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Future Prospect of Development of Light Water Reactor Fuels

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Introduction

- Nuclear Energy is a key technology to solve the global energy and environment problems.
- LWRs are mostly utilized and most reliable nuclear power plants.
- Japan is now operating 55 LWRs and constructing more of them.
- Worldwide demands for LWRs have led to global grouping of the reactor vendors including Japanese makers as key players.
- LWR fuel designs are advancing to attain the targets such as higher fuel burn-up, plant up-rating, longer operation cycles as well as higher fuel performance and higher reliability.

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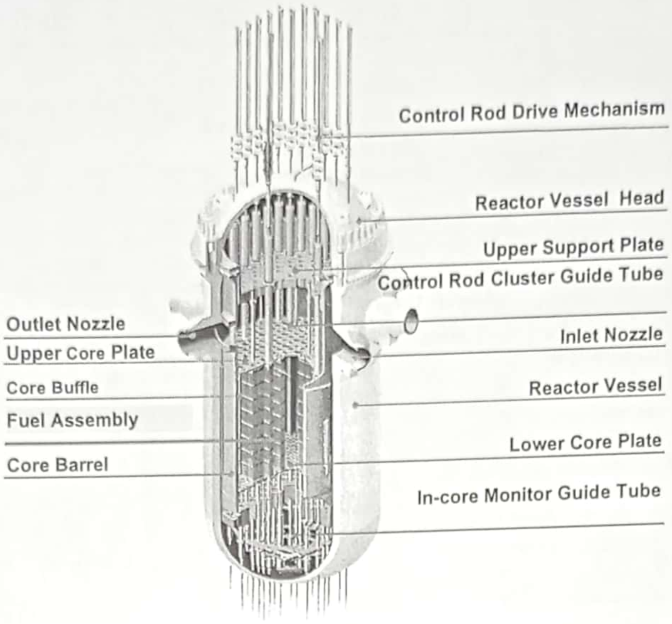
International Grouping of Nuclear Reactor Vendors

- Toshiba – Westinghouse : PWR & BWR
- Hitachi – General Electric : BWR
- Mitsubishi Heavy Industry – Areba : PWR

I) PWR Fuel Development

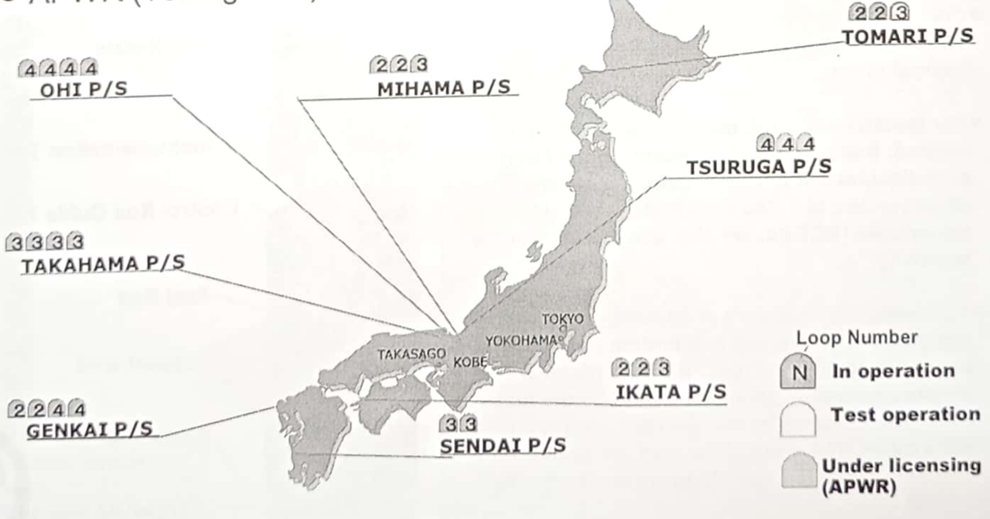
PWR Plant and Fuel



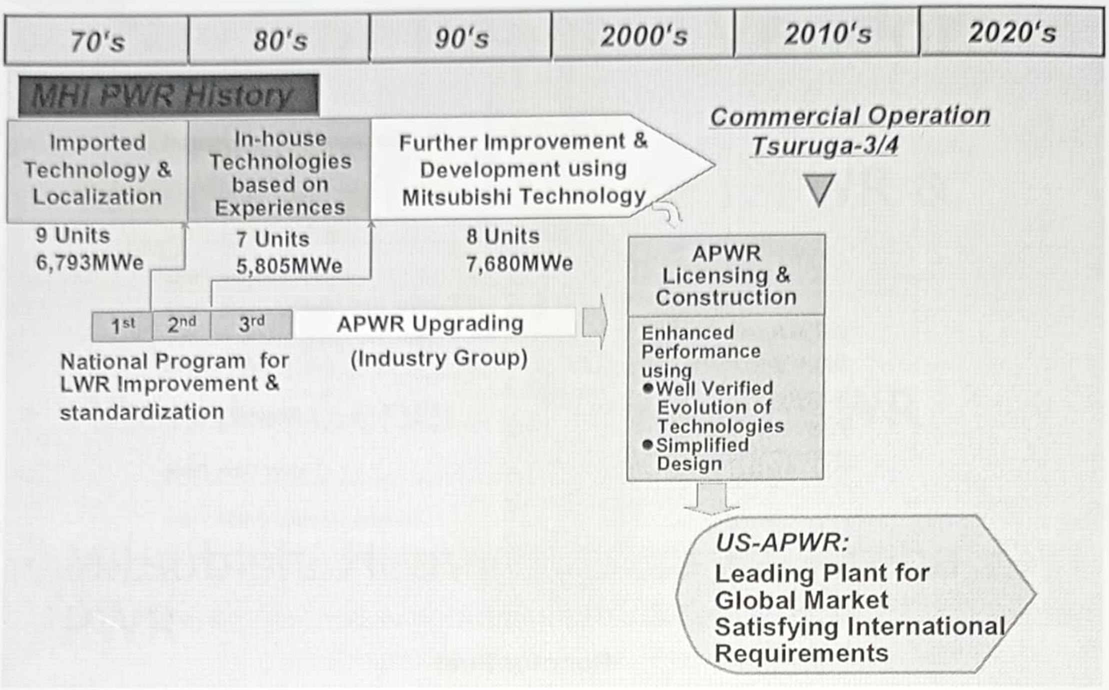
Reactor/Fuel

PWR NPPs in Japan

- 24 PWRs in operation (most recent : Tomari-3 of Hokkaido)
- APWR (Tsuruga-3/4) are under licensing



Mitsubishi PWR NPPs



70's	80's	90's	2000's	2010's	2020's

MHI PWR History

Imported Technology & Localization
9 Units
6,793MWe

In-house Technologies based on Experiences
7 Units
5,805MWe

Further Improvement & Development using Mitsubishi Technology
8 Units
7,680MWe

1st 2nd 3rd APWR Upgrading

National Program for LWR Improvement & standardization

(Industry Group)

Commercial Operation Tsuruga-3/4

APWR Licensing & Construction

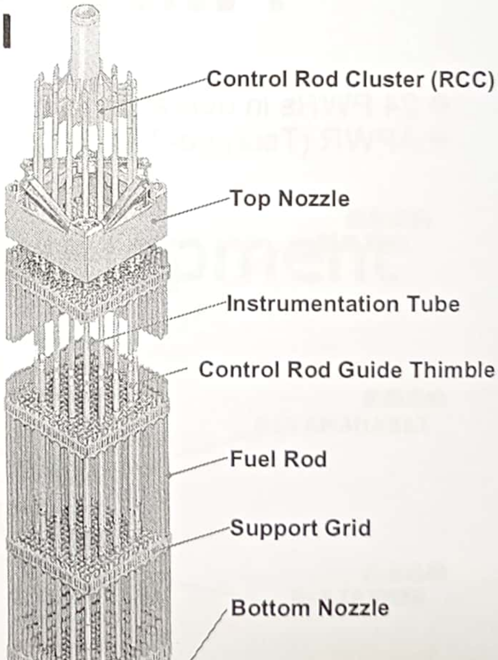
Enhanced Performance using
- Well Verified Evolution of Technologies
- Simplified Design

US-APWR:
Leading Plant for Global Market Satisfying International Requirements

Features of PWR Fuel

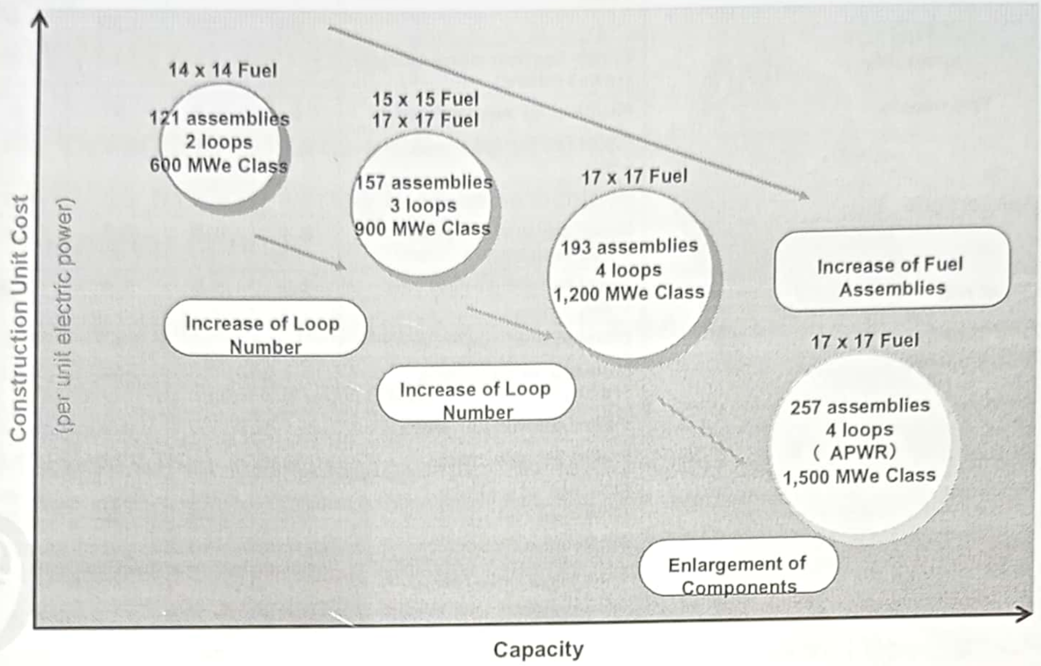
Features

- Core of PWR plant is composed of required number of fuel assemblies depending on the thermal power.
- For reactivity control, mainly, chemical shim method, that is to adjust concentration of boric acid dissolved in primary coolant as neutron absorber, is used .The rod cluster control assemblies (RCCAs) are also used to control the reactivity.
- Fuel assembly consists of support grids, control rod guide thimbles, top and bottom nozzles and about 200 to 300 fuel rods. Single enrichment pellets of uranium dioxide are put into the fuel rods. The cladding of the fuel rods are zirconium alloy tubes. The ends of the clad are sealed with end plug. The clad and plugs are weld together.



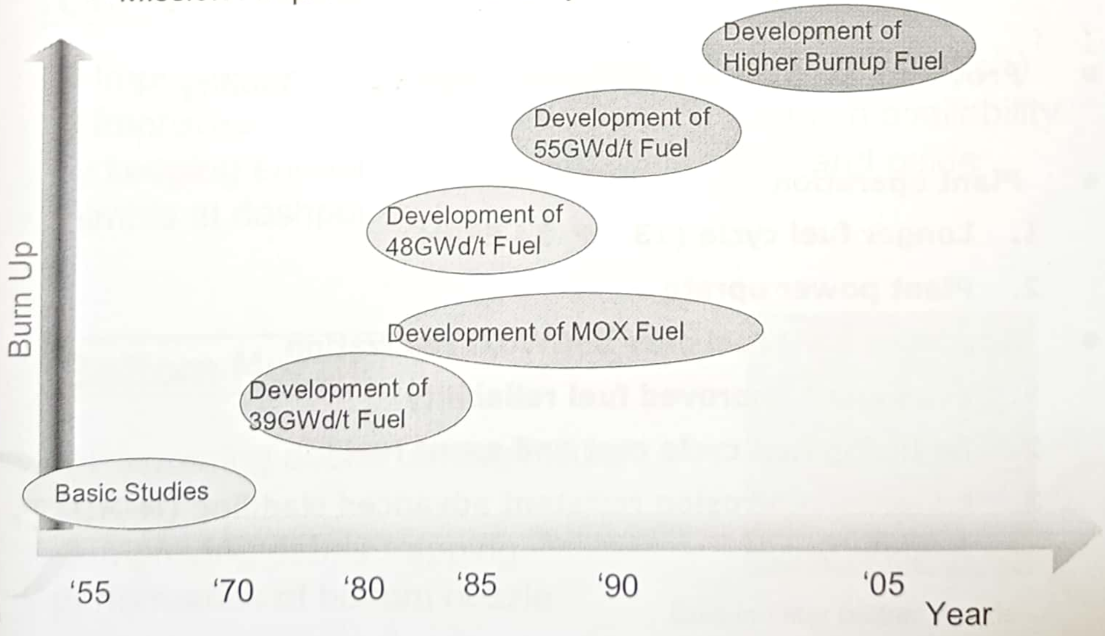
Schematic view of Fuel Assembly （17×17）

Pursuit of Economy



History of Design Improvement

<< Mission : Improve Fuel Economy & Reduce Spent Fuels>>



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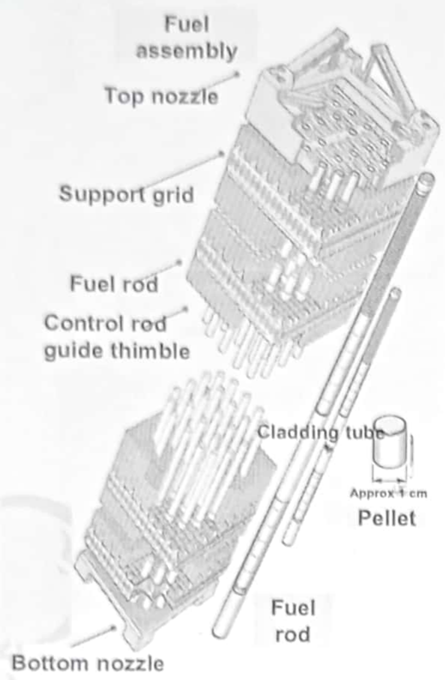
Types and Basic Specifications of PWR Fuel in Japan



Type	14×14		15×15	17×17
	10ft	12ft	12ft	12ft
Cross section dimensions (mm square)	197		214	214
Number of support grids	6	7,8	7	9
Total length of assembly (m)	3.5	4.1	4.1	4.1
Weight of assembly	0.5	0.6	0.7	0.7
Uranium weight (ton UO2/assembly)	0.4	0.5	0.5	0.5
Total length of fuel rod (m)	3.2	3.9	3.9	3.9
Diameter of fuel rod	10.7		10.7	9.5
Number of fuel rods (rods)	179		204	264
Pellet diameter(mm)	9.3		9.3	8.2
Pellet length(mm)	12.6		12.6	11.5
Number of pellets (pellets)	Appr. 240	Appr. 290	Appr. 290	Appr. 320
Materials: Pellet Cladding tube Control rod guide thimble Support grid Top and Bottom nozzles	Uranium dioxide, gadolinium containing uranium dioxide Zircaloy-4, etc. Zircaloy-4 Inconel, etc. Stainless steel			

Advanced PWR fuel over 55GWd/t(A)

⇓

- **Providing Step2 fuel (55GWd/t) with high reliability**

- **Plant operation**
  1. **Longer fuel cycle (13 → 24 EFPM)**
  2. **Plant power uprate**
- **Advanced PWR fuel over 55GWd/t realization**
  1. **Even more improved fuel reliability**
  2. **Reducing fuel cycle cost and spent fuel**
  3. **Enhanced corrosion resistant advanced cladding (M-MDA™, J-Alloy™)**

Improving Reliability (1)

PWR Grid Spacer

◆Preventing Grid-to-Rod-Fretting Wear

<u>Stable spring force</u> against rod vibration and rod diameter change

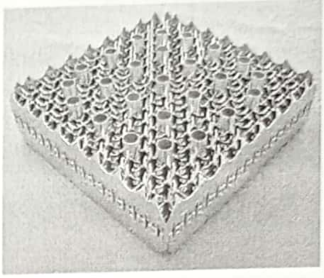
⬇

●Improving reliability to GTRF wear issue

◆Seismic reinforcement

◆High DNB margin

Modified mixing vane shape and angle



High performance I-type grid

Improving Reliability (2)

Guide thimble

◆Improved design against IRI (Incomplete Rod Insertion)

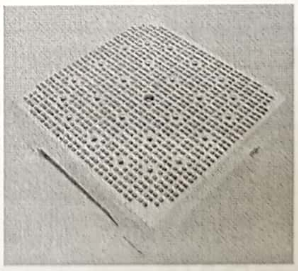
◆Improved RCC (Rod Cluster Control) insertion availability by keeping enough clearance between RCC and guide thimble at dashpot area

Bottom Nozzle

◆Preventing debris fretting failure

⇩

◆Improving debris trapping performance of bottom nozzle



Built-in Filter bottom nozzle

Advanced Cladding Composition

Alloy	Concentration [wt%]					
	Sn	Nb	Fe	Cr	O	Zr
Zircaloy-4	1.2-1.7	-	0.2	0.1	-	Balance
MDA	0.8	0.5	0.2	0.1	-	Balance
M-MDA™	**0.5**	**0.5**	**0.3**	**0.4**	**-**	**Balance**
J1 (J-Alloy™)	**-**	**1.8**	**-**	**-**	**0.1**	**Balance**
J2 (J-Alloy™)	**-**	**1.6**	**-**	**0.1**	**0.1**	**Balance**
J3 (J-Alloy™)	**-**	**2.5**	**-**	**-**	**0.1**	**Balance**

What is M-MDA™ ?

- M-MDA™ (Modified MDA)
  - ✓ Corrosion resistance is highly improved, but the basic properties are maintained, with :
    - Optimization of Sn, Fe, Cr content
    - Inheritance of Nb content

Alloys	Sn	Nb	Fe	Cr	Heat Treatment
Zircaloy 4	**1.2-1.7**	**-**	**0.2**	**0.1**	**Stress Relieved**
MDA	**0.8**	**0.5**	**0.2**	**0.1**	**Stress Relieved**
M-MDA™	**0.5**	**0.5**	**0.3**	**0.4**	**Stress Relieved**

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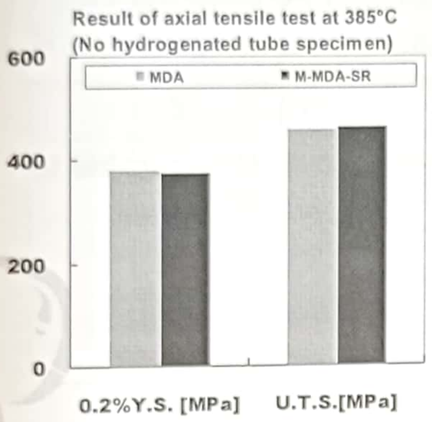
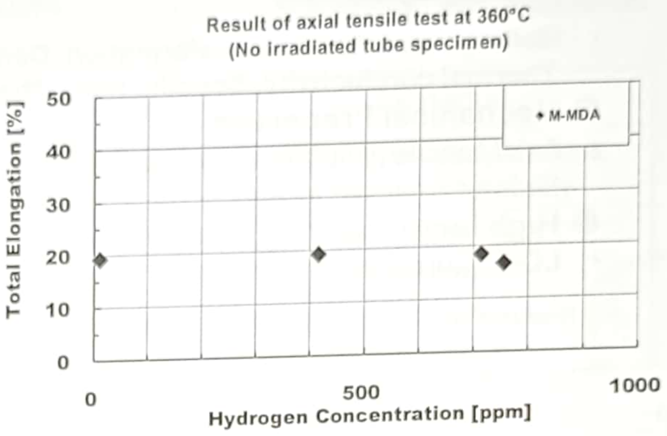
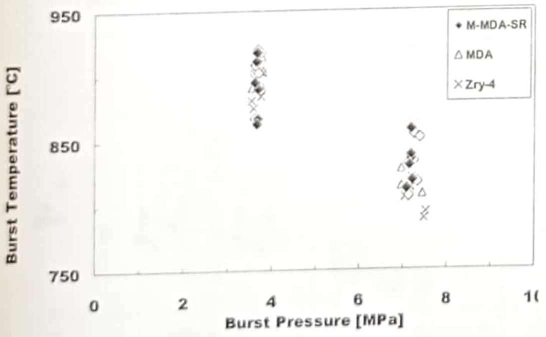
Mechanical Properties

- Enough strength (similar to MDA)
- Enough ductility even hydrogenated up to 800ppm H

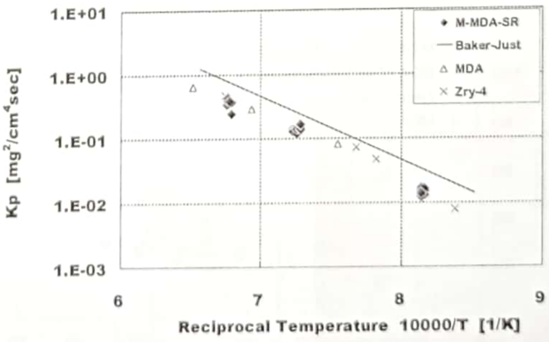

Result of axial tensile test at 385°C
(No hydrogenated tube specimen)


Result of axial tensile test at 360°C
(No irradiated tube specimen)

LOCA Properties



Burst temperature vs burst pressure



High Temperature corrosion rate

✓ **M-MDA** has similar properties for LOCA busts and HT corrosion tests compared to **Zry4** and **MDA**.

Out-of-pile properties

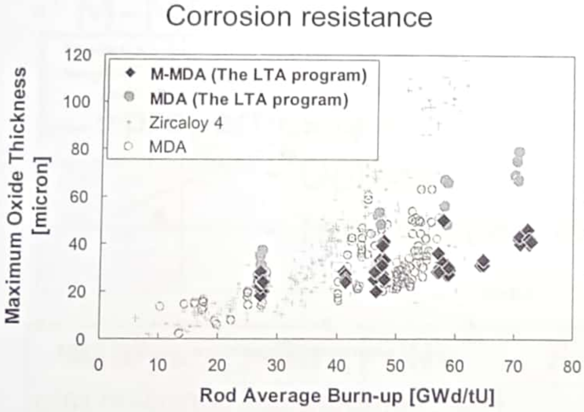
- Corrosion Test (Autocrave)
  - Pure water, RCS (2.2ppmLi+500ppmB)
    Steam, 70ppmLi

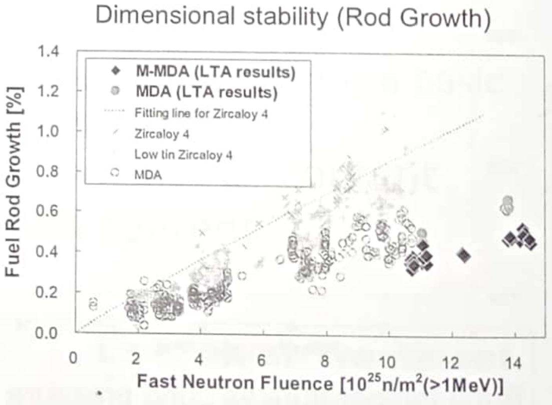
Superior Corr. Resistance than MDA

- Basic Properties
  - Melting point, Phase transformation, Density, Thermal conductivity, Specific heat, Thermal expansion
- Mechanical Properties
  - Axial tensile (High/Room temp, hydrogenated)
- High temperature properties
  - LOCA burst, Hight temp oxidation, LOCA quench

Comparable to MDA

In-pile performances of M-MDA™


Corrosion resistance


Dimensional stability (Rod Growth)

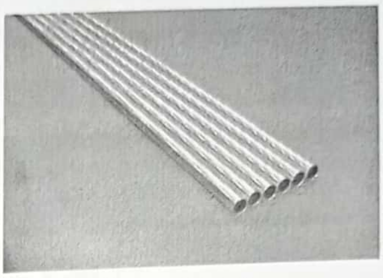
Watanabe et al, WRFPM2008, Seoul, Korea

What is J-Alloy™ ?

- Corrosion and hydriding resistance

  Enhanced property than conventional alloys
- PWR stakeholders jointly developed

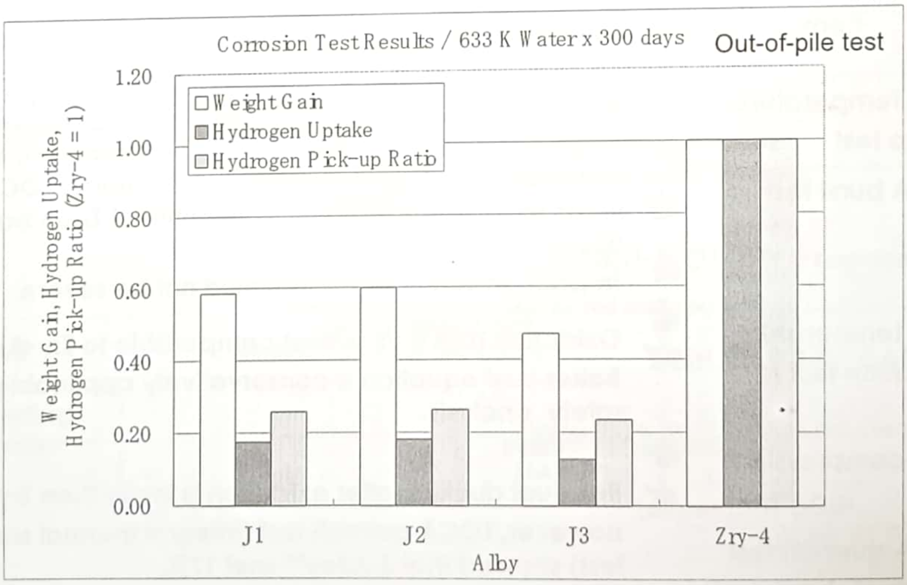
  5 PWR utilities + Fuel vendors
  + Tube manufacturers



J1 apperance

	Sn	Nb	Cr	Zr	Remarks
J1	-	1.8	-	Balance	**High corrosion resistance & proper manufacturability**
J2	-	1.6	0.1	Balance	**Corrosion resistance in lithiated environment**
J3	-	2.5	-	Balance	**Challenge for the highest corrosion resistance**

Corrosion Resistance and Hydrogen Pick-up of J-Alloy™



Takabatake et al, TopFuel 2006, Salamanca, Spain

Out of Pile Test Summary(1)

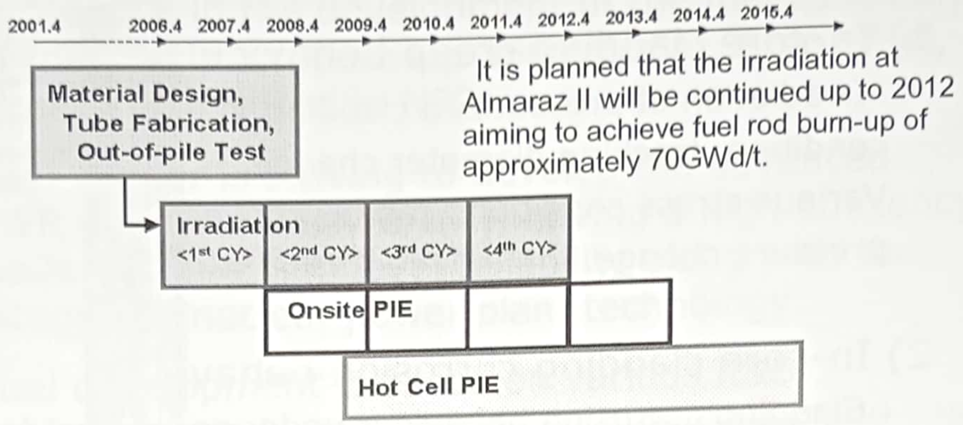
Item	Characteristics of J-Alloy™
Microstructure	Mainly Zr-Nb base compounds precipitated on a-Zr matrix.
Fatigue/Creep/SCC	Different to the conventional Zr-Sn base stress-relieved alloys, but enough applicable to PWR fuel cladding.
Physical properties	Almost comparable to the conventional Zr-Sn base alloys, except for at high temperature region.
Phase transformation temperature	Lower than the conventional Zr-Sn base alloys.
Corrosion properties	Better than Zry-4. Accelerated in neither lithiated nor oxygenated environment.
Hydride related properties	No severe degradation even when hydrogenated up to 800ppm.

Out of Pile Test Summary(2)

Item	Characteristics of J-Alloy™
High temperature creep test	Due to low transformation temperature, creep strength degradation comes at relatively low temperature. Consequently, burst temperature simulating LOCA tends to be lower than the conventional Zr-Sn base alloys. Impact on safety analysis would not be severe.
LOCA burst test	
High temperature oxidation test	Oxidation rate was almost comparable to Zry-4, and Baker-Just equation is conservatively applicable in safety analysis.
Ring compression test	Residual ductility after oxidation is lower than Zry-4, however, LOCA quench test (integral thermal shock test) showed that J-Alloy™ met 17%.
LOCA quench test (Thermal shock test)	

Plan for J-Alloy™ Irradiation and PIE

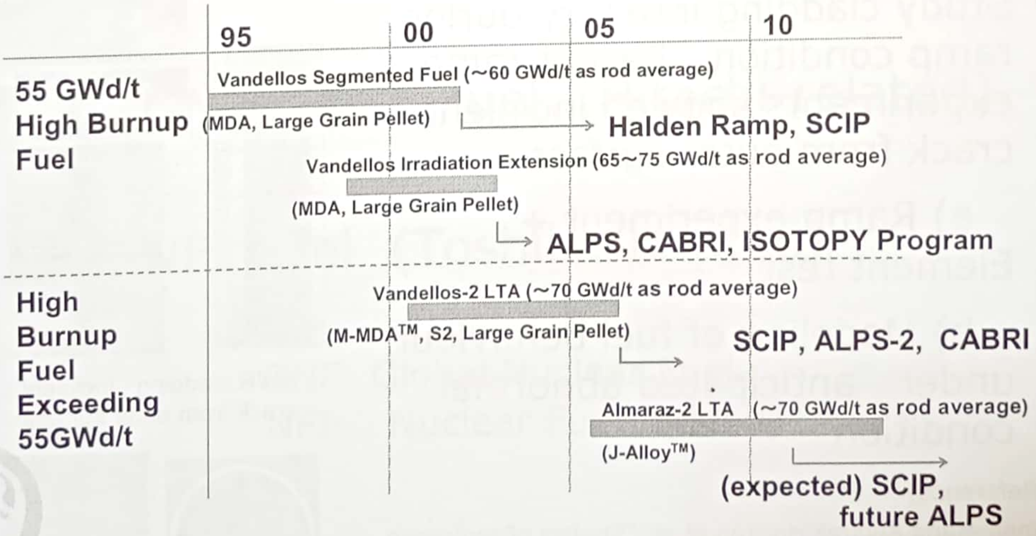
- After verifying required performance of the J-Alloy™ cladding tubes in these out-of-pile tests, lead test assemblies including J-Alloy™ cladding fuel rods have been irradiated in the Spanish commercial reactor, Almaraz II, since April 2006,



It is planned that the irradiation at Almaraz II will be continued up to 2012 aiming to achieve fuel rod burn-up of approximately 70GWd/t.

- After each cycle of irradiation, on-site examinations, which focus on cladding corrosion and LTA dimensional measurements, will be carried out.
- Then following tests such as hot cell PIE and power ramp test on selected J-Alloy™ cladding fuel rods will be carried.

High Burnup Fuel Program International collaboration

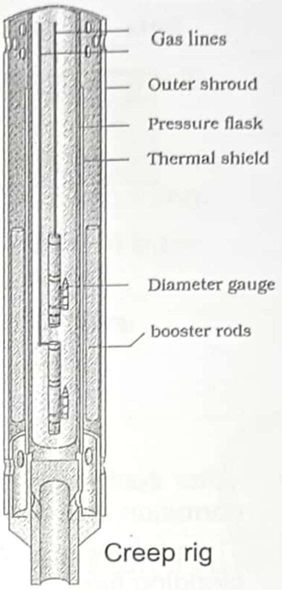


Halden Joint Programme

- Recent joint program of cladding

  1) In-core cladding creep behaviour
  Irradiation of pressurized cladding in P
  condition, tracking diameter change.
  Various stress conditions can be applied
  pressure change.

  2) In-core cladding corrosion behav
  Cladding corrosion behaviour under se
  coolant condition exceeding current PW
  (local boiling, high power, high Li)



Creep rig

SCIP OECD／Studsvik Cladding Integrity Project

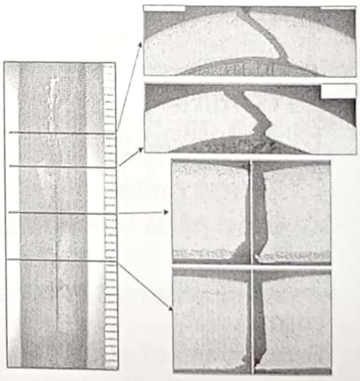
- Study cladding integrity during ramp condition. Recent ramp experiments showed incipient crack from outer surface

  a) Ramp experiment + Element test

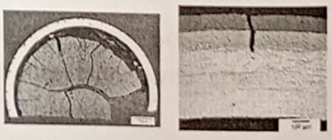
  b) Modeling of fuel behaviour under anticipated abnormal condition

(Reference)

Anna-Maria Alvarez Holston,et.al.,"Studies of Hydrogen Assisted Failures Initiated at the Outer Surface of High Burn-up Fuel" 2007 WRFPM,San Francisco



BWR cladding : incipient crack from outer surface



PWR cladding : un-penetrated crack

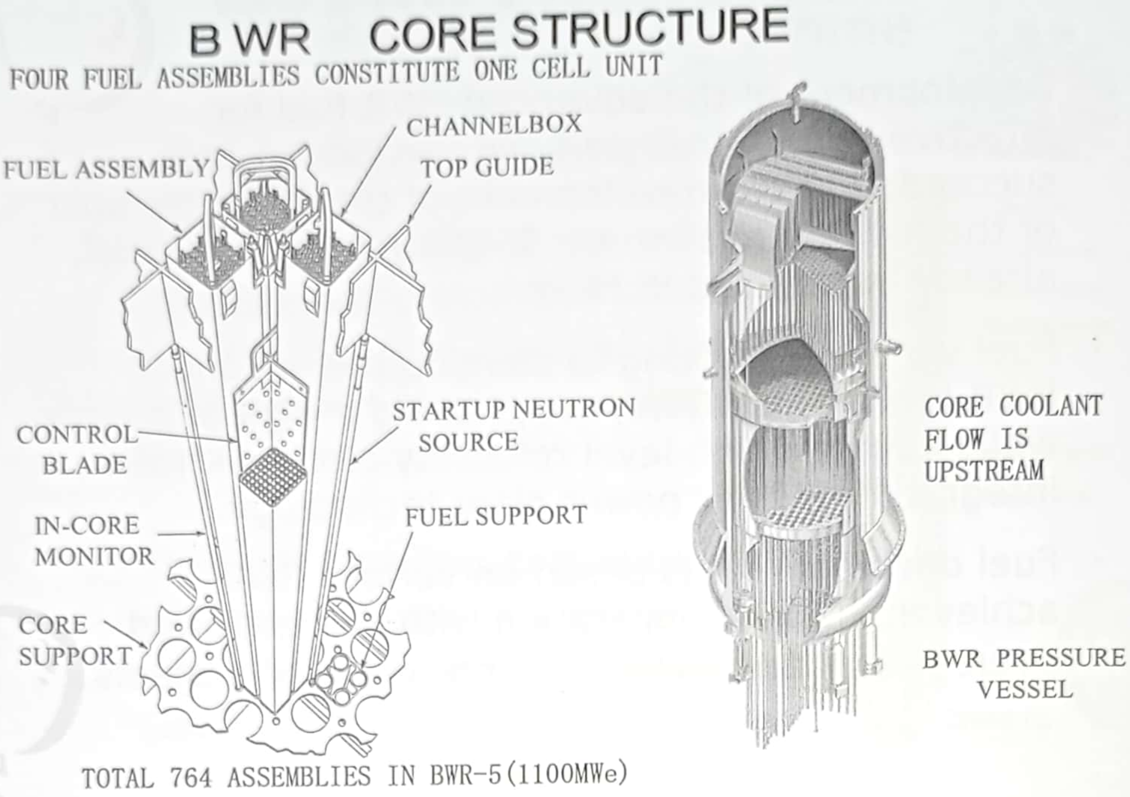
SUMMARY of PWR Fuel

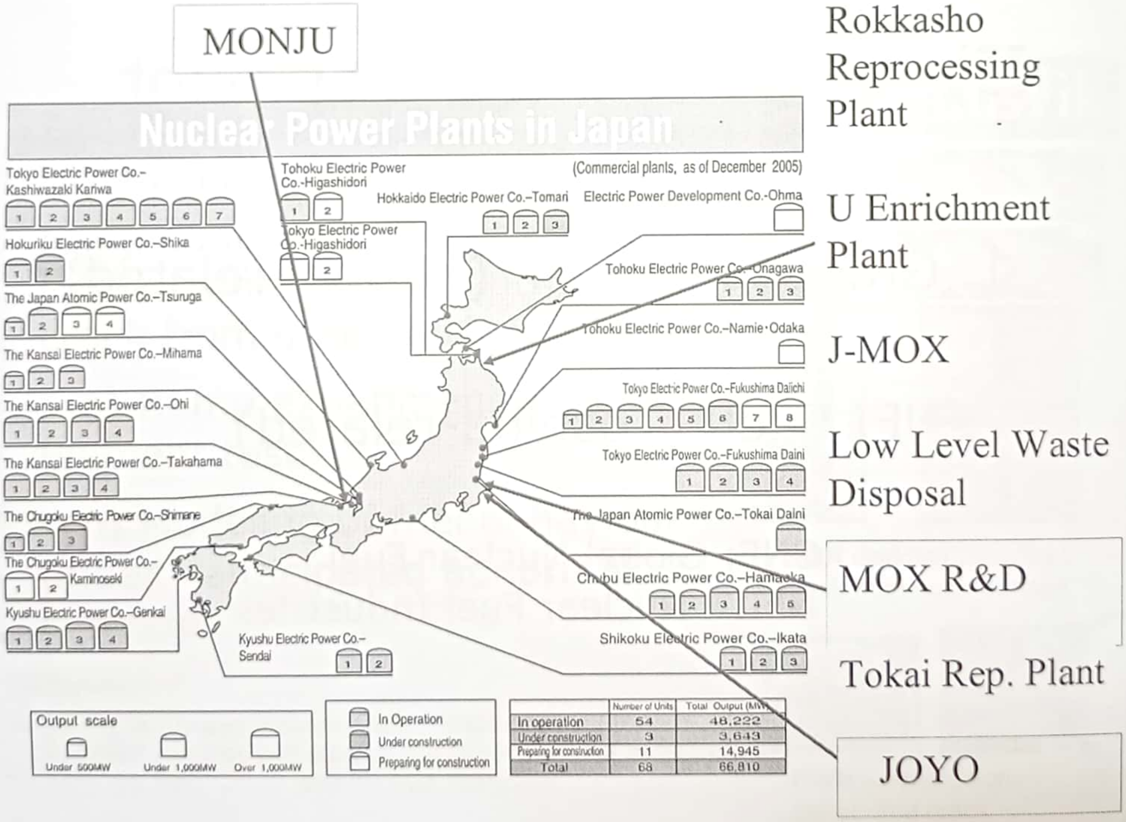
- Development of the advanced PWR fuel for effective operations has been carried out and succeeded in the development of the fuel assembly of the maximum burn-up 55GWd/t(A), Step2 fuel, already introduced in NPPs.
- Fuel vendor is striving to develop the advanced PWR fuel over 55GWd/t(A), having a high efficiency while keeping high level reliability along with the integrated nuclear power plant technology.
- Fuel development is based on various R&D achievements in cooperation with domestic and overseas organizations and international projects.

II) BWR Fuel Development

1. GNF-Japan Fuel (Hitachi-related)
2. NFI Fuel (Toshiba-related)

GNF: Global Nuclear Fuel
NFI: Nuclear Fuel Industries



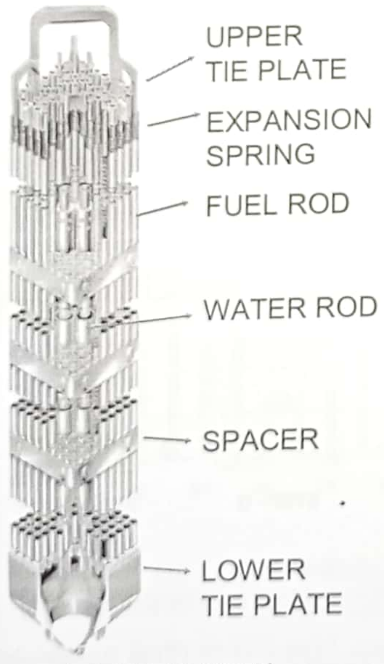


	Number of Units	Total Output (MW)
In operation	54	48,222
Under construction	3	3,643
Preparing for construction	11	14,945
Total	68	66,810

CHARACTERISTICS OF BWR FUEL

- **Channel boxes separate coolant flow for each fuel bundles.**
- **Core design flexibility allows coexistence of different fuel designs, 9x9 and 8x8 types as well as UOX and MOX.**
- **Keeping channel dimension, fuel rod array designs can be selectable for reload fuel, so that latest (most reliable and economical) fuel designs can be adopted commonly in all BWR types.**

FUEL ASSEMBLY MECHANICAL DESIGN



Example (STEP-III 9X9A)

- **BWR fuel assembly has square Lattice of 13cm x 13cm, with the length of 4.5m**
- **Fuel rods and water rods are bundled with spacers and upper/lower tie plates.**
- **Eight of peripheral fuel rods (two of each side) are screwed into lower tie plate and fixed to upper tie plate, holding full assembly weight while fuel handling.**
- **Expansion spring adjusts elongation difference between fuel rods and water rods.**

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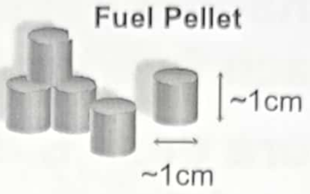
FUEL ROD

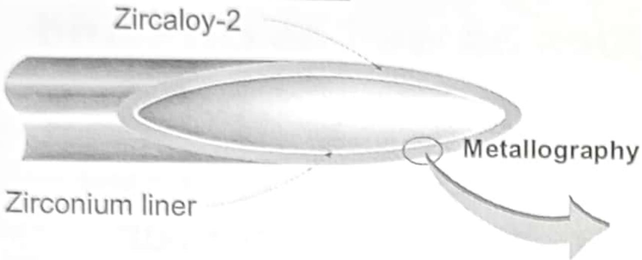
- **FUEL PELLET**

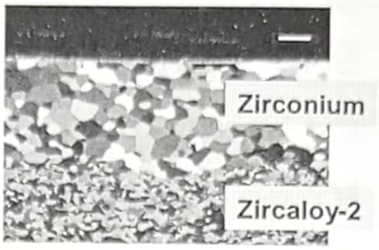
  UO2 or UO2-Gd2O3, Sintered to 96-97%TD

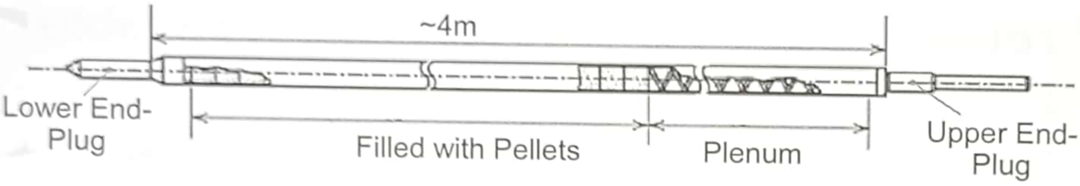
  (Gd: burnable absorber for reactivity control)



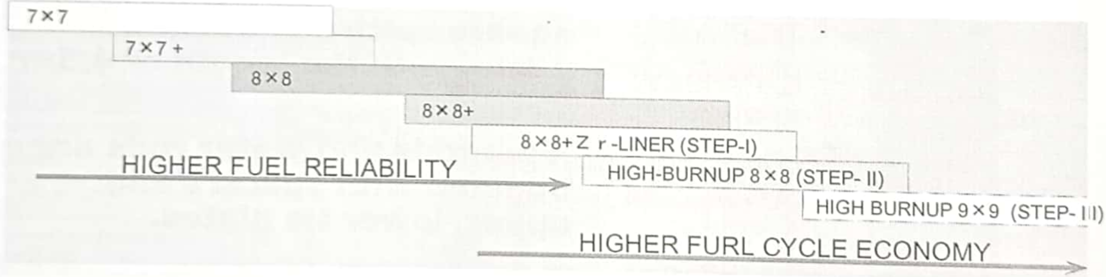
- **CLADDING TUBE**







LATTICE DESIGN CHANGES IN 40 YEARS



7×7

7×7 +

8×8

8×8+

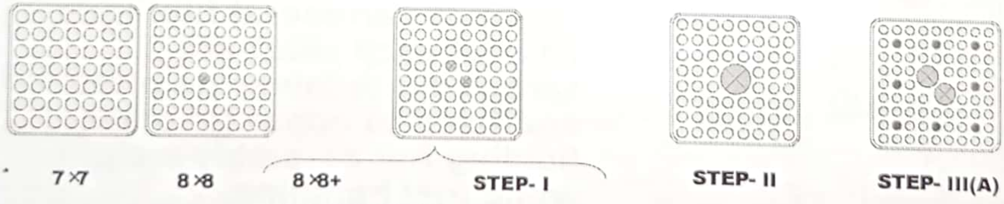
8×8+Zr-LINER (STEP-I)

HIGHER FUEL RELIABILITY

HIGH-BURNUP 8×8 (STEP- II)

HIGH BURNUP 9×9 (STEP- III)

HIGHER FURL CYCLE ECONOMY



	8×8+	STEP- I	STEP- II	STEP- III(A)
AVERAGE BURNUP	29.5 GWD/TU	33 GWD/TU	39.5 GWD/TU	45 GWD/TU
AVERAGE ENRICHMENT	3.0%	3.0%	3.4%	3.7%

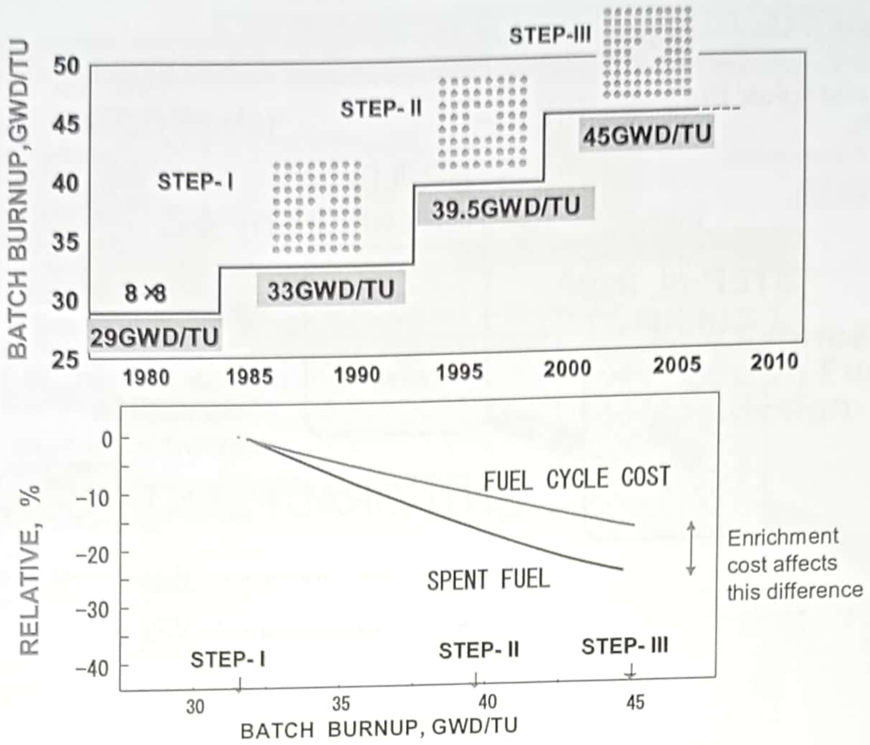
Zr-liner Fuel for PCI Resistance

Ferrule Spacer for Thermal Margin

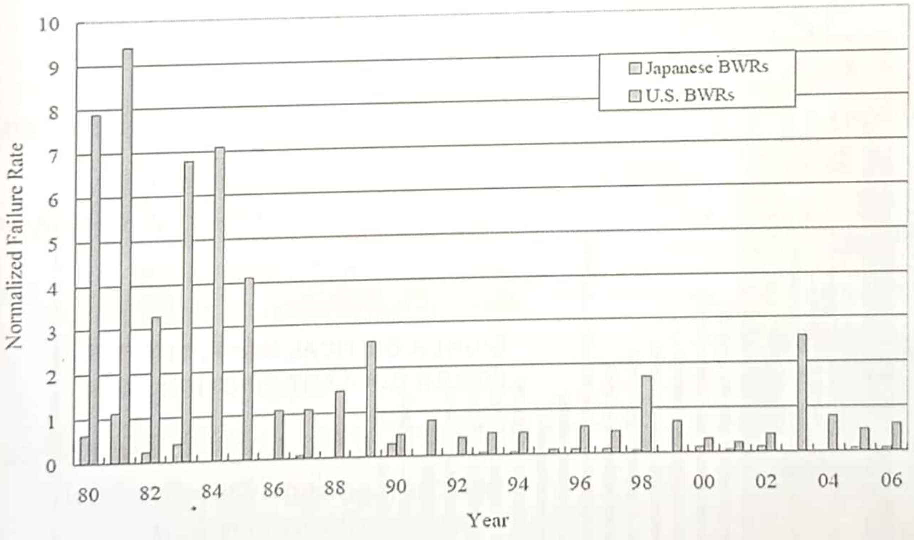
● : WATER ROD

● : PART-LENGTH ROD

ACHIEVEMENT OF FUEL CYCLE ECONOMY



FUEL RELIABILITY TREND



BWR FUEL FAILURE RATE

Y. Otsuka et al., "Fuel Performance Update at Japanese BWRs", 16th Pacific Basin Nuclear Conference, 2008

Fuel failure rate is low in recent years. Debris-fretting is most frequent failure cause both in US and Japan. Longer cycles and plant up-rate may increase PCI failure potential.

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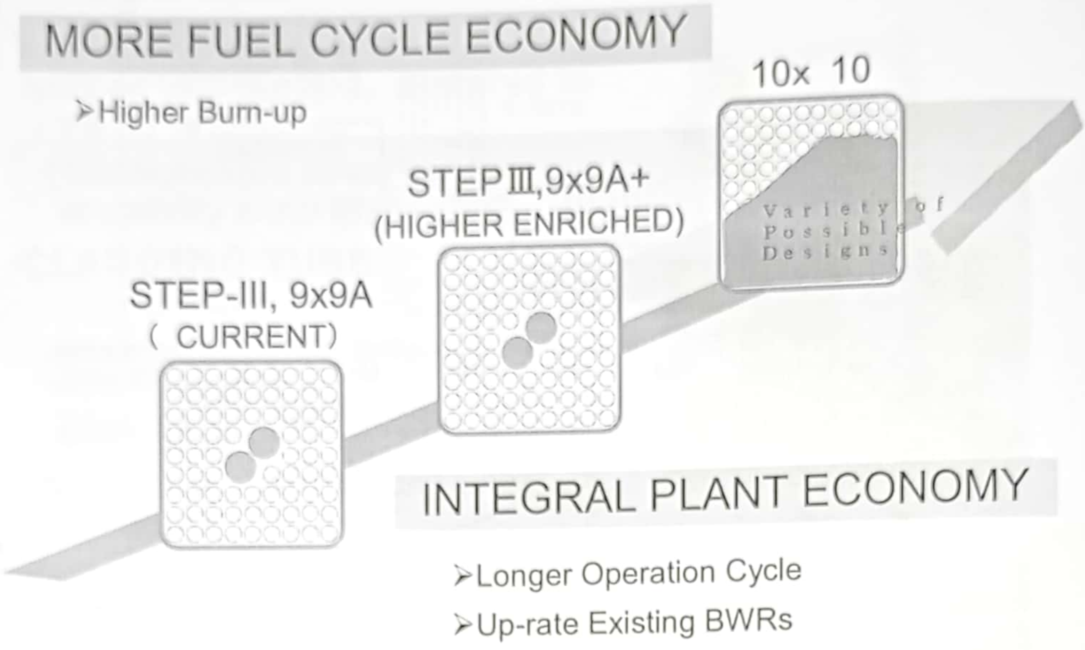
WHERE TO MOVE NEXT



MORE FUEL CYCLE ECONOMY

- Higher Burn-up

STEP-III, 9x9A
(CURRENT)

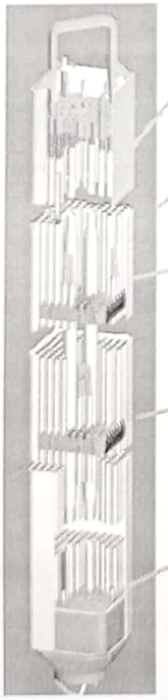
STEPⅢ,9x9A+
(HIGHER ENRICHED)

10x 10

INTEGRAL PLANT ECONOMY

- Longer Operation Cycle
- Up-rate Existing BWRs

GNF10x10 FUEL DESIGN (GNF2)



10×10 LATTICE

HIGHER FUEL THERMAL MARGIN
MORE OPERATIONAL FLEXIBILITY

ADVANCED FUEL MATERIALS

CORROSION RESISTANT CLADDING (GNF-ZIRON)
ADVANCED ADDITIVE FUEL

ADVANCED INCONEL SPACER

HIGHER CRITICAL HEAT FLUX
LOWER COOLANT FRICTION

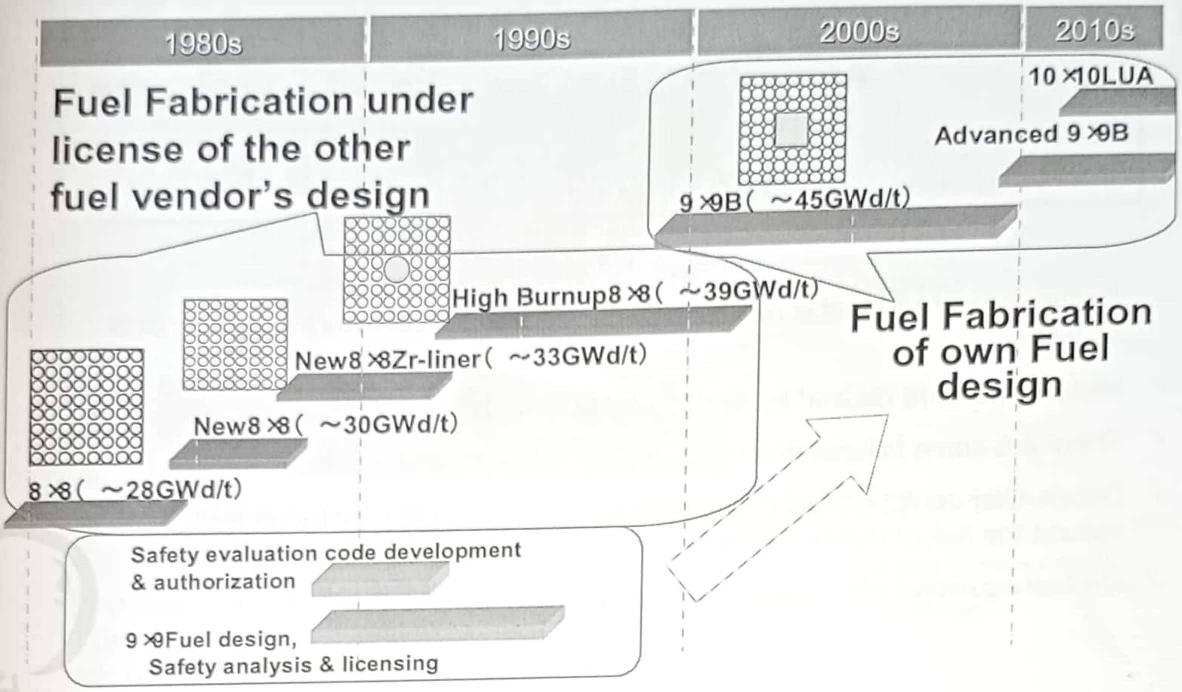
OPTIMIZED PART-LENGTH RODS

NEUTRON ECONOMY IMPROVEMENT
LOWER COORANT FRICTION

ANTI-DEBRIS LOWER TIE PLATE

PROTECT FUEL FROM DEBRIS INTRUSION

BWR Fuel Design Change Experience and Forecast of *N F I*



1980s | 1990s | 2000s | 2010s

Fuel Fabrication under license of the other fuel vendor's design

8×8(~28GWd/t)

New8×8(~30GWd/t)

New8×8Zr-liner(~33GWd/t)

High Burnup8×8(~39GWd/t)

9×9B(~45GWd/t)

Advanced 9×9B

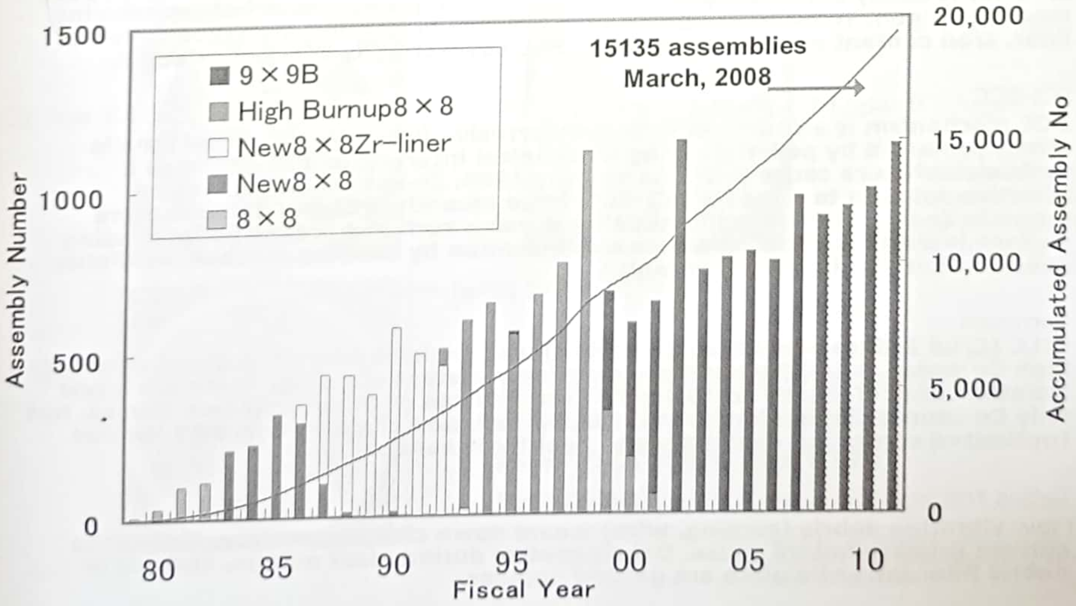
10×10LUA

Fuel Fabrication of own Fuel design

Safety evaluation code development & authorization

9×9Fuel design, Safety analysis & licensing

BWR Fuel Fabrication Experience and Forecast



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Reliability of NFI Fuel

	Assembly Number	Fuel rod Number	No. of leaker	Leak rate
BWR Fuel	15,135	990,652	9	9E-06

- ✓ Failure rate of NFI fuel is relatively low compared to fuel failure rate in foreign countries.
- ✓ No leakage were caused by design and/or Manufacturing problem.
- ✓ There are some failures due to suspected debris fretting.
- ✓ Debris-filter equipped fuel assemblies were delivered per customer requirement to reduce the risk of debris fretting and to improve the reliability of NFI fuel.
- ✓ No fuel equipped with debris-filter was defected up to today.

RECENT FUEL RELIABILITY CONCERNS (US)

- SECONDARY HYDRIDING
  Secondary fuel degradation of failed rod was found in 1990s. The story is that Zr-liner fuel degrades more quickly after failure by secondary hydriding, as pure Zr- liner is easily oxidized by steam intruded from primary leak hole, producing more hydrogen. To improve corrosion resistance of Zr-liner, Iron was added to liner. Iron content was selected where SCC susceptibility was not affected.

- PCI-SCC
  SCC mechanism is a combined effect of corrosive fission product and tensile stress produced by pellet-cladding mechanical interaction. PCI-SCC was a systematic failure cause in 1970s to early 1980. Zr-liner cladding was an effective solution to mitigate PCI-SCC. More recently, PCI-SCC failures were found in Zr-liner fuel, locating at pellet missing surface because pellet missing surface intensifies cladding stress concentration by bending mechanism. Pellet specification was tightened recently.

- Corrosion
  CILC (Crud Induced Localized Corrosion) was explained by a combined effect of high Cu water chemistry and low corrosion resistant cladding. There are a few isolated cases of heavy corrosion by crud induced or other unknown causes. Not only Cu source elimination, but corrosion resistant cladding was also applied (optimized controlled chemistry and heat treatment).

- Debris Fretting
  Flow vibrating debris (turning, wire) wears down cladding surface. This is the current primary failure cause. Debris control during plant outage, and use of debris filter lower tie plate are getting popular.

SECONDARY HYDRIDING

Typical "Sun Burst"
of secondary hydriding

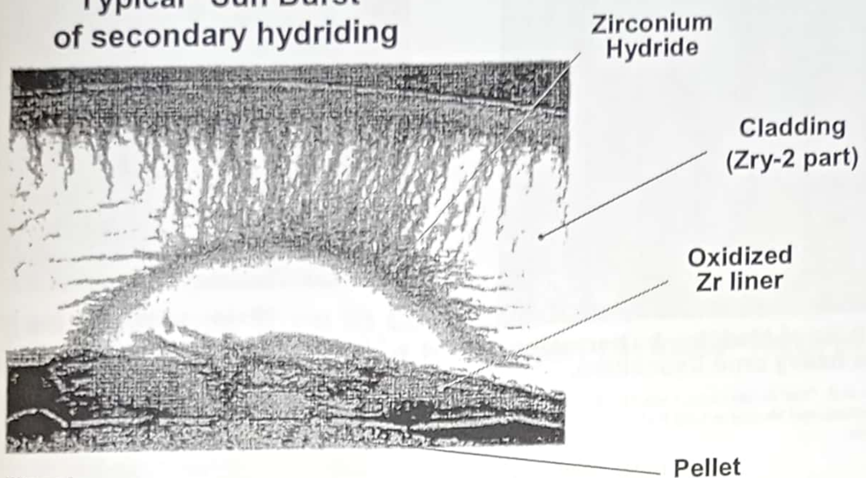


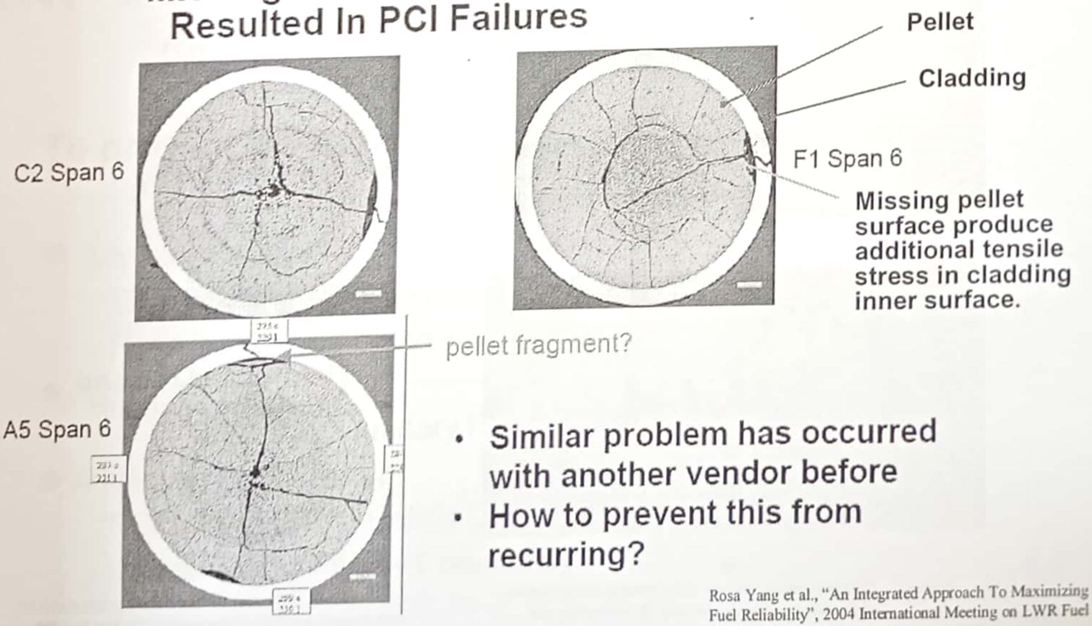
Figure 1.
Oxidized barrier and radial hydrides through the cladding wall.

Jonsson,A.,et al.:"Failure of a Barrier Rod in Oskarshamn 3",LWR Fuel Performance (Proc.Int.Top.Mtg.,Avignon,France,1991),American Nuclear Society-European Nuclear Society,vol.1,(1991)371.

Secondary hydriding causes long cladding cracks resulting in serious radioactivity release to coolant.

PCI-SCC FAILURE OF Zr-LINER FUEL

Missing Pellet Surface Has
Resulted In PCI Failures



- Similar problem has occurred with another vendor before
- How to prevent this from recurring?

Rosa Yang et al., "An Integrated Approach To Maximizing Fuel Reliability", 2004 International Meeting on LWR Fuel Performance, Orlando, Florida.

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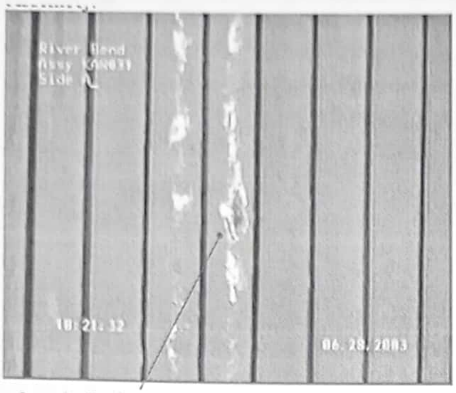
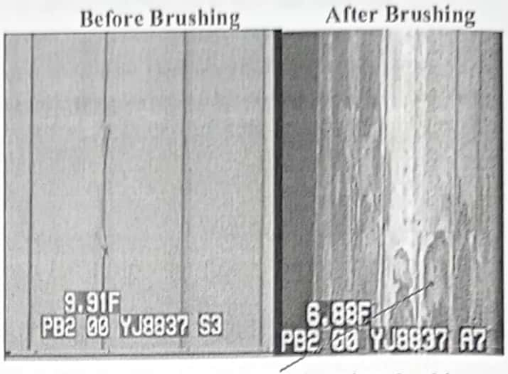
CORROSION



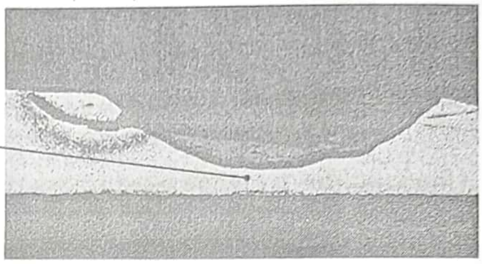
Leak hole of cladding by corrosion due to heavy crud deposition.

E.J. Ruzauskas et al., "Fuel Failure During Cycle 11 at River Bend", 2004 International Meeting on LWR Fuel Performance, Orlando, Florida.



Oxide spallation (no leak).

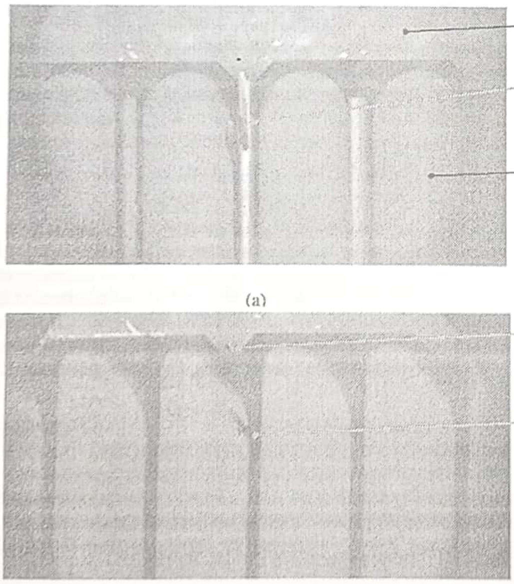
B. Cheng et al., "Effects of Noble Metal Chemical Application on Fuel Performance", 2004 International Meeting on LWR Fuel Performance, Orlando, Florida.



Thinning of cladding thickness by corrosion (CILC).

W.E. Baily et al., "RECENT GE BWR FUEL EXPERIENCE", 1991 International Topical Meeting on LWR Fuel Performance, Avignon, France.

DEBRIS-FRETTING



(a)

(b)

Figure 3. Debris Fretting Failure, (a) showing the presence of the responsible debris, and (b) revealing the cladding perforation after removal of the debris.

W.E.Baily et al., "RECENT GE BWR FUEL EXPERIENCE", 1991 International Topical Meeting on LWR Fuel Performance, Avignon, France.

HIGHER PERFORMANCE WITH MORE RELIABILITY

More reliability margins are required for higher fuel duty:

HIGHER BURNUP

Longer residence time in core enhances waterside corrosion and associated hydrogen pickup. Hydrides affect cladding ductility.

HIGHER PLANT CAPACITY FACTOR

Longer cycle and up-rate increase fuel rod power, resulting in higher cladding tensile stress by pellet-cladding interaction (PCI).

GNF DEFENSE-IN-DEPTH PROGRAM

To provide solutions towards zero fuel failure:

- Advanced Alloys to Lower Hydrogen Pickup
  - "GNF-Ziron" (High Iron Alloy) to Lower Hydrogen Pickup
  - Hydride-free new alloys under study
- Advanced Additive Fuel
  - "Al-Si-O" (Grain-boundary Phase) for PCI-SCC Resistance
- Advanced Debris-Filter
  - "DEFENDER"(Anti-Debris Lower Tie plate) to Eliminate Debris-fretting Failure Completely.