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Fuel Rod Mechanical Behaviour Under Dynamic Load Condition on High Burnup Spent Fuel of BWR and PWR

International Conference on Management of Spent Fuel from Nuclear Power Reactors: An Integrated Approach to the Back-End of the Fuel Cycle

15-19 June 2015

Vienna, Austria

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Contents

1. Background

- **Under existing conditions, Mutsu Interim Spent Fuel Storage Facility can storage the following spent fuel.**

  BWR ≤50 GWd/t, PWR ≤ 48 GWd/t

- **High burnup spent fuel (55 GWd/t) are also candidates for future storage.**
  - **Concerns of high burnup spent fuels**
    - **Increase of hydrogen content in cladding**
    - **Increase of hydrides precipitated in radial orientation during storage**
  - **Concerns on cladding ductility or fuel rod integrity and potential criticality (pellet dispersal) under accident condition during storage and transportation**

- **From FY2009 to FY2014, for the assessment of high burnup fuel integrity at the dry cask drop accident, mechanical performance of cladding and fuel rod under the dynamic load condition was examined using BWR and PWR fuel irradiated up to 55GWd/t.**

  This test was planned and conducted by Japan Nuclear Energy Safety Organization (JNES) which was consolidated into NRA in March 2014.

2. Test Plan

2.1 Objectives

For the assessment of high burnup spent fuel integrity at the cask drop accident ;

- To acquire the elemental mechanical properties of BWR and PWR fuel cladding under dynamic load condition
- To evaluate the dynamic behaviour of BWR and PWR fuel rod under accident condition during storage and transportation

2.2 Test Items

Test \ Drop mode	Axial drop	Lateral drop
Elemental mechanical tests of cladding	Dynamic tensile test	Dynamic ring compression test
Dynamic load impact tests of fuel rod	Axial load test	Lateral load test
Examinations after impact tests	Dispersed pellet survey (particle size, amount), Metallography, SEM, etc.	

2.3 Test Matrix

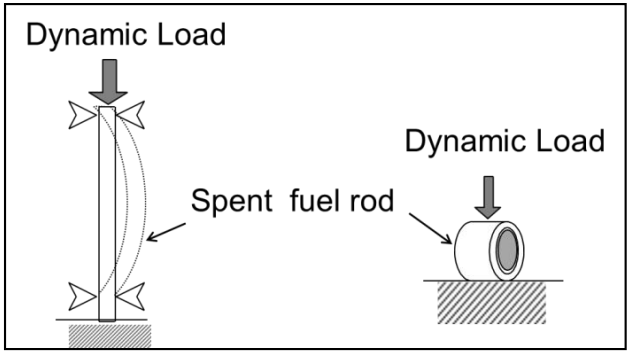
				55GWd/t type[a]	
Test fuel rod	Fuel Type			BWR 9X9	PWR 17X17
	Rod average burnup (GWd/t)			56	52-55
	Cladding material			Zry-2[b]	MDA[c]
	Heat treatment			RX[d]	SR[e]
	Hydrogen content (ppm)			100 - 140	70 - 170
Test item and number	Elemental mechanical test of cladding	Dynamic tensile test (up to 200 s^{-1})	As-irradiated	6	12
		Dynamic ring compression test (up to 4000 mm/s)	As-irradiated	4	3
			Hydride reoriented[f]	4	6
	Dynamic load impact test of fuel rod	Axial load test	As-irradiated	5	5
		Lateral load test	As-irradiated	5	3
			Hydride reoriented[f]	1	2

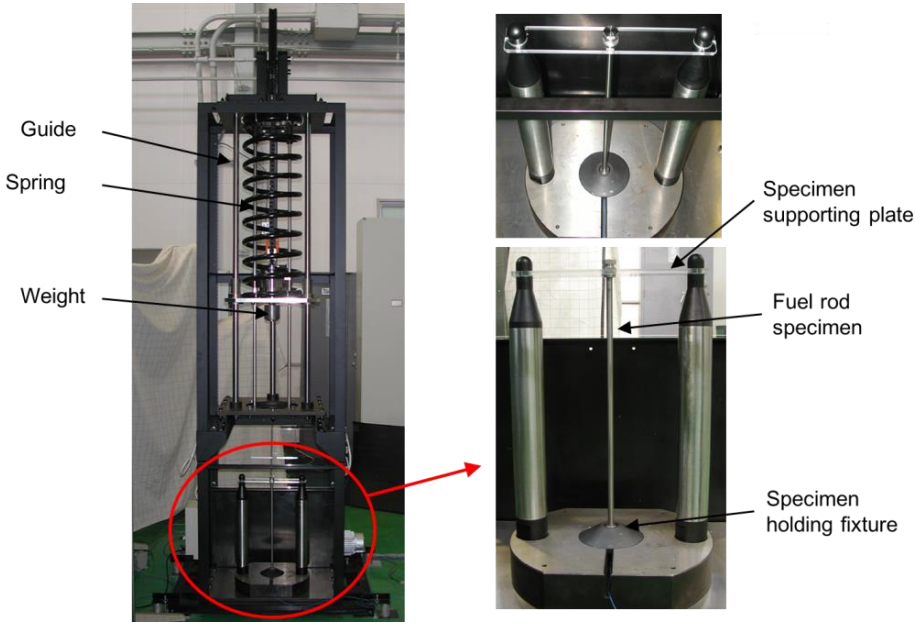
[a] Licensed maximum bundle average burnup ≤ 55GWd/t
[b] With Zr liner
[c] Mitsubishi Developed Alloy (Zr-0.8Sn-0.2Fe-0.1Cr-0.5Nb)
[d] Recrystallized annealing
[e] Stress relieved annealing
[f] Dummy pellets (made of forsterite (Mg_2SiO_4)) loaded

3. Test Equipment and Test Specimen

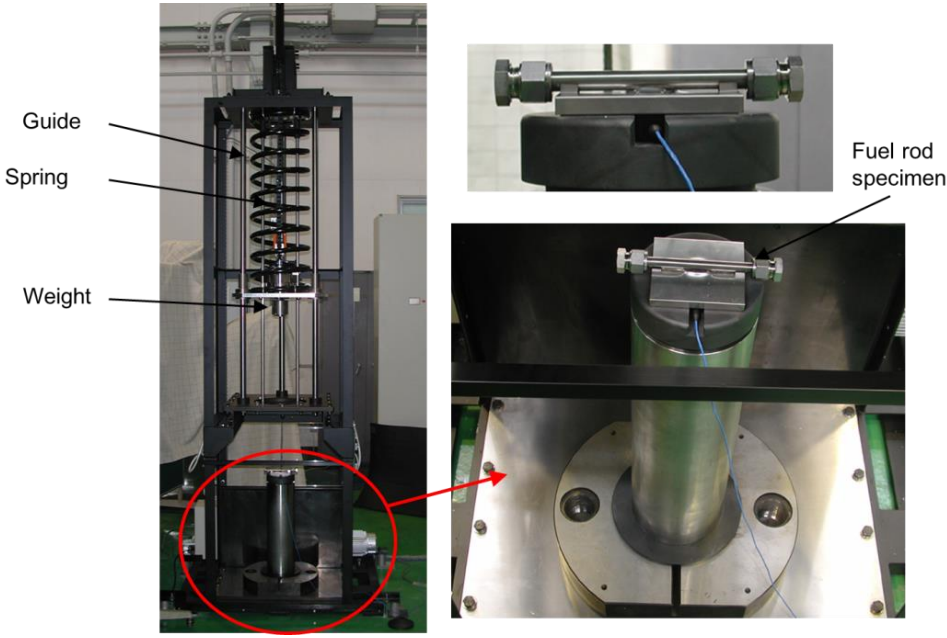
3.1 Test Equipment for Dynamic Load Impact Test (BWR)

- Dynamic load or impact speed to specimen was controlled by drop velocity of weight using spring expansion force.
- Deformation behaviour of specimen was recorded by high speed cameras.
- This equipment was also used for a part of dynamic tensile test (200 s^{-1}) and dynamic ring compression test (4000mm/s).





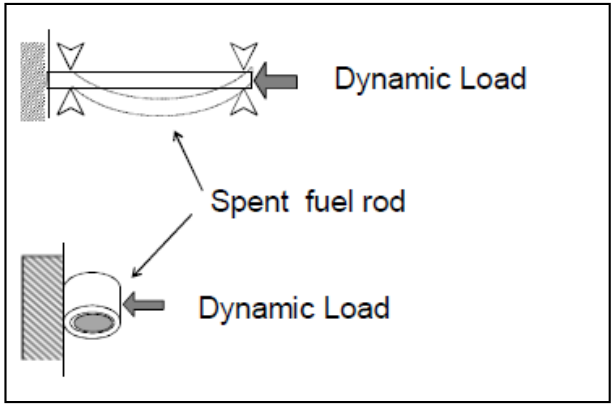
Setup for axial load

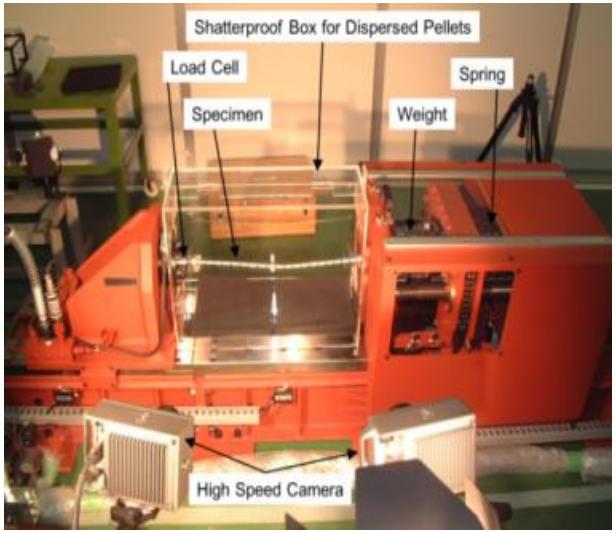


Setup for lateral load

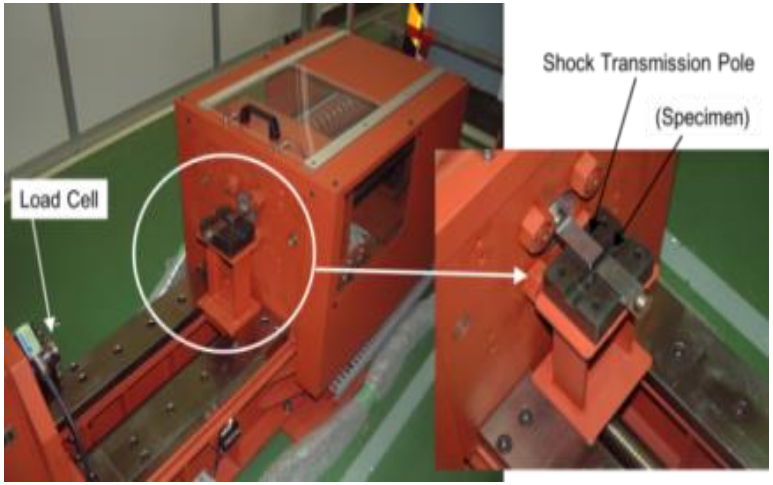
3.2 Test Equipment for Dynamic Load Impact Test (PWR)

- The test equipment was designed to install transversely due to the height restriction of the PIE facility.
- Dynamic load or impact speed to specimen was controlled by horizontal velocity of weight using spring expansion force.
- Deformation behaviour of specimen was recorded by high speed cameras.





Setup for axial load



Setup for lateral load

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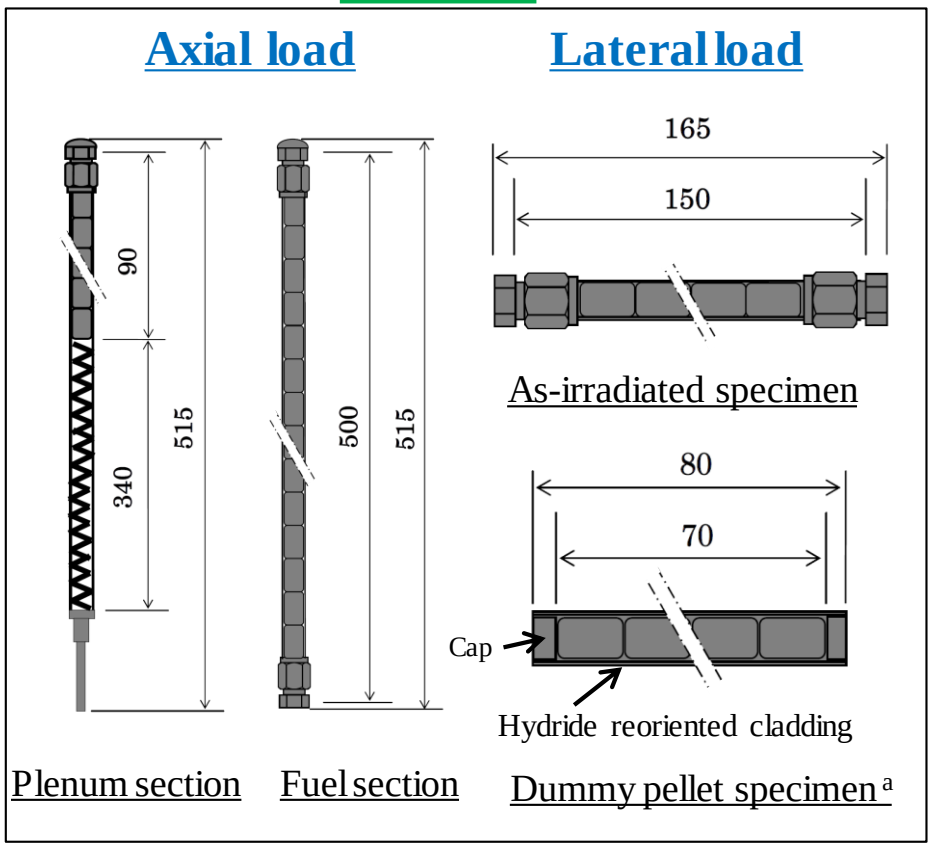
3.3 Test Specimen for Dynamic Load Impact Test

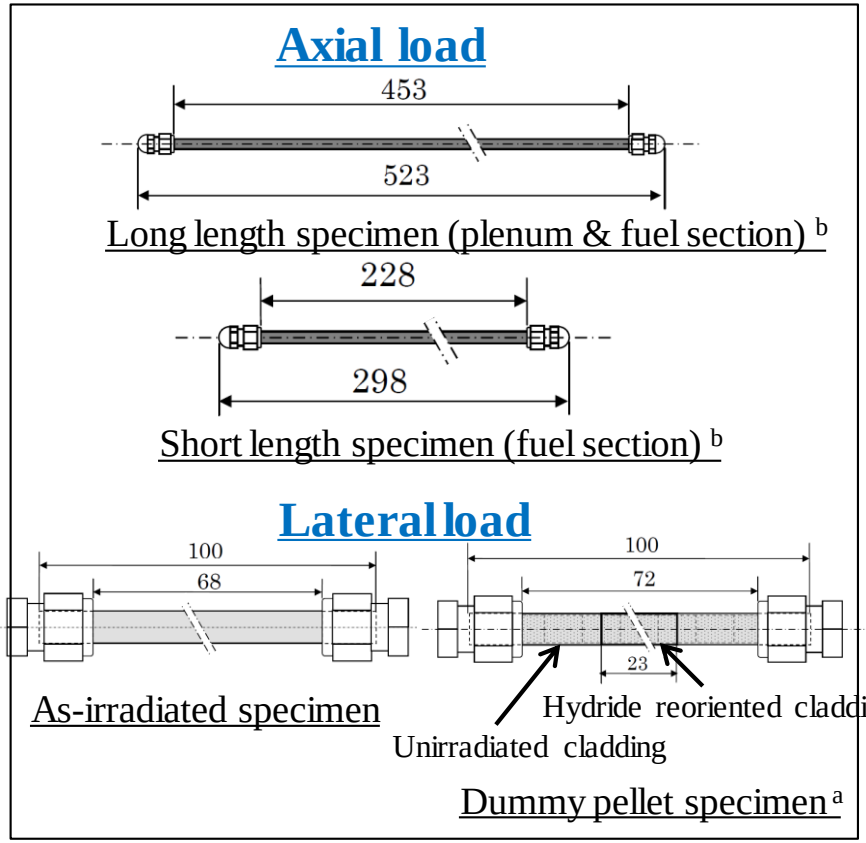
BWR

(unit:mm)



PWR

(unit:mm)

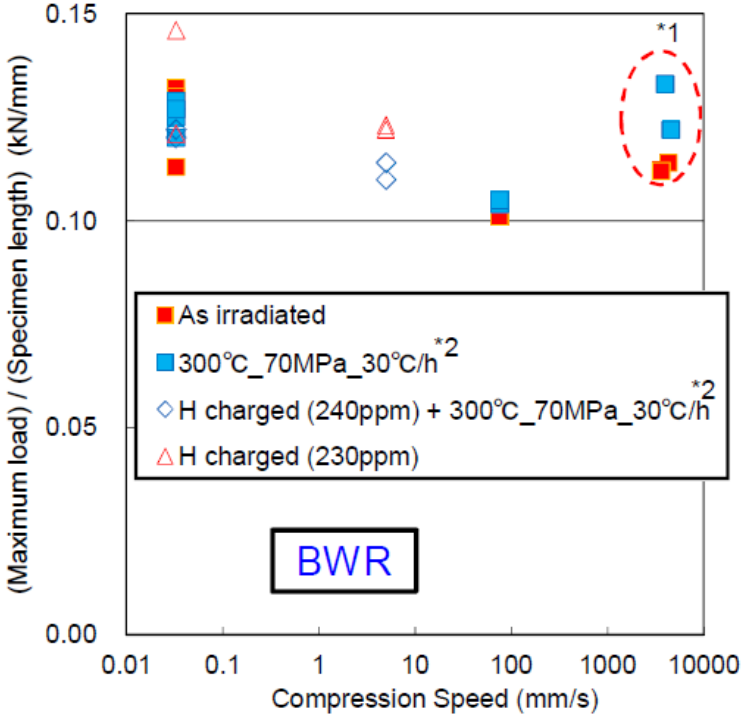


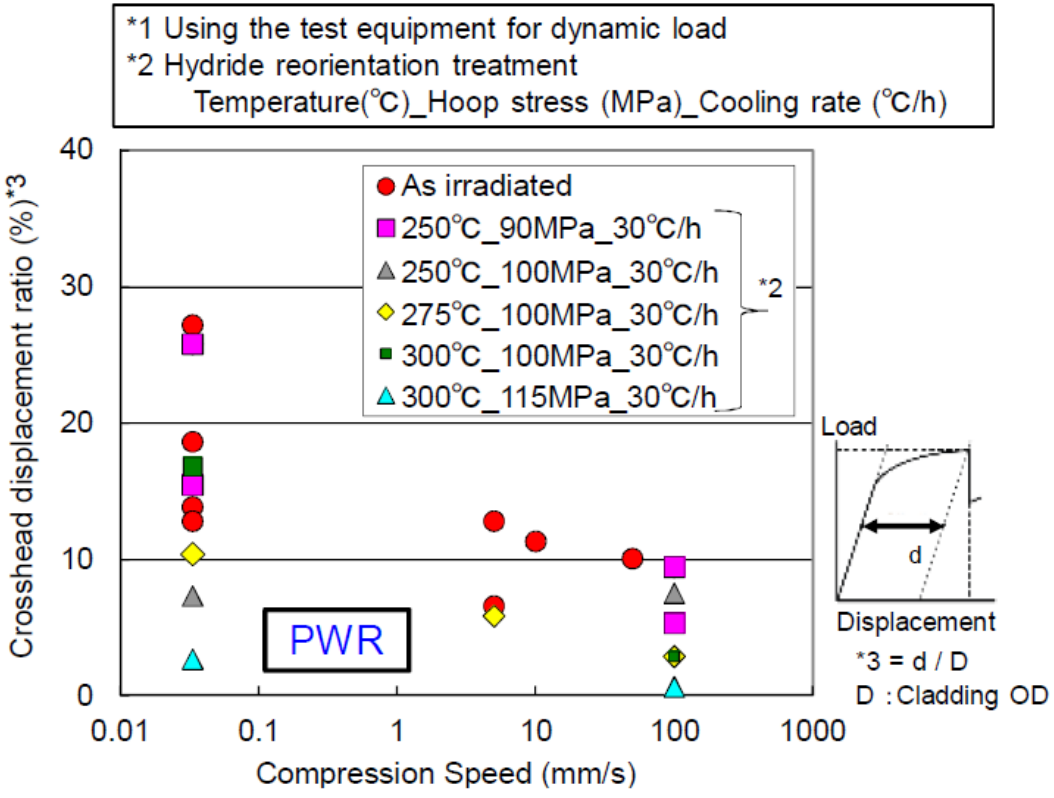
[a] Influence of hydride reorientation was evaluated using dummy pellet specimen

[b] Influence of rod length on dynamic behaviour was evaluated using long length and short length specimens

4. Elemental Mechanical Tests of Cladding

4.1 Results of Dynamic Ring Compression Test (BWR & PWR)





- **With increase of compression speed (<100mm/s), strength decreased, however, increased at ~4000 mm/s.**

- **With increase of compression speed (<100mm/s), ductility decreased.**
- **Influence of hydride reorientation was observed at 300℃_115MPa_30℃/h.**

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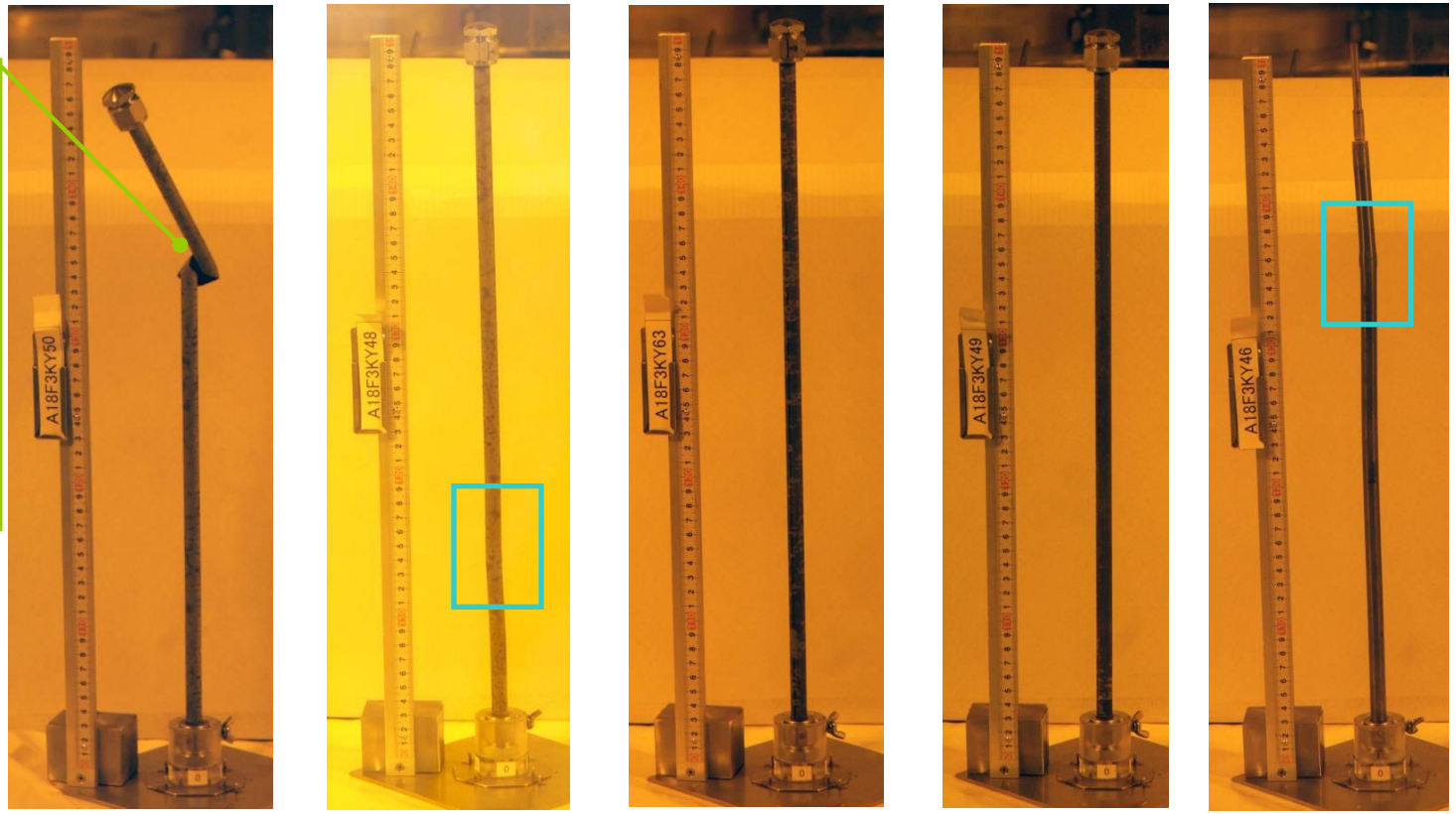
5. Dynamic Load Impact Tests of Fuel Rod

5.1-1 Results of Axial Dynamic Load Impact Test (BWR)

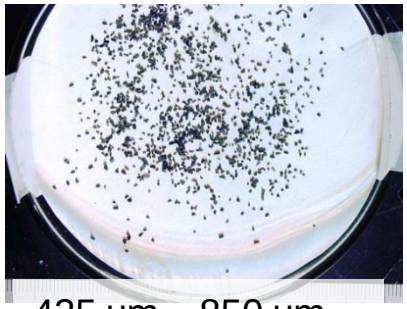
- Shearing failure occurred.
- Sparks flied from the breakage part at 0.3 ms after maximum load.



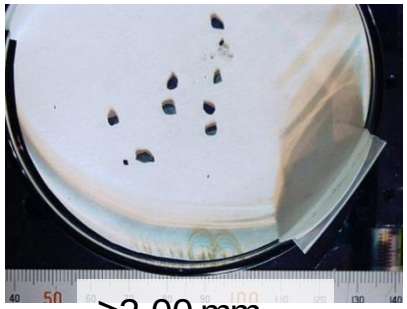
Weight mass	3.5kg				
Impact speed	12m/s	9m/s	6m/s	3.7m/s	6m/s
Specimen type	Fuel section				Plenum section
Maximum load	60 kN	53kN	46kN	29 kN	22 kN
Pellet dispersal	18.2 g	No failure	No failure	No failure	No failure
Deformation	Spiral breakage	Bowing at lower part	No deformation	No deformation	Dog-leg at plenum part

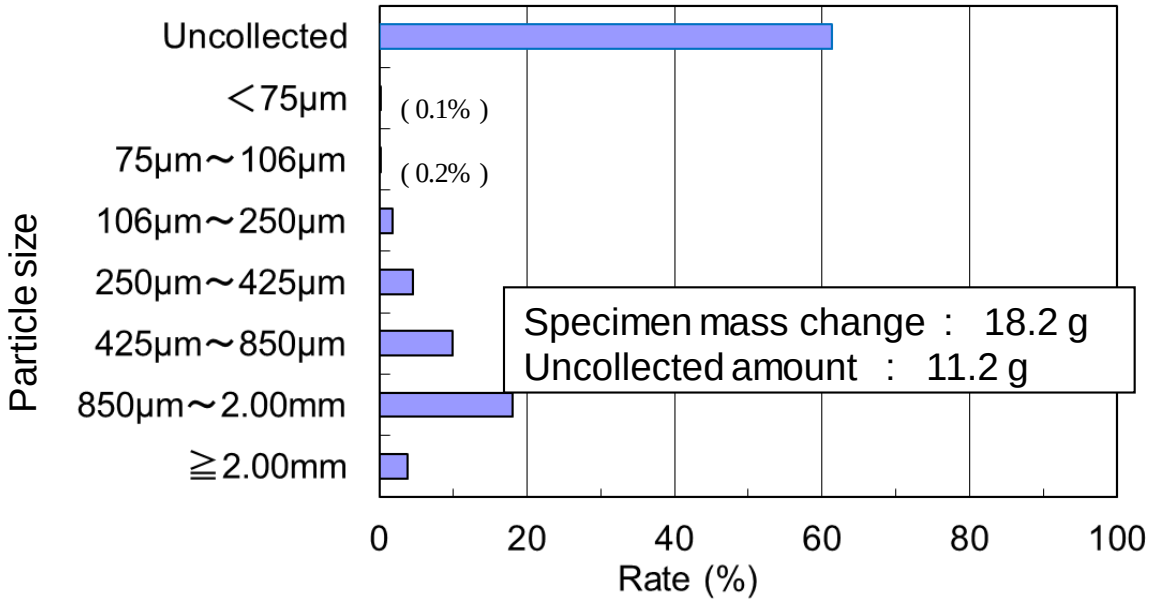
5.1-2 Axial Dynamic Load Impact Test (BWR): Amount of Dispersed Pellet and Particle Size Distribution (12m/s, 60 kN)

Dispersed pellet at the moment of breakage


425 μm – 850 μm


850 μm – 2.00 mm


≥2.00 mm



- **Amount of dispersed pellet at the breakage was equivalent to about 2 pellets.**
- **Particle size distributions were measured.**
- **Pellets exceeding 60% of dispersed amount were not collected, and those were very fine.**

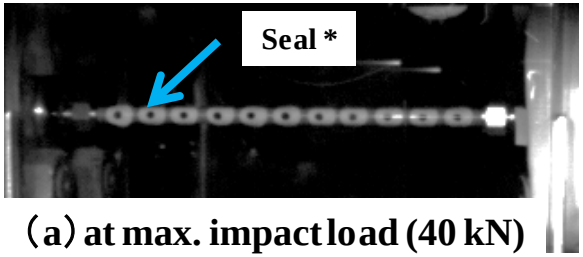
* Uncollected = (Specimen mass before test) – ((Specimen mass after test) + (Collected mass))
* Since element analysis was not carried out, a little impurities might be mixed.

5.2-1 Results of Axial Dynamic Load Impact Test (PWR)

Specimen No. & type		S-1	L-3	S-2	L-2	L-1
		Short/Fuel	Long/Fuel	Short/Fuel	Long/Fuel	Long/Plenum
Weight mass		3 kg				3 kg
Impact speed		11 m/s		8 m/s	11 m/s	11 m/s
Maximum load (With LPF of 3 kHz)		40 kN	36 kN	35 kN	33 kN	17 kN
Failure mode S:Sound F:Failure	Shearing	F	S	S	S	F
	Bending (high-order)	-	F	S	S	-
	Bending (first-order)	-	-	F	S	-
Crack direction		Spiral	Circumferential + Axial	Circumferential	-	Circumferential + Axial
Pellet dispersal		11.2 g	8.9 g	0.6 g	-	0 g

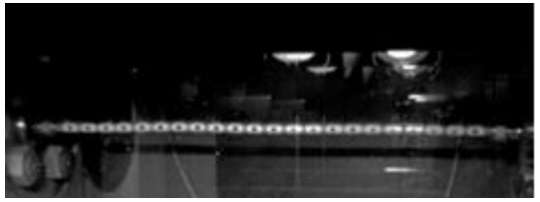
- Failures occurred at maximum load of 35 kN or more except L-1 (Plenum specimen).
- L-1 was failed at plenum spring area without pellet dispersal.
- After initial impact, axial load increased with compression, and high-order mode bending occurred, then first-order mode bending occurred. “Shearing failure” and “Bending failure” were observed.
- In the failed specimens, circumferential and/or spiral cracks were observed and some cracks branched in the axial direction.
- The effect of specimen length on dynamic behaviour was not observed.

5.2-2 Axial Dynamic Load Impact Test (PWR): Time History of Deformation State by High Speed Camera Image

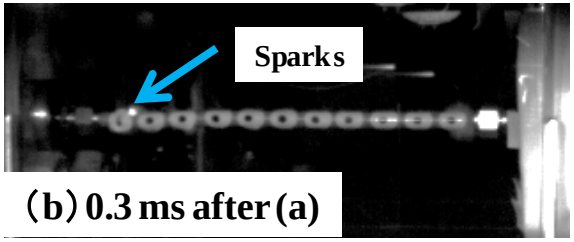


(a) at max. impact load (40 kN)

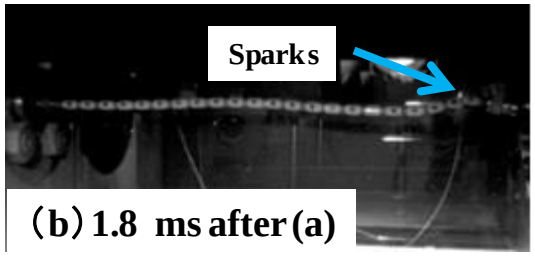
(a) at max. impact load (36 kN)



(a) at max. impact load (33 kN)

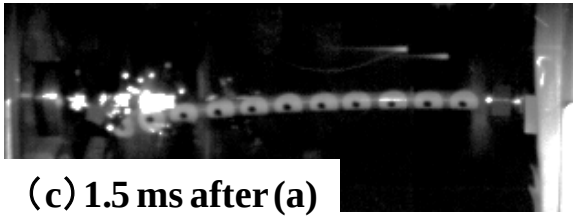


(b) 0.3 ms after (a)

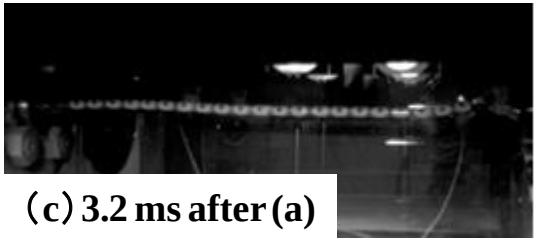


(b) 1.8 ms after (a)

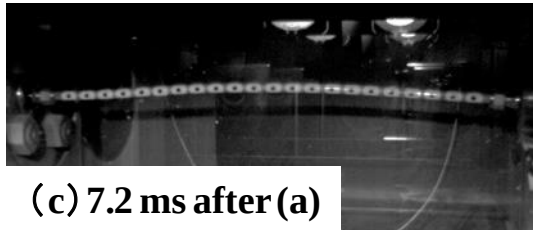
(b) 1.0 ms after (a)



(c) 1.5 ms after (a)



(c) 3.2 ms after (a)

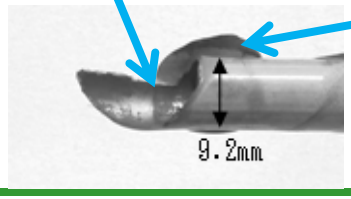


(c) 7.2 ms after (a)

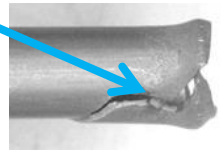
S-1 (Short/Fuel)
- Shearing failure
- Spiral crack

L-3 (Long/Fuel)
- Bending (high-order) failure
- Circum. + Axial crack

L-2 (Long/Fuel)
- No failure

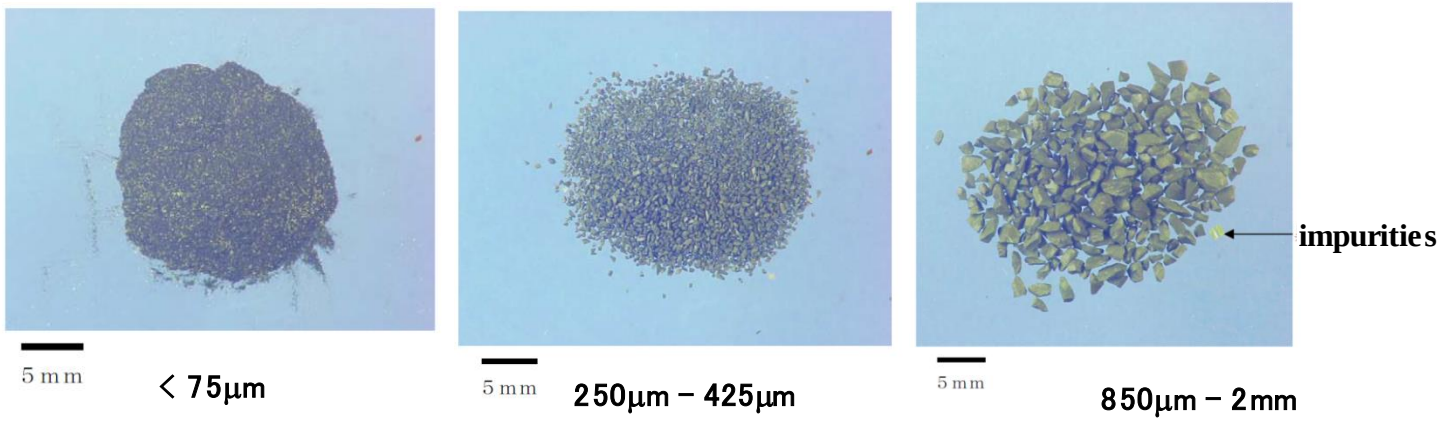


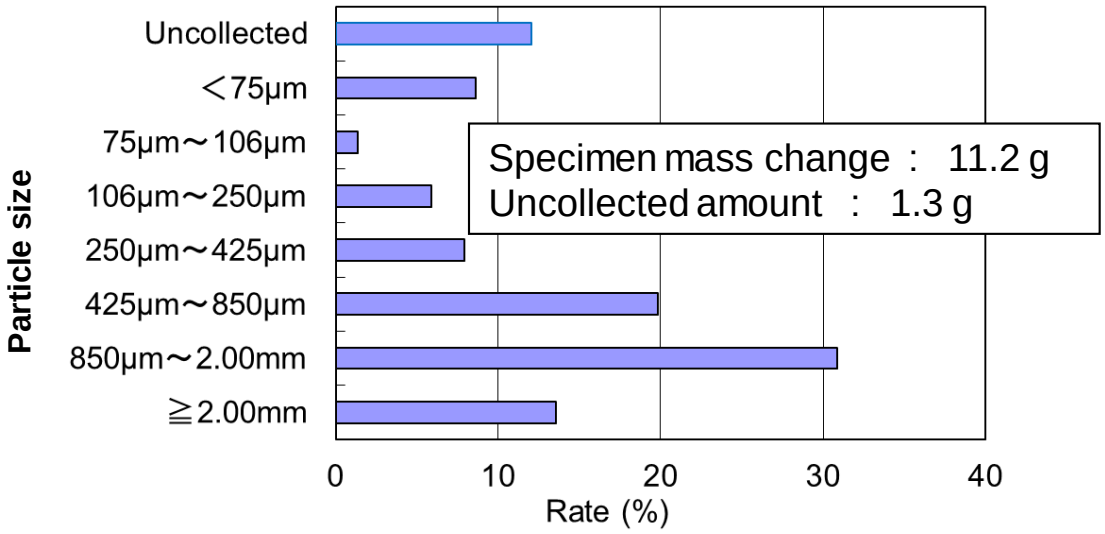
* Ocellated seals were attached on the surface of cladding in order to record the chronological change of deformation



5.2-3 Axial Dynamic Load Impact Test (PWR): Amount of Dispersed Pellet and Particle Size Distribution (S-1:11m/s, 40 kN)

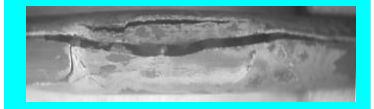
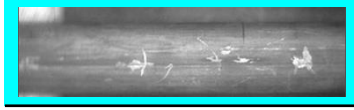
Dispersed pellet at the moment of breakage

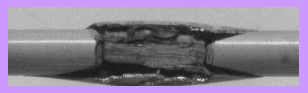
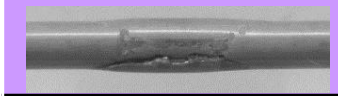
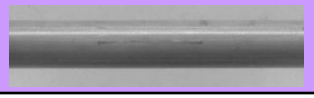


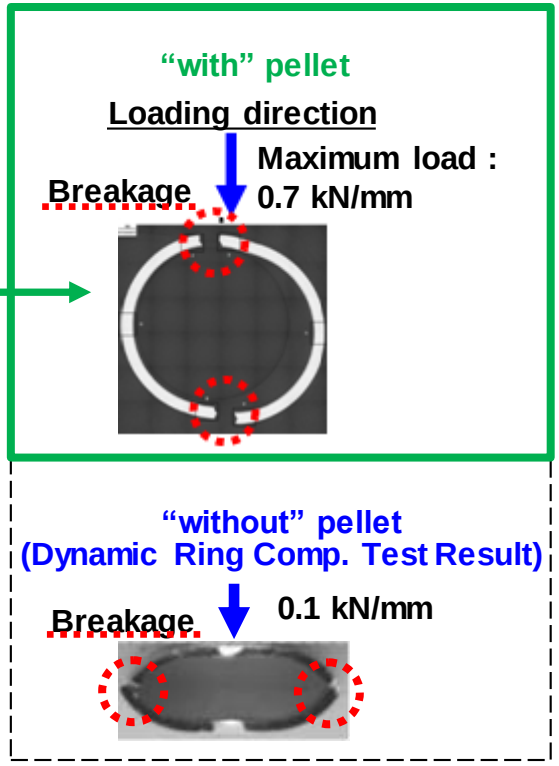


- **Amount of dispersed pellet at the breakage was equivalent to about 2 pellets as same as BWR.**
- **Particle size distributions were measured.**
- **Uncollected amount was smaller than that of BWR due to the difference in test equipment and pellet characteristics.**

5.3 Outline of Lateral Dynamic Load Impact Test Result (BWR & PWR)

BWR Push rod dia. = 30mm	Weight mass	Impact speed	Maximum load	Pellet dispersal*2
	2.6 kg	8 m/s	1.0 kN/mm	Failure 21.6 g
	2.6 kg	4 m/s	0.7 kN/mm	Failure 0 g
	0.6 kg	4 m/s	0.5 kN/mm	No failure

PWR Push rod dia. = 20mm	Weight mass	Impact speed	Maximum load *1	Pellet Dispersal *2
	3 kg	13 m/s	1.5 kN/mm	Failure 3.1 g
	3 kg	11 m/s	1.1 kN/mm	Failure 0.4 g
	3 kg	9 m/s	0.9 kN/mm	No failure



*1 With LPF of 3 kHz
*2 Amount of dispersed pellet at the moment of breakage + during handling

- Failure mode and strength were different between "with" pellet (lateral dynamic load impact test of fuel rod) and "without" pellet (dynamic ring compression test of cladding).
- Amount of dispersed pellet and particle size distributions were also measured.
- Influence of hydride reoriented (test results of dummy pellet specimen) is under evaluation.

6. Summary

- Mechanical properties of cladding and mechanical performances of fuel rod under the dynamic load condition were examined using high burnup spent fuels.
- In the axial dynamic load impact tests, shearing failure caused by initial impact (BWR and PWR) and bending failure with time delay (PWR) were observed.
- In the lateral impact tests (BWR and PWR) , different failure mode and strength were observed between “with” and “without” pellet.
- Amount of dispersed pellet and particle size were measured.

Thank You for Your Attention!