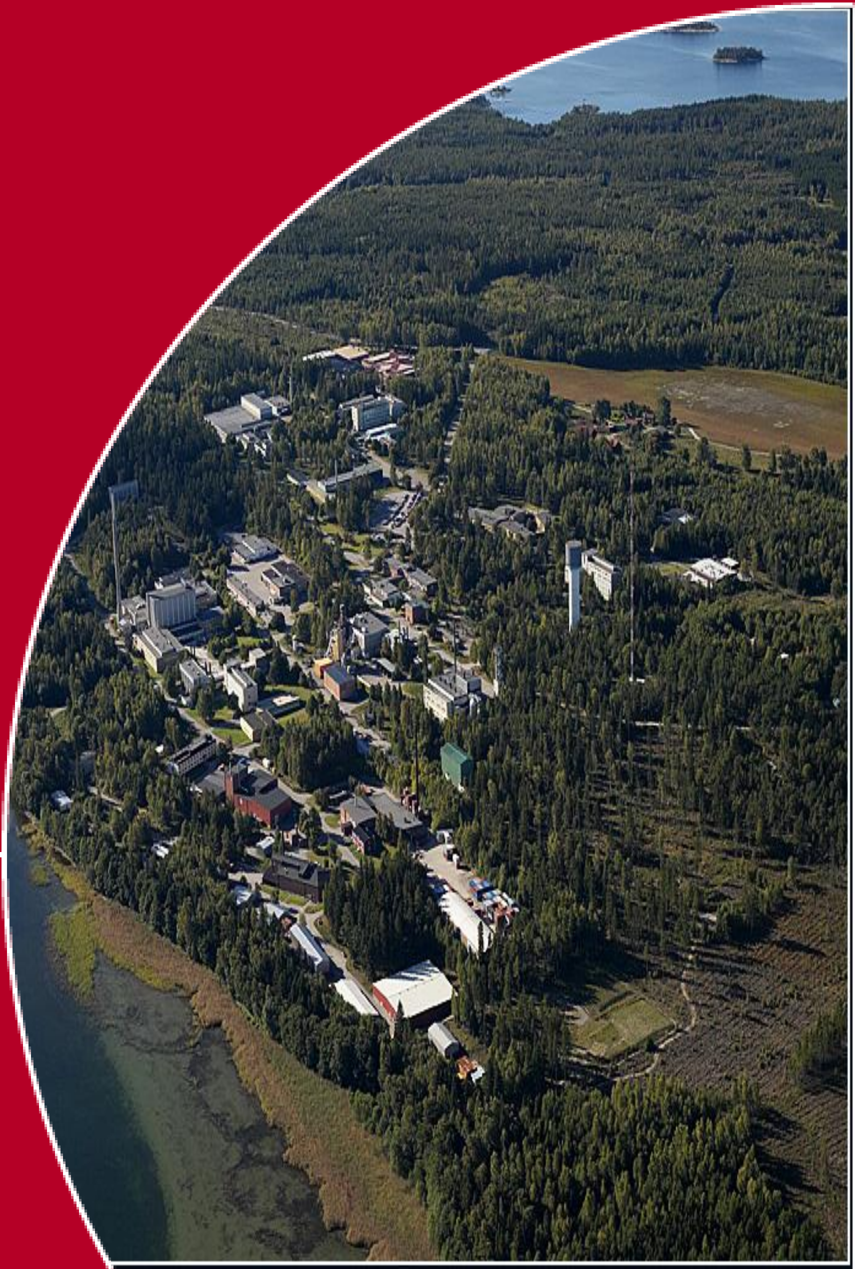
Studsvik

SCIP III - Overview Revised program proposal

Studsvik Nuclear,
Materials Technology,
2013



SCIP III

- Task - LOCA and off-normal temperature transients
  - Fuel fragmentation and dispersal in LOCA
  - Clad overheating. Consequences of off-normal temperature transients for handling and storage of fuel
  - Spent fuel pool LOCA – Cladding behaviour in steam/air mixture
  - Axial load effects on cladding failure
- Task - PCI
  - PCI mitigation effects of slow ramp rates
- Task - Modeling

Fuel fragmentation and SCIPIII

- Fine fuel fragmentation and dispersal in LOCA tests of high burnup fuel has been observed in Studsvik and Halden tests
- Dispersal of fuel in a LOCA is of potential safety significance depending on the quantity released
- Assessments of released fuel depend on scarce experimental data on the thresholds for fine fragmentation (burnup, temperature) and dispersal (strain, rupture size, fill pressure)
- Improved experimental determination of thresholds is required => SCIPIII

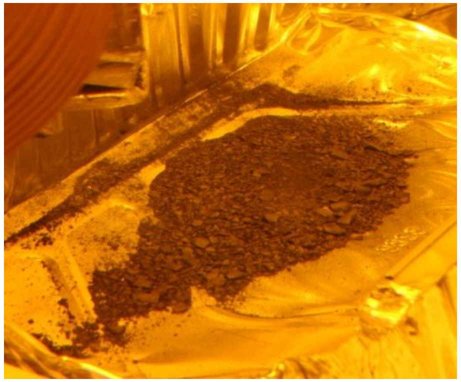
TABLE I. Mass of dispersed fine fuel fragments, in kilograms, based on different choices of burnup, strain, and size thresholds.

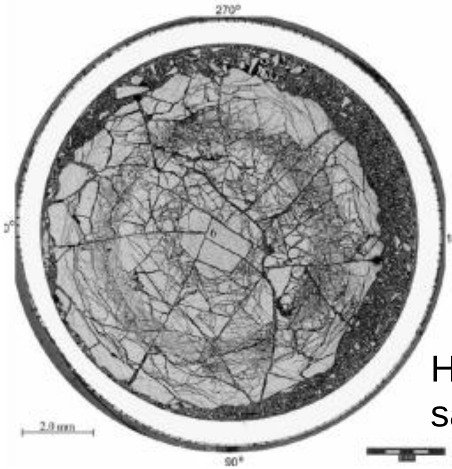
Mass of Fine Fuel Dispersed (kg)		Fine-Enough-to-Disperse Size Threshold (mm)					
Fine Fragmentation Threshold Burnup (GWd/MTU)	Fuel Fragment Mobility Threshold Strain (%)	0.125	0.25	0.5	1	2	4
50	3	9.9	18.0	26.0	34.0	46.8	230.0
	5	3.0	5.5	7.9	10.3	14.2	69.3
	7	2.9	5.2	7.6	9.9	13.6	65.4
60	3	5.8	12.0	17.5	22.4	31.8	215.7
	5	1.7	3.6	5.3	6.7	9.6	64.9
	7	1.6	3.4	4.9	6.3	9.0	61.0
70	3	5.8	12.0	17.5	22.4	31.8	215.7
	5	1.7	3.6	5.3	6.7	9.6	64.9
	7	1.6	3.4	4.9	6.3	9.0	61.0

Ref. P. Raynaud, Core-wide stimates of fuel dispersal during a LOCA, Topfuel 2013

Mechanism for fuel fragmentation

- Burnup threshold for fine fragmentation?
  But fuel microstructure evolves gradually with increasing burnup
- What is the mechanism behind the threshold effect and what is the connection to fuel microstructure and FG distribution in the fuel?
- Examinations of the fuel structure coupling to fragmentation is needed to improve understanding of the mechanism and support model development => SCIPIII





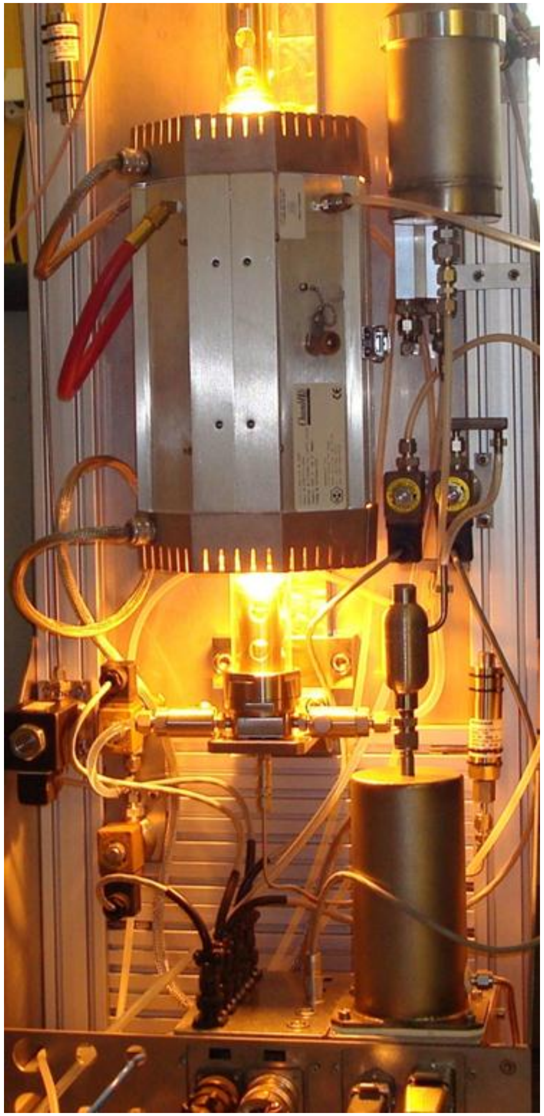
Halden IFA-650.5 test sample (83 MWd/kg)

Why SCIPIII?

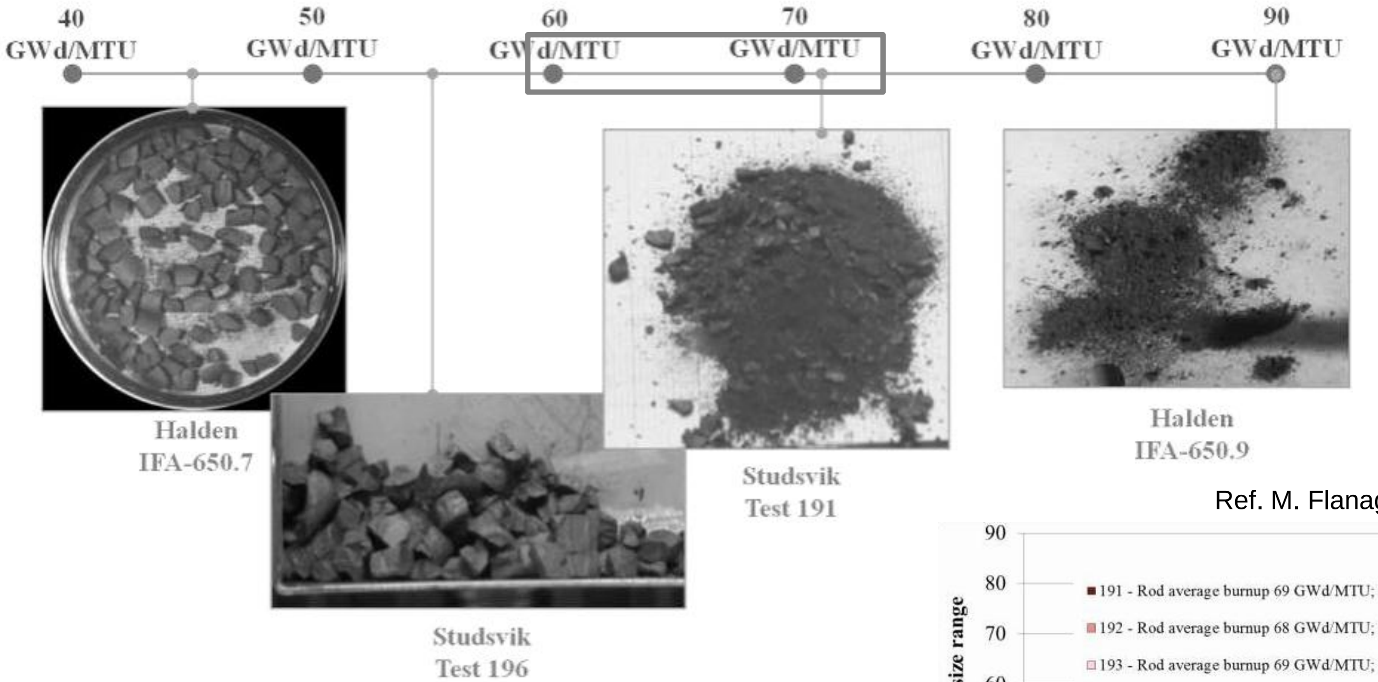
- Safety assessments with respect to fuel dispersal in a LOCA would benefit from the information obtained in SCIPIII
- With more detailed information available potential regulation will be balanced
- Vendors would benefit from more detailed information on the fuel fragmentation for evaluation of the possible impact on fuel design and fuel performance

SCIPIII - Fuel fragmentation and dispersal in LOCA

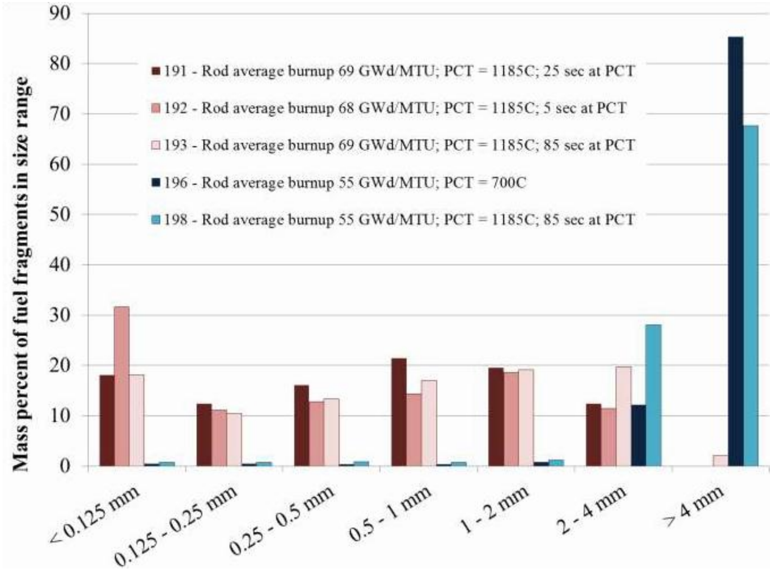
- Experimental program for determining thresholds:
  - Burnup dependence
  - Strain dependence
  - Temperature dependence
  - Gas pressure/volume and depressurization on fragmentation and dispersal
  - Fuel structure effects (effects of power history, additives, fuel-clad bonding)
- Detailed characterization to support understanding of mechanism and modeling
- Benchmark integral tests Halden – Studsvik (Integral tests on sibling material)



Burnup dependence



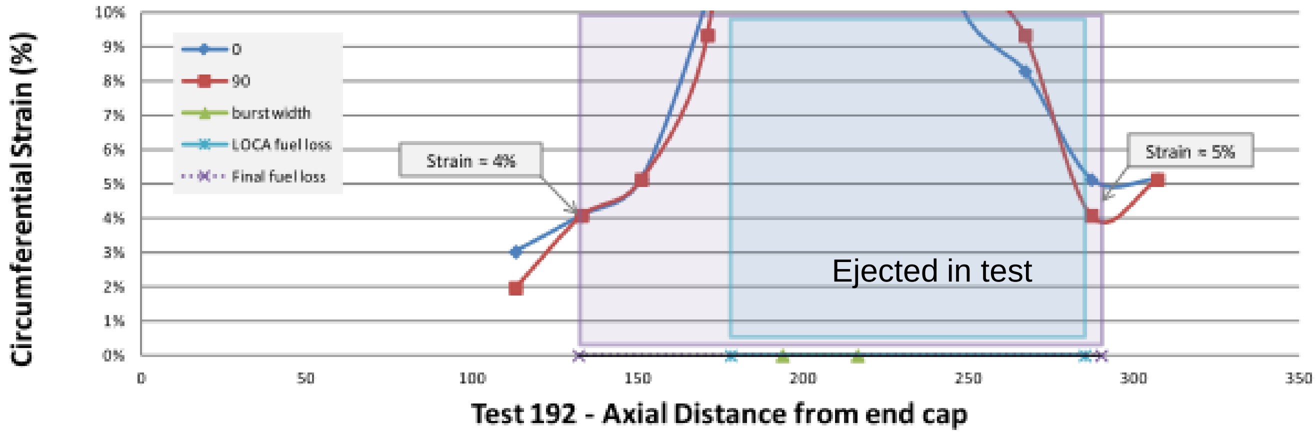
Ref. M. Flanagan et. al., Topfuel 2013



Fragment size distribution

- Improved determination of the burnup threshold for fine fragmentation
- Tests on ~4 samples in the range of 60-75 MWd/kgU

Strain dependence



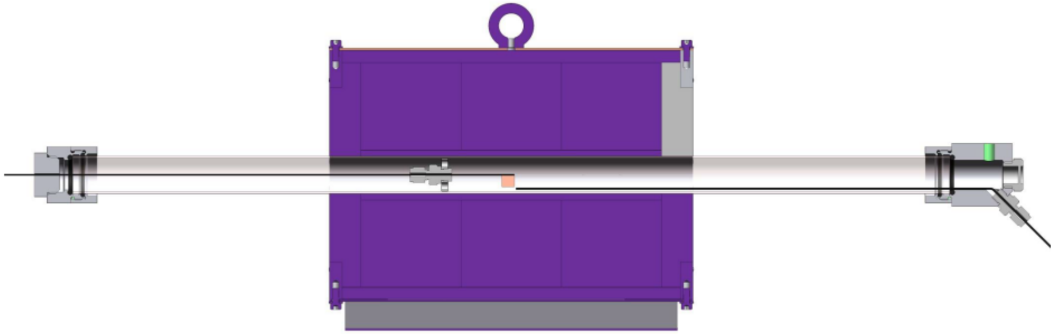
Burnup ~70 MWd/kg

Ref. P. Raynaud, NUREG-2121, 2012

- LOCA tests without rupture for determination of fragment size distribution and mobility as a function strain (avoid effect of depressurization shock)
- Interrupted LOCA tests. Terminate temperature ramp before rupture.
- Test material above the burnup threshold. Consider variation of pressure/temperature conditions
- Connection between fuel fragmentation morphology and pre-transient fuel structure => Support interpretation of fragmentation mechanism

Temperature dependence

- Furnace heating tests of fuel with slit clad (no constraint) gives ”worst” case fragmentation vs. temperature and burnup without depressurization
- FGR will also be obtained using closed capsules
- Tests at several burnup levels (above and below burnup threshold) and at temperatures 650-800 °C
- Fragmentation will be characterized and compared to integral test samples

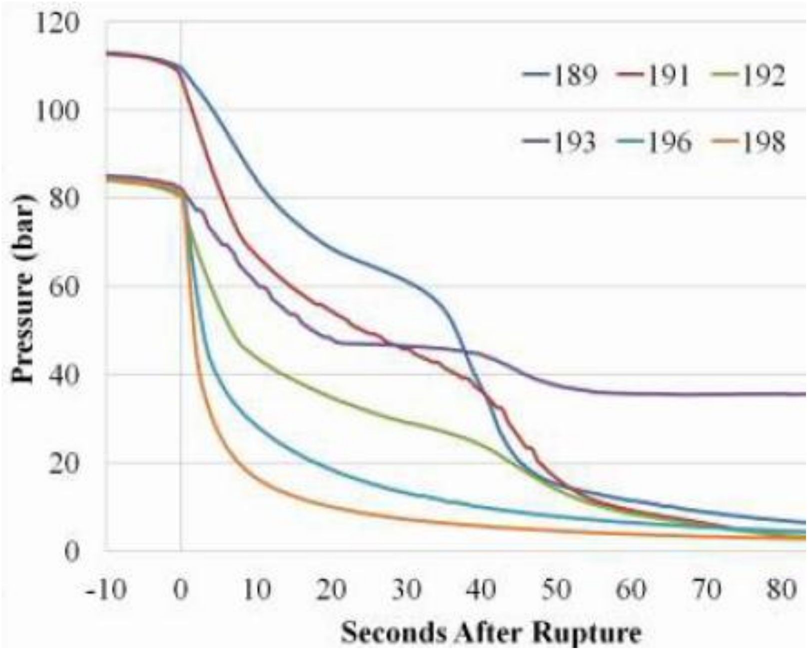


Gas pressure and depressurization on rupture

- Gas pressure determines rupture temperature and opening size
- Rapid depressurization may impact fuel fragmentation and dispersal (ejection of fragments)
- Tests performed above burnup threshold and at different pressures will show the influence of depressurization on fragmentation and fragment ejection
- Effect of depressurization is convoluted with temperature and strain => Use results from temperature tests and tests without rupture to aid interpretation

Plenum volume – Dispersal by gas flow

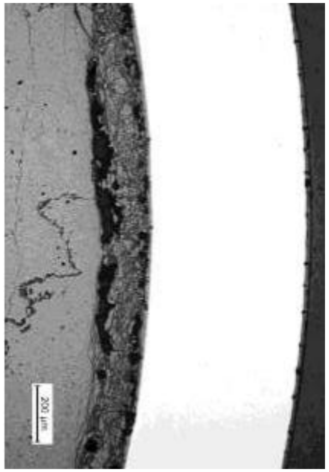
- Large plenum volume may increase fuel dispersal by carrying fragments in the gas flow
- Slow depressurization of the plenum due to ”intact” fuel acting as a plug restricting gas flow
- Limited impact of plenum volume on dispersal
- Test with a different plenum volume and/or gas flow constriction



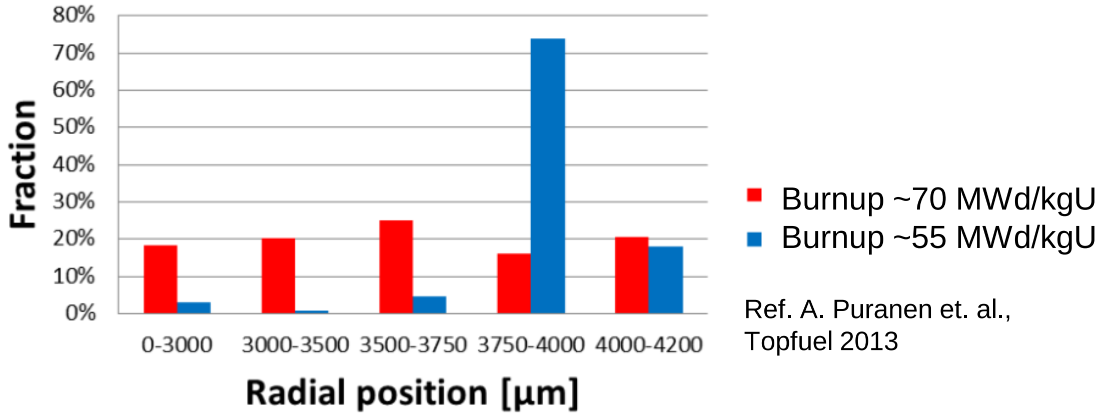
Ref. M. Flanagan et. al., Topfuel 2013

Fuel structure and origin of fragments

- HBS fragments readily from ~50 MWd/kg
- The radial origin of fuel fragments is determined using isotopic profiles (LA, SEM-EPMA), but flat profile over a large radius
- Over the burnup threshold fine fragmentation appears to occur at all radii

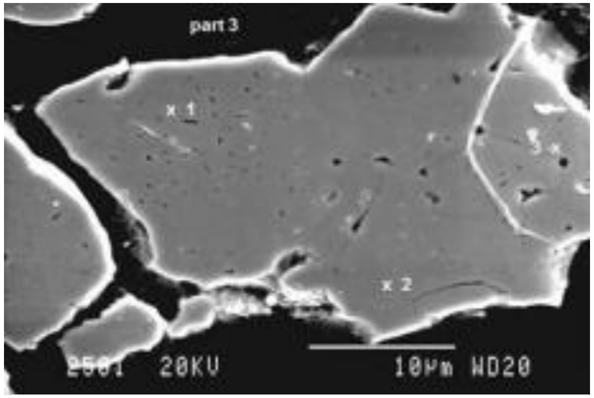


Burnup ~70 MWd/kgU, 120 mm from rupture, small strain



Radial **fine** fragment distribution (Laser-Ablation results)

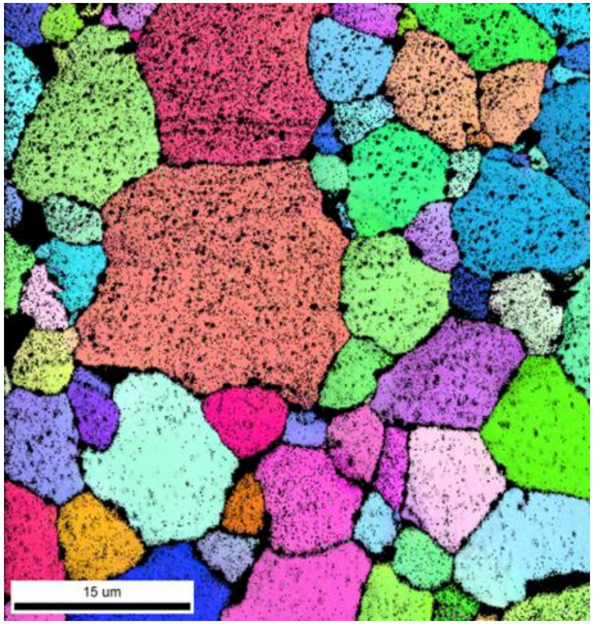
Ref. A. Puranen et. al., Topfuel 2013



SEM of ejected fine fragment. Burnup ~70 MWd/kgU. From inner part of fuel

Fuel structure dependence

- Examine the connection between fragmentation and fuel structure over the burnup threshold
- Gas pore interlinkage on GB and crack opening => large fragments?
- Intragranular pores and subgrain formation => small fragments?
- Position and size distributions of FG bubbles – characterisation & modeling
- SEM-EBSD gives a measure of strain deformation in grains =>"Defect density" as a function of radius
- Tests on fuel with different structure:
  - Additive fuel (large grains and retained FG)
  - Fuel with different power history & fuel-clad bonding

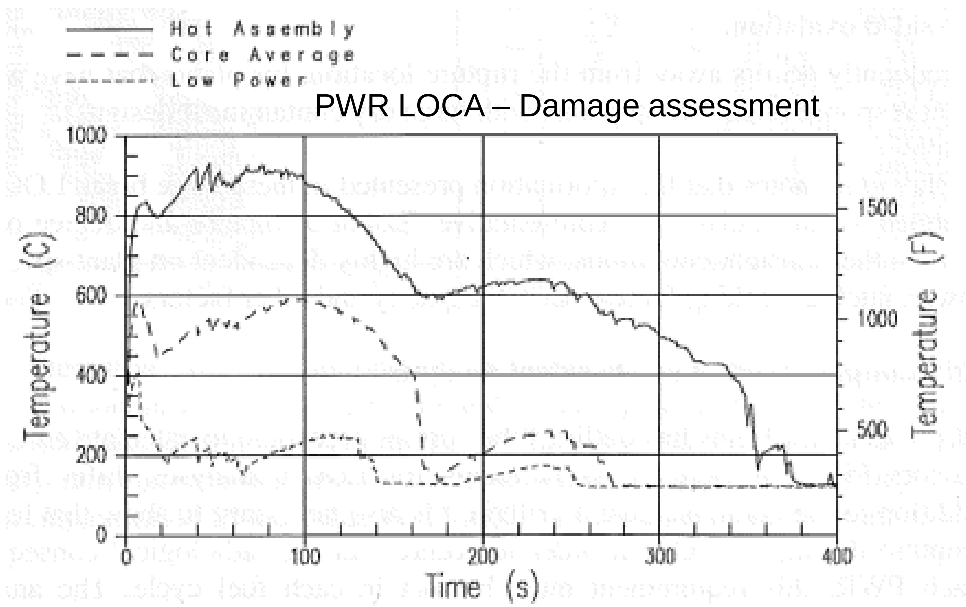


SEM-EBSD gives local information on grain misorientation (strain in grains). Example pellet centre after ramp

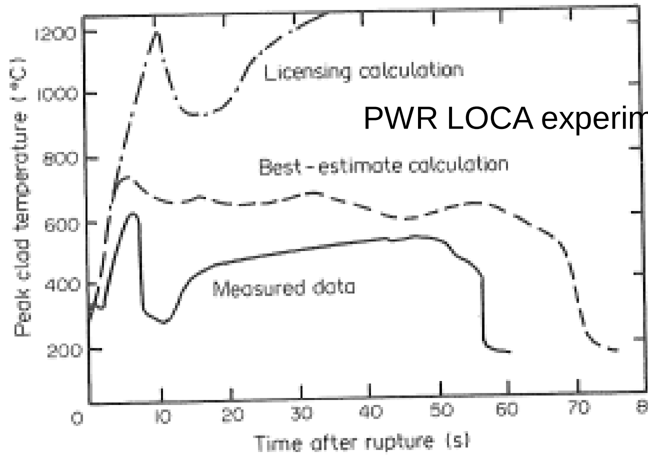
Normal handling of fuel after an off-normal temperature transient?

- Clad overheating occurs in PCM transients, from dry-out scenarios to LOCA
- Depending on severity of the transient fuel may be fit for reuse, not fit for reuse but ”undamaged” or ”damaged”
- SCIPIII studies:
  - Overheating tests on fuel rods
  - Characterization of tested rods
  - Analysis of the ability to meet operational and SNF safety functions
- Basis for establishing criteria for classifying the fuel condition
- Utilities and regulators will benefit from a clarification of the consequences of off-normal temperature transients

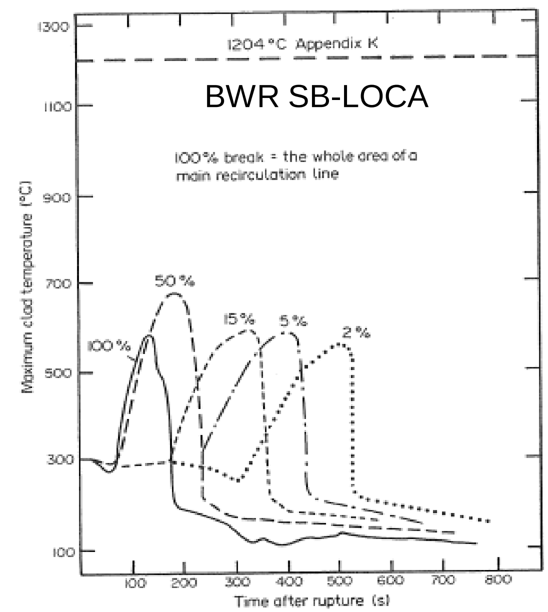
Clad overheating



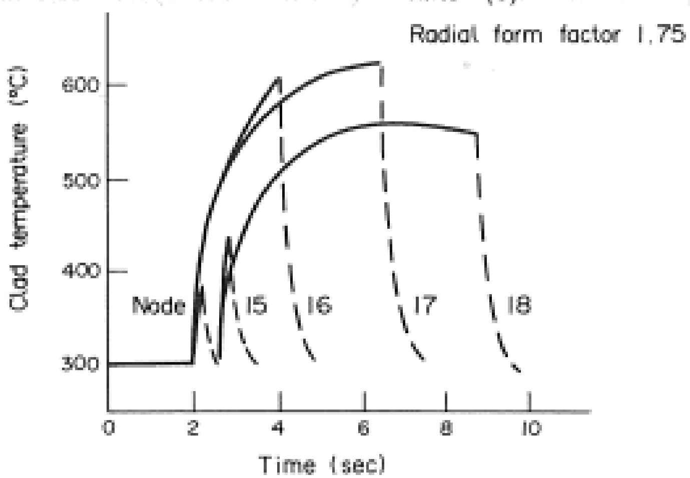
PWR LOCA – Damage assessment



PWR LOCA experiments



BWR SB-LOCA

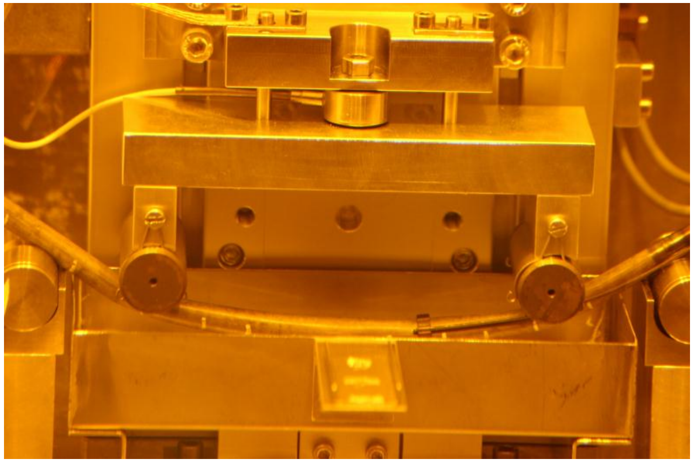


BWR Inadvertent MSIV closure

Peak clad temperatures 500-700°C (1000°C)
Times from 2-3 s to 100-200 s
No or few cladding ruptures
No oxidation

Integral tests

- Simulation of time-temperature histories for different off-normal temperature transients
- Tests without rupture and negligible oxidation
- Main effects to be examined:
  - Integrity and dimensional stability
  - Ductility
  - Creep
  - Oxide and hydrogen characteristics
  - Clad microstructure
  - FGR



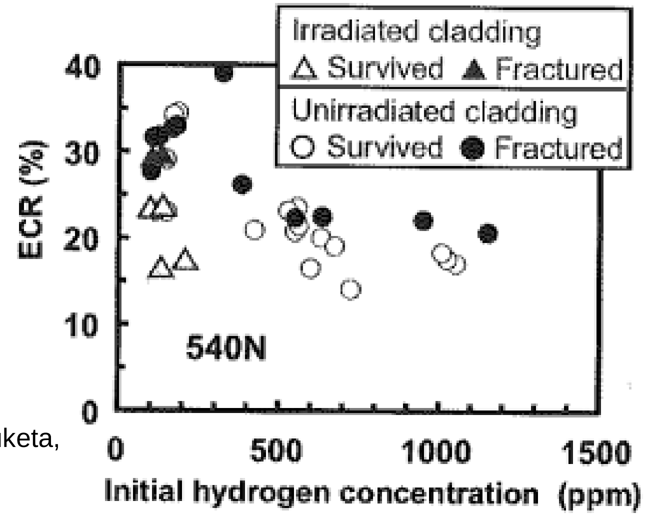
Bend test on fuel rod without oxidation => high ductility

Spent fuel pool LOCA

- The Fukushima accident has shown the importance in considering LOCA scenarios at SFP
- LOCA in SFP would result in clad overheating in a steam+air mixture
- Objective – Support evaluation of fuel degradation under LOCA at spent fuel pools
- Test conditions should be defined to simulate reasonable scenarios:
  - LOCA test in steam+air. Slow ramp 5°C/h.
Long time at peak clad temperature (~1000 °C),
clad rupture and quench
- Characterize cladding condition and PQD

Axial load effects

- For LOCA acceptance criteria based on cladding strength rather than ductility, the conditions that can cause break of the fuel rod need to include axial load effects during the quench phase
- Axial tensile stress can occur in the quench phase if the rod is locked by rod-to-grid linkage
- Limited data. No tests on irradiated rod sections with fuel

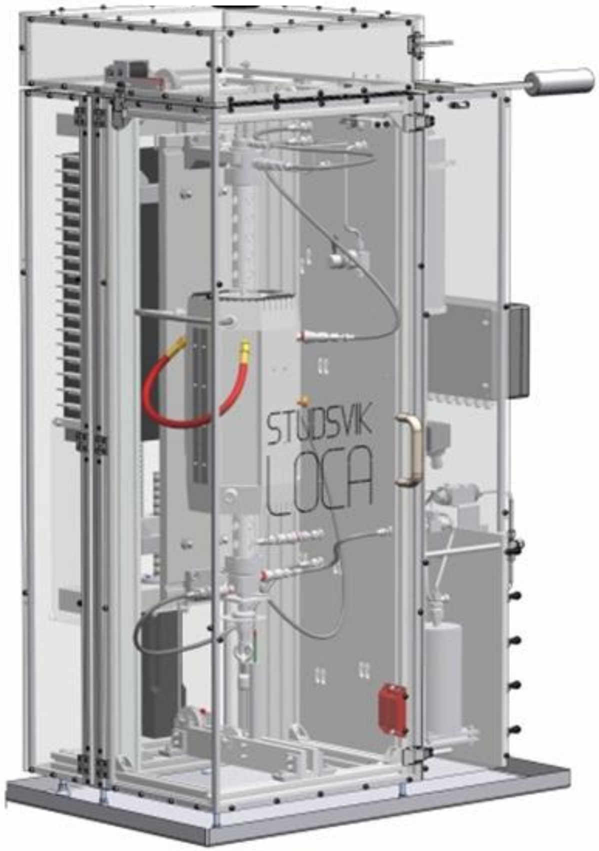


Ref. F. Nagase and T. Fuketa, Nuclera safety research conference 2004

ECR failure threshold under axial load

Axial load - scope

- Develop integral LOCA device with axial loading capability
(+Additional improvements)
- Validate with tests on non-irradiated material
- Test irradiated fuel rod segments under axial load during quench
- Investigations:
  - ECR failure threshold under axial load for medium and high burnups
  - Impact of fuel bonding
  - Fuel loss on break



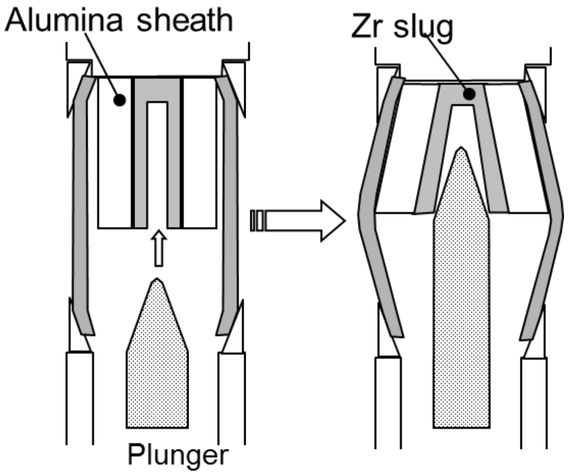
Conceptual design of new LOCA apparatus

PCI - Impact of ramp rates and ramp testing

- The ramp rate is generally considered very important for PCI and operating guidelines often limits the power increase rate.
- Few ramp test programs have focused on ramp rates

Studies:

- Investigate the mitigating effects of slow ramp rates on PCI by the means of ramp tests, out-of-pile mandrel tests, and modeling



Modeling

- Integrated part of project
- Bilateral and voluntary contributions in workshops
- Support the program with pre- and post-test calculations using existing codes and models
  - Give input to the design of test matrices and selection of test parameters
  - Improve evaluation/interpretation of the experimental results
  - Identify model improvements and the data needs for such improvements

Budget shares

- Task - LOCA (**72 %**)
  - Fuel fragmentation and dispersal in LOCA **(44 %)**
  - Clad overheating. Consequences of off-normal temperature transients for handling and storage of fuel **(14 %)**
    - Spent fuel pool LOCA – Cladding behaviour in steam/air mixture
  - Axial load effects on cladding failure **(14 %)**
- Task - PCI **(13 %)**
  - PCI mitigation effects of slow ramp rates
- Task - Modeling **(5 %)**
- Not allocated **(10 %)**
- **100% = 120 MSEK (over 5 years)**

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