R&D Project of Small-to-Medium Reactor for Multipurpose Use of Energy

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Abstract

Hitachi-GE Nuclear Energy, Ltd. (Hitachi-GE), GE Hitachi Nuclear Energy Americas LLC (GEH), and Global Nuclear Fuel - Americas, LLC (GNF-A) have signed a memorandum of understanding (MOU) with the government of Saskatchewan to discuss the potential of working together on future nuclear R&D projects, including the feasibility of small modular reactor technologies. As the base plant, Hitachi-GE plans to adopt the DMS (Double MS: Modular Simplified & Medium Small Reactor), which has been developed under the sponsorship of The Japan Atomic Power Company. In this paper, we describe the desirable features of the DMS and present a tentative R&D project plan.

1. Introduction

The importance of nuclear power as an energy source must increase because of the needs for energy security and lowered greenhouse-gas emissions. Development of nuclear power plants has been mainly aimed at large-capacity power generation to increase cost efficiency (construction cost per unit power output). On the other hand, demand for medium or small sized distributed power sources is expected to increase [1], because they have merits that their initial investments for plant construction are limited and they can be used even if electricity transmission networks have not been fully constructed. However, medium or small sized nuclear power reactors have not been commercialized yet because of their scale demerit. Therefore, the most important point to their development is overcoming scale demerit.

In Canada, 18 CANDU (Canada deuterium uranium) reactors are currently in operation, delivering about 15% of the country's overall generating capacity. Canada is one of the world's largest producers of uranium, which serves as a nuclear fuel, and all of Canada's uranium is produced in Saskatchewan. Thus, the Saskatchewan government, Hitachi-GE, GEH, and GNF-A plan to collaborate on potential nuclear R&D projects of mutual interest including the feasibility of small modular reactor technology in the Saskatchewan context.

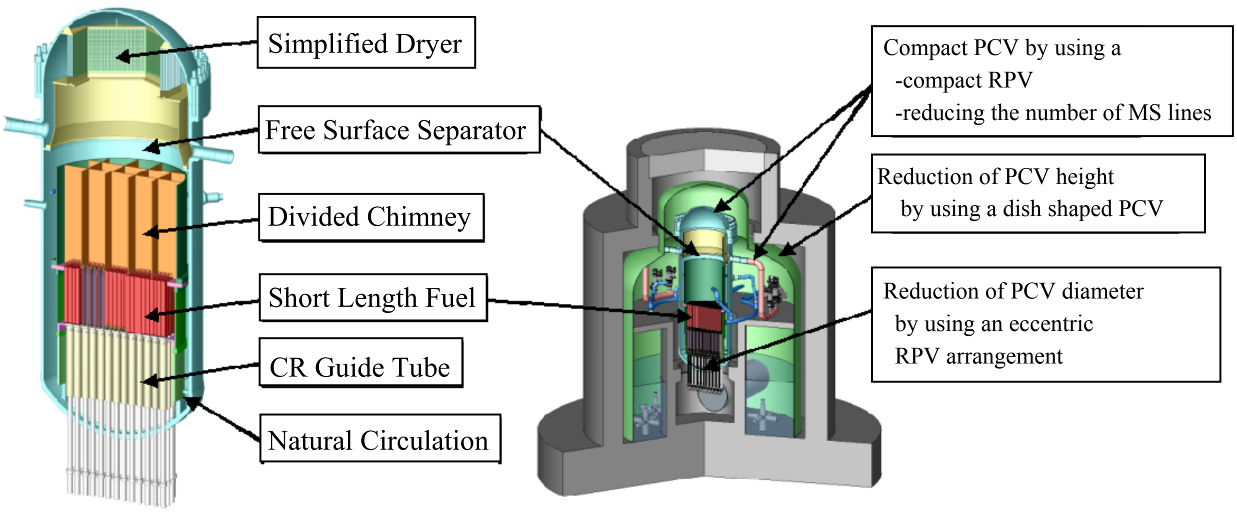
As the base plant, Hitachi-GE plans to adopt the DMS (Double MS: Modular Simplified & Medium Small Reactor) developed under the sponsorship of The Japan Atomic Energy Company [2]-[6]. The DMS is an innovative 300-400MWe class BWR which has been estimated to almost overcome the scale demerit using only proven technologies of the conventional BWR plant. To achieve this, three goals are adopted: (1) simplification of the plant system, (2) elimination of equipment, and (3) standardization of the plant layout and modular construction method. The latest DMS is classified as small-to-medium sized reactor according to the definition of IAEA [7].

In order to make the DMS even more attractive, Hitachi-GE plans to study 2 additional items: (1) development of the core that does not use the control rods during normal operation, which means it is easy to operate the reactor because no control rod pattern change is needed; and (2) strengthening of the safety characteristics in consideration of the severe accident of the Fukushima Daiichi Nuclear Power Plant, especially against a long-term station blackout (SBO) event. Though the R&D plan with the Saskatchewan government is still under discussion, Hitachi-GE tentatively plans to study development of the balance of plant (BOP) system for multipurpose uses of energy (electricity, district heat source, etc.) which is especially suitable for meeting the needs of Saskatchewan.

In this paper, we introduce the desirable features of the DMS and show a tentative R&D plan.

2. Advantageous Features of the DMS

The DMS [2]-[6] has been developed with 4 targets in mind: (1) plant output of 400MWe class; (2) construction cost competitive with that of the conventional ABWR; (3) safety level equivalent to that of the conventional ABWR; and (4) minimum R&D by utilizing the proven technologies. **Figure 1** shows the DMS plant cutaway view and **Figure 2** shows the DMS system configuration. Extensive simplification, elimination, and standardization have been applied to this plant. Details are described below.



(a) RPV cutaway (b) PCV cutaway

Figure 1 The DMS plant cutaway view

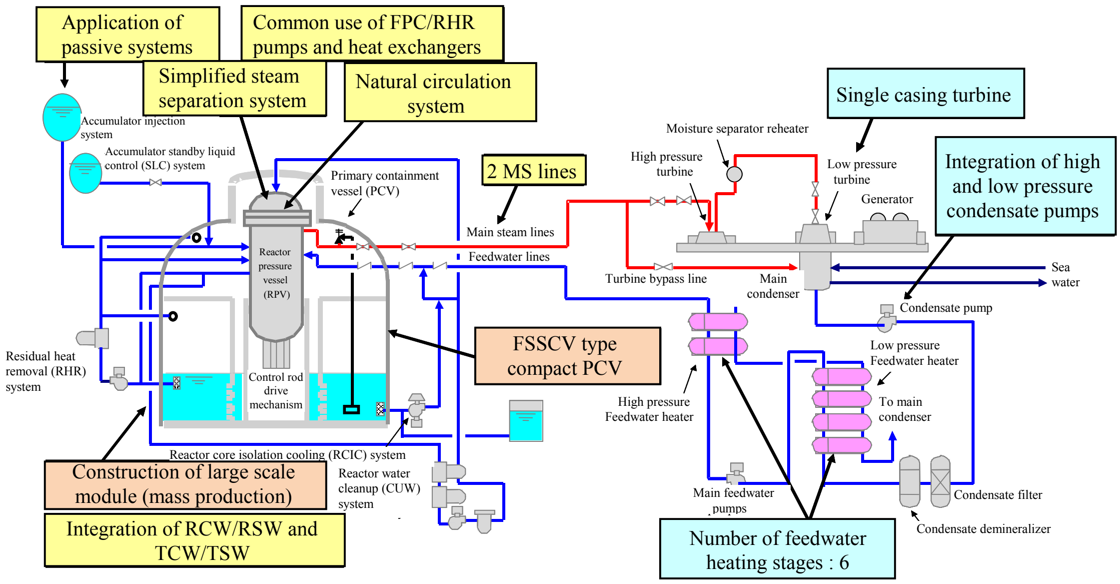


Figure 2 The DMS plant system configuration

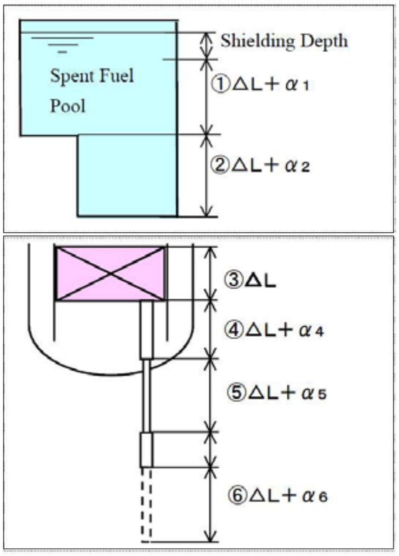
2.1 Reactor Pressure Vessel (RPV)

To simplify the equipment in the RPV, the "Natural Circulation" core cooling system has been applied to eliminate the large sized RIPs (reactor internal pumps) and their accompanying drive power systems which are applied with the conventional ABWR. In addition, a "Short Length Fuel" with an AFL (active fuel length) of 2.0m has been also adopted, instead of about 3.7m for the conventional ABWR. Merits of the short length fuel include reduction of the RPV height by decreasing the core height, and decreasing the "Divided Chimney" height; the chimney is equipment to enhance natural circulation driving force because of the low pressure drop in the shortened length core. Table 1 shows the plant specification of the DMS and the ABWR. Since rated power of the DMS per core volume was smaller than that of the ABWR, the core power density of the DMS was set to 44MW/m^3, which was less than that of the conventional ABWR of 50.6MW/m^3, to reduce superficial steam velocity. This was based on the expectation that steam and liquid water can be separated by gravitational force without using the steam separators which are necessary equipment for the conventional ABWR to separate steam from water. According to an experimental study [8, 9] and a semi-theoretical study [10], steam separation by gravitational force is possible when the superficial steam velocity is 0.7m/s or less. We call this system using gravitation force the "FSS (free surface separation) system". In addition, the DMS has the "Simplified Dryer" integrated into the RPV head to reduce humidity below 0.1% at the inlet of the main steam lines.

By adoption of the FSS, many advantages can be introduced to the DMS such as increased natural circulation flow rate due to elimination of the steam separators, simplification of the core internal components, compaction of the RPV, and shortened annual inspection period. In addition, elimination of the steam separators can reduce the RPV height (approx. 2.5m). As a result, major reactor internal components of the DMS are just the reactor core, core support equipment in the lower plenum, shroud, and divided chimney. Therefore, many pieces of the equipment in the RPV have been eliminated to overcome the scale demerit. In addition, as shown in **Figure 3**, the short length fuel (ΔL: fuel assembly length) yields a height reduction effect of 6 times ΔL for the reactor building (R/B) height, 4 times ΔL for the primary containment vessel (PCV) height, and 2 times ΔL for the RPV height. The short length fuel also realizes fewer floor numbers in the R/B and a shorter construction period as described in section 2.5.

Table 1 Plant specifications

	DMS	ABWR
Plant output (MWe / MWt)	428 / 1200	1356 / 3926
Number of fuel assembly	568	872
Active fuel length (m)	2.0	3.7
Power density (MW/m3)	44	50.6



Items		RPV	PCV	R/B
(1) Spent Fuel Pool	①Fuel Handling Space	–	–	ΔL
	②Spent Fuel Rack	–	–	ΔL
(2) RPV	③Active Fuel Length	ΔL	ΔL	ΔL
	④CR Guide Tube	ΔL	ΔL	ΔL
(3) Lower Drywell	⑤CR Housing	–	ΔL	ΔL
	⑥CR Replacement Space	–	ΔL	ΔL
Total		2ΔL	4ΔL	6ΔL

Figure 3 Effects of the short length fuel adoption to the DMS

We have evaluated feasibility of natural circulation performance, core stability, and thermal margin of the DMS core. Regarding the natural circulation system, we considered all pressure drops along the natural circulation loop. The core pressure drop and the void fraction in the divided chimney were evaluated by the current design method for the BWR core. As a result, we confirmed that the natural circulation system of the DMS could provide sufficient core flow rate. Based on the evaluated core flow rate, we evaluated stability characteristics by using a conventional analysis code named HIBLE [11]. In order to evaluate the core stability, feedback between the thermal hydraulics and core nuclear kinetics, the reactivity feedback by the void coefficient, time constant and flow gain of the natural circulation loop are important factors. We checked sensitivities of these parameters for the core stability and we confirmed that the core design of the DMS was feasible with respect to the core stability. By using the short length fuel, the channel stability of the DMS core had a sufficient design margin. Evaluation of the core thermal margins, such as MCPR (minimum critical power ratio) and MLHGR (maximum linear heat generation ratio), is important for the core design. Since the DMS core was designed for the latest 10×10 fuel assembly, the core power density was lower than that of the conventional BWR. Thus the DMS core has sufficient thermal margins.

2.2 Primary Containment Vessel (PCV)

The PCV and the R/B of the DMS are designed to be compact from an economical viewpoint. As shown in **Figure 2**, the compact PCV (17mϕ×24.4mH) can be achieved by the "Compact RPV" described in section 2.1, the "Dish Shaped PCV" and the "Eccentric RPV Arrangement". As shown in **Figure 4**, by adopting the dish shaped PCV instead of the spherical shaped PCV, the PCV height can be decreased by about 1m. **Figure 5** illustrates the PCV horizontal section with some equipment. The direction forward to the turbine building that is, toward the top of **Figure 5**, is very crowded because there are 4 large sized pipes (2 main steam lines and 2 feedwater lines). On the other hand, the opposite direction in which the PCV air cooler and other items are installed is not so crowded. Therefore, by shifting the RPV location from the center to the direction where the PCV air cooler is located, the PCV diameter can be reduced by about 2m.

The pressure suppression type PCV for which we have many operation experiences with current BWR plants is adopted for the DMS. Because the DMS has an accumulator to inject water into the RPV from outside the PCV when an accident occurs as part of the ECCS (emergency core cooling system) described in section 2.4, water inventory of the suppression pool can be reduced, which contributes to reduction of the PCV volume. **Figure 6** shows pressure change in the PCV in the case of a feedwater line break accident as the most severe PCV pressure increase event. Analytical results showed that there was an adequate margin to the maximum design pressure of the PCV.

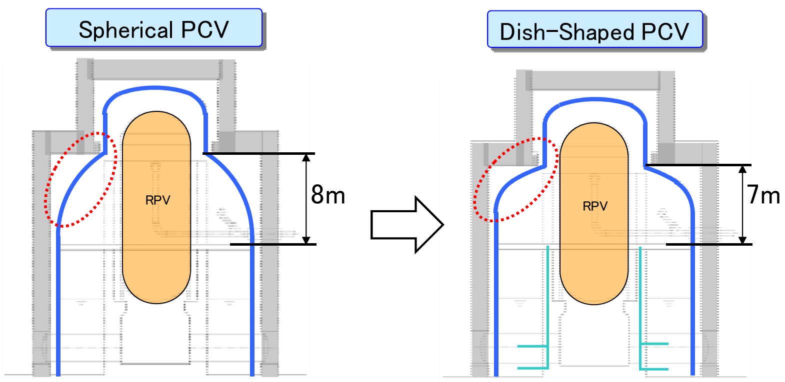


Figure 4 Adoption of the "Dish Shaped PCV"

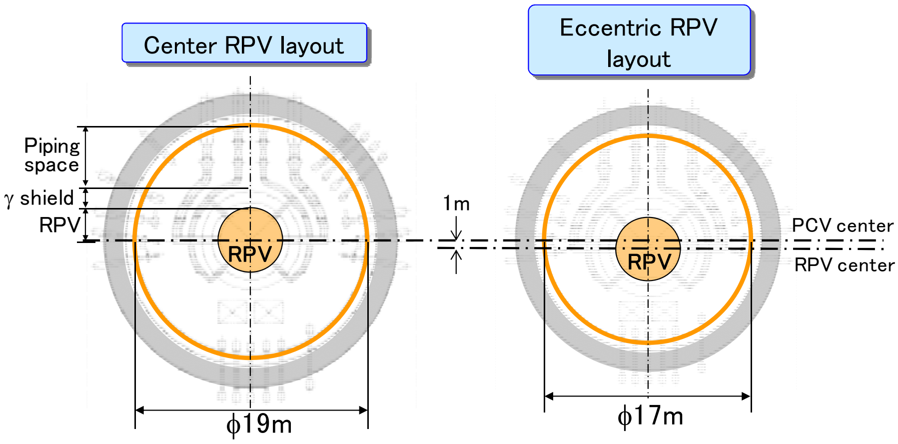


Figure 5 Adoption of the “Eccentric RPV layout”

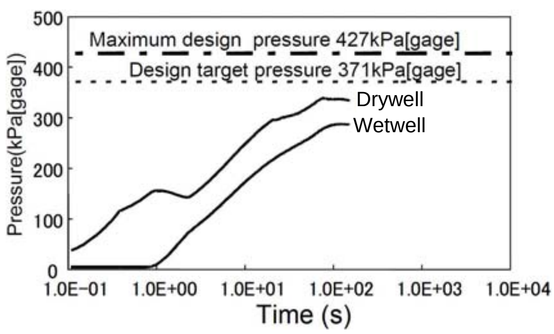


Figure 6 PCV pressure change in the event of a feedwater line break accident

2.3 Plant System (NSSS and BOP)

The system configuration of the NSSS (nuclear steam supply system) and the BOP are shown in **Figure 2**. The DMS systems are rationalized by reduction of several systems, by integration of several systems with the application of large capacity equipment, and by using passive systems and non-specific devices. For example, the DMS adopts the “2 MS (main steam) lines” and the “single casing turbine” by adoption of the large capacity turbine. The RCW (reactor building cooling water system) and the TCW (turbine building cooling water system) are not only integrated into a single system, but the FPC (fuel pool cooling and filtering system) and the SPCU (suppression pool clean up system) are also integrated. Instead of expensive high pressure pumps, the accumulator described in section 2.4 is adopted as the passive ECCS with a view to cost reduction. Looking at the BOP specifications for the 400MWe class reactor, we adopt a TCDF (tandem compound dual flow)-52 reheat cycle turbine system and 6 feedwater heaters with a single train. In addition, the low pressure condensation pump and the high pressure condensation pump are integrated into a single common pump.

2.4 Simplified and Enhanced Safety System

The ECCS of the DMS has been simplified without sacrificing safety performance of the conventional ABWR by adopting a hybrid system of active and passive components. Adopting the active and passive hybrid system leads to improved reliability of the safety system and a reduced number of safety equipment maintenance tasks. **Figure 7** shows the ECCS configuration chart of the DMS compared with the conventional ABWR. In the ABWR, there are 2 HPCF (high pressure core flooder) systems, 1 RCIC (reactor core isolation cooling system), 3 LPFL (low pressure flooder) systems, and 3 DGs (diesel generators) as an emergency power source for the HPCF and LPFL systems. Since the DMS has a bigger safety margin against LOCAs (loss of coolant accidents) because a natural circulation type BWR such as the DMS has a larger RPV water inventory than the conventional ABWR, we decided to eliminate the 2 HPCF systems which require a large amount of power. Instead of the HPCF systems, we add one passive system, called the AIS (accumulator injection system). The AIS can inject make-up water into the RPV for LOCAs when the RPV pressure is less than 0.5MPa. Even if the RPV pressure is kept high because of a small fracture area of the RPV (a small break LOCA), the AIS can be operated in conjunction with the ADS (automatic depressurization system). Since capacity of the emergency power supply was reduced by about 30% compared with the conventional ABWR by eliminating HPCF systems, we intended to use non-specific gas turbine type emergency generators instead of the conventional DGs to decrease the safety related cost. Next, we focused on the LPFL systems. Each of these systems has a heat exchanger function, called RHR (residual heat removal) to remove residual heat generated from the core and release it to the environment. For the conventional ABWR, we had selected 50%×3 systems because of the heat exchanger sizing problem. On the other hand, because of its small-to-medium-sized output, no such restriction is present for the DMS. Therefore, from the viewpoint of economy, 100%×2 systems were chosen for the LPFL systems of the DMS. To compensate for the low pressure water injection capacity, we planned to adopt a new RCIC system named the hybrid RCIC. Though the conventional RCIC which requires a high RPV steam pressure as the driving force of the RCIC steam turbine cannot be applied for large break LOCA conditions because the RPV pressure becomes low, the hybrid RCIC for the DMS can inject water into the RPV by switching its driving source from the RCIC steam turbine to an electric motor automatically when the RPV pressure becomes low. Consequently, as shown in **Figure 7**, the DMS has 1 AIS (accumulator injection system) as a passive system, 1 hybrid RCIC, 2 LPFL systems, and 3 gas turbine type emergency generators as an emergency power source for the LPFL systems.

We confirmed that the safety level of the DMS was the same as the conventional ABWR despite the safety system simplicity of the former. **Figure 8** shows water level changes in the RPV for the LPFL pipe large break LOCA as the most severe case. In this analysis, a single failure of another side of the LPFL system was postulated conservatively. As a result, we confirmed that the reactor core could be covered with coolant by initiation of the hybrid RCIC and the accumulator. Even after finishing water injection from the accumulator, the reactor core could be covered for a long period by LPFL water injection.

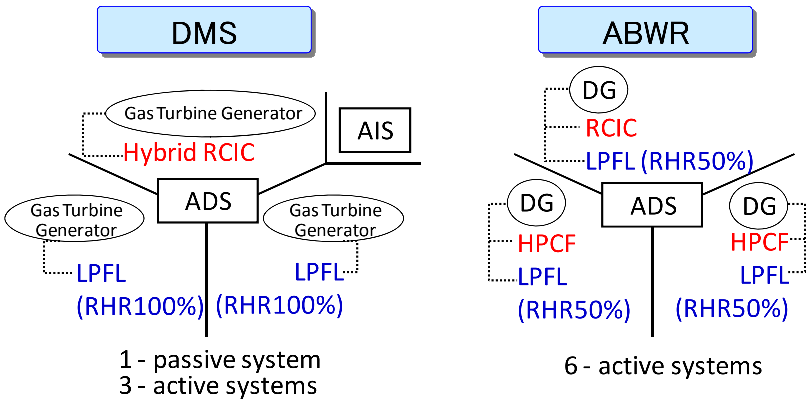


Figure 7 ECCS configuration charts of the DMS and conventional ABWR

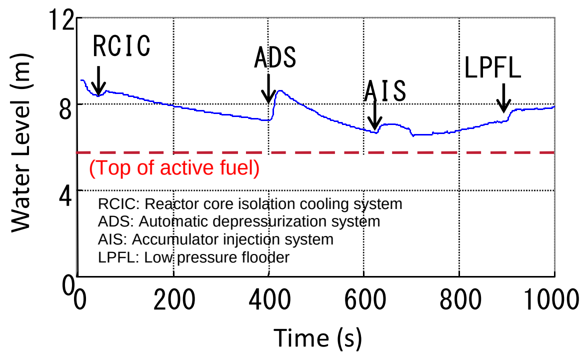
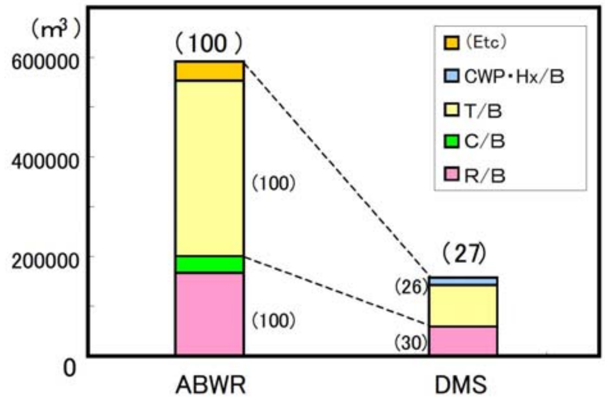


Figure 8 Safety analysis result of the DMS (LPFL LOCA)

2.5 Standardization of Plant Layout and Modular Construction Method

2.5.1 Standardization of plant layout

In order to reduce construction cost, standardization of the plant layout is important especially for medium or small sized reactors. Therefore, the R/B area of the DMS was divided into a fixed standard area and a variable flexible area. For example, a secondary containment area including the PCV is designed as a standard area. On the other hand, the circumferential area that includes electrical equipment and plant make up facilities, etc., is designed as a flexible area which can be changed according to each site's conditions. **Figure 9** compares building capacity between the DMS and the conventional ABWR. The ratio of building volume per unit output power of the DMS was almost equivalent to that of the conventional large sized ABWR.



CWP circulating water pump
Hx/B heat exchanger building
T/B turbine building
C/B control building
R/B reactor building

Figure 9 Comparison of building capacity

2.5.2 <u>Concept of construction method</u>

Recently, construction of nuclear power plant has aimed at reducing the fieldwork and construction period by widely applying a modularization strategy. Construction using large cranes has been applied to construct existing ABWRs, which has given experiences in handling modules with a maximum weight of approximately 700 tons. For the small sized reactor, additional concepts were added to the strategy that made it possible to assemble equipment, piping, etc. in the factory, to minimize the number of temporary structures used, and to reduce the quantity of field installation materials and construction period. These can be achieved by adoption of the BM (building/machine) integrated modular construction and by applying SC (steel plate reinforced concrete) structures especially for the cylindrical part of the PCV. **Figure 10** shows the concept of the modular construction when carrying in a module in which equipment, facility and building structures are integrated. In order to start working early for the PCV which is a critical point for the construction schedule, internals of the PCV have been integrated into large modules as much as possible in the factory. Application of the compact steel containment and the SC structure to the biological shielding wall which is constructed around the PCV makes it possible to apply the BM integrated modular construction that integrates steel containment (including penetration) and the SC steel plate of the biological shielding wall into one. This method not only rationalizes the PCV construction work but also reduces the construction period.

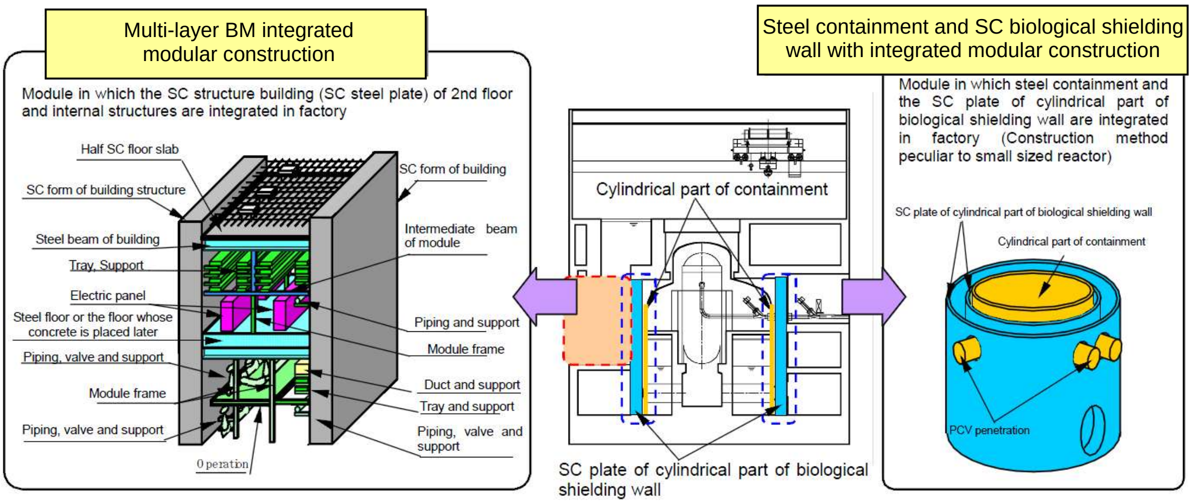


Figure 10 Concept of the modular construction

3. R&D Project Plans

The DMS has already finished a conceptual design. In order to make the DMS more attractive, Hitachi-GE plans to study 2 additional items as shown below.

(1) Development of the core which does not use control rods during normal operation

As same as the conventional BWR plant, the DMS has two independent shutdown capabilities, which are the CRD (control rod drive) system and the SLCS (standby liquid control system). In the conventional BWR plant, the core thermal power level during normal operation is controlled by inserting or withdrawing control rods. Since control rod pattern change results in a 3D power distribution change in the core, control rod pattern change is conducted so that the thermal margin in the core does not exceed the design limit. Therefore, the control rod pattern plan is evaluated before start-up of plant operation. In this study, we will attempt to study an innovative core concept which does not use control rods during normal operation by optimizing the concentration of the burnable poison (gadolinia) in the fuel pellet, without using a soluble poison. Early start-up procedure after an inadvertent reactor trip will be studied.

(2) Strengthening of the safety characteristics

At the Fukushima Daiichi Nuclear Power Plant, a long-term SBO was experienced by loss of on-site and back-up power supplies due to the huge tsunami which exceeded the design criteria. As a result of this long-term SBO, core meltdown occurred and volatile fission products such as Cs and I generated in the core have been released to the environment. We plan to study an advanced safety system suitable for the DMS which will be able to operate in the long-term SBO. No evacuation of residents around the plant even if the long-term SBO occurs is being set as our target tentatively.

Although the R&D plan with the Saskatchewan government is under discussion, Hitachi-GE tentatively plans to study development of a new BOP system. In order to improve the DMS more conveniently, we will propose a new BOP system suitable for thermal utilizations. Types of thermal utilization such as district heating may be considered. The BOP of the DMS has been designed to accommodate grid disturbance encountered for use in Japan, however, not for use outside Japan. The BOP system which is suitable for grid disturbance that are experienced in Saskatchewan might also be studied.

4. Conclusion

Hitachi-GE Nuclear Energy, Ltd. (Hitachi-GE), GE Hitachi Nuclear Energy Americas LLC (GEH), and Global Nuclear Fuel - Americas, LLC (GNF-A) have signed a memorandum of understanding (MOU) with the government of Saskatchewan to discuss the potential of working together on future nuclear R&D projects including the feasibility of small modular reactor technologies, in the context of meeting the needs of Saskatchewan residents and industries.

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