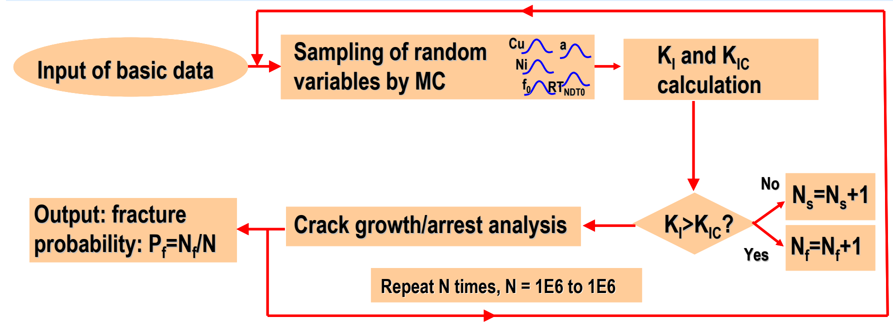
For postulated cracks & all operating & selected bounding accident (e.g., PTS) conditions

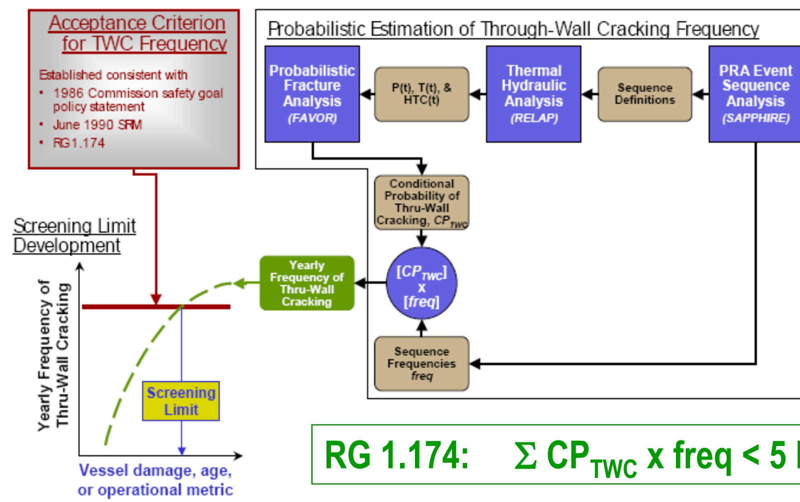
K_I = f(a, load) < K_{IC} or K_{Ia}

Operating conditions → a = ¼ of wall thickness

Accident conditions → a = 2 x NDT resolution limit

Probabilistic



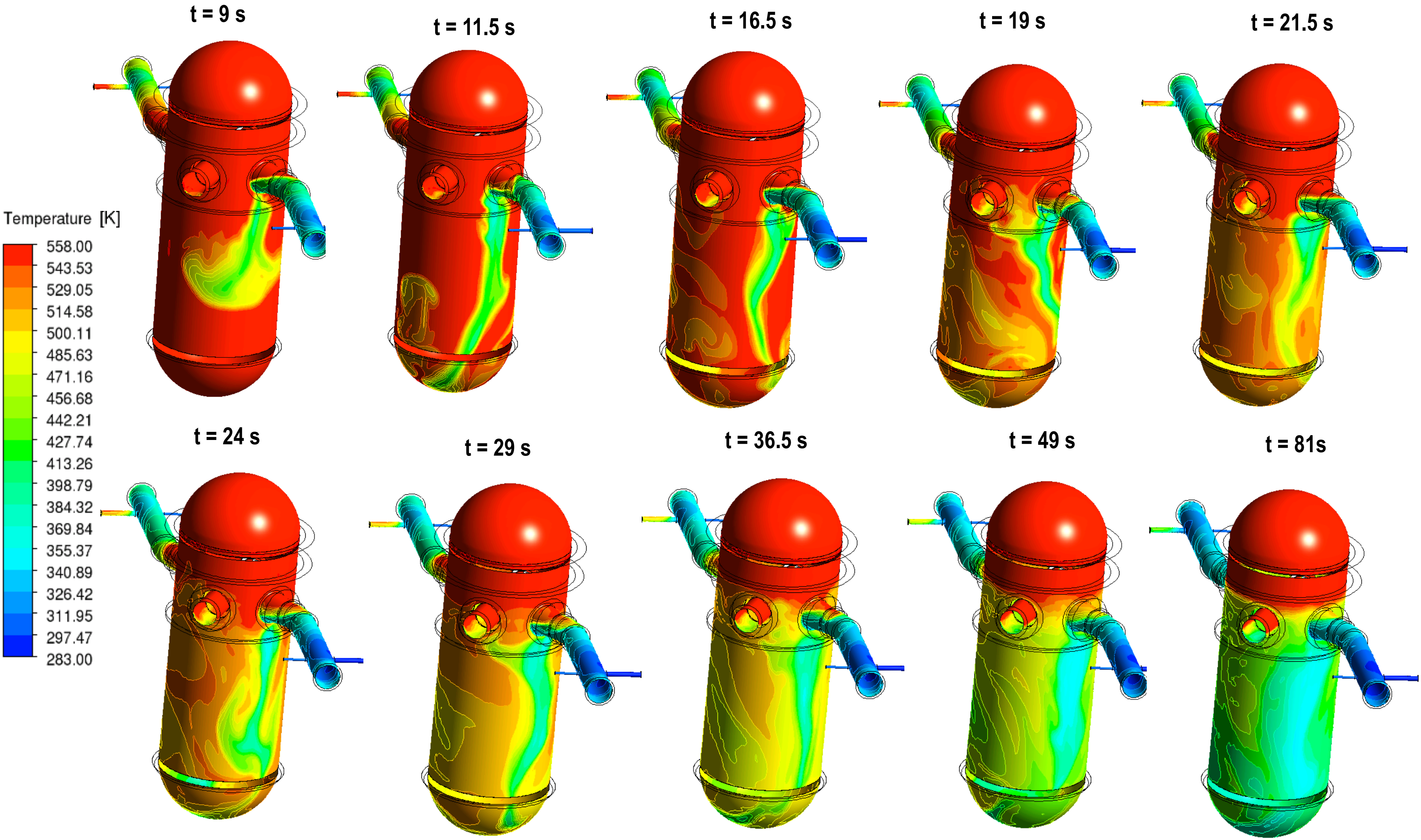


RG 1.174: $\Sigma\, CP_{TWC}$ x freq < 5 E-6 /a

- 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-CFD Analysis of Loss of Coolant Transients

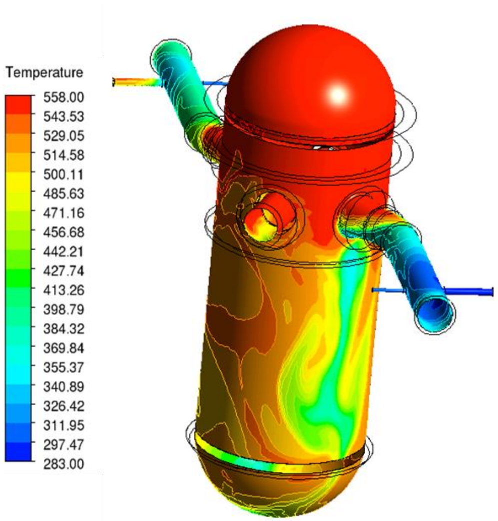
70 cm^2 MLOCA transient with cold water injection in one loop only



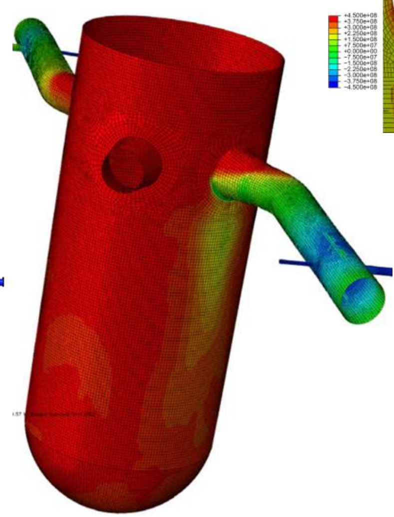
PAUL SCHERRER INSTITUT

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

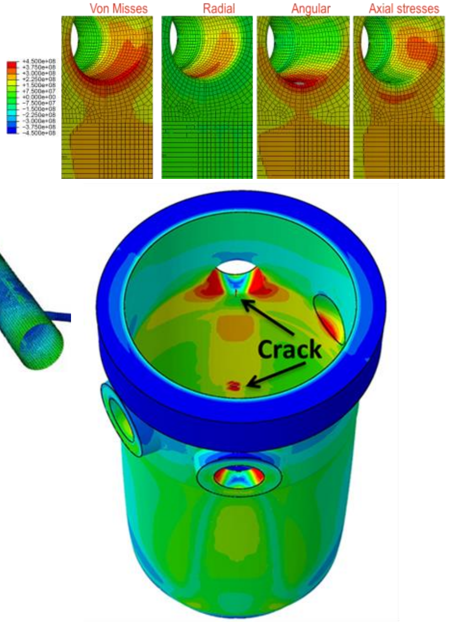
Fluid T



Wall T

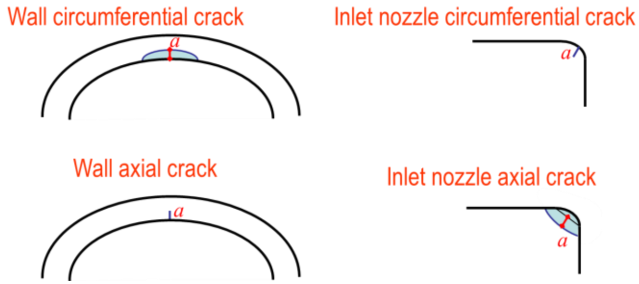


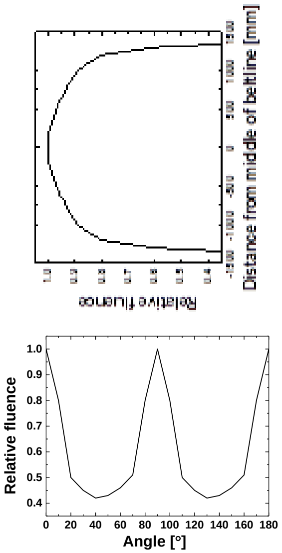
Stress σ



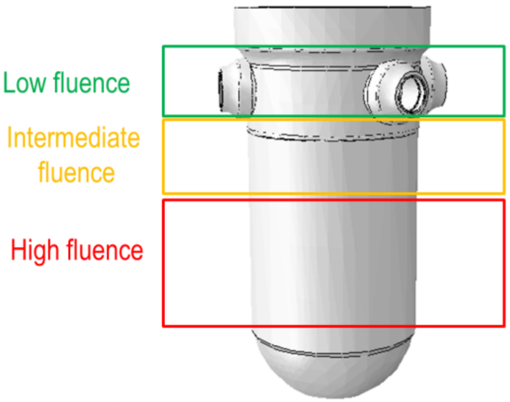
Crack configurations

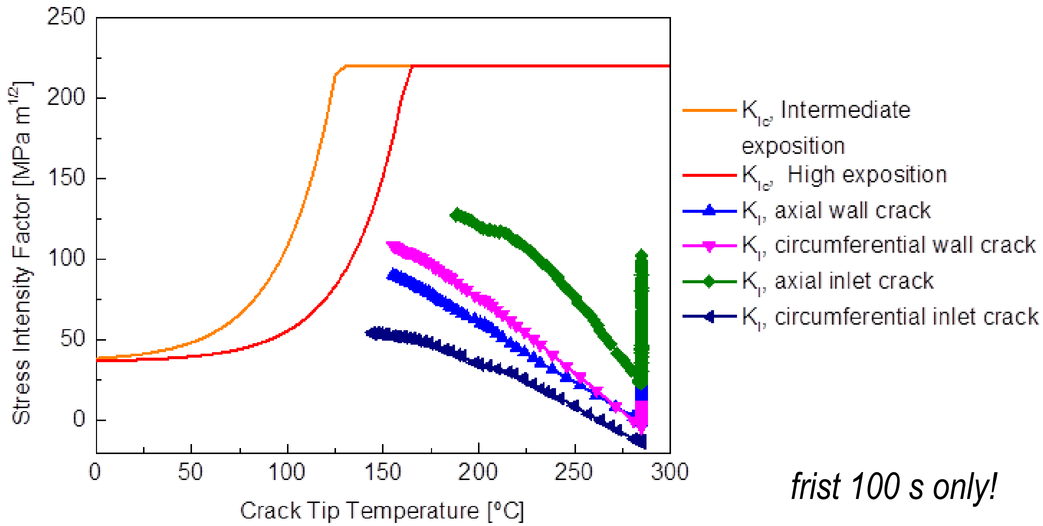
- axial & cirmumferential cracks
- at nozzle corner & cylindrical shell
- inside & outside the plume region
- surface & underclad cracks
- base metal or weld





Fluence
= f(location, operation time)





frist 100 s only!