COMPARISON AND ANALYSIS ON INTEGRAL SMALL MODULAR REACTOR WITH TWO DIFFERENT ESF DESIGNS RESPONSE TO POSTULATED EVENTS

Guoxu Zhang, Heng Xie
Institute of Nuclear and New Energy Technology, Collaborative Innovation Center of Advanced nuclear Energy Technology, Key Laboratory of Advanced Reactor engineering and Safety of Ministry of Education
Tsinghua University, Beijing, 100084, China
chang6667@163.com

ABSTRACT

Small Modular Reactor (SMR) with an electric power less than 300MWe has gained much attention in recent years. By incorporating the safety-by-design and passive concept into the design process, SMRs have made a progress in meeting the safety demand of nuclear energy. There are many similar design features among integral pressurized water SMRs, and the differences are mainly on the design of ESF (Engineered Safety Features). To get a comprehensive understanding of the influence that is aroused by ESF in terms of accident scenario, two simplified simulation models of integral SMR are built by the use of best estimate code Relap5/Mod3.2 in this paper. One connects ESF to primary coolant side, the other to secondary coolant side and uses OTSG to remove residual heat from primary coolant system. A SBO (Station Blackout Accident) and a SBLOCA (Small Break Loss of Coolant Accident) are introduced to simulation model respectively. The calculation results show that both two cases can successfully remove decay heat from the core, and could keep reactor safe for an elegant of time. But there are still some differences between two cases in aspects of accident performances. Comparisons between the results from two cases are conducted in this paper, and the differences are carefully analyzed. The results show that primary side ESF connection design can maintain good residual heat removal ability both in SBO and SBLOCA, and the whole response process in different accidents is similar to each other. While, secondary side ESF design case performs differently in different accident scenarios, and the PRHRS in this case only works well in SBO.

KEYWORDS
SMR, ESF, PRHRS, natural circulation

1. INTRODUCTION

SMR with an electric power less than 300MWe has gained much attention in recent years. The reason owes to their prominent advantages of safety and feasibility over large loop-type commercial reactors. In the aspect of safety design, which is also the most important issue in nuclear energy utilization, SMRs eliminate as many accidents initiators as possible and strengthen passive safety to mitigate accident consequences during the process of preliminary design. As for feasibility, smaller power output and enhanced safety help SMRs provide electricity to isolated or remote locations with small electric grid, and also could be applied in non-electrical fields, such as desalination and district heating [1].

Currently, more than 40 advanced SMRs are at preliminary stage of design. They include all principal reactor lines. LWR-based SMRs absorb the existing LWR experience, is considered to have the lowest technical risk. Thus, LWR-SMRs occupy the most part of advanced SMR designs, and they are expected to be the first kind of SMR that can be deployed in next decade. According to a report from IAEA [2], most advanced LWR-SMRs refer to integral small modular pressurized water reactors. Based on the design experience learned from marine or land reactors, these reactors pay more attention to inherent safety issues, and in some extend reach a higher safety level than large reactors.

Although different reactor has its own design characteristics, a common set of design principles that they all follow during the design process can still be drawn, such as the safety-by-design [3] concept, which can be illustrated as “design the plant in such a way as to eliminate accidents from occurring, rather than from coping with their consequences”. Most of the integral SMR designs also follow passive safety rule, by relying on the natural force, passive safety can be achieved without outside power, and is thought to be effective in any circumstances [4], which greatly enhance the reactors’ inherent safety ability and help to prevent accident from progressing into a disaster..

There are several typical advanced integral SMRs that are fairly active in the domain of SMRs, such as mPower from Babcock&Wilcox; NuScale from Nuscale Power; W-SMR from Westinghouse Electric; IRIS (International Reactor Innovative and Secure) from Westinghouse Consortium; SMART (System integrated Modular Advanced Reactor) from KAERI (Korea Atomic Energy Research Institute). There are lots of articles and reviews that introduce or summarize the features of these particular SMR designs, but the abundant information maybe dazzle one’s eyes from seeing the true similarities and differences of the integral SMR designs. By thoroughly comparing all of these SMR designs, we find out that integral SMRs share lots of similarities, and these similarities together formed the general characteristics of SMR design, such as integral RPV and OTSG. While, the differences that diversifies SMRs mainly owe to different ESF designs. ESF in most integral SMRs is designed to cool the reactor and mitigate the consequence of accident passively, it consists of two parts, namely PSIS (Passive Safety Injection System) and PRHRS. According to different residual heat removal approach of PRHRS, SMRs’ ESF designs could be roughly classified into two categories, namely primary side ESF connection and secondary side ESF connection [5].

In this paper, an integral SMR simulation model with primary and secondary loop system is built by using thermal-hydraulic code Relap5, which is based on the similar design features that shared by most of integral SMRs. After a stable operation of primary and secondary coolant system is reached, two different designs of ESF are separately added to this model. The postulated accidents in this paper are station blackout and SBLOCA, and they are introduced separately to further investigate the performance of SMR model with different ESFs.

2. INTRODUCTION ON SIMULATION MODEL

In this section, a brief introduction on the simulation model will be conducted. The introduction contains three parts, and they are model introduction, design parameters and design assumptions.

2.1. Introduction of Simulation Model

As is discussed in the former section, integral SMRs share a lot of similar design features. These features origin from similar design principles, which at one hand enhance the reactor resilience, and at another facilitate easy use of many passive safety features [6]. Fig. 1 shows two simplified integral SMR simulation models. In these two cases, primary and secondary coolant system designs are kept the same, and the only difference lies in the design of ESF.

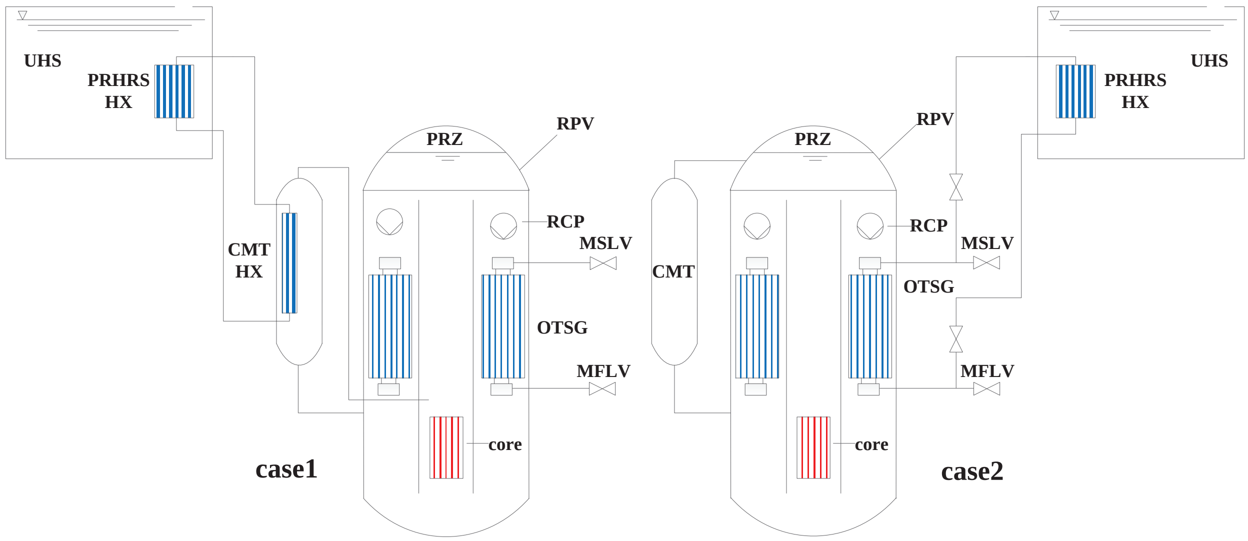


Figure 1. Schematic Diagram of Two Model Cases.

In reference with the design of W-SMR, ESF in case1 is connected to the primary side of coolant circuit, and a few simplifications have been conducted on the simulation model, such as the design of passive safety system and passive recirculate system. As in case1, for the reason of high elevation of CMT (Core Makeup Tank), cold water flows directly into RPV when accident occurs. Hot reactor coolant will enter CMT and be cooled by the heat exchanger immersed in CMT. The heat will be transferred by secondary natural circulation in PRHR loop, and be rejected to UHS (Ultimate Heat Sink). By the two natural circulations: RPV and CMT, CMT and PRHRS HX, the reactor residual heat is constantly removed.

The simulation model of case2 represents the design of ESF secondary connection, which is widely used in SMR designs such as IRIS, SMART and NuScale. In case2, ESF is connected to the secondary coolant circuit. By connecting PRHRS directly with OTSG for heat removal, primary circuit side changes little. For its simplification, this kind of design is used by many SMRs. When accident happens, the MFIV and MSIV (Main Feedwater/Steam Isolation Valve) will be closed by a signal of reactor protection system, and the PRHRS isolation valves will be opened simultaneously. Superheat steam flows out of OTSG and into the PRHRS HX, and then is condensed to water there. Cooled water flows downward to enter OTSG and absorbs residual heat from primary circuit side once again. Natural circulation is achieved in both primary loop and the PRHRS loop, and the residual heat is continuously extracted from primary coolant system to UHS.

CMT in case2 is used for making up water storage of RPV, and as assumed in the simulation, that it only comes into function when the water level and pressure in RPV drop to certain extent. In this paper, CMT is specifically used in SBLOCA calculation.

2.2. Design Parameters of Simulation Model

The simulation model is built by using best estimate Relap5/Mod3.2 code, and the design parameters of the model are in reference to the typical parameters that shared by most integral SMRs. It should also be noted that reference [7] provides some useful ideas in building the simulation model for coping with two-phase instability. Some major design parameters of the model are listed below, as in Table I.

Table I. Major parameters in simulation model

Parameter	Value
Initial core power	525.0MW
Reactor core inlet temperature	565.2K
Reactor core outlet temperature	601.4K
Pressurizer pressure	15.45MPa
Primary coolant flow rate	2497.0kg/s
Initial feedwater flow rate	263.0kg/s
OTSG pressure	5.5MPa
Superheat of steam	46.0K

2.3. Assumptions in Simulation Model

In this paper, the analysis is focused on comparison of different performance in SMR model with two different ESF design. For the sake of simplifying the issue, the primary and secondary coolant systems and the ESF design are simulated with a lot of simplifications.

2.3.1. Decay heat curve

When the reactor scram trip is triggered, control rods are immediately inserted into reactor core by gravity. Hence the fission power decreases rapidly, and the fission product decay heat becomes the main part of reactor power, and it decreases with time. In this paper, a conservative ANS-73 decay heat curve [8] with a 1.2 multiplication factor is used, which is shown in Fig. 2.

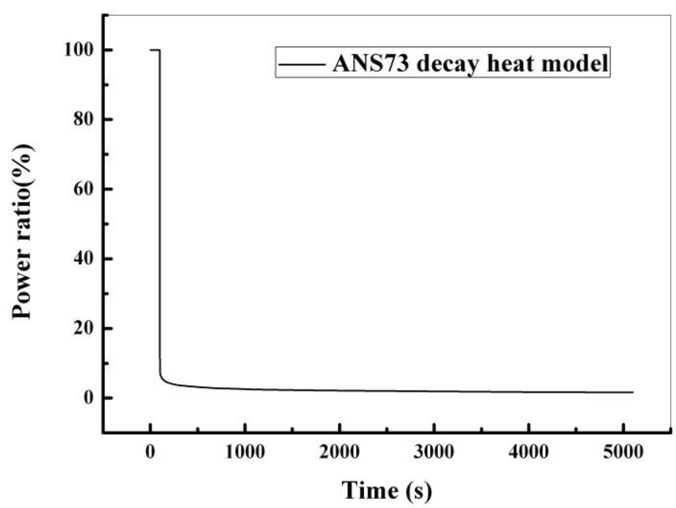


Fig 2. The Decay Heat Curve.

2.3.2. Reactor trip sequence

In two cases, most of the trips are assumed to be the same as is shown in Table. 2, except for the CMT in SBLOCA of case2, which only come into function when there is low pressure and low water level in RPV.

Table Π. Reactor trip sequence

Event	Event description	case 1	case 2
1	Accident occurrence Pump coastdown Reactor scram Feedwater decrease	100.0s	100.0s
2	MFIV closure	101.0s	101.0s
3	MSIV closure	101.0s	101.0s
4	PRHRS valves opening	106.0s	106.0s

2.4. Summary

The aim of this paper is to draw some general conclusions instead of solving practical engineering problems, thus the simulation model is rather simple. However, with all major features of SMR included, the simulation model can fulfil the requirement of analysis, and could provide us confidential results.

3. RESULTS AND DISCUSSIONS

After the simulation model operates stably for an enough of time, station blackout accident and SBLOCA is separately introduced. After a few seconds delay, ESF comes into function. During the whole accident calculation time, both two cases function well. However, there are still many differences between them, and a careful analysis is worth doing to find out how different ESF designs influence reactor safety performance.

3.1. Station Blackout Accident Analysis

In the simulation model, station blackout accident happens at 100s of the calculation time, and both on-site and off-site power is cut out. Primary coolant pump and secondary feedwater pump lose power, and reactor scram is acted simultaneously, the power of reactor core decays with time. After a few seconds delay, ESF comes into function, and continuously removes residual heat to UHS as in Fig. 3.

3.1.1. Case1 responses to blackout

In case1, shortly after the power being shut down, the feedwater will be cut off in seconds, and the reactor only depends on the ESF to remove residual heat. The whole blackout response process in this case could be roughly divided into three parts, namely the transient part, transition part and long-term cooling part.

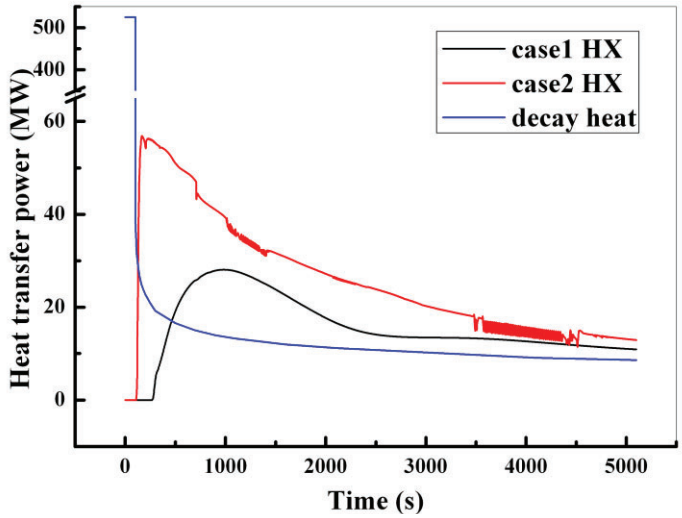
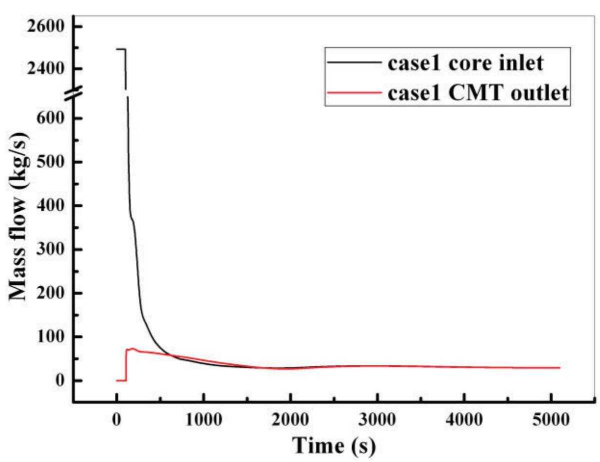


Fig 3. Blackout: Heat Transfer Power Curve.

(1) The transient part

The transient part starts from 100s, and ends at the point that CMT outlet water temperature changes to 300K, the whole part lasts 400s. During this period, in the primary circuit side, the core inlet flow mass gradually decreases with time, but for the reason of flow inertia, it remains a relatively large amount, as in Fig. 4. This large coolant flow mass is very important in helping with removing decay heat from reactor core, for during this time, the cool water that is injected into RPV is relatively small, and so is its effect in cooling. Slowly, with the flow mass in core inlet declines, the ratio of CMT outlet water flow mass to core inlet flow mass increases, and the function that CMT plays in cooling coolant system becomes more and more important, as in Fig. 5, the core inlet and outlet temperature decreases by the time.



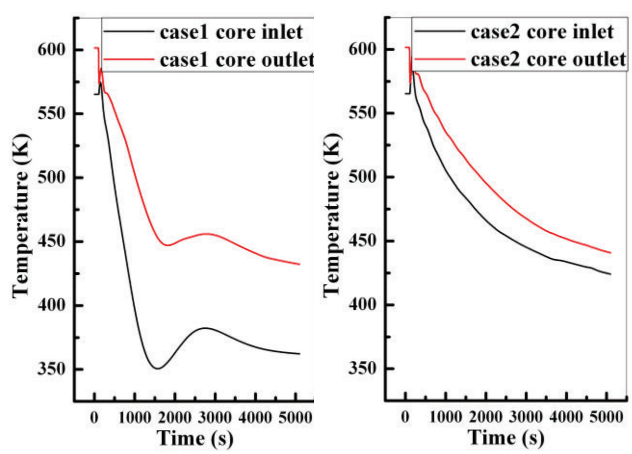


Fig 4. Blackout: Mass Flow Curve. **Fig 5. Blackout: Coolant Temperature Curve.**

The passive residual heat removal ability of ESF in this part is rather weak. During this time, residual heat that is removed to UHS by natural circulation is even less than core decay heat power, the task for cooling coolant system and reactor core is mainly undertaken by the cool water injection from CMT.

(2) The transition part

The transition part is from 500s to 2500s, and when the water temperature in CMT outlet and core inlet gradually reaches to the same level as in Fig. 6, the transition part ends. With the time goes by, in primary side, the flow mass in core inlet and CMT outlet closes to each other, and after a slightly and slowly oscillation, they reaches to the same level, as in Fig. 4. This means that the original primary coolant circuit in RPV finally finishes the transition to the natural circulation between reactor core and CMT.

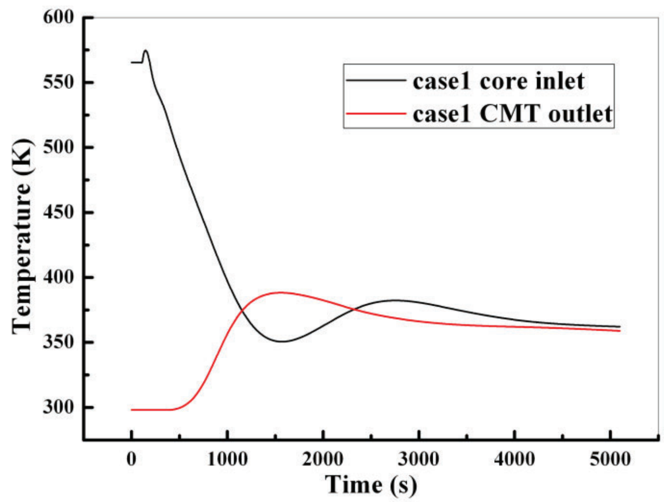


Fig 6. Blackout: Water Temperature Curve.

In PRHRS side, with the temperature of water in CMT increases, there is more residual heat being rejected into PRHR loop. The natural circulation in PRHR loop becomes stronger and stronger and PRHRS finally takes the responsibility in removing residual heat. However, the natural circulation in PRHR loop is a complicated physical phenomenon and is easily affected by many factors, such as the change of primary water temperature and core decay heat power. With the residual heat level decreases in primary side, the residual heat removal ability of PRHRS firstly reaches to the peak and then slowly decreases.

(3) Long-term cooling part

After 2500s, the PRHRS stably removes residual heat to UHS, and the accident response process comes to the long-term cooling part.

During this period, the primary coolant continuously flows through reactor core, and the temperature in core inlet and outlet slowly decreases and with a stable temperature difference. As the residual heat of the reactor system constantly decreases, as Fig. 3 shows, at the later time of calculation, the removed residual heat power closes to the core decay heat power.

3.1.2. Case2 responses to blackout

The process in case2 could also be divided into three parts, and with the same name. However, these parts have different time division criterion, and compared to that of case1each part has its own characteristics.

(1) Transient response part

The transient part in case2 ends at the point that water temperature in core inlet reaches to its high peak, the time domain is 100s-160s. Compared to case1, case2 spends a shorter time in transient part.

PRHRS in case2 is connected to OTSG, after 6s' delay. The high temperature steam flows upward and into the PRHRS HX. The steam will be condensed to water and flow back into OTSG. During the short time after accident occurs, the heat that is transferred from primary side to secondary side decreases, which owes to the power decay in reactor core and the water mixture of high temperature and low temperature in RPV. However, the amount of residual heat that is transferred to PRHR loop is still too much for the weak secondary natural circulation. Residual heat then deposits in OTSG secondary side, and promotes water to evaporate into steam, which also greatly helps with the development of secondary natural circulation. As Fig. 3 shows that, the residual heat removal power in case2 abruptly increases during the transient part, and reaches to the peak at the end of this part.

In primary side, although the reaction of PRHRS is fast and it constantly removes residual heat, but compared with the large coolant sensible heat, the residual heat removal ability is still inadequate, which leads to the large mass of coolant flows out of OTSG primary side without sufficient cooling. Therefore, the core inlet water temperature gradually increases, as in Fig. 5.

(2) Transition part
The transition part in case2 also takes shorter time, from 160s to 700s. During which period the flow mass in primary side gradually decreases to a relatively stable level of 125kg/s, and the natural circulation in primary and secondary side cooperates with each other in stably removing residual heat.

The flow resistance slows primary coolant since the accident happens, but the flow mass will not always decreases, with the help of heat removal by OTSG secondary side, a natural circulation between reactor core and OTSG is gradually established, and the driving pressure from the density difference between riser and downcomer forces coolant to flow continuously. In secondary side, the natural circulation also develops with time, and adapts to the requirement of residual heat removal in primary side.

(3) Long-term cooling part
After 700s, the response process comes to the long-term cooling part. During this period, the primary coolant stably flows through reactor core, and the temperature in core inlet and outlet slowly decreases, and so the RPV pressure.

3.1.3. Summary

As the former discussions show that, ESFs in both two cases function well under blackout accident scenario and the residual heat is constantly removed to UHS. In conclusion, several general characteristics are summarized as follows:

- In case1, the residual heat removal process needs longer time to build. After a few seconds delay, the residual heat that removed by PRHRS HX gradually increases to the peak, and then slowly decreases. For an elegant of time, the heat power that is rejected to UHS remains larger than the reactor core decay heat power. In case2, shortly after PRHRS is connected to the OTSG, the amount of removed residual heat abruptly reaches to the peak, and then slowly decreases. During the whole residual heat removal process, PRHRS removes the heat relatively stable, except for some slight oscillation parts.
- According to Fig .3 the heat power that is removed to UHS in case2 is obviously bigger than that in case1in most time, but in the later stage of accident response process, they reaches to the same level, and slowly close to core decay heat power.
- Both of the two cases meet the residual heat removal requirement during blackout accident, the residual heat is continuously removed to UHS, and the reactor coolant temperature decreases by the

time.

The preliminary analysis shows that both two cases meet the residual heat removal requirement, and could keep reactor safe for an elegant time during station blackout accident.

3.2.SBLOCA Analysis

In the simulation model, SBLOCA happens at 100s, and the power is cut off simultaneously. When the accident happens, the break damages the integrity of RPV. As to the reason of large pressure difference between inside and outside RPV, coolant quickly flows out, and the pressure in RPV abruptly decreases. Although the performances in two cases are different, results as in Fig. 7 show that both of them can keep the core well covered for a relatively long time.

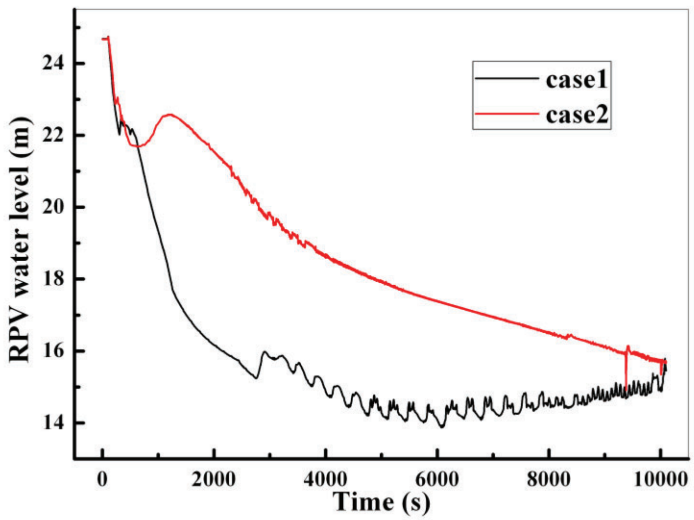


Fig 7. SBLOCA: RPV Water Level Curve.

3.2.1. Case1 responses to SBLOCA

The response process to SBLOCA in case1 is very similar to that of blackout accident. Both two processes have same three parts, and with same division criterion. To be brief, in the following part, we neglect the similarities, and only focus on analyzing some distinctive characteristics in the SBLOCA performance.

(1) In primary side, with the coolant flows to the outside through the break, the water storage in coolant system continuously decreases. The outward flow of coolant undermines flow inertia of original circulation, and as a result, helps with the transition of original circulation to a new one, which is combined by reactor core and CMT.

(2)After the integrity of RPV is broken, the pressure constantly decreases, and the saturation temperature decreases simultaneously, and the high temperature water in RPV starts to evaporate. Around 500s, the water temperature in core outlet reaches to saturation temperature, and evaporation happens. With the steam flows into CMT, the cool water stored in CMT instantly injects into RPV and cools the reactor core, this makeup of water increase the water level in RPV, as in Fig. 7. After a while, the water temperature in core outlet falls below saturation temperature, and the evaporation simultaneously stops.

However, the RPV pressure still decreases, and the evaporation in core outlet will happen once again for the sake of inadequate cooling. This whole process will continually recur to the end of calculation, and the oscillation of water temperature change in core outlet can be found in Fig. 8.

(3)As Fig. 9 shows that, the coolant flow mass in core inlet has an obvious vibration during calculation. This vibration owes to the unbalanced water gravity pressure between riser and downcomer, and the water is forced to constantly flow between two parts. However, the general trend of flow mass in CMT core inlet accords with the CMT outlet water flow mass.

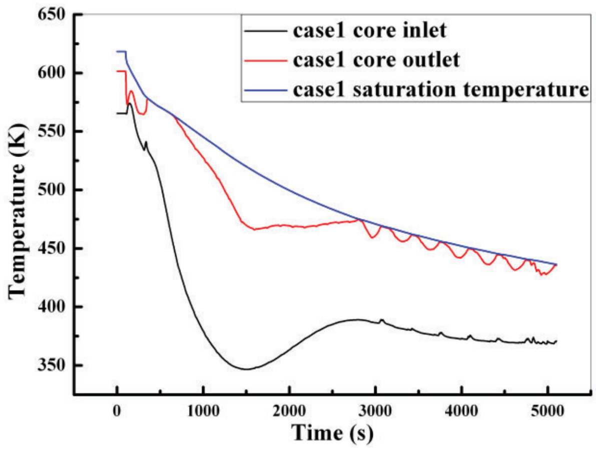


Fig 8. SBLOCA: Coolant Temperature Curve.

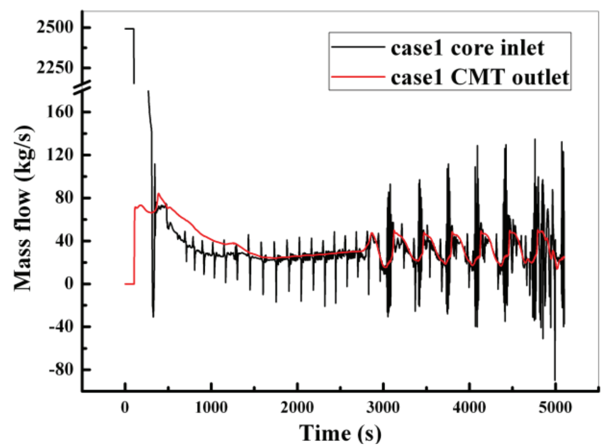


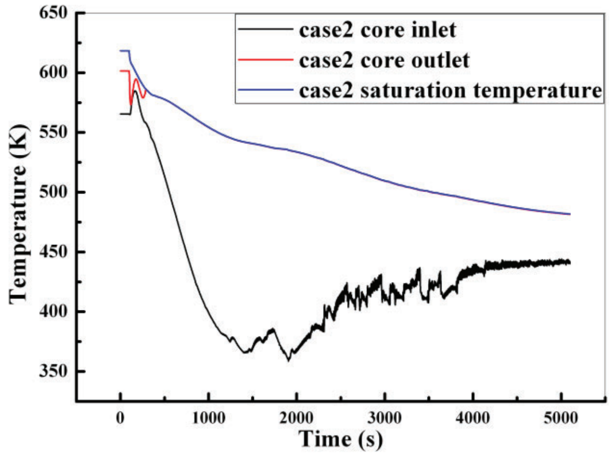
Fig 9. SBLOCA: Water Mass Flow Curve.

3.2.2 Case2 responses to SBLOCA

A CMT is added to the original case2 simulation model for making up RPV water storage during SBLOCA analysis. CMT will come into use only when the valve under it is tripped to open in terms of low water level and low pressure in RPV. According to the calculation result, this valve opens at 228s. As a result the whole accident response process can be roughly divided into three parts, namely early transient part, CMT function part and long-term leaking part.

(1) Early transient part

Before CMT comes into function, the calculation model is similar to that of blackout model, except for the break on top of RPV. Although the break decreases saturation temperature in RPV, the water temperature in core outlet as in Fig.10 shows, still bellows the saturation. With almost no evaporation undermines the primary coolant flow, the flow mass of primary circulation keeps in a relatively large amount as in blackout. And the water that is leaked outside during this time, mostly from the evaporation of high temperature water stored in pressurizer zone. Therefore, the break brings little changes to the accident performance in SBLOCA, when it is compared with blackout accident performance.



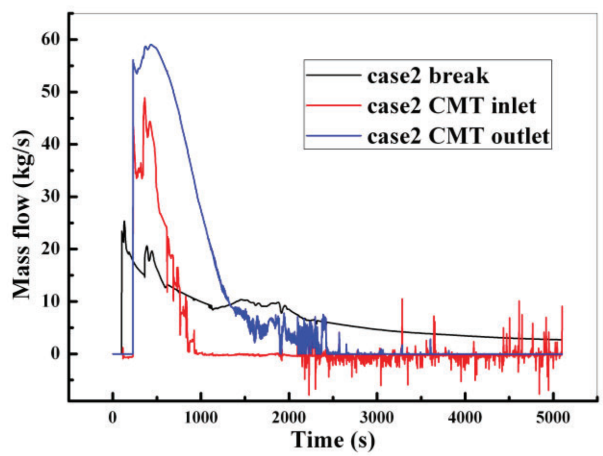


Fig 10. SBLOCA: Coolant Temperature Curve. **Fig 11. SBLOCA: Water Mass Flow Curve.**

(2) CMT function part

The check valve under CMT controls CMT to replenish water intermittently as in Fig. 11, and the CMT function part that we describe here is the first long period of replenishment, which from 228s to 2500s.

With the pressure decreases, the temperature of saturation decreases faster than that of coolant water, and the water in core outlet starts to evaporate. The occurrence of evaporation undermines primary coolant circulation. As a result of, the heat amount that is transferred from primary to secondary side declines, and so as to the residual heat that is removed to UHS as in Fig. 12.

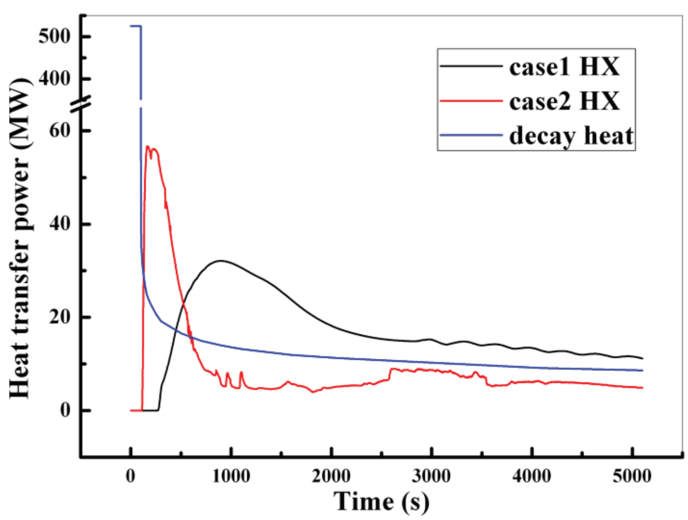


Fig 12. SBLOCA: Heat Transfer Power Curve.

Around 600s, when RPV water level reaches to the top of CMT connection, water in CMT quickly replenishes RPV by gravity force, as the replenishment amount is larger than the leakage, RPV water level starts to increase, and reaches to the peak by 1300s. During this time, the residual heat removal ability of PRHRS continuously decreases, and the injection of cool water and water evaporation take the responsibility in removing heat of the reactor.

The CMT water replenishment ability decreases with time, as to the reason of water storage decrease and hot water inflow. After 1300s, the water level of RPV falls again but in lower speed, as to the decrease in the pressure difference between RPV inside and outside.

(3) Long-term leaking part

During this time, the CMT water replenishment ability is poor and so the ability of PRHRS, the primary coolant system in RPV mainly depends on its own water storage to absorb core decay heat, and removes heat to the outside by water evaporation. As in Fig. 10, the water stored in lower part of RPV absorbs heat, and its temperature in core inlet slowly increases. However, with a large amount of water that is stored in RPV, the core remains covered for a relatively long time.

3.2.3. Summary of SBLOCA

During the SBLOCA analysis, the most important parameter that we care about is RPV water level, for once there is no enough water covering reactor core, the accident situation will become very serious. As the results in Fig. 7 show that, both two cases have good performances in keeping core covered during the calculation time, and water level is well above the top of core 5.46m. Although two cases both meet the requirement for covering the core in a relatively long time, they act in totally different ways, there are several distinct characteristics that can be drawn from former discussion:

- In case1, there is an obvious periodic oscillation in parameters such as temperature and flow mass in core outlet, which is caused by the effect of pressure decrease as is explained in former section.
- In case1, RPV water level changes very fast at first, and later with the steam flows into CMT, CMT water makes up water storage in RPV, and the water level decreases in a much slower speed. In case2, CMT works as a communicating vessel to replenish water storage in RPV, the whole compensating process is rather stable, and the water level drops in a relatively uniform speed as compared to case1.
- PRHRS in case2 does not work well except in the early stage of accident process, and its residual heat removal ability drops very fast after evaporation happens in primary circuit, and within a short time, the residual heat power that is removed to UHS by PRHRS is less than decay heat power. This means that the PRHRS in case2 cannot works normally to remove residual heat. While in case1, PRHRS removes residual heat constantly as in blackout, only with some slightly periodic oscillations.

3.3. Comparisons on Performance in Different Accidents

A comparison on the performance in different accidents of two cases is done separately in the following part, and the major differences are pointed out.

3.3.1 Case1

ESF in case1 is connected to the primary side of coolant circuit, and the design of CMT can be used for removing residual heat as well as making up water storage in RPV. For the reason of low connections of CMT, only the lower part of coolant system in RPV takes part in the natural circulation between CMT and reactor core. In blackout accident, after a few hundreds of seconds the coolant in middle and upper part of RPV almost stand still. While in SBLOCA, the same thing should have happened, but the break breaks this silence. With the pressure in RPV decreases, water saturation temperature decreases in the same time. When the coolant water in primary side reaches to saturation temperature, evaporation will happen, and then follows the periodic core cooling and CMT water injection as 3.2.1 described.

Compared with blackout accident, the break brings a lot of changes to primary coolant side, but the change to the whole accident performance trend is not very significant.

3.3.2. Case2

The SBLOCA simulation model only adds with CMT and break, but the whole response changes a lot compared to blackout results. Before the valve under CMT opens, break has little influence on primary coolant flow in SBLOCA, and the performance of blackout and SBLOCA is similar to each other, except for the occurrence of pressure drop and coolant outflow. After a while, CMT comes into function, with hot water flows into CMT instead of flowing to OTSG, the primary circulation is partially jeopardized. And with the decrease in RPV pressure, the coolant in primary circuit partially evaporates into steam, which greatly undermines the driving force in primary coolant circuit. As a result, the diminishing primary coolant circulation could not meet the demands for removing core decay heat, and the PRHRS loses most of its ability in removing residual heat.

The responses to different accident scenarios in case2 are not quite the same. In blackout, PRHRS can constantly remove residual heat to UHS and keep reactor safe, while in SBLOCA, with the primary natural circulation falls out, the reactor mostly depends on the water injection to absorb heat and keep core covered.

4. CONCLUSIONS

The results drawn from two cases under different scenarios show that, the two kinds of ESF designs could both meet the demands for keeping reactor safe, which specifically removes residual heat in blackout accident, and keeps reactor core covered for enough time.

Some general conclusion can be summarized from former discussion, that in case1, PRHRS shows a more stable performance in removing residual heat in different scenarios. While in case2, PRHRS is easy to be influenced by the change in primary coolant flow.

Further development will be concentrated in improving simulation model design, and a more detailed model will be built for accident analyzing. Thoroughly analyses for the OTSG and PRHRS HX will also be performed, to find out factors that may influence two-phase instabilities.

ACRONYMS

SMR	Small Modular Reactor
ESF	Engineered Safety Feature
RPV	Reactor Pressure Vessel
SBO	Station Blackout
HX	Heat Exchanger
PRHRS	Passive Residual Heat Removal System
SBLOCA	Small Break Loss of Coolant Water Accident
OTSG	Once-through Steam Generator
RCP	Reactor Coolant Pump
PRZ	Pressurizer
UHS	Ultimate Heat Sink
MSLV	Main Steam Line Valve
MFLV	Main Feedwater Line Valve

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