**GAMMA-RAY AND FAST NEUTRON ANNULAR
STREAMING EVALUATION THROUGH SODIUM
REACTOR EXPERIMENT (SRE)
MARK II CONTROL AND SAFETY ROD ASSEMBLIES**

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ABSTRACT

An experimental program was initiated to determine the extent of fast neutron and gamma-ray streaming through the SRE Mark II control and safety rods and to evaluate the adequacy of the shielding provided in these control and safety rods. The methods and procedures used to evaluate these problems are routine and proven for determining gamma-ray and fast neutron dosages using radiation sensitive films and gold foils. The final experimental results indicated that no excessive streaming of either gamma-rays or fast neutrons is present above or around the SRE Mark II control and safety rods. The analytical attenuation methods used to calculate the fast neutron and gamma-ray streaming dose rates gave results that compared favorably with the experimental data. Even though the agreement was favorable, it cannot be concluded that these analytical methods would be equally valid for other annular geometries. Additional experimental work will be necessary in order to establish the validity for performing similar analysis but the favorable agreement encourages the use of such methods until other methods are determined.

CORE CONFIGURATION 43 FUEL ELEMENTS

LEGEND

- ⊗ POISON RING TEST
- ⊗ SAFETY RODS
- ⊗ CONTROL RODS
- ⊗ DUMMY ELEMENTS (GRAPHITE)
- ⊗ SOURCE
- ⊕ TEMPERATURE TEST PLUG
- ⊖ SPECIAL STREAMING TEST PLUG

**Figure 1. SRE Core Configuration During Radiation Measurements
About Rotatable Top Shield Area**

I. INTRODUCTION

An experimental program was initiated to evaluate the adequacy of the shielding design in the SRE Mark II control and safety rods. The main concern of the experiments was the analysis of fast neutron and gamma-ray streaming through the annuli in these control and safety rods. By comparing the experimental results with analytical methods, a more firm basis on which to base recommendations concerning future reactor control and safety rod shield designs could be made.

It should be noted that the interests of the control and/or safety rod designs are opposite to those of shielding. For operational purposes, the control and/or safety rod should have as much freedom of operation as possible, i.e., large annular gaps and voids. For shielding purposes, the control and/or safety rod should have as few voids as possible; similarly, the number of streaming paths through the assembly, i.e., small annular gaps and a solid assembly, should be minimized. Therefore, another purpose of the experimental program was to determine the proper shielding design from a radiation safety standpoint and still not impair the proper operation of the control and/or safety rod from a reactor safety operation standpoint.

Since a determination of the size and extent of annular streaming paths is impossible by routine monitoring techniques, a complete mapping of suspected critical areas was performed using both fast neutron and gamma-ray sensitive films. A special streaming test plug was designed, manufactured, and installed in the SRE top shield to determine, if possible, the neutron energies emerging from the streaming paths. A complete fast neutron and gamma-ray film survey was performed on the sides and above the SRE Mark II control and safety rods. Special detection equipment was designed to read and record the results of the 14- by 17-in. gamma-ray monitoring films used in the survey. The fast neutron film packets and the gold foils were analyzed by routine techniques.

The location of the experiments which were performed is shown in Figure 1. The special streaming test plug was placed in position No. 3 in the top shield. The control and safety rods were located in positions 28, 51, and 62 and in

positions 27, 40, 48, and 63 respectively. A pictorial view of the portion of the control and safety rods located above the reactor floor level is shown in Figure 2. The neutron streaming detector arrangement used to determine the energy and flux of the neutrons streaming through the special streaming test plug is shown in Figure 3.

Figure 2. Pictorial View of SRE Control and Safety Rods Above Reactor Floor Level

Figure 3. Special Streaming Shield Plug Assembly

Figure 4. Continuous Film-Scanning Detection Equipment for Gamma-ray Film Measurements

Figure 5. Calibration of Kodak Industrial X-ray Type KK Film for Use with Constant Film-Reading Equipment and Linear Chart Paper of 100 Unit Full Scale in Recorder

II. EXPERIMENTAL TECHNIQUES AND PROCEDURES

A. GAMMA-RAY STREAMING DETERMINATION

Kodak Industrial X-ray Type KK film was used for all of the gamma-ray streaming experiments. The films were placed in flexible cassettes for protection and positioning, both on and above the SRE Mark II control and safety rod assemblies. This type of film will record a minimum detectable gamma-ray dose of 50 mr and a maximum detectable gamma-ray dose of 2,000 mr. Thus, the integrated gamma-ray dosages used in the analyses were between these two limits.

The gamma-ray sensitive films were positioned over the areas to be investigated and taped securely to the particular control or safety rod assembly being investigated. After exposure of the films (mostly 14- by 17-in. size) for a given integrated thermal reactor power and/or time increment, the films were removed for development and analysis. The films were read using the special detection equipment shown in Figure 4. The density readings were recorded on a continuous graph, converted to integrated gamma doses by use of the calibration graph given in Figure 5, and recorded on the films. Thus, the streaming areas and their radiation intensities were distinctly marked. By knowing either the integrated power or the exposure time and power level, the gamma-ray dose rates for full reactor thermal power (20 mw) could be obtained.

The special detection equipment was designed to give a complete film density mapping of the gamma-ray films placed both on and above the SRE Mark II control and safety rods. As shown in Figure 4, the following equipment was used in the detection arrangement:

- 1) two-dimensional film holding device,
- 2) densitometer, and
- 3) continuous (single-pen) graphic recorder

The 2-dimensional film-holding device was capable of revolving while a screw-type assembly raised or lowered the revolving platform. In this manner, a continuous scan of the film was made as the densitometer moved in a helical path over the entire height of the cylinder formed by the film. Thus, a complete mapping of streaming areas was possible in an accurate and time saving manner. Micro-switches were positioned to stop the scan at the top or bottom of the film to prevent binding of the motor driven device. The distance between helical paths was approximately one-half inch.

A typical densitometer was separated so that the film continuously passed between the light source and the phototube while the density readings were made by the photometer and recorded on the continuous graph. The distance between light source and phototube was constant so that readings would be uniform. Initial readings were taken with a calibration film which had only background radiation exposure and had been developed with the exposed films. Thus, the densitometer was calibrated to subtract the background exposure density from the total exposure density to give the net exposure density on the densitometer.

The continuous graphic recorder had a speed equal to the rotational speed of the platform holding the film. The recorder was calibrated to record the film densities measured by the densitometer.

B. FAST NEUTRON STREAMING DETERMINATION

The fast neutron dose measurements were made using the standard 1-1/4 by 1-3/4 in. Kodak Special Nuclear Track NTA safety film. The calibration curve and other pertinent data for this type of film are given in Reference 1. A total gamma-ray dose of approximately 5 r can be received by these films without loss of neutron track integrity.¹ Since the gamma-ray film used in conjunction with the neutron films had a maximum detectable gamma-ray dose of 2 r, no detection difficulty was found as long as the gamma-ray films used in conjunction with the neutron packets were readable. The minimum and maximum readable neutron exposures would be approximately $8 \text{ by } 10^5 \text{ n/cm}^2$ and $4 \text{ by } 10^8 \text{ n/cm}^2$, respectively.¹

NTA neutron film packets were taped to the outside of control rod No. 3 and safety rod No. 3 at a height of 4 ft above the reactor floor level. At the same

time, NTA neutron film packets were placed on top of the drive assemblies. The film packets were taped completely around the circumference and also were centered over the drive assemblies of the control and safety rod assemblies. The film packets were removed from the control and safety rods after a 203.8 Mwd power run which took place during July and August, 1958. The film packets were then developed and read. After an evaluation of the exposure time, integrated reactor power, neutron film calibration, and dose conversion, results were obtained for the extent of fast neutron streaming through the typical SRE Mark II control and safety rods.

C. ENERGY AND FLUX DETERMINATION OF NEUTRON STREAMING

Gold foils were positioned in a lucite arrangement (Figure 6) to determine the magnitude of the flux and energy of neutrons streaming through a special

streaming plug, shown in Figure 3.

The lucite arrangement consisted of alternate layers of $\frac{1}{8}$ and $\frac{3}{8}$ in.

lucite sheets surrounded by paraffin so as to present an infinite hydrogenous media to not only the streaming neutrons but, also, to the gold foil neutron detectors. The gold foils were placed over the two annuli of the streaming plug during two separate power runs to determine the total streaming neutron flux and the energies of the streaming neutrons. The gold foils were placed around the periphery of the two annuli in the plug at eight equidistant positions and were helically positioned in alternating layers of lucite. The use of eight positions was to prevent a depression of the neutron flux by the gold foils throughout the lucite arrangement. At the same time, the helically positioned

Figure 6. Lucite Arrangement for Gold Foil Measurements

gold foils, by use of the method given in Reference 2, determined the energy spectrum of the streaming neutrons. Due to the low neutron flux streaming through the plug annuli, the integrated streaming neutron flux could not be determined and the neutron flux peaks, as determined by the foils, could only be extrapolated to the most probable energy.

After the gold foils were positioned in the lucite arrangement and irradiated during the SRE power runs, they were removed and sent for counting and analysis. The energy peaks extrapolated from the foil data for the two special plug annuli were determined from data given in Reference 2.

III. RESULTS

A. GAMMA-RAY STREAMING THROUGH SRE MARK II CONTROL AND SAFETY ROD ASSEMBLIES

1. Experimental Results

The results for the SRE Mark II control and safety rod assemblies and the special streaming test plug are summarized in Table 1 below.

TABLE I
GAMMA-RAY STREAMING DOSE RATES THROUGH MARK II CONTROL
AND SAFETY RODS AND SPECIAL STREAMING PLUG
IN THE SRE TOP SHIELD
(Power Level = 20 Mwt)

Component	Maximum Gamma-ray Dose Rate (mr/hr)	
	Top of Assembly	Side of Assembly
Mark II Spare Safety Rod	3.0	-
Mark II Safety Rod No. 2	5.0	-
Mark II Safety Rod No. 3	5.0 - 8.5	3.0
Mark II Safety Rod No. 4	3.0	-
Mark II Control Rod No. 2	1.5	-
Mark II Control Rod No. 3	-	1.0
Mark II Control Rod No. 4	0.7	-
Special Streaming Plug (1.25 in. diameter annuli with 60 mil gap) (See Figure 3)	60	-
Special Streaming Plug (4.16 in. diameter area of plug, except annuli) (See Figure 3)	12	-

2. Analytical Method and Results

The following equation⁴ was used to determine the gamma-ray streaming dose rates from an annular region:

$$D = D_0 \frac{5.6R^{3/2} (R - r)^{3/2}}{(R + r)L^2} \quad \dots(1)$$

where

D_0 = initial gamma-ray dose rate (mr/hr),

R = outside radius of annulus (inches),

r = inside radius of annulus (inches),

L = distance from source to detector (inches),

and

D = final gamma-ray dose rate (mr/hr).

The following gamma-ray dose rates were analytically determined immediately above the SRE top sodium pool for a thermal power level of 20 Mw:

Gamma-Ray Source	Gamma-Ray Strength
Core and Reflector	5×10^3 r/hr
Sodium Pool Activity	8.9×10^5 r/hr
Sodium Pool Neutron Capture	1.17×10^4 r/hr
Thermal Shield	1.43×10^3 r/hr
Concrete Shield	negligible
Total	9×10^5 r/hr

Since 99% of the gamma-ray dose rate at the surface of the sodium is due to the sodium activity, only this source strength was considered in calculating the attenuation through the SRE Mark II control and safety rod assemblies. Furthermore, since the source area of the sodium pool can be considered infinite in respect to the annulus area, the source strength ($D = 8.9 \times 10^5$ r/hr) at the surface of the sodium was also assumed to exist under the annulus area at this point.

The decay gamma-ray photons from Na^{24} have energies of 2.76 Mev and 1.38 Mev and are emitted in cascade. The division of the gamma-ray dose rate at the surface of the sodium would be the following for the two sodium decay gamma energies:

a) D_1 (2.76 Mev) = 6.3×10^5 r/hr and

b) D_2 (1.38 Mev) = 2.6×10^5 r/hr.

Therefore, the determination of the attenuation of these radiations through shield materials in the path of the streaming gamma-rays will be calculated on the basis of these two energies and the total gamma-ray dose rate will be assumed to be divided according to the ratio of D_1 and D_2 to D_o . The gamma-ray dose rate at the position of the film measurements will be determined by the following equation:

$$D_t = D_1(n) + D_2(n) \quad \dots(2)$$

where

D_t = total gamma-ray dose rate at detector (mr/hr),

$$D_1(n) = D \frac{D_1}{D_o} e^{-\mu_1 t} \quad \dots(3)$$

$$D_2(n) = D \frac{D_2}{D_o} e^{-\mu_2 t} \quad \dots(4)$$

here

μ_1 = linear absorption coefficient for 2.76 Mev gamma-ray (cm^{-1}),

μ_2 = linear absorption coefficient for 1.38 Mev gamma-ray (cm^{-1}), and

t = thickness of shield material (cm).

All remaining terms have previously been defined.

The following data (See Table II) were used to determine the range of gamma-ray dose rates at the top of an SRE Mark II control rod. The maximum value was determined for the condition when the control rod was positioned to one side, in which case the width of the annular gap was twice the normal gap size. The minimum value was determined for the normal gap size, i. e., with the control rod positioned in the center of the void so as to form a perfect annulus.

Substituting the data for the SRE Mark II control rod assemblies into Equations (1), (2), (3), and (4), the maximum gamma-ray dose rate was obtained.

TABLE II

DATA FOR SRE MARK II CONTROL ROD ASSEMBLIES

<hr/>		
$D_o = 8.9 \times 10^8 \text{ mr/hr}$		$L = 226.9 \text{ in.}$
$R = 0.312 \text{ in.}$		$r = 0.25 \text{ in.}$
<u>Iron</u>	<u>Aluminum</u>	<u>Oil</u>
$t = 8.5 \text{ cm}$	$t = 4.5 \text{ cm}$	$t = 6.3 \text{ cm}$
$\mu_1 = 0.346 \text{ cm}^{-1*}$	$\mu_1 = 0.10 \text{ cm}^{-1*}$	$\mu_1 = 0.040 \text{ cm}^{-1*}$
$\mu_2 = 0.39 \text{ cm}^{-1*}$	$\mu_2 = 0.14 \text{ cm}^{-1*}$	$\mu_2 = 0.058 \text{ cm}^{-1*}$
<hr/>		

* See Reference 6.

Using the above data, the following results were obtained:

- a) $D = 148 \text{ mr/hr,}$
- b) $D_1(n) = 2.73 \text{ mr/hr,}$
- c) $D_2(n) = 0.60 \text{ mr/hr, and}$
- d) $D_t(\text{max}) = 3.33 \text{ mr/hr.}$

For the normal gap size in the SRE Mark II control rod, i. e., $R = 0.28 \text{ in.}$ the following results were obtained.

- a) $D = 44.5 \text{ mr/hr,}$
- b) $D_1(n) = 0.82 \text{ mr/hr,}$
- c) $D_2(n) = 0.18 \text{ mr/hr, and}$
- d) $D_t(\text{min}) = 1.0 \text{ mr/hr.}$

At the present time, there is no method available to determine the gamma-ray dose rate that could be expected through the sides of the control rod assemblies. Thus, the experimental data obtained from the sides was used to assure that the side gamma-ray dose rate would be less than that appearing at the top of the assembly.

Assuming the same conditions for the positioning of the safety rod within the assembly, the maximum gamma-ray dose rate is obtained by substituting the following data (See Table III) into Equations (1), (2), (3), and (4).

TABLE III
DATA FOR SRE MARK II SAFETY ROD ASSEMBLIES

$$\begin{array}{ll} D_0 = 8.9 \times 10^8 \text{ mr/hr} & L = 188.7 \text{ in.} \\ R = 0.687 \text{ in.} & r = 0.50 \text{ in.} \end{array}$$

$$\begin{array}{l} \text{Iron} \\ t = 12.0 \text{ cm} \\ \mu_1 = 0.346 \text{ cm}^{-1*} \\ \mu_2 = 0.39 \text{ cm}^{-1*} \end{array}$$

* See Reference 6.

Using the above values, the following results were obtained:

- a) $D = 1700 \text{ mr/hr}$,
- b) $D_1(n) = 19.2 \text{ mr/hr}$,
- c) $D_2(n) = 4.6 \text{ mr/hr}$, and
- d) $D_t(\text{max}) = 23.8 \text{ mr/hr}$.

For the normal gap size in the SRE Mark II safety rod, i.e., $R = 0.594 \text{ in.}$, the following results were obtained:

- a) $D = 515 \text{ mr/hr}$,
- b) $D_1(n) = 4.2 \text{ mr/hr}$,
- c) $D_2(n) = 1.4 \text{ mr/hr}$, and
- d) $D_t(\text{min}) = 5.6 \text{ mr/hr}$.

Since the special streaming test plug has only one gap size, the following data were used (See Table IV).

TABLE IV
DATA FOR SPECIAL STREAMING TEST PLUG

$D_o = 8.9 \times 10^8 \text{ mr/hr}$	$L = 113.5 \text{ in.}$
$R = 0.69 \text{ in.}$	$r = 0.63 \text{ in.}$

Iron

$$t = 2.6 \text{ cm}$$
$$\mu_1 = 0.346 \text{ cm}^{-1*}$$
$$\mu_2 = 0.39 \text{ cm}^{-1*}$$

*See Reference 6.

Using the above data, the following results were obtained:

- a) $D = 790 \text{ mr/hr,}$
- b) $D_1(n) = 224 \text{ mr/hr,}$
- c) $D_2(n) = 83 \text{ mr/hr, and}$
- d) $D_t = 307 \text{ mr/hr.}$

However, a void space of 3.5 in. is present between the steel plate covering the annulus in the streaming plug and the film position (Figure 3). From the film placed at this position, an annular ring, in the form of excessive darkening as would be expected from the above calculations, was apparent on the developed film. However, the form of the annular ring reflected on the film had a width of 80-100 mils rather than the known gap size of 60 mils. In order to account for this increased area, it was postulated that the collimated beam streaming up the 60 mil annulus would be spread into the experimentally shown larger area by scattering in the steel plate. Applying this effect to the special streaming test plug, the following results are obtained:

- a) $D = 180 \text{ mr/hr}$,
- b) $D_1(n) = 51.2 \text{ mr/hr}$,
- c) $D_2(n) = 18.7 \text{ mr/hr}$, and
- d) $D_t = 69.9 \text{ mr/hr}$.

3. Comparison of Analytical and Experimental Results

Only the results for the SRE Mark II control and safety rod assemblies will be compared. The comparison of results is summarized in Table V below.

TABLE V

COMPARISON OF ANALYTICAL AND EXPERIMENTAL DOSE RATES
AT TOP OF SRE MARK II CONTROL AND SAFETY ROD ASSEMBLIES

Component	Experimental (mr/hr)		Analytical (mr/hr)	
	Maximum	Minimum	Maximum	Minimum
Mark II Control Rod Assembly	1.5	0.7	3.3	1.0
Mark II Safety Rod Assembly	8.5	3.0	23.8	5.6

As can be noted, the minimum gamma-ray dose rate calculated for both the control and the safety rod assemblies lies between the maximum and minimum experimental results. If the maximum gap size that would be possible in either assembly was assumed for the purpose of including a safety factor in the design, the calculated gamma-ray dose rate would be less than a factor of three higher than the maximum gamma-ray dose rate measured.

B. FAST NEUTRON STREAMING THROUGH SRE MARK II CONTROL AND SAFETY ROD ASSEMBLIES

1. Experimental Results

The results for the SRE Mark II control and safety rod assemblies are summarized in Table VI below.

TABLE VI
FAST NEUTRON STREAMING THROUGH TYPICAL SRE MARK II
CONTROL AND SAFETY RODS

Position	Safety Rod No. 3	Control Rod No. 3
Side Dose (max)	2700 mrem/203.8 Mwd	396 mrem/203.8 Mwd
Top Dose (max)	540 mrem/203.8 Mwd	36 mrem/203.8 Mwd
Side Dose Rate (max)	11 mrem/hr at 20 Mwt	1.6 mrem/hr at 20 Mwt
Top Dose Rate (max)	2.2 mrem/hr at 20 Mwt	0.15 mrem/hr at 20 Mwt
Side Dose Rate (min)	1.1 mrem/hr at 20 Mwt	0.22 mrem/hr at 20 Mwt
Top Dose Rate (min)	0.15 mrem/hr at 20 Mwt	0 mrem/hr at 20 Mwt

2. Analytical Method and Results

The following equation⁵ was used to determine the fast neutron streaming dose rates through the annuli:

$$D = \frac{\bar{\phi}_f (R^2 - r^2)}{2C(z^2)} \left[1 + F(z, b, c, \beta) \right], \quad \dots (5)$$

where

D = fast neutron dose rate at top of annulus (mrem/hr),

$\bar{\phi}_f$ = average fast neutron flux at entrance of annulus ($\text{n/cm}^2\text{-sec}$),

R = outside radius of annulus (in.),

r = inside radius of annulus (in.),

C = flux to dose conversion constant $8.5 \frac{\text{n/cm}^2\text{-sec}}{\text{mrem/hr}}$,⁴

z = distance from neutron source to detector (in.), and

$F(zb, c, \beta)$ = scattered neutron contribution function

Since any fast neutron that is scattered out of the beam will be lost to the beam as a fast neutron, the contribution due to scattering from the annulus walls is negligible. Therefore, Equation 5 can be reduced to the following:

$$D = \frac{\bar{\phi}_f(R^2 - r^2)}{2C(z^2)} \quad \dots(6)$$

Assuming that any material in the streaming path of the fast neutrons will attenuate the beam according to the removal cross-section of the material, the following equation was determined:

$$D_n = \frac{\bar{\phi}_f(R^2 - r^2)}{C(2z^2)} e^{-\sum_r t} \quad \dots(7)$$

where

$\sum_r$ = removal cross-section for the given material (cm^{-1}), and
 t = thickness of given material (cm).

All remaining terms have been defined.

Recent neutron flux measurements performed in an SRE dummy element located in hole No. 50 (Figure 1) provided sufficient information to permit a reasonably accurate extrapolation of the thermal neutron flux at the pool surface. The extrapolation yielded a flux of $1.8 \times 10^8 \text{ n/cm}^2\text{-sec}$. From Reference 3, a ratio of fast to thermal neutron flux was obtained at the surface boundary of the top sodium pool. This ratio (1 to 3) was used to convert the extrapolated experimental thermal neutron flux ($1.8 \times 10^8 \text{ n/cm}^2\text{-sec}$) to the fast neutron flux used in the present analytical calculations ($\bar{\phi}_f = 6 \times 10^7 \text{ n/cm}^2\text{-sec}$). The maximum error for these extrapolations and assumptions is expected to be less than a factor of 2.

In order to get a maximum and minimum value for the fast neutron dose rate streaming through the SRE Mark II control and safety rod assemblies, the same assumptions were made as used in Section III-A above for the streaming gamma-ray dose rates.

The following data were used in the calculation of the maximum fast neutron dose rate streaming through the top and side of the SRE Mark II control rod assembly.

TABLE VII

DATA FOR SRE MARK II CONTROL ROD ASSEMBLY

$\phi_f = 6 \times 10^7 \text{ n/cm}^2\text{-sec}$	$C = 8.5 \text{ n/cm}^2\text{-sec/mrem/hr}^*$
$R = 0.312 \text{ in.}$	$r = 0.25 \text{ in.}$

Top Streaming Path

<u>Iron</u>	<u>Aluminum</u>	<u>Oil</u>
$t = 8.5 \text{ cm}$	$t = 4.5 \text{ cm}$	$t = 6.3 \text{ cm}$
$\Sigma_r = 0.168 \text{ cm}^{-1}\dagger$	$\Sigma_r = 0.079 \text{ cm}^{-1}\dagger$	$\Sigma_r = 0.107 \text{ cm}^{-1}\dagger$
	$z = 226.9 \text{ in.}$	

Side Streaming Path

<u>Iron</u>
$t = 3.8 \text{ cm}$
$\Sigma_r = 0.168 \text{ cm}^{-1}$
$z = 161.5 \text{ in.}$

*See Reference 4.

†See Reference 6.

Substituting the above data for the top streaming path into Equation 7, a fast neutron dose rate of 0.20 mrem/hr was obtained. Assuming a normal gap size, i.e., $R = 0.28 \text{ in.}$, a fast neutron dose rate of 0.09 mrem/hr was obtained.

As previously stated, any fast neutrons scattered out of the annulus were assumed to be lost from the beam. However, due to the scattering properties of the shield materials for fast neutrons, a calculation was performed to determine the expected fast neutron dose rate streaming through the sides of the SRE Mark II control rod assemblies.

Substituting the above values for the side streaming path into Equation 7, a fast neutron dose rate of 2.5 mrem/hr was obtained through the sides of the control rod housing at a height of 4 ft from the reactor floor level. Assuming a normal gap size, i.e., $R = 0.28$ in. a fast neutron dose rate of 1.13 mrem/hr was obtained at the same position.

The following values were used for calculating the maximum fast neutron dose rate streaming through the top and sides of the SRE Mark II safety rod assembly.

TABLE VIII

DATA FOR SRE MARK II SAFETY ROD ASSEMBLY

$\bar{\phi}_f = 6 \times 10^7 \text{ n/cm}^2\text{-sec}$	$C = \frac{8.5 \text{ n/cm}^2\text{-sec}^*}{\text{mrem/hr}}$
$R = 0.687 \text{ in.}$	$r = 0.50 \text{ in.}$
<u>Top Streaming Path</u>	
<u>Iron</u>	
$t = 12.0 \text{ cm}$	$z = 188.7 \text{ in.}$
$\Sigma_r = 0.168 \text{ cm}^{-1}\dagger$	
<u>Side Streaming Path</u>	
<u>Iron</u>	
$t = 2.5 \text{ cm}$	$z = 161.5 \text{ in.}$
$\Sigma_r = 0.168 \text{ cm}^{-1}\dagger$	

*See Reference 4.

†See Reference 6.

Substituting the above values for the top streaming path into Equation 7, a fast neutron dose rate of 2.9 mrem/hr was obtained. Assuming a normal gap size, i.e., $R = 0.594$ in., a fast neutron dose rate of 1.32 mrem/hr was obtained.

Substituting the above values for the side streaming path into Equation 7, a fast neutron dose rate of 17.4 mrem/hr was obtained. Assuming a normal gap size, i.e., $R = 0.594$ in., a fast neutron dose rate of 7.9 mrem/hr was obtained.

3. Comparison of Analytical and Experimental Results

The comparison of the analytical and experimental results for the fast neutron dose rates streaming through the top and sides of the SRE Mark II control and safety rod assemblies is summarized in Table IX below.

TABLE IX

COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS FOR FAST
NEUTRON DOSE RATE THROUGH TOP AND SIDES OF
MARK II CONTROL AND SAFETY ROD ASSEMBLIES

Component	Position	Experimental (mrem/hr)		Analytical (mrem/hr)	
		Maximum	Minimum	Maximum	Minimum
Mark II Control Rod Assembly	Top	0.15	0	0.20	0.09
	Side (4 ft from reactor floor level)	1.6	0.22	2.5	1.13
Mark II Safety Assembly	Top	2.2	0.15	2.9	1.32
	Side (4 ft from reactor floor level)	11.0	1.1	17.4	7.9

As can be noted from Table IX, the minimum fast neutron dose rate calculated for both the control and the safety rod assemblies lies between the maximum and minimum experimental results. If the maximum gap size that would be possible in either assembly was assumed for the purpose of including a safety factor in the design, the calculated fast neutron dose rate would be less than a factor of 2 higher than the maximum fast neutron dose rate measured.

C. ENERGIES AND FLUXES OF NEUTRONS STREAMING THROUGH ANNULI IN SPECIAL STREAMING TEST PLUG

Gold foils were placed above the annuli in the special streaming test plug at the 1.25 and 3.8 in. diameters. The energy distribution of the neutrons

streaming through the annuli was approximated by using the method and data given in Reference 2. The approximated energies of 0.03 ev and 1 kev were obtained from the 1.25 in. diameter annulus which has steel media on both sides. The 24 kev peak is not definite since this energy peak actually may exist further into the plastic, resulting in a higher neutron energy. The approximated energies of 0.03 ev, 24 kev, 700 to 800 kev and 4.1 Mev were obtained from the 3.8 in. diameter annulus which has steel and concrete media with the concrete around the inner dimension. Due to the counting statistics for the gold foils and the varying thicknesses of the plastic media in which the gold foils were positioned (in order to determine the neutron streaming energies), the energy peaks could be in error by the vertical distances between foil positions and the $\pm 30\%$ counting error. Due to the high counting error (in this case, due to low counting rates), no value can be given for the integrated neutron streaming flux.

Table X summarizes the data obtained from the gold foils and the estimates of the neutron energies and fluxes.

TABLE X
NEUTRON ENERGIES AND FLUXES STREAMING THROUGH THE
ANNULI IN THE SPECIAL STREAMING TEST PLUG

1.25 in. Diameter Annulus		3.8 in. Diameter Annulus	
E_n (ev)	ϕ_{app} (n/cm ² -sec)	E_n (ev)	ϕ_{app} (n/cm ² -sec)
0.03	3.5×10^2	0.03	1.1×10^2
1×10^3	2.8×10^2	2.4×10^4	1.5×10^2
2.4×10^4	7×10^1	7.8×10^5	2.1×10^2
-	-	4.1×10^6	1.1×10^2

IV. CONCLUSIONS

Based upon the experimental results recorded in Table I, there appears to be no excessive gamma-ray streaming through the SRE Mark II control and safety rods. Excessive gamma-ray streaming was found through the special streaming plug. This special streaming plug was designed as a mock-up of a control rod for the specific purpose of determining the magnitude of possible streaming (gamma-ray and neutron) problems that might be present in the design. However, the streaming gamma-ray dose rate was found to be drastically reduced by the control rod assembly located above the typical control rod.

Based upon the experimental results recorded in Table VI, there does not appear to be any excessive fast neutron streaming through the SRE control and safety rods. The neutron streaming, due to scattering within the rod assemblies, is much higher (by a factor of about 5) through the sides of the assemblies than through the top of the assemblies. These results would indicate that thermal neutron streaming would also be negligible in these areas. The above statement is considered valid due to the following conditions:

- a) The attenuation of the thermal neutron flux through the assembly will be greater than for the fast neutron flux due to the composition of the assembly components.
- b) The ratio of thermal neutron flux to fast neutron flux for the same dose rate is a factor of about 60.
- c) The thermal neutron flux streaming through the annuli of the special shielding plug was approximately $2-5 \times 10^2$ n/cm²-sec, corresponding to a dose rate of 0.4 - 1.0 mrem/hr. The remaining area of the assembly would have a much lower thermal neutron flux due to item a) above.

As mentioned in Section III C, the energy distribution of the streaming neutrons was determined by approximating the energy values given in Reference 3 with the neutron flux peaks found by the experimental arrangement. A more exacting and time-consuming experiment would have to be performed to accurately determine the energies of the streaming neutrons. This type of exact measurement might

give a better estimate of the total neutron flux in these areas. However, the measurements that were made indicated that no excessive neutron streaming was present in the SRE top shield area, which was the problem that was to be resolved by these experiments.

The analytical methods used to calculate the gamma-ray dose rates streaming through the annuli of the SRE Mark II control and safety rods gave good agreement with the experimental results. Whether or not these methods are adequate to predict future gamma-ray dose rates streaming through annuli with different geometries cannot be stated until more experimental data is obtained. However, at the present time, these methods, using the maximum tolerances for the annulus size, should provide reasonable shield designs for such configurations.

The analytical methods used to calculate the fast neutron dose rates streaming through the annuli of the SRE Mark II control and safety rods also gave good agreement with experimental results. However, in the case of fast neutrons, the analytical methods seem to be adequate for predicting the fast neutron dose rates streaming through annuli with different geometries since less dependence is placed on the attenuation due to the amount and type of materials in the fast neutron beam. Therefore, it appears that more reliance can be placed in the analytical methods used for fast neutron dose rate calculations than for gamma-ray dose rate calculations.

As stated in the Introduction, the aims of control and/or safety rod design and shielding must be compromised to satisfy the aspects of both reactor operation and radiation safety. The experimental results from the SRE Mark II control and safety rods indicate that such a compromise is possible. From the standpoint of SRE reactor operations, the design of the control and safety rods has been adequate for safe reactor operation. At the same time, the extent of radiation streaming through the tops and sides of the control and safety rods has not been excessive and does not cause a radiation hazard to operation personnel. Therefore, the design of the SRE control and safety rods indicates that both aspects (radiation and operation) of safety necessary in control and safety rods can be satisfied by proper design and analysis.

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