ANALYSIS ON UCRW-ATWS IN TMSR-SF1

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ABSTRACT

Fluoride salt cooled High temperature Reactor (FHR) is one of six Generation IV candidate reactors. FHR has significant safety characteristics different from other reactors, such as high temperature, low pressure, large heat capacity, passive decay heat rejection system and sufficient margin of fuel and coolant temperature. TMSR-SF1, which is the first solid fuel thorium molten salt experimental reactor, is planned by CAS-TMSR (Chinese Academy of Sciences - Thorium Molten Salt Reactor) center. Anticipated transient without scram (ATWS) is one of the worst cases with safety system in reactor operations. Accident analysis of ATWS in FHR is considered great importance in assessment of its safety limits .This paper presents a preliminary analysis of UCRW (Uncontrolled Control Rod Withdrawal) -ATWS in TMSR-SF1 by using RELAP5/MOD 4.0 code (Reactor Excursion and Leak Analysis Program). RELAP5 code was developed for best-estimate transient simulation of light water reactors by INEL (Idaho National Laboratory). Properties of fluoride salt and heat exchange correlations are modified and implanted for transient analysis of FHR. The reactor core, two circulation loops and passive residual heat removal system are equivalent established. In ATWS analysis, transient responses of key parameters including reactivity, power, mass flux, coolant temperature and fuel temperature are analyzed. Because coolant flux will affect heat exchange and reactivity feedback of coolant and fuel in the core and determine critical safety values eventually, all these parameters are also analyzed under different pump rotation speed for pump handling strategy in ATWS. The preliminary result shows that TMSR-SF1 possesses inherent safety features in UCRW-ATWS. With analysis of different initial conditions, no parameters exceed design limits. Sensitivity analysis of feedback reactivity coefficients shows that fuel has dominant influence rather than coolant and graphite.

KEYWORDS
TMSR-SF1, RELAP5, UCRW-ATWS

1. INTRODUCTION

Thorium Molten Salt Reactor is a reactor founded by Chinese Academy of Science for "the Future of Advanced Nuclear Fission Energy" strategic pilot science and technology project. TMSR special group in SINAP (Shanghai Institute of Applied Physics) started up a design project of world first solid fuel thorium-based molten salt reactor in April, 2012 and formally plan to reach zero power criticality and operation in 10MW full power by 2017. [1] [2] FHR is originally based on the idea of MSRE (Molten Salt Reactor Experiment) by ORNL in 1950s, which features high temperature, low pressure, large heat capacity, passive decay heat rejection system and sufficient margin of fuel and coolant temperature. Inherent safety, which is provided by the negative temperature coefficients of reactivity, enables the core to shut down automatically in any reactivity insertion accidents. And decay heat can be extracted from the core through heat conduction, radiation and convection to a passive residual heat removal system. The safety properties of TMSR have been proved and confirmed by defense-in-depth concept, which is made up of three barriers. The innermost part is five coating layers of TRISO (Tristructural-isotropic) and pebble bed, then high temperature fluoride salt, pressure boundaries of primary and secondary looping circuits and the outermost confinement.

TRISO is a micro spherical all-ceramic fuel particle, fuel elements are dispersed and random distributed in the pebble-bed core. Safety cap temperature can be as high as 1600°C staying stable chemical and physical characteristics. [3] [4] In order to strengthen the coating integrity and prevent radioactivity fission products from leaking, the maximum temperature has been reduced to 1250°C proven by experiments. [1] Unlike to other typical advanced reactors like HTR-10, the rated pressure of TMSR is no more than several atmospheres, which ensures superiority in extreme accidents.

The critical conceptual design of TMSR has been finished and typical accidents analysis became the priority task. This paper emphasized on UCRW-ATWS, which is believed to be a typical severer accident (Level IV). In UCRW, unexpected reactivity is suddenly introduced into the reactor by control rods withdrawal, leading to a sharp rise in reactor power and occurrence of overcritical. However, protection system failed to shut the core down mainly due to protection signal failure, thus the heat extracted by loops and hot sink cannot satisfy the rising power, resulting in temperature and pressure boost. [6] [7] [8] Because TMSR does not contain any safety accumulator or emergency core cooling system (ECCS) as light water power plant to prevent safety margins from being broken, UCRW-ATWS becomes one of the most possible transients that can demonstrate the worst thermal-hydraulic accidental situation and verify whether any design flaw exists in TMSR [2].

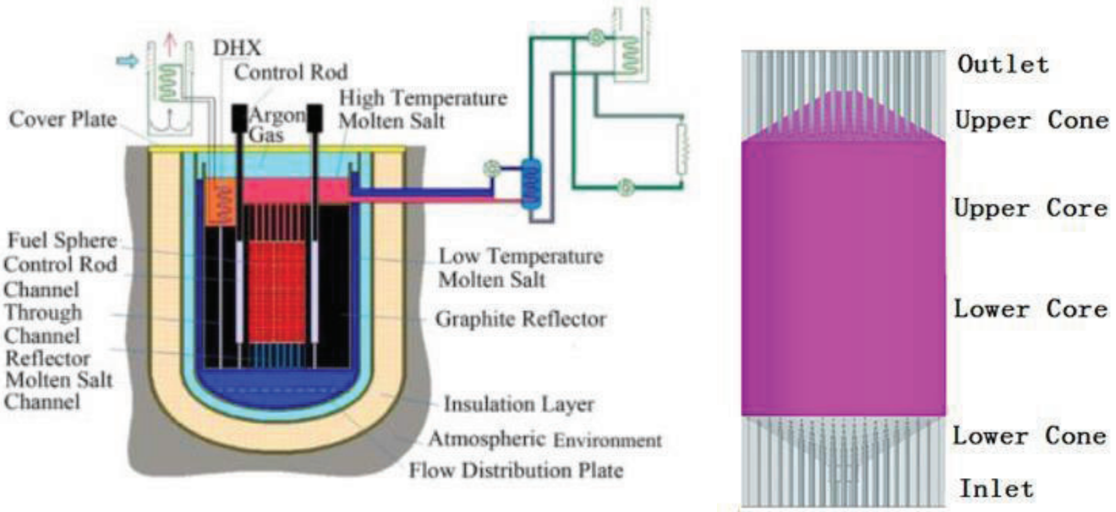


Figure 1. Schematic diagram of TMSR and Lateral View of Core

2. SAFETY-RELEVANT SYSTEM

2.1. Primary Looping System

There are three pressure boundaries as radioactive inclusive boundaries, i.e. the reactor pressure vessel (RPV), pressure boundary of primary coolant and pebble-bed elements. The material of RPV and pressure boundary is Hastelloy alloy, because it maintains industrial strength and good oxidation resistance to hot fluoride salts in the temperature range of 1300 to 1600°F (704 to 871°C) [9] and fully capable of serving under 750°C [10] [11] [12] [13]. The three loops of TMSR are shown in Fig.1.

The pebble bed in the core consists of 10800 (first loading) or 14650 (full loading) spherical fuel elements. Each of them is 6cm in diameter, 1.70g/cm^3 in density and contains about 5g of uranium. According to the preliminary design, the average burnup of fuel particles is about 28 GWd/tU while the mean power is no more than 3.5kW per element. The pebble bed is a cylinder with 1.3 or 1.8m in height (first or full loading), 1.35m in diameter, 1.22 or 1.9m^3 in volume (first or full loading). The entire core is made up of four parts: upper cone, upper core, lower core and lower cone. Because of buoyancy force, some of the fuel elements stay in the upper cone occupying about 0.123m^3. The pebble bed is surrounded by a graphite reflector wall as neutron shield and thermal buffer between the core and downcomer.

The properties of Flibe reduce primary loop rated pressure to several atms. Inlet rated temperature is 873K and 901K in outlet, which leaves great amount of margins from boiling point (1623K). Considering huge heat capacity, great dissolving capacity of radioactivity and high reactivity temperature coefficient, Flibe can provide extraordinary thermal inertia and safety protection in accidents like LOCA (Lost-of-Coolant Accident).

The shutdown and control system is made up of sixteen rods embed inside the graphite reflector and six of them are implanted for reactivity control. Each of them is 246.4cm in effective length, 130mm in diameter and provides integral worth at about 1260pcm (first loading).

2.2. Passive Heat Removal System

The reactor passive heat removal system consists of three parts, an RPV heat-removal system, an air heat exchanger and a heat-removal concrete wall around the cement silo. The discharge capacity is designed to be at least 125kW.(1% total power and considering safety margin) The decay heat can be conducted through graphite reflector, metal wrapper, downcomer, RPV, boron steel to the argon gas gap, then by the way of radiation and convection, the heat is passed onto RPV and insulation layer.

The majority of heat is removed through argon-air heat-removal and air-air heat exchanger into outer atmosphere gradually, while RPV heat- removal system and the concrete wall play a supporting role. Some of the terminologies are not shown in Fig.1 because of the limitation of size. Unlike DRACS (Direct Reactor Auxiliary Cooling System), the coolant inside heat-removal system is air, for the low total power of TMSR-SF1does not require an excess of heat removal ability.

2.3. Reactor Protection System

Reactor protection system will shut down the system once the outlet coolant temperature or reactivity exceeds triggering values. After the reactor scrams, the main pipe of primary and second circuits will also be closed. The following table shows the triggering values and triggering delay time of the protection system in TMSR. Delay time results from signal measurement and signal transforming process.

Table I. Sample table: accuracy of nodal and characteristic methods

Protection Parameter	Triggering Value	Delaying time
Neutron flux	\	10s
Reactor power	13.0MW	10 s
Coolant outlet	704℃	10s

In the UCRW-ATWS, protection system is failed to react to corresponding limit values, all control rods are blocked in the reflector. This is an extreme severe accident (level IV) and requires specific analysis in TMSR.

3. CALCULATION SOFTWARE AND PARAMETERS

3.1. Calculation Software

RELAP (Reactor Leak and Power Safety Excursion) is used in the transient analysis of this paper, it is a one-dimension system analysis program based on best-estimate methods written by INEL under the assistance of NRC. Since 1970s, RELAP has been widely applied in rule-making processes, examining administration permissions, evaluations on accident mitigation and operator disciplines, analysis of experimental plans. The program has proven its excellent performance in simulating most typical light water reactor accidents including LOCA, ATWS, LOFT (Lost of Fluid Tests), loss of off-site power, station blackout and turbine trip. RELAP/MOD4.0, its latest version, adds molten salt coolant as coolant, and opens implant interfaces to modify properties. Given its successful application in accident analysis and integrity source codes, RELAP5/MOD4.0 has be particularly modified to add necessary functions and adopted as a basic tool for simulation in this paper. [14]

Fig.2 is a zoning map of TMSR in RELAP, three circuits and critical safety systems are all modified in accordance with original parameters. Some complex components are partly simplified, for example, two secondary loops are considered as one and heat leak from main pipes are ignored. The passive residual heat removal system is attached to the core shown in Fig 1 with heat transfer.

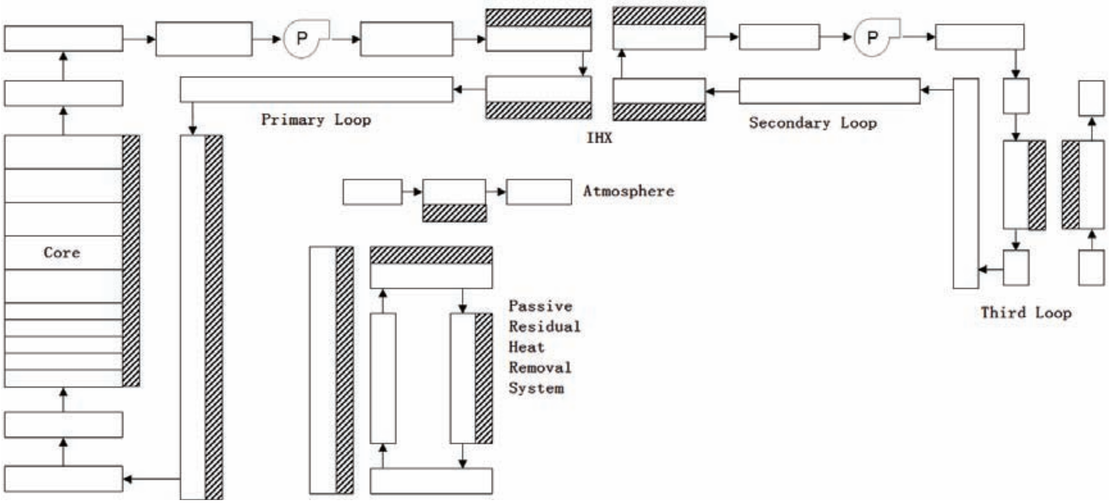


Figure 2. Zoning map of TMSR-SF1 in RELAP

3.2. Calculation Parameters

In accident modification, all initial condition values are as shown in Table III. The differential worth of one control rod is calibrated in given in Table II. Analyze is based on the following conservative assumptions:

A maximum value control rod withdraws at a speed of 5cm/s due to mechanical failure in safety system. It takes 30s to rise 150.0cm and introduce 450.0pcm reactivity. Though the total length of a rod is 246.4cm, taken into consideration that the actual height of pebble-bed is only 130cm for the reactor is at the begging of core-lifer, 150.0cm is the real effective length. And according to the different differential worth, 3pcm/s is a conservative reactivity insertion rate that can possibly occur. No other automatic actions from other rods are taken into account in this transient.

In other reactivity insertion accidents, the protection system will trigger the isolation of circuits and shut down the main pump in both loops, but in ATWS only passive safety system can be activated. Moreover whether the main pump should be scrammed or not has a decisive effect on the final results.

Table II. Differential value of control rod first loading

Height of rod (cm)	20	40	60	80	100	120	140	160	180	200	220	246.4
Differential value (pcm/cm)	2.2	3.8	8.7	8.3	15.6	11.1	4.5	2.9	2.6	1.5	1.7	2.2

Table III. TMSF-SF1 key parameters and temperature limitations

Key Parameter	**Value**
Total power (MW）	10.0
Total fuel pebble elements number	10800（first loading）/14650（full
Temperature reactivity coefficient of fuel(pcm/K）	-2.72（130cm first loading）
Temperature reactivity coefficient of moderator(pcm/K）	-4.82（130cm first loading）
Temperature reactivity coefficient of coolant(pcm/K）	-2.27（130cm first loading）
Temperature reactivity coefficient of reflector(pcm/K）	0.74（130cm first loading）
Rated mass flow in primary loop	150kg/s
Rated temperature of inlet coolant	873K
effective delayed neutron fraction β_{eff}	0.625%
Safety margin of coolant	1400℃
Safety margin of fuel	1250℃
Safety margin of Hastelloy steel	704℃

4. ACCIDENT ANALYSES

In this chapter, detailed analysis is performed in two sections whether main pump is shut down or not. Reactivity insertion takes place at 100s from a stable status. According to the principle of 30 minutes non-intervention and 15 minutes operator operating, the maximum abscissa is up to 45minuts (2700s).

4.1. Pump Scrams

Table IV describes a sequence of accident with pump scrammed by safety trigger. Fig.4 and Fig.5 respectively demonstrate transient of power, reactivity and temperature after ATWS
As reactivity inserted, reactivity rises 0.123$ at 110s and reduces to 0.0$ at 127s because of reactivity feedback, then continues decreasing rapidly to -0.639$ at 254s. After reaching the minimum value, reactivity picks up with a much slower speed and stables around -0.0487$ at 4000s. Fig.4 shows the changing pattern from 100s to 800s, because after 850s little changes can be observed from the graph.

Total power rises after the increasing reactivity and reaches 13MW to trigger pump within 10s. In Fig.4 power curve follows the same pattern as reactivity line between 127s and 254s, proving their strong connection. After 254s, power continues decreasing gradually and reaches minimum 0.582MW at 456s and then rises up slightly to about 1.0456MW at 4000s. No re-critical occurs afterwards.

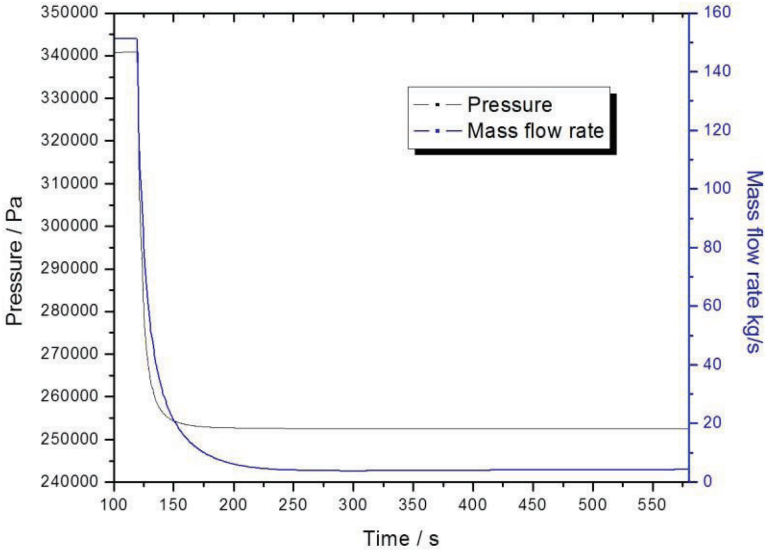


Figure 3. Pressure and mass flow rate in primary looping system (Pump scrams)

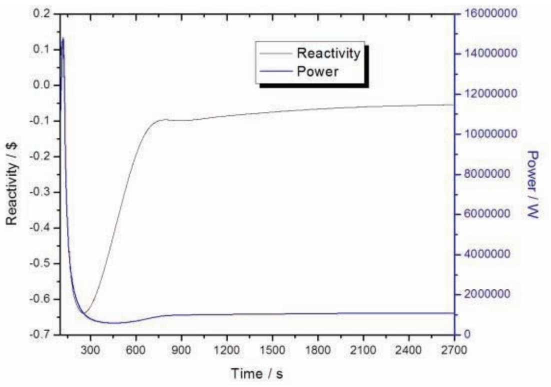


Figure 4. Power and reactivity (Pump scrams)

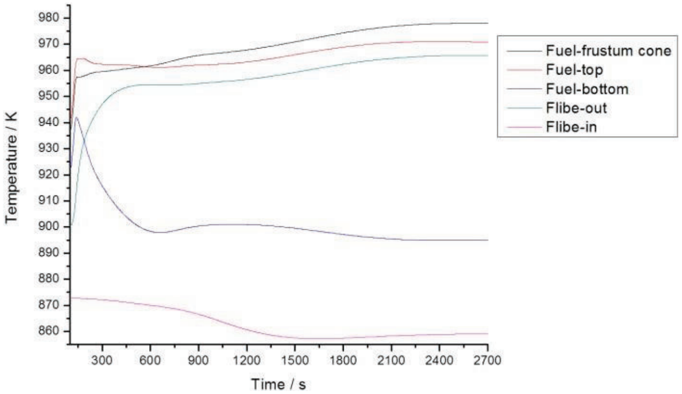


Figure 5. Coolant and fuel temperature (Pump scrams)

Table IV. Development sequences of UCRW-ATWS (Pump scrammed)

Sequences	Time/s
One control rod with maximum reactivity worth withdraws	100
Reactor power reach 13MW and trigger the pump	110
Reactivity reaches peak 0.123$	111
Pump starts to scram	120
Reactor power reaches peak 14.840MW	121
Reactor shutdown by feedback	127
Control rod finishes withdrawing	130
Mass flow 90% reduction	163
Fuel temperature reaches peak 964.633K	180
Reactivity reaches minimum -0.639$	254
Reactor power reaches minimum 0.582MW	456
Fuel temperature reaches maximum 978.078K	2618
Coolant temperature reaches maximum 965.738K	2631
Reactor reaches steady state (relatively)	4000
Steady reactivity -0.0487$	4000
Steady power 10.456MW	4000
Steady fuel temperature 977.122K	4000
Steady outlet temperature965.023K	4000

Fig.5 shows the temperature of coolant in inlet and outlet, fuel temperature of upper cone, upper core and lower core. The upper core and lower core data comes from the highest and lowest part of the fuel part in RELAP5.

Fig.3 indicates that primary loop has already lost 76.45% after 39s and kinetic energy natural circulation becomes priority factor in removing heat after 141s, holding a residual velocity at about 0.15m/s. Mass flow is reduced by 90% in the first 43s, and after safety shutdown, kinetic energy loss and decay heat is removed through residual velocity, natural circulation flow and heat conduction. Because of that, inlet coolant temperature decreases gradually from 873K to 860K but outlet temperature increases rapidly from 900K to 965K. Meanwhile, the geometry structure of upper cone (shown in Fig.1) has less flow area than the upstream core, preventing the cooling down efficiency, so lower cone fuel temperature drops to 895K and both fuel temperature of upper cone and upper core increase, the highest fuel temperature locates in the upper core before about 580s and in the upper cone afterwards. The minimum difference from temperature limitations of fuel, coolant and Hastelloy steel are respectively 544.922K, 708.042K and 12.042K.

Summary on pump scrams:

- TMSR can realize safety shutdown by negative reactivity feedback from fuel and coolant alone in UCRW-ATWS with pump scrammed and all temperature and pressure safety limits have not been breached.
- In steady state after safety shutdown, natural circulation provides 2.5% total mass flow, which can be used to remove decay heat.
- No re-criticality happens in transient simulation after shut down by temperature reactivity.

4.2. Pump Operates

Table V demonstrates the accident sequence of UCRW-ATWS with pump operating.

Table V. Development sequence of UCRW-ATWS (Pump operates)

Sequences	Time/s
One control rod with maximum reactivity worth withdraws	100
Reactivity reaches peak 0.122$	111
Control rod finishes withdrawing	130
Power reaches peak 15.650MW	130
Passive shutdown	136
Reactivity reaches peak -0.0227$	141
Fuel temperature reaches maximum 960.593K	143
Coolant temperature reaches maximum 909.256	156
Reactivity reaches peak -0.00101$	158
Reactivity reaches minimum -0.0289$	190
Steady state (relatively)	1500
Steady reactivity -0.000331$	1500
Steady power10.772MW	1500
Steady fuel maximum temperature 952.791K	1500
Steady coolant maximum temperature 909.893K	1500

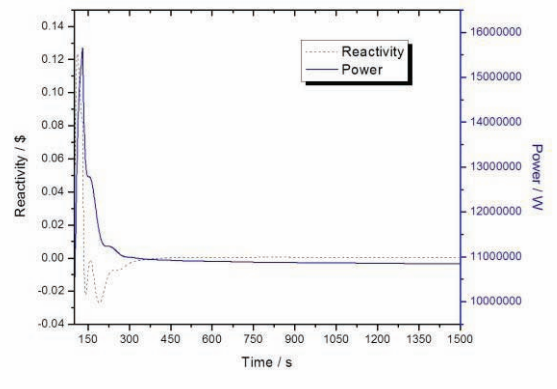


Figure 6. Power and reactivity (Pump operates)

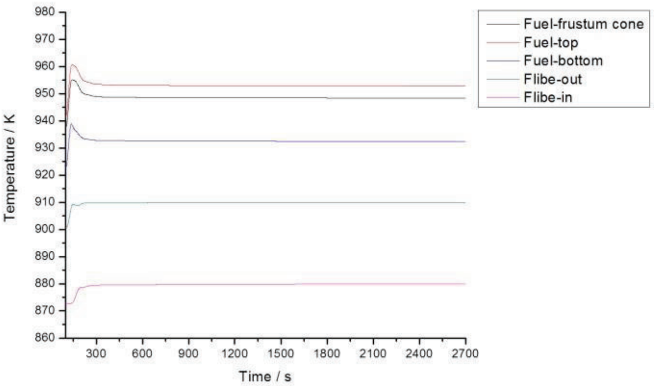


Figure 7. Coolant and fuel temperature (Pump operates)

This accident is a compare to draw a conclusion in safety strategy. Before 120s all parameters in Fig.6 and Fig.7 are the same as Fig.4 and Fig.5. Due to mass flow rate and heat transfer unchanged in primary loop, temperature rises so slightly that inlet coolant temperature increment is merely 0.0078K. Negative reactivity feedback insertion increases even more slowly and total power rises continuously until 130s and reaches 15.650MW. But passive shutdown was still achieved successfully 6s after the insertion of rod finishes while in above case it is brought forward 9s.

After 56s temperature reaches turning point, then brings out reactivity increased by 0.000658$ just within 2s. The decline of temperature in coolant and fuel will bring in an extra plus reactivity, reactivity rises an d power decreases after 158s in Fig.6, and temperature in outlet vibrates in Fig.7. Because the remaining stream in this case will delay the phenomenon corresponding, a synchronous oscillation in these curves can be observed apparently. Before re-criticality can occur, inlet coolant introduces negative reactivity in time and stabilizes total reactivity below zero. The same situation happens again after 77s which is much slighter and develops gradually into steady state.

During this transient, the maximum temperature of coolant ranges from 901.047K to 909.256K (outlet) and the maximum temperature of fuel is from 941.86K (upper core) to 960.593K (upper core). The minimum difference from temperature limitations of fuel, coolant and Hastelloy steel are respectively 613.107, 712.407K and 16.407K.

Summary on pump operates:

- TMSR-SF1 can realize safety shutdown by negative reactivity feedback from fuel and coolant alone in UCRW-ATWS with pump operating and all temperature and pressure safety margins have not been breached.
- Inlet coolant temperature increases later than outlet and fuel temperature about 31s.
- No re-criticality happens in transient simulation though at least two rebounds do occur.

4.3. Comparisons:

- Keeping pump operating can maintain heat transferring and reduce maximum temperatures, maintaining more safety margins.
- Pump scrammed case performs much lower reactivity and power, quicker speed in passive shutdown and deeper shutdown depth. Reactivity and power changes are shown in Fig.8 and Fig.9. However, heat removal ability is totally relied on the quality of natural circulation.
- The minimum difference of temperature limitation in pump operates case is smaller, providing larger safety margin. The most important and least temperature margin is Hastolley steel margin in both cases. In pump operates case the value is16.407K, the other is 12. 042K, which implicates the container wall surrounding the outlet may exceeds its limit of 704K under conservative assumption, however, this situation will exist no longer than 300s in pump operating case.

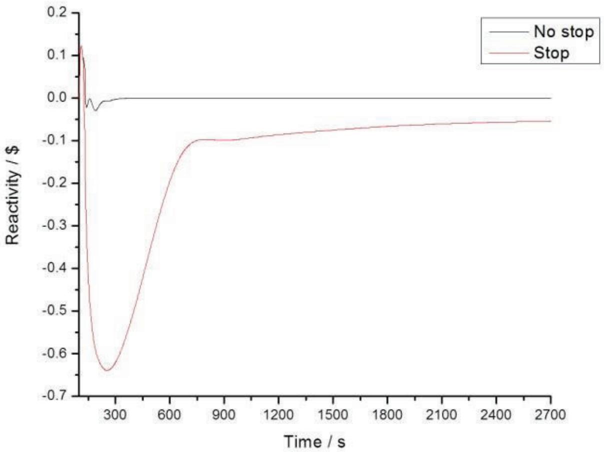


Figure 8. Comparison of reactivity evolution (Pump scrams and pump operates)

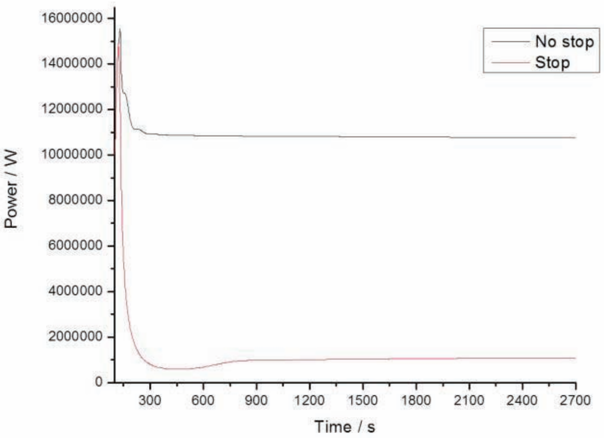
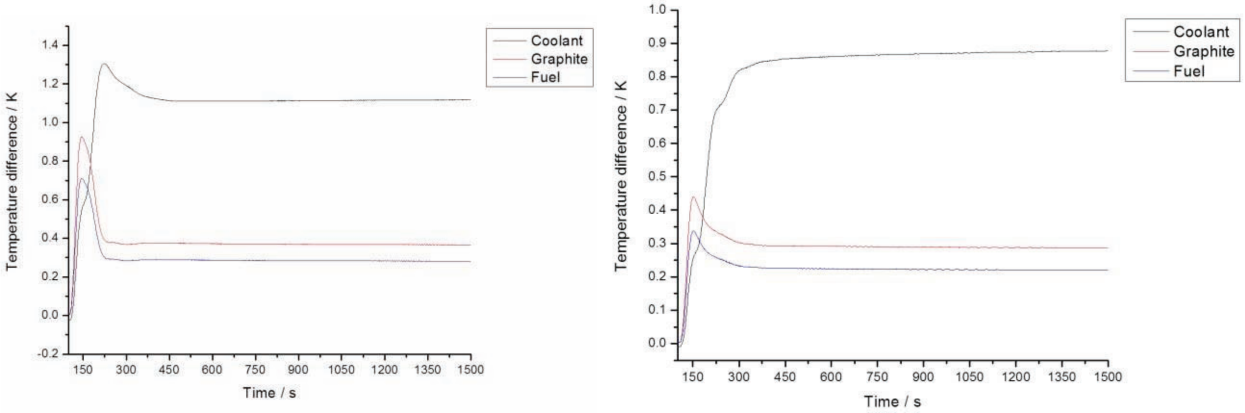


Figure 9. Comparison of power evolution (Pump scrams and pump operates)

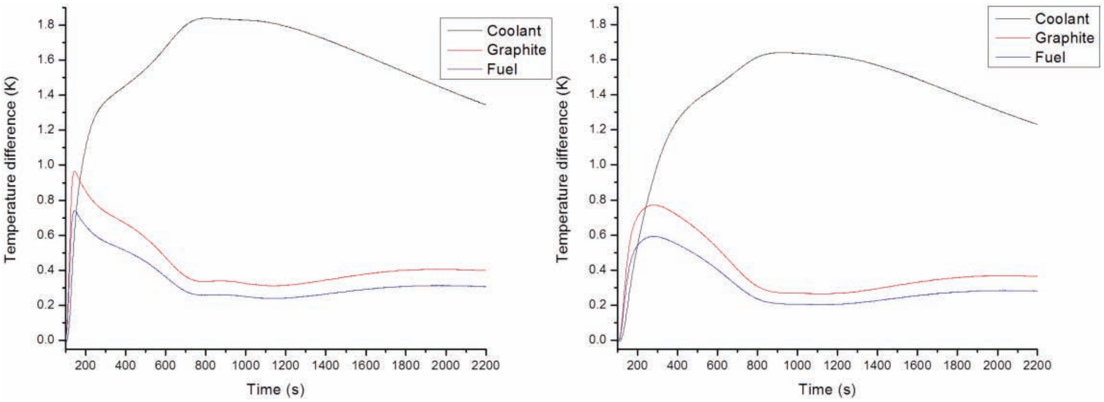
5. SENSITIVITY ANALYSES

The differences in Table.VI are modification values minus original. Original values are obtained from 1500s in operating case and 2700s in scrammed case, referring as steady state. Fig 6 shows the transient differences in both cases focusing on fuel and outlet coolant temperature. No visible changes occur after 1500s in Fig 10 (a) and (b), so the abscissa is cut down to 1500 to enlarge the changing parts.



(a) Comparison of fuel temperature (Pump operates)

(b) Comparison of outlet coolant temperature (Pump operates)



(c) Comparison of fuel temperature (Pump scrams)

(d) Comparison of outlet coolant temperature (Pump scrams)

Figure 10. Comparison of key temperatures after three coefficients decreases by 10%

Table VI. Development sequence of UCRW-ATWS (Pump operates)

△T/K	Pump operates		Pump scrams	
Factor	Fuel Temperature Comparison	Coolant Temperature Comparison	Fuel Temperature Comparison	Coolant Temperature Comparison
Coolant coeffcient-10%	+1.118	+0.878	+1.092	+1.014
Moderator coefficient -10%	+0.366	+0.288	+0.296	+0.275
Fuel coefficient -10%	+0.281	+0.222	+0.228	+0.212

These conclusions can be come to according to Table.VI and Fig. 10.

- Conservative values do affect the safety margin of critical parameters, but do not exceed any design limitations.
- Reactivity temperature coefficient of fuel has the least effect, because coefficient is only -2.72pcm/K and change in temperature is lesser than coolant during both cases.
- Reactivity temperature coefficient of graphite plays a medium role, though the temperature change is almost the same as fuel, its value is as highs as -4.82pcm/K.
- Reactivity temperature coefficient of coolant is only -2.27pcm/K, but dominants the feedback effects in later periods and steady states. Due to significant temperature change, its feedback influence on steady temperature is three times larger than coolant and about triple the moderator.
- Negative reactivity feedback effects by coolant are triggered by the heat conducted from pebble bed. A 50 seconds delay exists between the peaks which can be considered as time constants in ATWS.
- Reactivity coefficient of graphite reflector is +0.74pcm/K and is counted but not mentioned in detail.

6. CONCLUSION

In this paper, a preliminary analysis of UCRW-ATWS in TMSR-SF1 by using RELAP5/MOD 4.0 is presented and these points are concluded as follows:

(1) In the UCRW-ATWS, passive safety shutdown can be achieved in 30s via negative temperature reactivity coefficient. Steady state remains stable and no re-criticality occurs. The performance of this severer accident shows perfect safety properties of FHR.

(2) The maximum fuel and coolant temperature, the maximum pressure in reactor core lie far below the safety limitations. The Hastelloy maximum temperature is much smaller than safety value in short-term accident and might exceed the limit under conservative assumption, but in the pump operation case primary circuit pressure boundary remains intact for the short-lived overheating situation will vanish. [9]

(3) Scramming pump will delay passive shutdown speed and increase maximum temperature, but reduce power and reactivity in steady state and deepen the shutdown depth effectively. The decay heat can be transferred out by natural circulation through passive residual heat removal system.

(4) The greatest influence of reactivity coefficient is coolant and then down to moderator and finally to fuel. In the first 50s of transient, the last two plays a leading role and coolant coefficient dominates the rest period.

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