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

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Report title

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Summary

The U.S. Nuclear Regulatory Commission (NRC) is a member of the OECD Halden Reactor Project and is participating in the joint programme of LOCA experiments in the Halden Reactor. The presentation "Overview of Halden Reactor LOCA Experiments and plans" by B. Oberlander and W. Wiesenack was given at the United States Nuclear Regulatory Commission (US_NRC) Public Meeting on Fuel Fragmentation, Relocation and Dispersal - in Rockville, MD, USA on March 13-14, 2014. The presentation has the US-NRC document no. ML14071A197 in

http://meetings.nrc.gov/pmns/mtg?do=details&Code=20140319

NRC Public Meeting / Public hearing on on "fuel fragmentation, relocation and dispersal under Loss-of-Coolant Accident (LOCA) conditions". The U.S. Nuclear Regulatory Commission staff is performing additional research and analysis on fuel fragmentation, relocation and dispersal under Loss-of-Coolant Accident (LOCA) conditions and is soliciting relevant input from interested parties on various technical issues associated with this subject. The purpose of this meeting is to have technical discussions and an information exchange related to research on fuel fragmentation, relocation and dispersal under LOCA conditions. Various potential approaches to regulatory resolution of fuel fragmentation, relocation and dispersal under LOCA conditions will also be discussed. The potential implications of the research findings to the analysis of non-LOCA events that result in fuel rod rupture will also be discussed. Stakeholders from industry, research institutes, licensees and utilities, regulatory agencies, both domestic and international, and other interested public stakeholders are encouraged to participate in the meeting.

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1 Introduction

The U.S. Nuclear Regulatory Commission (NRC) is a member of the OECD Halden Reactor Project and is participating in the joint programme of LOCA experiments in the Halden Reactor. The presentation “Overview of Halden Reactor LOCA Experiments and plans” by B. Oberlander and W. Wiesenack was given at the United States Nuclear Regulatory Commission (US_NRC) Public Meeting on Fuel Fragmentation, Relocation and Dispersal - in Rockville, MD, USA on March 13-14, 2014. The presentation has the US-NRC document no. ML14071A197 in

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2 Presentation

2.1 HRP IFA-650 LOCA test series – Objectives

The Halden Reactor Project LOCA testing started about ten years ago with a workshop and a group of experts defining the objectives. They identified

- fuel fragmentation, relocation and dispersal

as one of the major issues of high burnup fuel behaviour in a LOCA. This has been the main focus of the test series after the execution of IFA-650.4 which showed considerable fuel fragmentation and dispersal. The presentation will mainly summarise the results related to these issues.

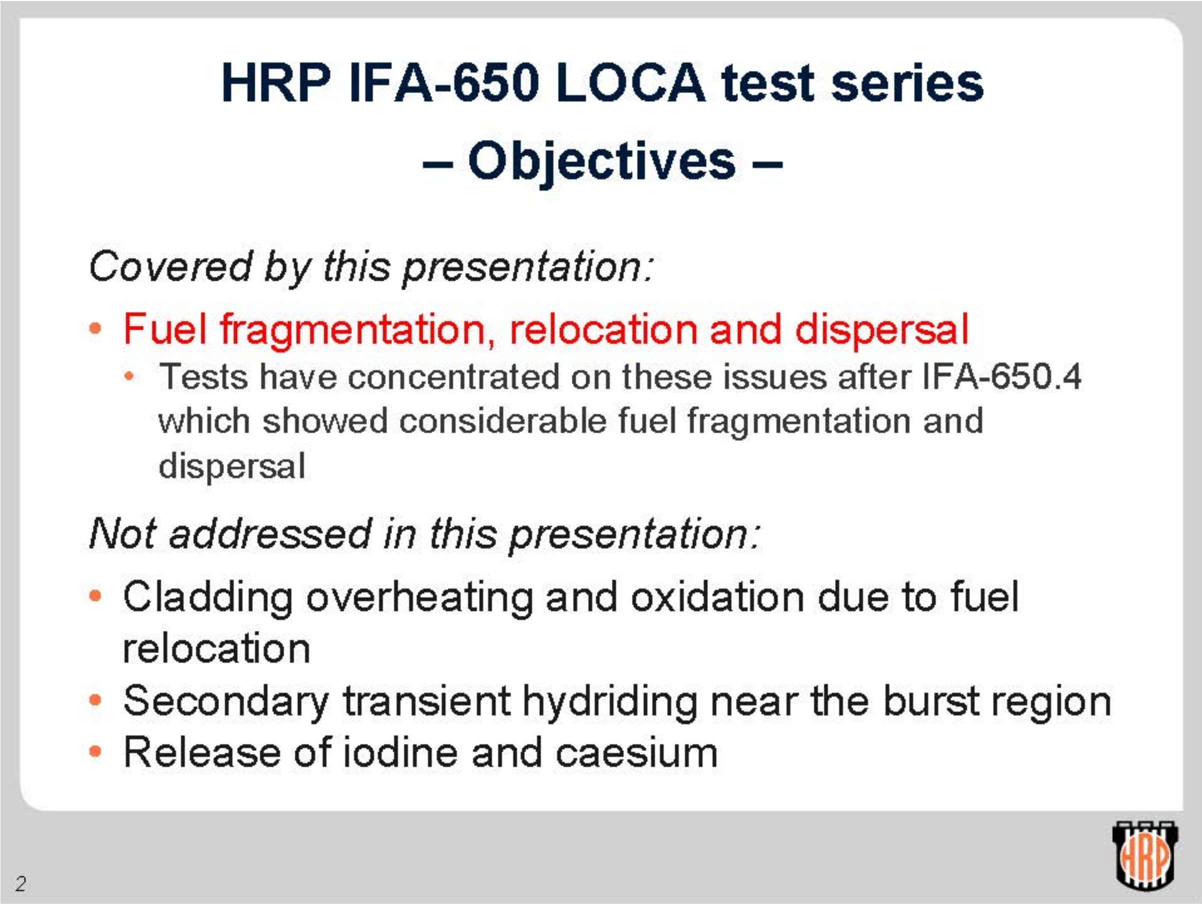


Figure 1 HRP IFA-650 LOCA test series – Objectives

The other objectives are not particularly addressed in this presentation:

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

With respect to these objectives, PIE was done on some segments subjected to LOCA conditions in the test series.

- Release of iodine and caesium

The release of the radioactive fission products iodine and caesium was measured in several tests. The results are not reported in this presentation, but it can be said that the release was found to be lower than usually assumed in safety assessments.

2.2 Tests carried out

The table gives an overview of the tests carried out so far. They comprise five tests with PWR fuel, four tests with BWR fuel, and two with VVER fuel, all using high burnup fuel segments from commercial irradiations. Important parameters are burnup from 44 to 92 MWd/kg, cladding oxide thickness and the related hydrogen content which influence cladding

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 (yellow)

Figure 2 Tests carried out

ductility and ballooning, and the fill gas pressure as a test design parameter. This pressure will approximately double during test execution in response to the temperature increase in the system.

The tests have been used in several international code comparisons and benchmarking exercises. The commissioning tests number 1 and 2 were used for calibrating the codes to the conditions of the LOCA experiment system in the Halden Reactor.

2.3 How fuel fragmentation is observed

We have several ways to observe fuel fragmentation:

1. Gamma scanning

is carried out a few days after test execution. The test rig is slowly pulled out of the reactor and moved to a handling compartment in the reactor hall where the gamma scanning takes place. The fuel segment is kept vertical all the time in order to not change the fuel distribution in the cladding tube. The ragged appearance of the fuel column in the left gamma scan indicates coarse fragments which have moved laterally where ballooning has created some extra space. A small axial gap at the upper end indicates a little downward movement of the fuel column. The segments are from test 12 (left) and 5 (right).

The scan to the right shows no discernible structure and is an example of fine fragmentation and no lateral movement due to little ballooning.

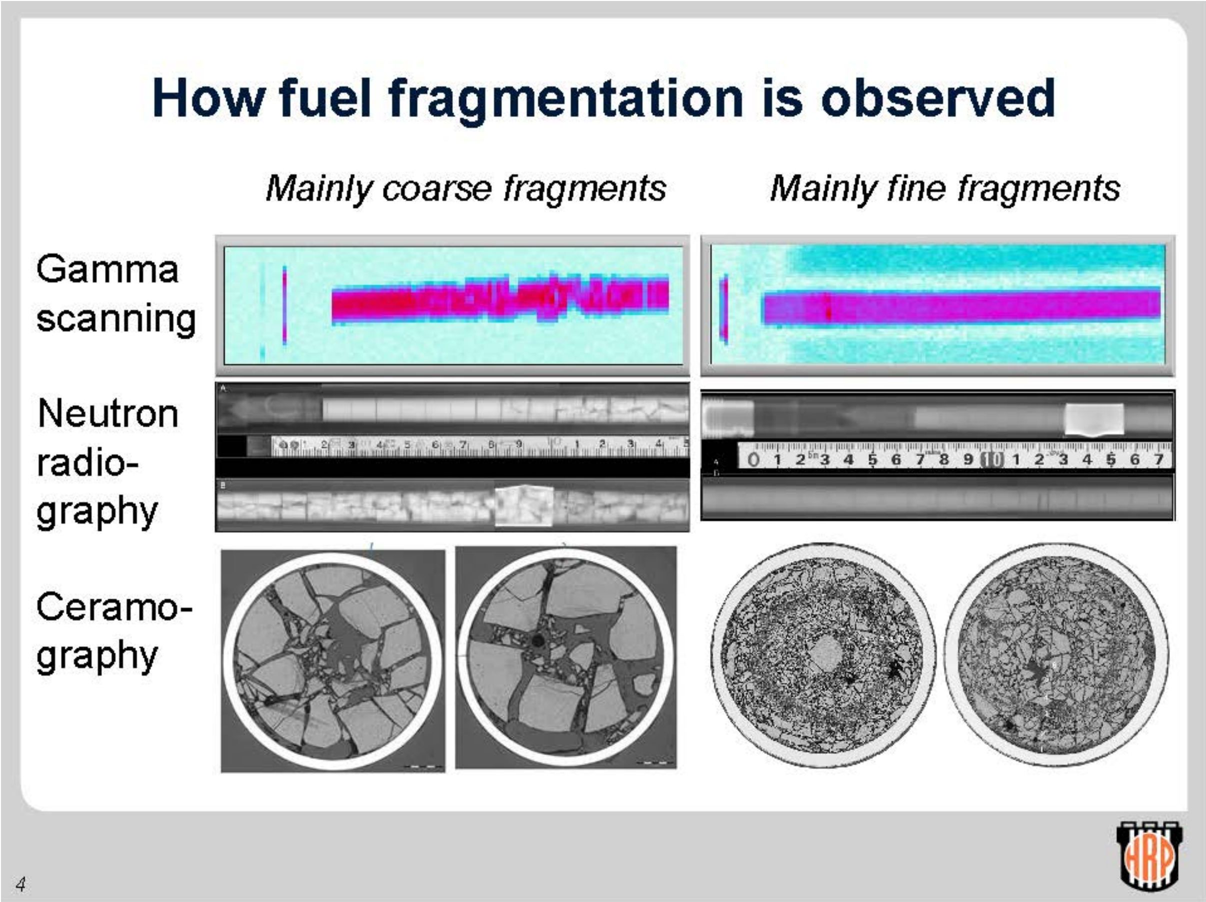


Figure 3 Fuel fragemtation can be observed by gamma scanning, neutronradiography and ceramogrpahy

2. Neutron radiography

The next step is neutron radiography which is done a few months after test execution when the fuel has cooled sufficiently. The pictures show the same fuel as the gamma scanning. Neutron radiography reveals more details. In the left picture, it shows intact pellets and coarse fragments. In the right picture, one can see that the lower part of the segment must be strongly fragmented since pellet-pellet interfaces and dishings are not visible, while they are discernible in the upper part.

3. Ceramography

is the final examination. The ceramographs confirm the fragmentation deduced from gamma scanning and neutron radiography, but with much more detail at selected locations.

2.4 Neutron radiography details

This slide shows more examples of fragmentation as seen by neutron radiography. The pictures are arranged in order of increasing burnup. For the first four segments until 72 MWd/kg burnup, they show coarse fragments. This does not exclude the existence of fine fragments which cannot be seen with neutron radiography.

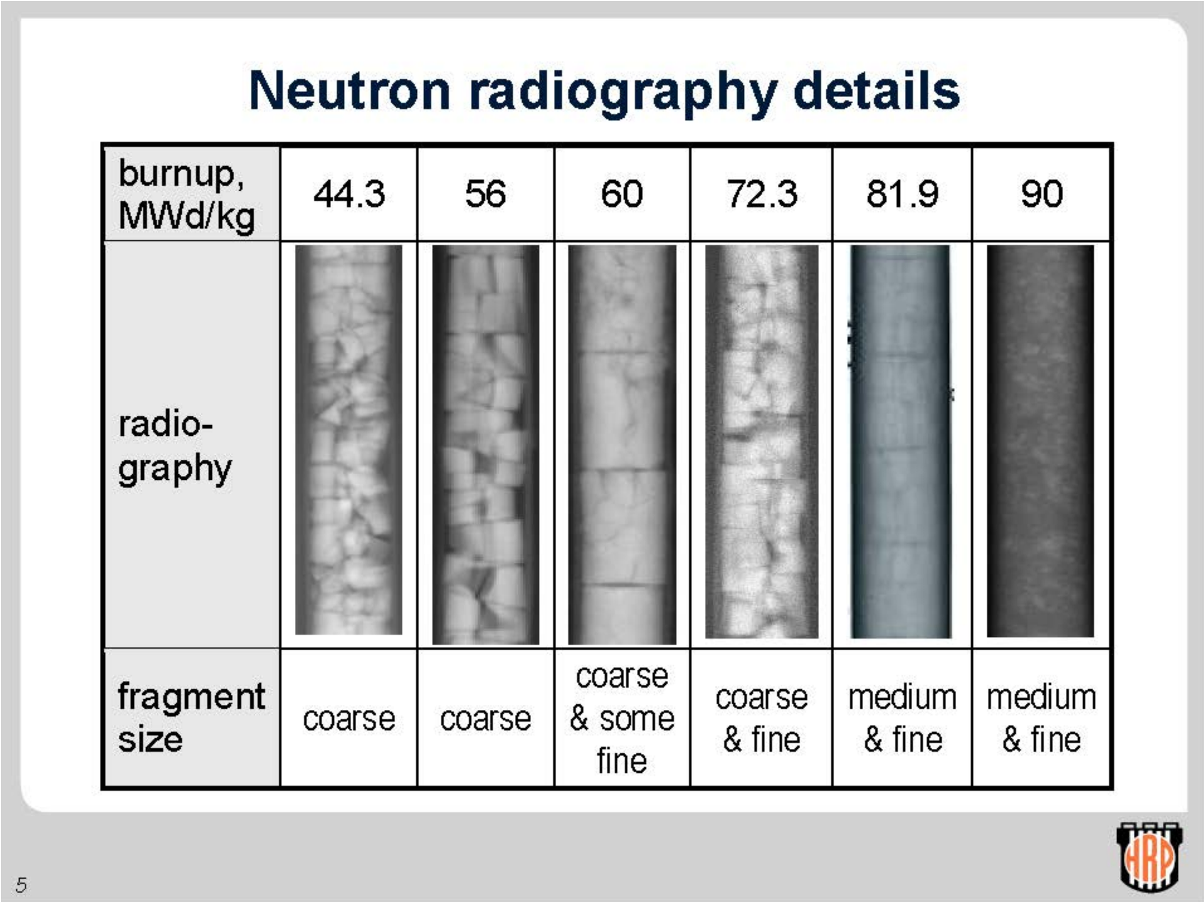


Figure 4 Neutron radiography details

2.5 Fuel rim fragmentation

Irradiated fuel develops an outer rim of so-called high burnup structure. Ceramography reveals fragmentation of this rim structure fuel which increases with burnup. The first example with the lowest burnup shows some delamination of the rim structure fuel, but the fragments did not move. The third example with the highest burnup and thickest rim (calculated to be 1800 micro meter) shows very fine, relocated fragments. In comparison, the average width of a strand of human hair is about 100 micro meter.

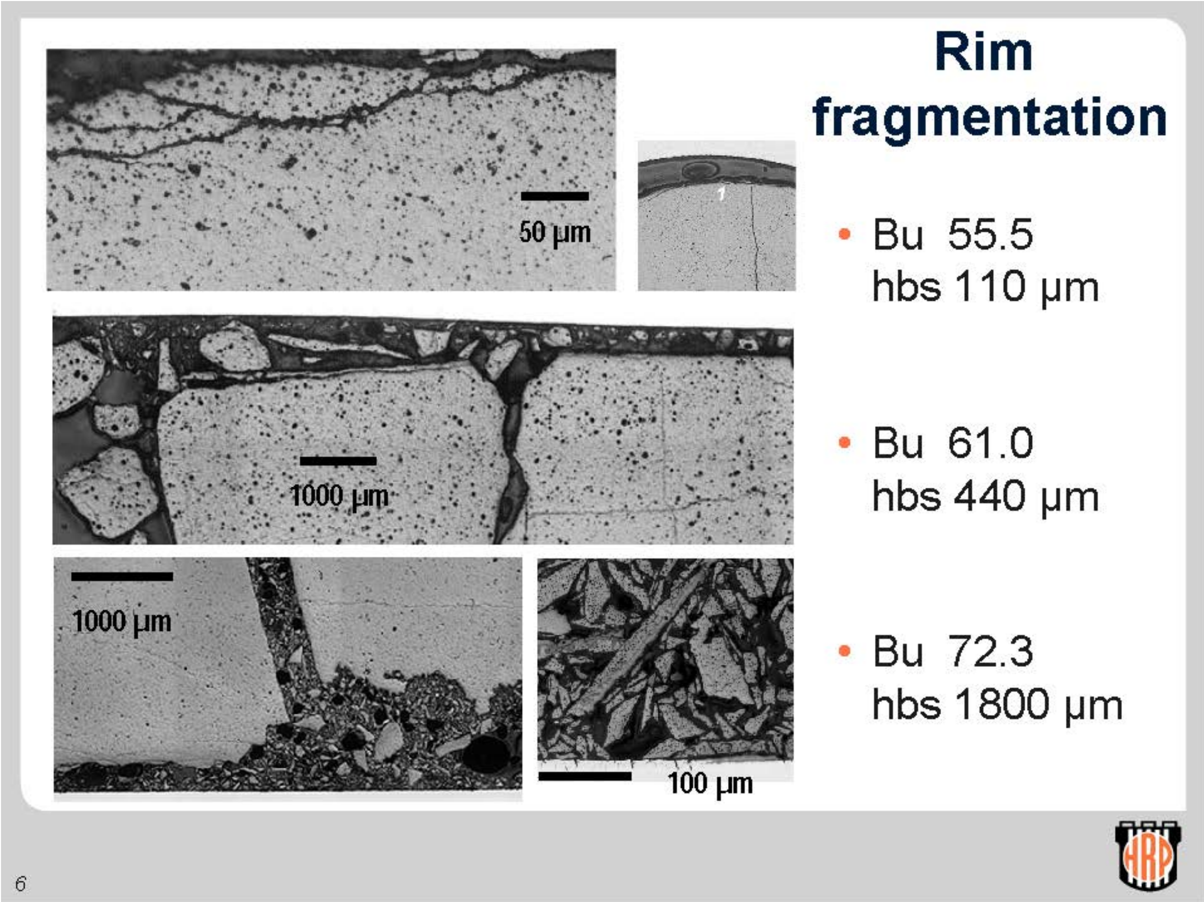


Fig. 5 Rim fragmentation

2.6 Cladding distension and fuel cracking

This slide tries to illustrate how cladding distension and fuel cracking are linked. Both segments, BWR fuel with similar burnup of about 72 MWd/kg, show coarse fragmentation in the vicinity of the ballooning where distension is strongest. Cracking decreases towards the lower end where the pellets still seem to be intact. The local cladding strain must exceed about 5% to produce visible fuel cracking and to allow fragment separation and movement.

The rotated, intact pellet at the lower end of IFA-650.13 had certainly enough free space around it to separate its fragments if they existed, but it did not do so. The distance to the burst location, from where a sudden pressure decrease propagates through the fuel stack on burst, may therefore play a role as well. Since distension is a function of distance to the burst location as well, the two possible influences on fragmentation would be correlated.

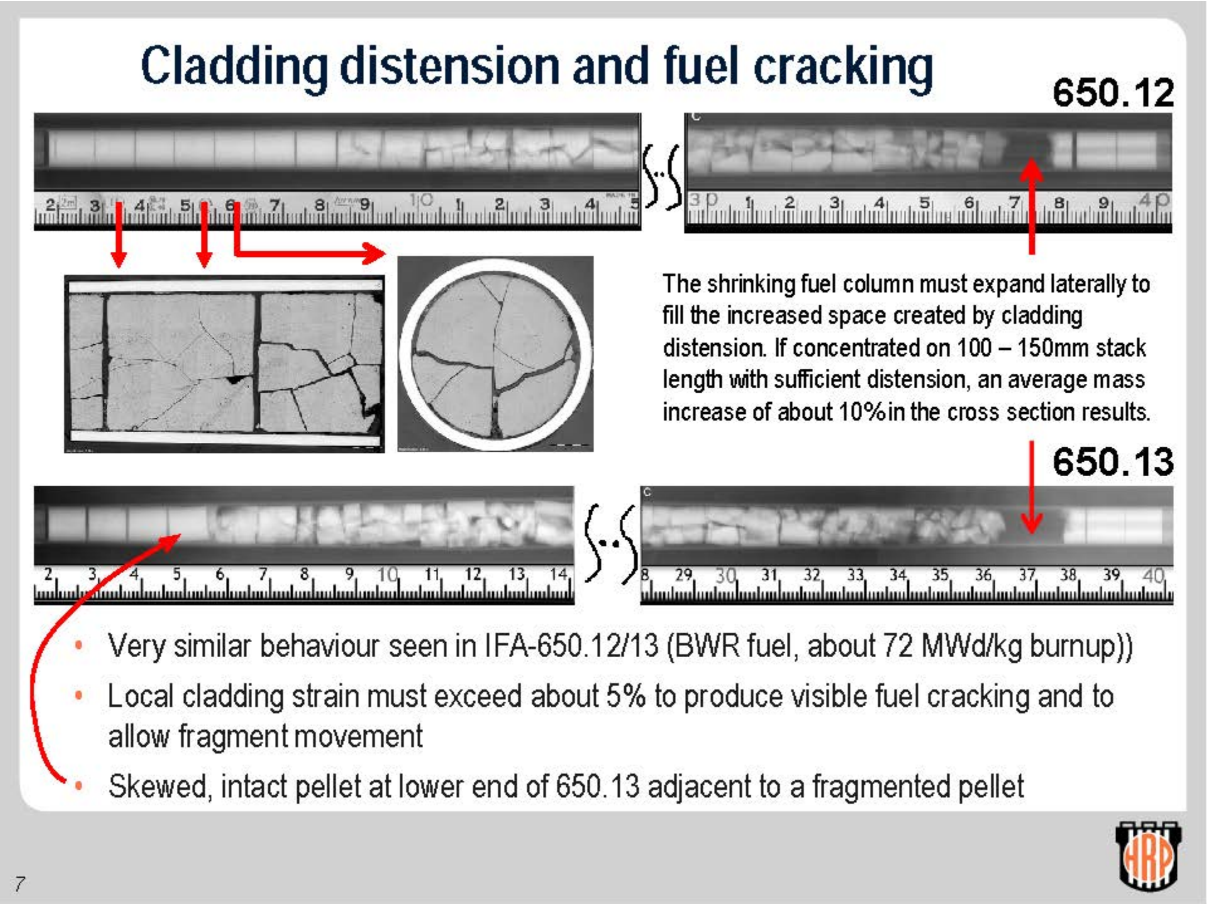
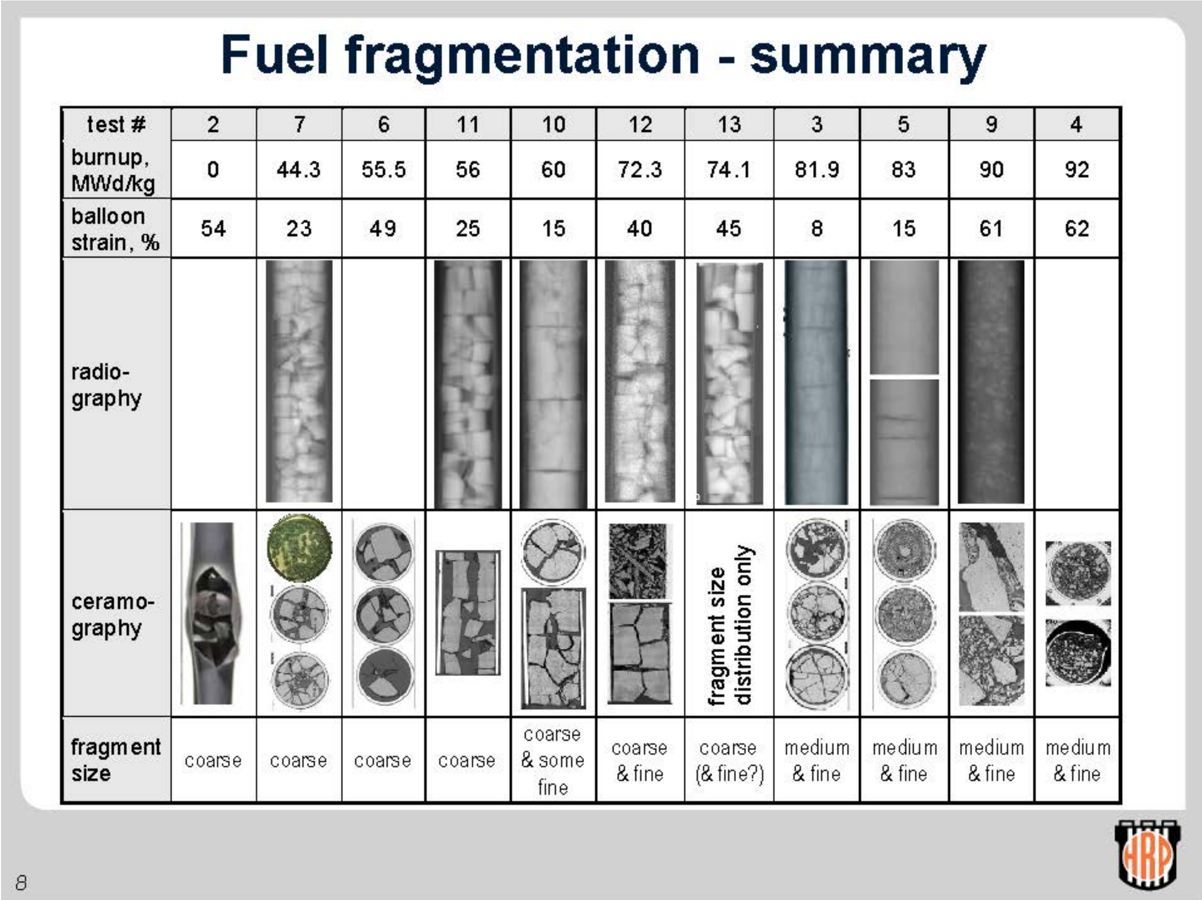


Figure 6 Cladding distension and fuel cracking

The upper end shows an axial gap of about 15mm in both cases. 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 would result.

2.7 Fuel fragmentation – summary

This slide summarises the evidence for fuel fragmentation presented in the previous slides. The qualitative impression is that up to a certain burnup, say 60 MWd/kg, fragmentation is more or less caused by the cracking during normal operation. The test segments with burnup of 72 MWd/kg and higher show additional fragmentation which progressively affects more and more of the pellet as burnup increases. The behaviour between 60 and 72 MWd/kg will be studied with the next test in the Halden reactor LOCA program.



Fuel fragmentation - summary

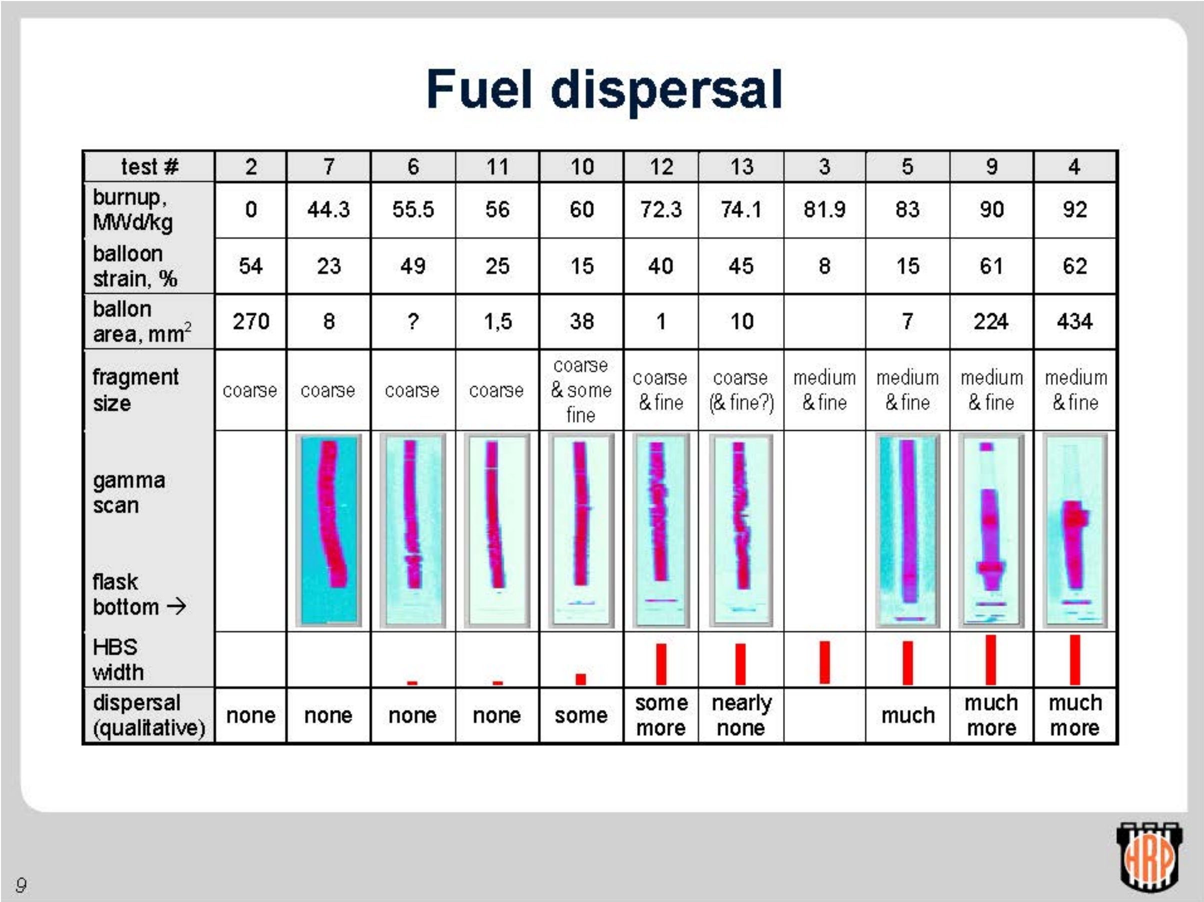
test #	2	7	6	11	10	12	13	3	5	9	4
burnup, MWd/kg	0	44.3	55.5	56	60	72.3	74.1	81.9	83	90	92
balloon strain, %	54	23	49	25	15	40	45	8	15	61	62
radio-graphy											
ceramo-graphy							fragment size distribution only				
fragment size	coarse	coarse	coarse	coarse	coarse & some fine	coarse & fine	coarse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

8

Figure 7 Fuel fragmentation – summary

2.8 Fuel dispersal

If the fragments are small enough to pass through the burst opening, they can be dispersed driven by the rapid and strong outflow of gas when the cladding bursts. Evidence of dispersal can be seen in the gamma scanning pictures where a gamma signal coming from the bottom of the pressure flask indicates fuel that was expelled from the rod. Again, a correlation with burnup and the amount of high burnup structure is evident, but dispersal only happens for burnup above a threshold of about 60 MWd/kg.



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

Figure 8 Fuel dispersal

2.9 Plans for HRP LOCA testing

The Halden Reactor Project plans for LOCA testing 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 held in Lyon in 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

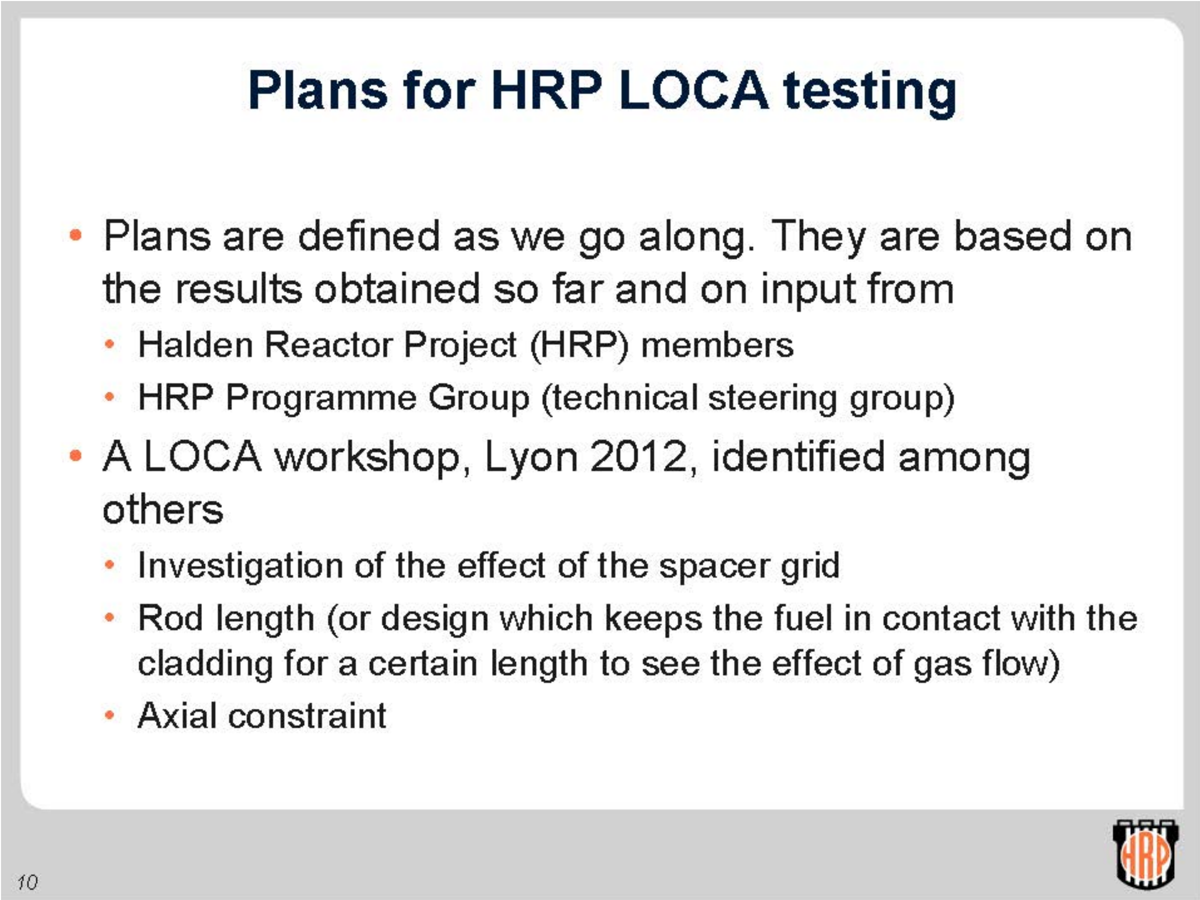


Figure 9 Plans for HRP LOCA testing

2.10 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 mostly coarse fragmentation and onset of fine fragmentation and test 12 which showed more fine fragmentation and more dispersal.

The peak clad temperature, PCT, will be 850 °C, and the fill gas pressure will be 40 bar. These conditions are the same as those of test 10 to which the next test will be compared.

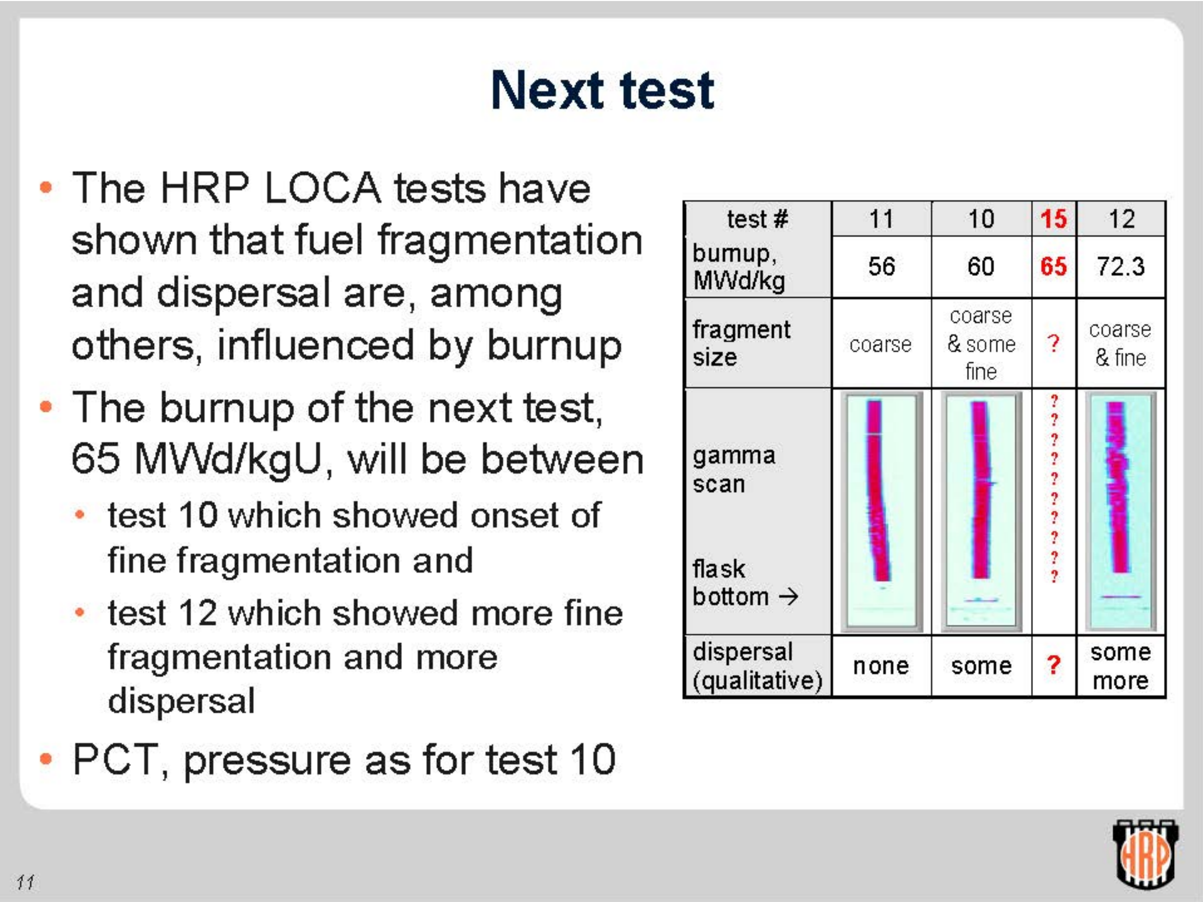


Figure 10 Next test

2.11 Pressure drop

The test after the next one will probably address the influence of a phenomenon which was observed in three of the eleven tests with pre-irradiated fuel, namely a slow decrease of the pressure in the rod plenum after burst. This is shown in the plot which also contains an example of instantaneous pressure loss, curve labelled “4”. The graph to the right shows the post-LOCA cladding diameter of test IFA-650.5 and cross sections taken at positions with little and strong cladding distension. The difference in fragmentation is evident. The fuel maintained tight contact with the cladding along a certain length, and the cracking pattern depends on position.

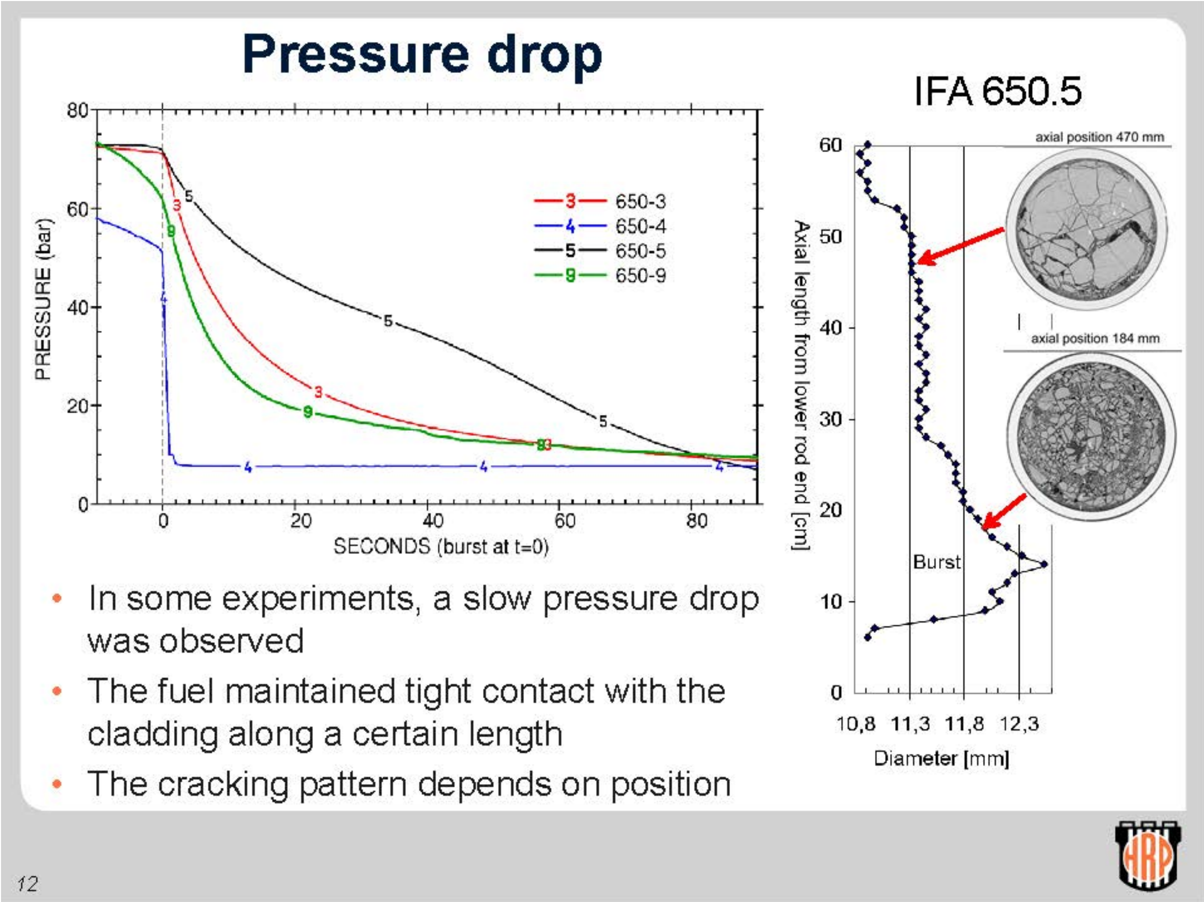


Figure 11 Pressure drop

2.12 Test with spacer grid

The intention is then to 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 and impeding gas communication which possibly has an influence on fuel fragmentation and dispersal.

The shape of the grid is not decided. The example illustrates possible designs.

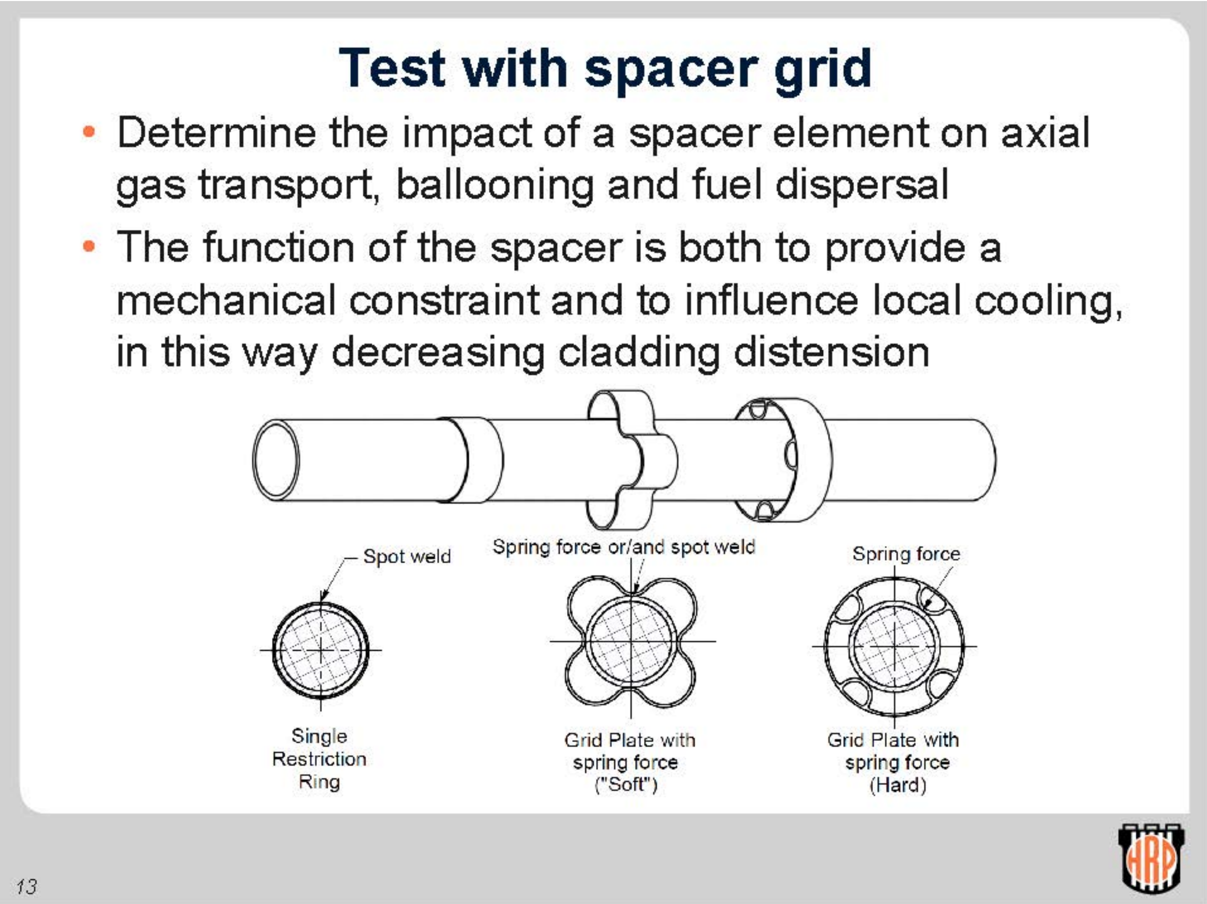


Figure 12 Test with spacer grid

2.13 Acknowledgement

The OECD HRP LOCA test series IFA-650 is the result of the combined efforts of many contributors. Their contributions are gratefully acknowledged.

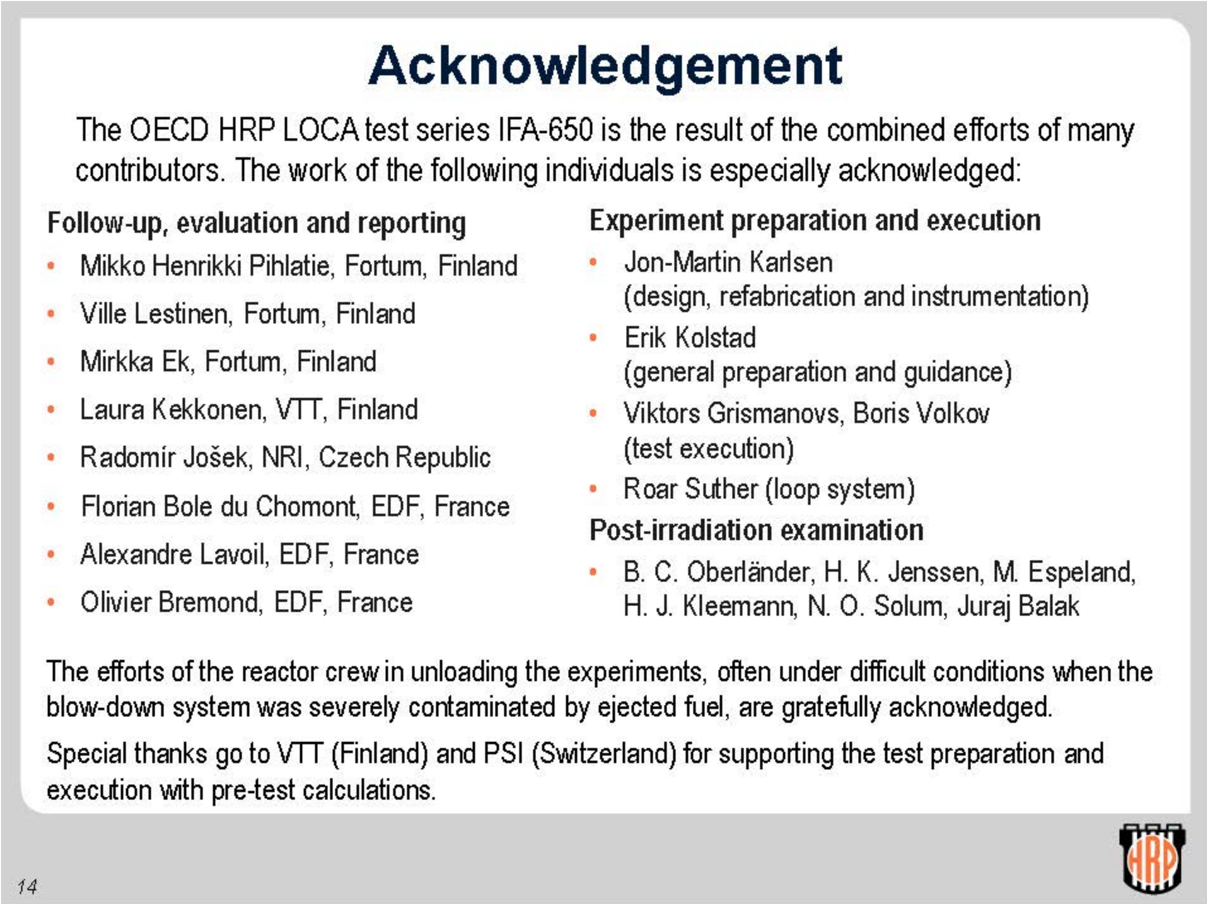


Figure 13 Acknowledgement

Appendix 1 Meeting agenda and picture

Agenda

Topic	Speaker, Organization	Day	Time
1. Welcome	RES/NRR Management	Thursday	12:00 -12:15
2. Ground Rules and Meeting Logistics	Meeting Facilitator		12:15-12:30
3. Introduction and Meeting Objectives	T. Inverso, NRC		12:30-1:00
4. Research on Fuel Fragmentation, Relocation and Dispersal	-		-
a. LOCA Experiments	-		-
i. Fuel Fragmentation, Relocation and Dispersal Under LOCA Conditions: Experimental Observations	M. Flanagan, NRC		1:00-2:00
ii. Fuel Fragmentation, Relocation and Dispersal, Current Understanding and Test Results	K. Yueh, EPRI		2:00-2:30
BREAK	-		*2:30-3:00*
iii. LOCA and fuel fragmentation tests in SCIP III	P. Askeljung, Studsvik		3:00-3:30
iv. Overview of Halden Reactor LOCA experiments (with emphasis on fuel fragmentation) and plans	B. Oberlander, Halden		3:30-4:00
v. Open Discussion*	ALL		4:00-5:00
5. Welcome and brief summary of Thursday's sessions	M. Flanagan, NRC	Friday	9:00-9:15
b. LOCA Analysis	-		-
i. Methodology for Core-Wide Estimates of Fuel Dispersal During a LOCA	I. Porter & P. Raynaud, NRC		9:15-10:00
ii. Analytical Assessment of High-Exposure Fuel Dispersal Potential During BWR LOCA	K. Muftuoglu, GEH		10:00-10:30
iii. Assessment of Extent of Rupture in a Large Break LOCA	M. Nissley, Westinghouse		10:30-10:50
i. Open Discussion*	ALL		10:50-11:15
BREAK	-		*11:15-11:30*
6. Perspectives on Experiments and Analysis			
i. Potential Impacts on Design Basis Accidents	P. Clifford, NRC		11:30-12:00
ii. IRSN views on fuel dispersion in RIA and LOCA accidents	M. Petit, IRSN		12:00-12:20
iii. JAEA perspective on fuel fragmentation and dispersal	F. Nagase, JAEA		12:20-12:40
iv. AREVA Perspective on Fuel Fragmentation and Dispersal During Design Basis Accidents	B. Dunn, AREVA		12:40-1:00
LUNCH	-		*1:00-2:00*
v. Open Discussion*	ALL		2:00-2:30
7. Summary and Conclusions, Next Steps	M. Flanagan, NRC		2:30-3:00

* Each agenda item includes time for 5-10 minutes of clarification-type questions immediately following each presentation. The designated open discussions are intended to provide time for in-depth discussion and public comment.

Mr. K.Yueh (EPRI), B.Oberländer (Halden Prosject,), Mr. P. Askeljung (Studsvik), M. Flanagan (US-NRC)