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《**Review**》

Neutron Streaming and PWR Cavity Shielding Design

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Abstract

Shielding problems associated with neutron streaming through the reactor vessel cavity of pressurized water reactors are discussed to a certain extent with the actual examples in the currently operating reactors. Various remedial techniques are proposed herein to mitigate the tedious neutron streaming phenomena including piling up in heaps of temporary boron-containing bags and the installation of permanent shield structure making use of a certain refractory materials. In conclusion, optimum cavity shielding design concepts are presented with special emphasis on such major factors as the identification of major neutron streaming path, selection of necessary shielding materials with acceptable constraints, detailed design characteristics and physical configuration as well as the formulation of dependable mathematical tools to predict the final outcome of each design concept proposed in the context.

요 약

최근 가압경수로에서 압력용기 상단주변의 캐비티에 중성자가 새어나오는 사실이 판명되자 이에 대한 차폐문제가 심각하게 논의되기 시작했다. 본 논문에서는 현재 운전중인 원자로에서 이것을 어떻게 해결하고 있는가를 예시하였다. 예를들면 붕소가 들어있는 주머니를 쌓아 올리는 것에서 부터 차폐구조물을 영구히 설치하는 것에 이르기까지 여러가지 방법으로 중성자흐름을 막는 대책을 논의하였다. 결론적으로 이 문제해결을 위한 가장 현실적이고 가능한 차폐설계안 몇가지를 제시하였다. 특히 그중에서도 중성자가 어떤 경로로 흘러 나오는가의 규명, 차폐자료의 선정, 차폐설계의 특성과 외형문제 그리고 각 설계안을 검토키 위한 수학적 모델 제시에 역점을 두었다.

1. Introduction

It has become one of the most serious problems in recent years that neutron streaming through the cavity of reactor vessel (RV) of the pressurized water reactors (PWR's) jeopardized the reactor operation so that additional shielding design and its installation around the RV cavity become inevitable. This neutron streaming problem is amplified for the later vintage PWR's where the cavity is widened to relieve the cavity pressure in the unlikely event of a design basis accident including high energy pipe rupture.

Recently neutron streaming into the cavity of reactor vessel was found to have taken place at Calvert Cliffs Unit 1 and Japanese Mutsu reactors, which eventually suffered from serious difficulties in routine operation. In case of Calvert Cliffs, the dose rate at the outside of the containment was measured to be in the range of 0.5 mrem/hr when the reactor was operated only at 0.1% of the designed power level. The Mutsu nuclear ship was obliged to stop her trials as soon as the dose rates on the deck were found to exceed the permissible design level of 0.054 mrem/hr even at 1.4% of the nominal output of the reactor power. It was estimated that the extra shielding required to minimize the neutron streaming would impose the refueling outage for four more days with a subsequent financial burden of about 1.5 million dollars due to the loss of power generation.

Various remedial techniques have been proposed to mitigate the neutron streaming problems ranging from piling up in heaps of temporary boron bags to the installation of permanent shield structure making use of a certain refractory materials. The optimum cavity shielding design can be made after the following factors have been determined:

a. Identification of major streaming path;
b. Shielding materials with acceptable nuclear, physical, chemical, mechanical and thermal properties;
c. Detailed design and configuration such that the shield does not interfere with various phases of reactor operation;
d. Dependable mathematical tools to predict the final outcome of each proposed design.

2. The Proposed Reactor Vessel Cavity Shielding

Numerous pressurized water reactors at various design and construction stages recognize the neutron streaming problem through the reactor vessel cavity, and some of the remedial measures have already taken place to solve this impending subject.

2.1. Calvert Cliffs, Unit 1[1]

The Calvert Cliffs, Unit 1 is a PWR designed and supplied by Combustion Engineering Company with the air gap of 2.5 feet around the nozzle and 1.5 feet at the core midplane. When the reactor was constructed, dose rates somewhat higher than previously expected were observed during the initial low power testing period. The dose rates at the full power operating condition, estimated from the measured data at 20% power, fell within the range of 3,500 mrem/hr to 35,000 mrem/hr at the operating floor. The cause of such high radiation was identified to have been attributed to neutron streaming through:

a. Annulus gap around RV flange and the primary shield wall;
b. Annulus around the reactor coolant piping where it penetrates the primary shield wall; and
c. To a lesser extent, access opening through the lower part of the primary shield.

Although the exact amount of contribution

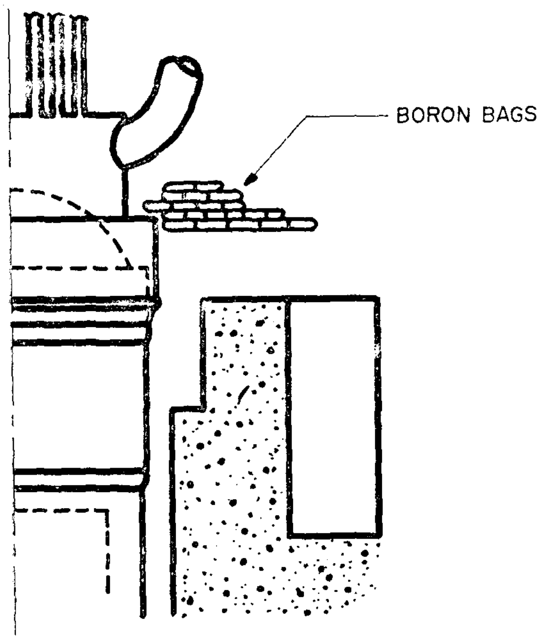

Fig. 1. Boron Bag Neutron Shield in Calvert Cliffs, Unit 1

from each of the above three sources could not be determined, the source (a) was considered as the primary contributory. Subsequently a temporary shielding was installed utilizing approximately 750 twenty-five kg bags of crystalline boric acid placed over the reactor vessel annulus as shown in Figure 1.

The location of the shield is less than ideal due to the difficulties of installing the support grid at a "fully constructed reactor." The modification resulted in dose reduction by a factor of 30 to 100 at most locations, and by a factor of 50 at the equipment hatch. A further reduction by a factor of 5 to 10 would be necessary to reach a nominal target level of 100 mrem/hr.

Currently a permanent shield modification with approximately 25 inch thick polyethylene is considered at the Calvert Cliffs.

2.2. Bellefonte (TVA)[2]

The TVA's Bellefonte Nuclear Unit is a Babcock & Wilcox's PWR. The annular gap between the RV and the cavity wall is approximately 50 inches wide at the core midplane, 21 inches above the level of the RV nozzles, and 14 inches around the flange. A permanent shielding design utilizing type 277 heat-resistance blocks (by Nuclear Experiment, Inc.) is underway. The proposed location of this permanent shielding is within the gap above the the nozzle (see Figure 2). This type of neutron shielding requires detailed studies so as to meet such cases as cavity pressure transients, uplift, lateral and asymmetric forces upon the pressure vessel, potential missile, as well as the preservice and inservice inspection provisions. An overall dose reduction factor of 100 is expected at the Bellefonte reactor.

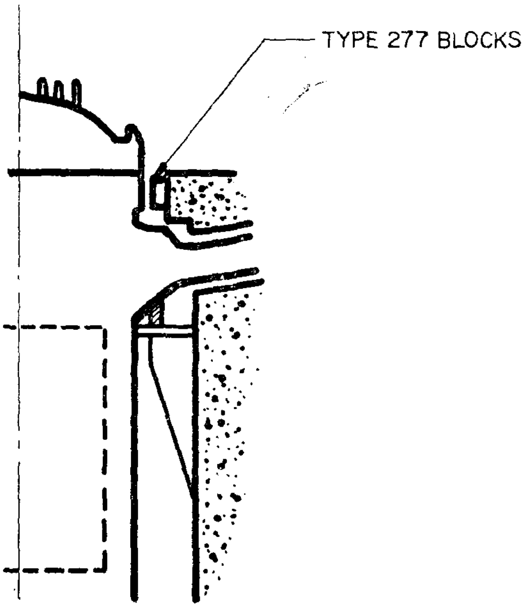

Fig. 2. Type 277 Heat-Resistance Shield in Bellefonte

2.3. Seabrook Station (PSNH)

The Seabrook Nuclear Units are Westinghouse's PRW's with the annular gaps of 40 inches around the flange and 19 inches around the core midplane. Recent Monte Carlo calculations[3] indicated that the radiation levels on the containment operating floor inside the secondary shield may be 300~500 rems/hr and 1~2 rems/hr at the outside of the secondary shield. These radiation levels exceed the current PSAR limits and Westinghouse specification for the control rod drive mechanism by a wide margin. Several alternatives are under consideration at present, but no final conclusions have been made yet.

2.4. "Water Tank" Concept[4]

Water tank concept was proposed and practiced by Stone & Webster Engineering Corporation. The potential problems associated with this design are evaporation and thermal shock to RV in the event of an earthquake. Additional shielding with thermal neutron absorbers are necessary to reduce the dose rate at the operating floor to an acceptable level.

2.5. Arkansas Nuclear One, Unit 2[5]

The 16,000 pound shield plug using NSII (by BISCO) was designed to be suspended around the pressure vessel on reinforced steel supports with steel grating fitting tightly around the support steel and reactor support legs. The shield was located immediately below the top pivots of the pressure vessel as illustrated in Figure 3. An overall dose reduction factor of 30 is expected on the operating deck.

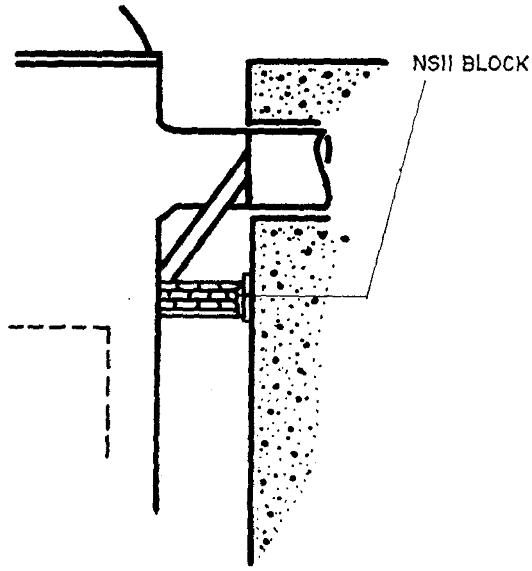

Fig. 3. Ns II Shield in Arkansas Nuclear One, Unit 2

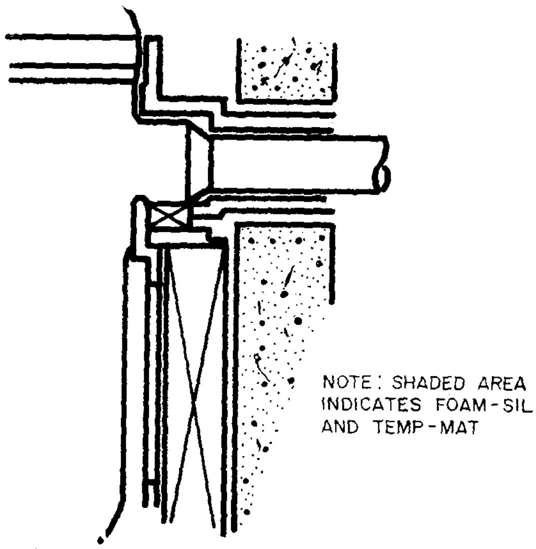

Fig. 4. Temp-Mat and Foam-Sil in Millstone, Unit 3

2.6. Millstone, Unit 3[6]

The reactor was originally designed with annular neutron shield tank (water tank). Additional neutron shielding is proposed utilizing borated thermal insulation blankets (Temp-Mat and Foam-Sil). As shown in Figure 4. the insulation blankets almost entirely cover the plausible neutron stream path. The information with respect to dose reduction factor is not available yet; however, combined dose reduction factor of the water tank and proposed thermal insulation geometry may be as high as 500.

2.7. Fessenheim Reactor (France)[7]

"Neobar" and "Limonite" collar shields as shown in Figure 5 are proposed. The Limonite is an iron ore ($Fe_2O_3 \cdot H_2O$) containing 10% of water, whereas Neobar is borated hydrogeneous water-soluble sand ($Na_2B_4O_7 \cdot 5H_2O$). An overall dose reduction factor is estimated to be around 200. Long-term radiation effects on these materials should be carefully studied, since any change of hydrogen contents would certainly affect the overall dose reduction capability.

2.8. Permali "Umbrella"[8]

An "umbrella" type shielding utilizing permali is studied with respect to cavity neutron streaming problems as depicted in Figure 6. The permali is laminated beech-

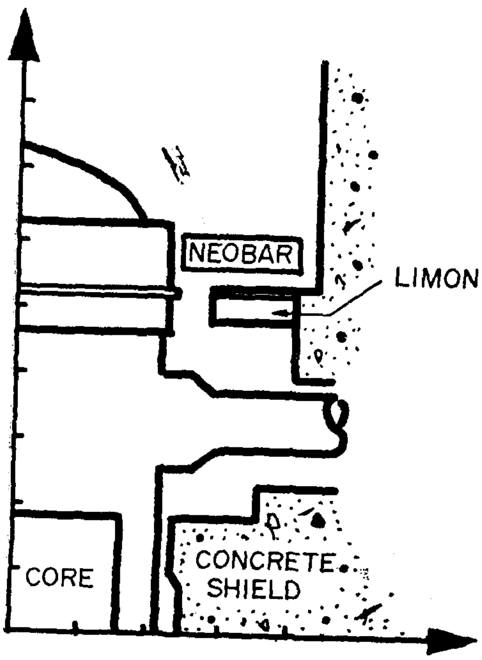

Fig. 5. Himonite and Neobar in Fessenheim

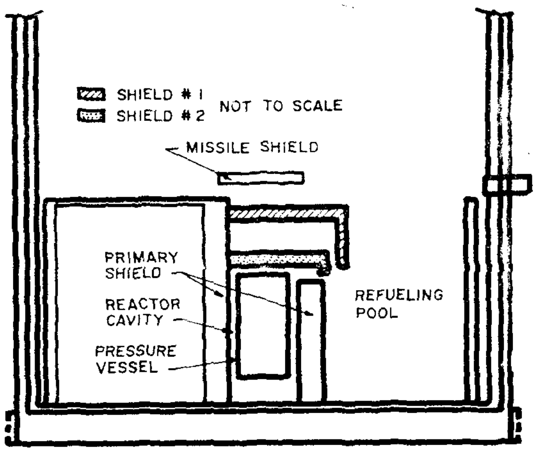

Fig. 6. Permit Umbrella

wood with thermal neutron absorption cross section of 0.12 cm^{-1} which is comparable to polyethylene. The dose reduction factor is estimated to be approximately 40. Due to the potential fire-hazard, the Permali shield cannot be installed near the cavity.

2.9. Westinghouse's Redesign Concept

Westinghouse is currenty underway of redesigning the entire cavity geometry. The basic concept is to eliminate the large vertical gap above the nozzle and to install horizontal annular duct connecting nozzle cavity and inservice inspection ports. The cavity pressure is relieved through inservice inspection ports[9].

3. Candidate Shielding Materials

Various shielding materials have been developed recently to solve the cavity streaming problems. As a reference, detailed properties of commercially available materials are compared in Table 1. Specific choice should be made after the considerations of specific NSSS design, operational condition and accessibility requirements. For example, if permanent shield around the flange is preferable, then a refractory material should

Table 1. Candidate Shield Materials

	Type 277	Permali	Ricorad	Poly-ethylene	NS II	Boric Acid
Thermal Neutron Absorption Cross Section (cm^{-1})	1.06	0.12	0.1	0.1	—	0.09
Radiation Resistance						
Neutron (nvt)	10^{20}	10^{18}	10^{18}	10^{18}	1.5×10^{18}	
Gamma (Rad)	10^{11}	10^{9}	10^{9}	5×10^{8}	10^{12}	
Operating Temperature (°F)	350	220	600	180	—	—
Density (lb/ft^3)	105	81	59	58	—	—
Tensile Strength (psi)	100	15,000	2,500	—	—	—
Thermal Expansion Coefficient (inch/°F)	8×10^{-6}	1.1×10^{-7}	1.9×10^{-4}	—	—	—
Initial Hydrogen Gas Generation	Yes*	No	Yes	Yes	Yes*	Yes
Fire Resistance	Non-flammable	—	—	—	Fire retardant	
Physical Form	Precast block or castable drymix	Laminated beechwood			Flexible solid	Powder

*These materials have small hydrogen gas generated during initial days of exposure, which would not cause flammability and can be eliminated during the initial purge following operation. No quantitative data are available for other materials.

be the choice since this material in general can withstand severer radiation and thermal environment.

Recent MORSE-CG calculations[10] for a wide gap geometry indicated that the neutron flux distribution at the gap "mouth" is dominated by fast neutrons (see Figure 7). Therefore, any materials for only thermal neutron attenuation/absorption (e.g., boron-containing material) may not be good enough for this situation.

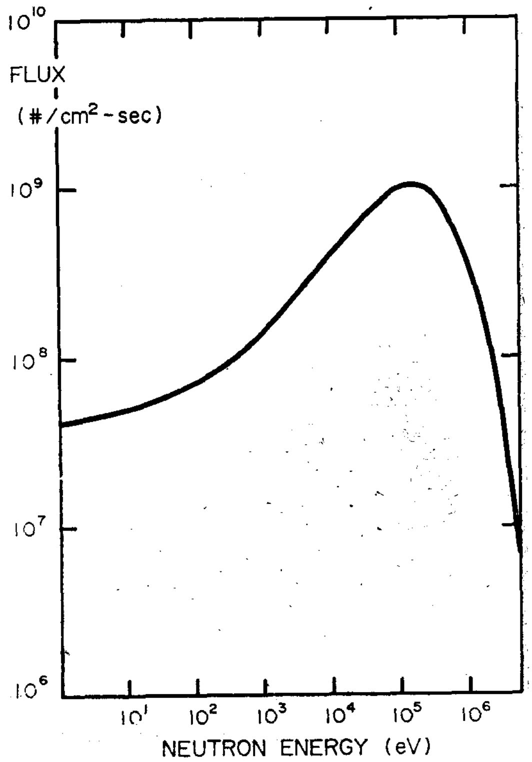

Fig. 7. Neutron Flux Profile vs. Neutron Energy

4. Discussion

The problems associated with RV cavity shielding requires a lot of considerations including physical design of shielding, material choice, numerical analysis as well as engineering policy decisions.

4.1. Policy

The overall radiation level on the operating floor increases linearly (approximately) with the size of RV cavity gap. Therefore, neutron streaming problems can be solved by sizing the cavity gap opening just enough for ventilation to keep the cavity temperature below design temperatures (135°F～150°F). However, the optimum size of gap for the ventilation and radiation protection is not enough to relieve the cavity pressure, which may then cause the uplift of RV in the event of high energy piping rupture inside the cavity. The choice is between real problems but small consequence versus hypothetical problem with high potential consequence. The engineering and design policy on this problem should be made after a proper evaluation of trade-off between a design for low probability/high consequence event and high probability/low consequence event.

4.2. Shielding Design

A list of factors that should be considered in cavity shielding design is given previously[11].

a. Removable Shielding

This choice requires lay-down area. Additional radiation exposures can occur during removal and installation operation. Allocation of lay-down area for the removable shielding may not be that easy especially during refueling operation. Easy access for preservice and inservice inspections of RV and nozzle will be achievable.

b. Blowout Design

This approach is used in Bellefonte where the neutron shielding blocks are designed to be blown out due to the cavity pressure. The geometry, weight and material of shielding should be carefully analyzed in such a way that, (1) the initial point of contact of missiles would not be any critical components, (2) initial impact breaks up the momentum of the missile to eliminate any secondary missile problems, and (3) shielding elements are blown out before any significant pressure buildup.

4.3. Material Selection

The following characteristics should be evaluated:

a. Hydrogenated and borated materials.
b. Radiation and heat resistance.
c. Fire hazard.
d. Gas generation.
e. Secondary radiation (impurity).
f. Mechanical characteristics (missile impact).
g. Easy fabrication.

4.4. Analytical Tool

Dependable analytical tools to evaluate the effectiveness of various shielding designs without mockup tests are essential for successful design. One or two dimensional transport codes such as ANISN and DOT systems were successfully used for relatively simple geometries such as simple primary penetrations or bomb shelter designs. However, these codes failed badly for the case involving complicated geometry and materials as exemplified in the original Mutsu nuclear ship design. Three dimensional Monte Carlo methods (e.g., MORSE-CG, SAM-CE, COHORT, etc.) are proved to be adequate tools for the neutron stream shield design[12].

4.5. Gamma Radiation

The dose level due to gamma radiation was found to be less than 30% of that due to neutrons inside the containment of Calvert

Cliffs, Unit 1[1]. Moreover, the gamma and neutron radiations were reduced by approximately the same factor when the boron bags were installed. Since the crystalline boric acid is not as effective for gamma attenuation as for neutrons, it is likely that the gamma radiation is due to the secondary gamma rather than streaming gamma from the RV region. Although the high energy gamma radiation such as that from N-16 is generally considered as a significant radiation source (e.g., BWR turbine plant), this contribution in a PWR containment is likely to be much less than that from neutrons.

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