ANALYSIS ON ANTICIPATED TRANSIENT WITHOUT SCRAM (ATWS) ACCIDENTS OF THE HTR-10GT

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ABSTRACT

The 10MW High Temperature Gas Cooled Test Reactor (HTR-10) was constructed in the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University and has been operated successfully since 2003. To verify the technology of gas-turbine direct cycle, INET first planned to raise the core outlet temperature from 700℃ to 750℃ and to use a helium gas turbine to replace the steam generator (then the reactor is named as HTR-10GT). The design basis accidents and beyond design basis accidents of HTR10-GT must be analyzed again according to China's nuclear regulations for the changed operating parameters. The THERMIX code system has been used to analyze ATWS accidents induced by station blackout or by one control rod withdrawal out of the core due to a mistake. When the accidents were initiated, the protection system should trigger reactor scram signals, and in turn should lead the reactor to shutdown. But it was assumed that all the control rods in the reflectors had been blocked at the locations when reactor was operated at the rated power and the reactor could not scram. Thus the accident would continue and the reactor shutdown could only be implemented at last by its intrinsic negative temperature reactivity feedback mechanism. The ATWS accident in addition with loss of the system pressure and the ATWS induced by station blackout were also analyzed. During these accidents the maximum fuel temperature is 1242.4℃ and there is no release of any radioactivity. So the HTR-10GT is safe during the ATWS accidents studied in this paper. The paper also compares the analysis results of HTR-10GT to that of HTR-10.

KEYWORDS
HTR-10GT, ATWS, THERMIX, safety

1. INTRODUCTION

Since Lohnert and Reutler proposed the concept of modular high temperature gas-cooled reactor (MHTGR) in the end of the 1970s, several countries have paid a lot of attention to development of MHTGR for its high inherent safety and excellent future of the utility with high temperature gas [1, 2]. Several test reactors at different power levels have been constructed in the last 30 years, such as AVR and THTR-300 in Germany, Peach Bottom-1 and Fort St. Vrain HTGR in U.S., etc. Up to now, only the HTTR (30MW thermal) in Japan, and HTR-10 (the 10MW High Temperature gas-cooled test Reactor) in China are still running as test reactors, while other earlier HTGRs have been shut down for years. China now is designing and constructing a commercial demonstration HTGR power plant named as HTR-PM (High Temperature gas-cooled Reactor-Pebble-bed Module), after a 3 year suspension since the Fukushima accident.

The HTR-10 of China was the first pebble-bed modular test HTR in the world, which was designed, constructed and operated by the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University. In December of 2000, the HTR-10 reached criticality for the first time and in January of 2003 it achieved the rated power operation with a thermal power output of 10 MW at a coolant outlet temperature of 700℃ [3]. As time went on, many planned commissioning tests have been performed on HTR-10 to test the performance of sphere fuel elements and to demonstrate its passive safety characteristic, etc. The com puter codes used for the HTR-10 design were also validated by the test results in the mean time [4-7].

The HTR with a gas turbine in direct cycle power conversion mode can get higher generation efficiency. To verify this, INET first planned to raise the outlet temperature to 750℃ in the HTR-10 core with the same sphere fuels and to replace the steam generator by a gas turbine power conversion unit. The new designed reactor is named by HTR-10GT, and its main operating parameters are listed in Table I.

Table I: Main operation parameters of the HTR-10GT, the HTR-10 and HTR-PM

Core	HTR-10GT	HTR-10	HTR-PM
Power MW	10	10	250
Inlet/Outlet Temp ℃	330/750	250/700	250/750
System Pressure MPa	1.59	3.0	7.0
Helium Flow rate kg/s	4.56	4.32	96

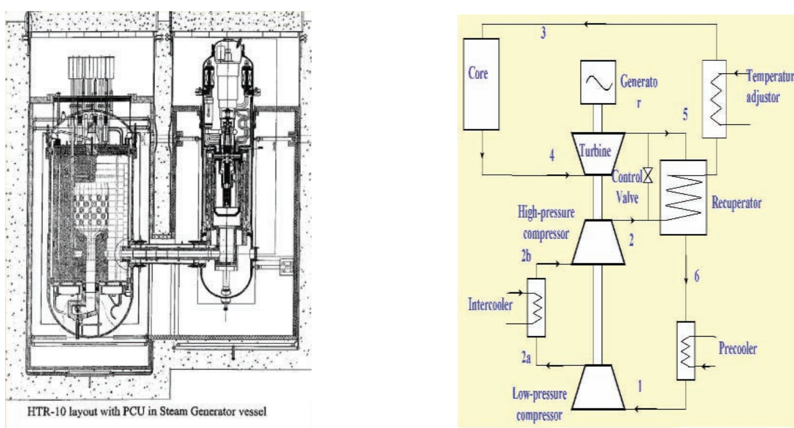


Figure 1. The Layout and Schematic diagram of HTR-10GT

The preliminary scheme of the HTR-10GT is to replace the steam generator with a helium gas turbine, while keeping pressure boundary of the primary loop system and the layout of the RPV unchanged. Figure 1 gives the layout and schematic of the HTR-10GT. The key parameters of the protection system of the HTR-10GT are similar to those of the HTR-10, but the parameters related to the secondary loop, such as flow rate of feedwater and humidity, are excluded. The limiting temperature of helium flow passing through the core inlet and outlet are increased by 50℃ and 80℃, respectively. In addition, the value of the ratio between flow rates of the primary loop and the secondary loop was changed to a normalized value of the ratio between the flow rate of the primary loop and the power of the gas turbine. The detailed parameters of the protection system of the HTR-10GT are illustrated in Table 2. The temperatures of the metal components contained in the RPV (Reactor Pressure Vessel) and the hot gas duct connecting the RPV and the pressure vessel of the PCU (Power Conversion Unit) were raised as the helium temperatures at the core inlet and outlet increased, but the components were unchanged due to their temperatures were still below the safe margin of the HTR-10.

Table II: The parameters of protection system

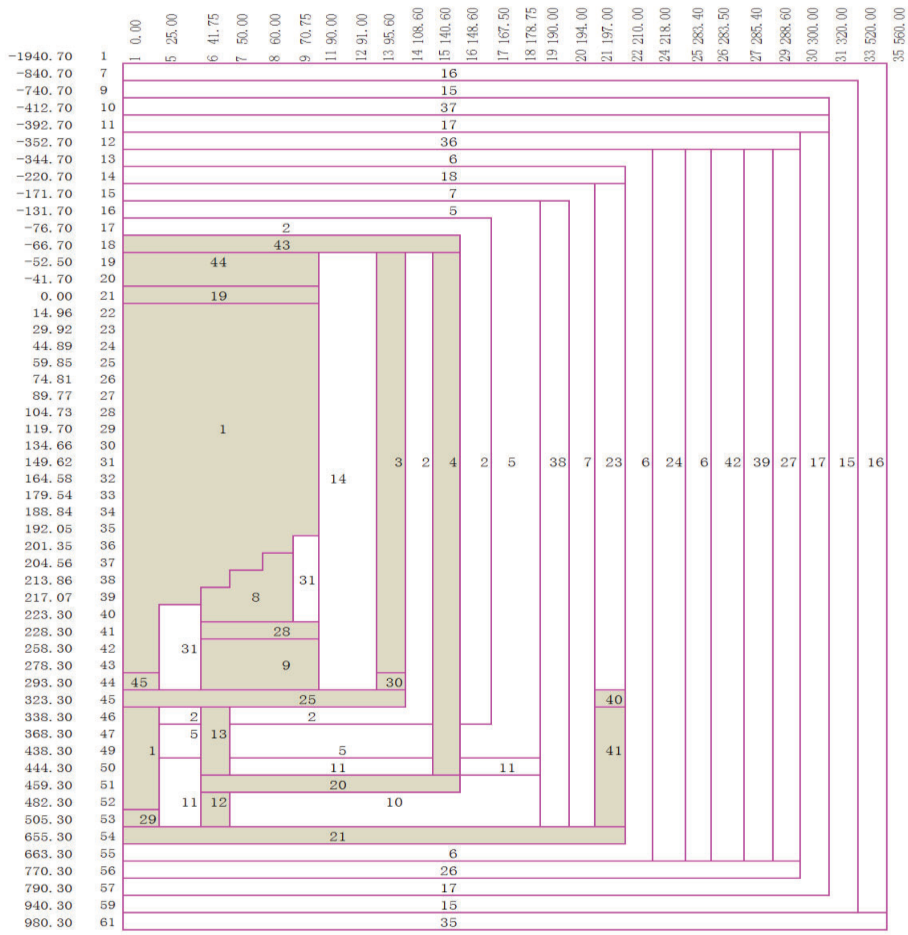
Protection parameters	Triggering value	Triggering error	Delay time
The neutron flux of full power level	≥120%	3%	1 s
The neutron flux of middle power level	≥200%	10%	1-30 s
The reactor period	≤20s		1 s
The temperature of hot helium	≥790℃	10℃	8 s
The temperature of cold helium	≥345℃	4℃	8 s
The relative varying of the primary flow rate	0.75≤or≥1.3	3%	1 s
The absolute sliding rate of the primary loop pressure	≥.03MPa/min	0.053MPa/h	1 s
The negative relative varying of the turbine power	≥25%/min	3%	1s

The passive safety characteristic of the HTR-10 has been approved by the National Nuclear Safety Administration (NNSA) of China, after analysis on design basis accidents (DBA) and beyond design basis accidents (BDBA) had been completed [8]. However, safety analysis of the HTR-10GT at operating and accidental states should be certified again because the main operating parameters have changed, according to China's nuclear regulations. The paper studied three DBA cases induced either by station blackout or by one control rod withdrawal out of the core with a mistake. Transient analysis on the three cases was performed by THERMIX code and the safety characteristics of the HTR-10GT were discussed in detail in the paper. The results may be meaningful to the HTR-PM, as the helium temperature at the core outlet of the HTR-PM is similar to HTR-10GT [9].

2. ANALYSIS TOOLS AND MODELS

The ATWS accidents were analyzed by THERMIX code system, a thermal-hydraulic code introduced from Germany, which is able to simulate normal operating states and accidents of pebble-bed HTGRs. THERMIX code consists of calculation modules of neutron kinetics (Kinex), solid heat conduction in reactor (Thermix), gas convection in reactor (Konvek) and fluid flow simulation in primary circuit (Kismet). A brief description of major modules in THERMIX has been presented in reference [8].

The THERMIX model of the HTR-10GT has been established with some reasonable approximation and simplification to its structures and components. The geometry and meshes of the core model could be seen in Fig. 2. The meshes are kept consistent with HTR-10 in order to do a better comparison.



1 the core; 2, 14, 31 the side reflectors without channels; 3 the side reflectors within control rod channels; 4 the side reflectors withi cooling channels; 5 the carbon brick; 6 the reactor pressure vessel; 7 the core shell; 8 the top part of the bottom reflector within flow channels; 9 the lower part of the bottom reflector within flow channels; 10, 11 the steel support in the core bottom; 12 the annulus passage of cold helium at the core bottom; 13 the leakage inside the metal internals; 15 the concrete; 16 the side boundary of flow; 1 the thermal insulation; 18 the top helium cavity in the RPV; 19 the core inlet cavity; 20 the flow passages around the core bottom; 2 the bottom helium cavity in RPV; 23 the helium gap between the RPV and the core shell; 24 the side air cavity outside the RPV; 25 the outlet cavity at the core bottom; 26 the bottom air cavity outside the RPV; 27 the side part of the reactor cavity; 28 the cavity inside the bottom reflectors; 29 the inlet throttle of the refueling pipe; 30 the outlet throttle of control rod channels; 35 the bottom boundary of flow; 36 the top air cavity outside the RPV; 37 the air cavity in the top of the reactor cavity; 38 the side helium gap inside the core shell; 39 the cavity cooling system; 40 the helium inlet channel in the core shell; 41the annular flow passage inside th core shell; 42 the air gap outside the thermal insulation of the reactor cavity; 43 the helium cavity in the top reflectors; 44 the heliun passage in the top reflectors;

Figure 2. The THERMIX Model of the HTR-10GT Core

3. DESCRIPTION OF THE ACCIDENTS

The paper simulated three ATWS cases of the HTR-10GT. The first ATWS studied here is the developing and proceeding of the accident induced by station blackout during normal operation, if all the control rods were blocked. Once the gas turbine became offline, the fission heat could not transfer out from the primary loop and the temperature of the core and the system pressure increased very quickly. But control rods were blocked and the reactor could not scram. Thus it initiated a Beyond Design Basis Accident (BDBA) with a very low probability. After that, the core temperature and the system pressure continued to increase, but at last the reactor shut down itself because of the negative temperature reactivity feedback mechanism. The residual decay heat would be removed out of the core by the cavity cooling system through conduction, convection and radiation heat transfer of the in-vessel structure and reactor core.

The second case is the ATWS caused by one control rod withdrawal out of the HTR-10GT core, which is the development of the DBA accident of one control rod withdrawal out of the core by a mistake. During the accident the main protective actions which the reactor protection system takes include dropping the control rods into the reflectors by gravity, trip of the primary circuit blower and the gas turbine, isolating the primary system, etc. When the reactor control system was disabled or operators made a mistake to withdraw a control rod out of the reflector, the core power increased quickly and the reactor should scram after the protection signal of dropping the control rods by gravity was triggered. The system of accident detecting and protecting measures of the reactor would be triggered by the following three signals: too high of the neutron flux in the power measuring range (>=1.23); too high of the helium temperature at the core outlet (>=743℃); and the absolute sliding rate of the system pressure is larger than 0.031 MPa/min.

The first scram signal was “too high of the neutron flux in the power measuring range” and was skipped as usually done in safety analysis. If the control rods were blocked after the second scram signal “too high of the helium temperature of the core outlet” sent out, the reactor could not scram and would initiate a level IV accident (the utmost limit accident) with a very low probability. After that, the reactor core would be heated by the fission and decay heat of the fuel as the accident continued, and the core temperature and the system pressure would increase. The reactor shut itself down in the end because of the negative temperature reactivity feedback mechanism. The residual decay heat would be removed out of the reactor vessel by the cavity cooling system.

The last case studied here is the accident which is also caused by one control rod withdrawal out of the core. It is the further evolution of the DBA accident and at the same time the system pressure lost for some reason. During the accident the main protective actions which the reactor protection system takes were similar with those in the previous case. As the core power increased quickly, the reactor should scram after the protection signal of dropping the control rods by gravity was sent out. The accident detecting and protecting system would be triggered by the following two signals: too high of the neutron flux in the relative power range referenced to the rated power (>=1.23); and the absolute sliding rate of the system pressure is larger than 0.031 MPa/min.

The first scram signal was skipped as well. If the control rods were blocked after the second scram signal was detected, the reactor could not scram and would initiate a level IV accident with a very low probability. After that, the reactor core would be heated by the fission and decay heat as the accident continued, and the core temperature and the system pressure would increase, but at last the reactor shut itself down because of the negative temperature reactivity feedback mechanism. The residual decay heat would be removed out of the reactor vessel by the cavity cooling system through conduction, convection and radiation heat transfer of the in-vessel structure and reactor core.

4. HYPOTHESIS AND CALCULATING CONDITIONS

The safety criterion of HTR-10 is that the fuel peak temperature does not exceed 1230℃ under all hypothesis accidents [6]. For the HTR-10GT, the limit of accident fuel peak temperature is raised to 1620℃ after the performance test of the sphere fuel elements which are also used in HTR-PM with a temperature limitation of 1620℃.

The positive reactivity inserted by the control rod withdrawal accident was determined by the initial state of the reactor and the position of the control rod in the reactor. Under rated power, the reactivity inserted during the ATWS accident was shown in Fig.3

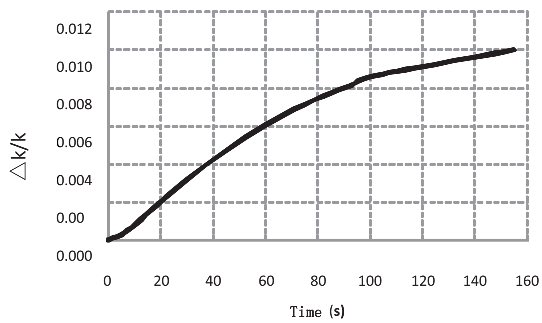


Figure 3. The Reactivity Inserted by a Control Rod Withdrawal

This paper analyzed the typical operating case of HTR-10GT with full power. The initial conditions of the reactor when the ATWS accident happened were supposed as following:

- The operating power of the core is the rated power with an addition of 5% of measuring error;
- The initial cooling flow through the core at beginning is 86% of the rated flow;
- The failure of the control and adjustment system of the primary pressure;
- The cooling flow decreased to 0.001 kg/s in 0.25s after the protection measure action;
- In consideration of the longest delay time of acting of the protecting measures;
- All the control rods in the reflections were blocked and failed to fall.
- The core was in equilibrium state at beginning and the total reactivity induced by a control rod withdrawal is 1%;
- One control rod in the reflector was drawn up at a speed of 1 cm/s;
- With consideration of the worst effect of the measuring error of reactor instruments on the trigger of the scram signal;
- In consideration of the longest delay time of acting of the protecting measures;
- The loss of the system pressure happened in 0 second in the last case;

5. CALCULATING RESULTS

5.1. ATWS Induced by Station Blackout

For HTR-10GT, the initial core and the equilibrium core would have different physical characteristics. The HTR-10GT core does not have one 'truly' initial state since the HTR-10 has been running for years. The paper studied the ATWS sequence of an initial core state, which is similar to HTR-10 in order to analyze the accident consequence and to get more information. The case for an equilibrium core was simulated, too. Table III&IV gave the main events after the station blackout happened. The accident consequences of HTR-10 were also compared in those tables. Fig.3~10 shows the varying plots of some main parameters of HTR-10GT during the ATWS accident for both initial core and equilibrium core, which includes the reactor power, the maximum fuel temperature, the average fuel temperature, the temperature feedback reactivity, the system pressure, the main loop flow rate, and the helium temperature at the core inlet and outlet.

Once the station blackout happened, the gas turbine became offline and a scram signal should be detected. At the same time all the control rods should fall into reflectors because of gravity, but they were supposed to be blocked. On the other hand, protection measures acted to isolate the second loop. Then the core temperature increased quickly and induced a negative reactivity, which can be seen in Fig. 4. Thus the reactor would shut down by itself because of its negative temperature reactivity feedback mechanism. The peak fuel temperature during the accident was 1066.5℃and 992.8℃ for the initial core and the equilibrium core, respectively, while those temperatures are 1033.0℃ and 950.0℃for HTR-10. The peak fuel temperature of HTR-10GT is about 43℃ higher than that of HTR-10, and it is lower than 1230℃ (the fuel temperature limitation of HTR-10). As the fuel temperature limitation increased to 1620℃from 1230℃, for HTR-10GT, the peak fuel temperature is far lower than the limitation, too. In another hand, the system pressure kept below 1.8 MPa during the accident, which is also far lower than the designing pressure--3.5 MPa. So the HTR-10GT is safe after the ATWS accident caused by station blackout.

Table III. The ATWS Accident Sequence of an Initial Core

Events	HTR-10GT	HTR-10
The loss of offsite power	0.s	0.0s
The negative variety rate of change of the main steam pressure ≥1.03 MPa/min	20.0s	20.s
The variety rate of the primary pressure ≥0.031MPa/min	35.8s	35.8s
The peak moment of the fuel temperature	0.0s	0.0s
The peak fuel temperature	1066.5℃	1033.℃
The reactor shutdown by itself	233s	265s

Table IV. The ATWS Accident Sequence of an Equilibrium Core

Events	HTR-10GT	HTR-10
The loss of offsite power	0.s	0.0s
The negative variety rate of change of the main steam pressure ≥1.03 MPa/min	0.54s	20.0s
The variety rate of the primary pressure ≥0.031MPa/min	36.0s	36.0s
The peak moment of the fuel temperature	97.2 s	146.0s
The peak fuel temperature	992.8℃	850℃
The reactor shutdown by itself	256s	284s

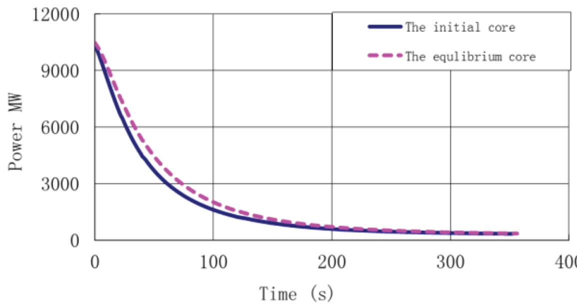


Figure 4. The Power Curve of the ATWS Induced by Station Blackout

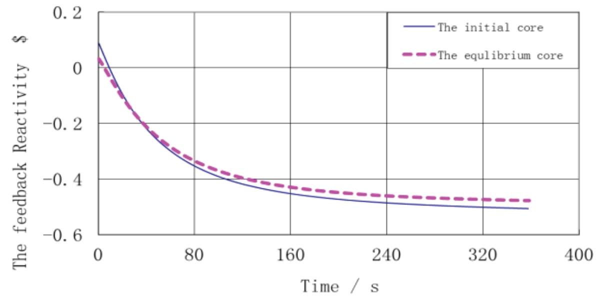


Figure 5. The Feedback Reactivity Curve of the ATWS Induced by Station Blackout

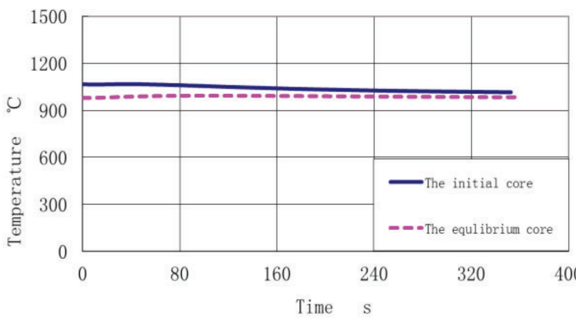


Figure 6. The Peak Fuel Temperature Curve of the ATWS Induced by Station Blackout

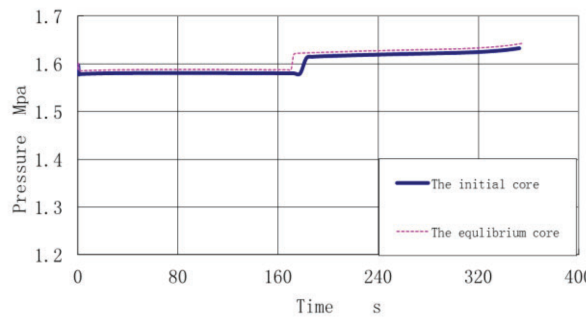


Figure 7. The System Pressure Curve of the ATWS Induced by Station Blackout

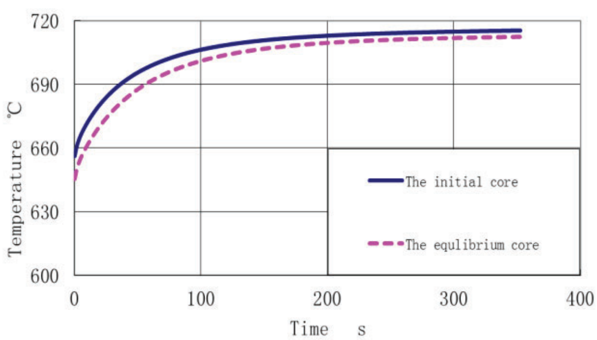


Figure 8. The Mean Temperature Curve of the ATWS Induced by Station Blackout

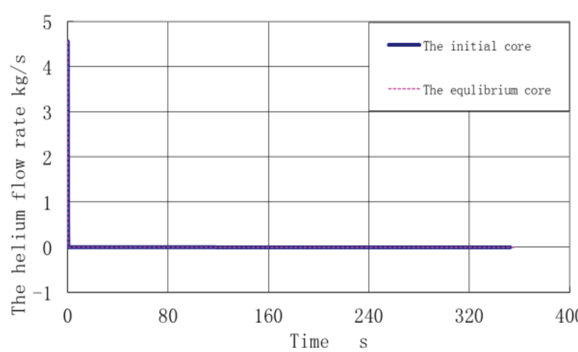


Figure 9. The Helium Flow Rate Curve of the ATWS Induced by Station Blackout

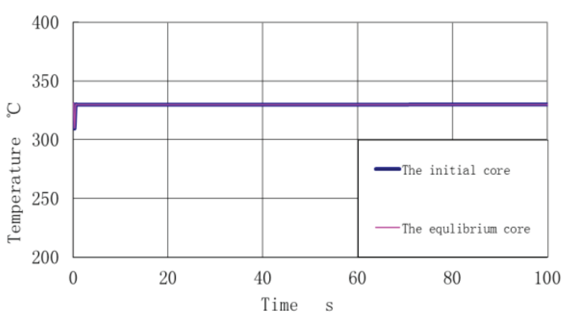


Figure 10. The Inlet Temperature Curve of the ATWS Induced by Station Blackout

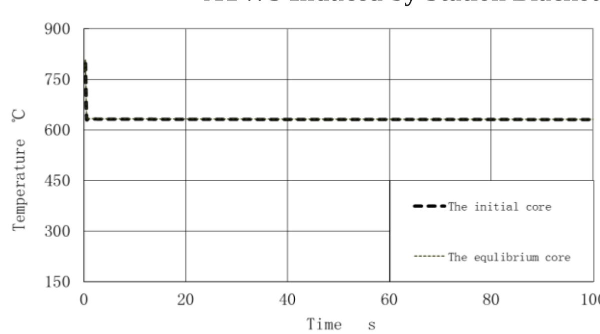


Figure 11. The Outlet Temperature Curve of the ATWS Induced by Station Blackout

From Table III we could see that the peak temperature of the HTR-10GT is higher than that of the HTR-10 core because the absolute value of its temperature reactivity feedback coefficient became smaller as the core operating temperature raised and Instantaneous response of temperature feedback reactivity, which could be seen from Fig.5. Thus for HTR-10GT, the peak power was higher. The peak fuel temperature increased during the accident was about 48K, which was near to 50K--the helium temperature of the core outlet raised.

Comparing the simulating results, we found that during the ATWS accident the power of an initial core increased faster than that of an equilibrium core. The reason is that the initial core has been inserted a much larger positive reactivity because of fresh fuel and a small value of absolute temperature reactivity feedback coefficient.

Fig.6 showed the initial core has peak temperature at the beginning of the accident, while the equilibrium core has a smaller increase than the beginning because the feedback procedure of temperature was very quick. Fig.8 also showed us the same result.

From Fig.10&11 we can know that the temperature of core inlet and outlet did not change much in seconds after the station blackout. This is caused by a very small flow rate, which is demonstrated in Fig.9.

5.2. ATWS Induced by One Control Rod Withdrawal

The accident consequence of an initial core and an equilibrium core for the HTR-10GT ATWS were studied here. Table V&VI listed the main events after one control rod was withdrawn out of the reflector at a speed of 1 cm/s by a mistake. The accident consequences of HTR-10 were compared in the same tables too. Figures 12~17 shows the varying curve of some main parameters of HTR-10GT during the ATWS accident for both an initial core and an equilibrium core, which consists of the following parameters: the reactor power, the maximum fuel temperature, the average fuel temperature, the temperature feedback reactivity, the total reactivity, the main loop flow rate, and the helium temperature of the core inlet and outlet.

Table V: The accident sequence with one control rod withdrawal out of an initial core

Events	HTR-10GT	HTR-10
One control rod withdrawal out of the reflector at a speed of 1cm/s by a mistake	0.s	0.0s
The neutron flux in power measuring range ≥1.23 (The signal was skipped)	10.3s	12.1s
The reactor power reached a peak	42.8s	41.1s
The peak power	28.3MW	26.4MW
The moment that the hot helium's temperature exceeded the protection value	70.8s	80.4s
The moment that the fuel temperature reached a peak	99.8s	114.0s
The peak fuel temperature	1242.4℃	1200.6℃
The reactor shutdown by itself	250.0s	300.0s

In 300 seconds after the ATWS accident had happened and the core temperature had increased, the reactor would shutdown by itself because of its negative temperature reactivity feedback mechanism. The peak fuel temperatures during the accident were 1242℃ and 1140.2℃ for the initial core and the equilibrium core, respectively, while those temperature are 1200.6℃ and 1118.3℃ for HTR-10. The peak fuel temperature of HTR-10GT is about 40℃ higher than that of HTR-10, and is a little bit higher than 1230℃. As the fuel temperature limitation was increased to 1620℃, the peak fuel temperature is far lower than the limitation. In the meantime, the system pressure kept below 1.8 MPa during the accident, which is also far lower than the designing pressure--3.5 MPa. So the HTR-10GT is safe after the ATWS accident of a control rod withdrawal out of the core.

Table VI: The accident sequence with one control rod withdrawal out of an equilibrium core

Events	HTR-10GT	HTR-10
One control rod withdrawal out of the reflector at a speed of 1cm/s by a mistake	0.s	0.0s
The neutron flux in power measuring range ≥1.23 (The signal was skipped)	9.5s	10.5s
The reactor power reached a peak	42.1s	40.9s
The peak power	36.9MW	34.8MW
The moment that the hot helium's temperature exceeded the protection value	49.1s	54.9s
The moment that the fuel temperature reached a peak	152.3s	192.0s
The peak fuel temperature	1140.2℃	1118.3℃
The reactor shutdown by itself	276.0s	300.0s

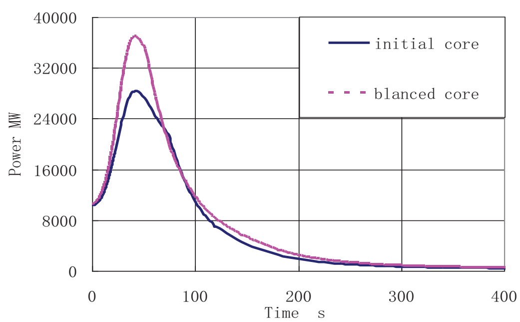


Figure 12. The Power Curve of ATWS Accident Induced by One Control Rod Withdrawal

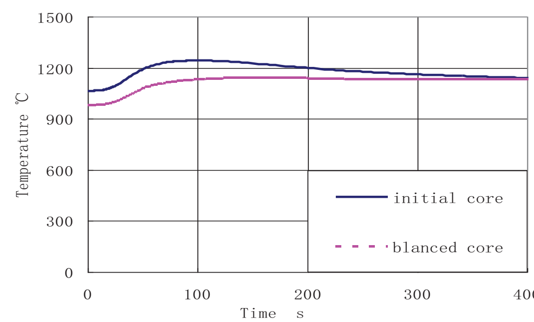


Figure 13. The Fuel Maximum Temperature Curve of the ATWS Induced by a Control Rod Withdrawal

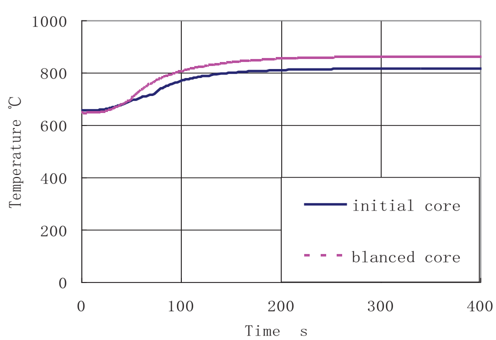


Figure 14. The Fuel Average Temperature Curve of the ATWS Induced by One Control Rod Withdrawal

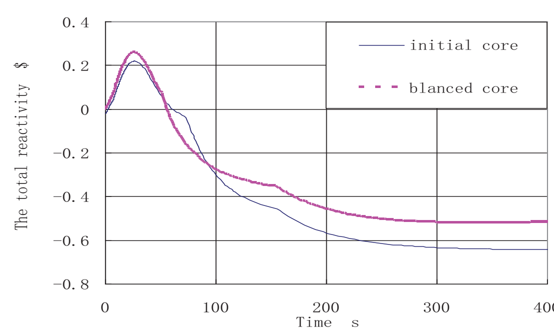
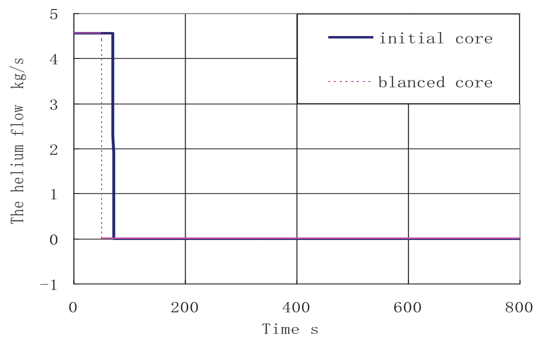


Figure 15. The Total Reactivity Curve of the ATWS Induced by One Control Rod Withdrawal



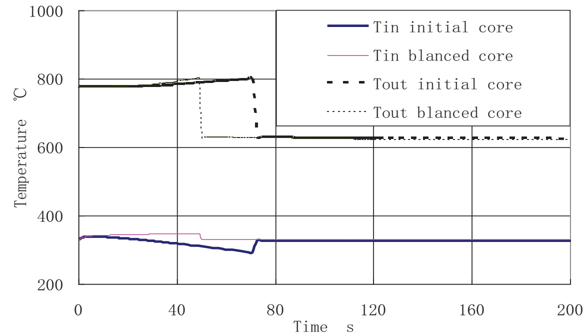


Figure 16. The Main Loop Flow Curve of the ATWS Induced by One Control Rod Withdrawal

Figure 17. The Core Inlet and Outlet Temperature Curve of the ATWS Induced by One control Rod Withdrawal

From Table V we could see that the neutron flux of the HTR-10GT core increased more rapidly than that of the HTR-10 core because the absolute value of its temperature reactivity feedback coefficient became smaller as the core operating temperature raised. Thus for HTR-10GT, the power increased rapidly and the peak power was higher, which induced an earlier scram signal for the second time. The peak fuel temperature increased during the accident was about 42K, which was smaller than 50K--the helium temperature of the core outlet raised.

Comparing the simulating results, we found that during the ATWS accident the power of an initial core increased slower than that of an equilibrium core, so the peak power was a little bit lower and the scram signal of the hot helium appeared late, which caused a higher peak fuel temperature. The reason is that the initial core has a small value of absolute temperature reactivity feedback coefficient.

5.3. ATWS Induced by One Control Rod Withdrawal Under Loss of the System Pressure

The last case studied in the paper is the ATWS induced by one control rod withdrawal out of the HTR-10GT core in addition with loss of the system pressure, in the same time when the accident happened. Accident consequences both for initial core and equilibrium core were simulated. Table VII&VIII showed the main events since one control rod was withdrawn out of the reflector at a speed of 1 cm/s by a mistake and accompanied by the loss of the system pressure. The accident consequences of the HTR-10 were compared in tables VII&VIII too. Figure 18~25 shows varying of the following main parameters of the HTR-10GT during the ATWS accident for both an initial core and an equilibrium core: the reactor power, the peak fuel temperature, the average fuel temperature, the temperature feedback reactivity, the total reactivity, the main loop flow rate, The temperature feedback reactivity, and the helium temperature of the core inlet and outlet.

In less than 400 seconds after the ATWS accident had happened and the core temperature had increased, the reactor would shutdown by itself because of its negative temperature reactivity feedback mechanism. The peak fuel temperature during the accident was 1203.4℃ and 1170.1℃ for the initial core and the equilibrium core, respectively, while for HTR-10 those temperatures are 1109℃ and 1053.3℃, respectively. The peak fuel temperature of HTR-10GT is about 94℃ higher than that of HTR-10, and is lower than 1230℃. So the HTR-10GT is safe after the ATWS accident of a control rod withdrawal out of the core.

Table VII: The ATWS accident sequence of an initial core

Events	HTR-10GT	HTR-10
One control rod withdrawal out of the reflector at a speed of 1cm/s by a mistake	0.s	0.0s
The absolute sliding rate of the system pressure ⩾ 0.031 MPa/min (The signal was skipped)	0.s	0.0s
The neutron flux in power measuring range⩾1.23	10.3s	12.1s
The reactor power reached a peak	37.3s	41.1s
The peak power (MW)	15.34	13.42
The moment that the fuel temperature reached a peak	127.5s	100.5s
The peak fuel temperature	1203.4℃	1109.0℃
The reactor shutdown by itself	347.5s	334.0s

Table VIII: The ATWS accident sequence of an equilibrium core

Events	HTR-10GT	HTR-10
One control rod withdrawal out of the reflector at a speed of 1cm/s by a mistake	0.s	0.0s
The absolute sliding rate of the system pressure ⩾ 0.031 MPa/min (The signal was skipped)	0. s	0.0s
The neutron flux in power measuring range⩾1.23	9.5	10.5s
The reactor power reached a peak	50.2s	45.1s
The peak power (MW)	22.28	16.43
The peak fuel temperature	1170.1℃	1053.3℃
The reactor shutdown by itself	386.3s	364.0s

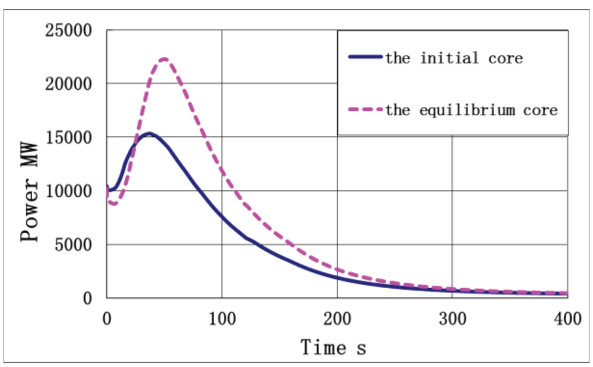


Figure 18. The Power Curve of the Last ATWS

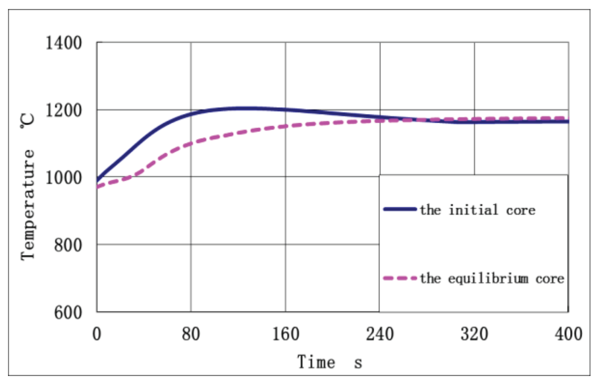


Figure 19. The Fuel Peak Temperature Curve of the Last ATWS

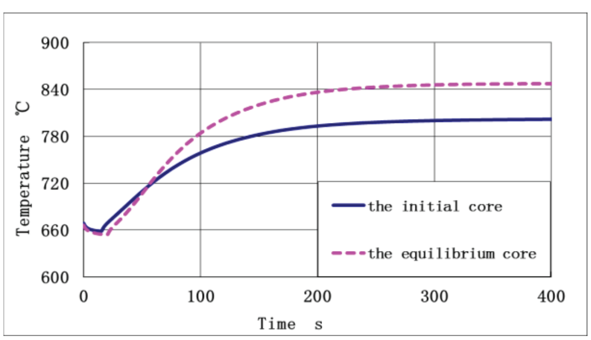


Figure 20. The Fuel Average Temperature Curve of the Last ATWS

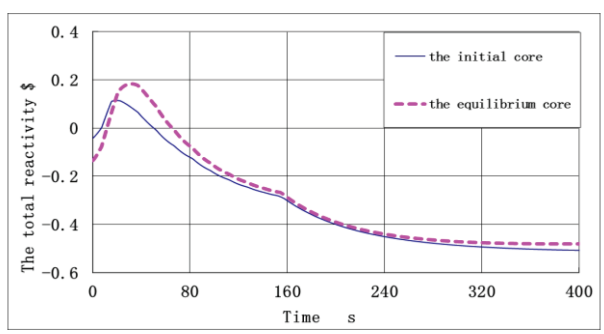


Figure 21. The Total Reactivity Curve of the Last ATWS

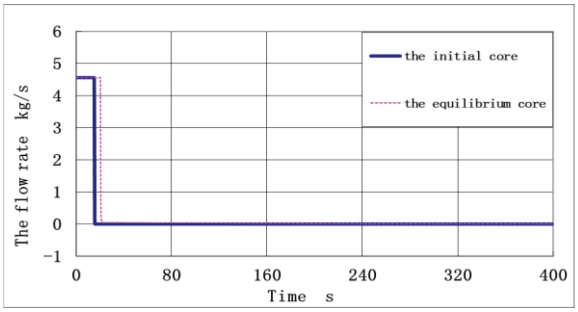


Figure 22. The Main Loop Flow Curve of the Last ATWS

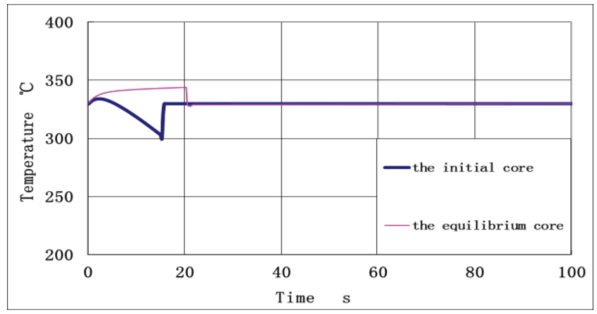


Figure 23. The Core Inlet Helium Temperature Curve of the Last ATWS

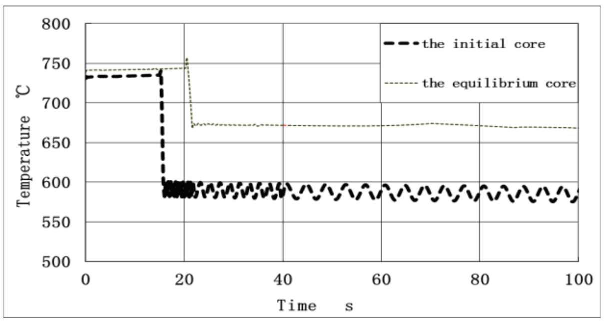


Figure 24. The Core Outlet Helium Temperature Curve of the Last ATWS

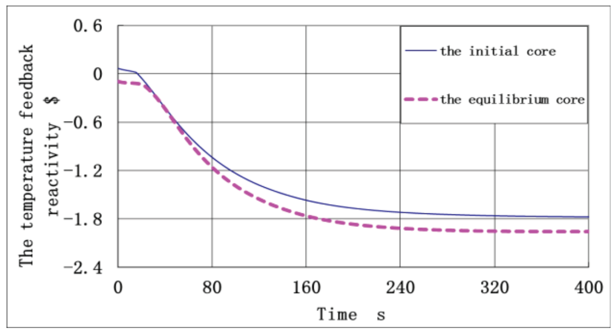


Figure 25. The Temperature Feedback Reactivity Curve of the Last ATWS

From Table VII we could see that the neutron flux of the HTR-10GT core increased more quickly than that of the HTR-10 core because the absolute value of its temperature reactivity feedback coefficient dropped as the core operating temperature raised. Thus for HTR-10GT, the power increased rapidly and the peak power was larger, which induced an earlier scram signal for the second time. The peak fuel temperature increased during the accident was about 94K, which exceeded 50K--the helium temperature of the core outlet raised. From Fig. VIII we found that during the ATWS accident the power of an initial core increased slower than that of an equilibrium core, so the peak power was lower, which caused a higher peak fuel temperature. The reason is that the initial core has a smaller value of absolute temperature reactivity feedback coefficient, which is shown in Fig. 25.We can see from Fig. 19 that the initial core of HTR-10GT has a higher fuel peak temperature, while the equilibrium core has a higher average fuel temperature. This is also due to the reactivity characteristics of the HTR-10GT core.

Fig. 23&24 gave out the helium temperature of the core inlet and outlet. As the system pressure lost, the temperature of the inlets of the initial core and the equilibrium core became similar after the complete isolation of the primary loop. We could see that there is a high frequency Temperature oscillation in the initial case in Fig.24. The oscillation is caused by the calculating error of THERMIX code in case of a flow rate at zero. As the helium temperature of the core outlet of HTR-10GT and HTR-PW both are 750℃, the peak fuel temperature during the ATWS accident of one control rod withdrawal out of the core may be helpful for the HTR-PM.

6. CONCLUSIONS

The following conclusions from the preceding analysis are addressed:

1. In the ATWS accidents of the HTR-10GT simulated in the paper, the peak fuel temperature is 1200.9℃and it has a tolerance of 400℃ to the safe margin of 1620℃.
2. The HTR-10GT is safe in the ATWS accidents induced either by station blackout or by a control rod withdrawal out with a mistake and in addition with loss of the system pressure. There is no additional radioactivity release and no fuel element damage in accident.

After the Fukushima accident, more and more attention was focused on mitigation measure for severe accident, especially for accidents induced by station blackout. From the analysis above, we can see that HTRs don't need special actions to response after station blackout and they have advantages in dealing with BDBAs.

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