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Analysis of the TMI-2 Source Range Detector Response*

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Introduction In the first few hours following the TMI-2 accident large variations (factors of 10-100) in the source range (SR) detector response were observed. These variations are evident in the TMI-2 SR response depicted in Figure 1.

The purpose of this analysis was to quantify the various effects which could contribute to these large variations. The effects evaluated included, the transmission of neutrons and photons from the core to detector and the reduction in the multiplication of the Am-Be startup sources, and subsequent reduction in SR detector response, due to core voiding.

Analysis A one-dimensional ANISN slab model of the TMI-2 core, core externals, pressure vessel and containment has been constructed for calculation of the SR detector response and is presented in Table I. The fixed spatial source for both neutrons and photons, based on an expected radial power distribution, input to this model is presented in Table II. The ANISN transport calculations were performed in the S_8-P_3 approximation using the RSIC DLC-37/EPR (100 group, ENDF/B-IV) cross section library and the spatial mesh given in Table I. This mesh has been tested and found accurate to within $\lesssim$1% in the flux solution.

1. Fixed Source Calculations

In order to determine the effect of core and/or downcomer voiding on the transport of neutrons and photons from the core to the SR detectors, fixed source ANISN calculations were performed. Calculations were performed at the nominal operating moderator density and reduced densities of 40.0 and 0.0% of nominal. Four cases in which the exterior-core water was varied were considered; Case (1) - the core barrel (Region 4) and downcomer (Region 6 and 8) are flooded, T_W = 16 in., Case (2) - the core barrel is voided and the downcomer is flooded, T_W = 11 in., Case (3) - the core barrel is flooded and the downcomer is voided, T_W = 5 in. and Case (4) - the core barrel and downcomer are both voided, T_W = 0.0 in. The SR detector neutron response for these cases is presented in Table III and in Figure 2. It is seen that voiding the core results in a factor of ~3 increase in detector response in Case (1), T_W = 16 in., and a factor of ~10 increase in Case (4), T_W = 0.0 in. Since most of the source attenuation takes place outside of the core, the SR detector response is more sensitive to changes in this region and voiding the core barrel and downcomer results in a factor of ~10^3 increase in SR signal with the core at the nominal moderator density. This signal attenuation (SR^n/SR_0^n) may be described by the approximate expression,

$$SR^n/SR_0^n = e^{-\Sigma_R^n T_W} \tag{1}$$

where T_W is the exterior-core water thickness and Σ_R^n is an average neutron removal cross section for water, $\Sigma_R^n = .17\ cm^{-1}$.*

In order to determine the sensitivity of these results to cross section treatment, calculations were also performed for Case (1) and Case (4) using the RSIC DLC-23E/CASK (22 Group, ENDF/B-II) cross section set. In Table IV the results of these calculations are presented and are seen to agree with the DLC-37/EPR results (Table III) to within 20%. This difference has been traced to a difference in the fast hydrogen removal cross section between the two libraries.

In Tables V and VI and in Figure 3 the relative SR detector gamma (photon) response is presented for Cases (1) - (4). Voiding the core results in an ~10% increase in the detector γ-response for all cases. Voiding the core barrel and downcomer results in a factor of ~3.0 increase in gamma response with the core at the nominal moderator density. This signal attenuation ($SR\gamma/SR_0^\gamma$) may be described by the approximate relation,

$$SR^\gamma/SR_0^\gamma = e^{-\Sigma_R^\gamma T_W} \tag{2}$$

where Σ_R^γ is an average photon removal cross section for water, $\Sigma_R^\gamma = .027\ cm^{-1}$.

2. Source Multiplication Calculations

In order to determine the effect of reduced source multiplication when the core is voided, ANISN iterated source calculations have been performed. For convenience in these calculations, the CASK 22 group neutronics library was used. As a first step, the boron concentration and fuel enrichment were adjusted to obtain an initial subcritical target eigenvalue of $k_{eff} = .92$. The Am-Be start-up source was represented as a planar source in the center of the outer-core region (corresponding to the peripheral assemblies) and the spectrum was obtained from Reference 1.

In Table VII and in Figure 2 the SR detector neutron response is presented for Cases (1) - (4). Voiding the core barrel and downcomer results in a factor of 5×10^2 increase in the detector response for the nominal core. This source attenuation (SR^{AB}/SR_0^{AB}) is approximately represented by the relation,

$$SR^{AB}/SR_0^{AB} = e^{-\Sigma_R^{AB} T_W} \tag{3}$$

where Σ_R^{AB} is an average neutron removal cross section for water, $\Sigma_R^{AB} = .15\ cm^{-1}$†. This cross section and source attenuation is slightly reduced relative to the fission source (Equation (1)) due to the harder spectrum

* In the almost completely flooded Case (2) the transmitted neutron spectrum is hardened relative to the voided cases and Σ_R^n is reduced slightly: $\Sigma_R^n = .11\ cm^{-1}$.

† Like Σ_R^n, Σ_R^{AB} is slightly lower for Case (2): $\Sigma_R^{AB} = .10\ cm^{-1}$.

characteristic of the Am-Be source. Voiding the core results in a reduced source multiplication and an increased transmission, the net effect of which is a detector signal increase of ~50% in the completely flooded Case (1), T_W = 16 in., and a factor of ~2 increase in the voided Case (4), T_W = 0 in. In Table VIII the system eigenvalue and multiplied neutron source is presented together with the one-group point multiplication for these cases.

In order to determine the effect of partial core voiding, the completely flooded Case (1) and completely voided Case (4) have been calculated with the outer-core at nominal moderator density and the inner-core at various stages of voiding. In Figure 2 and in Table IX the results are presented and indicate the SR detector neutron response will increase by $\lesssim$10% when only the central core is voided.

Summary Detailed one-dimensional ANISN neutron and photon transport calculations of the TMI-2 source range detector response have been performed. For a fixed source the SR detector neutron response was found to increase by a factor of ~3-10 as a result of core voiding and by a factor of ~1000 due to the voiding of the core barrel and downcomer. The photon response was less sensitive with an ~10% increase resulting from core voiding and a factor of ~3.0 increase due to voiding of the core barrel and downcomer. The effect of core voiding on neutron source multiplication and transmission has also been evaluated for the Am-Be startup sources and found to result in a net increase of a factor of $\gtrsim$2 in SR detector neutron response.

Reference

1. D. Bogart, D. F. Shook and Daniel Fieno, "Transport Analysis of Measured Neutron Leakage Spectra from Spheres as Tests of Evaluated High-Energy Cross Sections," NSE, 53, 285 (1974).

Table I

ONE-DIMENSIONAL S_8-P_3 ANISN MODEL

#	REGION	MATERIAL	THICKNESS (cm)	MESH
1	Inner Core	Fuel and Moderator	144.24	15
2	Outer Core	Fuel and Moderator	19.55	10
3	Liner	SS304	1.91	4
4	Water		13.37	11
5	Barrel	SS304	5.08	4
6	Water		2.54	4
7	Thermal Shield	SS304	5.08	9
8	Water		24.92	10
9	Pressure Vessel	A533B	21.75	25
10	Air Gap	Air	49.37	5
11	Containment	Concrete (Type-04)	52.59	9

Table II

FIXED SPATIAL SOURCE

Mesh Point	Source
1	1.298
2	1.328
3	1.313
4	1.249
5	1.063
6	1.063
7	1.174
8	1.315
9	1.346
10	1.186
11	1.136
12	1.123
13	1.148
14	1.076
15	0.958
16	0.861
17	0.825
18	0.785
19	0.740
20	0.692
21	0.645
22	0.606
23	0.580
24	0.564
25	0.551

TABLE III

RELATIVE SR TOTAL NEUTRON FLUX

Relative Core Moderator Density, ρ	T_W - Thickness of Exterior-Core Water (in.) 16	11	5	0
1.0	1.00	4.15	1.09×10^2	1.04×10^3
0.4	1.65	7.01	1.98×10^2	2.16×10^3
0.0	2.80	1.26×10	4.07×10^2	9.26×10^3

TABLE IV

CASK RELATIVE SR TOTAL NEUTRON FLUX

Relative Core Moderator Density, ρ	T_W - Thickness of Exterior-Core Water (in.) 16	0
1.0	1.00	8.43×10^2
0.0	3.16	9.13×10^3

TABLE V

RELATIVE SR TOTAL GAMMA FLUX (eV/cm^2-sec)

Relative Core Moderator Density, ρ	T_W - Thickness of Exterior-Core Water (in.)			
	16	11	5	0
1.0	1.00	1.33	1.90	2.58
0.4	1.04	1.40	2.01	2.74
0.0	1.09	1.46	2.09	2.86

TABLE VI

RELATIVE SR TOTAL GAMMA FLUX (Photon/cm^2-sec)

Relative Core Moderator Density, ρ	T_W - Thickness of Exterior Core Water (in.) 16	11	5	0
1.0	1.00	1.40	2.12	3.04
0.4	1.06	1.49	2.26	3.25
0.0	1.11	1.56	2.37	3.41

TABLE VII

RELATIVE SR TOTAL NEUTRON FLUX RESULTING FROM
THE Am-Be STARTUP SOURCES

Relative Core Moderator Density, ρ	T_W - Thickness of Exterior-Core Water (in.) 16	11	5	0
1.0	1.00	3.59	6.25×10	4.69×10^2
0.4	1.22	4.18	7.25×10	5.01×10^2
0.0	1.61	5.50	1.03×10^2	1.09×10^3

TABLE VIII

CORE EIGENVALUE AND MULTIPLIED NEUTRON SOURCE vs. CORE MODERATOR DENSITY (T_H = 16.0 in.)

Relative Core Moderator Density, ρ	k-Eigenvalue	Relative Neutron Source	$(1-k_0)/(1-k)$
1.0	.92	1.0	1.0
0.4	.72	.32	.29
0.0	.66	.21	.24

TABLE IX

RELATIVE SR TOTAL NEUTRON FLUX RESULTING FROM THE
Am-Be STARTUP SOURCES

	T_W - Thickness of Exterior Core Water (in.)	
	16	0
Relative Inner-Core Moderator Density, ρ		
1.0	1.00	4.69×10^2
0.4	.98	4.53×10^2
0.0	1.04	5.26×10^2

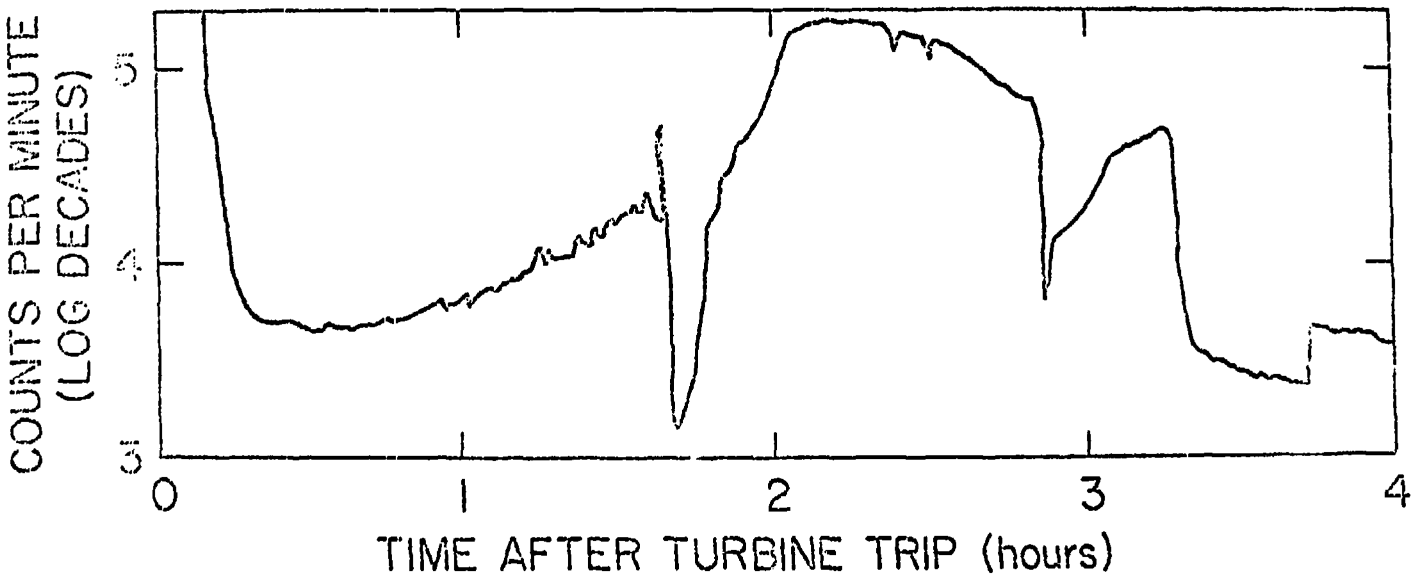

Figure 1 Source range channel NI-1

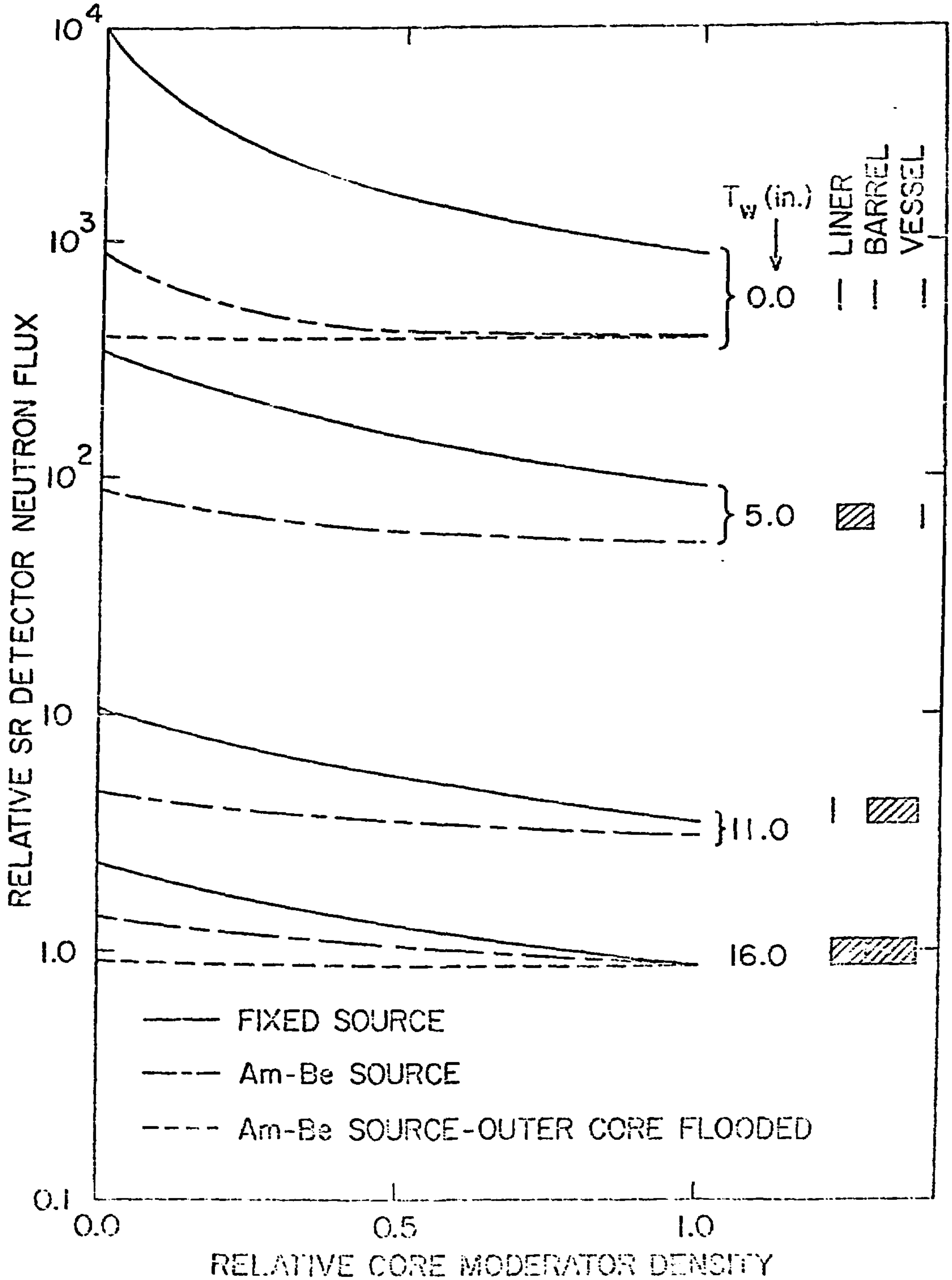

Figure 2 Relative SR Detector Neutron Flux

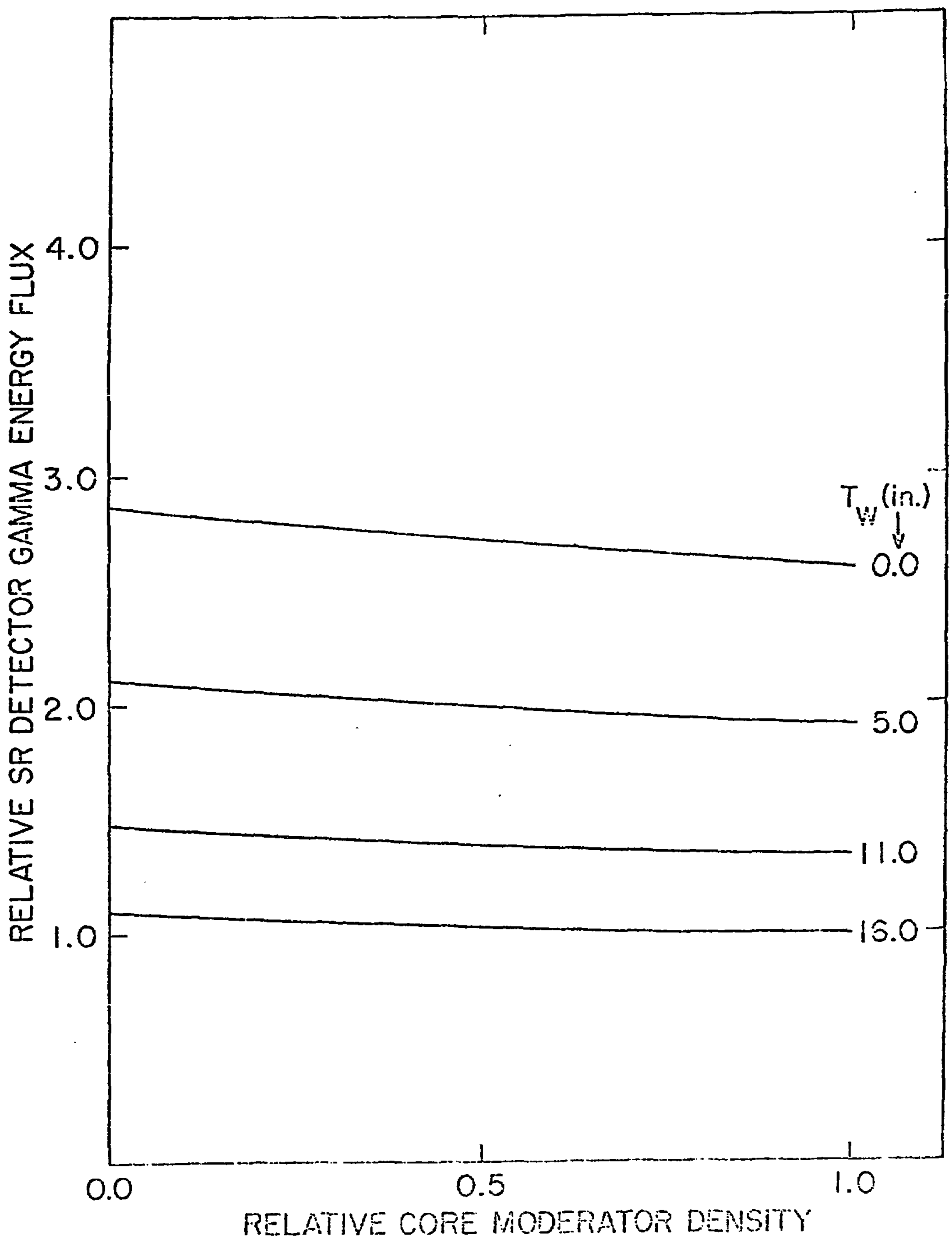

Figure 3 Relative SR Detector Gamma Energy Flux