The design and calculation of the delayed neutron detection system for PWR and CEFR

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Abstract: This paper discussed the importance of the delayed neutron detection system. We improved the delayed neutron detection station and delayed neutron detector, so the noise was greatly decreased and the detection efficiency was greatly increased. After the improvement the stability of the detector was enhanced and the false alarm was eliminated. We introduced the principle of the gas lift pump designed for the sodium cooled fast reactor. A calculation model of the failed fuel detection system of CEFR was proposed, and from the model a code using LabWindows/CVI was developed. The minimum broken area that could be detected by the delayed neutron detection system of CEFR was calculated and the delayed neutron detection signal in a few representative transient conditions during fuel failure happened was stimulated.

Key words: reactor; fuel failure; delayed neutron; gas lift pump; calculation model

1 Introduction

The failed fuel detection system is used to monitor the fuel of reactor, prevent fission products from leaking to the first loop coolant and contaminating the reactor as well as environment, safeguard the safety of reactor operation. Delayed neutron detection system can detect the broken area of fuel failure. It is one of the most important system for the safety of reactor. The delayed neutron detection signal can be used to decide whether we need to shut down the reactor. Another most often used fuel failure monitoring system for PWR is overall γ detection system and for CEFR is cover gas monitoring system. These systems can only detect the gas leaking failure. It can't give the information abort the severity of the failure. Reduce unnecessary reactor stop can bring great benefit for nuclear power plant. Elaborate design of delayed neutron detection system can contribute to reducing unnecessary reactor stop. This paper introduced the improvement of delayed neutron detection system of PWR and CEFR. Table 1 lists the main precursors of delayed neutron. Most of them are isotopes of Br and I. Their half lives are very short, so the coolant sampling time is very important for the detection of delayed neutron. For PWR the sample of water transferred from failed fuel subassembly to detector should be 30 ~ 60 s. Because the isotopes of Br and I would decay to a little amount that could not be detected if the transfer time is above 60 s, and the inference of ^{16}N would be serious when the transfer time is less than 30 s. For sodium cooled fast reactor the sample of sodium transferred from failed fuel subassembly to detector should be 15 ~ 90 s. The γ radiation emitted from ^{24}Na and the neutrons leaked from reactor core construct the main interference for delayed neutron detection signal. To reduce the interference the first loop coolant is often elicited out of reactor core. For PWR we need to elicit high temperature high pressure water and for sodium cooled fast reactor we need elicit high temperature liquid sodium, both of which are difficult and dangerous. This paper introduced a gas lift pump used for sampling high temperature sodium, which would be a simple and economical method.

Table 1 The main nuclides that release delayed neutron

Nuclide	Half life /s	Fission yield / %	DN branching ratio / %	DN energy /MeV
^{137}I	24.6	6.27	5.4	0.56
^{138}I	6.55	6.8	2.5	
^{87}Br	55.7	2.64	2.3	0.45
^{88}Br	15.9	3.69	4.6	0.53

2 The improvement of delayed neutron detection system for PWR

2.1 The structure and principle of failed fuel detection system for PWR

The flow chart of failed fuel detection system for PWR is shown in Fig. 1. The high temperature high pressure water (350 ℃, 17.5 MPa) sampled from first

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loop is cooled by two heat exchangers to less than 45 ℃ and then transferred to delayed neutron detection station and overall γ detection station finally brought back to first loop. If there was a nuclear fuel failed, fission products would leak to first loop. The delayed neutron precursors (such as ^{87}Br and ^{137}I, etc.) would be transferred to delayed neutron detection station. The delayed neutrons emitted by precursors could be detected by neutron detector.

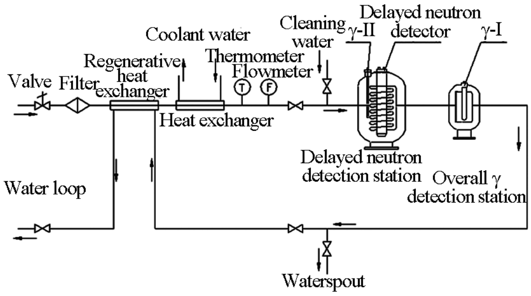
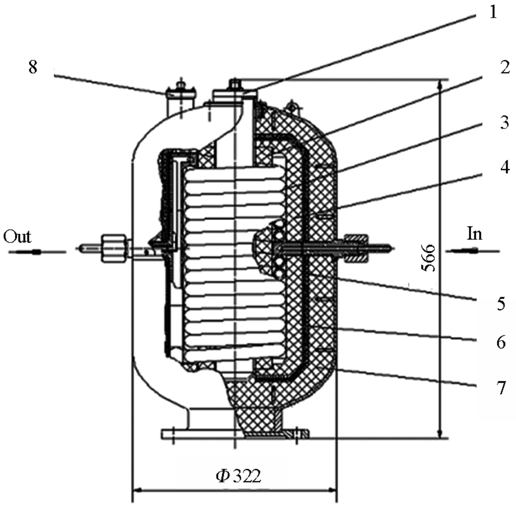


Fig. 1 The failed fuel detection system of PWR

2.2 The improvement of delayed neutron detection station for PWR

The delayed neutron detection station for PWR has 8 layers (Fig. 2). The helical pipe is the wiring part. The sampling water is injected from the middle of the helical pipe, then divided into two branches, one of which flow up another of which flow down. Finally two branches join together and flow back to first loop. As a result of the improvement the middle of helical pipe where most of delayed neutrons are emitted is in front of the middle of the detector where the sensitivity is highest. So we get higher detection sensitivity.



1—Heat-resistant high sensitivity delayed neutron detector;
2—Moderator of delayed neutron; 3—Helical pipe;
4—Neutron reflector; 5—Cadmium neutron absorber;
6—Cadmium mixed with boron neutron absorber;
7—Moderator of background nertron; 8—γ-II detector

Fig. 2 The delayed neutron detection station of PWR

2.3 The improvement of neutron moderating material and absorbing material

We use high density polyethylene as neutron moderating material. The moderating effect of high density polyethylene is good, which can reduce the thickness of moderator and reflector to 25 mm, so as to reduce the volume of the detection station. As a result, the detector can be closer to the sampling water. So the detection sensitivity is increased.

In order to decrease the background neutrons, both of moderator and absorber are used. We select polyethylene as moderator and cadmium mixed with boron as absorber. Cadmium is mainly used to absorb thermal neutrons whose energy is below 0.5 eV and boron is mainly used to absorb epithermal neutrons whose energy is between 0.5 eV and 1 keV.

The system was used for HWER of ALGERIA. These improvements decreased the backgrounds effectively, increased the stability of the detectors, resolved the fault alarm problem which had not been resolved for a long time, and increased the detecting sensitivity ten times.

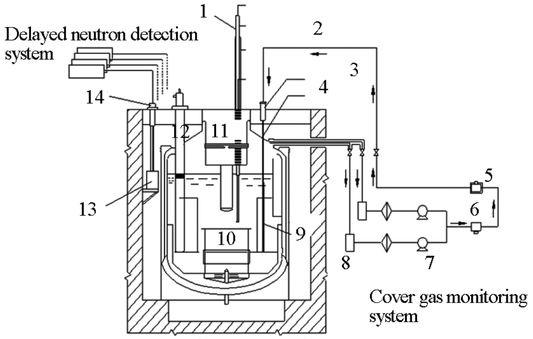
3 The improvement of delayed neutron detection system for CEFR

3.1 The performance of failed fuel detection system of CEFR

The failed fuel detection system of CEFR includes the cover gas monitoring system and the delayed neutron detection system. The cover gas monitoring system is used to detect the gas-leaking failure and the delayed neutron detection system is used to detect the contact failure. The detection limit of the cover gas monitoring system is 0.1 % (about 5 fuel pins). As for the delayed neutron detection system, the detection limit is 0.01 % (about 1 fuel pin). For the safety of CEFR, the minimum broken area that could be detected by delayed neutron detection system must not be above 10 cm^2.

3.2 The makeup of the delayed neutron detection system of CEFR

This system has four delayed neutron detection stations. They are placed out of reactor vessel and in front of inter-medial heat exchanger (up left part of Fig. 3). Each detection station has two BF$_3$ proportional countertubes, which are used for detecting delayed neutrons emitted from inter-medial heat exchanger. Furthermore, each detection station has a neutron source used for checking the function of the detection system.



1—Charger and discharger; 14—Preamplifier
2—Gas lift pump for sampling high temperature sodium;
3—Sodium container; 4—Lift pipe; 5—Spectrometer;
6—Monitor; 7—Gas compressor; 8—Sodium steam trap;
9—Flow guiding pipe; 10—Reactor core; 11—Sampling ring;
12—IHX; 13—Delayed neutron detetion station

Fig. 3 The failed fuel detection system of CEFR

3.3 The delayed neutron detection station of CEFR (Fig. 4)

Inside the detection station there are lead shielding materials (50 ~ 150 mm) around the detectors used for shielding γ radiation. In order to reduce the interference from background neutrons, there are moderators and absorbers upside, downside and backside of the detection station. Polyethylene (80 mm) is used as moderators. Cadmium (10 mm) is used as absorbers for absorbing thermal neutrons and polyethylene mixed with boron (30 mm) is used for absorbing epithermal neutrons. For the sake of detecting delayed neutrons emitted from inter-medial heat exchanger, there are no absorbers in front of the detection station. But there is polyethylene (25 mm) around the detector to moderate delayed neutrons. There is a neutron source canal near the detector canal. The source check device consists of a drive machine with Am-Be neutron source and hanger rope. The activity of the neutron source is 100 mCi, and the neutron yield is 2.2 × 10^5 n/s. The lead shielding materials, moderators and absorbers are all block shape, installed in solid steel shuck. Even if temperature exceeds the melting point of polyethylene, the detection station could not collapse.

3.4 The delayed neutron detectors of CEFR (Fig. 5)

The detectors could be installed from the detector canal. The detectors have two parts, which are abort 4 meters apart from each other. The BF_3 proportional countertube is installed in downside part. The rated temperature of countertube is abort 80 ℃ and the sensitivity of countertube is 1 cps/nv. In the upside part there are amplifiers and shaping circuits. Their rated temperature is below 50 ℃. The pulse signal out from shaping circuits is transferred to control room for analyzing, recording and alarming. We select BF_3 proportional countertube as neutron detector because it can greatly decrease γ interference.

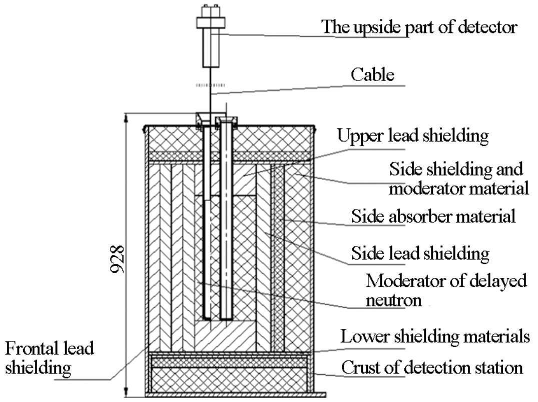
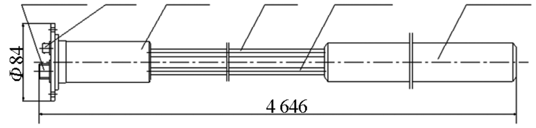


Fig. 4 The delayed neutron detection station of CEFR



1—Low voltage and signal connector; 2—High voltage connector;
3—Amplifier and discriminator; 4—High voltage cable;
5—Low voltage and signal cabl; 6—Neutron detector with preamplifier

Fig. 5 The delayed neutron detector of CEFR

3.5 The gas lift pump for sodium sampling of sodium cooled fast reactors[1]

To detect delayed neutrons, the background neutrons should be as least as possible. So the first loop sodium is often sampled out of reactor vessel for detection. For the safety of reactor, we could not punch the reactor sidewall. The sodium could only be pumped from upside of the reactor vessel. The traditional electromagnetic pump used for sodium sampling has some shortcomings, such as complex, short life and expensive. We design a gas lift pump (up right part of Fig. 3) which could draw out the first loop sodium from the reactor vessel into a container for detection through a pipe. The pipe, diameter of which is 60 mm, is inserted into the reactor vessel from the upside. The volume of the container is 10 L. Sodium could flow back to reactor vessel when the pump is out of work. The gas lift pump is smaller, life longer and easier to replace compare to traditional electromagnetic pump. The experiment verified that the lift and flux of the gas lift pump satisfy our request. However, it was not used by CEFR because of the space limit of the top of CEFR.

3.5.1 The principle of the gas lift pump (Fig. 6)

Purifying argon is emitted from the argon entrance at the upside, then flows down through the gas pipe and enters the lift pipe from the gas emitting entrance at the downside. The argon is divided into seriate bubbles. It's these bubbles that lift the high temperature sodium flowing up. The sodium is separated from argon at the separate chamber and collected by the bell-mouthed flow guiding pipe. Then the sodium flows down in the guiding pipe. When it arrives at the bottom of the container the sodium gets out of the guiding pipe and flows up. Finally the sodium overflows the container and flows back to reactor vessel. The separated argon flows out of the air hole and then back into reactor vessel through adiabatic sleeve. The guiding pipe is used to collect sodium and make sure they flow in and out in order. The sodium flowing in the guiding pipe would emit delayed neutrons which could be detected by neutron detectors. The adiabatic sleeve doesn't contact with high temperature sodium to decrease energy loss. The adiabatic sleeve and the entry tube join together as a part of pressure boundary of the reactor.

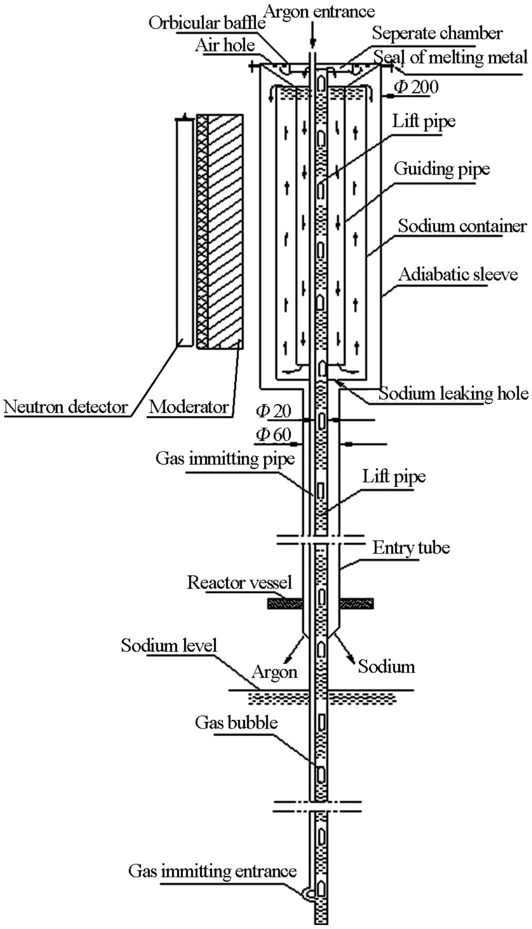


Fig. 6 The gas lift pump of high temperature sodium

3.5.2 Argon source

We can connect this device to the cover gas monitoring system and use the sampled argon from this system as the argon source, which would be convenient and economical.

4 The modeling and calculation of delayed neutron detection system

Through the modeling and calculation of delayed neutron detection system, we can set the detection limit for the failed fuel detection system of CEFR more precisely, so as to set the appropriate operation parameter and provide theory basis for the commissioning and operation of this system. Therefore, it's of great importance to this work.

4.1 The modeling of delayed neutron detection system for CEFR

According to the international research in this area up to the date, the model is generally set up following the behavior of delayed neutron precursors in fuel matrix, fuel-to-clad gap and first loop coolant. Therein, the behavior in fuel matrix is the most complex process. The model shows a little difference for different types of reactor. What will we introduce in the following is the model of delayed neutron detection system for CEFR.

4.1.1 The release of precursors from fuel matrix to fuel-to-clad gap

It is generally believed that there are three main mechanisms: recoil, diffusion and knockout governing the precursors' release from fuel matrix to fuel-to-clad gap, among which recoil and diffusion have the most share.

1) Recoil[2]

$$R_{\mathrm{rec}} = \frac{1}{4} B \eta (S_{\mathrm{g}}/V) u_{\mathrm{f}} \qquad (1)$$

In Eq. (1), R_{rec} is the release rate of certain precursor from fuel pellet to gap or gas plenum of fuel rod, 1/s; B is the total birth rate of certain precursor from one fuel rod, 1/s; η is the probability of recoil fission product not embedded into the clad; u_{f} is the mean range of certain precursor in the fuel pellet, cm; S_{g}/V is the ratio of geometrical area to volume of failed fuel pellet, 1/cm.

2) Diffusion[3]

$$\frac{\partial C(r,t)}{\partial t} = \frac{D(t)}{r^2} \frac{\partial}{\partial r}\left[r^2 \frac{\partial C(r,t)}{\partial r} \right] - \lambda C(r,t) + \frac{F_{\mathrm{f}}(t) y}{V} \qquad (2)$$

In Eq. (2), $C(r, t)$ is the concentration of certain precursor at the radial position r in the fuel pellet at time t, 1/ cm^3; $D(t)$ is the diffusion coefficient of certain precursor in fuel pellet at time t, cm/s; λ is the decay constant of certain precursor, 1/s; $F_{\mathrm{f}}(t)$ is the total fission rate of one fuel rod, 1/s; y is the cumulative fission yield of certain precursor; V is the volume of fuel pellet, cm^3.

4.1.2 The leakage of precursors from fuel-to-clad gap to coolant

$$\frac{\mathrm{d}N_g(t)}{\mathrm{d}t} = R_{\mathrm{dif}}(t) + R_{\mathrm{rec}}(t) - (\lambda + v(t))N_g(t) \tag{3}$$

In Eq. (3), $N_g(t)$ is the amount of certain precursor in the fuel-to-clad gap at time t; $v(t)$ is the leak rate of certain precursor from gap to sodium through cladding failure at time t, 1/s. This equation is set up basing on the conservation of mass of precursor in the fuel-to-clad gap.

4.1.3 The calculation model for the delayed neutron detection signal

$$C(t) = \varepsilon \cdot \sum_k \sum_i \frac{v(t) \cdot N_g(t)}{Q} \cdot e^{(-\lambda_i t_k)} \cdot V_k \cdot f_i \cdot \lambda_i \cdot \sigma_i \tag{4}$$

In Eq. (4), $C(t)$ is the delayed neutron count rate at time t, 1/s; ε is the sensitivity of the delayed neutron detector; $v(t)N_g(t)$ is the leak rate of precursor i from fuel-to-clad gap to coolant, 1/s; Q is the flow rate of sodium at the exit of failed fuel subassembly; λ_i is the β decay constant of precursor i, 1/s; t_k is the time of precursors transferred from failed fuel subassembly to region k, s; V_k is the volume of sodium in region k covered by delayed neutron detectors, cm^3; f_i is the branching fraction of β decay of precursor i; σ_i is the amount of delayed neutrons emitted per β decay.

4.2 Calculating and analyzing

We developed a code for the delayed neutron detection system of CEFR based on the model set up upwards. The code realized two functions, one of which is to estimate the broken area of the failure basing on the detected signal and another of which is to calibrate the experiential parameter in the model. Using the code we calculated the minimum broken area that could be detected by the delayed neutron detection system of CEFR. We also simulated the delayed neutron detection signal in a few representative transient conditions during fuel failure happened.

4.2.1 The calculation of minimum broken area detected by the delayed neutron detection system[4]

We make following presuppositions before calculation: a. The mean range of fission products in the fuel pellet is 9 μm; b. The total flux of sodium in the reactor core is 300 kg/s; c. The precursors of delayed neutron released are equably blended in the quarter of quadrant just up the failed fuel; d. The precursors to be considered are ^{87}Br and ^{137}I; e. The release mechanism is recoil and diffusion to first loop sodium; f. The diffusion constant of precursors in fuel pellet is 6.8×10^{-10}. The following table lists the calculation result:

Table 2 The result of minimum broken area that could be detected by the delayed neutron detection system of CEFR

Precursors of delayed neutrons	Leakage rate from gap to first loop sodium /(s^{-1}) (broken area was 1 cm^2)		Delayed neutron flux /($cm^{-2} \cdot s^{-1}$) (broken area was 1 cm^2)		Minimum broken area that could be detected / cm^2	
	Recoil	Recoil and diffusion	Recoil	Recoil and diffusion	Recoil	Recoil and diffusion
^{87}Br	$2.347\,5 \times 10^8$	$3.665\,5 \times 10^8$	8.15	11.96	15.0	10.2
^{137}I	$5.602\,0 \times 10^8$	$7.690\,2 \times 10^8$				

It can be concluded from the table that the calculated minimum broken area that could be detected by the delayed neutron detection system of CEFR is 10.2 cm^2 when both recoil and diffusion are considered, which is very close to the objective 10 cm^2. So the system basically satisfies the demand of design.

4.2.2 The simulation of the delayed neutron detection signal

As the improvement of manufacturing process, the performance of nuclear fuel clad is greatly increased. So the probability of fuel failure is very low. However, as the fuel burnup is higher and higher driven by the interests, the fuel failure is inevitable. So simulating the trends of delayed neutron detection signal in transient conditions and analyzing their transient characteristics is meaningful. The simulation result of delayed neutron detection signal in a few typical transient conditions is introduced in the following.

Firstly, if we suppose the fuel had failed before the reactor's startup, the precursors of delayed neutron would be yielded and accumulate in fuel pellet. Then they will be released to fuel to clad gap and finally leaked to first loop sodium. The pressure in the gap would not change much during the whole process, so we can suppose the leakage constant will not change. Fig. 7 is the simulation result.

In Fig. 7, the first graph is the trend of amount of delayed neutron precursors in fuel to clad gap. The second graph is the trend of amount of delayed neutron precursors in first loop sodium. The third graph is the trend of count rate of delayed neutrons. During the simulation, we suppose the reactor power is increased following $P = 5t$. The simulation result indicates that the count rate of delayed neutrons increases approximately linearly. Finally it stabilizes at a maximum value. The time for it to stabilize is abort 400 s.

If we suppose fuel failed during reactor was being in operation at rated power. The fuel to clad gap has accumulated a lot of fission products, so the pressure in the gap will be much higher than the first loop sodium at the moment of fuel failure happened. The leakage constant would be much larger at the beginning of fuel failure happened, and then the pressure as well as the leakage constant would decrease to a stable value. We suppose the leakage constant decreased following $v = 2.0e^{-0.01t}$ and finally stabilized to 2.0×10^{-4}. Fig. 9 is the simulation result.

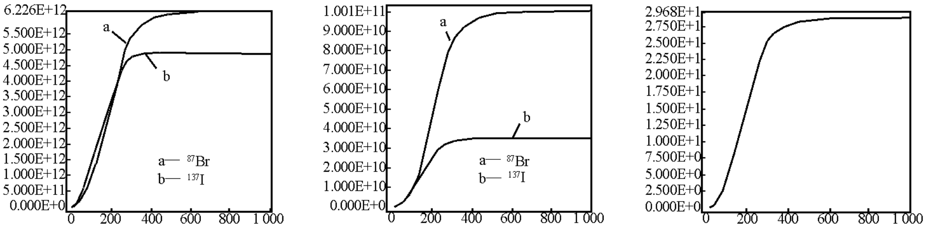


Fig. 7 The calculation result in the situation that the fuel failed before the power up

In the simulation upwards, we suppose the reactor was in operation at rated power and the fuel failed after fission products had gone into balance in fuel to clad gap. It can be concluded from Fig. 8 that the simulated count rate of delayed neutrons steps up soon after the fuel fails, then it decrease approximately exponentially to a stable value.

If we suppose the fuel failed at start moment of reactor's shutdown, the fuel to clad gap has accumulated a lot of fission products, so the pressure in the gap will be much higher than the first loop sodium at the moment of fuel failure happened. The leakage constant would be much larger at the beginning of fuel failure happened. We suppose the leakage constant decreased following $v = 2.0e^{-0.01t}$ and finally stabilized to 2.0×10^{-4}. Fig. 9 is the simulation result.

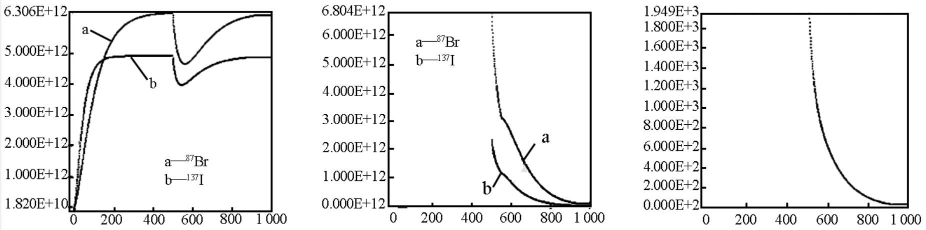


Fig. 8 The calculation result in the situation that the fuel failed during stable operation

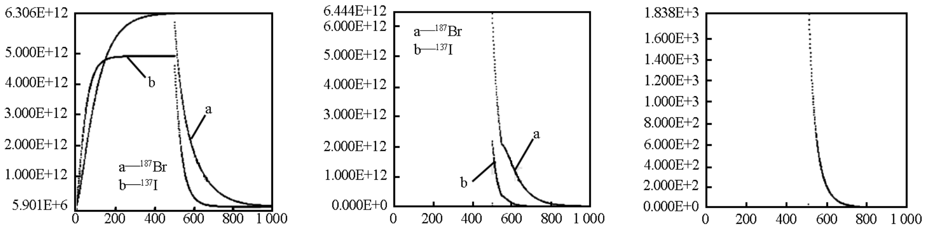


Fig. 9 The calculation result in the situation that the fuel failed before the power off

In the simulation upwards, we suppose the reactor power decreased following $P = P_0 \times e^{-0.1t}$ from rated power to zero and the fission products had gone into balance in fuel to clad gap before reactor power decreased. It can be concluded from the figure that the simulated count rate of delayed neutrons steps up soon after the fuel fails, then it decreases quickly to zero.

5 Conclusions

By the improvement of delayed neutron detection stations and detectors for two different types of reactor PWR and CEFR, the sensitivity and stability of the delayed neutron detection system was greatly improved, which has been verified by practice of project. We did some tentative research on the modeling and calculating of delayed neutron detection system for CEFR and calculated the minimum broken area that could be detected by it. The result indicated that the system basically satisfies the demand of design. We simulated the delayed neutron detection signal in a few typical transient conditions. The result would give important theoretical guidance for the operation of the system.

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