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ABSTRACT

One of the primary concerns for design of safety systems for reactors is the time response of external detectors to changes in the core. This paper describes a way to estimate the time delay between the core power production and the external detector response using Monte Carlo calculations and suggests a technique to measure the time delay. The Monte Carlo code KENO-NR was used to determine the time delay between the core power production and the external detector response for a conceptual design of the Advanced Neutron Source (ANS) reactor. The Monte Carlo estimated time delay was determined to be approximately 10 ms for this conceptual design of the ANS reactor.

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INTRODUCTION

The time delay between the core power production and the external detector response is one of the most important parameters for the design of the control and safety systems of a reactor with external detectors. In advent of a rapid power change in the core, the control and safety systems must respond quickly to mitigate the possibility of an excursion. Noise analysis techniques incorporated into the Monte Carlo calculation can be used to determine the time delay between the core power production and the external detector response.[1] This article shows how the time delay can be computed from noise analysis parameters that are computed in the Monte Carlo code KENO-NR.[2] This technique is applied to a conceptual design of the ANS[3] reactor. Some conclusions are then made about the results of this analysis.

THEORY

The external detector response can be considered as the output of a single-input single-output system whose input is the neutron production in the reactor core. The time delay can be obtained from the phase of the CPSD between the input and the output. If the output is a fraction of the delayed input, the phase of the CPSD is $\theta(\omega)=\omega D$. Thus, the delay is

$$D = \frac{\theta(f)}{360 f} \tag{1}$$

where f is the frequency in Hz. The phase of the CPSD between the core power production and the external detectors is used to determine the time delay for neutrons produced in the core to reach the external detectors.

KENO-NR

KENO-NR is an analog Monte Carlo code with "natural" tracking except for the use of group cross sections. The code starts with a source fission and the subsequent fission neutrons are followed to extinction. This code cannot be used for a critical system because the fission chain multiplication process does not terminate. The source particles and their progeny are tracked throughout the system. The time ordered sequences of pulses of at the detectors are then obtained for each source fission. The sequence of pulses from the various fission chains are superimposed in a manner consistent with the random distribution of ^{252}Cf fission to form the data block of the detector response. A data block is a sample of the detector response for a time period which is determined from the sampling rate and the number of points sampled. These blocks of data are then Fourier transformed and complex multiplied to obtain the various auto-and cross-power spectral densities. This process is repeated for many blocks to obtain averaged estimates of the auto-and cross-power spectral densities.

ADVANCED NEUTRON SOURCE (ANS) REACTOR

The ANS reactor facility was to be designed as an experimental facility for neutron research. The conceptual designs of this D_2O moderated and reflected reactor included numerous facilities for neutron scattering analyses, materials irradiation, isotope productions, and nuclear science studies. Figure 1 is a sketch of one of the conceptual designs of the ANS reactor. In this design, two different diameter annular fuel elements were vertically displaced. There were also three control rods that were located in the inner moderator region of the annular fuel elements. In-core irradiation facilities were located between the inner radius of the upper fuel element and the control rods. There were eight hafnium shutdown rods that are located outside the core pressure boundary tube in the heavy water reflector. The reflector vessel had a 3.5-m diameter and was approximately 4.3-m high. A pool of light water surrounded the reflector vessel on the sides and was contained within the reactor building by a biological shield. In this design, there were eight beam tubes, two cold neutron sources, and one hot neutron source located in the reflector vessel.

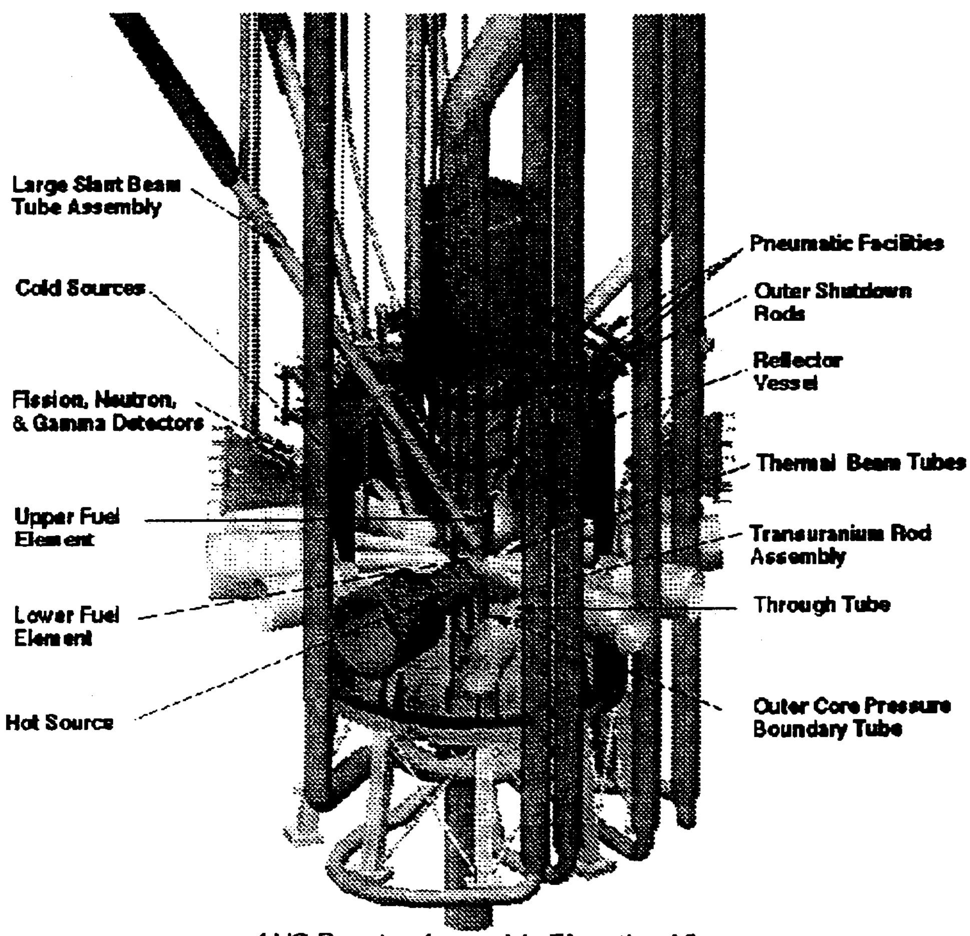

Figure 1. Sketch of a Conceptual Design of the ANS Reactor

The Monte Carlo model of the ANS reactor consisted of two annular fuel elements with three hafnium control rods, the heavy water reflector, and the light water pool. The beam tubes and the cold and hot neutron sources were not modeled explicitly in these calculations. Calculations were performed in which the components in the heavy water reflector were not included and in which the absorption of neutrons in the components in the heavy water reflector were accounted for by addition of aluminum to the heavy water reflector. In these calculations, the source was positioned at the midplane of the reactor core. Part of the upper fuel element and part of the lower fuel element were treated as fission detectors. The radial position of the external detectors was varied from ~400 mm to 2500 mm, the latter being the location of the external fission detectors for this design. To increase the statistical accuracy, the external detector was modeled as an annular ring of the relevant moderator (D_2O or H_2O) for a given radial position. In the model the detectors were 10 mm wide and 1080 mm high. Neutron scattering was the event scored as a detection. Modeling the detectors in this fashion decreased the computation time in that the efficiency was increased over that of a point detector.[1]

APPLICATION TO ANS REACTOR

The time delay between the core power production and the external detectors was determined from the phase of the CPSD between the fuel elements and the external scattering detectors. These calculations were performed with and without the aluminum in the heavy water reflector. The time delay was evaluated at various positions in the heavy water reflector and in the light water pool. The time delay increased as a function of distance from the core until it reached a saturation value in the light water pool. The results of the calculations are presented in Table I and are shown in Fig. 2. The time delay had a maximum (~18 ms) in the D_2O reflector and then decreased to 15 ms in the H_2O pool for the calculations that did not include the aluminum in the heavy water reflector. The decrease in the time delay is due to the fact that once a slowed-down neutron reached the light water pool it was absorbed locally due to hydrogen capture. The calculated time delay is the average flight time of thermal neutrons diffusing to each radial point because the flight path of a neutron to a radial point is not a direct path but consists of many scattering paths in all directions while diffusing to the radial point. Because more neutron scattering occurred in the D_2O, the average flight path was longer in the heavy water reflector; hence, the average flight time will be longer. Neutrons that have numerous scattering collisions in the D_2O may not contribute to the detector response in the light water pool because the neutrons could be scattered back into the reactor core. To evaluate further the understanding of this decrease in the time delay, a calculation was performed with the light water replaced by heavy water. For the all-D_2O case, the time delay increased with distance as shown in Fig. 2, thus confirming the effects of neutron absorption in the light water. Because the experimental facilities in the heavy water reflector were not modeled, the time delays were overestimated. Additional calculations were performed that included aluminum in the heavy water reflector. The aluminum in the heavy water reflector significantly reduced the time delays due to neutron absorption by the aluminum. The results for these calculations for the three detector positions in the light water pool are given in Table II. The time delay at the position of the external fission detectors is 10 ms if the aluminum is included in the heavy water reflector.

Table I. Monte Carlo Calculated Time Delays for Reactor Without Aluminum in the Heavy Water Reflector		
Position from Centerline (mm)	Time Delay for Upper Element (ms)	Time Delay for Lower Element (ms)
375	4.1	5.3
675	10.2	10.8
975	14.7	15.8
1275	17.7	17.8
1575	17.8	17.9
1745	16.8	16.9
2145	15.5	15.3
2495	15.5	15.3

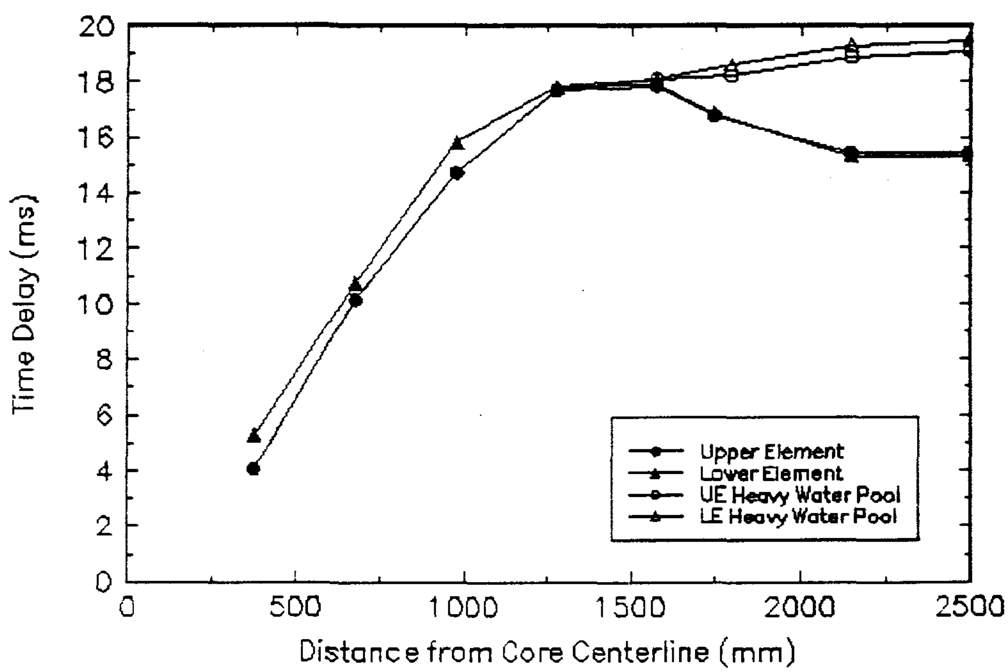

Figure 2. Calculated Neutron Time Delays as a Function of the Radial Position from the Core Centerline

Table II. Monte Carlo Calculated Time Delays for Reactor With Aluminum in the Heavy Water Reflector		
Position from Centerline (mm)	Time Delay for Upper Element (ms)	Time Delay for Lower Element (ms)
1795	12.1	12.2
2145	10.1	10.2
2495	10.1	10.2

CONCLUSIONS

The Monte Carlo analysis provides the means to determine the time delay between the core power production and the external detector response. This time delay is dependent on the assumptions made in the Monte Carlo model. The time delay between the core power and the external detector response is ~15 ms for the case without the aluminum in the heavy water reflector and is ~10 ms for the case with the aluminum in the heavy water reflector. An analysis performed with the model without the aluminum in the heavy water reflector is conservative and provided a limit for the design of the safety systems of the reactor. This time delay could be measured by measuring the CPSD between a detector placed near the core and a detector in the light water reflector tank. Although the ANS reactor was used in this analysis, this method could be applied to estimate detector response time delays for other reactors with external detectors.

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