BWR Core and Fuel Development for Highly-economical Power Generation

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OVERVIEW: Hitachi has developed and introduced highly economical cores and Step I, II and III fuel in cooperation with Global Nuclear Fuel - Japan Co., Ltd., and has encouraged a step-by-step improvement in burnup while also ensuring better fuel reliability and performance. Based on the belief that making effective use of plutonium is important in terms of resource efficiency, Hitachi has also developed a full MOX-ABWR core (an improved type of boiling water reactor in which MOX fuel can be used throughout the entire core). In order to improve plant economics further and save on resources through power uprating and the adoption of long-term operation cycle, Hitachi will continue to work on introducing and developing cores and fuel that facilitate these objectives.

INTRODUCTION

SINCE its first involvement in nuclear power development, Hitachi has recognized that core and fuel technologies play a central role in nuclear power

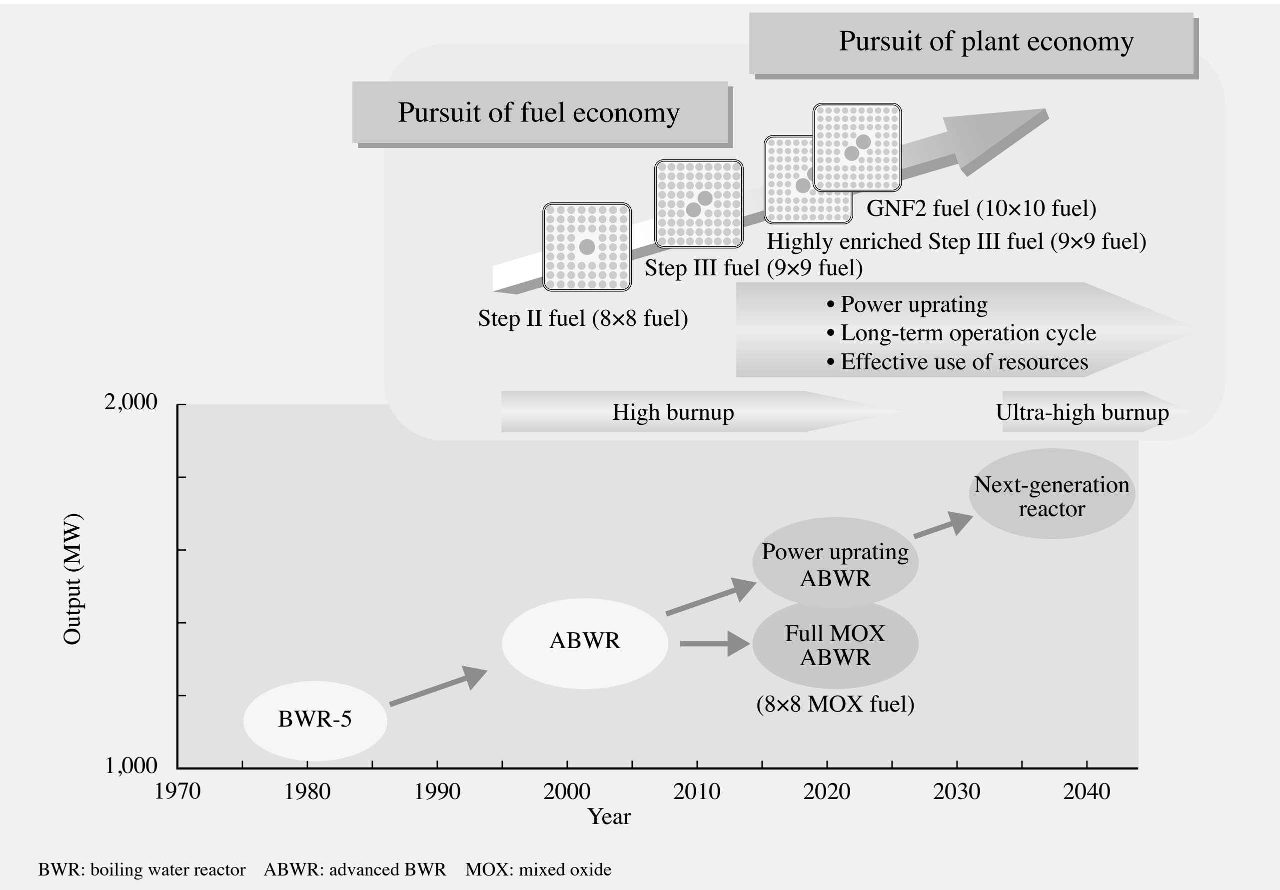


Fig. 1—Overview of Next-generation Fuels.
The objectives of core and fuel development are higher fuel reliability and better economics. The aim is to achieve better plant economics through power uprating and by adopting long-term operation cycle. Hitachi aims to introduce the highly enriched Step III (9×9 fuel) and GNF2 (10×10 fuel) fuels in Japan. The highly enriched Step III fuel (9×9 fuel) has higher average enrichment than the current Step III fuel and GNF2 fuel (10×10 fuel) has an excellent thermal margin and is suitable for both power uprating and long-term operation cycle.

and has aggressively engaged in the development of associated basic technologies. Increase in nuclear power generation in recent years has seen a need for highly reliable and highly economical cores and fuels. Hitachi has responded to this demand by commercializing its Step I, II and III fuels which feature excellent economics. Each generation of these fuels achieved an improvement in burnup performance of about 10% compared with the previous one. Subsequently, Hitachi has been working on long-term development in areas where it sees room for improvement to enhance the economics of BWR (boiling water reactor) plants, including long-term operation cycle, power uprating, and making effective use of uranium resources (see Fig. 1).

This article discusses the background to the past development of cores and fuel and what Hitachi is doing in this field to achieve excellent plant economics in the future.

BACKGROUND TO DEVELOPMENT OF CORES AND FUEL

Improvement in Fuel Reliability and Performance

Although their frequency was low, fuel failure started to occur when Japan started using large quantities of commercial reactor fuel in the 1970s. The commonest cause of the failures was “local hydriding” which can be completely prevented by improving fuel rod moisture control during fuel production. Measures for dealing with PCI (pellet clad interaction) included reducing the maximum linear heat generation rate in accordance with the pre-conditioning interim operating management recommendation and the adoption of 8×8 fuel. As a result, fuel failure has become very rare in Japan. Fig. 2 shows the cumulative number of BWR fuel bundles produced by Global Nuclear Fuel - Japan Co., Ltd. (GNF-J). The company has produced about 78,000 fuel bundles so far and has not had any fuel failures attributable to manufacturing defects in the 4.8 million fuel rods produced since adopting 8×8 fuel.

Improvements in Fuel Economics

Hitachi has developed techniques for minimizing uranium consumption and achieving high burnup, and, with its Step I, II and III fuels, it has developed and commercialized a series of cores and fuels with excellent economics while monitoring how they perform in actual use. Fig. 3 shows when each of these highly economical cores and fuels were introduced and their benefits in terms of reducing fuel cycle costs and minimizing spent fuel generation.

The highly economical Step I fuel achieved a reduction in fuel cycle costs of about 10% through better burnup despite maintaining the same structure and enrichment as its predecessor. This was achieved through the use of power peaking, flow spectrum shift operation, and other techniques for minimizing uranium consumption. In addition, the cladding used on the Step I fuel incorporated measures to prevent PCI and to improve the corrosion resistance of the

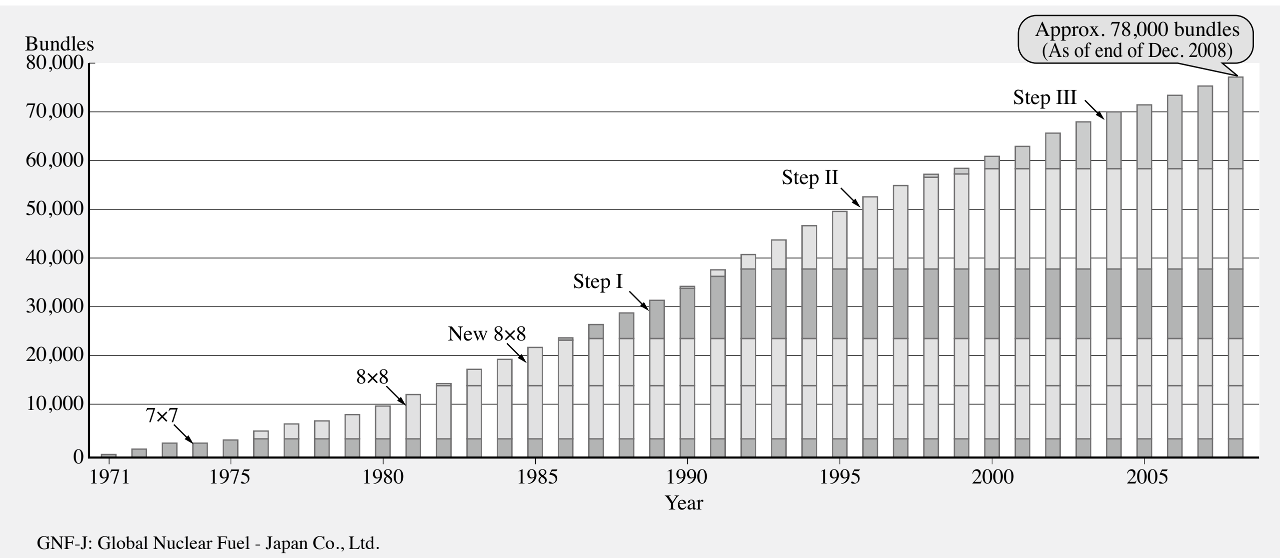


Fig. 2—Cumulative Number of BWR Fuel Bundles Produced (by GNF-J).
As of the end of December 2008, approximately 78,000 bundles had been produced.

zirconium alloy with respect to the coolant water.

The highly economical Step II fuel consists of 60 fuel rods arranged in 8×8 rod array. The water rod is a single large-diameter rod which increases the water-to-fuel volume ratio in the channel in a manner consistent with the increased enrichment for higher burnup. Other improvements are made to prevent the fuel temperature and fuel rod internal pressure from increasing under irradiation, including increasing the initial helium pressurization and pellet density.

The highly economical Step III fuel has an even higher level of enrichment and uses additional advanced techniques for minimizing uranium use and achieving higher burnup, giving it an average discharge burnup of 45 GWd/t.

The number of fuel rods in the Step III fuel is increased to 74 and they are arranged in 9×9 rod array to reduce the average linear heat generation rate. To reduce pressure drop, eight of these fuel rods are only two thirds the length of the standard fuel rods and are attached to the lower tie plate. The initial helium pressurization in the fuel rods is higher than in the Step II fuel in accordance with the higher burnup.

In keeping with the higher average enrichment level, the new fuel uses two water rods which have an area equivalent to seven fuel rods. The additional margin made available due to the lower pressure drop achieved by using the part-length fuel rods is passed to the pressure drop at the lower tie plate to increase the single-phase pressure drop compared to the Step II fuel, and stability is improved while keeping the total pressure drop of the fuel bundle at the same level as the Step II fuel.

At present, all new uranium fuel used in Japan is Step III fuel and experience with its use is steadily increasing.

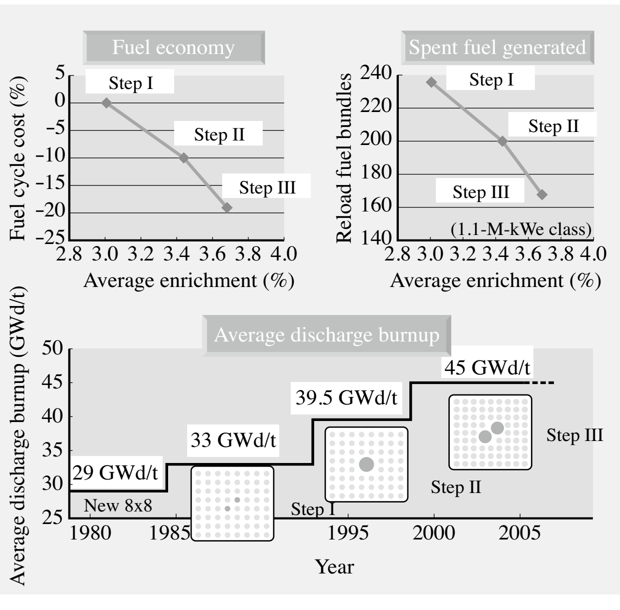


Fig. 3—Better Fuel Economy Achieved by Step-by-step Burnup Improvements.
A series of improvements in burnup performance have reduced fuel cycle costs.

MEASURES FOR IMPROVING PLANT ECONOMY

Past reductions in the fuel cycle cost were achieved by step-by-step improvements in burnup. However, the average discharge burnup has nearly reached the upper limit of what is achievable given the current uranium enrichment capability. Hitachi believes it is necessary to develop cores and fuel that can deliver broad-based improvements in plant-wide economics and make effective use of uranium resources, and it is working with GNF-J to produce cores and fuel that are compatible with the aims of improving plant capacity factor by adopting a long-term operation cycle and expanding capacity by power uprating.

Support for Long-term Operation Cycle

Studies looking into long-term operation cycle are ongoing in pursuit of improvements to plant economics through measures that consider the total plant operation such as reducing generating costs by increasing capacity factor. At present, the level of enrichment able to be used for light-water reactor fuel is restricted to 5% by weight (wt%). When designing near the upper limit of enrichment, extending the operating period per cycle reduces the average discharge burnup and this means higher fuel cycle costs. However, the lower power generation costs resulting from the increased capacity factor due to long-term operation cycle is believed to outweigh this drawback and Hitachi is working on fuel designs suitable for long-term operation cycle.

Specifically, Hitachi is already working with GNF-J on the detailed design for a highly enriched version of the Step III fuel that uses the same fuel structure as the current Step III fuel but higher enrichment. The aim is to use it for a 19-month operation cycle in the early 2010s followed later by a 24-month operation cycle.

Plans are also in progress for the early introduction in Japan of the GNF2 fuel (10×10 fuel) described below which is specifically intended for use with long-term operation cycle.

Support for Uprated Cores

In addition to long-term operation cycle, power uprating is another way to improve plant economics by increasing power generation. Uprates to existing reactors in other countries have made significant improvements in power output of up to around 20% by utilizing the operating margin in existing equipment to boost output and also by replacing turbines and generators. The possibility of step-by-step uprates to existing reactors in Japan is also being reviewed.

As power uprating increases the core power density, the key issue is to maintain the thermal margin (maximum linear heat generation rate and minimum critical power ratio) for the core and fuel.

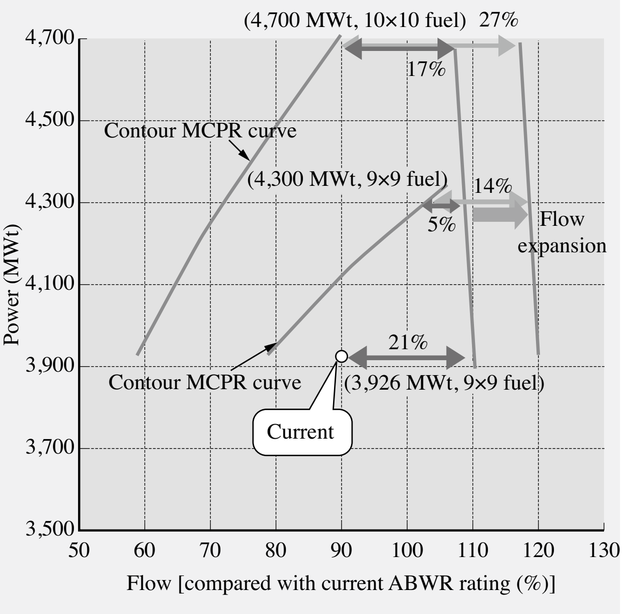
Use of Step III or highly enriched Step III fuel can provide a 10% improvement in power output. In this case, in order to maintain the margin of the minimum critical power ratio at the same level as a core running at the power level used currently, and to provide as much flow control range as possible to facilitate core operation, it is desirable that the change in fuel be accompanied by a reactor system design in which the reactor flow range when operating at rated power is shifted upwards compared to the previous range (see Fig. 4).

The full MOX (mixed oxide)-ABWR (advanced BWR) described below uses a recirculation pump system that has completed development and provides 120% of the maximum core flow at rated power output. The same system can be used on an uprated ABWR to recover the flow control range. For plants that use the jet pumps used prior to the ABWR, a high-performance jet pump is under development that should increase the maximum core flow and be easy to retrofit. In terms of the maximum linear heat generation rate, a 10-% increase in power should be possible due to an innovative design that decreases the power peaking in the core.

On the other hand, the GNF2 fuel discussed below can be used to uprate the power by 20%. In this case, the higher thermal margin of the GNF2 fuel means that it should be possible to maintain the same flow control range as the current ABWR without needing to increase the maximum core flow.

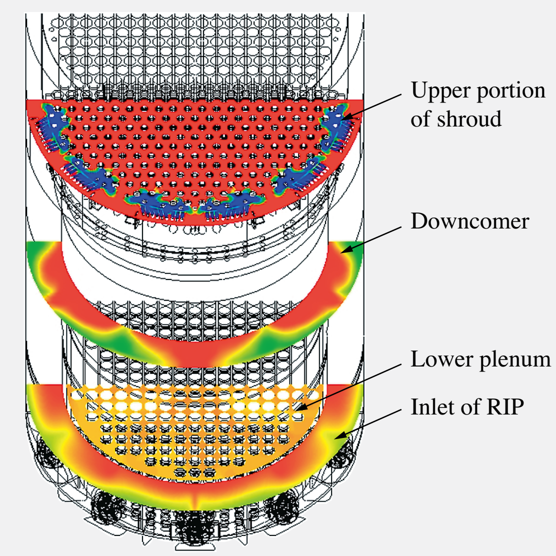
Hitachi is also developing a core flow evaluation method and reactor components such as dryers and separators that can handle the uprated power output.

To evaluate the flow, fluid analysis is utilized and a three-dimensional fluid analysis model has been



MCPR: minimum critical power ratio

Fig. 4—Estimated Feasibility of ABWR Core with Power Uprate.
The Step III fuel (9×9 fuel) needs a higher maximum flow for a wide flow control range. The GNF2 fuel (10×10 fuel) also ensures an adequate flow control range.



RIP: reactor internal pump.

Fig. 5—ABWR Flow Evaluation (Temperature Distribution Example).
Three-dimensional fluid analysis is used to determine the extent of flow mixing in the region from the downcomer to the lower plenum.

developed to determine the consequences of changes associated with power uprating such as the increased core flow and increased feedwater (see Fig. 5).

For the dryer, acoustic analysis and experiment are being used to evaluate the dryer acoustics and flow-induced vibration. Not only has this work enabled Hitachi to determine the mechanism behind incidents of dryer failure in the USA by conducting experiments and analyses, it is also being developed into a method for predicting the consequences of power uprating.

A combination of experiment and fluid analysis are being used to develop a low-pressure-loss separator able to provide both adequate steam-water separation performance and lower pressure losses even when power uprating increases the steam flow rate (see Fig. 6).

Making Effective Use of Resources (Plutonium and Thorium)

In an ABWR core, the percentage of thermal neutrons is increased by raising the water-to-fuel ratio through a larger water gap width between fuel bundles than conventional cores. As a result, the core is characterized by a lower absolute value of the void reactivity coefficient and increased reactor shutdown margin (see Fig. 7).

These characteristics allow the achievement of a full MOX-ABWR configuration in which MOX fuel containing plutonium is used throughout the entire core. The MOX-ABWR core has the same basic specifications as the current ABWR to avoid any major differences between the characteristics of a core with a load of MOX fuel and a conventional uranium core.

The Ohma Nuclear Power Station of Electric Power Development Co., Ltd. currently under construction will be the first plant to use a full MOX-ABWR and Hitachi is carrying out the detailed design for the equipment around the core in cooperation with GNF-J. A step-by-step transition to full MOX core operation is planned with MOX fuel bundles expected to make up between zero (all-uranium core) and about one third of the initial core. The basic structure of the MOX fuel bundles is the same as the well-proven Step II fuel. Table 1 lists the major specifications of the MOX fuel.

In response to the recent trend toward utilizing thorium resources in addition to plutonium, Hitachi is also taking advantage of its full MOX-ABWR technology to develop a core that uses thorium.

Work on Introducing GNF2 Fuels in Japan

Hitachi is working with GNF-J on preparations for the introduction of GNF2 fuel in Japan as a means of power uprating. GNF2 fuel has an excellent thermal margin. The number of fuel rods in GNF2 fuel is increased to 92, arranged in 10×10 rod array, and the average linear heat generation rate is about 20% lower than for Step III fuel. Also, the greater

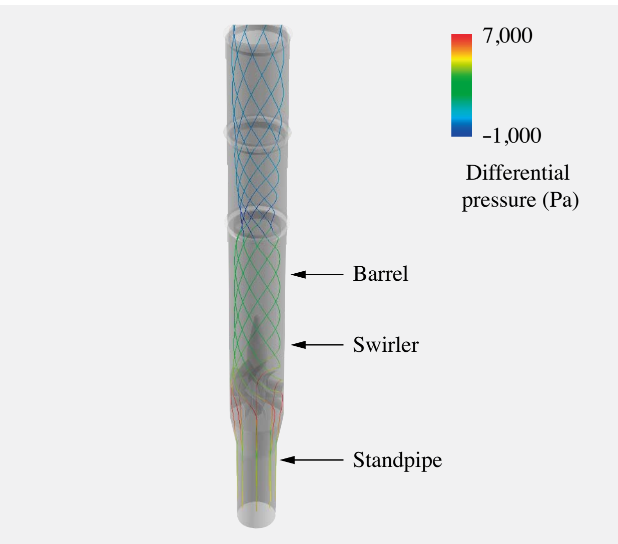


Fig. 6—Conceptual Diagram of Low-pressure-loss Separator (Differential Pressure Between Streamline and Exit).
This simulated image is based on the conditions in a real ABWR [water-steam (pressure: 7.2 MPa, flow: 41.5 kg/s, quality: 14.5%)]. The position of the swirl vane is changed to reduce pressure loss while maintaining steam-water separation performance.

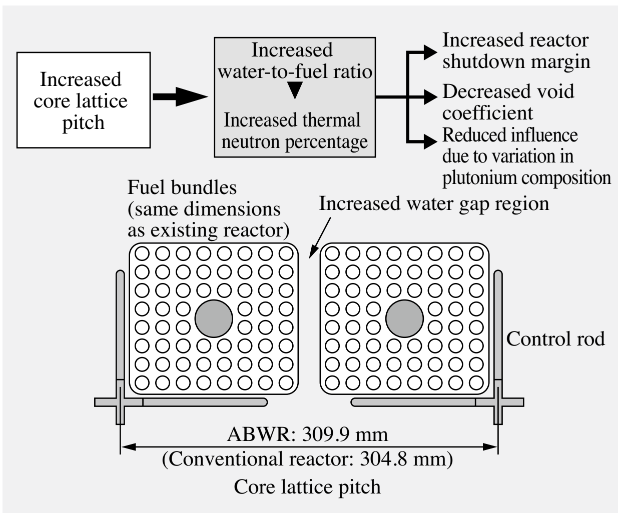


Fig. 7—Characteristics of ABWR Core and Fuel.
A full MOX core is used to take advantage of the large water-to-fuel ratio of an ABWR.

TABLE 1. Main Specifications of Uranium Fuel and MOX Fuel
The main specifications of the uranium fuel (Step III fuel) and MOX fuel (Step II fuel) are listed.

	Uranium fuel	MOX fuel
Fuel type	Step III	Step II
Lattice	9×9	8×8
Uranium enrichment (wt%)	Approx. 3.8	Approx. 1.2
Plutonium enrichment (wt%)	–	Approx. 4.3*
Maximum burnup (MWd/t)	55,000	40,000
No. of fuel rods	74 (including 8 short rods)	60
Pellet diameter (mm)	Approx. 9.6	Approx. 10.4
Pellet material	UO_2 UO_2-Gd_2O_3	UO_2 UO_2-PuO_2(MOX) UO_2-Gd_2O_3

* Initial percentage of fissile plutonium: Approx. 67%
wt: weight

heat transfer area provided by the increased number of fuel rods together with enhancements such as using advanced spacers at eight locations in the axial direction significantly improves the critical power compared with Step III fuel (see Fig. 8). By transferring this improvement to the thermal margin, GNF2 fuel can be used to achieve a 20% power uprating and 24-month operation.

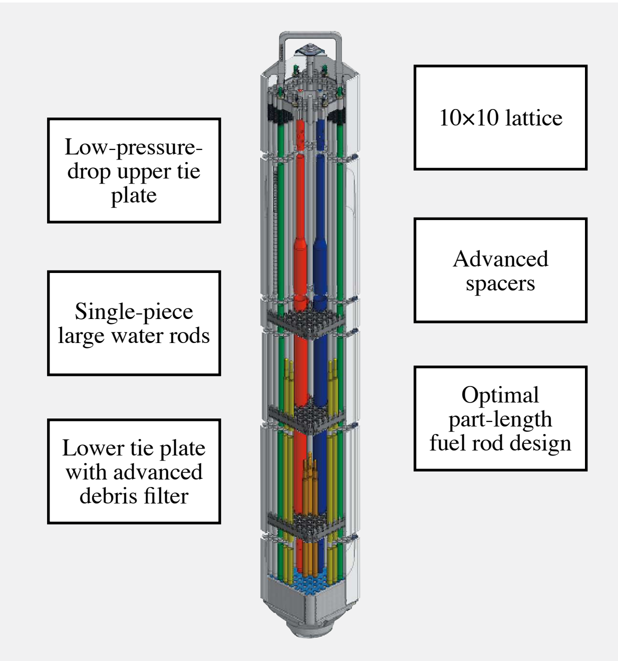


Fig. 8—Characteristics of GNF2 Fuel (10×10 Fuel).
GNF2 fuel can provide significant improvements in thermal margin compared with 9×9 fuel.

Another characteristic of the GNF2 fuel is that it uses two different lengths in its 92 fuel rods, 14 of which are part-length fuel rods, and this reduces pressure drop. The two water rods allow a higher burnup and occupy the area of eight fuel rods. The structure of the upper tie plate reduces pressure drop while the lower tie plate has an advanced debris filter.

GNF2 fuel has been used as reload fuel in the USA since 2008 after its performance was confirmed in lead fuel assemblies. Hitachi has also been working with GNF-J to prepare for the introduction of GNF2 fuel with aim of applying for approval in Japan in the early 2010s to meet future needs for long-term operation cycle and power uprating. This work includes developing design code and technical documentation (topical reports) for GNF2 fuel.

EFFORTS TOWARD FUTURE DEVELOPMENTS

For the cores and fuel used in the next generation of BWRs, it is anticipated that demands will be even stronger to reduce the burden on the environmental by reducing spent fuel generation through the adoption of ultra-high burnup, while also making effective use of resources by adopting long-term operation cycle and uranium-saving technologies.

To produce cores and fuel able to support ultra-high burnup, it will be necessary to obtain fuel cladding materials that can handle ultra-high burnup in excess of the current maximum fuel bundle burnup of 55 GWd/t.

Working with GNF-J, Hitachi is developing a new cladding material that has excellent corrosion resistance as well as low hydrogen absorption even when operating in the ultra-high burnup range. Hitachi was quick to focus its attention on how to optimize the composition of zirconium alloy to ensure that the fuel is resistant to corrosion during high burnup operation and has been developing materials containing a higher proportion of iron that combine high corrosion resistance with low hydrogen absorption. The work has confirmed the superior corrosion resistance and low hydrogen absorption properties of this material compared with the Zircaloy-2 used currently (see Fig. 9). GNF-J plans to commercialize the alloy under the name

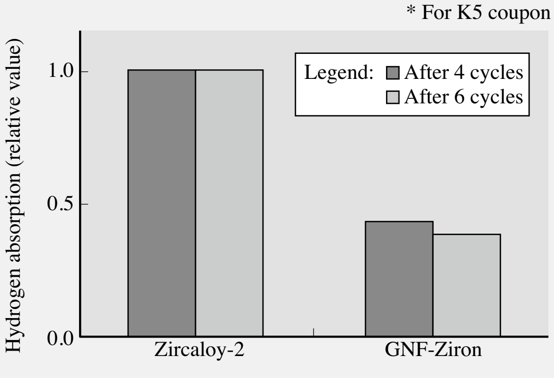
"GNF-Ziron" and use it as a cladding material for future fuel in Japan. Hitachi also aims to use its accumulated know-how to develop new alloys with even higher performance.

A method for reducing uranium consumption under development by Hitachi is the SSR (spectrum shift rod) which replaces the water rod in the fuel. The SSR has ascending and descending pipes and uses the balance of the pressure difference between the top and bottom of the lower fuel tie plate to determine the water level in the ascending pipe. This water level can be changed simply by the core flow using the recirculation pump speed control. In the early stages of the cycle, the water level in the SSR is lowered by reducing the core flow. This hardens the neutron spectrum in the top part of the fuel and encourages the accumulation of plutonium. In the latter part of the cycle, the water level in the SSR is raised by increasing the core flow to soften the neutron spectrum and burn the plutonium accumulated in the early stage of the cycle (see Fig. 10).

Hitachi is continuing to undertake development work with GNF-J aimed at the practical application of the SSR, including proposals for joint research on electricity and national development projects.

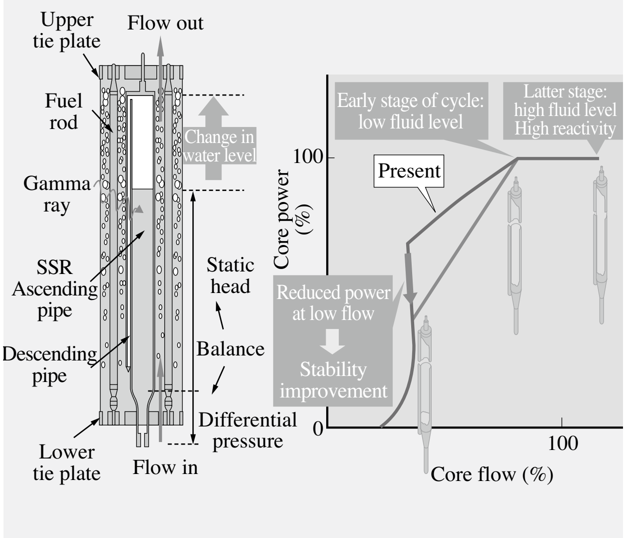
Alloy	Alloy element (wt%)			
	Tin	Iron	Chromium	Nickel
GNF-Ziron *	1.46	0.26	0.10	0.05
Zircaloy-2	1.2-1.7	0.07-0.20	0.05-0.15	0.03-0.08

* For K5 coupon test



Zry: zircaloy (a kind of zirconium alloy)

Fig. 9—GNF-Ziron (High-Fe Improved Zry).
The hydrogen absorption at high burnup is improved to about half that of Zircaloy-2(3).



SSR: spectrum shift rod

Fig. 10—Principle of Spectrum Shift Rod.
The SSR forms a water surface at the static head level that balances the pressure difference between the top and bottom of the lower tie plate. The water level can be changed simply by modifying the core flow. This increases the spectrum shift effect.

CONCLUSIONS

This article has discussed the background to the development of cores and fuel in the past and also the work being done on cores and fuel to realize the highly economical plants of the future.

Hitachi intends to continue working hard on the development of core and fuel technologies to meet future needs and to contribute to improving the safety and economics of BWR plants.

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