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Monitoring of MNSR operation by measuring subcritical photoneutron flux

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ABSTRACT

Passive nondestructive assay methods are used to monitor the reactor's operation. It is required for nuclear regulatory, calculation validation and safeguards purposes. So, it plays a vital role in the safety and security of the nuclear plants. The possibility of MNSR operation monitoring by measuring the subcritical state photoneutron flux were investigated in this work. The photoneutron flux is induced by the fuels hard gamma radiation in the beryllium reflector. Theoretical formulation and experimental tests were performed. The results show that within a specified cooling time range, the photoneutron flux is induced by a single dominant hard gamma emitter such as ^{117}Cd (activation product) and ^{140}Ba (^{140}La fission product). This phenomenon was utilized to monitor the cooling time and the operation neutron flux during the last campaign. Thus a passive nondestructive assay method is proposed with regard to the reactor operation's monitoring.

1. Introduction

Passive nondestructive assay methods are used to monitor reactor's operation. It is required for nuclear regulatory, calculation validation and safeguards purposes. So, it plays a vital role in the safety and security of nuclear plants. Irradiated fuel gamma radiation is used to extract important information on the fuel (Reilly et al., 1991). However, due to the extremely high activity and complicated gamma spectrum of the irradiated fuel, direct radiation measurement is time consuming, complicated and demanding. The indirect irradiated fuel radiation measurement was developed and has given good results (Nemeth et al., 1990; Lakosi et al., 1990, Lakosi and Veres, 1990). The indirect measurement was also used in the case of MNSR fuel burnup monitoring (Haddad, 2009). In this work, a detailed theoretical formulation of the correlation between the photoneutron flux of the subcritical MNSR and the reactor operation parameters was introduced. Experimental tests of the theoretical formulation and possible practical applications were also performed.

The MNSR reactor is a tank-in-pool type research reactor. It is a low power research reactor that uses highly enriched uranium as a fuel, light water as moderator and beryllium as reflector. The cadmium control rod is covered by 0.5 mm thick stainless steel. The reactor has annular, upper and lower beryllium reflectors of 10, 12 and 5 cm thicknesses, respectively. There are five inner and five outer irradiation sites in and around the annular beryllium reflector (CIAE, 1993). The beryllium reflector acts as a huge target for the core hard gamma radiation to generate photoneutrons by means of the (γ, n) reaction. Thus, the photoneutron flux in the subcritical state can be used to monitor hard gamma radiation emitters. This is the main idea in this work. The design of the inner irradiation site inside the Be reflector offers the possibility of measuring the generated photoneutron flux. The total neutron flux in the subcritical state was measured using pure gold foils of 0.1 mm thickness and 2 mm radius. Irradiation was performed at the inner irradiation site. HPGe coaxial gamma spectrometer was used to measure the activity of the irradiated gold foils.

2. Theoretical

2.1. Correlation of reactor operational parameters with accumulated fission and activation products

Correlation between the reactor operation parameters and the accumulated fission and activation products was formulated theoretically in this part of the work. The reactor operation and cooling periods vary according to the requirements. An index i was assigned to each reactor campaign, whereas the index k was reserved only for the campaign, after which the photoneutron flux was measured. During the ith campaign the reactor operates on power P_i for the period Δ_i^{op} that is defined as

$$\Delta_i^{op} = t_{ei} - t_{si} \quad (1)$$

where t_{si} *and* t_{ei} are the start and end times of the ith campaign, respectively.

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Because the initial fuel enrichment of MNSR is 90%, the ^{235}U fission dominates. Each ^{235}U fission liberates 202 MeV or 3.24×10^{-11} J (Reilly et al., 1991). If the power is expressed in Watts, the fission rate (R_{fi}) during the Δ_i^{op} is calculated by

$$R_{fi}=P_i/E_f^{235\mathrm{U}} \quad (2)$$

where $E_f^{235\mathrm{U}}$ is the energy released by one ^{235}U fission.

The reactor power is given in general as

$$P=\phi_{th}\Sigma_f V/3.12\times10^{10} \quad (3)$$

where P is the power (W), Σ_f the macroscopic cross section (cm^{-1}), V is the volume of the core (cm^3) andϕ_{th} is the thermal neutron flux (neutrons cm^{-2} s^{-1}).

Thus, MNSR power is monitored using the thermal neutron flux. The nominal MNSR power of 30 kW corresponds to ϕ_{th} of 10^{12} neutrons cm^{-2} s^{-1}.

The photoneutron flux in the subcritical MNSR, which is induced by hard gamma radiation emitters, will be used to monitor operation parameters. The hard gamma radiation emitters in the subcritical MNSR core are fission and activation products. Thus in principle both types of products must be included in the calculation. Let us assign the index l to the hard gamma radiation emitter. This emitter can be either a fission or an activation product. During reactor operation the lth emitter is accumulated according to

$$dN_l=R_l dt-\lambda_l N_l dt \quad (4)$$

where N_l is the number of accumulated lth hard gamma radiation emitters,R_l is the generation rate and λ_l is the decay constant.

Solving this equation at ($t=0$) is the irradiation start and for Δ_i^{op} operation period we obtain

$$N_{li}(\Delta_i^{op}) = (R_{li}/\lambda_l)[1-\exp(-\lambda_l\Delta_i^{op})] \quad (5)$$

where $N_{li}(\Delta_i^{op})$ is the lth emitter number accumulated at ith campaign.

The $N_{li}(\Delta_i^{op})$ amount is measured at the end of k.th campaign after Δ_{ki}^{co} cooling period defied as

$$\Delta_{ki}^{co}=t_{ek}-t_{ei} \quad (6)$$

where t_{ek} is the kth campaign end time.

Thus, ith campaign contribution in the lth emitter amount measured at t_{ek} will be

$$N_{lik}(t_{ek})=(R_{li}/\lambda_l)[1-\exp(-\lambda_l\Delta_i^{op})]\exp(-\lambda_l\Delta_{ki}^{co}) \quad (7)$$

To simplify this relation the lth operation period factor ($f_{op\ l\ i}$) and lth cooling period factor ($f_{co\ lik}$) will be defined as follows:

$$f_{op\ l\ i} = [1-\exp(-\lambda_l\Delta_i^{op})] \quad (8)$$

$$f_{co\ lik}=\exp(-\lambda_l\Delta_{ki}^{co}) \quad (9)$$

By substituting in Eq. (7) we obtain

$$N_{lik}(t_{ek})=f_{op\ li}f_{co\ lik}R_{li}/\lambda_l \quad (10)$$

This relation gives the ith campaign contribution in the hard gamma radiation emitter quantity measured at time t_{ek}. The total accumulated lth emitter nuclei at the end of kth campaign $N_{lk}(t_{ek})$ are generated during the last reactor campaigns. After cooling time equal to seven lth emitter half-lives, only less than 1% of the emitter amount remains. So, the $N_{lk}(t_{ek})$ quantity starts accumulating at the time given by the relation

$$t_{lk}^{s\ acc}=t_{ek}-7\times T_{1/2}^{l} \quad (11)$$

Let us define the lth emitter accumulation period at the end of kth campaign as

$$\Delta_{lk}^{acc}=t_{ek}-t_{lk}^{s\ acc} \quad (12)$$

The first campaign in this period Δ_{lk}^{acc} will be denoted by sub-indices $_{islk}$. So, the number of lth emitter nuclei $N_{lk}(t_{ek})$ at time t_{ek}, will be the summation of all generation and decay processes during the accumulation period Δ_{lk}^{acc}, i.e.

$$N_{lk}(t_{ek})=(1/\lambda_l)\sum_{islk}^{k}(f_{op\ li}f_{co\ lik}R_{li}) \quad (13)$$

If the lth hard gamma radiation emitter is a fission product then its generation rate $R_{l\ i}$will be

$$R_{l\ i}=\gamma_l R_{fi} \quad (14)$$

where γ_l is the fission yield of lth emitter andR_{fi} is the fission rate during the ith campaign.

Whereas if the lth hard gamma radiation emitter is an activation product then its generation rate $R_{l\ i}$ will be

$$R_{l\ i}=\Sigma_l\phi_i \quad (15)$$

where Σ_l is the macroscopic cross section of lth emitter generation reaction and ϕ_i is the activating neutron flux during ith campaign.

The activating neutron flux is most probably thermal because it is dominant in generating activation products. Thus Eq. (13) correlates theoretically with the lth emitter quantity $N_{lk}(t_{ek})$ with a set of operational parameters.

2.2. Correlation between the photoneutron flux and reactor operational parameters

Hard gamma photons are emitted by many fission and activation products. The measured photoneutron flux at the inner irradiation site during the subcritical state is induced by all hard gamma photons, whose energies are higher than the Be(γ,n) reaction threshold (1.67 MeV). Thus it is a summation of photoneutron fluxes induced by all effective gamma emitters, i.e.

$$\Phi_k(t_{ek})=\sum_l\varphi_{kl}(t_{ek}) \quad (16)$$

where is the $\Phi_k(t_{ek})$ the total measured photoneutron flux at time t_{ek} and $\varphi_{kl}(t_{ek})$ is the photoneutron flux induced by lth emitter.

The $\varphi_{kl}(t_{ek})$ value depends mainly on the following: lth emitter activity and its hard gamma spectrum as well as on photoneutron generation reaction cross section of lth emitter hard gamma photons and Be reflector geometry. Thus, it can be written as

$$\varphi_{kl}(t_{ek})=K\lambda_l N_{lk}(t_{ek})\sum_j BR_j\sigma_j \quad (17)$$

where K is the constant related to the geometry of the Be reflector and the reactor core and BR_j and σ_j are the branching ratio and photoneutron reaction cross section of jth effective gamma photon emitted by lth emitter, respectively.

By substituting Eq. (13) into Eq. (17) we obtain

$$\varphi_{kl}(t_{ek})=K\sum_{islk}^{k}(f_{op\ li}f_{co\ lik}R_{li})\sum_j BR_j\sigma_j \quad (18)$$

By substituting Eq. (18) into Eq. (16) we obtain

$$\Phi_k(t_{ek})=K\sum_l\sum_{islk}^{k}(f_{op\ li}f_{co\ lik}R_{li})\sum_j BR_j\sigma_j \quad (19)$$

The photoneutron generation cross section of lth emitter effective gamma photons will be defined as

$$\sigma_l=\sum_j BR_j\sigma_j \quad (20)$$

The value σ_l is practically constant because it is a summation of constant parameters. Substituting Eq. (20) into Eq. (19) we obtain

$$\Phi_k(t_{ek})=K\sum_l\sigma_l\sum_{islk}^{k}(f_{op\ li}f_{co\ lik}R_{li}) \quad (21)$$

This relation correlates the measured photoneutron flux to that of the effective gamma photon emitters.