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Thermal Hydraulic Analysis of the 80 MWth Pb–Bi cooled XADS with modified RELAP5/MOD3.3 code

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Abstract

The Experimental Accelerator-driven System (XADS) is a proposed 80 MWth Lead-Bismuth cooled pool type facility coupling a proton accelerator and a sub-critical fission core by means of a spallation target. A cascade fission reaction is sustained by the spallation neutrons. The facility primarily aims to demonstrate the operability of the whole complex and, subsequently, also the capability to reduce the inventory of Pu, Minor Actinides and selected long-lived fission products. The paper, after a brief description of the LBE-cooled XADS concept, focuses on the assessment of its response to the changing of core power which is caused by doubling and cutting the external neutron and loss of flow events affecting both the whole core and a single fuel assembly while the former are originated from the postulated malfunction or loss of the peculiar gas injection system employed to enhance primary coolant circulation, the latter may derive from significant flow blockages at a fuel assembly inlet. Through the whole research, the RELAP5/MOD3.3 code which is modified to fit the sub-critical fission core is used. The results of the performed analyses show the excellent natural circulation capability of the system and the safety performance leaded by negative feedback, specifically in an accident scenario with the assumed simultaneous failure to trip the proton beam, and highlight the indeed peculiar heat removal mechanisms from a fuel assembly in case the associated coolant flowrate drops to very small values.

1. Introduction

1.1 Background

Nuclear waste is one of the constraints that limit nuclear energy sustainable development. How to manage the high-level radioactive waste liquid and the solidified body produced by handling the spent fuel and high-level radioactive waste is the focus of society and the public for a long time. A PWR of 1000MW eliminates 25t spent fuel every year which contains 23.75t recyclable uranium, 200kg plutonium, 1 000kg FPs and 20kg MAs, 30kg LLFPs. These long-life and poisonous nuclear waste would do long-term harm to the human environment.

How to minimize the waste which means to minimize the volume of high-level radioactive waste and the radiation toxicity of it, and safe handle the high level radioactive waste, quarantine the waste from the biosphere for a long time and ensure the safety of future generations is such an important global problem.

1.2 The Accelerator Driven Sub-critical System

The ADS was originally suggested to burn or transmute considerable quantities of trans-uranic isotopes and/or fission products, and to produce power simultaneously. The inherent safety characteristics of the ADS device is believed to be guaranteed by the sub-criticality of the system and the ability to shut-off on demand the external neutron source (the proton beam) instantaneously making control rod systems unnecessary [1].

As the main goal of an ADS is to transmute actinides, it is quite evident that one should expect a discernible swing in the sub-criticality k_{eff} during normal operation (burn-up) of the plant as the isotopic composition of the fuel continuously changes due to the absorption of neutrons, leading to fission and/or to transmutation to other isotopes [2].

1.3 Introduction of XADS

The Experimental Accelerator-driven System (XADS) is a proposed 80 MWth Lead-Bismuth cooled pool type facility coupling a proton accelerator and a sub-critical fission core by means of a spallation target. The primary side coolant is LBE while the secondary is water. In this system, argon gas is injected into the risers to increase the mass flowrate. This research aims at analyzing the primary side and the secondary side is simplified.

2. Introduction of XADS model

2.1 The basic features of XADS

2.1.1 The engineering features of XADS

The system of ADS contains the proton accelerator and the subcritical core. As the subcritical reactor can not maintain the chain type response, external neutron is needed. The accelerator increases the energy of the proton so that the proton can hit the Pb nuclei and form the spallation neutron source. This system uses LBE for coolant and changes the external neutron to change the power of the reactor instead of moving the control rods.

The basic engineering features of XADS are as follows:

1. A simple primary side [3]. All LBE coolant is in the reactor vessel and the auxiliary facilities which would cleansing the coolant are also in the pool-type reactor system.

2. The natural circulation is the main way for heat transmission and the source, the risers, heat exchangers and the downcomers are in reasonable arrangement.

3. When it is in normal operation, argon air is injected into the risers to improve the coolant mass flowrate.

4. Use LBE as coolant because its melting point is low so that the system can run at a low temperature which is favourable to reduce the damage of the reactor structure and the corrosion of metal materials.

5. The heat exchanger and the target component are removable.

2.1.2 Introduction of the primary side of XADS

The Primary System: The Reactor Vessel contains entirely the Reactor Coolant System (RCS) which consists of a pool type heat transfer system. The main RCS functional parts are as follows:

1. The Core Region where the primary coolant removes the heat generated in the Fuel Assemblies (FA's) by fissions (80 MWth) as well as in the target by spallation (up to 3 MWt, according to the proton beam current). The fuel is of proven SPX1 technology (U and Pu MOX). The k_{eff} is set sufficiently low to ensure the safe operation of the Facility without the needs for control and shut-down rods. The fuel core is arranged as a honeycomb annular pattern of four fuel assemblies coaxial rounds (from the third to the sixth, accounting for 18, 24, 30 and 36 FA's/rounds) plus another twelve FA's distributed at the outer boundary (in total 120), has surrounded by an outer region also arranged as a honeycomb array of three rounds of dummy assemblies which, being essential empty ducts, permit to constitute a buffer region.

2. Risers - The Risers are a set of 24 distinct cylindrical vertical parallel tubes, where the primary coolant moves upwards; a gas injection is performed at their bottom for the purpose of enhancing the natural circulation mass flow rate. In the Risers the coolant moves upwards, until it overboards the top of the tubes at an elevation below the liquid free surface, and then turns down towards the upper downcomer region, where four Intermediate Heat Exchangers are located. 22 Risers, transport the coolant from the above-core region; the remaining two, instead, are connected with the top of the above core dead volume, a quasi stagnant lead-bismuth region between the upper plenum and the free surface. With this solution a small flowrate of lead-bismuth flows in the volume, descends vertically to the inlet of the two Risers and then, because of the Argon injection, is forced to move upwards and to exit into the upper downcomer region. By doing this, a portion of the coolant of the above core dead volume quasi stagnating zone is continuously moved to be reprocessed in the purification zone, located in the upper downcomer.

3. Upper Downcomer - It is the region of coolant at high temperature between the top of the Risers and the Intermediate Heat Exchangers inlet.

4. Heat exchangers - the two heat exchangers with respect to each other are located in the upper downcomer region comprised between the cylindrical inner vessel and the Reactor Vessel. A single bayonet assembly consists of a pair of concentric tubes, the external of which is shaped to allow the inversion of oil flow direction from downward to upward. The heat exchangers are supported at the Roof level, from which they hang, with penetrations through the Roof itself.

5. Downcomer - It is the annular region between the main vessel and the cylindrical inner vessel where the lead-bismuth coolant moves downwards all the way from the free surface down to the core inlet plenum.

6. Lower Downcomer - It is the region of coolant at lower temperature, after heat has been removed at the Intermediate Heat Exchangers level.

7. Core Inlet Plenum - It is the region, below the Core, that receives coolant from the lower downcomer and distributes the flow to the Core region.

2.1.3 The sketch map and parameter of XADS

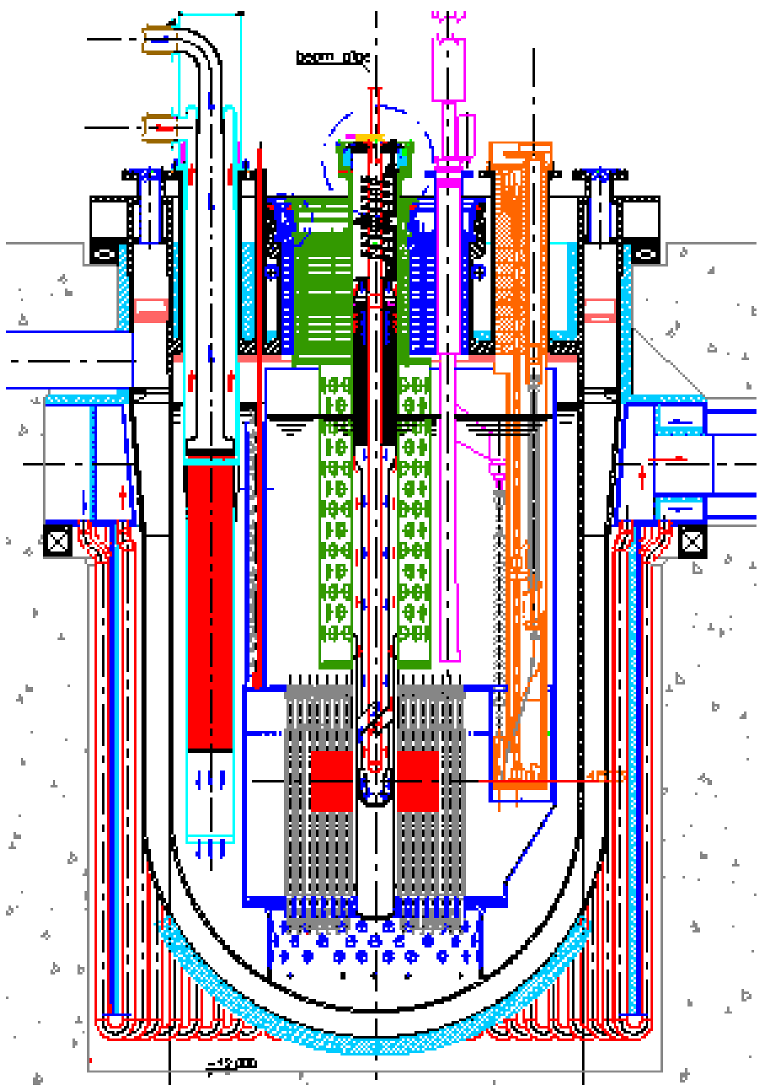

Figure 1 The sketch map of XADS.

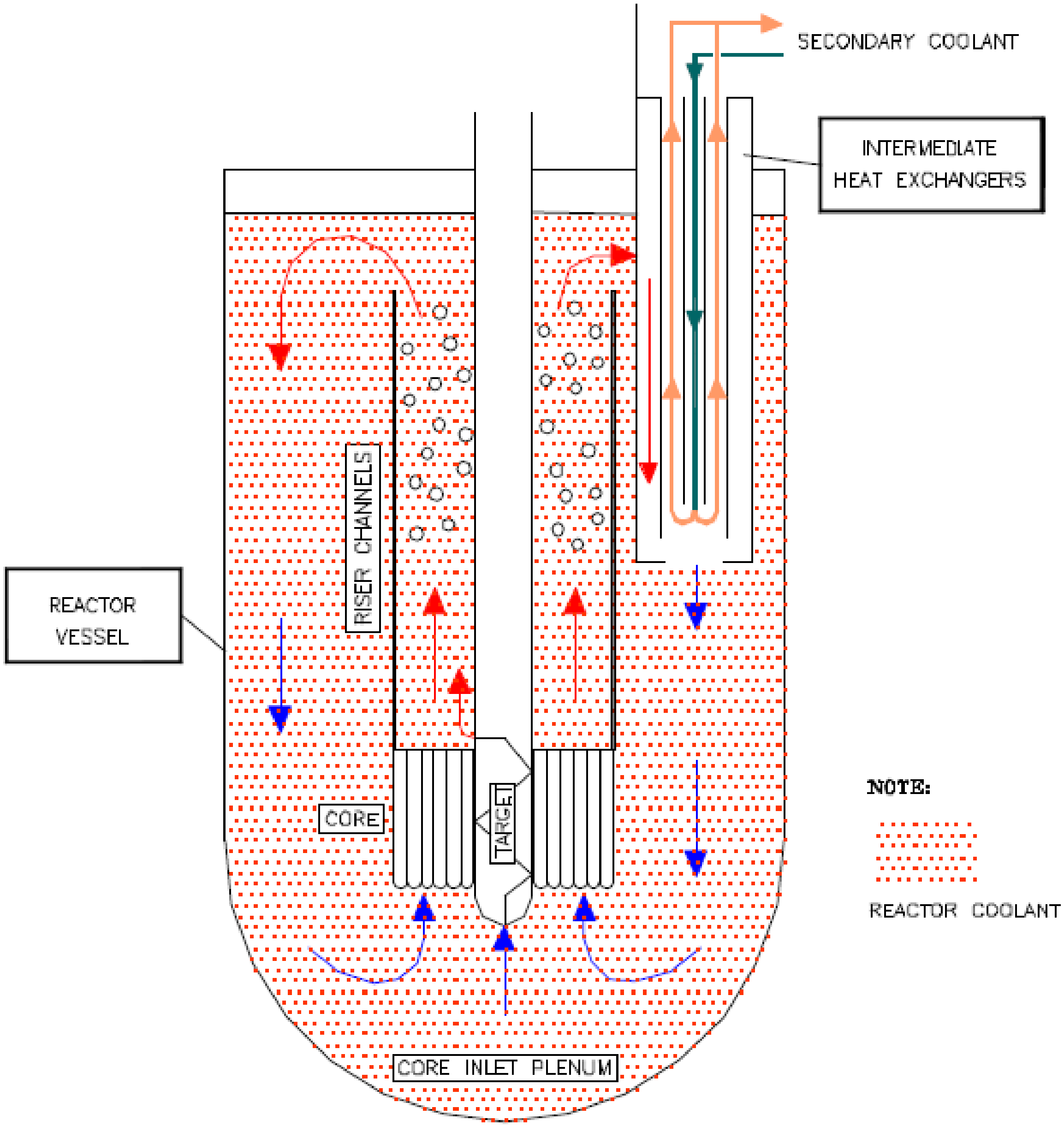

Figure 2 The major coolant flow direction of XADS.

Table 1 parameter table

Parameter	Value
Fission Power, MW	80
Reactor Pressure, MPa	0.11
Primary Coolant Flow rate, kg/s	5961
Core Flow Rate, kg/sec	5471
Core Inlet Temperature, °C	300
Core Outlet Temperature (at rated power), °C	400

2.1.4 <u>2.1.4 XADS model in RELAP5</u>

In this research, the primary side is analysed in detail and the secondary side is simplified. Figure 3 shows the model of the primary side of the system and in Table 2, the main parts of the primary side is listed..

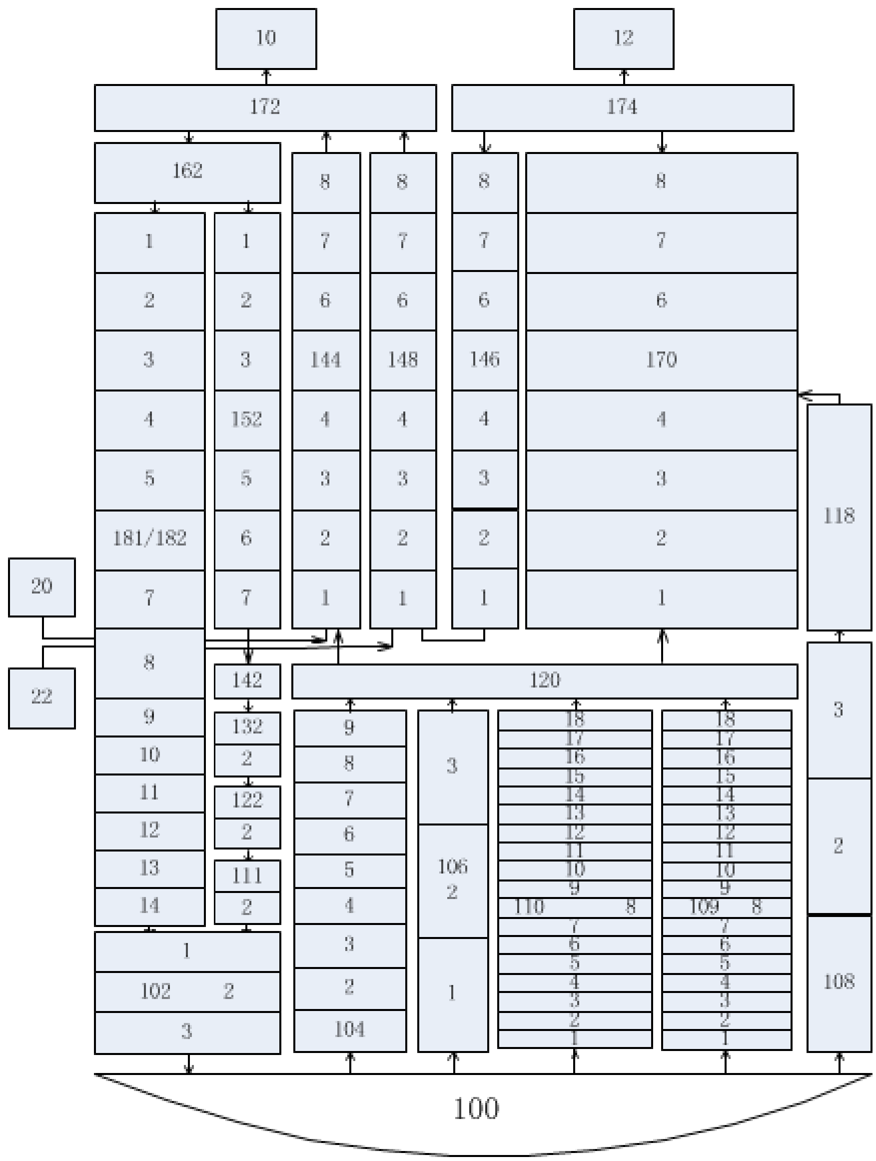

Figure 3 the model of XADS in RELAP5.

The argon gas is injected into the risers from volem 20 and 22 which are Tmdpvols. The main flow direction of the coolent is: 110 (Core region) – 120 (Upper plenum) – 144 (Main Risers) – 172, 162 (Downcomer) – 181/182 (IHX) – 102 (Downcomer) – 100 (Lower plenum). 110 is the normal assembly and 109 is hot assembly, their powers are 79.13334MW and 0.855MW.

Table 2 nodes of the primary side

General zone	Hydraulic zone	Node Number	Node Type
Reactor Vessel	Downcomer	10 , 12	Tmdpvol
		11,103,105,107,111,121	Sngljun
		102,112,122,132,152	Pipe
		164,142	Branch
		172	Branch
	Lower plenum	100	Branch
		106	Pipe
	Core region	110	Pipe
		109	Pipe
	Core bypass dummy Cells	106	Pipe
	Core bypass Reflector	104	Pipe
	Upper plenum	120	Branch
	Target	108	Pipe
		118	Branch
	Fuel Handling Volume (FHV)	170	Pipe
		174	Separatr
	Main Risers	144	Pipe
		20,22	Tmdpvol
		21,23	Sngljun
	FHV Risers	146,148	Pipe
		147	Sngljun
	IHX Loop1	181	Pipe
	IHX Loop2	182	Pipe

2.2 The modifying of the point kinetics model

The RELAP5/MOD3.3 program is based on a non-homogeneous and non-equilibrium model for the two-phase system that is solved by a fast, partially implicit numerical scheme to permit economical calculation of system transients. The objective of the RELAP5 development effort from the outset was to produce a code that included important first-order effects necessary for accurate prediction of system transients but that was sufficiently simple and cost effective so that parametric or sensitivity studies were possible. The code includes many generic component models from which general systems can be simulated. The component models include pumps, valves, pipes, heat releasing or absorbing structures, reactor point kinetics, electric heaters, jet pumps, turbines, separators, accumulators, and control system components. In addition, special process models are included for effects such as form loss, flow at an abrupt area change, branching, choked flow, boron tracking, and non condensable gas transport.

When the point kinetics model of a subcritical system is analysed by the RELAP5 code, the external neutron source strength is calculated using the fission power and the initial subcritical degree. Once the source strength is calculated, it is a constant and the other parameters such as power and the reactivity are then calculated by using Runge-Kutta [4]. By this way, the code can not simulate the external neutron changing accident. So the point kinetics model should be modified to simulate the accident cased by changing the accelerator.

In the XADS, the delayed neutron fraction is: $\beta \approx 0.00350 = 0.35\% = 350\,pcm$, and here $k_{eff} = 0.97$ is defaults.

The initial reactivity is:

$$r = \left(\frac{k_{eff} - 1}{k_{eff}}\right) \Big/ \beta = \left(\frac{0.97 - 1}{0.97}\right) \Big/ 0.0035 \approx -8.8365243$$

The external neutron source strength is calculated as follows:

$$n = \frac{P_{fiss}\nu}{\varepsilon}\left(\frac{1 - k_{eff}}{k_{eff}}\right)$$

P_{fiss} is fission power, MW, ν is neutrons released per fission (n fission−1), ε is the power fission, MW.

The external proton beam strength is calculated as follows:

$$I_{prot} = \frac{P_{fiss}\nu}{0.20\eta_{prot}}\left(\frac{1 - k_{eff}}{k_{eff}}\right)$$

I_{prot} is the external proton beam strength (mA), η_{prot} number of spallation neutrons released per proton and for Pb-target and1.2GeV proton beam, η_{prot} is about 20 n per proton[5,6].

$6.24 \times 10^{15}\, protons \cdot s^{-1} \cdot mA^{-1}$ multiply by $3.2 \times 10^{-17}\, MW \cdot s \cdot fission^{-1}$ is the constant 0.20.

After the code is modified, the external neutron source strength is not a constant and would change over time. The accidents of changing the accelerator operation condition can be simulated.

3. Accidents Analysis

In this research, the loss of LBE flowrate accident the blockage accident and external neutron doubled accident are calculated in this research as well as the analysis of cutting off the proton beam and restart it. The loss of LBE flowrate accident contains the protected LOFA and the unprotected LOFA [7].

3.1 Argon gas compressor trip with successful proton beam trip

In this accident, the argon gas fail to inject into the plant risers, and a sudden decrease brings the core coolant mass flow rate to a very low level which leads to a rise of the core temperature and the trip which controls the external neutron is triggered. Then the accelerator stops working, as the core is subcritical and the reactivity is negative, fission chain reaction will soon stop and the core power decreases. As the secondary side is still working, the temperature of the primary side will slowly fall and the system is safe in this accident. After the trip is triggered, natural circulation is the main circulation way and the decay power is the main power in the core. This accident is simulated by stopping the argon from injected into the system when it is in normal operation condition. The accident sequence is showed in Table 3.

Table 3 Accident sequence of PLOF

TIME	Incident
2000s	Stop the argon gas
2008s	Core outlet temperature reaches 420^{o}C Trigger trip
2010.5s	2.5s after the trip is triggered, cut the external neutron

After the argon gas fail to be injected into the system, the core outlet coolant temperature reach the warning value (420 ℃), the trip to shut down core is triggered, and the accelerator stop running. So the reactor power will decrease soon as is showed in Figure 4. In about 200s, the total power fall from 80MW to 3MW and it will still decrease slowly.

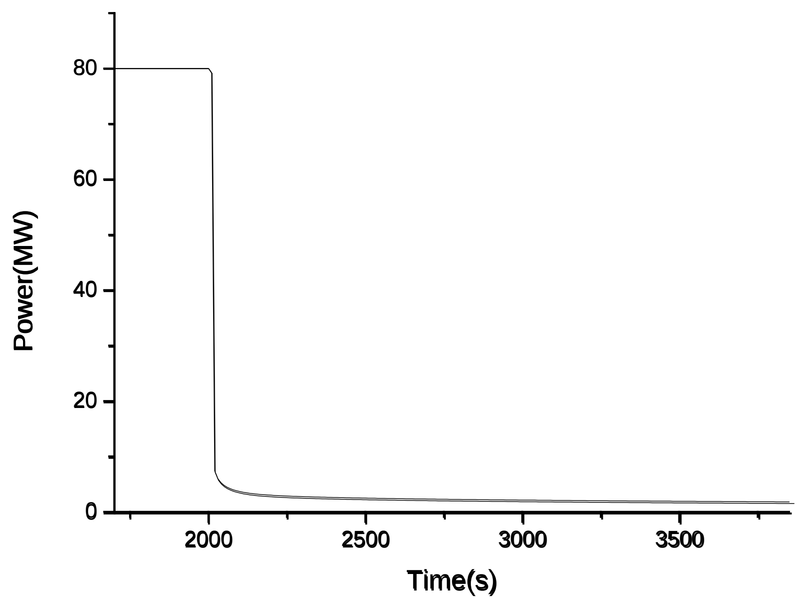

Figure 4   Power of the core.

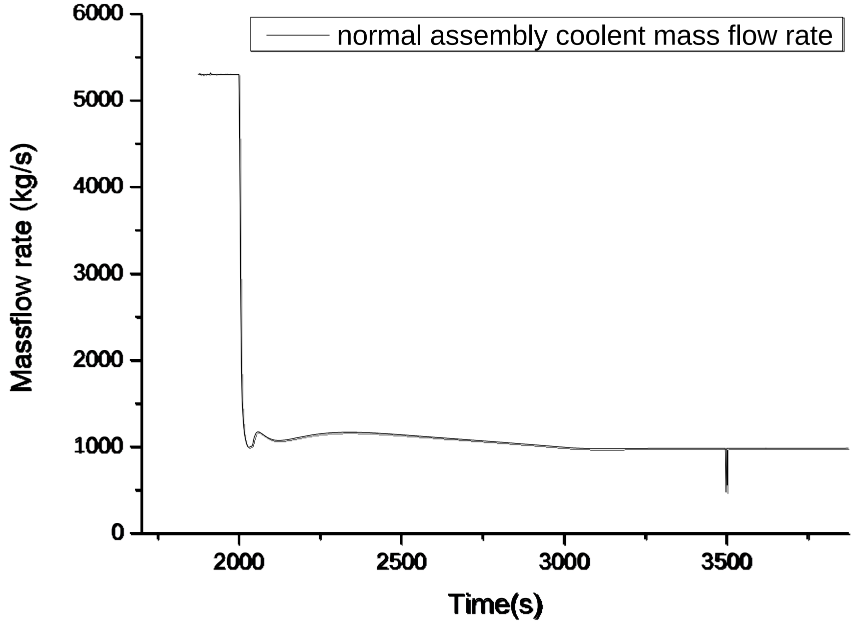

Figure 5 normal assembly coolant mass flow rate.

As the argon gas stops to be injected in, the flowrate decreases immediately because the natural circulation becomes weak (Figure 5). After the accelerator stops working, the decay power is the main power in the core, and the flow rate of the core coolant is about 1000kg/s.

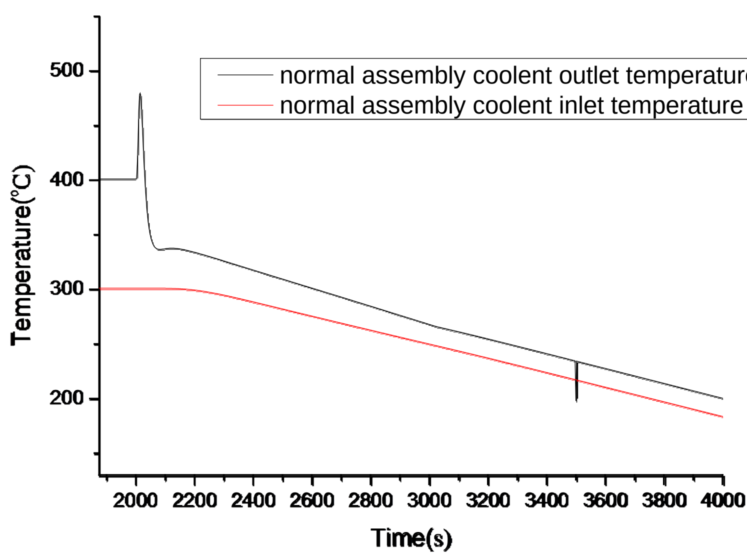

Figure 6 temperature of the coolant.

In this research, the secondary side is simplified, and when the power of the primary side is decreased, the average temperature of the secondary side will also fall. Here, to assume that the change of the secondary temperature is linear variation, the coolant temperature at the entrance of the core is also reduced (Figure 6).

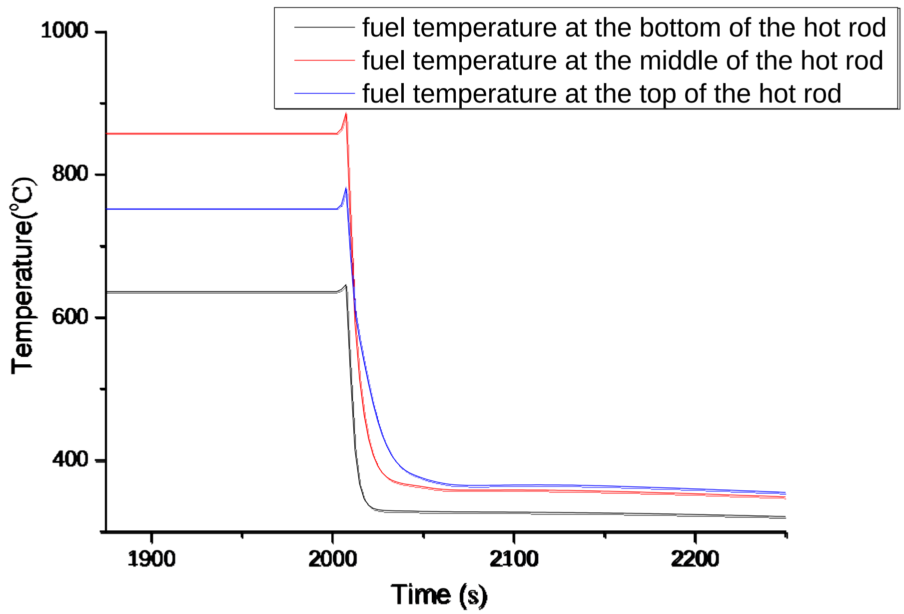

Figure 7 hot rod fuel temperature.

Before shutting down the core, the power of the fuel rod exhibits a nearly cosine scattering distribution and the power in the middle of the rod is the highest. Although the coolant temperature rises through the channel and the outlet coolant temperature is higher than it in the middle, the peak of the rod temperature is still in the middle. After shutting down the reactor, the total power is sharply reduced and the fuel rod temperature decreases immediately because of the effect of the coolant. When it is stable again, the core temperature in the middle is lower than it at the exit, as is showed in Figure 7.

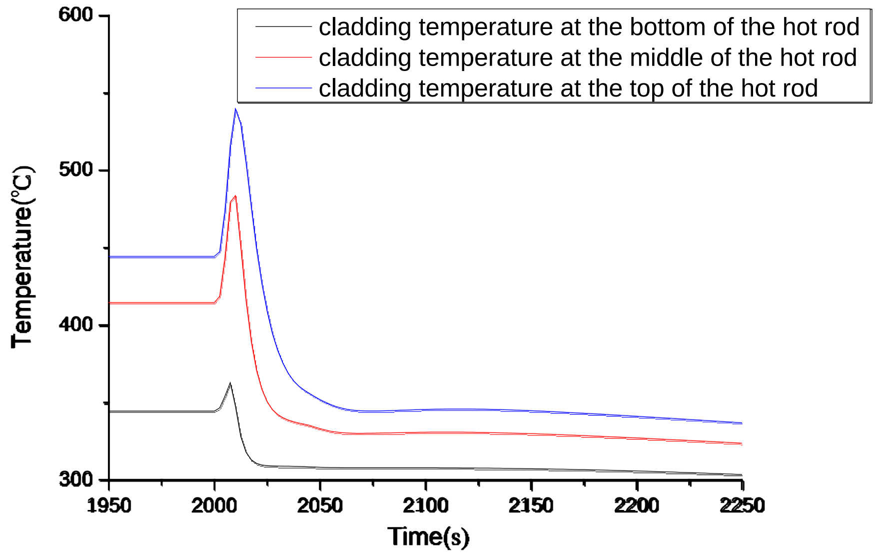

Figure 8   hot rod cladding temperature.

Because the argon air stops to be injected into the system at 2000s, within a short time (about 10 seconds, showed in Figure 8), the temperature of the cladding increases, and then it fall to a lower value.

3.2 Argon gas compressor trip with failure to trip the proton beam

In the second analyzed scenario it is assumed that, at t=2000.0 s no argon gas is injected into the system and the temperature at core outlet is high enough to actuate the proton beam trip ,but actually, the trip fail to work. Then this situation is analyzed in the following paper.

As a consequence of the total loss of argon gas injected into the risers, the flowrate of lead-bismuth in the core rapidly decreases to a minimum of about 1550 kg/s which is about 28.3% of the normal value. And then, as the temperature distribution in the main vessel raises, the natural circulation becomes more and more important and the flowrate slowly stabilizes at approximately 50% of the nominal value, as is showed in Figure 9. The temperature of the core is rising as the lead-bismuth flowrate decreasing which also lead to negative feedback and a decrease in the total power. After the argon gas failed to inject into the risers, the power immediately reduces by 2.5MW, and then stabilizes at a decrement of 1.3MW, as is showed in Figure 10.

Ignore the changing of the coolant temperature in the secondary side, when the argon gas stops, the outlet temperature rapidly increases, peaking for a short while at about 908 K (635°C), then decreasing and stabilizing at around 763 K (490°C) and the temperature of the hot channel is 20°C higher than the middle channels, showed in Figure 11. The LBE temperature increase across the core, after peaking, stabilizes at about 200°C. This is consistent with the practically halved lead-bismuth flowrate. From Figure 11, it can be observed that the LBE temperature decrease across the IHX stabilizes at around 100°C.

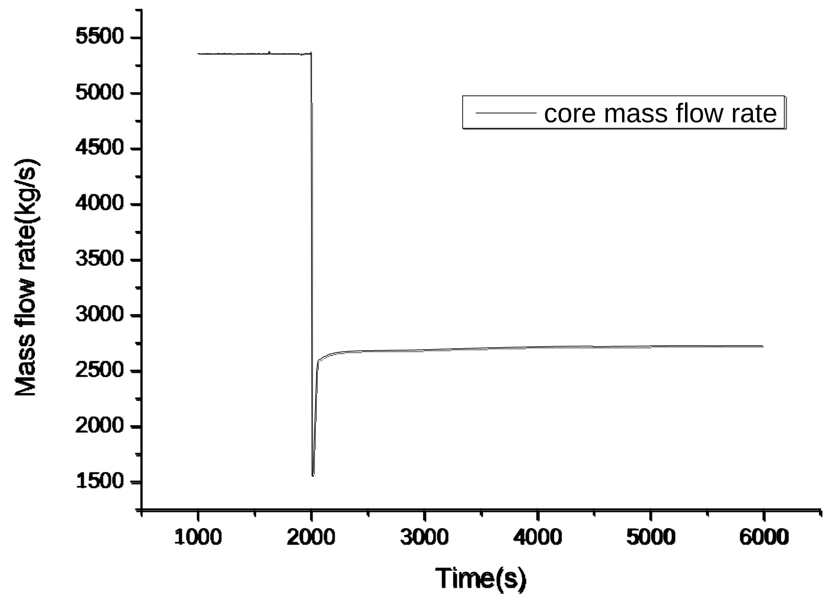

Figure 9 core mass flow rate after stopping argon gas

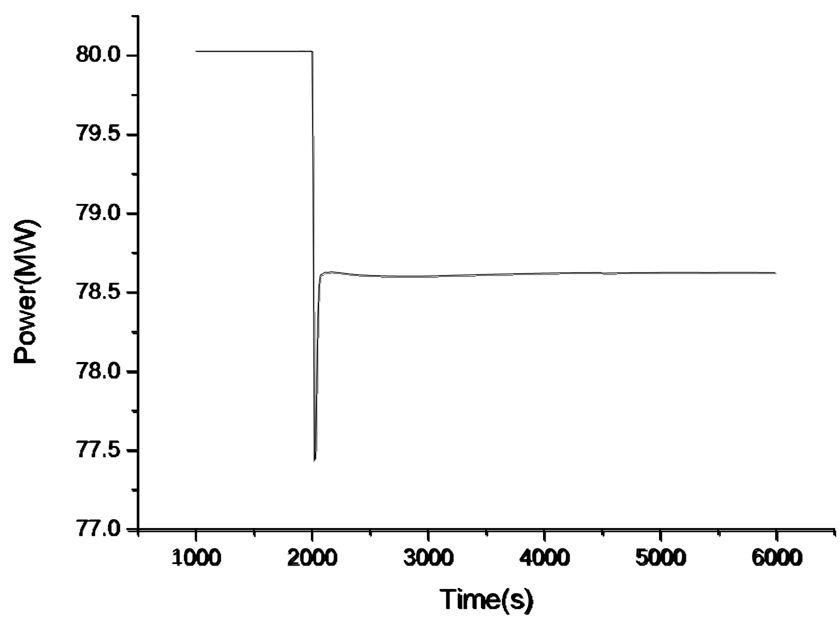

Figure 10 power after stopping argon gas

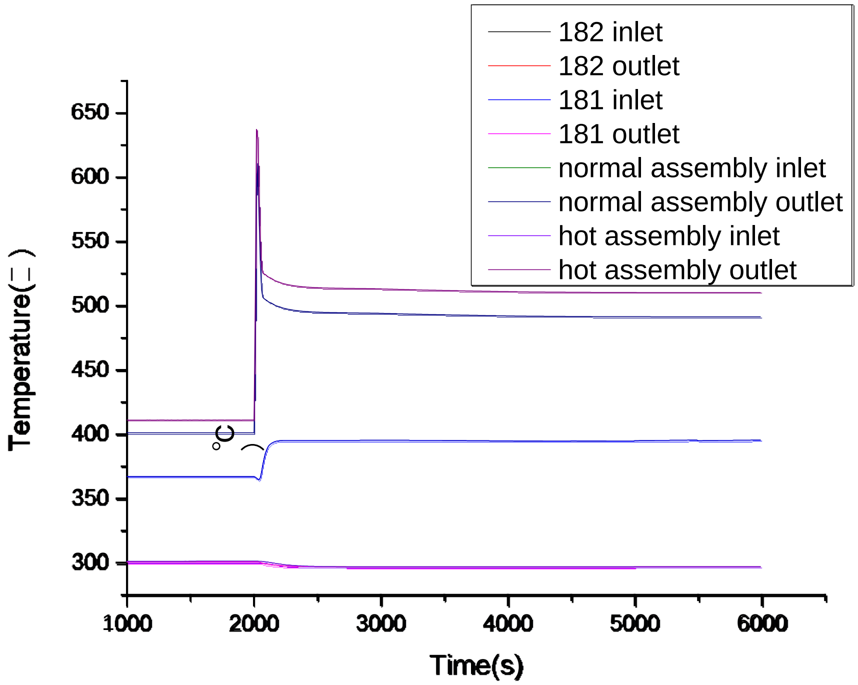

Figure 11 coolant temperature

The hot rod cladding temperature (see Figure 12, the 08, 09, 10, 11, 12 nodes of the cladding match the 13, 14, 15, 16, 17 nodes of the middle channel) varies according to the coolant temperature and the generated power. The main vessel wall temperatures close to and right below the lead-bismuth free surface also increase, up to approximately 75 K, reaching a maximum of about 747 K (474°C, Figure 13).

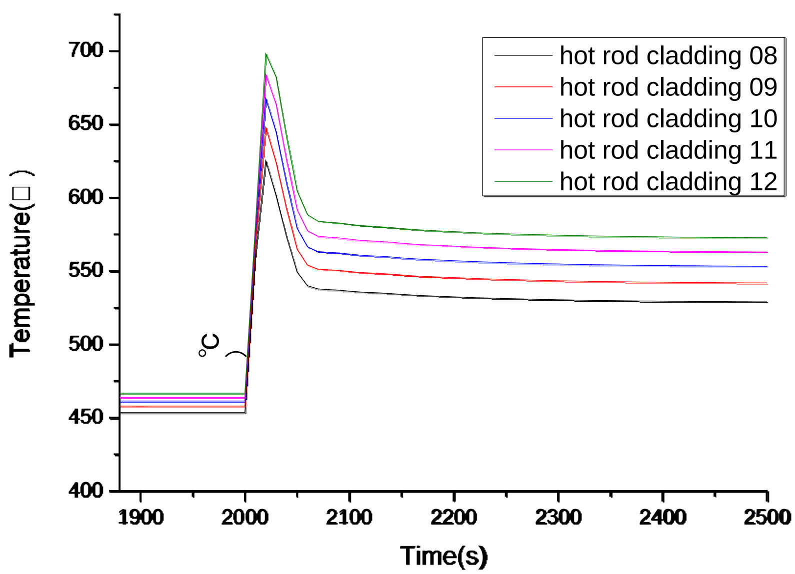

Figure 12 hot rod cladding temperature

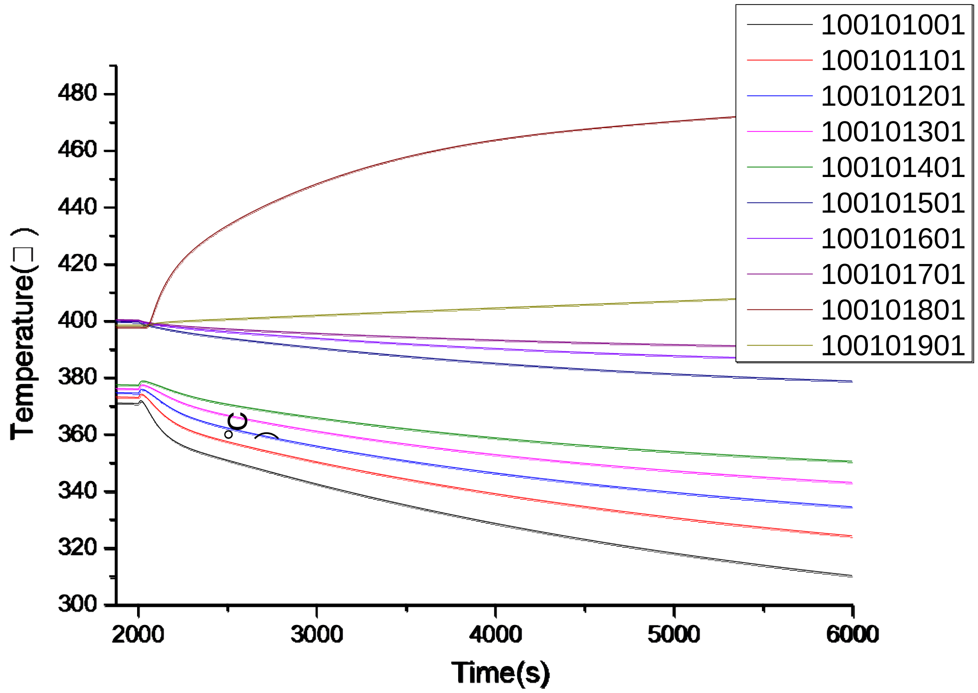

Figure 13 Gas compressor trip with no proton beam

3.3 Flow reduction in a single fuel assembly

The flowarea of the channel will reduce according to the oxidizing sedimentation of LBE, so it is necessary to analysis the flow reduction in a single fuel assembly. In order to consider the worst conditions, it is hypothesized that the flow area reduction takes place at the hottest channel, all other components being however well working and the total power of the reactor being stable, ignoring the negative feedback.

Different simulations have been performed in which the hottest fuel assembly inlet flow area was reduced by 10% per simulation. When reaching 80% flow area reduction, smaller reduction steps have been used, until the total flow blockage was reached. No proton beam trip is simulated.

In this research, the situation of 50%, 35%, 10%, 5% and 3.5% of the initial inlet flowarea are displayed and the changing of the temperature in each volume, fuel cladding and fuel is also compared (Figure 14).

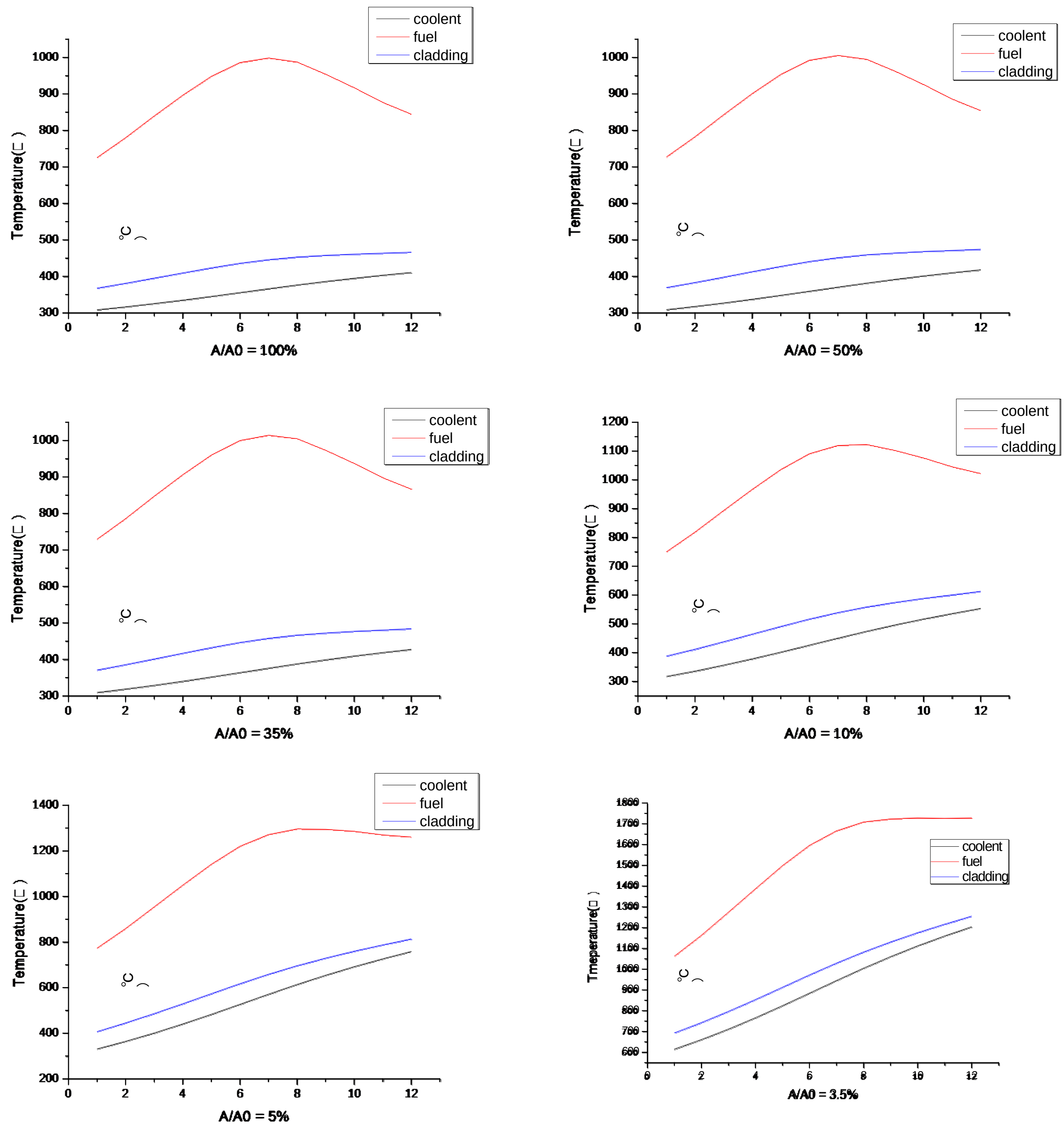

Figure 14 AFA axial temperature distribution for different A/A0

As seen above, where the maximum temperatures of coolant, clad and fuel in the affected channel are reported as function of the fractional residual flow area, up to approximately 65% flow area reduction (A/Ao = 0.35), the clad temperature increase is indeed small (less than 80°C). For reduced residual flow areas (A/Ao<0.35) the maximum clad temperature rises faster and faster; however the clad fusion temperature (1 473 K) is predicted only when the affected channel flow area reduces to about 3% of its nominal value. So it is important to keep the flowarea higher than 3.5% of the normal value.

3.4 External neutron doubled accident

The accident of doubling the external neutron is part of the reactivity insertion accident, in this paper the accident of doubling the external neutron in the unprotected situation.

When it happens, prompt critical accident may also be cased which will let the reactor get out of control and the power become so high that the pressure boundary of primary loop will be damaged.

There are two control plans: one is through changing external neutron and moving the control rods, the other is only changing the working state of the accelerator without moving the control rods. In this paper, the second plan is considered. If feedback effect is ignored, the total power will be doubled when the external neutron is twice as much as it used to be.

Doubling the external neutron while the reactor is normally operating, after it is stabilized again, the total power is 148MW which is about 185% of the initial power (Figure 15). The reactivity reduces 0.678 to about -9.5 (Figure 16).

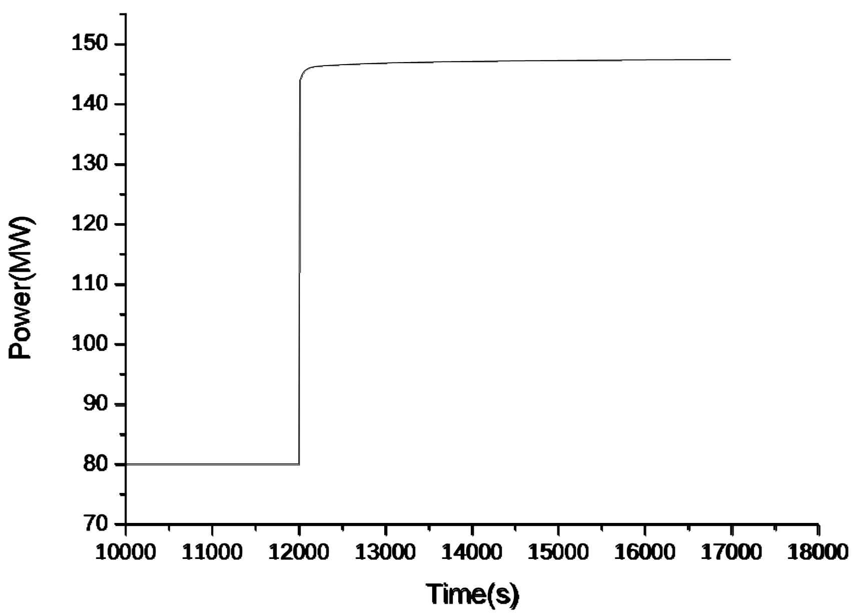

Figure 15 core power

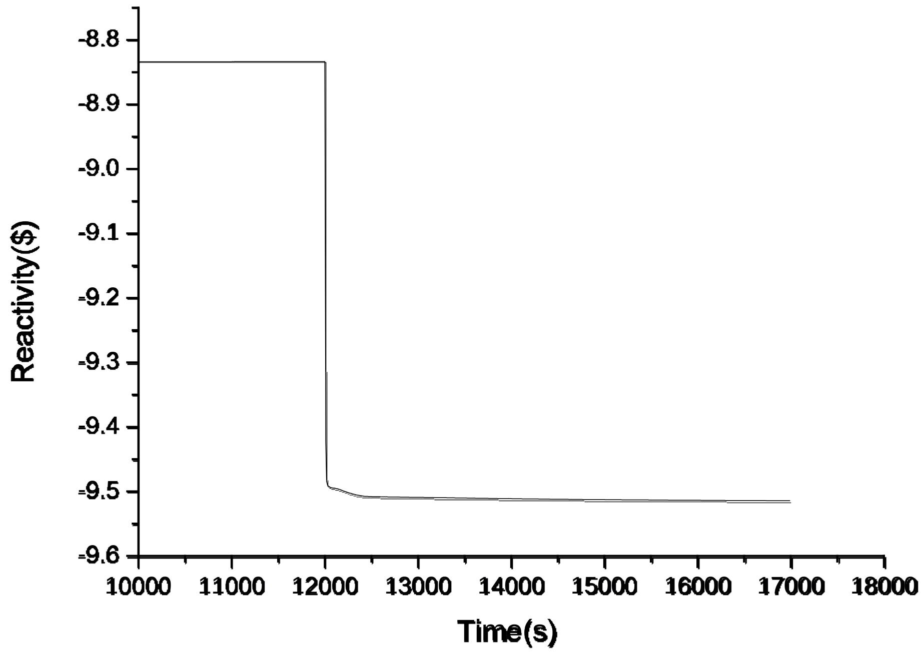

Figure 16 reactivity

As is showed in Figure 17 and Figure 18, the inlet temperature nearly remains the same after the external neutron doubling while the outlet temperature of the normal assembly rises from 401°C to 480°C and it of the hot assembly is from 411°C to 496°C, which is still much lower than the saturation temperature and the heat transfer deterioration is not happen.

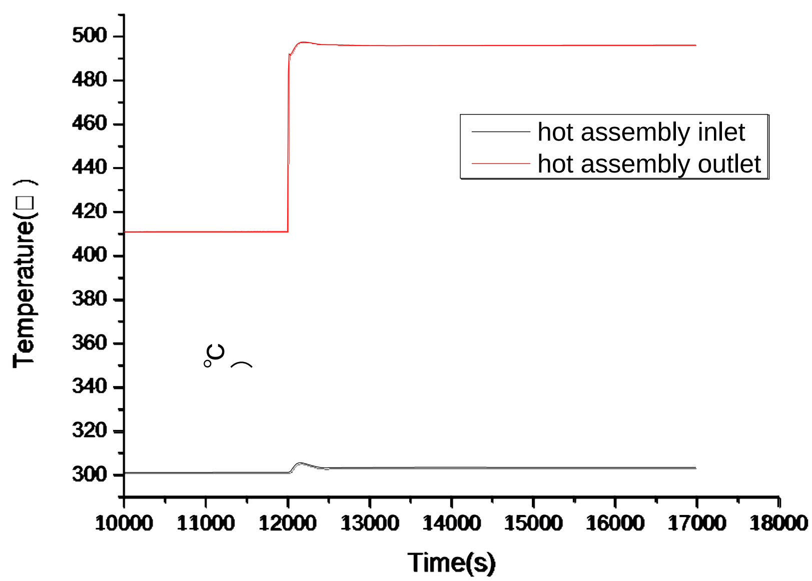

Figure 17 hot assembly coolant temperature

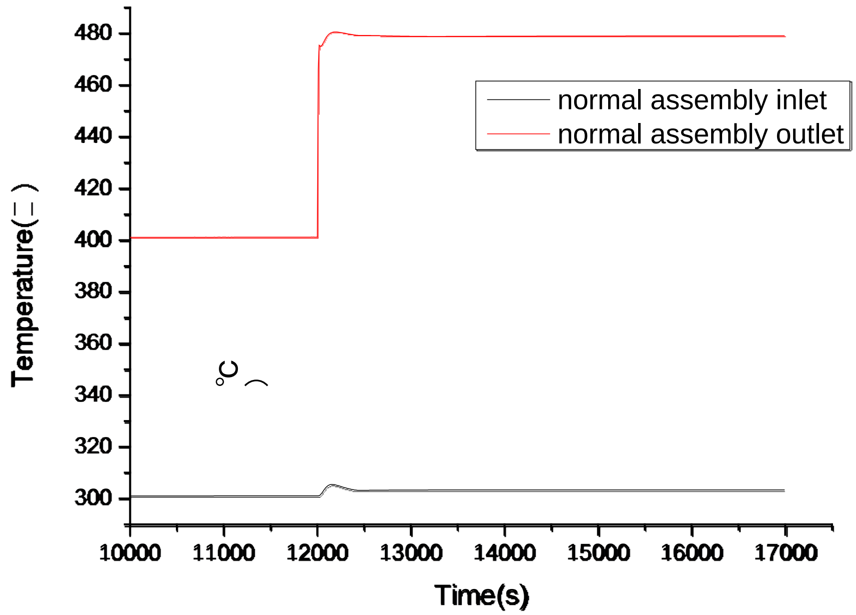

Figure 18 normal assembly coolant temperature

Figure 19 shows the changing of the coolant mass flow in the core. Because of the increasing of the power, the temperature difference between the inlet and outlet part of the core is higher and the mass flow rate rises from 5300 kg/s to 5600kg/s.

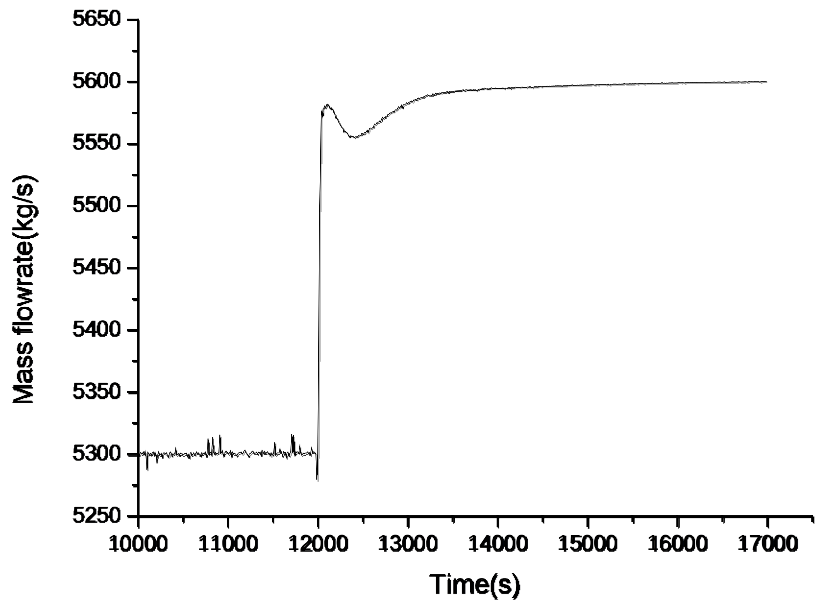

Figure 19 core coolant mass flowrate

As the effect of feedback, when the external neutron is doubled, the core temperature will increase which limit the power growth, and flowrate will also be limited. In conclusion, XADS is in a safe condition if the external neutron is doubled.

3.5 Analysis of cutting off the proton beam and restart it

When the reactor is normally operating, the accident of cutting off the neutron beam and then restarting it is simulated by cutting the external neutron and after ten seconds, recovering it. The argon is injected into the system constantly and the flowrate of the secondary side is constant.

As is showed in Figure 20 and Figure 21, after cutting the external neutron, the power decreases to 13.8MW immediately, and then, when the accelerator run again normally after 10 seconds' stopping, the power rises to 77.9MW and slowly restore to 80MW. At the same time when the accelerator stops, the reactivity rises to -8.20 and when the accelerator works again, it recovers to -8.7854, finally stabilizes about the initial power.

Figure 22 shows average inlet and outlet coolant temperature of the normal assembly. The inlet coolant temperature does not change so much after the accident while the outlet temperature falls from 411℃ to 326℃.
Figure 23 shows the flowrate in this accident. After cutting the external neurtron, the power decrease at the same time which cases the difference between the inlet coolant temperature and the outlet coolant temperature become smaller, and the flowrate fall from 5300 kg/s to 5168.4 kg/s.

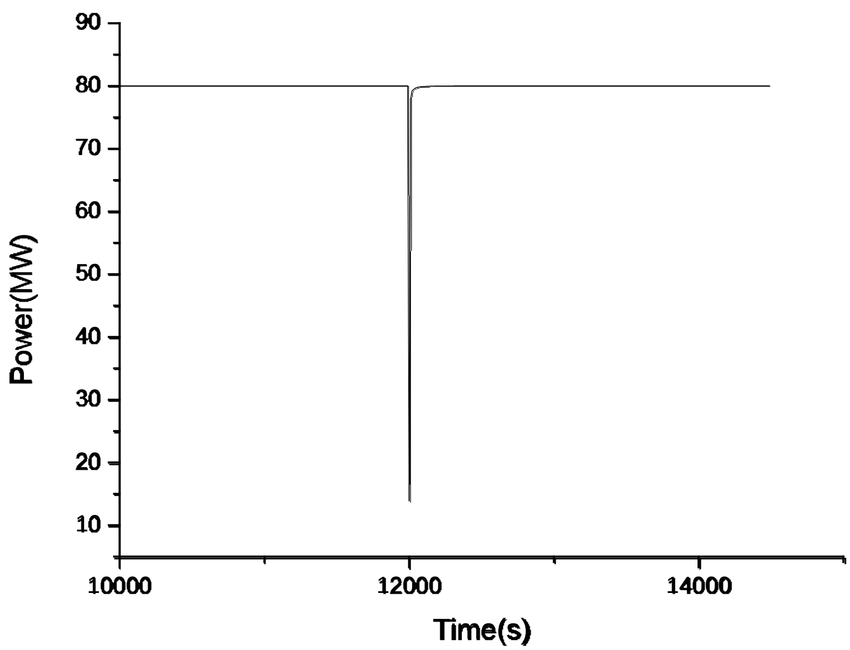

Figure 20 reactor power

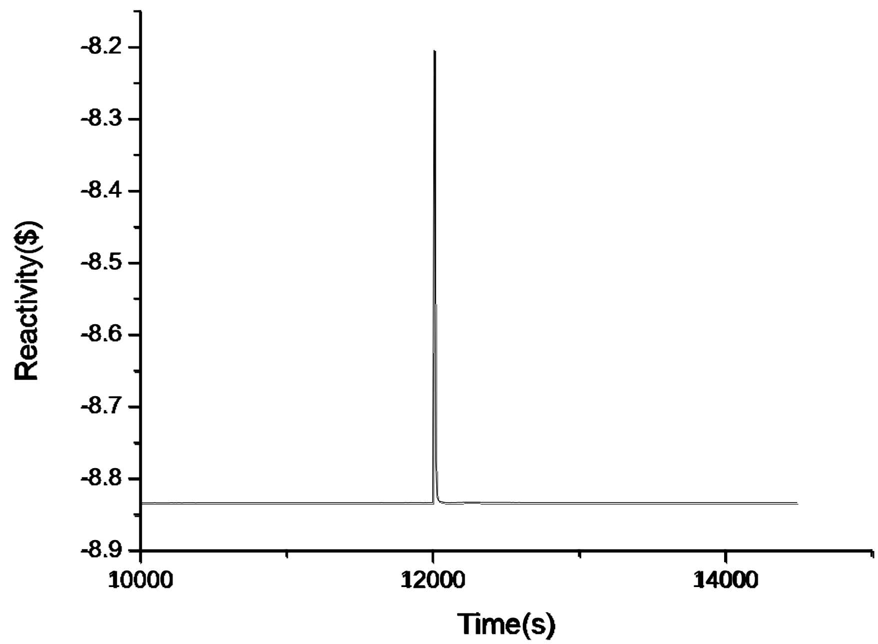

Figure 21 reactor reactivity

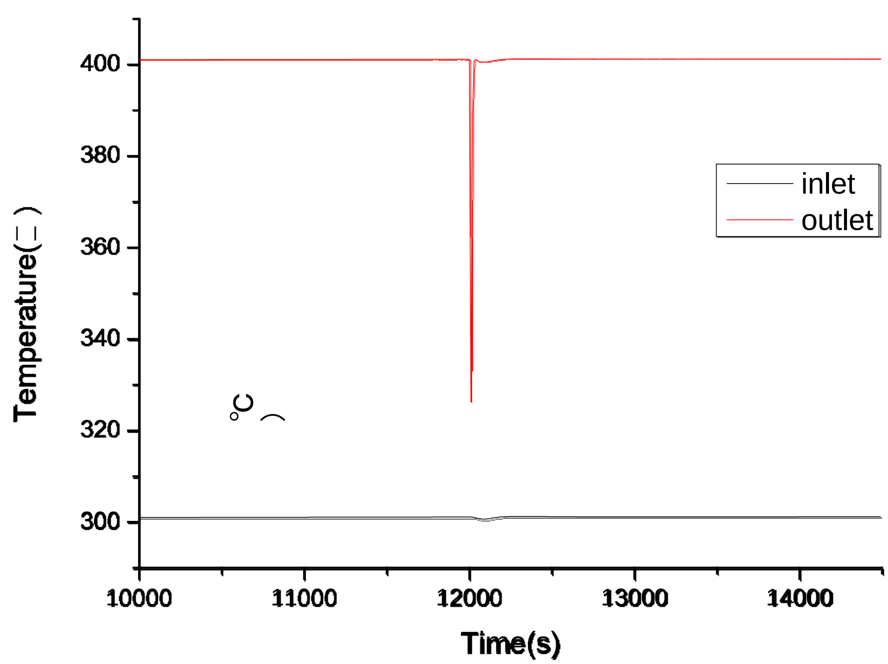

Figure 22 normal assembly temperature

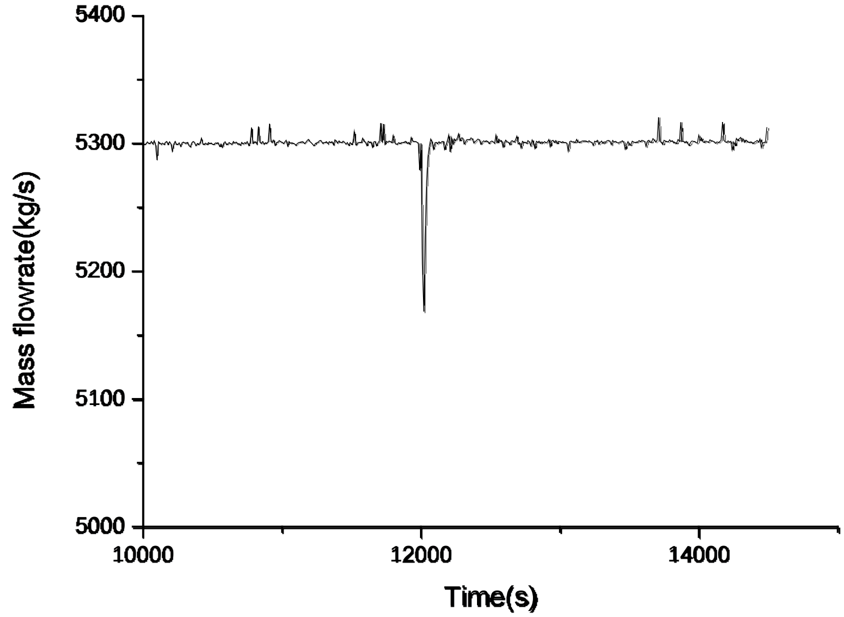

Figure 23 mass flowrate

4. Conclusion

In this research, the XADS model is analyzed and through modifying the RELAP5/MOD3.3 code, the accidents of changing the external neutron is calculated. The conclusion is as follows:

- following a loss of primary flow originated by a postulated total loss of argon injection to enhance it, the primary coolant mass flowrate decrease promptly causes higher differential temperature across the core which readily actuates the plant protection system (proton beam trip) as the high core outlet coolant temperature setpoint is attained. No significant challenges are experienced by the safety related physical barriers (actually there is no over-temperature transient at all for the vessel and only a minor over-temperature for a short time interval for the cladding).
- In case of accidental obstructions of the hot fuel channel inlet flow area up to total flow blockage, the affected fuel element coolant mass flow rate decrease causes the coolant temperature increase. Simulations results indicate that:
  - the LBE-cooled ADS is very tolerant to flow blockage (no significant temperature effects up to a 65% fuel assembly flow area reduction are predicted);
  - for higher flow blockage a peculiar heat transfer mechanism rejecting an increasing amount of heat radially to the coolant flowing outside the affected fuel assembly establishes; this prevents coolant boiling and fuel melting also assuming the plant at full power;
  - the complete flow blockage will be tolerated without any significant clad and fuel temperature increase crediting the proton beam trip on a LBE fuel element high outlet temperature protection signal.
- The accident of changing the external neutron is analyzed and the result shows with the effect of feedback, the reactor is safe even the external neutron is doubled.

5. References

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