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EXAMINATION OF INNOVATIVE PLANT CONSTRUCTION METHOD USING HULL STRUCUTRE AND SEISMIC ISOLATION BUILDING FOR GXBWR

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ABSTRACT

To be economically competitive, the GXBWR design should include system and structural simplifications, modularity for short construction times, and increased availability. Comprehensive safety features such as Isolation Condenser and Filtered Containment Venting System (FCVS) to prevent a primary containment vessel failure. It is not necessary to evacuate if the radiation level is low by FCVS.

Aiming at short construction period and high production quality, module fabrication and construction system for equipment and structures were studied for the GXBWR. As the GXBWR is a small size scale plant, it is possible to fabricate, transport and construct it in a one-piece pump and its supporting structures. Since a reactor building is usually a reinforced concrete structure, it is impossible to fabricate component modules fixed with the building module. In the shipbuilding industry,

The concept proposed here provides flexibility for different site conditions and power demands, reduces investment risk, and promotes public acceptance.

The IAEA guidelines for safety assessment for SMR reactors will soon be published and Technology roadmap for small modular reactor deployment is shown in the IAEA safety standards to establish fundamental principles, requirements and recommendations of new technology to ensure nuclear safety and serve as a global reference for SMR deployment.

Finally, the author introduces a new MMR (Middle Modular Reactor) named GXBWR, which uses a reactor internal recirculation pump (RIP) for the purpose to load follow with fluctuating renewable energy and enhances stable grid control.

INTRODUCTION

Nuclear power generation is a stable basic power source that does not emit CO_2 on the premise of ensuring safety, and has recently been re-evaluated as an attractive option from the viewpoints of energy security and environmental protection.

Factors such as recent sluggish power demand, power grid capacity limits, and initial investment limits to avoid risks do not favor large-scale plant output. To globalize nuclear power generation and mitigate the greenhouse effect, a small modular reactor (SMR) that can be easily adopted in any country and modularized and manufactured in factories with short construction periods is required.

The concept of the reactor introduced in this section has a simplified BWR configuration with, long operating cycle, and comprehensive safety features, which was presented in 1999 at the annual meetings of JSME and ICONE11by Narabayashi et al., (2003).

To be economically competitive, a long-operating simplified BWR (LS BWR) design includes system and structural simplifications, modularity for short construction times, and increased availability. Comprehensive safety features, such as extensive RPV inventory, lower core layout, molten core in-vessel retention (IVR) features, and hybrid ECCS, including passive features. It will be not necessary to be evacuated by using FCVS and reliable safety systems. IVR is very important, Narabayashi et. Al., (2005), because in the case of the Fukushima Daiichi NPP accident, the molten core penetrated the lower flange of the RPV and fell down to the pedestal floor, causing extreme contamination on the surface of the components, walls, and floors in the PCV, making decommissioning difficult. FCVS play an important role in preventing radiation exposure to local residents and plant personnel, as well as contamination of the surrounding soil.

The authors introduced a new BWR named GXBWR, which is a simplified BWR with a middle size modular reactor (MMR) and a load following function that can be easily adopted in any country and modularized and manufactured in factories with short construction periods.

The concept of the reactor was introduced as a simplified BWR (LSBWR) configuration with a low output, long operating cycle, and comprehensive safety features, and was presented in 1999 at the annual meeting of the JSME and ICONE11 by Narabayashi et al. Aiming at short construction period and high production quality, module fabrication and construction system for equipment and structures were studied for the GXBWR. As the GXBWR is a small size scale plant (SMR), it is possible to fabricate, transport and construct it in a one-piece pump and its supporting structures. If the site transport condition allows, as shown in Figure 1. Since a reactor building is usually a reinforced concrete structure, it is impossible to fabricate component modules fixed with the building module. In the shipbuilding industry, ship hull structure is applied for a large size ship such as a 500,000 tons class. In this paper, we show the load follow function by using reactor internal pimp (RTP) in order to symbiotic with renewable energy. The reactor's electrical output can be varied up to 800 MWe by using forced circulation in the reactor core. If you use the latest BWR fuel, it will be possible to increase the rate by 30%, so the output will be 1000MWe, making it the most cost-effective. However, if you carefully examine the characteristics of a steam turbine, it is found that when the output drops below 50%, the turbine efficiency drops significantly. Therefore, in this paper, we also considered increasing the number of turbines to two or four in a steel building.

OBJECTIVE OF LLBWR and GXBWR DESIGN

The future of nuclear power generation is uncertain because of the increasing competition with other sources of power generation, such as green energy. For greenhouse effect mitigation, nuclear power plants have the merits of stable operation and high-capacity factors and should be easily adopted in any country required to globalize nuclear power generation. Nuclear power generation is generally recognized as an attractive option from the perspectives of energy security and environmental protection. The GXBWR design has the following objectives:

Economic competition with other sources of power generation.

-Comprehensive safety features without evacuation.

(a) Forced recirculation core cooling

Forced recirculation core cooling was applied to obtain the lord following function by using a reactor internal recirculation pump (RIP), resulting in high reliability during operation. Fuel active length attaining core cooling is proven typical 3.7m.

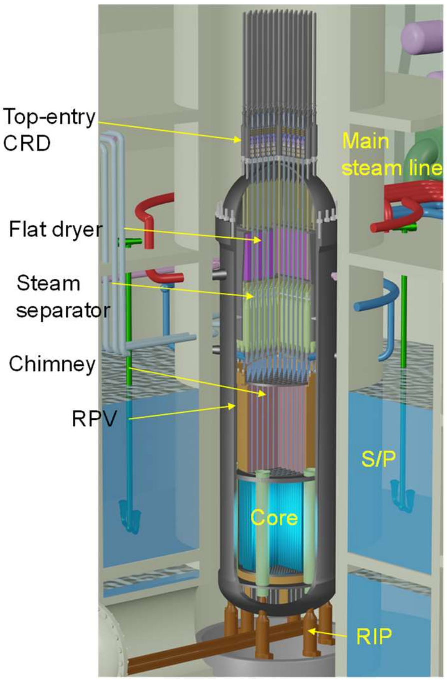
(b) Innovative internal upper-entry CRD and related reactor internals configuration

In the history of BWR reactor design, a lower-entry CRD has been applied for over 30 years. It is difficult to design an upper-entry CRD owing to the two-phase flow, separators, and dryers above the upper plenum. An innovative upper-entry CRD was developed for mounting above the core of the reactor, as shown in Figure 1. The guide chimney was designed to have two functions: a control rod (CR) guide and a two-phase flow path above the core, separated from the core flow. This design has the advantage of being free from the flow-induced vibration (FIV) of the CR. To avoid interference from the CRDs and separators, an offset square layout design was adopted between the CRDs and separators, as shown in Figure 1.

(c) Separator and dryer

Gravitational mist separation has been studied as an option for eliminating separators. Gravitational mist separation is performed using a low mist velocity and a suitable traveling distance. As shown in Figure 1, a cylindrical dryer was placed at top of the RPV. This cylindrical dryer was studied from the viewpoint of internal simplification and ease of fuel handling. The aim was to provide a large-flow passage to effectively-remove moisture from the steam flow.

Tokyo Tech also developed a flat-box-type separator concept using 3D-CAD, that allows the CRD to be removed from the upper flange of the RPV based on the relationship between the fuel assembly, control rods, and guide chimney, as shown in Figure 6 (Narabayashi et. Al., 2005). The width of the separator element was approximately 22 cm, and the distance between the CRD drive rod pitches was 1 ft (30.48 cm); thus, it was structurally feasible. CFD analyses confirmed that the passing flow velocities through the punching metal holes became uniform when the hole diameters were adjusted.



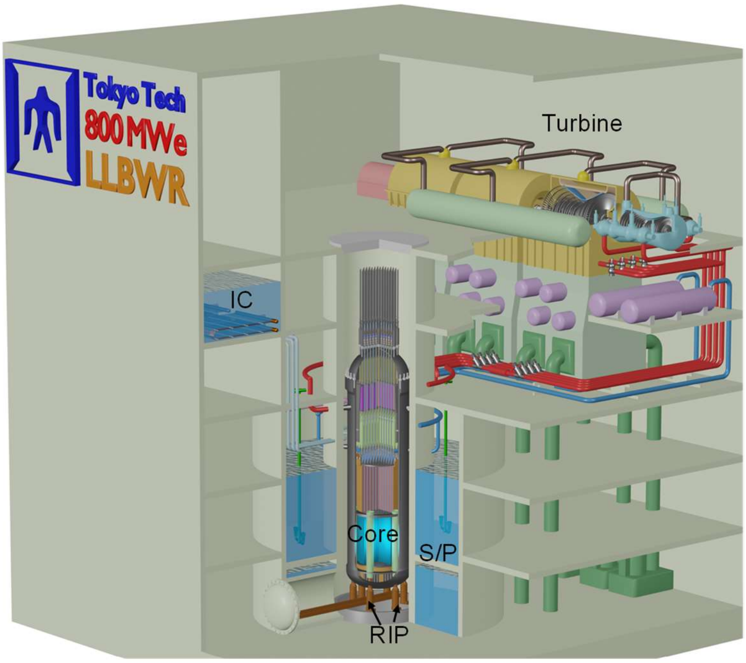


Fig.1 GXBWR Steel building layout. **Fig.2** Ship hull **structure for steel building.**

HULL STRUCUTRE AND SEISMIC ISOLATION BUILDING

Module fabrication and construction were studied for an LSBWR to achieve a short construction period and high production quality. In the system, a module refers to not only the system equipment but also the building structure. As the LSBWR was a small-scale plant, it was possible to fabricate, transport, and construct one piece as the whole plant if the site transport conditions allowed, as shown in Figure 10. pump, and its support structure. A reactor building is typically a reinforced-concrete structure.
It is impossible to fabricate component modules using a building module. In the shipbuilding industry, ship hull structures are applied to large ships such as the 500,000 tons class.

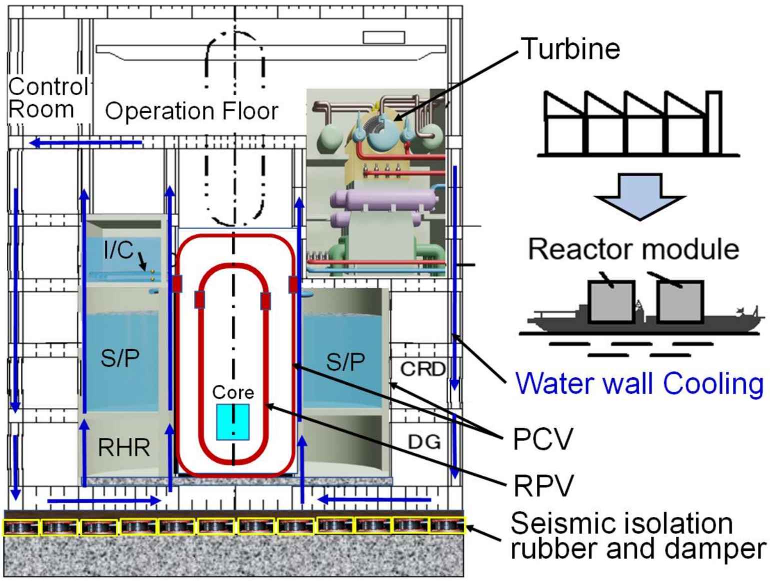


Figure 3 GX BWR building design using ship hull structure.

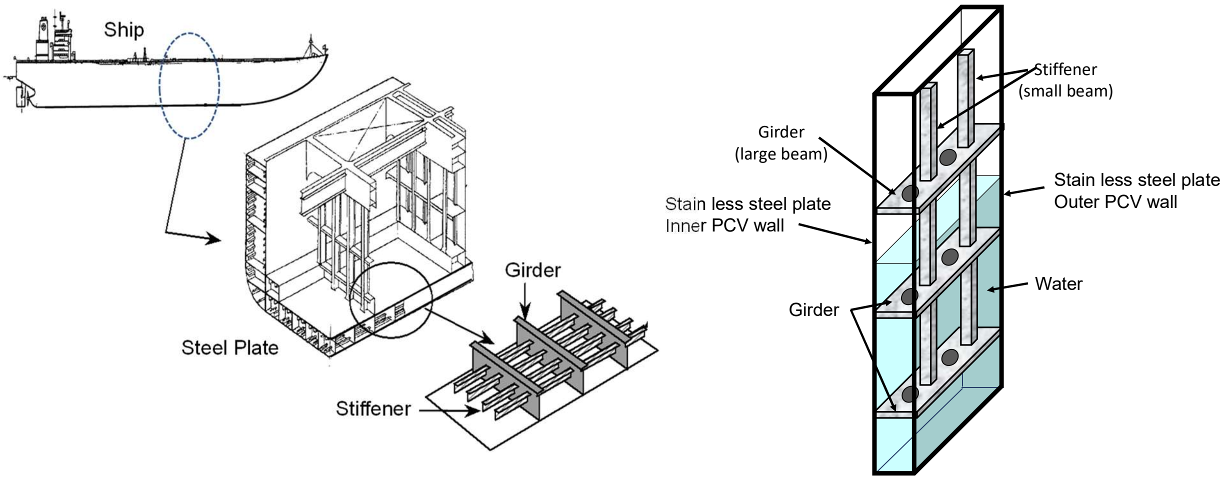


Figure 4 Double PCV walls of inner and outer wall with ship hull structure.

In the GX BWR building design, the reactor and turbine buildings are combined into a single building. Because the GX BWR is medium and lighter than large-sized plants, it is possible to mount the turbine system in the upper part of the reactor building. A building arrangement would reduce the building volume, and a seismic isolation rubber structure for aseismic design would be installed.
By applying the base isolation structure to the entire building, it is possible to standardize the building module regardless of the seismic conditions at various sites. The general arrangement of the LSBWR is shown in Figure 3.

Module construction methods have generally been applied to component assemblies. Narabayashi of Tokyo Institute of Technology recommend the necessity of load following function by using reactor internal pumps (RIP) to be able to change core flow rate and thermal output. By installing RIP as an ABWR, the core flow rate changes in response to changes in pump speed, and the void fraction in the core changes; thus, the heat output of the core can change rapidly.

Many SMRs employ natural core circulation; however, in the case of BWRs, the core output depends on the control rod operation. As the ball screw of the control rod drive mechanism requires accuracy, it is necessary to prevent the ball screw from being worn because of the load-following operation. It is more reliable to use RIP for load-following operations. Therefore, we developed GX BWR in a load-following and long-operating symbiotic BWR for renewable energy, it is possible to add a load-following function to control the power output in response to fluctuations in the electrical output of renewable energy. Therefore, GX BWR can cooperate with renewable energy sources. In combination with renewable energy, this will enable carbon neutrality by the 2050s.

(a) Shipping of LSBWR by barge ship. **(b) Installed LLBWR module reactor .**

Figure 5 Building design of LSBWR and LLBWR mounted on barge ship

SHIP HULL STRUCTUE EVALUATION FOR TRUBINE SUPPORT

Though the ship hull structure is lighter than the reinforced concrete structure, it has enough strength and appropriate characteristics to be able to applying for a nuclear reactor building. By using this ship hull structure, it is possible to fabricate modules containing RPV and PCV components and parts of the building at a shop at the same time.

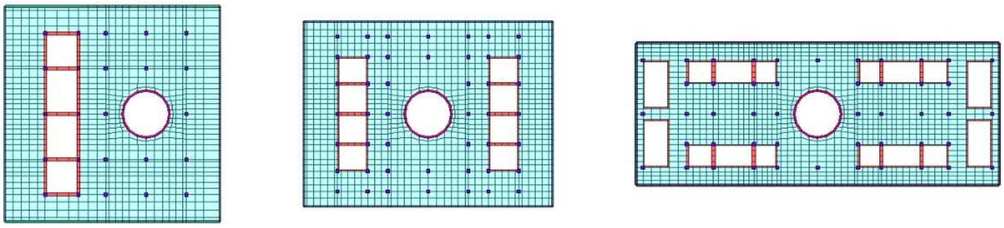
The ideal SMR must condense all necessary functions into a single building. One of significant issues in such a building is to minimize the effect of turbine vibrations on the reactor and vibration-sensitive systems. We considered the issue for the following three cases (Figs. 6 (a) to (c), respectively):

Case 1: Using a single and the largest turbine system at biased distance from the reactor.

Case 2: Using two turbine systems symmetrically placed with respect to the reactor.

Case 3: Using four turbine systems symmetrically placed with respect to the reactor.

Note that cases 2 and 3 have advantages of enabling control of electric output by operating fewer to all turbine systems.



(a) 1-turbine **(b) 2- turbines** **(c) 4-turbines**

Figure 6 3D-FEM models for 1-, 2-, and 4-turbine systems, respectively

Fig. 7 shows the FEM model for the left half structure of the Case 3 system (Fig. 6(C)). The weight of each turbine system is about 30% of that in Case 1, requiring considerably smaller sections of the beams, slabs, columns, and walls. The structural system was designed against strains, stresses, and vertical as well as horizontal deflections due to gravity and rotor vibrations. The system is located on the third floor at 20m height from the ground level.

Both steel construction and steel-concrete construction were compared, and the former was selected due to smaller weight and higher natural vibration frequency. The steel beam is H-section with 3.5m depth, and the column is concrete-filled steel tube of 2m×2m×0.04m. The in-fill wall is of SC-construction using 0.6m thick concrete and 0.025m thick steel plates on its both sides.

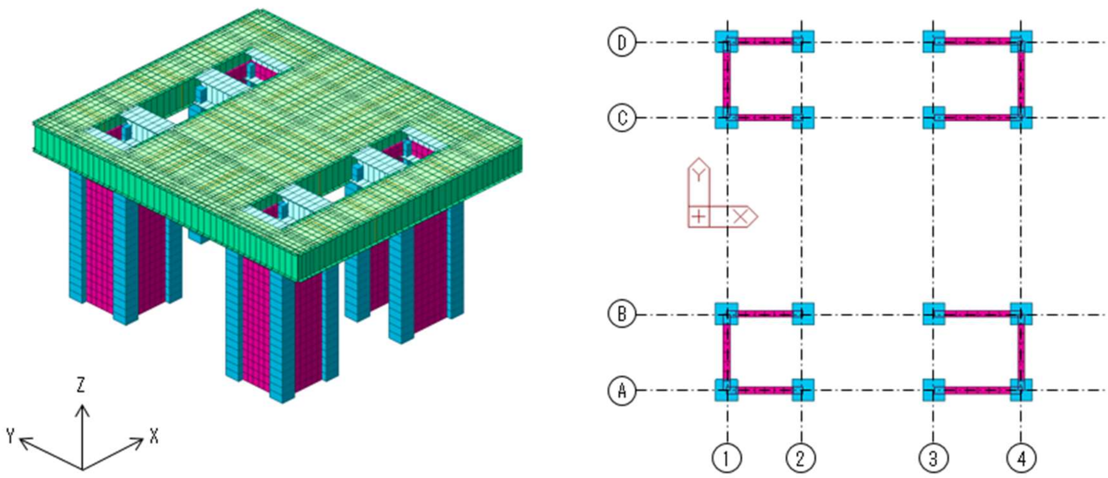


Figure 7 Half 3D-FEM model of the system in Fig. 6 (c).

As a result of analysis, by changing the number of turbines from 1 to two or four in a steel building, we found that in both cases, improvements such as the turbine floor and turbine support struts were required, but it was possible to increase the resonance point to a high frequency and short period. The resonance phenomenon with turbine shaft vibration could be avoided. Vibrations in the turbine shaft and floor must be analysed using an integrated computer model as shown in Figure 8, that has been verified in advance through seismic tests, etc. By utilizing this method, it is possible to avoid cost-increasing factors such as design costs and rework after construction.

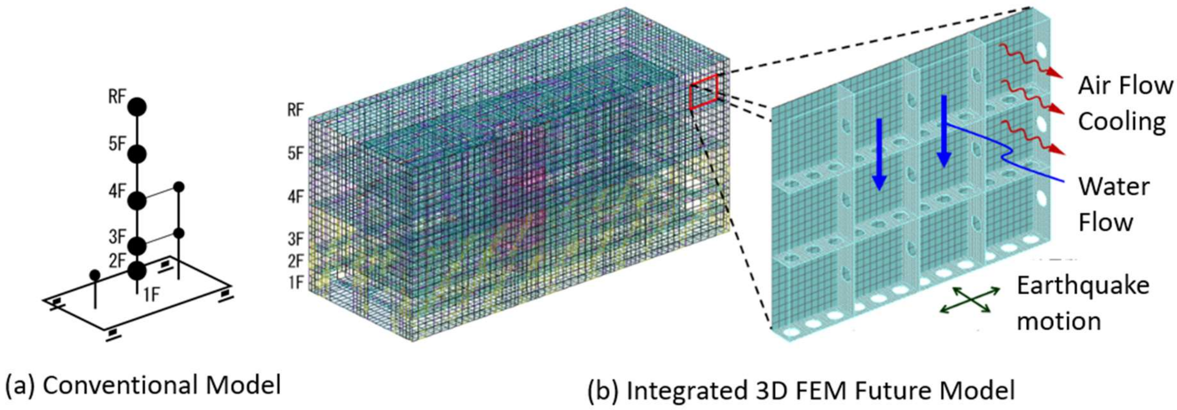


Figure 8 Integrated 3D-FEM future model.

SAFETY SYSTEM AND STEEL PCV CONCEPT

The employment of a passive safety system for emergency coolant injection and containment cooling. The emergency coolant injection system consisted of the depressurization valve (DPV) and the gravity-driven core cooling system (GDCS) was able to achieve the high reliable flooding the reactor core following an accident since the reactor core was placed at the bottom of the RPV by adopting the internal upper-entry CRD. In addition, even in a severe accident, the molten core was cooled and maintained in the RPV (IVR: In Vessel Retention) by RPV bottom cooling by flooding the lower drywell with suppression pool water by gravitational force because the CRD housing tubes were removed from the RPV bottom.

The primary containment vessel (PCV) has double steel inner and outer walls with a ship hull structure, as shown in Figure 9. The gap between the inner and outer walls was filled with cooling water, which was boiled to the atmosphere to passively cool the PCV during an accident. The concept of a double-wall containment vessel cooling system is also used for drywell cooling during normal operation. Therefore, the drywell arrangement is simplified without the drywell cooling component used in the current BWR containment. Building arrangement, ship hull structure building, and system simplification. It is expected that this will result in effective cost reduction despite the economic demerits of scaling down.

The specific volume, volume per electric power output (m^3/kWe), specific weight, and weight per electric power output (ton/kWe) of the LSBWR building are compared with those of the ABWR building in Figure 9. Those of the LSBWR were reduced to approximately 3/4 and 1/2 those of the ABWR, respectively. These results demonstrate the effects of innovative concepts such as one-piece.

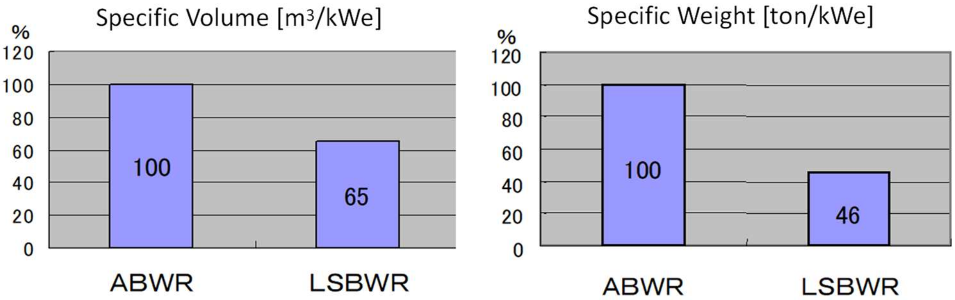
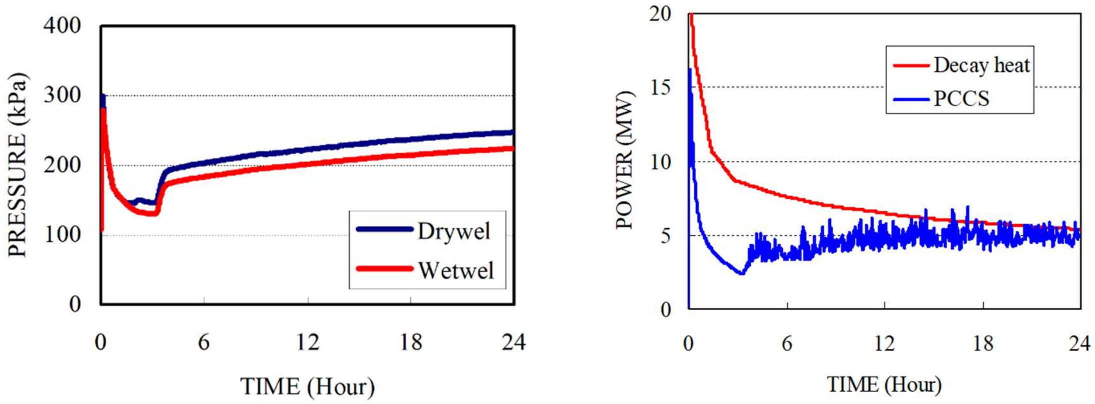


Figure 9 Comparisons of specific volume and weight of building of LSBWR and ABWR.

(a) GDCS cooling during Feed water line LOCA

The performance of the safety system was analysed for a feedwater-line break accident. The analysis was performed using the TRAC code incorporated with heat transfer models for natural convection cooling and steam condensation cooling with a non-condensable gas. Heat-transfer models were developed to estimate the heat-transfer coefficients in the containment space and containment wall coolant channels. The analysis results for the containment pressure and heat removal transients are shown in Figure 10. After reaching its peak value during the blowdown phase, the containment pressure continued to decrease, while the GDCS coolant flow was sufficient to suppress the steam production in the reactor core. The containment pressure begins to increase at approximately 3 h because the GDCS flow decreases, and steam is produced by the decay heat. However, the pressure increase was suppressed by containment wall cooling and was maintained well below the design pressure for 24 h. The heat removal rate of the containment wall cooling was comparable to the decay heat after 24 h. The condensate produced by cooling the containment wall flowed from the drywell to the RPV through the GDCS injection line, and the reactor core remained covered with cooling water, as shown 10.

These unique building concepts have resulted in remarkable building cost reductions through building volume reductions and standardized shop fabrication.



(a) PCV pressure response **(b) PCCS cooling performance**

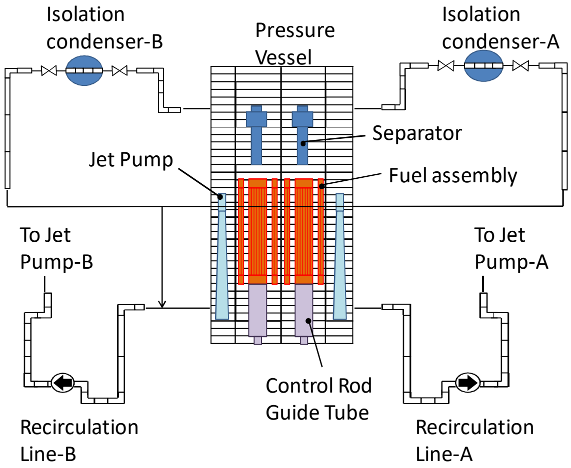
Figure 10 TRAC code analysis result of feedwater line break accident.

(b) IC performance analysis during Fukushima Daiichi

We are considering strengthening the isolation condenser as a countermeasure against abnormal transient events in the GX BWR. As a verification of the cooling function of the Isolation Condenser (IC), The model was created including two units of IC of the Fukushima Daiichi Unit 1 NPP for the TRAC code, as shown in Fig. 11, Shimoe, (2014) maid this model supported training at JAEA.

First, the IC cooling rate was 150°C/h, about three times the 55°C/h stipulated in the safety regulations, and the reactor pressure dropped from 7 MPa to 4 MPa in 15 minutes. One of the ICs tripped, and the remaining one operated on/off to keep the temperature at 55°C/h, and at the timing of the off, the tsunami came 48 minutes after the scram due to the earthquake, and the IC valve operation was interrupted. Another analysis result shows effective core cooling when restarting the IC after 5000 seconds.

According to this analysis result, if the IC restarts in 5,000 seconds, the reactor pressure will the RPV pressure drop to 1 MPa or less after about 3.2 hours, and will be sufficiently cooled by water injection from a low-pressure water injection pump or fire engine. As shown in Fig. 12(c), it was confirmed that the peak cladding temperature (PCT) is maintained at 500K or less, and a severe accident will not occur. In this way, if the fuel cooling water level is secured immediately after the accident, a severe accident will not occur. Decay heat removal by IC was effective and important to avoid severe accidents.



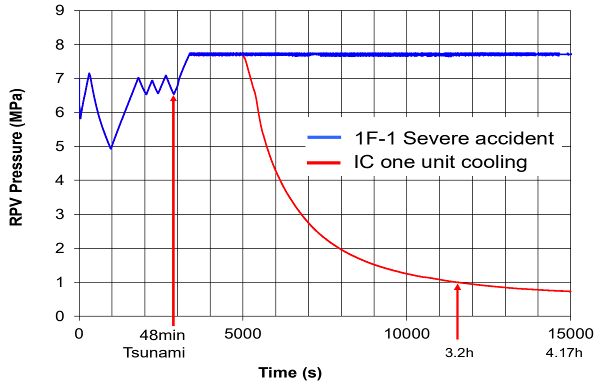
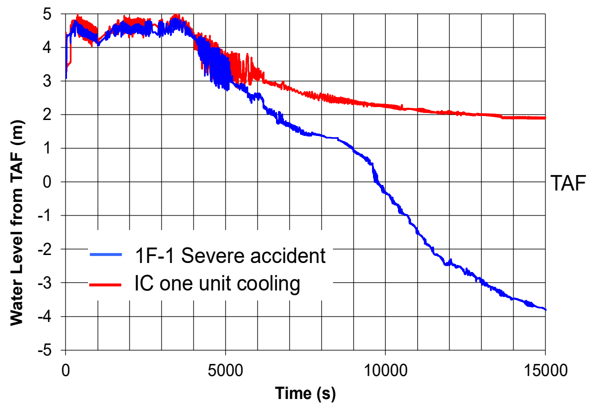
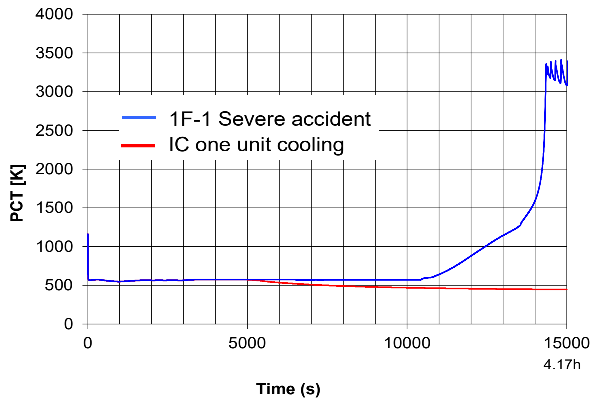


Fig. 11 TRAC code analysis model for 1F-1. Fig.12 (a) RPV pressure transient after the earthquake.



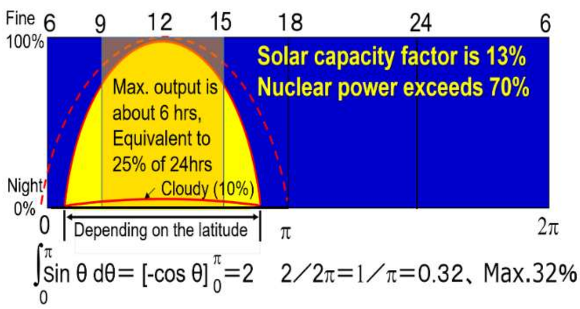


(b) Water level from TAF **(c) PCT transient after the earthquake**

Figure 12 TRAC code analysis result with without IC operation.

SYMBIOTIC WITH RENEWABLE ENERGY BY LOAD FOLLOW FUNCTION

Figure 13 shows the theoretical capacity factor for PV power generation. The integral of the output of photovoltaic power generation on a sunny day by approximating the sine curve is 0.32. Owing to the warm climate of Japan, the probability of sunny weather is approximately 0.5. When the probability of sunny weather was multiplied by 50%, it was 16%. When the electric circuit loss was subtracted, the maximum capacity factor was 13% in Japan. The double capacity factor is obtained in the UAE. The equivalent full power in Japan is 6 hours a day (25 %). The remainder should be supplemented with hydropower, thermal power, or nuclear power. Figure 14 shows the PV power in March 2022. The electricity demand in Tokyo in March was approximately 45 GW; however, the registered value of the installed solar power capacity was approximately 18 GW, accounting for 39%.



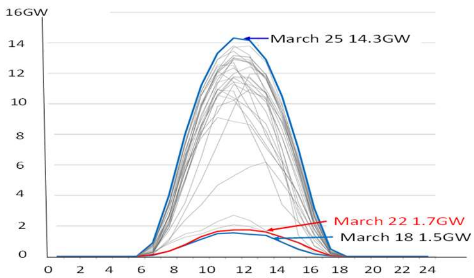


Figure 13 Theoretical capacity factor of PV power.

Figure 14 PV power in March, generation in Japan. 2022 (METI).

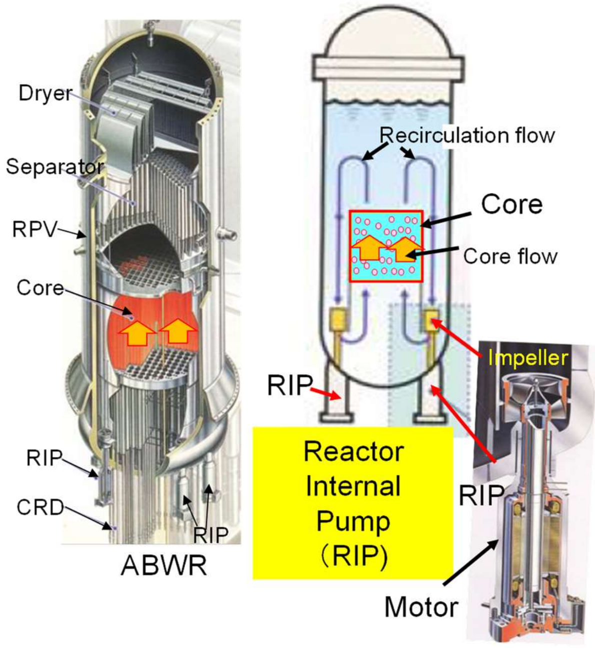


Figure 16 Recirculation of core flow of ABWR.

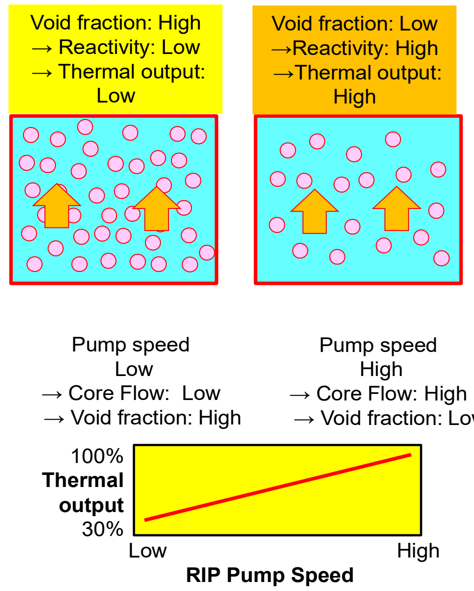


Figure 17 Output control in core void fraction is controlled by pump speed.

The peak output was 14.3 GW on March 25, but dropped to 1.7 GW on March 22, and 47 GW of electricity was required due to the cold cloudy day, which was accommodated by other parts of the country. The Ministry of Economy, Trade, and Industry (METI) issued a power supply and demand tight warning the night before, and the Minister of METI requested power savings on that day.

Figure 16 shows the recirculation of the core flow control of the ABWR by rotation speed. The thermal output is controlled by the void fraction in the core, which changes easily with the rotational speed of the RIP pump, as shown in Figure 17. This is a major merit of the ABWR, and because the core operates at the saturation temperature of the two-phase flow, thermal fatigue does not occur.

By setting the fuel length to 4m, an electric output of 800 MWe can be obtained, and the output can be freely selected from the 300 MWe of natural circulation. To be economically competitive, the GX BWR design should include system and structural simplifications, modularity for short construction times, and increased availability.

CONCLUSIONS

The author introduces a new SMR, named GXBWR, which uses a reactor internal recirculation pump (RIP) for the purpose to load follow with fluctuating renewable energy and enhance facilitates for stable grid control. By using RIP, GXBWR will be uprate operation up to 800MWe, and ordinally it will able to long operation, such as 36 or 48 months, depends on the load following operation. The core size is almost the same as 800MWe BWR. The concept proposed here is to provide flexibility for different site conditions and power demands, reduce investment risk and promote public acceptance.

Ship hull structure building technology employs advanced automation and remarkably improved assembly lines, because of competing in the severe international market.

Ship hull structure building technology employs advanced automation and remarkably improved assembly lines as a result of competing in the severe international market. The hull structure of a large ship is simply constructed with steel plates. The basic structure of the hull consists of steel plates, girders (large beams) and stiffeners (small beams) as shown in Figure Almost the entire process, including the receipt of materials~~,~~ forming large blocks, the welding process and the removal of distortion after welding, is performed automatically on an assembly line. The large blocks are transferred to a shipbuilding dock where they are assembled to shape a hull. When most of the construction work is completed, the hull is launched and adjusted

For places where radiation shielding is required, concrete is poured into the double steel plate lattice structure as one of the various methods. Since supporting brackets for piping and foundations for machines can be welded to walls or floors directly, the installation work will be simple compared with that in reactor conventional buildings. In this paper, we show the load follow function by using reactor internal pimp (RTP) in order to symbiotic with renewable energy. The reactor's electrical output can be varied up to 800 MWe by using forced circulation in the reactor core. If you use the latest BWR fuel, it will be possible to increase the rate by 30%, so the output will be 1000MWe, making it the most cost-effective. However, if you carefully examine the characteristics of a steam turbine, it is found that when the output drops below 50%, the turbine efficiency drops significantly. Therefore, in this paper, we also considered increasing the number of turbines to two or four in a steel building.

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