Overview of Halden Reactor LOCA experiments
(with emphasis on fuel fragmentation) and plans

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Presentation at the NRC public meeting on fuel fragmentation, relocation and dispersal under Loss-of-Coolant Accident (LOCA) conditions
March 13-14, 2014

HRP IFA-650 LOCA test series
– Objectives –

Covered by this presentation:

- Fuel fragmentation, relocation and dispersal
  - Tests have concentrated on these issues after IFA-650.4 which showed considerable fuel fragmentation and dispersal

Not addressed in this presentation:

- Cladding overheating and oxidation due to fuel relocation
- Secondary transient hydriding near the burst region
- Release of iodine and caesium

Tests carried out

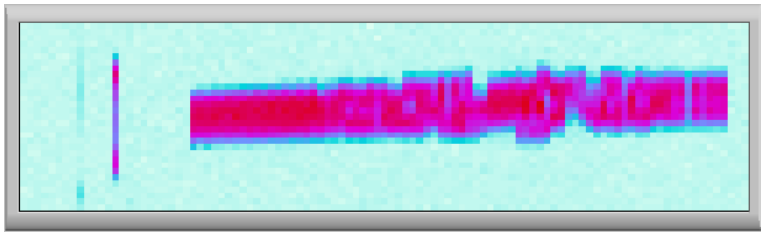
	1,2	3	4	5	6	7	8	9	10	11	12	13	14
Target PCT (°C)	Commissioning, fresh fuel (useful for code benchmarking)	800	800	1100	850	1100	System check-out test with fresh fuel	1100	850	1000	850	870	850
Fuel type		PWR	PWR	PWR	VVER	BWR		PWR	PWR	VVER	BWR	BWR	BWR
Rod ident.		V1-515/3	14D/7	V1-515/7	J13	AEB-070-E4		14D/3	F08/3	J13/3	AEB 072-E4	AEB 072-4C	AEB 072-J9
Span no.		2-3	5-6	5-6	---	3		2-3	3	---	3		
Fuel length (cm)		48	48	48	48	47		48	44	48	38	38	36
Cycles		6	7	6	4	3		7	6	4	5	7	7
Burnup (MWd/kgU)		81.9	92.3	83.4	55.5	44.3		89.9	61.0	56.0	72.3	74.1	70.8
Oxide thickness (μm)		18-27	10	65	~5	<10		7-8	20-30	~5	40	20	
Hydrogen, ppm		250	50	650	100	44		30	150-220	100	300	300	
Cladding		Zry-4/ 1.47%Sn	Zry-4/ 1.47%Sn	Zry-4/ 1.47%Sn	E110	LK3/L		Zry-4/ 1.47%Sn	Zry-4	E110	LK3/L	LK3/L	LK3/L
D_{out}/thickness (mm)		10.75/ 0.725	10.75/ 0.725	10.75/ 0.725	9.13/ 0.68	9.62/ 0.63		10.75/ 0.725	9.50/ 0.57	9.13/ 0.68	9.62/ 0.63	9.62/ 0.63	9.62/ 0.63
Liner (μm)		150	100	150	No	Yes		100	No	No	Yes	Yes	Yes
Heat treatment		SRA	SRA	SRA	stand.	stand.		SRA	SRA	stand.	stand.	stand.	stand.
pressure (bar at RT)		40	40	40	30	6		40	40	30	20	20	20

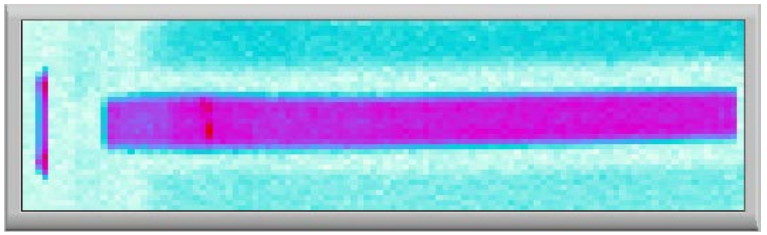
= important test parameters

How fuel fragmentation is observed

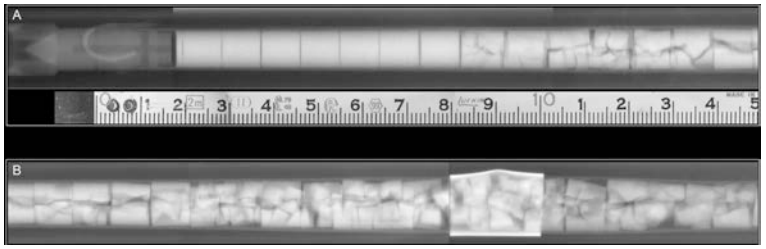
Mainly coarse fragments *Mainly fine fragments*

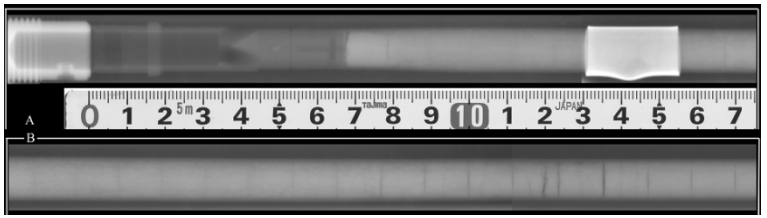
Gamma scanning



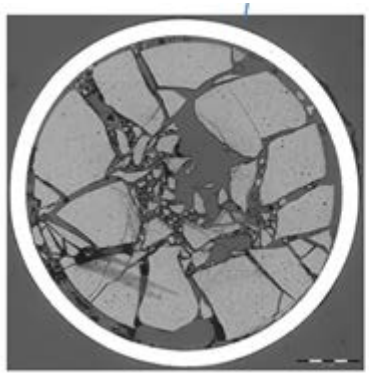


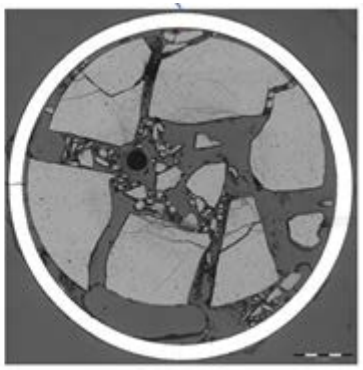
Neutron radio-graphy

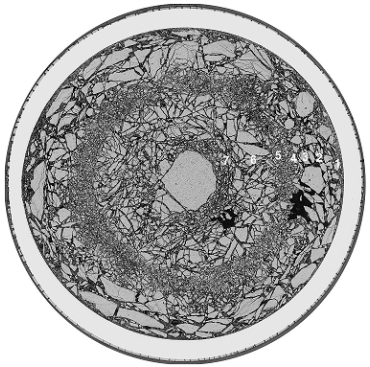


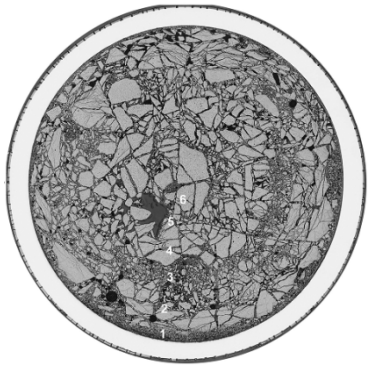


Ceramo-graphy

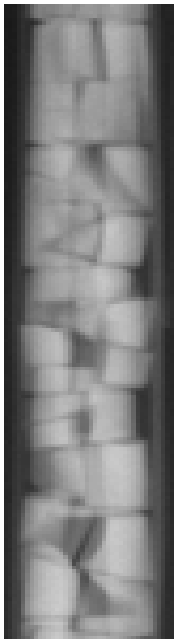
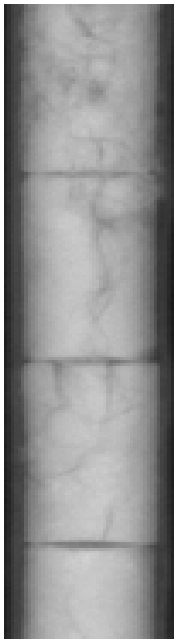
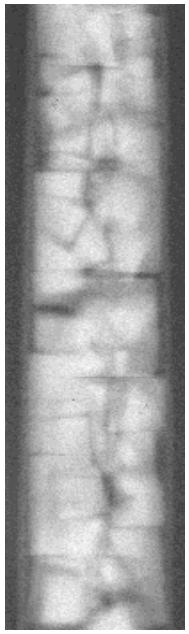
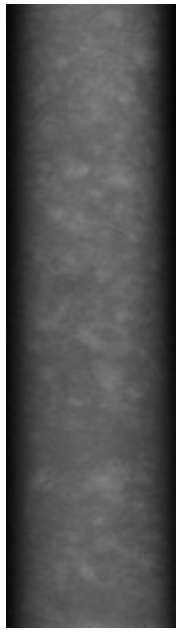




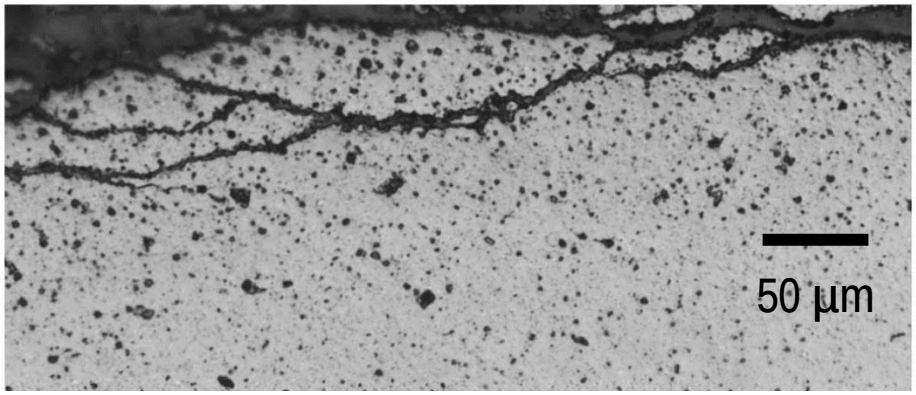


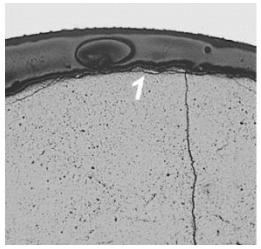


Neutron radiography details

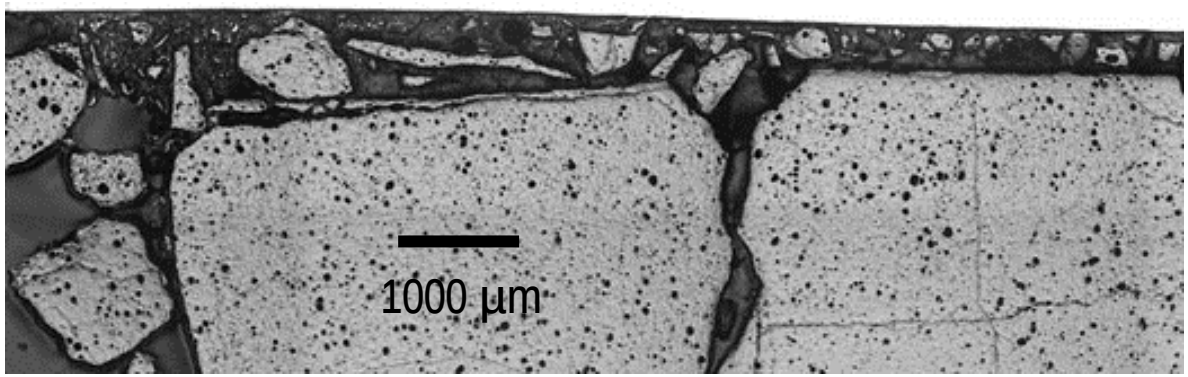
burnup, MWd/kg	44.3	56	60	72.3	81.9	90
radio-graphy						
fragment size	coarse	coarse	coarse & some fine	coarse & fine	medium & fine	medium & fine

Rim fragmentation

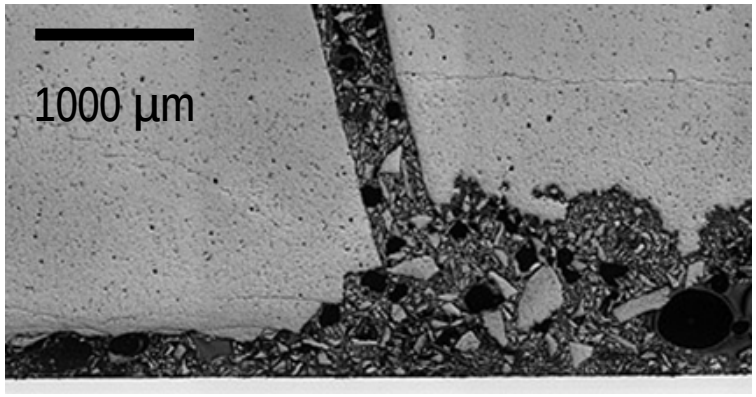


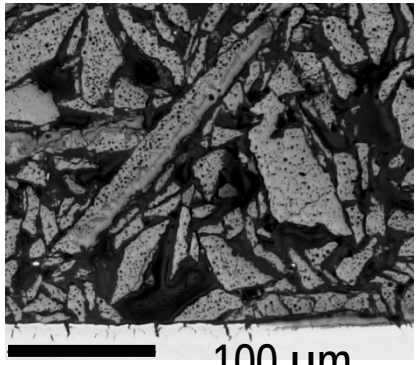


- Bu 55.5
  hbs 110 µm



- Bu 61.0
  hbs 440 µm

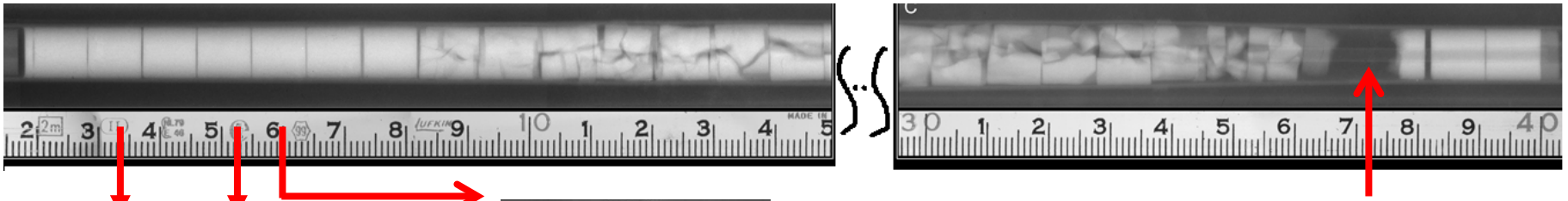


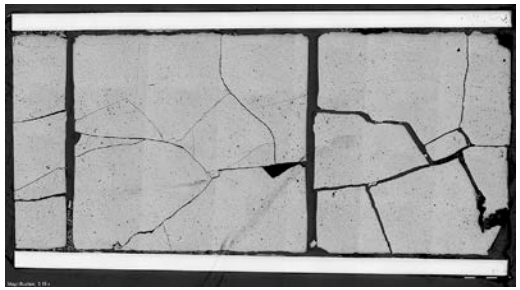


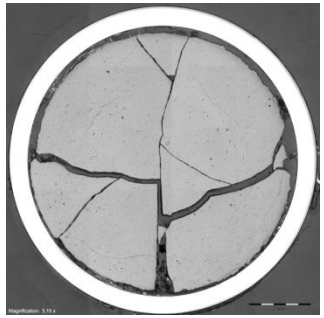
- Bu 72.3
  hbs 1800 µm

Cladding distension and fuel cracking

650.12

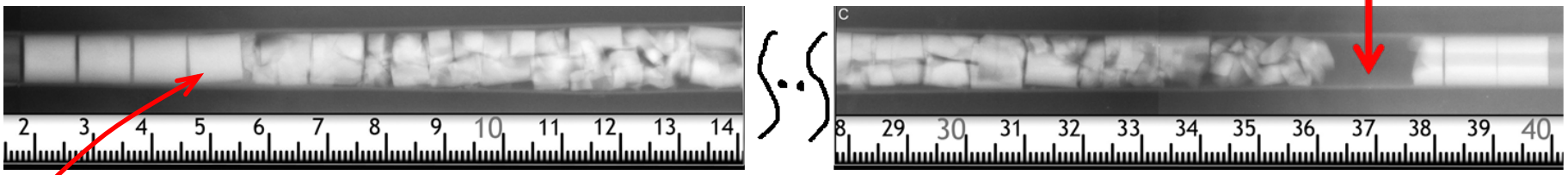






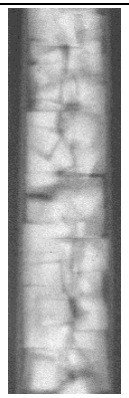
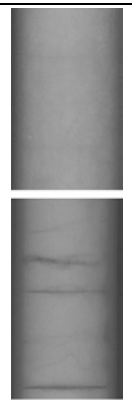
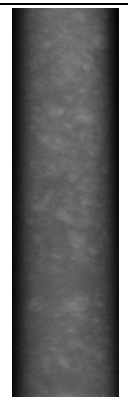
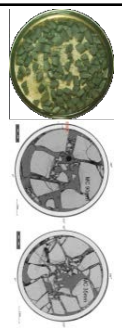
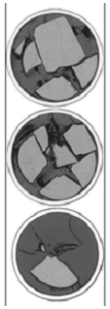
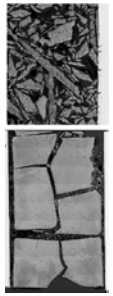
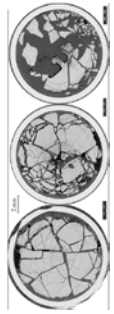
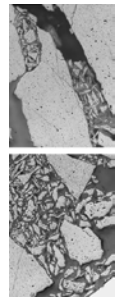
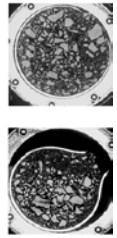
The shrinking fuel column must expand laterally to fill the increased space created by cladding distension. If concentrated on 100 – 150mm stack length with sufficient distension, an average mass increase of about 10% in the cross section results.

650.13

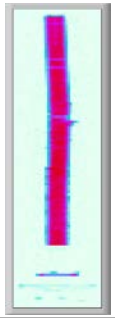
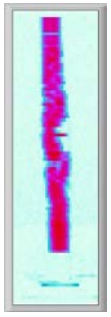
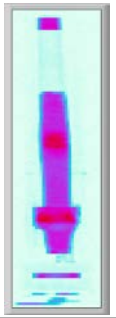


- Very similar behaviour seen in IFA-650.12/13 (BWR fuel, about 72 MWd/kg burnup))
- Local cladding strain must exceed about 5% to produce visible fuel cracking and to allow fragment movement
- Skewed, intact pellet at lower end of 650.13 adjacent to a fragmented pellet

Fuel fragmentation - summary

test #	2	7	6	11	10	12	13	3	5	9	4
burnup, MWd/kg	0	44.3	55.5	56	60	72.3	74.1	81.9	83	90	92
balloon strain, %	54	23	49	25	15	40	45	8	15	61	62
radio-graphy											
ceramo-graphy							fragment size distribution only				
fragment size	coarse	coarse	coarse	coarse	coarse & some fine	coarse & fine	coarse (& fine?)	medium & fine	medium & fine	medium & fine	medium & fine

Fuel dispersal

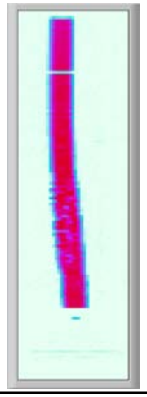
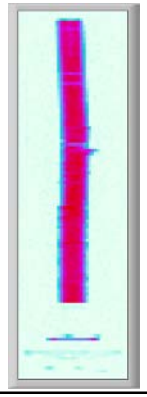
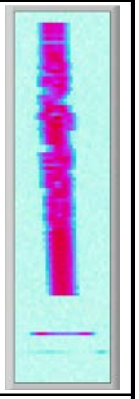
test #	2	7	6	11	10	12	13	3	5	9	4
burnup, MWd/kg	0	44.3	55.5	56	60	72.3	74.1	81.9	83	90	92
balloon strain, %	54	23	49	25	15	40	45	8	15	61	62
ballon area, mm^2	270	8	?	1,5	38	1	10		7	224	434
fragment size	coarse	coarse	coarse	coarse	coarse & some fine	coarse & fine	coarse (& fine?)	medium & fine	medium & fine	medium & fine	medium & fine
gamma scan flask bottom →											
HBS width											
dispersal (qualitative)	none	none	none	none	some	some more	nearly none		much	much more	much more

Plans for HRP LOCA testing

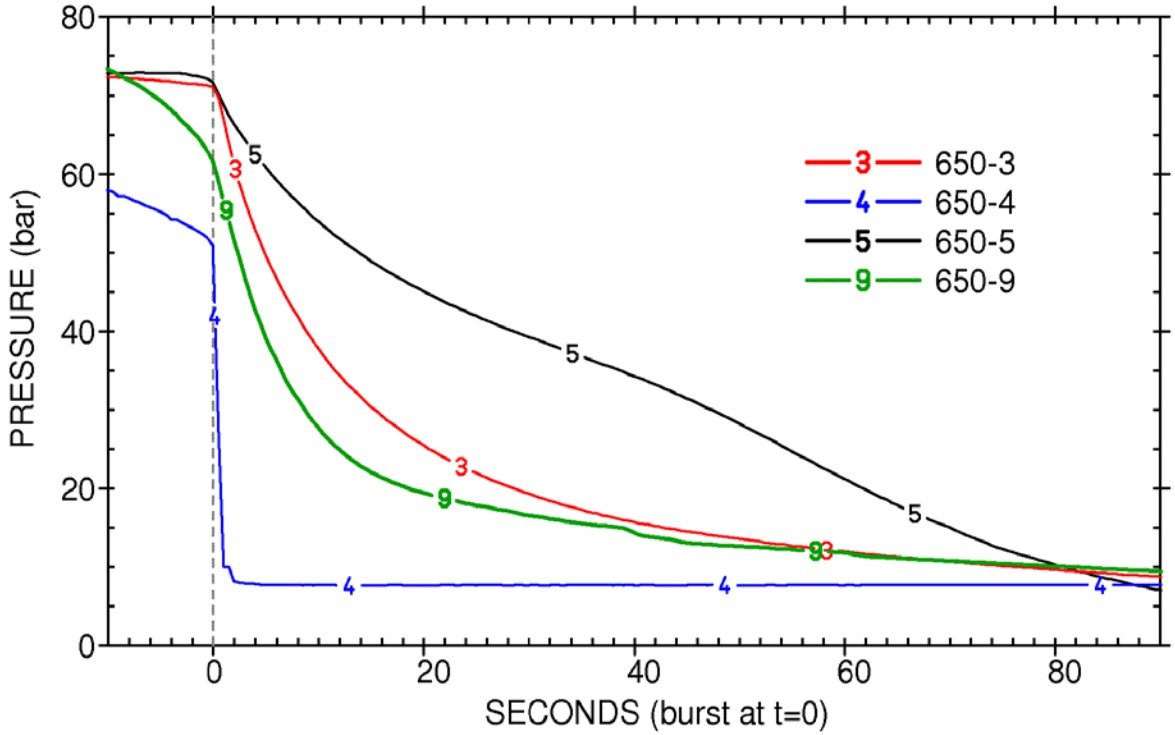
- Plans are defined as we go along. They are based on the results obtained so far and on input from
  - Halden Reactor Project (HRP) members
  - HRP Programme Group (technical steering group)
- A LOCA workshop, Lyon 2012, identified among others
  - Investigation of the effect of the spacer grid
  - Rod length (or design which keeps the fuel in contact with the cladding for a certain length to see the effect of gas flow)
  - Axial constraint

Next test

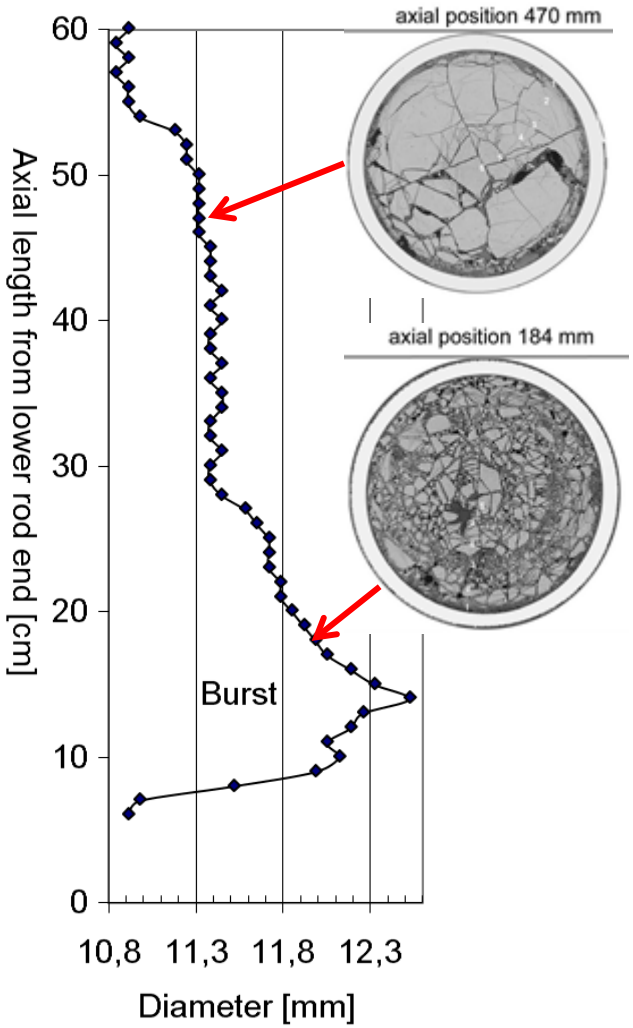
- The HRP LOCA tests have shown that fuel fragmentation and dispersal are, among others, influenced by burnup
- The burnup of the next test, 65 MWd/kgU, will be between
  - test 10 which showed onset of fine fragmentation and
  - test 12 which showed more fine fragmentation and more dispersal
- PCT, pressure as for test 10

test #	11	10	**15**	12
burnup, MWd/kg	56	60	**65**	72.3
fragment size	coarse	coarse & some fine	?	coarse & fine
gamma scan flask bottom →			? ? ? ? ? ? ? ? ? ? ?	
dispersal (qualitative)	none	some	**?**	some more

Pressure drop



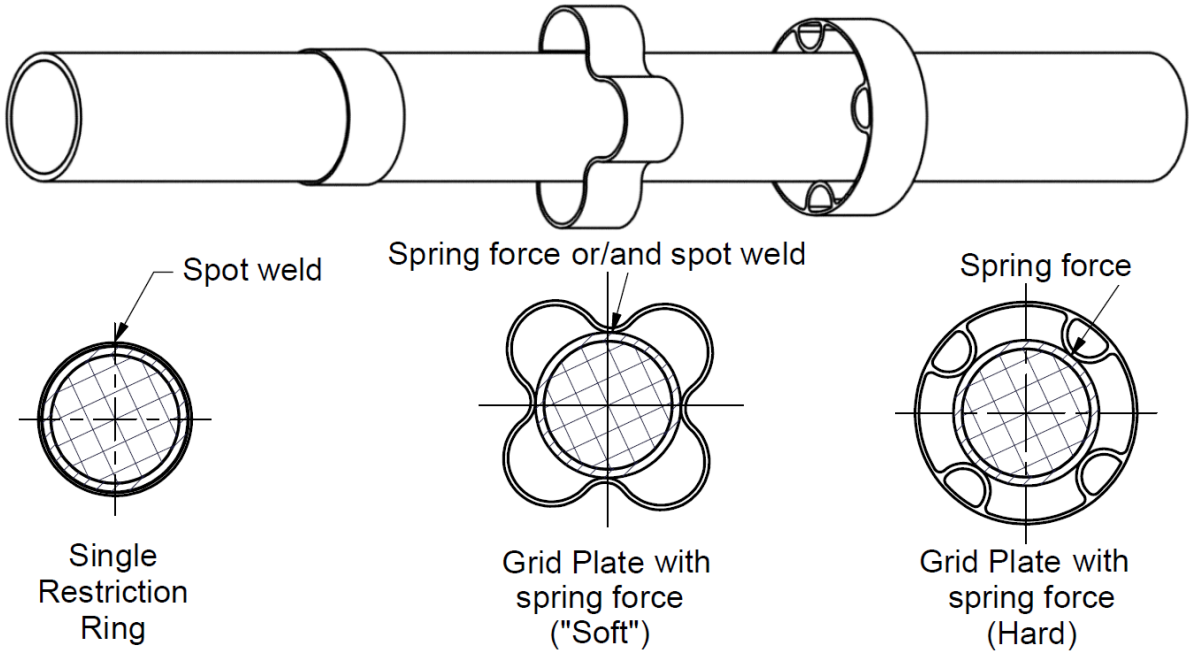
IFA 650.5



- In some experiments, a slow pressure drop was observed
- The fuel maintained tight contact with the cladding along a certain length
- The cracking pattern depends on position

Test with spacer grid

- Determine the impact of a spacer element on axial gas transport, ballooning and fuel dispersal
- The function of the spacer is both to provide a mechanical constraint and to influence local cooling, in this way decreasing cladding distension



Acknowledgement

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Follow-up, evaluation and reporting

- Mikko Henrikki Pihlatie, Fortum, Finland
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- Mirkka Ek, Fortum, Finland
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- Radomír Jošek, NRI, Czech Republic
- Florian Bole du Chomont, EDF, France
- Alexandre Lavoil, EDF, France
- Olivier Bremond, EDF, France

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- Erik Kolstad
  (general preparation and guidance)
- Viktors Grismanovs, Boris Volkov
  (test execution)
- Roar Suther (loop system)

Post-irradiation examination

- B. C. Oberländer, H. K. Jenssen, M. Espeland, H. J. Kleemann, N. O. Solum, Juraj Balak

The efforts of the reactor crew in unloading the experiments, often under difficult conditions when the blow-down system was severely contaminated by ejected fuel, are gratefully acknowledged.

Special thanks go to VTT (Finland) and PSI (Switzerland) for supporting the test preparation and execution with pre-test calculations.


HRP