Featured Articles

Light Water Reactor System Designed to Minimize Environmental Burden of Radioactive Waste

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OVERVIEW: One of the problems with nuclear power generation is the accumulation in radioactive waste of the long-lived TRUs generated as byproducts of the fission of uranium fuel. Hitachi is developing a nuclear reactor that can burn TRU fuel and is based on a BWR design that is already in use in commercial reactors. Achieving the efficient fission of TRUs requires that the spectrum of neutron energies in the nuclear reactor be modified to promote nuclear reactions by these elements. By taking advantage of one of the features of BWRs, namely that their neutron energy spectrum is more easily controlled than that of other reactor types, the new reactor combines effective use of resources with a reduction in the load on the environment by using TRUs as fuel that can be repeatedly recycled to burn these elements up.

INTRODUCTION

NUCLEAR power generation has an important role to play in both energy security and reducing emissions of carbon dioxide. One of its problems, however, is the accumulation in radioactive waste from the long-lived transuranium elements (TRUs) generated as byproducts of the fission of uranium fuel. The TRUs include many different isotopes with half-lives ranging from hundreds to tens of thousands of years or more. As a result, the radiotoxicity of TRU-containing radioactive waste (a measure of the intensity of radiation in terms of the combined effects on people of all radioactive isotopes in the waste) takes around 100,000 years to fall to a level equivalent to that of naturally occurring uranium ore. If, on the other hand, the TRUs could be burned up to eliminate them from the radioactive waste, this time could be reduced to a few hundred years(1).

Work is progressing on the research and development of nuclear reactors capable not only of eliminating TRUs from waste, but also of reducing the consumption of uranium by burning TRUs as fuel. Sodium-cooled fast reactors, which use sodium (Na) to cool the fuel, are one example.

Hitachi, meanwhile, is working on the development of its resource-renewable boiling water reactor (RBWR) based on a boiling water reactor (BWR) design that is already in use in commercial reactors.

This article describes the concept behind the RBWR along with the progress of its development, as well as its specifications and features.

RBWR CONCEPT

Plutonium Breeding Reactor

The original concept on which the RBWR is based was the plutonium generation boiling water reactor (PGBR) proposed by Takeda and others from Hitachi in 1988(2). The PGBR produces fissile plutonium (Puf), a TRU fuel for nuclear power generation containing plutonium-239 (^{239}Pu) and plutonium-241 (^{241}Pu), from uranium-238 (^{238}U), the non-fissile isotope that makes up more than 99% of natural uranium (U). Puf breeding means that more Puf is created during the burning of the fuel than is provided in the initial fuel as a startup neutron source. As it was generally assumed at the time that this could only be achieved using sodium-cooled fast reactors, the PGBR's ability to breed plutonium in a light water reactor made it a ground-breaking proposal.

To achieve the breeding of plutonium, it is necessary to promote the absorption of neutrons by ^{238}U to transmute it into ^{239}Pu. For it to be used in a power reactor, it also needs to be able to sustain a fission chain reaction in the nuclear reactor. That is, a higher number of neutrons than in a conventional BWR is required to maintain the simultaneous transmutation and fission chain reactions. Typically, the higher the energy of the neutrons that trigger fission, the more it encourages neutron absorption by ^{238}U and the higher, in relative terms, the number of neutrons emitted by the fission reaction. Accordingly, breeding plutonium requires that the mean neutron energy in the reactor be raised.

In a BWR, the heat from the fuel rods causes the water (coolant) that flows through the core of a nuclear reactor to boil, thereby removing heat from the fuel rods. Meanwhile, the coolant also acts to moderate the high energy of the neutrons generated by the fission reaction (reduce it down to a low level) through repeated collisions between neutrons and the hydrogen nuclei in the coolant. To minimize this effect, the PGBR reduces the proportional volume of coolant in the reactor core by having narrower coolant channels between fuel rods. Calculations have also demonstrated that the PGBR can achieve a high neutron energy and enable Pu breeding despite being a light water reactor by taking advantage of a characteristic of BWRs whereby the boiling of coolant to form steam reduces the density of hydrogen nuclei.

Intrinsic Safety

Nuclear reactors need to exhibit inherent safety, which means that, when the output of a reactor increases due to some external factor, the nature of its design means it automatically acts to reduce that output. The main mechanisms for inherent safety in a conventional BWR are the effect whereby fission is suppressed by the greater absorption of neutrons as the fuel temperature increases (Doppler effect), and the effect whereby higher temperatures promote more coolant boiling, which raises the proportional volume of steam (void fraction), reduces the moderation of neutrons, and thereby also suppresses fission.

This latter effect is a consequence of the fact that, in a conventional BWR, fission is primarily triggered by low energy neutrons (around 0.1 eV). This is because, at low energies, the fission of fissile ^{235}U and $^{239,241}Pu$ tends to become less likely as the neutron energy increases. An indicator that represents this relationship between void fraction and likelihood of fission is called the void reactivity coefficient. The void reactivity coefficient has a negative value in situations where an increase in void fraction makes fission less likely, as in a conventional BWR.

This relationship reverses at high energies of 100 keV or more, where the higher the neutron energy the more likely fission is to occur. Accordingly, when the proportion of fission reactions triggered by high-energy neutrons becomes large, as in the PGBR which is intended for plutonium breeding, the effect whereby a higher void ratio automatically acts to reduce reactor output becomes attenuated. Although the Doppler

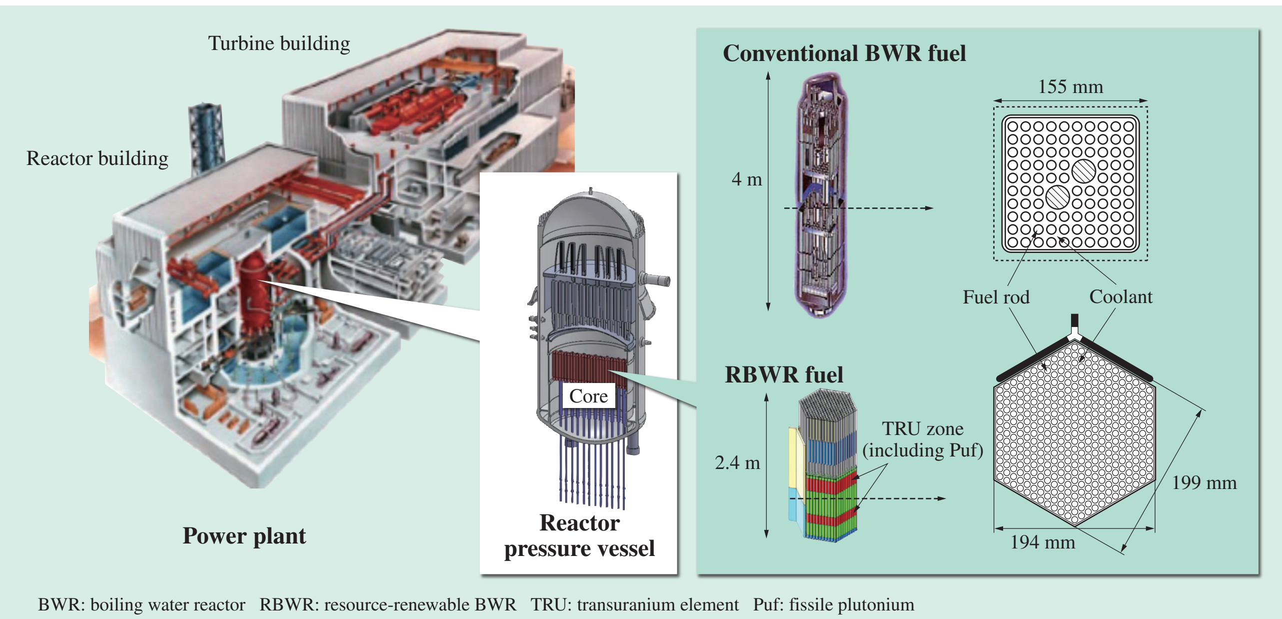


Fig. 1—RBWR Concept.
Apart from the core, the RBWR is largely the same as conventional BWR systems. To achieve effective burning of TRUs, the gaps between fuel rods through which the coolant flows are narrower on the RBWR. Also, the TRUs are contained in two separate zones to ensure inherent safety.

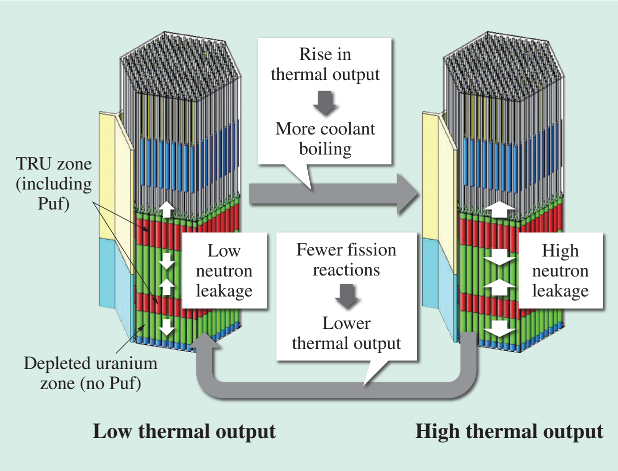


Fig. 2—Inherent Safety of RBWR.
A rise in thermal output leads to more coolant boiling and greater neutron leakage, thereby suppressing fission.

effect still works automatically to reduce output, the PGBR has a positive void reactivity coefficient.

Takeda and his team continued their work, and in 1995 proposed the concept of an RBWR actinide recycler (RBWR-AC) that combined plutonium breeding with a negative void reactivity coefficient(3). The name of the RBWR derives from its ability to recycle not only plutonium but also the other TRUs as fuel. A feature of the RBWR-AC is that Puf is added as a startup neutron source to the fuel in two separate zones (two-zoned core) (see Fig. 1). Because the increase in void fraction as the reactor output rises acts to reduce the probability that neutrons will collide with and bounce off hydrogen nuclei, the probability of the neutrons leaving the fuel increases. The idea behind the two-zoned core was to suppress fission by amplifying this effect whereby an increase in void fraction results in greater neutron leakage (see Fig. 2).

Multi-recycling

Another feature of the RBWR-AC is its multi-recycling capability whereby it can repeatedly recycle the TRUs contained in its own spent fuel (see Fig. 3). The TRUs consumed by the fission reactions that produce the heat needed to generate electric power are created by the operation of the reactor itself through the transmutation of depleted uranium. This means that the operating cycle of the RBWR-AC can be maintained simply by replenishing it with depleted uranium. Being the byproduct left over after the manufacture of the enriched uranium (which contains a high proportion of the fissile ^{235}U isotope) used to fuel conventional commercial light water reactors, depleted uranium is a plentiful resource that can provide the basis of a long-term energy supply.

Multi-recycling requires that the isotopic composition of TRUs in the fuel be kept the same before and after burning them in the reactor. If the proportion of fissile isotopes after use is lower, then the amount of these isotopes will diminish each time the fuel is recycled, ultimately resulting in loss of criticality in the reactor. There is also the risk of compromising reactor design and operation criteria, such as a change in the fuel composition causing the void reactivity coefficient to become positive. In addition to having narrower coolant channels, the RBWR-AC is able to satisfy a variety of criteria as it runs through repeated operation cycles by modifying the coolant flow rate to adjust the neutron energy spectrum during operation and maintain a constant isotopic composition of TRUs in the fuel before and after use.

TRU Burner

One of the advantages of nuclear power generation is that it has a higher energy density than thermal and other forms of power generation, meaning that it requires less fuel to produce the same amount of electric power. On the other hand, when TRUs are used to fuel a nuclear reactor, the percentage of the initial fuel load burned up in each operation cycle is only in the single digits or low teens. Accordingly, the fuel needs to be recycled many times to burn up a large amount of TRUs.

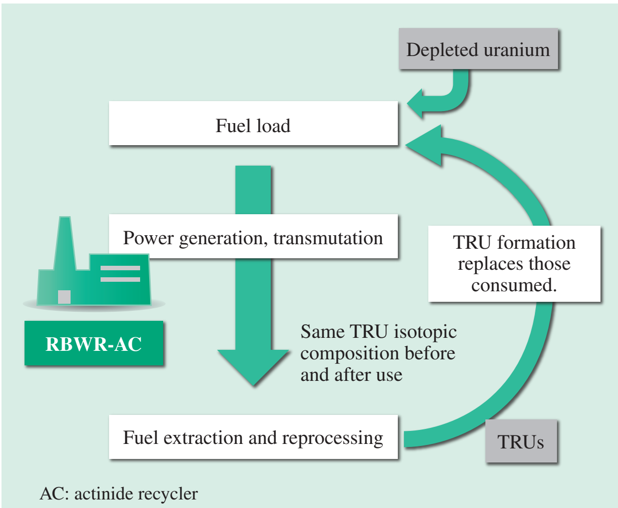


Fig. 3—Fuel Cycle for RBWR-AC.
Each operation cycle of the RBWR-AC forms its own TRUs to replace those consumed during operation while maintaining the same isotopic composition of TRUs before and after use.

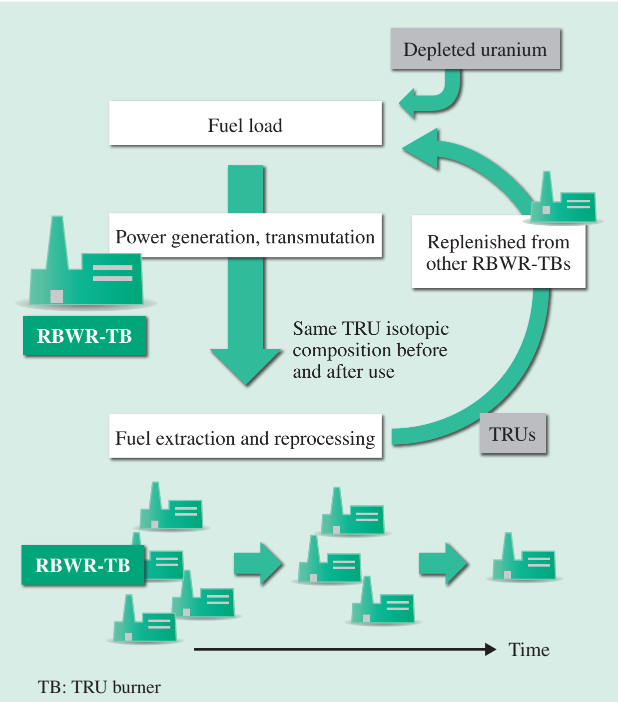


Fig. 4—Fuel Cycle for RBWR-TB.
The TRUs consumed during operation are replenished from the spent fuel of other RBWR-TBs. The fuel is recycled through progressively fewer reactors until all the TRUs are burned up apart from those in the final reactor.

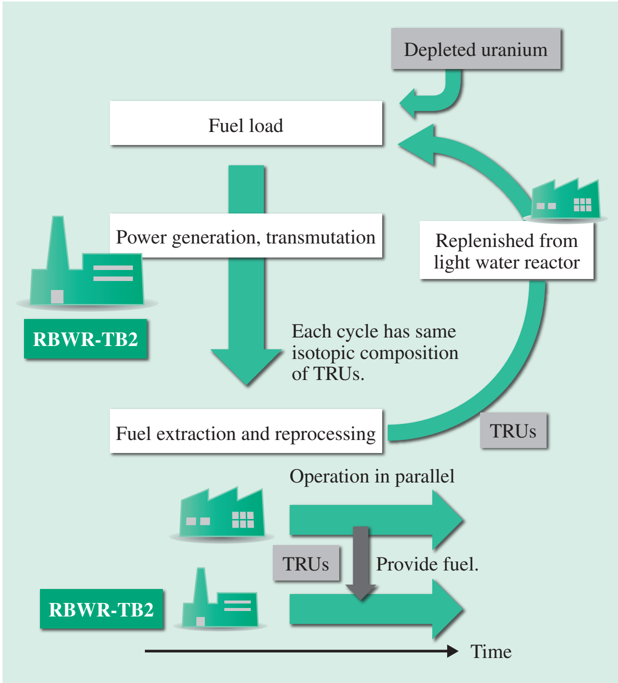


Fig. 5—Fuel Cycle for RBWR-TB2.
The TRUs consumed during operation are replenished from the spent fuel of light water reactors. The RBWR-TB2 operates in parallel with a light water reactor to minimize the buildup of excess TRUs.

Takeda and his team took advantage of the characteristics of the RBWR that allow it to repeatedly recycle fuel while keeping constant its isotopic composition of TRUs and proposed the concept of employing a TRU burner (RBWR-TB), meaning a reactor that could reduce the amount of TRUs by burning them up[(4), (5)]. Although the RBWR-TB shares the RBWR-AC's characteristic of maintaining a constant isotopic composition of TRUs in the fuel before and after use, the process of burning the fuel reduces the absolute quantity of TRUs. The operation cycle is repeated by making up for this loss of TRUs by supplying fuel from another RBWR-TB. That is, the concept behind the RBWR-TB is to run the operation cycle with progressively fewer reactors until all of the TRUs are burned up except for those loaded into the final reactor (see Fig. 4). This presents a scenario under which the fuel is first used for long-term energy production in RBWR-ACs, during which time the TRU fuel is maintained at a constant level. Subsequently, once alternative non-nuclear forms of energy production become available, RBWR-TBs are then used to burn up the TRUs and transition away from nuclear power generation without leaving behind long-lived radioactive waste.

Feasibility Study by US Universities

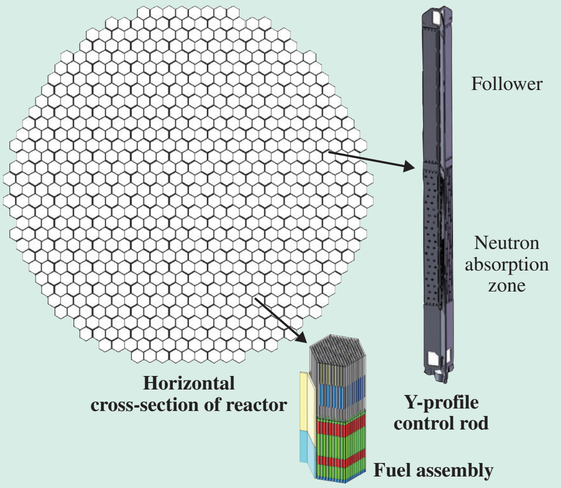
Between 2007 and 2011, three US universities (Massachusetts Institute of Technology, University of Michigan, and University of California, Berkeley) conducted feasibility studies of RBWR reactors under research contracted to the Electric Power Research Institute, Inc. (EPRI)[(6)]. Though some differences between the analysis results obtained by Hitachi and the universities need to be evaluated further, the analyses collectively indicated that the RBWRs appeared to be able to achieve their design objectives.

Part of the contracted study included the proposal of another TRU reactor, the RBWR-TB2, for comparison with sodium-cooled fast reactors. An RBWR-TB2 operates in parallel with a conventional light water reactor and burns the TRUs in its spent fuel (see Fig. 5). An RBWR-TB2 recycles fuel repeatedly, loading a mixture of fuels comprising the TRUs in both its own and the light water reactor's spent fuel. The operation of the RBWR-TB2 serves to minimize the buildup of excess TRUs.

RBWR SPECIFICATIONS

Plant Overview

The rated thermal output, power output, reactor pressure vessel diameter, and core pressure of the



Parameter	RBWR	ABWR
Thermal output (MWt)	3,926	3,926
Power output (MWe)	1,356	1,356
Reactor pressure vessel diameter (m)	7.1	7.1
Core pressure (MPa)	7.2	7.2
No. of fuel assemblies	720	872
Fuel lattice shape	Hexagonal lattice	Square lattice
No. of control rods	223	205
Control rod shape	Y-profile	Cross (+) profile

ABWR: advanced BWR

Fig. 6—Basic Specifications of RBWR Plant.
The rated thermal output, power output, reactor pressure vessel diameter, and core pressure of the RBWR are the same as an ABWR. A follower is fitted to the top of each control rod to prevent water entering the space vacated when the control rod is withdrawn.

RBWR are the same as the advanced BWR (ABWR), the latest commercial BWR (see Fig. 6). The core has 720 fuel assemblies and 223 Y-profile control rods. As the fuel assemblies for the RBWR-AC, -TB, and -TB2 all have roughly the same size, their cores can be swapped between each other by exchanging fuel assemblies. The following section describes the latest specifications for each reactor type(7).

Core Fuel Configuration

Fig. 7 shows the fuel assemblies for the RBWR-AC, -TB, and -TB2 respectively. The fuel assemblies for the RBWR-AC have upper and lower TRU zones (with heights of 280 mm and 193 mm), sandwiched between the upper, central, and lower depleted uranium zones (with heights of 70 mm, 520 mm, and 280 mm). Neutron absorber zones, meanwhile, are located respectively above and below the upper and lower depleted uranium zones. These are provided to enhance the output suppression effect by absorbing neutrons when a rise in output causes the void fraction of the coolant to increase, thereby increasing the leakage of neutrons from the fuel zones (TRU and depleted uranium zones). The heights of the depleted uranium and TRU zones are determined so as to maintain the same isotopic composition of TRUs before and after use.

Because the requirement for TRU breeding is lower on the RBWR-TB and -TB2 TRU burner reactors

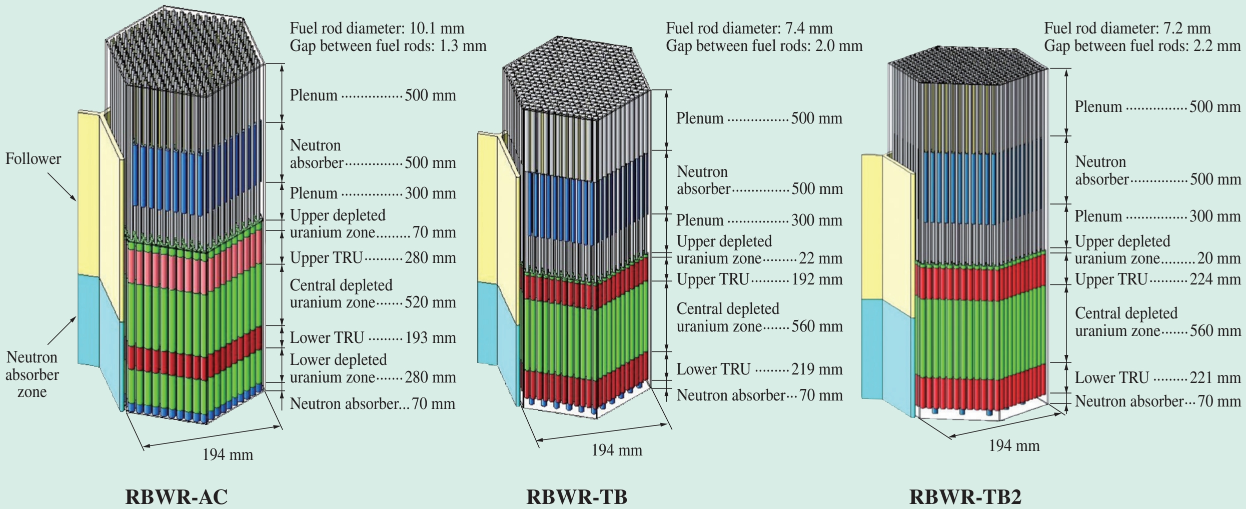


Fig. 7—RBWR Fuel Assembly.
The height of the TRU and depleted uranium zones, the fuel rod diameter, and the gap between fuel rods are adjusted to ensure that the multi-recycling of TRUs can be performed in a way that suits the purpose of each reactor design. As the RBWR-TB and -TB2 TRU burner reactors have less need for TRU formation, their fuel assemblies do not include the lower depleted uranium zone.

than it is on the RBWR-AC, their fuel assemblies do not have the lower depleted uranium zone. As in the RBWR-AC, they have neutron absorber zones above and below the fuel zones. The heights of the TRU and depleted uranium zones for the RBWR-TB are also determined so as to maintain the same isotopic composition of TRUs before and after use, as in the RBWR-AC. In the case of the RBWR-TB2, when the isotopic composition of TRUs in the fuel supplied from light water reactors is the same for each operation cycle, the heights of the TRU and depleted uranium zones are determined such that the isotopic composition that results after combining the RBWR-TB2's own spent fuel will be the same for each operation cycle.

Along with adjusting the heights of the TRU and depleted uranium zones in the RBWR-AC, -TB, and -TB2, the balance between consumption and creation of TRUs is also adjusted by modifying the fuel rod diameter and gaps between fuel rods to adjust the neutron energy spectrum (see Fig. 8). In the case of the RBWR-AC, where not only the isotopic composition of TRUs but also their quantity needs to be kept constant before and after use, it is necessary to increase the mean neutron energy by having the lowest proportion of coolant of the three designs so that the ratio of fissile TRU isotopes before and after use (breeding ratio) will be above 1.0. After the RBWR-AC, it is the RBWR-TB that has the next lowest proportion of coolant. This is because the breeding ratio of fissile TRU isotopes needs to be increased somewhat to keep the relative reduction in fissile TRU isotopes and non-fissile TRU isotopes the same in the RBWR-TB, where the isotopic composition needs to be kept constant even as the quantity decreases as the fuel is burned. The fuel configuration of the RBWR-TB2, on the other hand, has a higher proportion of coolant than the RBWR-TB because it is supplied with TRUs in spent fuel from light water reactors with a high proportion of fissile isotopes.

RBWR CORE CHARACTERISTICS

Burning uranium in a conventional BWR forms both fissile and non-fissile TRU isotopes (see Fig. 9). When using mixed oxide (MOX) fuel that contains plutonium and uranium, the fuel ends up with more of the non-fissile isotopes of plutonium and other TRUs than it had when loaded because, whereas the fissile isotopes of plutonium are consumed, the non-fissile isotopes are not. Calculations have demonstrated that the RBWR-TB and -TB2 TRU burner reactors are able to consume both fissile and non-fissile TRU isotopes at more than twice the rate they are produced by a conventional BWR.

Fig. 10 shows the dependence of the neutron capture rate and fission reaction rate on neutron energy in the nuclear reactor of an RBWR-TB, where the neutron capture rate is the proportion of

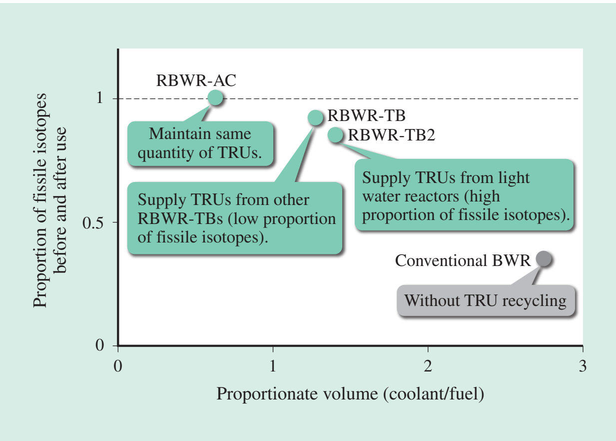


Fig. 8—Proportionate Volume of Coolant in RBWR and Conventional BWR Reactors.
Since the RBWR-AC and -TB need to continue the operation cycle without consuming fissile materials other than those contained in the fuel discharged from themselves, their water-to-fuel volume ratios are set lower than those of the RBWR-TB2 and conventional BWR.

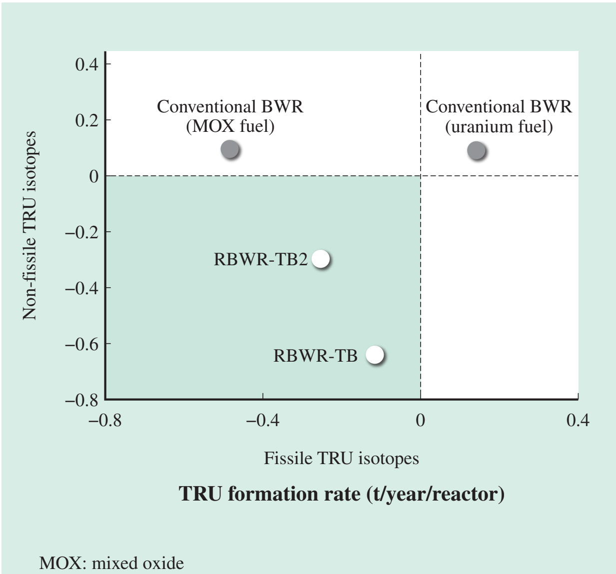


Fig. 9—Rate of Formation and Consumption of TRUs.
A negative value indicates that consumption of TRUs results in a reduction in their quantity. The value for conventional BWRs is from Ando and Takano[(8)].

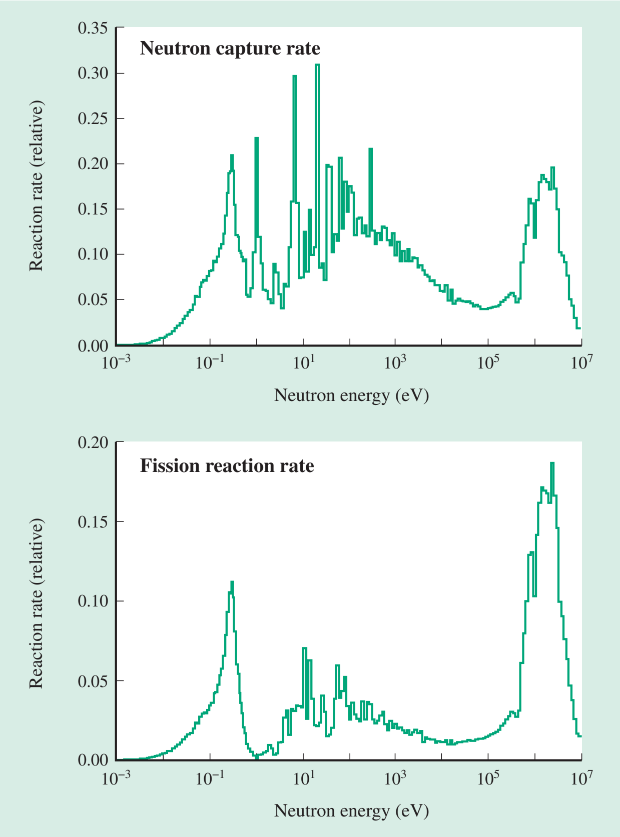


Fig. 10—Dependence on Neutron Energy of Neutron Capture and Fission Reactions in RBWR-TB Core.
Non-fissile TRUs are transmuted into fissile TRUs by the capture of a neutron.

cases in which a transmutation reaction occurs due to capture of a neutron and the fission reaction rate is the proportion of cases in which fission occurs(7). Neutron capture occurs for a wide range of energies, from low energies of around 10^{-1} eV up to high energies on the order of 10^6 eV. Non-fissile isotopes such as ^{240}Pu and americium-241 (^{241}Am) are transmuted by neutron capture into fissile ^{241}Pu and ^{242}Am respectively. Also, the direct fission of isotopes like ^{240}Pu and ^{241}Am occurs at high neutron energies in the vicinity of 10^6 eV. By using this wide distribution of neutron energies to achieve the fission of non-fissile TRUs, both by first transmuting them into fissile TRUs and also through direct fission by high-energy neutrons, the RBWR can burn up non-fissile TRUs in the same proportion as fissile TRUs and maintain the same isotopic composition of TRUs before and after use.

Table 1 lists the isotopic composition of TRUs before and after use and the core characteristics of the RBWR-AC, -TB, and -TB2. When the RBWR-AC and -TB are operated to keep the same isotopic composition of TRUs in the fuel before and after use, the quantity of TRUs increases in the case of the RBWR-AC and decreases in the case of RBWR-TB. When an RBWR-TB2 is loaded with fuel in which the TRUs in its own spent fuel and the spent fuel from a light water reactor are in the same proportion, and

TABLE 1. Change in Isotopic Composition of TRUs during Burning in Reactor
This considers the case when spent fuel is left for three years after removal from the reactor to allow radiation and heat generation to diminish.

	RBWR-AC		RBWR-TB		RBWR-TB2		
Isotope	When fuel loaded	Three years after removal	When fuel loaded	Three years after removal	When fuel loaded	Three years after removal	TRUs discharged from light water reactor
Np237	0.4	0.4	0.1	0.1	1.9	1.4	6.7
Pu238	2.9	2.9	4.7	4.7	6.3	6.7	2.8
Pu239	43.5	43.5	9.5	9.5	27.7	25.5	48.8
Pu240	36.3	36.3	39.5	39.6	38.5	40.1	23
Pu241	5.1	5.1	4.4	4.4	5.5	5.4	7
Pu242	5.1	5.1	25.4	25.4	9.6	10.1	5
Am241	3.6	3.6	4.7	4.7	5.4	5.4	4.7
Am242m	0.2	0.2	0.2	0.2	0.2	0.2	0
Am243	1.3	1.3	4.7	4.7	2.4	2.4	1.5
Cm244	1.1	1.1	4.1	4	1.8	2	0.5
Cm245	0.4	0.4	1.2	1.2	0.5	0.6	0
Cm246	0.1	0.1	1	1	0.2	0.2	0
Cm247	0	0	0.2	0.2	0	0	0
Cm248	0	0	0.2	0.2	0	0	0
Cm249	0	0	0.1	0.1	0	0	0
Puf (t)	1.94	1.96	1.14	1.06	2.06	1.74	0.32
TRU (t)	3.99	4.03	8.18	7.62	6.2	5.63	0.58

Np: neptunium Pu: plutonium Am: americium Cm: curium under conditions in which the isotopic composition of TRUs remains the same in each cycle, the quantity of TRUs decreases as the fuel is burned.

Calculations have also demonstrated that all of the reactor types have a negative void reactivity coefficient(7).

CONCLUSIONS

This article has provided an overview and described the latest specifications of the RBWR, a reactor that can recycle as fuel the TRUs formed in nuclear power generation to provide a long-term supply of energy while also preventing the TRUs from becoming radioactive waste that will continue to emit radiation for a long time.

Hitachi intends to continue development work aimed at commercializing the RBWR, seeing it as a valuable option, based on proven BWR technology, for meeting expectations for the long-term supply of energy from nuclear power while also solving the industry's problem of how to deal with TRUs.

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