Integrity Criteria of Spent Fuel for Dry Storage in Japan

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Katsuichiro KAMIMURA

Japan Nuclear Energy Safety Organization (JNES)

Contents

Regulatory Requirements for Spent Fuel Integrity

(1) Criticality shall be prevented.

(2) Integrity of spent fuel during the storage shall be maintained.

- **To prevent the failure of fuel due to cladding thermal creep**
- **To prevent the degradation of cladding mechanical properties**

(3) Fuel material properties used in the safety analyses shall have appropriate safety margin.

- **To consider the effect on mechanical properties during irradiation and storage**
- **To store only sound spent fuel assemblies**

Circumstances and Conditions for Fuel Cladding in Dry Storage

- **Max. <u>temperature</u>: 400- 300ºC (similar or little larger to the temperature in reactor core)**
- **Circumferential <u>hoop stress</u>: larger than in reactor core (due to large inner pressure and very small outer pressure)**
- **Duration <u>time</u>: 50 years (much longer than in reactor core)**
- **<u>Heat flux</u> through the cladding wall: small**
- **<u>Atmosphere</u>: He gas**
- **<u>Dual Purpose Cask</u>: Transportation without inspection of fuel after long term dry storage (Fuel <u>material properties</u> used in the safety analyses shall have <u>appropriate safety margin</u>.)**

1. Background and Objective

Technical Issues and Objectives

To prevent the failure of fuel due to cladding thermal creep

- **Thermal creep properties of high burn-up fuel cladding**

To prevent the degradation of cladding mechanical properties

To consider the effects on mechanical properties during irradiation and storage

- **Effects of hydrogen content and hydride reorientation** *
- **Effects of irradiation hardening and its recovery** *

***Mechanical properties under both the normal storage and the accident in transportation (ex. Cask or Fuel assembly Drop) should be evaluated.**

1. Background and Objective

JNES Test Plan on Spent Fuel Integrity

Technical Requirements in Japan	Technical Issues to be Evaluated
To prevent the failure of fuel due to cladding thermal creep	**Thermal creep**
To prevent the degradation of cladding mechanical properties	**» Hydride reorientation** **» Irradiation hardening recovery**

Item		2000	2001	2002	2003	2004	2005	2006	2007	2008
Survey and Planning		━				━				
Creep Test	Creep Test	PWR48GWd/t, BWR50GWd/t ━	━	━	━		PWR55GWd/t, BWR55GWd/t ━	━		
	Creep Rupture Test	PWR48GWd/t, BWR50GWd/t ━	━	━	━					
Hydride Effects Evaluation Test » Hydride Reorientation Test » Mechanical Property Test							PWR48GWd/t, 55GWd/t BWR40GWd/t, 50GWd/t, 55GWd/t ━	━	━	━
Irradiation Hardening Recovery Test				PWR48GWd/t, 55GWd/t (330-420ºC) ━	━		(<330ºC) ━	━		

Fuel Cladding Tube Materials in Japan

BWR

Zry-2 ; RX*[1]
without Zr Liner(40GWd/t)
with Zr Liner(50GWd/t)

→ Zry-2 ; RX*[1] (55GWd/t)

PWR

Low Sn Zry-4; SR*[2] (48GWd/t)

→ MDA, NDA, Zirlo™; SR*[2] (55GWd/t)

RX*[1] : Recrystallized annealing
SR*[2] : Stress Relieved annealing

General Results of The Test

(1) Thermal Creep and Creep Rupture Tests

- **Threshold strain of transition to tertiary creep region is larger than 1% for irradiated cladding. (It is confirmed that the 1% creep strain criteria has a margin for creep rupture.)**
- **Creep equations were driven for BWR and PWR irradiated claddings.**

(2) Hydride Reorientation and Mechanical Properties Test

- **Based on the experimental results, non-degradation limit values of temperature and stress in the dry storage were evaluated.**

(3) Irradiation Hardening Recovery Test

- **Recovery was confirmed > 330 ℃**
- **BWR: No Recovery ≦ 270℃**
- **PWR: No Recovery ≦ 300℃**

Evaluation of The Results

From Viewpoint of Fuel Integrity Criteria:

- Creep criteria does not become a predominant factor for determining the fuel integrity criteria.
- Recovery of irradiation hardening has a little affect but not predominant one.
- Hydride reorientation effect on cladding mechanical properties is predominant for fuel integrity criteria .

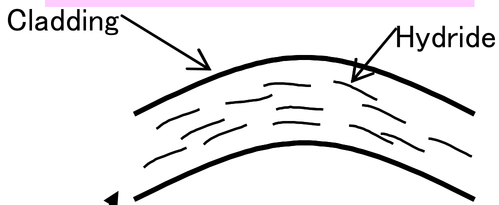
Detail Presentation on The following Aspects:

- Results of hydride reorientation effects on cladding mechanical properties
- Evaluation of them to derive fuel integrity criteria

3. Evaluation of Hydride Reorientation Test Results

Hydride Reorientation during Dry Storage

Before Dry Storage :～30℃



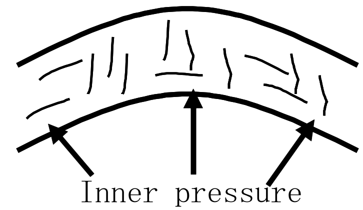
Hydride precipitation with circumferential orientation

Beginning of Dry Storage: ～300℃

Dissolution of a part of hydride

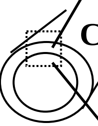
Temperature Decrease

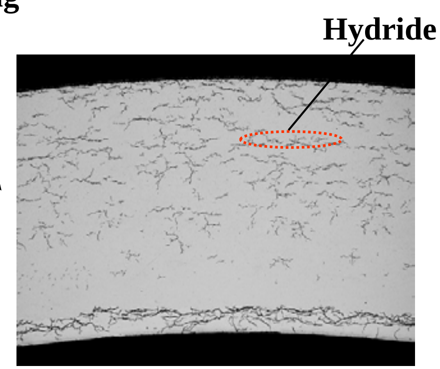
End of Dry Storage: ～100℃



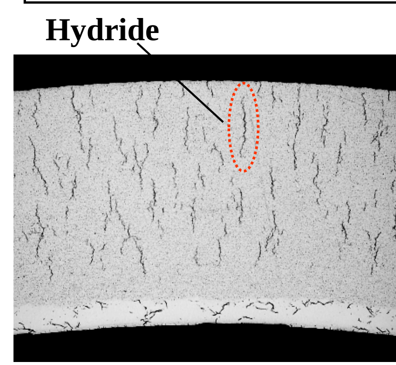
Hydride Reorientation

Hydride re-precipitation with radial orientation under the large hoop stress





As irradiated



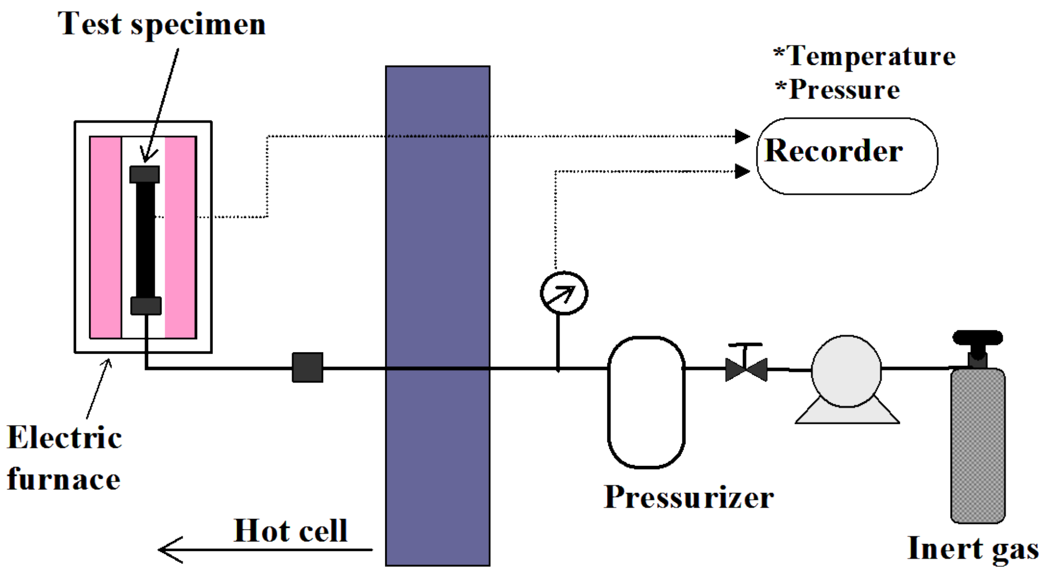
After creep test
170MPa, 420℃(BWR,50GWd/t type)

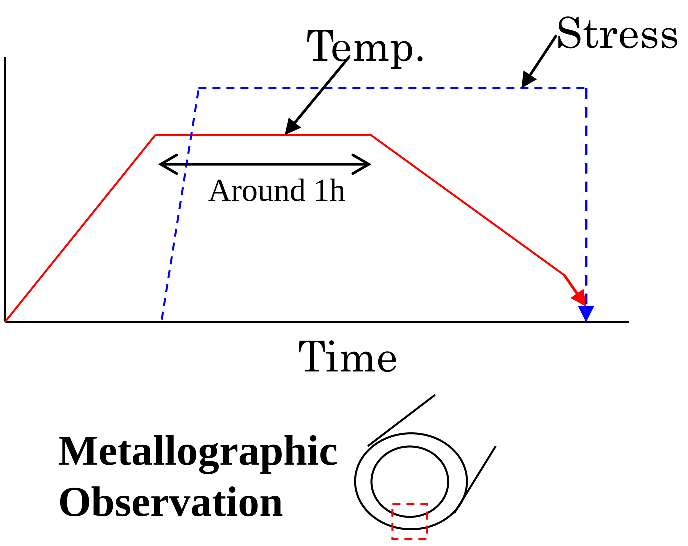
Ductility decrease?

・Hydride reorientation behavior? Mechanical properties? (irradiated materials)

3. Evaluation Test of Hydride Effects on Cladding Mechanical Properties

Hydride Reorientation Treatment (HRT) Method

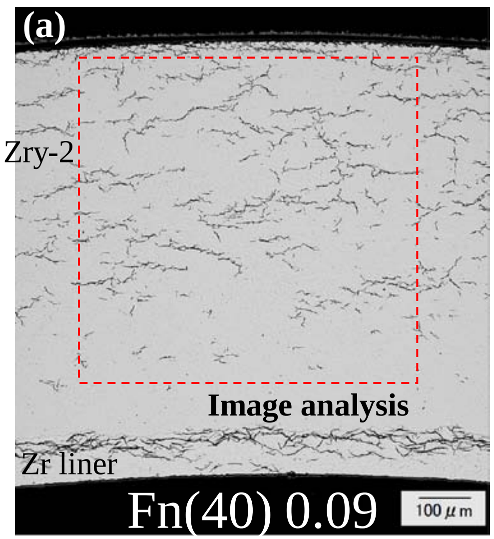




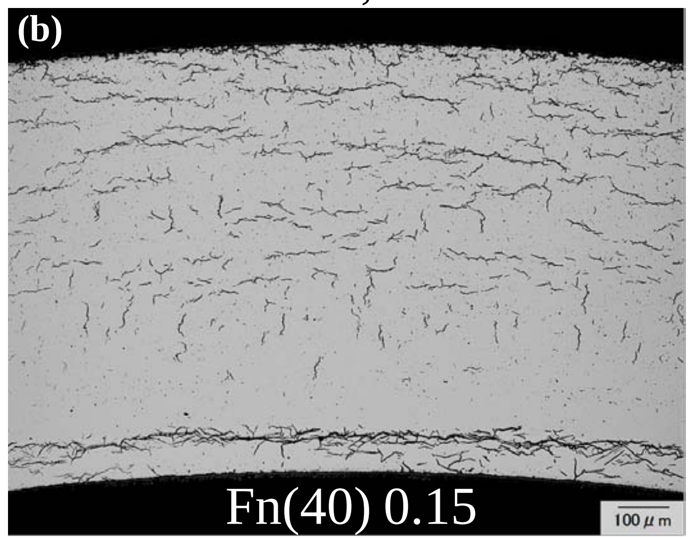
3. Evaluation Test of Hydride Effects on Cladding Mechanical Properties

Metallography of Hydride Reorientation Morphology

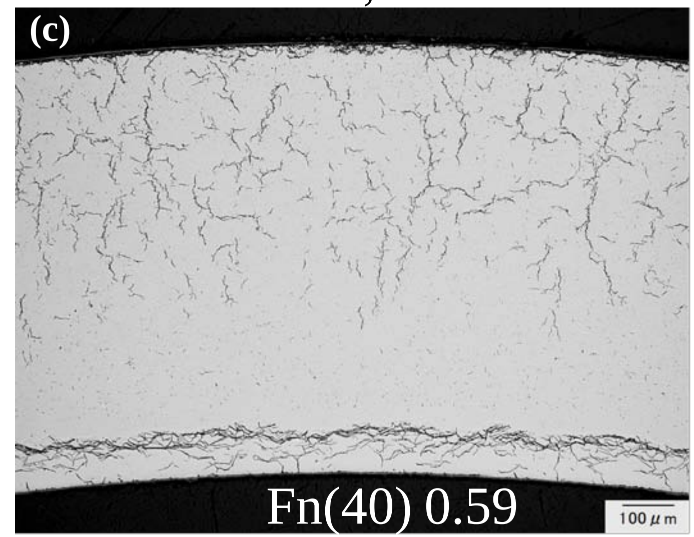
Before HRT
(As-Irradiated)



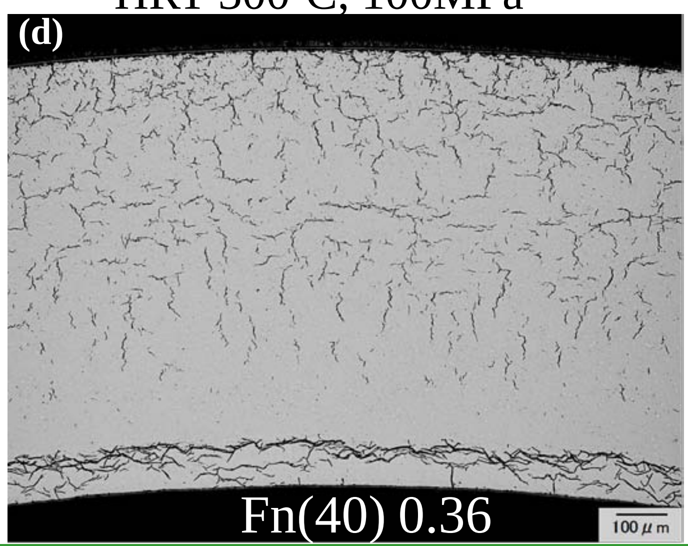
HRT 300°C, 70MPa



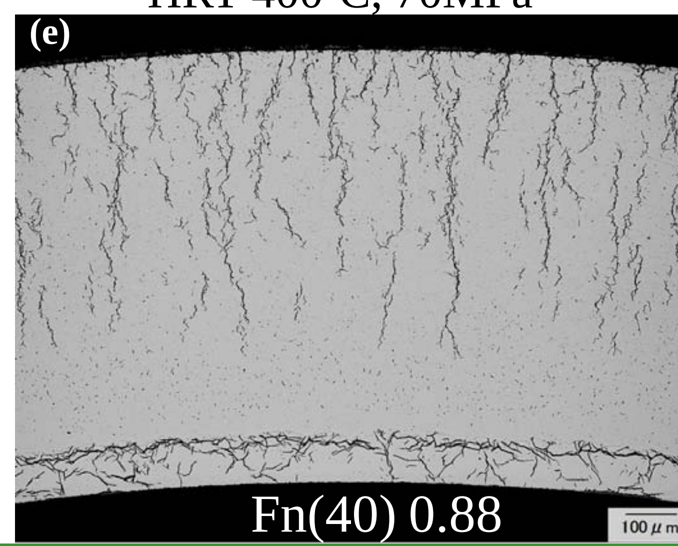
HRT 400°C, 40MPa



HRT 300°C, 100MPa



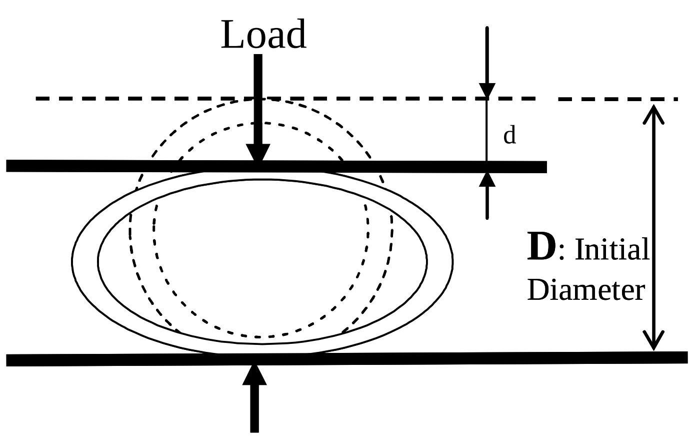
HRT 400°C, 70MPa



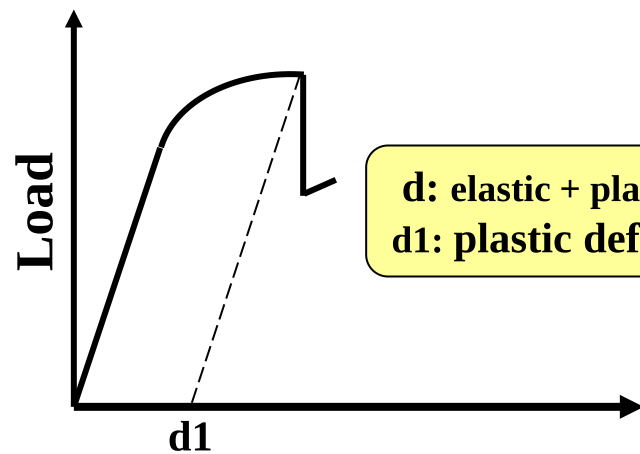
50GWd/t type Zry-2,
Cooling rate: 30°C/h

Ring Compression Test for Mechanical Property

**Considering conservative condition for brittleness of cladding in transportation after long term dry storage,
the tests were carried out at room temperature.**



Specimen length: 8mm

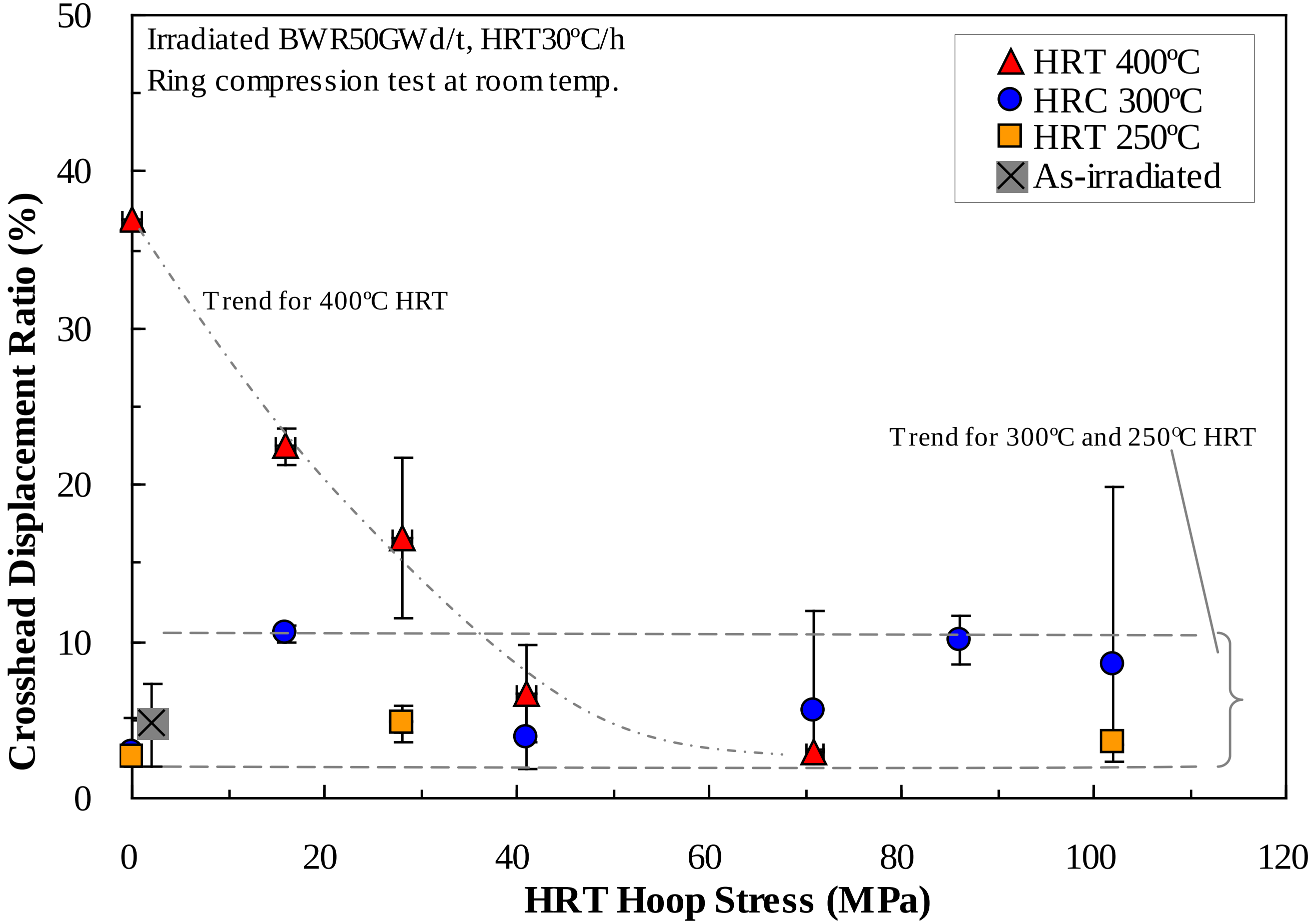


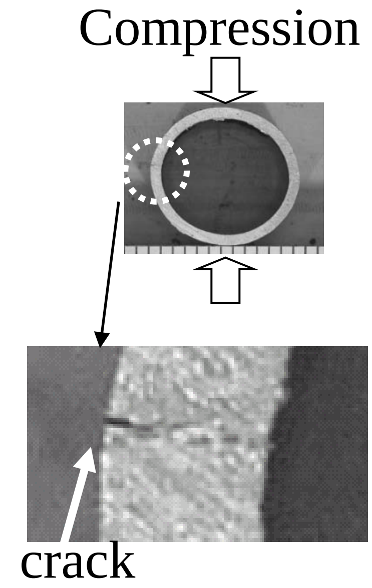
d: elastic + plastic deformation
d1: plastic deformation.

Ductility Index
=Crosshead Displacement Ratio (%)
=d1/D x 100

3. Evaluation Test of Hydride Effects on Cladding Mechanical Properties

Example of Ring Compression Test Result : Ductility vs. Radial Hydride Amount for BWR Zry-2





•At 300℃ and 250℃, radial hydride reorientation was not so large below 70MPa and no significant effect of HRT hoop stress on ductility was observed.
•At 400℃, the ductility increased compared to as irradiated material by heat treatment(annealing) at 0MPa, and it decreased with the hoop stress, or the amount of radial hydride.

3. Evaluation of Hydride Reorientation Test Results

HRT Effect on Hydride Reorientation and Mechanical Property (1) (BWR 40GWd/t：Zry-2 No Liner Cladding)

Radial Hydride Reorientation

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa)				
		16	28	40	50	70
300	3					■
250	30					■
	3				△	■
	3				△*2	
	0.6					■
200	3					○

○ : Same as As-Irradiated
△ : Unclear
■ : Hydride Reorientation
(solid red line) : Allowable Region
(dashed red line) : Additional Data Needed
*2 Hoop Stress Slightly Decreasing Cond.

Circumferential Mechanical Property

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa)				
		16	28	40	50	70
300	3					■
250	30					○*1
	3				○*1	○*1
	3				○*2	
	0.6					■
200	3					○

○ : Same as As-Irradiated
△ : Unclear
■ : Ductility Degradation
(solid red line) : Allowable Region
(dashed red line) : Additional Data Need
*1 Slight Ductility Degradation
*2 Hoop Stress Slightly Decreasing Cond.

Threshold for
- Hydride Reorientation : ≦200℃ and ≦70MPa
- Ductility Degradation : ≦200℃ and ≦70MPa

3. Evaluation of Hydride Reorientation Test Results

HRT Effect on Hydride Reorientation and Mechanical Property (2) (BWR 50GWd/t：Zry-2 with Zr Liner Cladding)

Radial Hydride Reorientation

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa)					
		16	28	40	70	85	100
400	30	■	■	■	■		
300	30	○	△	■	■	■	■
	3				△		
	0.6				○		
250	30		○	○			△

○：Same as As-Irradiated
△：Unclear
■：Hydride Reorientation
：Allowable Region

Circumferential Mechanical Property

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa)					
		16	28	40	70	85	100
400	30	△	△	△	△		
300	30	○	○	○	○	△	△
	3				○		
	0.6				○		
250	30		○				△

○：Same as As-Irradiated
△：Unclear
■：Ductility Degradation
：Allowable Region

Threshold for
- Hydride Reorientation：≦300℃ and ≦16MPa, or ≦250℃ and ≦40MPa
- Ductility Degradation：≦300℃ and ≦70MPa

HRT Effect on Hydride Reorientation and Mechanical Property (3) (BWR 55GWd/t : Zry-2 with Zr Liner Cladding)

Radial Hydride Reorientation

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa)						
		16	28	40	50	70	85	100
340	30			■		■		■
300	30	(○)	(△)			■	■	■
	3							
	0.6					(○)		
275	30					■		■
250	30			(○)				(△)

○ : Same as As-Irradiated
△ : Unclear
■ : Hydride Reorientation
( ) : Results of 50GWd/t Cladding
(red line) : Allowable Region

Circumferential Mechanical Property

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa)						
		16	28	40	50	70	85	100
340	30					△		
300	30					○	△	△
	3					(○)		
	0.6					(○)		
275	30							
250	30							(△)

○ : Same as As-Irradiated
△ : Unclear
■ : Ductility Degradation
( ) : Results of 50GWd/t Cladding
(red line) : Allowable Region

Threshold for

- Hydride Reorientation : ≦340℃ and ≦16MPa, or ≦250℃ and ≦40MPa
- Ductility Degradation : ≦300℃ and ≦70MPa

HRT Effect on Hydride Reorientation and Mechanical Property (4) (PWR 39GWd/t : Zry-4 Cladding)

Radial Hydride Reorientation

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa) 80	100	115	130
340	30				
300	30	○	■		■
	3				
	0.6				
275	30		○		■
	3				
250	30				

○ : Same as As-Irradiated
△ : Unclear
■ : Hydride Reorientation
(red line) : Allowable Region

Circumferential Mechanical Property

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa) 80	100	115	130
340	30				
300	30		■		■
	3				
	0.6				
275	30		(○)		
	3				
250	30		(○)		

○ : Same as As-Irradiated
△ : Unclear
■ : Ductility Degradation
( ) : Results of 48GWd/t Cladding
(red line) : Allowable Region

Threshold for
- Hydride Reorientation : ≦275℃ and ≦100MPa
- Ductility Degradation : ≦275℃ and ≦100MPa

3. Evaluation of Hydride Reorientation Test Results

HRT Effect on Hydride Reorientation and Mechanical Property (5) (PWR 48GWd/t : Zry-4 Cladding)

Radial Hydride Reorientation

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa) 85	100	115	130
340	30		○		■
300	30	○	○	■	■
	3			■	
	0.6			■	
275	30		○	■	△
	3			■	
250	30		○		△

○ : Same as As-Irradiated
△ : Unclear
■ : Hydride Reorientation
(red line) : Allowable Region

Circumferential Mechanical Property

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa) 85	100	115	130
340	30		■		■
300	30	■	■	■	■
	3			■	
	0.6			■	
275	30		○	△	△
	3			■	
250	30		○		△

○ : Same as As-Irradiated
△ : Unclear
■ : Ductility Degradation
(red line) : Allowable Region

Threshold for
- Hydride Reorientation : ≦340℃ and ≦100MPa
- Ductility Degradation : ≦275℃ and ≦100MPa

3. Evaluation of Hydride Reorientation Test Results

HRT Effect on Hydride Reorientation and Mechanical Property (6) (PWR 55GWd/t：MDA Cladding)

Radial Hydride Reorientation

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa)							
		55	70	85	90	95	100	115	130
300	30						△	■	■
275	30			○		△	△		
	3			○			△		
265	30								
	3								
260	30					△			
	3								
250	30				△		△		
	3								

○：Same as As-Irradiated
△：Unclear
■：Hydride Reorientation
：Allowable Region

Circumferential Mechanical Property

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress (MPa)							
		55	70	85	90	95	100	115	130
300	30						○	■	■
275	30			△		△	△		
	3			○			○		
265	30								
	3								
260	30					△			
	3								
250	30				○		■		
	3								

○：Same as As-Irradiated
△：Unclear
■：Ductility Degradation
：Allowable Region

Threshold for

- Hydride Reorientation：≦275℃ and ≦85MPa
- Ductility Degradation：≦250℃ and ≦90MPa

HRT Effect on Hydride Reorientation and Mechanical Property (7) (PWR 55GWd/t：ZIRLO Cladding)

Radial Hydride Reorientation

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress（MPa）							
		55	70	85	90	95	100	115	130
300	30		○				■	■	■
275	30		○				■		
	3	○	○						
265	30					△			
	3								
260	30					△			
	3								
250	30				△				
	3								

○：Same as As-Irradiated
△：Unclear
■：Hydride Reorientation
：Allowable Region

Circumferential Mechanical Property

Temp. (℃)	Cooling Rate (℃/h)	Hoop Stress（MPa）							
		55	70	85	90	95	100	115	130
300	30		○				■	■	■
275	30		△				△		
	3	○	△						
265	30					△			
	3								
260	30					△			
	3								
250	30				○				
	3								

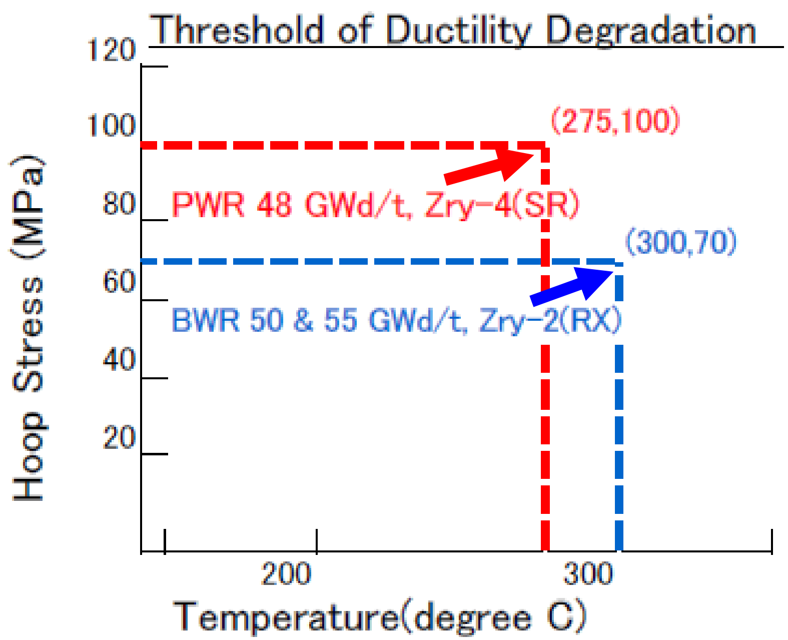
○：Same as As-Irradiated
△：Unclear
■：Ductility Degradation
：Allowable Region

Threshold for

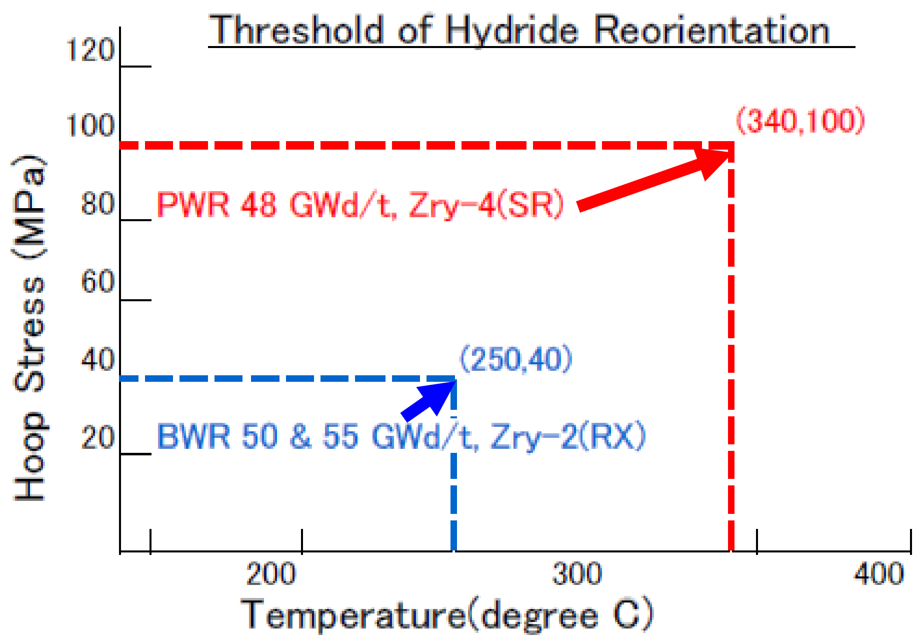
- Hydride Reorientation：≦300℃ and ≦70MPa
- Ductility Degradation：≦250℃ and ≦90MPa

3. Evaluation of Hydride Reorientation Test Results

HRT Thresholds for Hydride Reorientation and Ductility Degradation (Comparison between BWR and PWR)

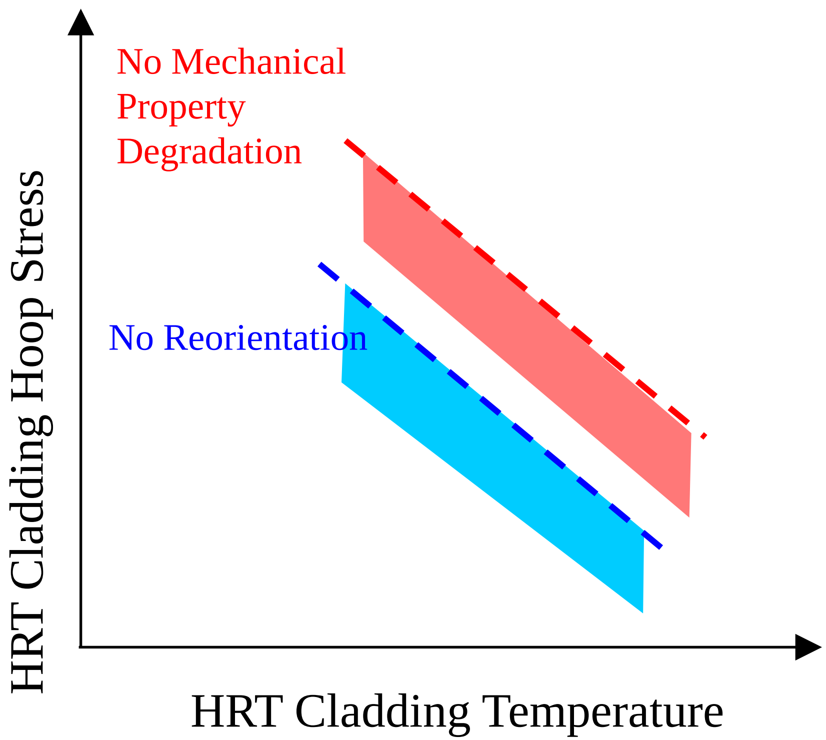


BWR Zry-2(RX) ~ PWR Zry-4(SR)



BWR Zry-2(RX) < PWR Zry-4(SR)

Initial Idea of Fuel Integrity Evaluation Methodology



Initial Hypotheses

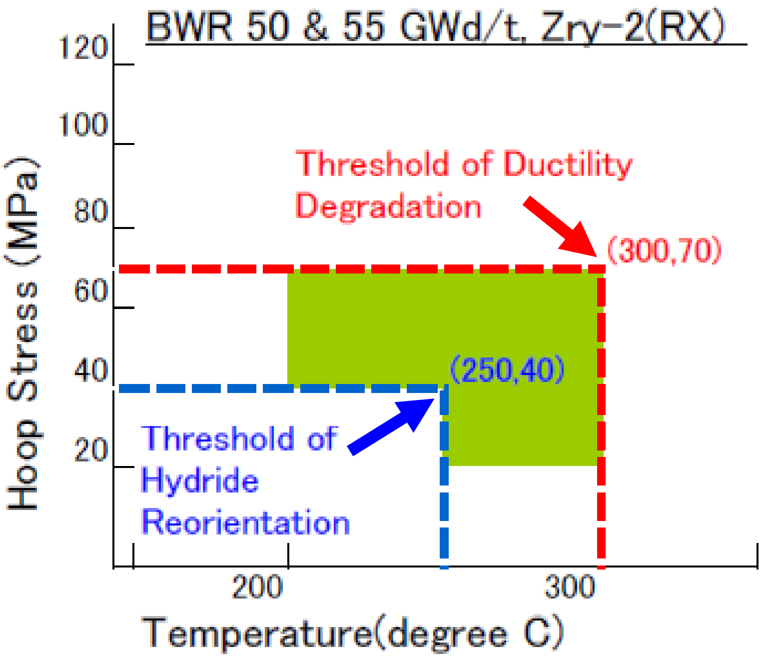
(1) Threshold of No Mechanical Property Degradation > Threshold of No Reorientation

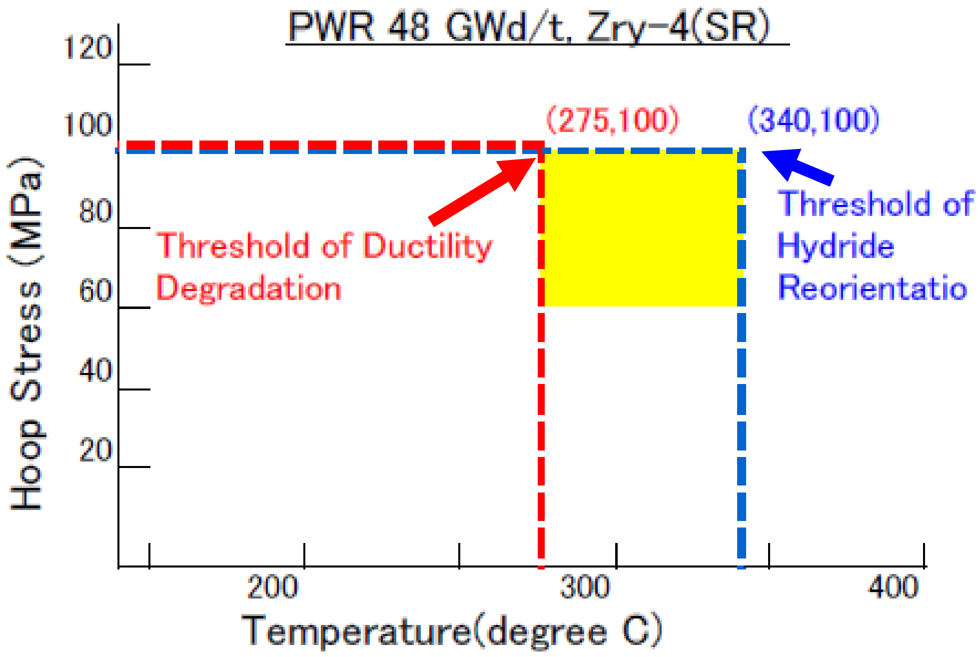
(2) Region (No Mechanical Property Degradation + Reorientation) : Small

"Threshold of No Reorientation" will be applicable as an index for fuel integrity criteria.

But !

HRT Thresholds for Hydride Reorientation and Ductility Degradation





Although hydride reorientation occurs, no degradation of ductility occurs in the green region.

Although no hydride reorientation occurs, degradation of ductility occurs in the yellow region.

HRT Thresholds for Hydride Reorientation and Ductility Degradation

Actual Findings

PWR Cladding:

Degradation of ductility occurs even in the region of no hydride reorientation.

BWR Cladding:

Hydride reorientation occurs even in the low temperature and stress region.

No degradation of ductility occurs in some region where hydride reorientation occurs.

Determined Methodology

- "Threshold of No Reorientation" is not directly applicable as an index for fuel integrity criteria.
- HRT temperature and stress related to "Threshold of No Mechanical Property Degradation" is adopted as fuel Integrity criteria for interim dry storage.

3. Evaluation of Hydride Reorientation Test Results

Summary of HRT Thresholds as Fuel Integrity Criteria for Interim Dry Storage

Cladding Type		Threshold of No Ductility Degradation Affected by Hydride Reorientation	
		Temperature (℃)	Hoop Stress (MPa)
BWR Zry-2 (RX)	40GWd/t No Liner	≦200	≦70
	50GWd/t with Liner	≦300	≦70
	55GWd/t with Liner	≦300	≦70
PWR (SR)	39GWd/t Zry-4	≦275	≦100
	48GWd/t Zry-4	≦275	≦100
	55GWd/t MDA	≦250	≦90
	55GWd/t ZIRLO	≦250	≦90

4. Application of Fuel Integrity Criteria

Remarks for Applying The Fuel Integrity Criteria to Cask Design

- **The conclusion in this project satisfies the sufficient condition for preventing degradation from a conservative viewpoint about the influence of hydride reorientation.**
- **Therefore even if some conditions are not satisfied in cask designs, the applications are not always rejected. In this case, the applicants (designers) shall either evaluate and prove the fuel integrity with their own data, or evaluate cask safety by using absolute mechanical properties of the degraded cladding.**

Because

- **The evaluation in this project are performed as comparative validation with as-irradiated materials. Absolute evaluation to determine acceptable degradation degree of mechanical properties have not been performed.**
- **Cladding ductility (integrity) might be maintained in some different conditions from the result of this project.**
- **Hydride reorientation tests are performed under conservative condition as applying uniform internal pressure which are different from actual storage condition.**

5. Summary

(1)The following <u>mechanical property tests</u> were carried out to derive fuel integrity criteria.

- **Thermal Creep and Creep Rupture Test**
- **Hydride Reorientation and Mechanical Properties Test**
- **Irradiation Hardening Recovery Test**

(2) <u>Hydride reorientation effect on cladding mechanical properties is predominant for fuel integrity criteria .</u>

(3) Based on the experimental results, non-degradation limit values of temperature and stress in the dry storage were evaluated.

(4) "<u>Threshold of No Reorientation</u>" is not directly applicable as an index for fuel integrity criteria.
HRT temperature and stress related to "<u>Threshold of No Ductility Degradation</u>" was adopted as fuel integrity criteria for interim dry storage.

(5) HRT thresholds as fuel integrity criteria are remarkably <u>depend on the cladding materials</u>.

6. References

(1)Kamimura, K., et al, "Thermal creep test of BWR and PWR spent fuel cladding", IAEA International Conference on Storage of Spent Fuel from Power Reactors, Vienna(2003).

(2) Ito, K., et al, "Evaluation of Irradiation Effect on Spent Fuel Cladding Creep Properties", 2004 International Meeting on LWR Fuel Performance, Orlando(2004).

(3)Aomi, M., et al, "High Burnup Fuel Cladding Tube Property Test for Evaluation of Spent Fuel Integrity in Interim Dry Storage", IAEA International Conference on Management of Spent Fuel from Nuclear Power Reactors, Vienna(2006).

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