Development of a small modular boiling water reactor combined with external superheaters

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Abstract

The balance between sustainability, energy security and affordability are important trade-offs to consider in decarbonizing the current energy system. The two practical alternatives for moving forward seem to be either reducing the energy storage costs to enable deployment the intermittent renewables on a large scale or developing an affordable and more flexible nuclear power. A small modular boiling water reactor combined with external superheaters offers a significant improvement to the conventional nuclear system. The potential benefits include improvement in cycle thermal efficiency, reduction in the size of the vessel, and the capability to adjust load while maintaining the reactor operation at 100% of its full power.

In this paper, the conceptual design of a Small Modular Boiling Water Reactor (SMBWR) combined with external superheaters is presented along with investigation into some of its core design performance characteristics. It is found that the 4-batch in-core fuel management scheme offers a more favorable performance compared to the 3-batch scheme as it has lower power peaking, less excess reactivity, and more negative coolant void coefficient (CVC). The combination of a multi-batch fuel arrangement, coolant temperature variation, and control rods are required to control the reactivity swing in the SMBWR while keeping the power peaking below the safety limit throughout the depletion cycle.

Keywords: Small Modular Boiling Water Reactor, Multi-batch Fuel Arrangement, Coolant Temperature Variation.

1. Introduction

With the increasing concern over the Climate Change, it is likely that the future electricity grid will be relying on low-carbon generators such as nuclear, wind and solar technology. In order to meet the daily and seasonal variation of electricity demand, it is important for the low-carbon system to integrate with energy storage for the intermittent renewables or find solutions for making load-following operation of Nuclear Power Plants (NPP) more economic. De Sisternes et al. **[1]** investigated the integration of low-carbon technology systems into the energy mix with respect to emissions limits and average generation costs and shows that the role of nuclear energy becomes more important as the emissions limit tightens. De Sisternes et al. **[1]** also found that installation of energy storage helps reduce average electricity generation costs by increasing the utilization of wind and solar. However, under a carbon emissions limit of 100 tCO_2/GWh, average system costs (including storage costs) increase in most cases. This suggests that there is a trade-off between the system costs and the flexibility of the system to meet daily and seasonal variation of demand. On one hand, by having more nuclear on the grid, the stability of electricity supply is improved. Nuclear is a base-load provider of electricity, but its electricity cost is

[a]The thermal power written for the SMBWR is the reactor thermal power. It should be noted that in order to produce the amount of electric power shown in the table, the SMBWR requires approximately 529 MW of additional thermal power for the superheating system.

sensitive to the load factor as nuclear is highly capital intensive and tends to have low operating costs. On the other hand, having more renewables, such as wind and solar, would reduce the average generation cost of the electricity. However, the intermittency of wind and solar would be a problem for the stability of the grid and, thus, storage systems are required, which would increase the average system costs. Thus, the options to minimize the system cost lie in how to reduce storage costs to utilize more renewables, or reduce costs for building NPPs and develop more flexible power generation for the NPPs to meet daily and seasonal demand variation, or some combination of the two.

One option to minimize the average system costs of electricity generation is by combining NPP steam cycle with external superheaters. The incentives for that are the improvement in the power cycle thermal efficiency and the possibility to follow the load to some extent by varying the heat provided to the superheater, while maintaining the nuclear reactor operating at 100% of its full rated power and thus maximizing its economic value. According to previous studies **[2, 3, 4]**, combining LWR with a gas fired superheater will provide additional electric power output (up to 80% of its full rated power), improve the plant thermal efficiency by 2 - 5%, and its operational load variation capability can be between 100% and 65% by only adjusting the heat supplied to the external superheaters. In a Boiling Water Reactor (BWR), adding external superheaters can provide additional benefits, namely, the possibility of eliminating the steam dryer, which is located above the core increasing the BWR vessel height. A steam dryer is required for a BWR to ensure high steam quality before entering the steam turbine. Since the hybrid system operates with superheated steam, the steam dryer could be removed and, thus, the vessel size could be reduced. Furthermore, by removing the steam dryer, the total recirculation loop pressure drop within the BWR vessel will also be reduced, resulting in higher steam pressure at the turbine entry, and thus, possibility of increasing the power conversion cycle efficiency. It is important to note that by having an external superheater powered by a conventional fossil fuel such as natural gas, the NPPs will not be totally carbon emission-free even though the emissions would not be as high as stand-alone gas turbines or combined cycle gas turbines (CCGT). There is also an option to rely on cleaner heat for the superheater heat source. For example, Concentrated Solar Power (CSP) technology is able to store thermal energy by using molten salt. Thus, there is a possibility that one could use the heat stored in the solar heated salt to power the superheater, which would reduce the CO_2 emissions of this hybrid energy system practically to zero.

Another problem faced by the nuclear industry is the financing of large new-build NPPs. Large initial capital investment is arguably one of the main reasons for relatively slow nuclear new-build in the recent years. A small reactor could be more attractive, especially for emerging economies, as the total financial commitment to build small reactors would be lower than large reactors. The fact that the size is smaller would also reduce the duration of the NPP construction, thus, reducing the financial risk of the project as well, making it more attractive for the potential investors. In addition, as mentioned in the previous section, SMRs are claimed to offer several possibilities to counter the economies of scale through their standardization, modularization and mass production in factories.

The development of a Small Modular Boiling Water Reactor (SMBWR) offers a possible solution by utilizing the superheating concept in the SMR. One of the design features for SMBWR that was adopted is to rely on natural circulation of coolant within the reactor vessel during normal operation to simplify and reduce the system cost. This will also allow passive decay heat removal under accident conditions, although safety analyses were outside the scope of this study. By adopting natural circulation, the recirculation pumps could be eliminated from the vessel, thus enabling the removal of some of the RPV penetrations below the core.

It is easier to develop natural circulation in BWR compared to PWR, because of the greater coolant density change (two-phase flow driving head). A smaller reactor would also mean a shorter core, and, thus, lower core pressure losses, resulting in a smaller chimney height required to provide the driving head to counter the pressure losses inside the loop. By having the external steam superheaters attached to the SMBWR, the power conversion cycle efficiency of SMBWR would be improved, which means more electric power could be generated, thus improving the economics of the reactor. Furthermore, it offers the possibility for the SMBWR to reduce its load only by adjusting the external heat supplied to the superheaters, while operating the reactor at full power all the time and improving its economics. For the reasons mentioned earlier, by adding superheaters, the SMBWR would no longer need steam dryers, further reducing the vessel height. The smaller vessel dimensions offer the possibility to increase the operating pressure of the SMBWR, which would further increase its thermodynamic performance.

A number of preliminary studies on SMBWR design choices have been published previously. These studies include the investigation on the effect of operating pressure of the SMBWR **[5]** and a core configuration study **[6]**. The objective of the former study was to investigate whether there was sufficient incentive for the SMBWR to operate at higher pressure. Whereas, the core configuration study was done in order to investigate the effect of core length to diameter ratio on the core performance. In the operating pressure study, it was found that increasing the operating pressure from 6.5 MPa to 10 MPa would not have a significant neutronic effect. In terms of thermal-hydraulics, with the fixed core thermal power, core mass flow rate, and inlet subcooling enthalpy, the higher operating pressure and temperature would result in a higher steam flow rate to the turbine, smaller recirculation rate, smaller core pressure drop, and a slightly taller chimney will be required to develop natural circulation **[5]**. By comparing the neutronics, thermal-hydraulics, and thermodynamics of power conversion, it is shown that there is a modest but non-negligible improvement in favor of high-pressure operation. However, further studies are required, such as the implications to safety margin degradation, stability and economic performance, to confirm whether the benefits of high-pressure operation could outweigh the drawbacks that arise from having a thicker pressure vessel. Therefore, the current phase of the SMBWR development is focused on the standard BWR operating pressure, which is approximately 7.17 MPa.

In the core configuration study, the main goal was to identify the effect of core dimensions (active fuel length and number fuel assemblies) on the performance of SMBWR. As the core dimensions for SMRs are smaller, the system becomes more sensitive to leakage. Therefore, the trade-offs between neutron leakage (neutronics), chimney height requirements for natural circulation (thermal-hydraulics), and the dimensions of the core and vessel which would affect the manufacturing and transportation complexity are interesting subjects to investigate. Three core configurations, with variation of length to diameter ratio, were investigated by keeping a constant thermal power, core power density, coolant mass flow rate and inlet conditions. Table 1 summarizes the design parameters of the three compared cases **[6]**. After considering the neutron economy, core performance, CPR limit, and transportation challenges, it was concluded that SMBWR development should focus on the core with 256 FAs and fuel length of 2.70 m.

This paper presents additional investigations related to the SMBWR which have not been covered in the previous publications and can be divided into two main parts. The first part of the paper focuses on the strategies that can be implemented by the SMBWR to reduce initial excess reactivity and maintain core criticality throughout the fuel depletion. While the second part of this paper highlights some additional benefits of having a SMBWR combined with external superheaters.

Table 1. Design Parameters and Core Performance of the Studied Geometries [6]

Parameter	Geometrical Variation		
	1	2	3
No. of fuel assemblies	192	256	368
Power density (kW/L)	48.2	48.2	48.2
Active fuel length (m)	3.60	2.70	1.88
Shroud inlet diameter (m)	2.60	2.90	3.52
Core length to diameter ratio	1.47	1.01	0.60
Estimated vessel diameter (m)	3.71	3.94	4.44
Operating pressure (MPa)	7.17	7.17	7.17
Feedwater inlet temperature (°C)	192	192	192
Core inlet temperature (°C)	273	273	273
Core average void	0.32	0.36	0.40
Core mass flow rate (kg/s)	2414.3	2414.3	2414.3
Core pressure drop (kPa)	63.58	50.70	42.33
Minimum required height of chimney (m)	4. 84	3.58	3.09
Estimated vessel height (m)	18.5	16.3	15.2
MCPR	1.47	1.56	1.65

2. Design Parameters & Analytical Tools

Three initial design constraints are imposed on the Small Modular Boiling Water Reactor. The first constraint postulates that the reactor power should be in the category of small or medium sized reactors. According to the IAEA [7], medium sized reactors are those with electric power between 300 to 700 MWe and small sized reactors have less than 300 MWe. The second one is to require natural circulation for the reactor coolant within the RPV. The last postulated feature is that the SMBWR would have an external superheater system added to its balance of plant (BOP) and used to adjust the plant's power to match the load, while maintaining the reactor operation always at 100% of its full rated power.

The tools used to perform the neutronic analysis in this work were WIMS [8] and PANTHER [9], while COBRA-EN [10] was used for the thermal-hydraulic analysis of the core. A simulation model of reactor coolant flow and steam Rankine cycle were built in the MATLAB programming environment in order to analyze the natural circulation loop inside the vessel and the BOP of the SMBWR, respectively. More detailed information on the capabilities of these tools and explanation of how they interacted with one another to perform the analysis for this work have been presented in the previous publication [5], and thus, will not be repeated in detail here.

The reference fuel assembly design adopted in this study was the GE14 BWR design with specification listed in Table 2. The fuel assembly configuration used for this study is displayed in Fig. 1, while the axial zoning is shown in Fig. 2. The axial configuration is designed to minimize the axial leakage of fast neutrons. As BWRs have better moderation in the lower part of the core compared to the upper part, in order to control the axial power shape, the highest fuel enrichment is located in the middle part of the core and higher poison concentration is placed in the lower part of the core. Additional design parameters selected for the SMBWR are summarized below.

- Hydrogen to heavy metal ratio (3.5 – 4.5): the hydrogen to heavy metal ratio is related to the core average void fraction. The nominal H/HM of all GE-Hitachi designs have been around 4 for an average void fraction of 40 %.
- Subcooling temperature at the core inlet (10 – 50 °C): this limit is restricted by BWR stability. The core inlet subcooling temperature would determine the boiling length inside the core and, thus, affect the ratio of single-phase pressure drop to two-phase pressure drop. The single-phase to two-phase pressure drop ratio could affect both channel stability and core-wide stability **[11]**. In the comparative study on SMBWR operating pressure, the value of the core inlet subcooling temperature is varied depending on feedwater temperature. However, in all cases considered, the value is still within the range of the parameter limits.
- MCPR (> 1.05): MCPR limit is commonly taken as the thermal safety margin of BWRs. Thus, it was one of the thermal-hydraulic constraints that has to be met for a feasible SMBWR design.
- Void reactivity coefficient (< 0): a negative coolant void coefficient is one of the neutronic parameters set as a constraint for the SMBWR design.
- Average fuel temperature (< 1400 °C): this limit is commonly used in previous studies to limit fission gas release and control the fuel pin internal pressure.
- Maximum fuel temperature (< 2500 °C): this limit provides minimum margin to the fuel centerline temperature before the onset of melting.

Table 2. Specification of the Fuel Assembly

Parameter	Value
Fuel rod outside diameter (cm)	1.026
Water rod outside diameter (cm)	2.489
Rod pitch (cm)	1.295
Channel box inside width (cm)	14.0
Assembly pitch (cm)	15.5
Fuel assembly type	10x10 (GE14)
Number of fuel rods per assembly	92
Number of water rods	2

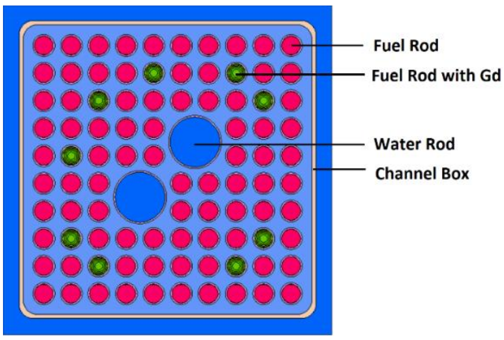


Fig. 1. Fuel assembly configuration.

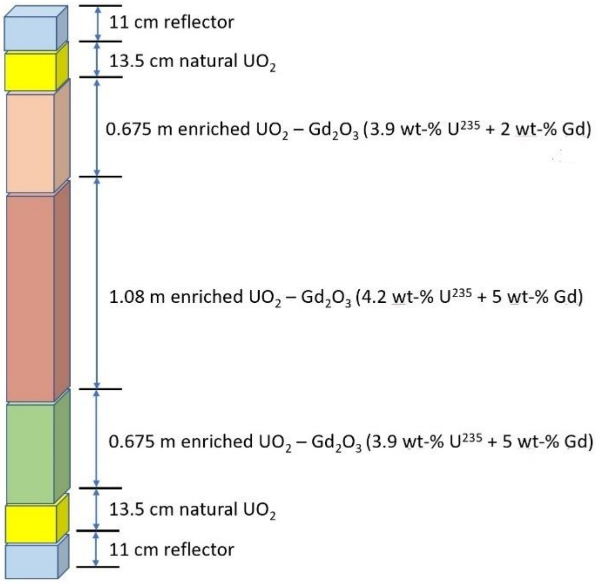


Fig. 2. Axial loading pattern.

3. SMBWR Fuel Management & Reactivity Control

Reactivity control is an important part of reactor operation. In PWRs, it is normally achieved by a combination of soluble boron, control rods and burnable poisons, while BWRs usually rely on burnable poisons, control rods and the speed of the recirculation pump. In a natural circulation BWR system, the removal of the recirculation pump means that the system needs to rely exclusively on control rods for managing the excess reactivity and facilitating start-up and shut-down operations. As mentioned earlier, the use of burnable poisons can reduce this reliance. This section focuses on options for managing the excess reactivity of the SMBWR. The two methods of reactivity control presented in this paper are multi-batch fuel management and feedwater coolant temperature variation.

3.1. Multi-batch fuel management

In terms of multi-batch management options, both 3- and 4-batch arrangements were considered and their depletion behavior was compared in terms of excess reactivity and channel power peaking factors ($F_{\Delta H}$), as shown in Fig. 3 and Fig. 4 respectively. Channel $F_{\Delta H}$, also known as enthalpy rise hot channel factor, is defined as the ratio of maximum individual assembly channel enthalpy rise to core average enthalpy rise. A typical limit for Channel $F_{\Delta H}$ in BWRs is 1.5 at the reactor full power **[12]**. The loading pattern for the 3-batch arrangement was defined to follow the configuration defined in Fig. 5, while the loading pattern for the 4-batch arrangement is shown in Fig. 6. The assembly type denoted “0” represents a fresh fuel assembly, while types 1, 2, and 3 represent once, twice, and thrice burnt fuel, respectively, and R represents the reflector.

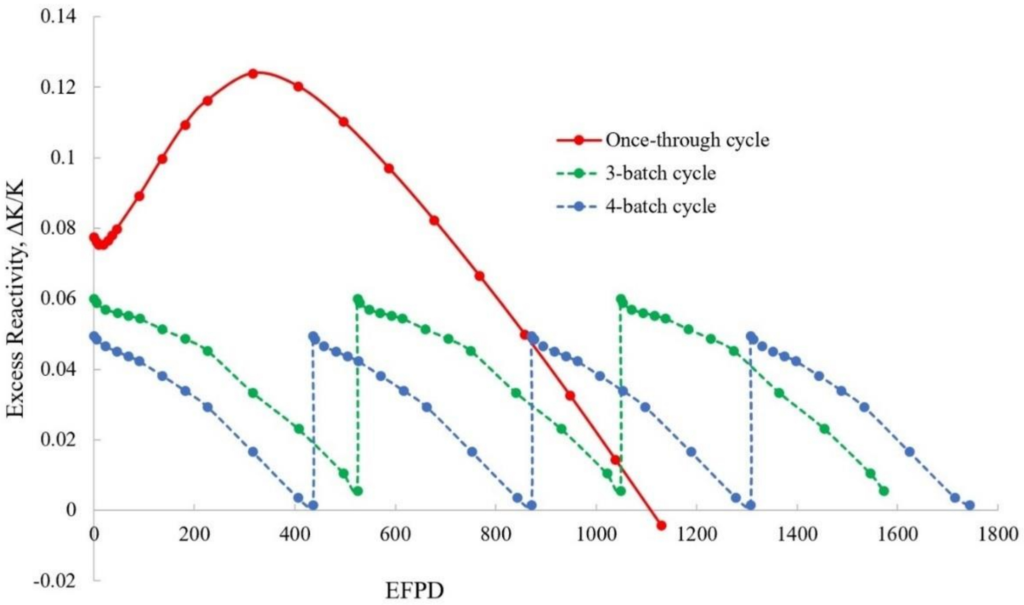


Fig. 3. Excess reactivity of the SMBWR with various fuel management schemes.

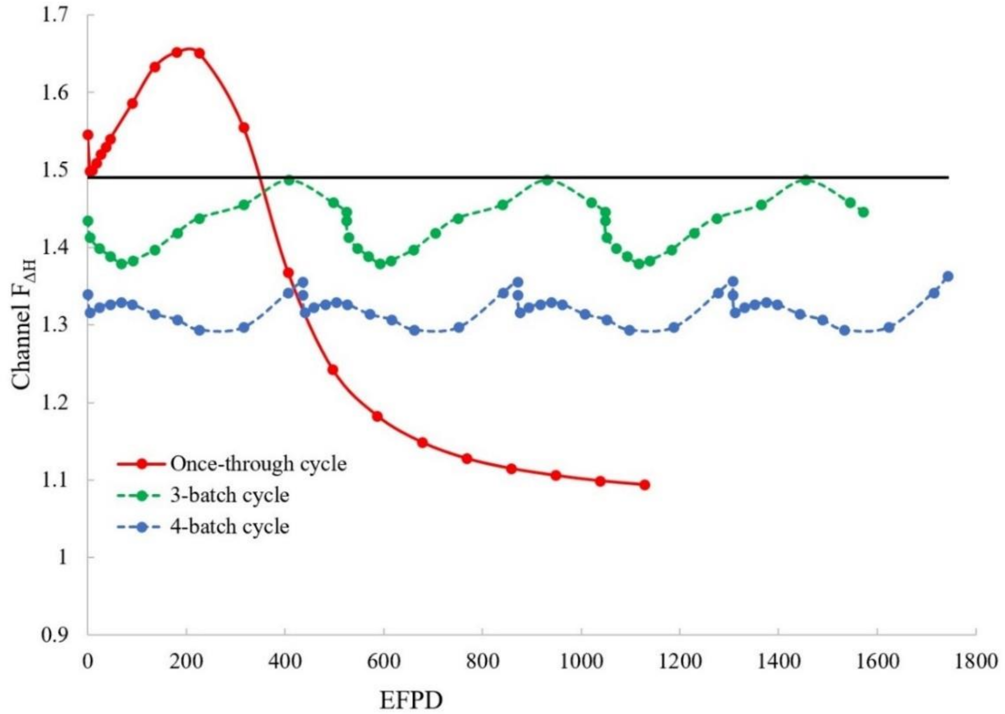


Fig. 4. Channel $F_{\Delta H}$ of the SMBWR with various fuel management schemes.

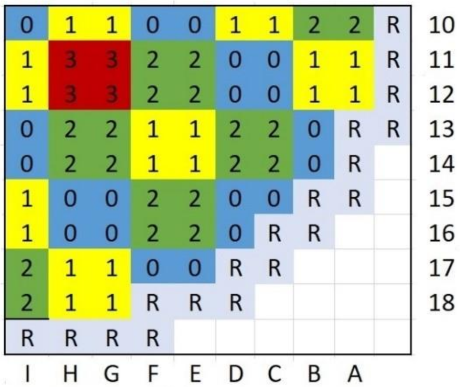


Fig. 5. Loading pattern configuration for 3-batch arrangement.

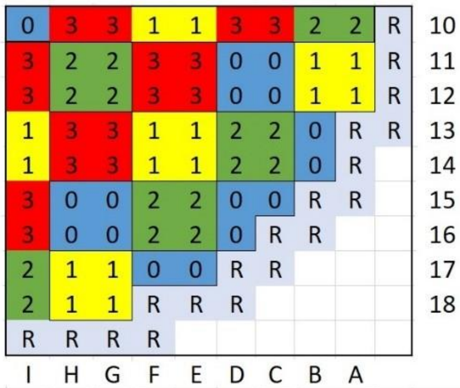
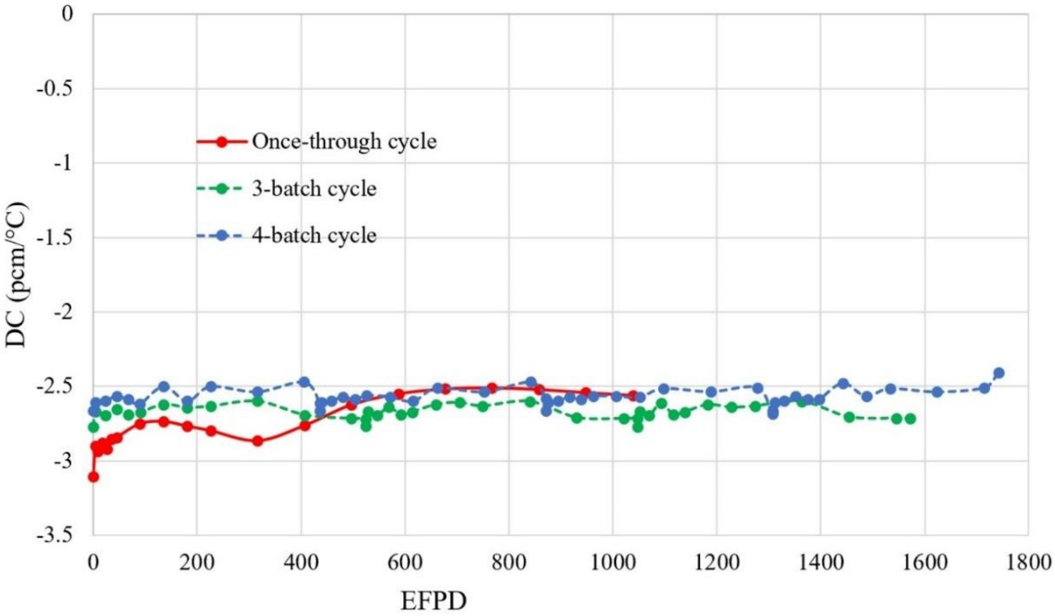


Fig. 6. Loading pattern configuration for 4-batch arrangement.

Fig. 3 shows that the greater the number of batches used, the lower the core excess reactivity throughout the irradiation cycle. In the once-through cycle, the core reactivity increases as the gadolinium poison depletes, and once it is fully burned, the core reactivity starts decreasing. As expected, this behavior is altered in the multi-batch configuration as the average core reactivity is approximately an average of the reactivity of the pins from different stages of the irradiation cycle. It is shown that in the multi-batch configurations, the initial excess reactivity has the highest value throughout the cycle. Considering the maximum value of core reactivity in each scheme, it is shown that using a 4-batch scheme would result in an excess reactivity reduction of roughly ~1000 pcm compared to a 3-batch scheme. As mentioned before, in BWRs with natural circulation, utilizing the control rods is the primary means to maintain the reactivity throughout the cycle. Having less excess reactivity is preferable as it would mean fewer CRs are required. It should be noted that the 4-batch schemes shorten the cycle length compared to 3-batch scheme. A shorter cycle length leads to more frequent outages, which may or may not be desirable depending on the seasonal demand of the electricity in the country when the power plant is located and the costs associated with the outage itself. In the case where longer cycle length is necessary, increasing the enrichment of the feed fuel assemblies could be an option. It should also be noted that increasing the enrichment of the feed FAs would increase the excess reactivity, at least partially offsetting the benefits of multi-batch management, and alter the peaking factor behavior compared to the results shown in Fig. 3 and Fig. 4.

Fig. 4 shows that both the 3- and 4-batch schemes are able to meet the design criterion for power peaking by having Channel $F_{\Delta H}$ below the specification limit (< 1.5). In terms of the margin to the design limit, it is shown that the 4-batch configuration has a better margin, which might be due to a better shuffling arrangement. The core reactivity feedbacks are shown in Fig. 7. While there is no significant difference in the DC by having a multi-batch configuration, the CVC is becoming more negative with increasing number of batches used, which could partially offset the benefit of requiring fewer control rods.



(a)

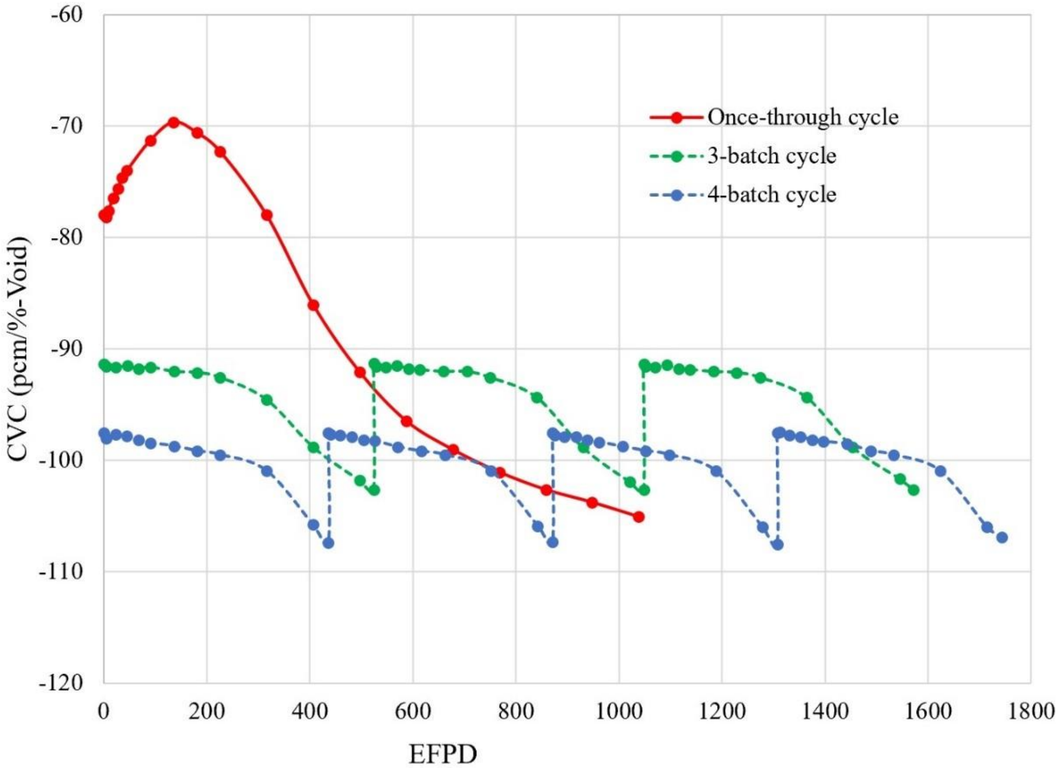


Fig. 7. Reactivity feedbacks of the SMBWR with various fuel management schemes: (a) Doppler Coefficient; (b) Coolant Void Coefficient.

By comparing the 3- and 4-batch management schemes, it can be observed that the 4-batch scheme offers a more favorable performance compared to the 3-batch scheme as it has lower power peaking, less excess reactivity, and more negative CVC. A stronger negative CVC could be advantageous if some of the excess reactivity is to be controlled by varying the coolant inlet temperature and, as a result, void distribution. It should also be noted that a more negative CVC means the core would require more control rods in order to ensure shutdown margin as reactivity is added between the hot full power and cold zero power shutdown conditions. Although the 4-batch scheme has a shorter cycle duration and thus the reactor would have more frequent outages throughout its lifetime, the cycle duration is still longer than a year, and therefore should be acceptable. In addition, in a 4-batch scheme the fuel could achieve a higher discharge burnup, and thus, have better fuel utilization.

3.2. Coolant void variation

The coolant temperature inside the core can be used to control the reactivity in the SMBWR by leveraging the negative MTC and CVC to reduce the excess reactivity. It is known that the coolant density changes with temperature, resulting in changes in neutron moderation. In addition, assuming that the linear heat generation is fixed, the increase in core inlet temperature will reduce the inlet subcooling and extend the boiling length inside the core, which also leads to less efficient moderation. Fig. 8 shows the reactivity suppression worth when the coolant inlet temperature of the SMBWR with a 4-batch fuel management scheme is increased to 275 and 280 °C. It is shown that increasing the core inlet temperature to 275 °C would reduce excess reactivity by approximately 200 pcm, while increasing it further to 280 °C would give a further reduction of approximately 600 pcm. This coolant temperature reactivity suppression by itself seems insignificant; however, it is still important to understand to what extent the combination of a multi-batch arrangement and coolant temperature variation is able to reduce the core excess reactivity and hence reduce the system dependency on control rods.

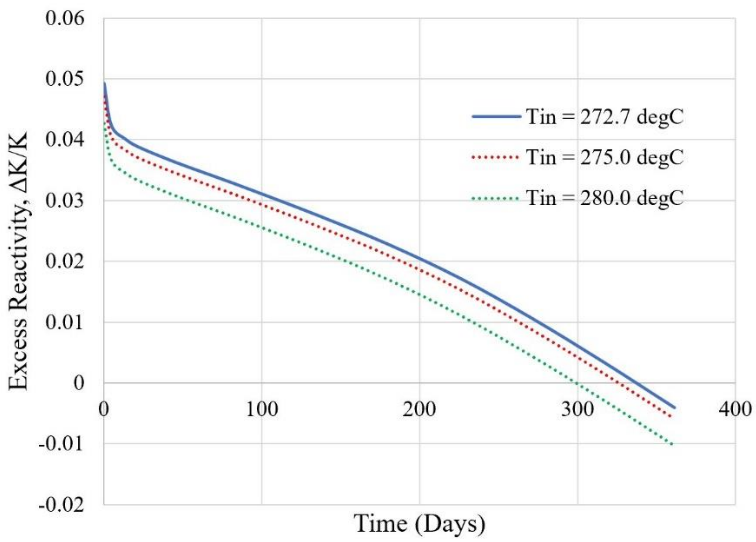


Fig. 8. Excess reactivity at various core inlet temperatures.

It can be observed from Fig. 8 that increasing the core inlet temperature would reduce the cycle burnup, and thus, might negatively impact the economics. However, the main purpose of this study is not to select the optimum operating condition, but rather to demonstrate that this method is available to be used for controlling the reactivity of the SMWBR. As this method is only used for reactivity control, it can be assumed that the SMBWR will not be used with the lower core inlet temperature for the entire cycle. In case this method is used only in the beginning of the cycle, it may have a positive impact on the economics. While reactivity is reduced at higher temperature, the fertile capture rate increases, and thus, more breeding of fissile Pu would happen. This will contribute to an increase in reactivity later in the cycle through a spectral shift operation, as the core inlet temperature is reduced, which could result in longer cycle and higher burnup.

In order to change the core inlet temperature in a BWR system with natural circulation, the most practical way is by adjusting the feedwater inlet temperature, without perturbing the reactor coolant inventory. Therefore, it is important to investigate the effect of this feedwater inlet temperature adjustment on the thermodynamic performance of the SMBWR steam cycle. Fig. 9 shows that in order to increase the core inlet temperature to 280 °C without changing the mass flow rate through the core, the feedwater temperature has to be increased to approximately 247 °C. The reactor vessel steam outlet condition would not change as steam exiting the reactor is at saturation conditions. The boiling length is increased as the inlet subcooling temperature is reduced at constant mass flow rate and linear power. Fig. 10 shows the power plant electric output and power conversion cycle efficiency, which are affected by this increase in feedwater temperature, while Fig. 11 shows how this temperature change would affect the core exit quality and steam flow rate exiting the reactor vessel to the superheater.

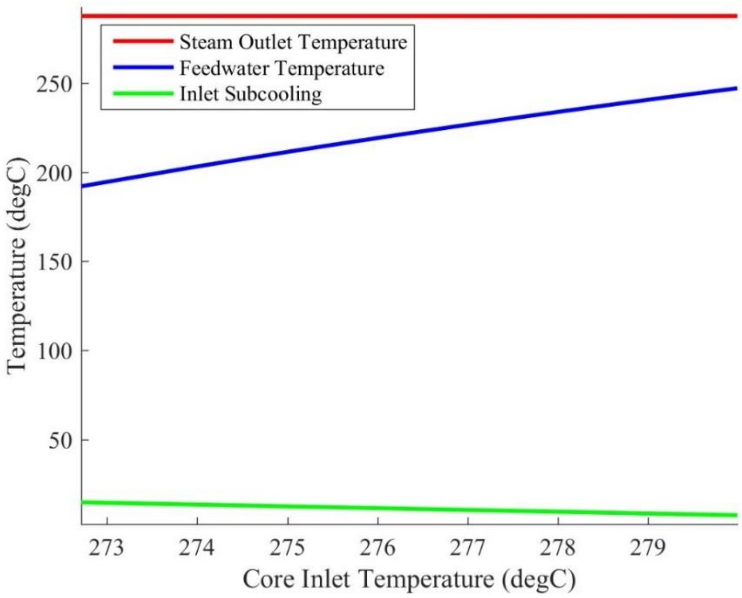


Fig. 9. Relevant SMBWR operating temperatures at various core inlet temperatures.

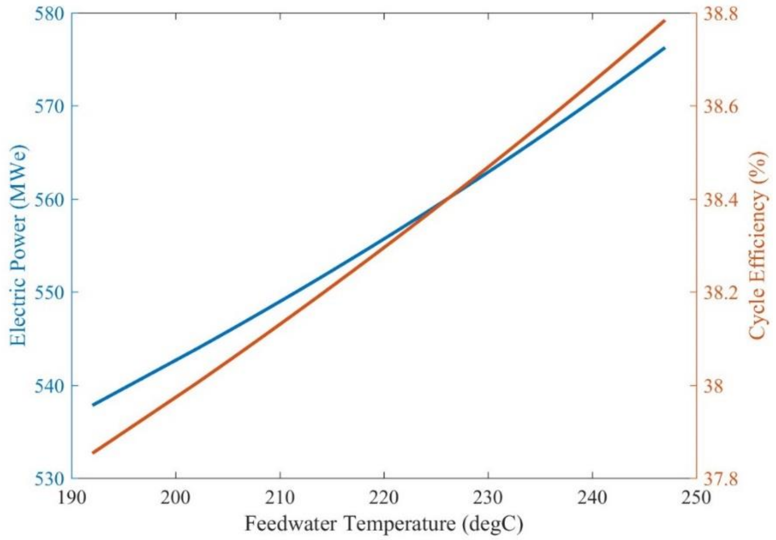


Fig. 10. Electric power produced and resulting steam cycle efficiency of the SMBWR at various feedwater temperatures.

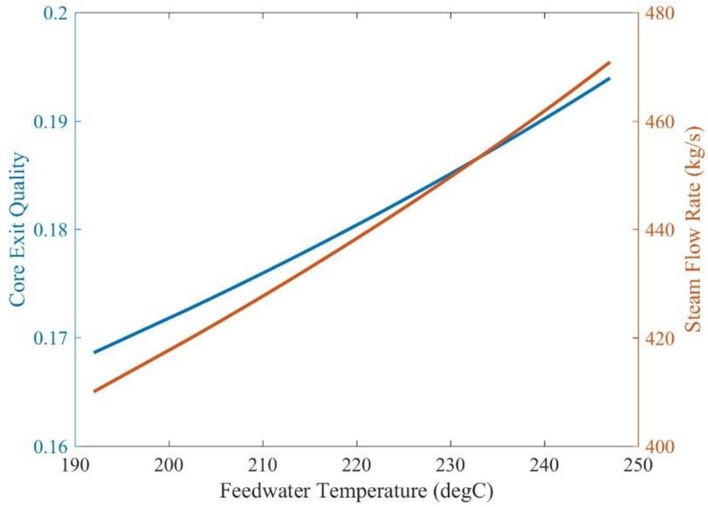


Fig. 11. SMBWR core exit quality and steam flow rate at various feedwater temperatures.

It can be observed from Fig. 10 and Fig. 11 that, as the feedwater temperature increases, the core exit quality increases and more steam can be produced by the reactor and supplied to the superheater. This effect leads to higher production of electric power and a small increase in cycle thermal efficiency. Although increasing feedwater temperature seems to offer some benefits for the SMBWR (reducing excess reactivity and improving cycle thermal efficiency), there is a limit to the extent the feedwater temperature could be increased. A higher feedwater and core inlet temperature would increase the length of the boiling region inside the core. Although it is beneficial to have a longer boiling region in terms of excess reactivity, the MCPR margin becomes smaller as the core inlet temperature approaches the saturation temperature. Another effect that needs to be considered is that, although a higher feedwater temperature means higher cycle thermal efficiency, more external heat is required, as shown in Fig. 12. Therefore, if the source of external heat for the SMBWR does not come from a clean energy source, the CO_2 emissions for the hybrid system are going to be increased.

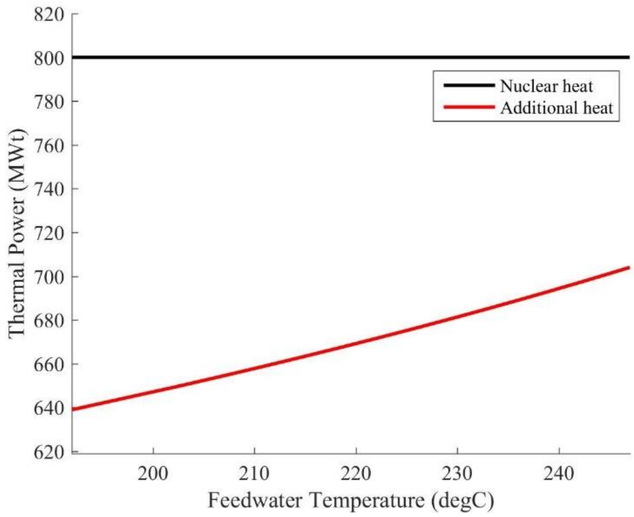


Fig. 12. Proportion of heat sources for the SMBWR at various feedwater temperatures.

It should be noted that increasing core inlet temperature may affect the core pressure drop, heat transfer characteristic, and flow instabilities. The main factors that could affect the core pressure drop and heat transfer are coolant mass flux and coolant properties. Since the core inlet temperature is increased by increasing the feedwater temperature while keeping the core coolant inventory, the coolant mass flux will remain constant as the core geometry does not change. Since the coolant mass flux is approximately constant, only the change in core inlet temperature, will affect the core pressure drop and heat transfer characteristic. Further investigations are required to fully understand how the increase in core inlet temperature might affect these characteristics. However, since the scope of this section is to discuss methods that are available for reactivity control in SMBWR and not finding the optimum operating condition, no detailed investigation on these effects is included here.

4. Balance of Plant and Operational Flexibility of the SMBWR

A distinctive feature of the SMBWR is the addition of external superheaters to its BOP. The saturated steam is generated by the reactor core and heated further to the superheated conditions by the external superheater before entering the high-pressure (HP) turbines. The exhaust steam from the HP turbines can then be reheated before expansion in the low-pressure (LP) turbines. The heat supplied to the superheater and reheater can either be taken from a conventional fossil fuel combustion, such as hot air from a gas-fired boiler or exhaust gas from gas turbines. The heat can also be supplied by a renewable heat source such as molten salt from a concentrated solar power (CSP) system. There are two main benefits of having an external heat source for the superheater and reheater. They provide the improvement of thermal efficiency and the ability to vary the system power to match the load demand by adjusting the external heat provided to the superheater. In most LWR steam cycles, a fraction of the steam is diverted before entering the HP turbines to supply heat to the moisture separator and reheaters (MSRs). By having the reheater which utilizes an external heat source, all the steam generated by the reactor can generate useful work in the HP turbine, improving the thermal efficiency of the cycle. Small portion of steam is bled from the turbine to preheat the feedwater. The turbine outlet stream is then condensed in the condenser and directed through several stages of feedwater heaters before returning to the reactor. The last stage of the feedwater heaters cascade is an economizer which utilizes the heat exhausted from both superheater and reheater to further preheat the feed water before entering the core. The BOP for the SMBWR is displayed schematically in Fig. 13. A detailed summary on how the MATLAB model for the Balance of Plant (BOP) of the SMBWR has been reported previously in **[5]**, thus, will not be repeated here.

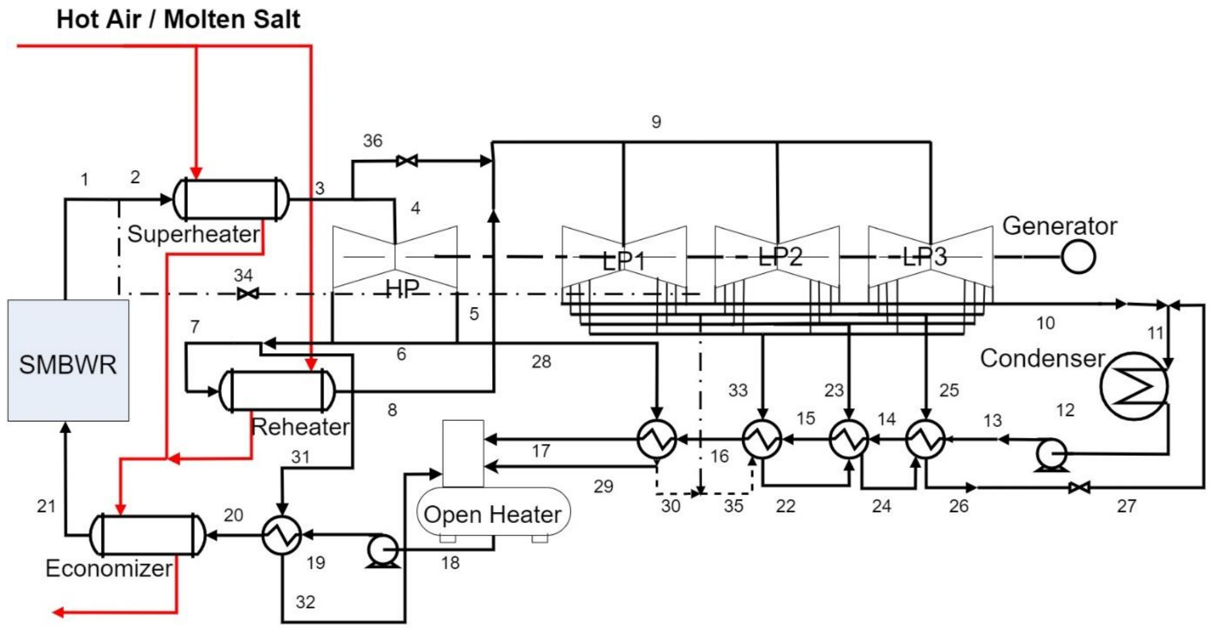


Fig. 13. BOP of the hybrid SMBWR **[5]**.

The steam turbines are known to be sensitive to the steam conditions and adjusting the external heat to follow the load can result in significant variation in these conditions, which may cause thermal stress and fatigue problems in the steam turbine. In order to avoid these problems, the load-follow operation is accomplished by introducing a bypass line from the HP turbine inlet to the LP turbine inlet (point 36 in Fig. 13). The SMBWR steam cycle is designed so that the steam entering the HP turbine (point 3) has the same enthalpy as the steam exiting the reheater (point 8). By throttling the bypass line (point 36) and reducing the pressure of the steam at point 3 to the value of that at point 8, there will be no significant perturbation in the LP turbine inlet conditions. The change in mass flow rate of the steam entering the HP turbine will cause the work of the HP turbine and the external heat required to reheat the steam before entering LP turbines to vary. It should be noted that although the bypass flow rate may change the steam flow rate entering the turbines, it will not significantly perturb the steam conditions. At full load, most of the steam entering HP turbine will be expanded, reheated, and then routed to the LP turbine, with a small portion of the steam taken for feedwater preheating (point 28 and 31). By reducing the load with the bypass line (point 36), the mass flow rate at point 7 will be reduced. The reheater heat will be reduced by adjusting the steam flow rate entering the reheater. A more detailed explanation on the load-following operation of the SMBWR has been reported in **[5]**. With this method of load-follow, the steam conditions at the entrance of both HP and LP turbines are fixed and independent of the load. The load variation is achieved by adjusting the steam flow rate through the turbines. This method of load-follow allows maintaining the reactor operation constantly at 100% of its full rated power. However, there is a minimum limit to the extent the system power could be adjusted using this method, which will be discussed later.

In designing the BOP for SMBWR, the reactor feedwater inlet and steam outlet condition are used as the boundary condition. It is known that the steam cycle performance is determined by the operating parameters selected for the steam cycle such as turbine inlet temperature, turbine outlet pressure, and the fraction of steam bled from the turbine to preheat the feedwater. The HP turbine inlet temperature for full power case in this study is set to 540 °C. The main reason for choosing this operating temperature is to open the possibilities for various external heat sources, such as conventional gas boiler, exhaust gas from a gas turbine in a combined cycle mode, and heat stored in molten salt from a CSP plant. The conventional gas boiler can reach temperature as high as 1600 °C, while gas turbine exhaust temperature varies between 500 – 700 °C. In case of using heat from CSP, the molten nitrate salt (60 wt-% $NANO_3$ and 40 wt-% KNO_3) is known to be a stable mixture and suitable for use as thermal storage medium within a temperature range of 260 °C to 621 °C **[13]**.

The power maneuvering capability of the SMBWR has also been part of the previous study **[5]**, thus, will only be summarized briefly here. It was shown that the SMBWR was able to reduce its load down to 65% without perturbing the reactor thermal power output. When the power demanded by the grid is less than 100%, some portion of the superheated steam entering HP turbine could be bypassed through line no. 36, as shown in Fig. 13. The reduction of steam mass flow entering the reheater should be proportional to the load and the heat supplied to the reheater in order to maintain the steam operating condition before entering the LP turbine. By doing so, the load reduction could be achieved by adjusting the heat provided to the reheater and reducing steam mass flow rate entering HP turbine, thus, reducing the work produced by the turbine. In the case of BWR with natural circulation, the elimination of reactor recirculation pump will force such system to rely heavily on control rods to perform load-following. The fact that SMBWR has an ability to load-follow to some extent without changing the reactor thermal power offers an alternative load-following method for BWR system with natural circulation.

5. Comparison of the SMBWR with the Other Reactors

This section discusses additional potential benefits of the SMBWR as compared to other reactors.

Table *3* shows a comparison of SMBWR power and estimated vessel dimension with a number of other SMR designs **[**7**]**. DMS is another BWR-type SMR, while both IRIS and the Westinghouse SMR are integral PWRs (IPWRs). In this section, the value of reducing the reactor vessel size for the SMBWR (vessel diameter and height) has been estimated. The vessel diameter can be inferred from the circumferential diameter of the core, which can be calculated from the number of rows of the FAs and the assembly pitch. The vessel height can be estimated by summing up the lengths of the vessel components (lower & upper plenum, core, chimney, and dome). It should be noted that the thermal power of the SMBWR shown in

[a]The thermal power written for the SMBWR is the reactor thermal power. It should be noted that in order to produce the amount of electric power shown in the table, the SMBWR requires approximately 529 MW of additional thermal power for the superheating system.

Table *3* is the reactor power only. In order to produce the amount of electric power shown in

[a]The thermal power written for the SMBWR is the reactor thermal power. It should be noted that in order to produce the amount of electric power shown in the table, the SMBWR requires approximately 529 MW of additional thermal power for the superheating system.

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Table 3. Comparison of the SMBWR with Other SMR Systems

Parameter	Reactor			
	SMBWR[a]	DMS	IRIS	Westinghouse SMR
Type	SMR - BWR	SMR - BWR	IPWR	IPWR
Thermal power (MWth)	800	840	1000	800
Electric power (MWe)	515	300	335	225
Cycle efficiency (%)	39.5	36.4	34.2	28.7
Fuel active length (m)	2.70	2.00	4.26	2.40
Vessel diameter (m)	3.94	5.80	6.20	3.70
Vessel height (m)	16.3	15.5	21.3	28.0
Power to volume ratio ($MWth/m^3$)	4.03	2.05	1.56	2.66

By comparing both the thermal power and electric power of the SMBWR with other small LWRs, as shown in

[a]The thermal power written for the SMBWR is the reactor thermal power. It should be noted that in order to produce the amount of electric power shown in the table, the SMBWR requires approximately 529 MW of additional thermal power for the superheating system.

Table *3*, it is clear that the SMBWR has the highest power conversion cycle efficiency, even after taking into account the amount of additional heat needed to be supplied for the superheaters.

[a]The thermal power written for the SMBWR is the reactor thermal power. It should be noted that in order to produce the amount of electric power shown in the table, the SMBWR requires approximately 529 MW of additional thermal power for the superheating system.

Table *3* also shows that, although these SMRs have similar thermal power, both the SMBWR and DMS (BWR-type SMR) have a shorter vessel compared to those of the IPWRs. The reason is obviously because in the IPWR design concept, the steam generators are designed to be integrated into the RPV. By examining the power to volume ratio, which is calculated by dividing the thermal power output by the vessel volume, it is shown that the SMBWR could achieve the highest power density compared to other SMRs on the market. The DMS relies on having a large flow area to reduce the steam velocity and implement a free surface moisture separation system (FSS). This FSS allows the DMS to eliminate the steam separator and thus reduce the height of its vessel. In contrast to the DMS, the SMBWR has a standard flow area, and thus still requires a steam separator. However, the fact that the SMBWR is combined with external superheaters means that the steam dryer could be eliminated as the superheaters will ensure that steam is going to enter turbines in a dry condition. Therefore, the SMBWR is able to achieve nearly the same vessel height as the DMS with a smaller vessel diameter, which could be more important for enabling less complex and costly manufacturing and transportation.

Although having a high power density may affect the reactor safety, it should be noted that the power density mentioned above is not referring to the core power density, but rather power per unit volume of the entire pressure vessel. In terms of core power density, the SMBWR has a core power density of 48 kW/L **[5]**, which is similar to the average core power density of BWRs of approximately 50 kW/L. Therefore, the fact that the SMBWR core power density is slightly below the average of conventional BWRs suggests that the safety case of the SMBWR would be similar compared to conventional BWRs.

A comparison of core design and average performance parameters of the SMBWR with the ESBWR **[14]** and ABWR **[15]** are shown in Table 4. It can be observed that the SMBWR could achieve a much smaller core pressure drop compared to the ESBWR and ABWR, which is one of the reasons why the SMBWR does not require partial length fuel rods. The core pressure drop is a strong function of mass flow rate and length. The SMBWR and ESBWR could have smaller core pressure losses compared to the ABWR due to their smaller mass flow rate per assembly and shorter core length. The assembly flow rate of the SMBWR is similar to that of the ESBWR as both reactors are designed to operate with natural circulation. However, it is shown that the core pressure losses of the SMBWR are approximately a third of that of the ESBWR due to the reasons mentioned above. It can be observed that the total length of fuel rods of the SMBWR are approximately 1 m shorter than the ESBWR. This difference in total length along with differences in the boiling length (as shown in Fig. 14) are the major contributors to the difference in the core pressure drop. As discussed earlier, the pressure losses in a 2-phase flow are higher than those of single-phase flow. Fig. 14 shows that the ESBWR has a longer boiling length compared to the SMBWR. Besides that, the fact that the SMBWR fuel assembly has only 4 spacer grids is also contributing to the difference in pressure drop, as the total core pressure drop is also proportional to the local pressure losses due to spacers.

Table 4. Comparison of Core Parameters of Selected BWRs

Parameter	SMBWR	ESBWR	ABWR
Active fuel rod height (m)	2.70	3.05	3.71
Total fuel rod height / FA length (m)	2.92	3.79	4.47
No. of FAs	256	1132	872
No. of spacer grids	4	6	8

[a]The thermal power written for the SMBWR is the reactor thermal power. It should be noted that in order to produce the amount of electric power shown in the table, the SMBWR requires approximately 529 MW of additional thermal power for the superheating system.

Core mass flow rate (kg/s)	2414.3	9583	14500
Core pressure drop (kPa) at 7.1 MPa	50.70	71.8	168.2

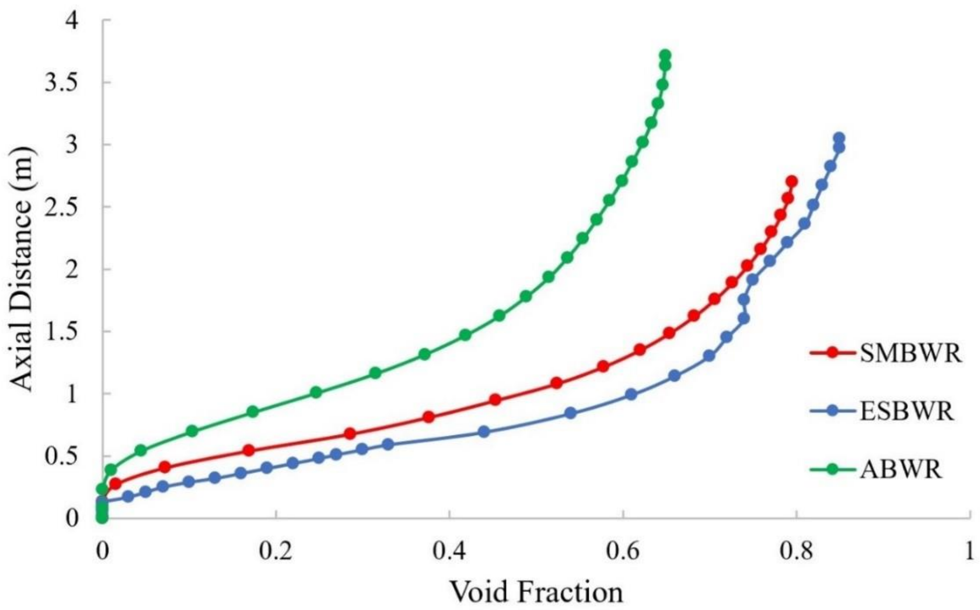

Fig. 14. Core average axial void distributions of the SMBWR, ESBWR and ABWR at MOC.

6. Fuel Consumption and Emission Rate

It is expected that if natural gas is used as the external heat source for the superheater system, the CO_2 emission rate of the SMBWR system would need to be accounted for. Therefore, it is important to quantify and compare SMBWR emissions with both stand-alone gas turbines and combined cycle gas turbine (CCGT) systems, as shown in Table 5. The reference gas turbines used in Table 5 are those developed by Siemens **[16]**. The SMBWR type-1 in Table 5 are 2 units of SMBWR, with capacity of 515 MWe each, and use conventional gas boiler for the superheating system. The SMBWR type-2 is a single unit of SMBWR combined with 2 gas turbine units. It can be observed that even though SMBWR combined with fossil-fuel superheaters would have higher emission rate compared to a stand-alone NPP, their emission rate would still be considerably smaller compared to a stand-alone gas turbine system or CCGT system. It is also observed that the fuel consumption rate and emission rate is smaller for the SMBWR system which utilizes conventional boiler compared to the one using gas turbines.

It should be noted that the values for SMBWR displayed in Table 5 refer only to the plant operating at 100% capacity (where both the reactor and superheater have maximum power output). If the plant operates below 100% capacity, Case 1, where the external heat is supplied by conventional gas boiler, would obviously require less external heat supply, and thus, resulting in lower fuel consumption rate and emission rate. It should be noted that the emissions listed in Table 5 assume that both nuclear and fossil fuel burning parts of the power plant operate at 100% of their capacity. In a more realistic scenario, only the nuclear part will operate at its full rated power, while the gas burning rate will be varied (reduced) to follow the grid demand. Therefore, the emission rates reported here are a conservative estimate, while the actual ones are likely to be considerably lower.

Table 5. Comparison of the SMBWR with the Other GT Systems

Parameter	SMBWR		Stand-alone GT	CCGT
	1	2		
GT type	N/A	SGT5-4000F	SGT5-8000HL	SGT5-4000F
No. of GT required	0	2	2	2
Total electric power (MWe)	1030	1173	1186	950
Power conversion cycle efficiency (%)	39.2	48.8	42.8	59.7
Fuel consumption rate (Btu/kWh)	3502	4668	7972	5716
Emission rate (gCO_2/kWh)	185.84	247.70	422.99	303.29

It is also understandable that in the low-carbon economy, the fact that SMBWR have higher emission rate compared to a stand-alone NPP might raise a concern. However, any renewable energy source such as wind or solar as an alternative to nuclear energy is also not entirely emission free. In the absence of large scale and economically competitive energy storage option, intermittency of renewables will normally require a backup generation system. This backup generator can be either conventional gas power system or diesel generators, both of which would have non-negligible amount of CO_2 emission. The hybrid energy system of wind turbine and diesel generator or gas turbine can be categorized into low, medium and high penetration fraction of renewable energy generators on the grid. The low penetration systems are defined as the system which have less than 20% average wind power and less than 50% contribution to total generation. Medium penetration systems operate with average wind power contributions between 20% and 50% and instantaneous penetration levels between 50% and 100%. While high penetration systems are defined as systems with average wind power fraction above 50% and instantaneous penetration levels between 100% and 400% **[17]**. Table 6 displays the estimated emission rate and fuel consumption of wind power and its backup generation system. In creating Table 6, it is assumed that the backup generation system is powered by natural gas with power conversion efficiency of 40%, and the average wind power penetration for the high, medium and low penetration case are assumed to be 80%, 40%, and 15%. It is postulated that wind and solar have large variation in capacity factor and thus, assuming that there is no storage system in place, they would require different amounts of backup generation. Therefore, there is a limitation on the assumptions that are used for creating Table 6.

Table 6. Fuel Consumption and Emission Rate of Wind Turbine Hybrid Energy System

Parameter	High Penetration	Medium Penetration	Low Penetration
Average wind power penetration (%)	80	40	15

Fuel consumption rate (Btu/kWh)	1706	5118	7251
Emission rate (gCO_2/kWh)	90.52	271.56	384.71

Table 6 shows that the fuel consumption and emission rate of the wind turbine hybrid energy system is very much dependent on the level of average wind power penetration. It is shown that SMBWR hybrid energy system could consume less fuel and produce less emission compared to wind turbine hybrid energy system at low and medium level of wind power penetration. Even the hybrid system of SMBWR and gas turbines, which produce the highest amount of CO_2 emission compared to the other types of SMBWR hybrid energy system is still able to compete with wind turbine hybrid system at medium wind power penetration, in terms of its fuel consumption and emission rate. It should be noted that Table 6 is created with the assumption that the backup generator for the wind turbine system comes from a gas turbine system. In the case where diesel generator is used as backup power for the wind turbine hybrid system, the emission rate of the wind turbine hybrid system would be higher compared to the values shown in Table 6.

7. Conclusions

The trade-offs between sustainability, energy security, and affordability need to be considered in order to transform the current energy supply to low-carbon technologies. The path forward lies between two alternatives, reducing the storage costs for the backup of intermittent renewables or developing an affordable and more flexible nuclear power. A conceptual design of a hybrid energy system of a Small Modular Boiling Water Reactor (SMBWR) combined with external superheaters is proposed in this work as one of the possible solutions. This SMBWR has several distinct design features. First, it is a BWR-type small modular reactor, which offers several potential economic advantages and would be more attractive to countries with emerging economies compared to a large reactor. It is designed to adopt natural circulation for coolant recirculation within the reactor pressure vessel. It is easier to develop natural circulation in BWR compared to PWR due to the fact that BWR could rely on two-phase flow driving head due to larger variation of coolant density. The most distinctive design feature considered is an external steam superheater added at the outlet of SMBWR. The superheater consists of 3 pieces of equipment: a superheater, reheater and economizer. The external heat can be provided by a conventional gas boiler, waste heat from gas turbines, or heat stored in molten salt from Concentrated Solar Power (CSP) technology. This addition of the superheaters allows elimination of Moisture Separator and Reheater (MSR) and high-pressure feedwater heater from the SMBWR Balance of Plant (BOP). In addition, the combination of having both superheater system and natural circulation allow the SMBWR to eliminate both steam dryer and recirculation pump, which can potentially reduce the reactor pressure vessel size, reducing its costs and improving the economic competitiveness of the power plant.

This paper highlights several features of the SMBWR, including methods for the core reactivity control, BOP and steam cycle flexibility, and the performance of the SMBWR compared to other systems. In terms of managing excess reactivity, the combination of a multi-batch fuel arrangement, coolant temperature variation, and control rods are required to control the reactivity swing in the SMBWR while keeping the power peaking below the commonly adopted safety limits throughout the depletion cycle. It is observed that the 4-batch scheme offers a more favorable performance compared to the 3-batch scheme as it has lower power peaking, less excess reactivity, and more negative coolant void coefficient (CVC). In addition, it is also found that SMBWR could utilize coolant void variation to reduce excess reactivity to some extent. In the absence of the recirculation pumps used in conventional BWRs, the core void fraction could be controlled by feedwater subcooling through variation of power conversion cycle parameters. The pressure vessel size comparison of the SMBWR with the other SMRs shows that the SMBWR could have either smaller diameter or shorter vessel compared to the other SMRs system which have roughly the same amount of thermal power. In addition, by having the external superheaters, the SMBWR could have higher thermal cycle efficiency compared to the other SMRs considered in the study. In terms of fuel consumption and emission rate, it is found that the SMBWR system which has external heat coming from a conventional gas-fired boiler, will have smaller fuel consumption and emission rate compared to the one which uses exhaust gas from the gas turbines. However, the latter option will have higher power conversion cycle efficiency compared to the former. Furthermore, both options could have lower emissions than a renewables-dominated system backed up by fast acting gas turbines.

The work on system maneuverability presented in this paper has only covered steady-state operation. The dynamic response and control of this system are important topics that should be covered in the future investigations, along with their techno-economic analysis of such system. Superheating of steam in nuclear power plants is not an entirely new concept. It has been implemented in several reactors in the past, such as Indian Point 1 (USA), Garigliano (Italy), and Lingen (Germany). This previous experience shows that the dynamics and control of such a system is possible. The same can be noted with regards to the bypass steam for the load-following operation. The fact that throttling valves have been used extensively in steam cycles to reduce steam pressure provide confidence that SMBWR could rely on similar technology when a load reduction is required.

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Nomenclature

EFPD	effective full power day
$F_{\Delta H}$	enthalpy rise hot channel factor
GT	gas turbine
MOC	middle of fuel cycle
T_{in}	core inlet temperature

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