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ANALYSIS OF THE TMI-2 SOURCE RANGE DETECTOR RESPONSE

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ABSTRACT

In order to explain the large variations (factors of 10-100) in source range monitor (SRM) response that occurred immediately following the TMI-2 Accident, detailed neutron and photon transport calculations have been performed. The SRM neutron response was found to increase by a factor of 3-10 as a result of core voiding and by a factor of $\sim$1000 due to voiding of the core bypass region and downcomer. The photon response was less sensitive with an $\sim$10% increase resulting from core voiding and a factor of $\sim$3.0 increase due to voiding of the core bypass and downcomer. The effect of core voiding on the multiplication and transmission of the Am-Be-Cm startup sources has also been evaluated and found to result in a net increase of a factor of $\lesssim$2 in SRM neutron response. These calculations and the TMI-2 event chronology suggest that the downcomer was voided during the accident.

INTRODUCTION

During the first few hours following the Three Mile Island Unit-2 (TMI-2) accident large variations (factors of 10-100) in the source range monitor (SRM) response were observed. A SRM channel trace recorded during the four hours following the turbine trip is presented in Figure 1 and indicates large signal reductions and/or increases occurred at $\sim$1.7, 2.9, 3.3, and 3.7 hours following the accident. Several mechanisms have been suggested in order to explain these variations including: (1) increased core source multiplication with k_{eff} approaching criticality, (2) voiding of the core moderator resulting in increased source leakage, (3) voiding of the core bypass (between the liner and barrel) and downcomer resulting in reduced source attenuation and (4) detector failure. The detectors are believed to have been operating normally and to explain the Figure 1 SRM response in terms of reactivity would require k_{eff} remaining within $\lesssim$1% of critical during a period when large changes in reactivity were occurring and is, therefore, considered unlikely.(1) The purpose of this study is to quantify the effects of core, core bypass and downcomer voiding in order to determine if any of these could be responsible for the observed SRM signal variations.

The analysis is carried out in three steps. First, fixed (core) neutron source calculations are performed in which the flux attenuation from core to detector is calculated for both flooded and voided conditions and the effect on SRM response determined. Second, iterated source calculations are performed in which the Am-Be-Cm (ABC) startup source multiplication is first established and then the attentuation through the voided barrel and downcomer determined. In the third step, the SR detectors are assumed to be responding to photons and the gamma flux attenuation is calculated for a fixed (core) gamma source.

ANALYSIS

Calculational Model

A one-dimensional ANISN[2] model of the TMI-2 core, core externals, pressure vessel and containment has been constructed for calculation of the SRM neutron and gamma response and is presented in Table I. The fuel, moderator and structural materials have been homogenized in the core regions and the detectors are located in the air gap outside the pressure vessel. The calculations were performed in the S8-P3 approximation using the spatial mesh indicated in Table I. Although azimuthal and axial geometric effects and core heterogeneities have been neglected, it is believed this model will provide meaningful estimates of detector response to voiding.

Neutron Flux Attenuation

Voiding of the core affects the source magnitude as well as the attenuation of the flux to the SRM detectors. A core neutron source will decrease in magnitude with voiding as a result of reduced core reactivity. A distributed $D_2O(\gamma,n)$ source, produced via decay gamma activity, will be further decreased due to a reduction in D_2O density. The reduction in attenuation results from the reduced optical path length for the high energy neutrons (or possibly photons) which provide the SRM response. In order to isolate this reduction in attenuation in the first set of calculations the source was held fixed and various stages of core, bypass and downcomer voiding were considered.

The calculations were performed using the RSIC DLC-37/EPR (100 neutron/21 Gamma Group, ENDF/B-IV) cross section library.[3] The fixed core neutron source was constructed using an equilibrium radial power distribution and an ENDF/B-IV fission spectrum. Denoting the total water thickness of the bypass (Region 4) and downcomer, T_W, the four cases considered are; Case (1) -bypass and downcomer flooded (T_W=40.8 cm.), Case (2) - bypass voided and downcomer flooded (T_W=27.4 cm.), Case (3) - bypass flooded and downcomer voided (T_W=13.4 cm.), Case (4) - Bypass and downcomer voided (T_W=0.0 cm). In each case calculations were performed at the nominal core moderator density and at the reduced densities of 40% and 0% of nominal.

The SRM response is produced by fast neutrons moderated at the detector and since the detector flux is ~80% fast, the SRM response was taken proportional to the detector total flux. In Figure 2 and in Table II the SRM detector flux (normalized relative to Case 1) is presented as a function of core moderator density with the specific voided bypass and downcomer regions indicated at the right. In the fixed fission source case voiding the core results in a factor of ~3 increase in detector response in Case (1) with the bypass and downcomer flooded (T_N=40.8 cm) and a factor of ~10 increase in Case (4) with the bypass and downcomer voided. Since most of the flux attenuation takes place outside the core, the detector response is more sensitive to changes in this region and voiding the bypass and downcomer results in a factor of ~10^3 increase in signal with the core at nominal moderator density.

The SRM signal may be approximated using the first flight (SLAB) transport kernel,

$$SRM = Se^{-\Sigma_W t_W - \Sigma_s t_s} \tag{1}$$

where $\Sigma_W(\Sigma_s)$ is the water (steel) neutron removal cross section, $t_W(t_s)$ is the optical path length in water (steel) and S is the core neutron source. The relative signal increase resulting from a reduction in path length, $\Delta t_W<0$, is then

$$SRM/SRM_0 = e^{-\Sigma_W \Delta t_W} . \tag{2}$$

The source increases from the fully flooded Case (1) to Case (3) and the voided Case (4) at nominal core density suggest a Σ_W=.17 cm^{-1} removal cross section which is in agreement with the ANISN cross section at the ~2 Mev spectrum peak. (In the almost completely flooded Case (2) the transmitted neutron spectum is hardened relative to the voided case; and Σ_W is reduced to Σ_W=.11 cm^{-1}.) The increased sensitivity of the SRM response at lower optical thickness in Figure 2 (e.g., Case (4) at 0% moderator density) is a result of the exponential form in Equation (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(4) cross section set. In Table III the relative SRM response for both the RSIC/EPR and RSIC/CASK libraries is presented and the results are seen to be in general agreement. (The decreased cask sensitivity to downcomer voiding is due to a reduced hydrogen removal cross section in CASK relative to the more accurate EPR Library.)

Source Multiplication

Iterated source ANISN calculations were performed in order to determine the effect of reduced source multiplication on SRM response. For convenience, in these calculations the CASK 22-Group Cross Section Library was used and as a first step the boron concentration and fuel enrichment were adjusted to obtain an initial subcritical target eigenvalue of k_{eff} = .92. It is assumed that all rods are inserted (-10% Δk/k) and the core is at 530° F (~ +2% Δk/k). The startup source was represented as a planar source in the center of the outer-core region (corresponding to the actual peripheral assembly locations) and the Am-Be-Cm source spectrum was taken from Reference 5. Calculations were performed for both a uniformly voided core and a partially voided core in which the outer core remained flooded.

In Figure 2 the results of these calculations (normalized relative to Case (1)) are presented. The decrease in attenuation dominates the reactivity induced source reduction when the entire core is voided and the detector response increases with core voiding. Voiding the core results in a detector signal increase of ~50% in the completely flooded case (T_W=40.8 cm) and a factor of ~2 increase in the voided case (T_W=0.0 cm).

The sensitivity of the SRM response to bypass and downcomer voiding is weaker in this case due to the harder spectrum of the ABC source and resulting reduction in water removal cross section. Voiding the core bypass and downcomer results in a factor of 500 increase in detector response for the nominal core. This source attenuation may be approximated using Equation (1) with an average removal cross section of $\Sigma_W^{ABC} = .15\ cm^{-1}$. (Again in Case (2) the transmitted spectrum is hardened and Σ_W^{ABC} is reduced to $\Sigma_W^{ABC} = .10\ cm^{-1}$).

In the partially voided case the source attenuation and multiplication introduced by inner-core voiding tend to cancel. In Figure 2 the SRM response is presented for T_W = 40.8 cm and T_W = 0.0 cm and is seen to increase by $\lesssim$10% in both cases as a result of partial core voiding.

The effect of core reactivity on source multiplication may be estimated using a One-Group point multiplication,

$$S = S_0/(1-k_{eff}) \tag{3}$$

where S_0 is the unmultiplied source and k_{eff} is the core eigenvalue. In Table IV the ANISN core eigenvalue and relative multiplied source together with the estimated point source multiplication are presented for the uniformly voided core. Voiding the core reduces the source by a factor of ~5 and the point multiplication is seen to provide a good estimate of the source multiplication. It is important to note that the strongest source multiplication occurs in the inner-core and since the SRM detectors receive ~80% of their signal from the outer core, the effective source multiplication observed at the detector is significantly less than indicated in Table IV.

Gamma Flux Attenuation

High gamma flux, discriminator missetting or detector failure could have lead to a situation in which the SRM detectors were responding to photons rather than neutrons. In order to determine if core, bypass or downcomer voiding could result in large variations in detector gamma response gamma transport calculations were performed. Since the γ-source is unaffected by core voiding the calculations were performed in a fixed source mode using the 21-Group DLC-37/EPR γ-cross sections. The γ-source was constructed from the group wise fission product decay energy profiles (at 10^3 sec after shutdown) included in Reference 6 and a spatial distribution based on an equilibrium radial power shape. In Table V the SRM response is presented for Case (1) and Case (4) and unlike the neutron response the detector gamma flux is relatively insensitive to voiding. Voiding the core results in an ~10% increase in γ-response while voiding the core bypass and downcomer results in a factor ~3.0 increase in SRM γ-response. This signal increase may be approximated using Equation (2) with an average photon removal cross section, $\Sigma_W^{\gamma} = .027\ cm^{-1}$.

DISCUSSION

Any interpretation of the observed fluctuations in SRM response (Figure 1) will suffer from the uncertainty in the conditions that existed in the reactor during this period. However, using the observed SRM response and the calculated ANISN response sensitivities the likelihood of specific reactor conditions contributing to the observed variations may be established. The weak sensitivity of the SRM γ-response indicates that, if the SRM was responding to photons originating in the core, neither voiding of the core, bypass or downcomer would result in the observed variations in the SRM signal.

The reduced attenuation introduced by core and bypass voiding results in a factor of $\lesssim 13$ increase in SRM response for a core neutron source (Table 2). The reduction in source multiplication which accompanies core voiding will tend to reduce this signal enhancement. For the ABC startup sources this signal increase is reduced to a factor of ~5 in the case of uniform core voiding and to a factor of ~3 for partial core voiding. For a more uniformly distributed source (e.g., $D_2O(\gamma,n)$) an even greater reduction in the multiplication of the outer core source would occur and the signal enhancement would be reduced further. On the other hand, if k_{eff} was significantly less than the assumed $k_{eff} = .92$ the reduction in source would be less. In any case, the SRM increase would be less than a factor of 13 and core and bypass voiding alone is not sufficient to produce the observed factors of 10 - 100. It is important to note that although the SRM response does not require it, other evidence strongly suggests that some core voiding did occur.

Voiding the downcomer results in an increase in SRM response large enough to explain the observed variations; for the distributed fission spectrum source a factor of ~100 increase (Table 2) and a factor of 60 increase for the ABC startup source. Assuming the core and bypass are simultaneously voided to 70% of their nominal moderator density, (and using Equation (2)) the SRM response will increase by a factor of ~300 for the distributed fission source and by a factor of ~120 for the startup source. Most likely partial voiding of the core, bypass and downcomer regions actually occurred and in order to construct the observed SRM response the detailed void distribution history is required.

The chronology of events following the accident also tend to support voiding of the downcomer. At 1.67 hrs. following the turbine trip the A-loop reactor coolant pumps (RCPs) were tripped (Loop B RCPs had been tripped earlier) and the SRM response spiked upward (Figure 1, Point A). Tripping the pumps reduced inlet flow and presumably resulted in the partial voiding of the downcomer and increased readings. The high pressure injection (HPI) flow was then increased and then SRM response dropped rapidly (Figure 1, Point B). The subsequent SRM reduction could be explained by the reflooding of the downcomer. The gradual increase in SRM readings over the next quarter hour (Figure 1, Point C) may be due to a gradual decrease in downcomer level or density. At 2.9 hrs. the operators restarted RCP 2B, flow was established for a few seconds and the SRM response dropped rapidly (Figure 1, Point D). Again this SRM decrease could be explained by downcomer reflooding. Similarly at 3.3 hours the HPI pumps were started and then one turned off at 3.7 hours. The SRM first dropped (Figure 1, Point E) and then increased (Figure 1, Point F) presumably in response to an increase and then subsequent decrease in downcomer level.(7)

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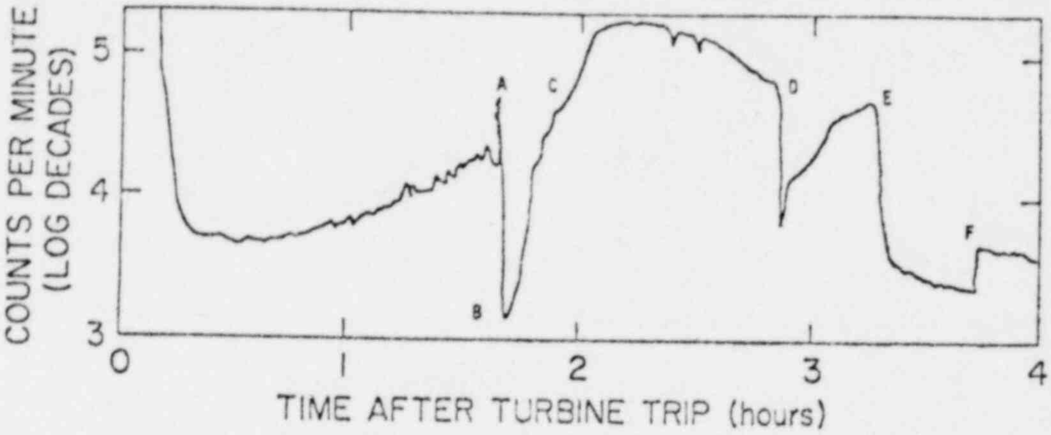

Figure 1 Source range channel NI-1

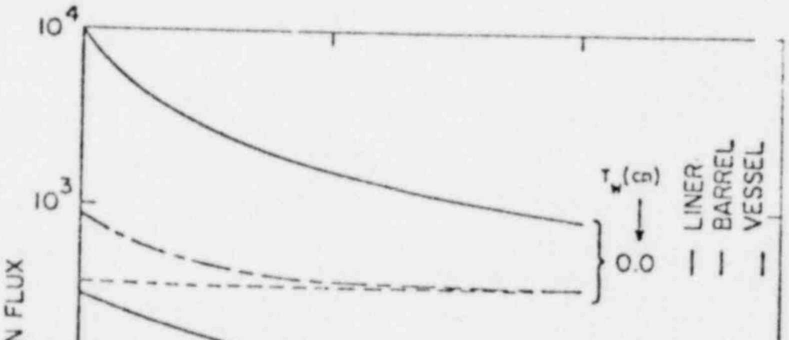

Figure 2 Relative SR detector neutron flux

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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 (Bypass)		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

RELATIVE SRM NEUTRON FLUX

	T_W - Thickness of Exterior-Core Water (cm)			
Relative Core Moderator Density	40.8	27.4	13.4	0.0
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 III

COMPARISON OF THE CASK AND EPR

RELATIVE SRM NEUTRON FLUX

Relative Core Moderator Density	T_W = 40.8 cm		T_W = 0.00 cm	
	EPR	CASK	EPR	CASK
1.0	1.0	1.0	1.04×10^3	8.43×10^2
0.0	2.80	6	9.26×10^3	9.13×10^3

TABLE IV

CORE EIGENVALUE AND MULTIPLIED NEUTRON SOURCE VS. CORE MODERATOR DENSITY (T_W = 40.8 cm)

Relative Core Moderator Density	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 V

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

	T_W - Thickness of Exterior Core Water (cm)			
Relative Core Moderator Density	40.8	27.4	13.4	0.0
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