Xenon poisoning calculation code for miniature neutron source reactor (MNSR)

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Abstract In line with the actual requirements and based upon the specific characteristics of MNSR, a revised point-reactor model was adopted to model MNSR's xenon poisoning. The corresponding calculation code, MNSRXPCC (Xenon Poisoning Calculation Code for MNSR), was developed and tested by the Shanghai MNSR data.

Keywords Miniature neutron source reactor (MNSR), Xenon poisoning

CLC numbers TL411+.7, TL36

1 INTRODUCTION

The MNSR, developed by CIAE in March 1984, is a simple, safe, reliable and cheap nuclear facility without any potential radiation effect on the environment and public domain. It can be constructed at research institution, hospitals or training centers in city areas with dense population for the purposes of neutron activation analysis, medium- and short-life radioisotope preparation and personnel training for nuclear technique application. Up to now, there are nine domestic and overseas MNSRs.

In order to guarantee the inherent safety feature, some effective measures in physics design are adopted, such as under-moderated reactor core, limited excess reactivity, etc. Because the initial cold excess reactivity of MNSR is strictly limited to 3.5~4.0 mk (1mk=$10^{-3}\Delta k/k$), which is not enough to overcome the equilibrium xenon poison and temperature negative reactivity. Therefore the MNSR's operation can only be defined by the xenon poisoning, that is, the MNSR can only be operated in an intermittent mode. This feature is different from other research reactor and power reactor, thus particular xenon reactivity calculation method is required.

A computer software for modeling the MNSR's xenon reactivity was developed. Its model, method, and calculating process for MNSR' xenon poisoning are described in this article. The calculated values for reference reactor, Shanghai MNSR, are also analyzed and discussed.

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2 ANALYZING MODEL

Xenon poisoning is significant to the reactor operation because of its numerous thermal neutron absorption cross-section and its relatively large fission yield. Depending on the particular flux behavior of different operating modes, three parts were included: i.e., xenon poisonings following start-up, shutdown and power level changes. In addition, xenon poisoning versus burn-up level was also analyzed.

Actually, xenon-poisoning reactivity is spatially dependent. An approximated method was applied in this report. The detailed model is depicted in Fig.1. First, 2-dimensional or 3- dimensional code[1] is used to calculate the equilibrium xenon-poisoning reactivity, which is dependent spatially on the average neutron flux of core. Then, homogeneous reactor (namely, point-reactor model) is considered. Here a revised point-reactor model was adopted.

Let us suppose one-group treatment is applied, in the light of quality conservation and simplified decay scheme of ^{135}Xe, the differential equations for the concentration of ^{135}I and ^{135}Xe are as follows:

$$\frac{\mathrm{d}N_{\mathrm{I}}(t)}{\mathrm{d}t} = \gamma_{\mathrm{I}}\Sigma_{\mathrm{f}}\Phi - \lambda_{\mathrm{I}}N_{\mathrm{I}}(t) \tag{1}$$

$$\frac{dN_{\mathrm{Xe}}(t)}{\mathrm{d}t} = \gamma_{\mathrm{Xe}}\Sigma_{\mathrm{f}}\Phi + \lambda_{\mathrm{I}}N_{\mathrm{I}}(t) - (\lambda_{\mathrm{Xe}} + \sigma_{\Phi}^{\mathrm{Xe}}\Phi)N_{\mathrm{Xe}}(t) \tag{2}$$

where $N_{\mathrm{Xe}}(t)$, $N_{\mathrm{I}}(t)$ are concentrations of ^{135}Xe and ^{135}I at time t; γ_{Xe}, γ_{I} are fission yields of ^{135}Xe and ^{135}I; λ_{Xe}, λ_{I} are decay constants of ^{135}Xe and ^{135}I; Σ_{f} is the equivalent macro fission cross-section of the core; $\sigma_{\mathrm{a}}^{\mathrm{Xe}}$ is the equivalent micro thermal neutron absorption cross-section of ^{135}Xe; Φ is the average neutron flux of the core.

In Eqs.(1) and (2), variables γ_{Xe}, γ_{I}, λ_{Xe}, and λ_{I} are constant. If the equivalent cross-section, Σ_{f} and $\sigma_{\mathrm{a}}^{\mathrm{Xe}}$, and the neutron fluxes, Φ, can be determined, and the initial conditions, $N_{\mathrm{Xe}}(0)$ and $N_{\mathrm{I}}(0)$ are known, the time behavior of the concentration of ^{135}Xe and ^{135}I, $N_{\mathrm{Xe}}(t)$, and $N_{\mathrm{I}}(t)$ can be easily obtained.

Besides, we know that these concentrations may eventually reduce to equilibrium levels at some time following start-up. The reactivity, which the xenon will contribute at its equilibrium level, is called as equilibrium xenon-poisoning reactivity. It is expressed as $\rho_{\mathrm{Xe}}(\infty)$ and written approximately as follows:

$$\rho_{\mathrm{Xe}}(\infty) = \frac{\Sigma_{\mathrm{f}}(\gamma_{\mathrm{I}} + \gamma_{\mathrm{Xe}})}{\Sigma_{\mathrm{a}}} \frac{\Phi}{\frac{\lambda_{\mathrm{Xe}}}{\sigma_{\mathrm{a}}^{\mathrm{Xe}}} + \Phi} \tag{3}$$

Σ_{a} is the average macro thermal neutron cross-section of the core.

Lattice spectrum calculation code, WIMSD-4[1] can be used to get few group constants, such as effective thermal neutron fission cross-section Σ_{f} and thermal neutron absorption cross-section Σ_{a}, including constants with equilibrium xenon poisoning and without xenon poisoning and the constants versus burn-up level. 3-dimensional finite-difference diffusion code, CITATION[2] can be applied to attain the equilibrium xenon-

poisoning reactivity and the average neutron flux of core at rated power or other power level. Solving expression (3) can get the equivalent thermal neutron absorption cross-section of ^{135}Xe, σ_a^{Xe}. Solving equations (1) and (2), we get the solutions: $N_{Xe}(t)$ and $N_I(t)$. And, the time behavior of negative reactivity due to xenon, $\rho_{Xe}(t)$ is also obtained easily by the following formula:

$$\rho_{Xe}(t) = \frac{N_{Xe}(t)\sigma_a^{Xe}}{\Sigma_\alpha} \tag{4}$$

2.1 Xenon poisoning following startup

Suppose that we suddenly bring MNSR to a steady-state flux level Φ_0 at time t=0, and furthermore, we will assume that prior to this time, the reactor has been in shutdown state with zero fission product poison concentration (i.e., clean core). Namely, the initial conditions for Eq.(1) and (2) are $N_{Xe}(0) = N_I(0) = 0.0$.

2.2 Xenon poisoning following shutdown

Suppose now that after operating the MNSR reactor for several hours at a constant flux level Φ_0, we suddenly shut the reactor down. Therefore, the neutron flux can be set zero. The concentrations of ^{135}Xe and ^{135}I at time t=0 are as follows: $N_I(0) = N_I(t_1)$, $N_{Xe}(0) = N_{Xe}(t_1)$. Here, t_1 is the duration of reactor operation at a given power level.

2.3 Xenon transients following power level changes

Suppose that MNSR has been operating for t_1 hours at power level $P1$, then transit to operate at power level P2 suddenly. If we assume that this change occurs at t=0, we can solve the equations (1) and (2) as an initial value problem with flux from Φ_1 to Φ_2 and $N_{Xe}(0)$=$N_{Xe}(t_1)$, $N_I(0) = N_I(t_1)$.

2.4 Xenon poisoning versus burnup level

The nuclear properties of MNSR change with burnup, and the behavior of xenon poisoning changes, too. The few group constants with burnup level can be obtained using program module WIMSD-4, then the module CITATION can be used to calculate MNSR's criticality with these constants (corresponding to different burnup levels). Therefore, the initial values for Eq.(1) and (2) can be obtained. Finally, the module XPCC, developped here by the author, can be applied to determine the time-behavior of xenon poisoning at various burnup levels.

3 DESCRIPTION OF MNSRXPCC

This xenon poisoning calculation code, aiming specially at MNSR reactor is sketched in Fig.1, MNSRXPCC, which is composed of 4 modules: WIMSD-4, CSMAKE, CITATION, and XPCC. Each program is coded as a separate module and communication between modules is fulfilled through well-matched interfaces that read and write files in a standardized format. All of the MNSRXPCC programs are run under Windows 95 system, with Visual Fortran compiling system, or under DOS operating system with NDP-Fortran compiling system.

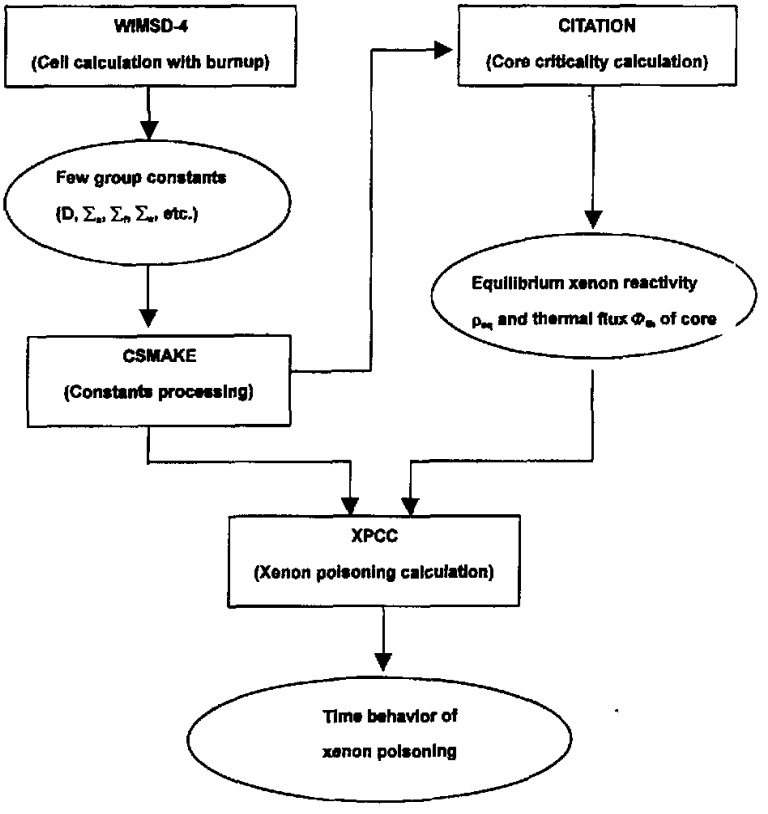

Fig.1 Sketch of xenon poisoning calculation

WIMSD-4—the module to generate the few group constants;

CSMAKE—the module of constants processing;

CITATION—the module of criticality calculation;

XPCC—the module to determine the xenon poisoning as a function of time.

WIMSD-4 and CITATION are world widely used programs. Only some modifications have been made in their input and output files in order to satisfy the requirements of MNSRXPCC as integrated system at I/O.

CSMAKE is a module to process the constants, according to the actual requirement of MNSRXPCC. The least-square method is used to fit the group constants as a function of burnup level (Bu). Fitted functions ($CDFs$, Cell Description Functions) as variable of Bu of various constants are as follows:

$$CDFs(Bu) = a_0 + a_1 Bu + a_2 Bu^2 + \cdots \tag{5}$$

Bu-burnup level(MWd/tU);

a_1, a_2, a_3-fitted polynomial coefficients;

CDFs—few group constants, including diffusion coefficient (D), absorption cross-section (Σ_a), fission products cross-section ($\nu\Sigma_f$) and scattering cross-section matrix ($\Sigma_s(g\rightarrow g')$).

A binomial or higher order polynomial can be chosen at user's will or depending on precision requirement. This module can also provide the constants with appropriate format to CITATION and XPCC. The constants corresponding to different Bu can be attained from *CDFs*, whereas the burnup level can be gotten by the formula:

$$Bu(\vec{r}, t + \Delta t) = Bu(\vec{r}, t) + P(\vec{r}, t)\Delta t \tag{6}$$

Bu ($\vec{r}$, t)—burnup level at a position $\vec{r}$ and at time t (MWd/tU);

Bu ($\vec{r}$, $+\Delta t$)—burnup level at a position $\vec{r}$ and at time $t + \Delta t$ (MWd/tU);

$P(\vec{r}, t + \Delta t)$—power density at a position and at time t (MW/tU);

T, Δt—time and time step (d).

XPCC is a xenon poisoning calculation module developed from the approximate module of point-reactor and one-group. For MNSR reactor, special attention to be paid is: the initial conditions, $N_I(0)$, $N_{Xe}(0)$ following shutdown or power-level change are the actual values at the time of shutdown and power-level change, but not their equilibrium values. This module can easily obtain the time behavior of xenon poisoning characterizing different flux behavior.

4 RESULTS AND DISCUSSIONS

MNSRXPCC is used to analyze the xenon transients at different flux conditions of Shanghai MNSR, including Xe poisonings following startup, shutdown, power-level change and burnup- level change. The calculated values will be described respectively in the following sections.

4.1 Xenon poisoning following startup

The qualitative time behavior of the concentrations for ^{135}Xe following startup of Shanghai MNSR is shown in Fig.2. The reactivity due to ^{135}Xe buildup following startup is sketched in Fig.3 and Table 1. As depicted in Fig. 2 and Fig. 3, it is about 60 hours when these concentrations reach their equilibrium values for MNSR operation with nominal flux $\Phi = 1.0 \times 10^{12}cm^{-2}\cdot s^{-1}$, and the equilibrium values are: $N_{Xe}(\infty) = 2.354 \times 10^{12}cm^{-3}$, $\rho_{Xe}(\infty) = 6.135\,mk$.

Table 1 Xenon reactivity of shanghai MNSR during operation

Operating time/h	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0	8.0
Xenon reactivity/mk	0.015	0.042	0.080	0.126	0.182	0.245	0.390	0.557	0.740	0.936	1.114

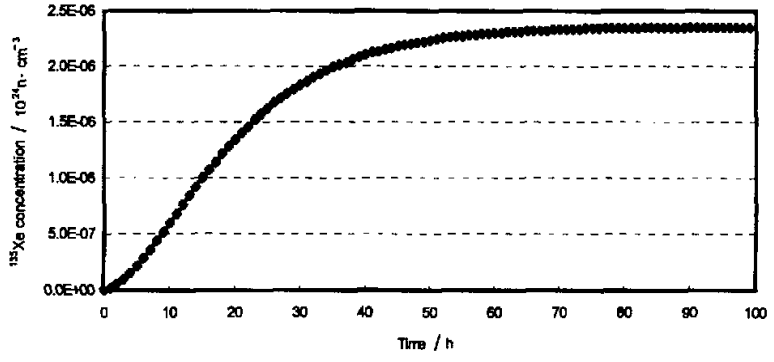

Fig.2 Variation in ^{135}Xe concentration following a cold, clean startup

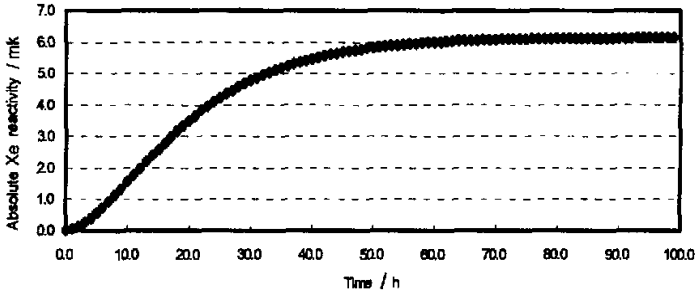

Fig.3 Xenon reactivity variation of ^{135}Xe follwoing a cold, clean startup for Shanghai's MNSR at rated flux

According to the measurement[3], the cold excess reactivity is about 3.9 mk for Shanghai MNSR. The average operable time is 2~2.5 h per day at ratedpower, and the maximum operable time is about 7.25 h per day. The inlet and outlet temperatures tend to be stable when Shanghai MNSR operates for 2~2.5 h, and the temperature effect is approximately -2.8 mk, it is actually the total reactivity effect including moderator temperature, flow and power. The sample reactivity has about a reactivity equivalent of -1.0 mk. It is thus clear that most of the cold excess reactivity is lost due to the temperature effect. And the hot excess reactivity is relatively small. It has only about 0.1 mk reactivity that can be used to overcome the xenon poison if the sample reactivity is taken into account. From Table 1, it is known that Shanghai MNSR can operate for about 2h. The maximum operable time of the reactor is about 8h (the control rod reaches its top position and the sample is not in the reactor). The calculated results of operating

time of 2 and 8 h are in accordance with the actual measurements[3] for Shanghai MNSR.

4.2 Xenon poisoning following shutdown

Fig.4 and Table 2 show the xenon reactivity variation after shutdown for different operating time under nominal flux condition. For Shanghai MNSR for 2.5 hours time of steady operation at the rated flux condition, the xenon buildup is 0.562 mk after shutdown. The maximum xenon reactivity occurs at about 10 hours. According to Fig.4, the poison will be eliminated automatically and gradually, whose speed is dependent on the operating time and the power level before shutdown. The longer the operating time and the higher the power, the less cold excess reactivity available at the same time the next day when restart up the reactor, thus the shorter the operable time available that day. For Shanghai MNSR under standard operating condition, it is unnecessary to pay attention to the "iodine well" phenomena during restart up of the reactor.

Table 2 Maximum xenon reactivity following shutdown of Shanghai MNSR

Operating time before shutdown/h	2.0	2.5	6.0	7.25
Maximum xenon reactivity/mk	0.45	0.56	1.33	1.60
Time approach to maximum xenon reactivity/h	10.0	9.8	8.3	7.8

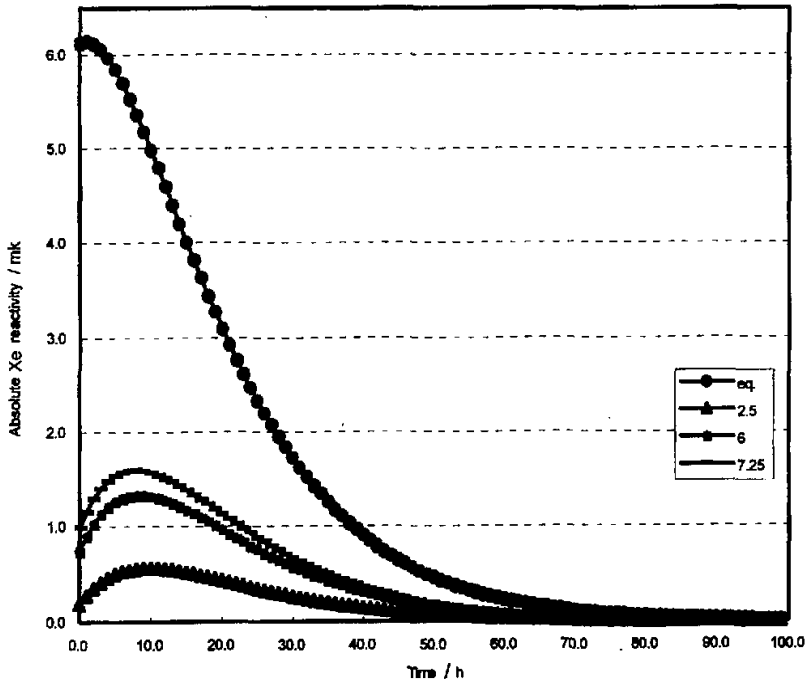

Fig.4 Negative reactivity due to ^{135}Xe buildup following shutdown of Shanghai's MNSR

4.3 Xenon poisoning following power-level change

Table 3 gives the equilibrium xenon reactivity vs. core average flux. This shows that the operable time available can be prolonged through reducing the power level.

Table 3 Xenon reactivity vs. flux level

Flux level/1.0×10^{16}n·cm^{-2}·s^{-1}	1.0	0.8	0.6	0.4	0.2	0.1
Equilibrium xenon reactivity/mk	6.13	5.03	3.88	2.65	1.36	0.69
Xenon reactivity for 2.5 h of operating time/mk	0.18	0.15	0.11	0.07	0.04	0.02

4.4 Xenon poisoning versus burnup level

Table 4 gives the equilibrium xenon reactivity vs. burnup level. Thus it can be seen that the xenon reactivity varies very little with increase of burnup level.

Table 4 Equilibrium xenon reactivity vs. burnup level

Burnup/MWd·tU^{-1}	0.0	100.0	1000.0	2000.0	4000.0	8000.0	10000.0	15000.0	20000.0	30000.0
Equilibrium xenon reactivity/mk	6.135	6.134	6.126	6.118	6.106	6.090	6.087	6.095	6.125	6.253

5 CONCLUSION

A xenon poison calculation code applying only to MNSR, MNSRXPCC, was developed based upon the approximate point reactor model. For Shanghai MNSR, some calculated values are compared with the actual measurements. It shows that MNSRXPCC is appropriate for modeling MNSR xenon poisoning.

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