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Analysis of Gamma Radiation Fields in the MAPLE-X10 Facility Associated with Loss-of-Pool-Water Accident Conditions

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LOSS-OF-POOL-WATER 사고시 연구용 원자로 MAPLE-X10 시설에서의 감마 방사선장 해석

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Abstract

An analysis for the gamma radiation fields in the research reactor MAPLE-X10 facility has been performed under the assumption of partial loss of reactor and service pool water to assess the safety from the view point of design. Four photon source terms considered in the analysis were calculated using the ORIGEN-S code. Gamma dose rate calculations over the reactor and service pools during the water-loss accident conditions were performed using QAD-CG code. MCNP code (Monte Carlo Neutron and Photon Transport code), also, was used to assess the scattered radiation fields away from the pools, which is appropriate for calculating the scattered photon dose rates outside of the solid angle subtended by the source and pool walls.

요 약

연구용 원자로 MAPLE-X10 시설의 안전성을 평가하기 위하여 원자로 pool 및 보조 pool로부터 물의 상실이 가정되었을 때 시설에 대한 감마 방사선장을 해석하였다. 차폐 해석에 고려된 4개의 photon 선원항은 ORIGEN-S코드를 이용하여 계산하였다. 또한, pool물 상실 사고 조건하에서 원자로 pool 및 보조 pool에서의 감마 선량율은 QAD-CG 코드를, 그리고 pool 외부의 방사선장은 입체각 외부에서의 산란 photon 선량율 계산에도 적합한 MCNP 코드를 이용하여 평가하였다.

1. Introduction

The gamma radiation fields in the MAPLE-X10 (MX-10) facility have been calculated for several postulated accident conditions involving partial loss of reactor and service pool water. The assement was performed to assist in the preperation of the MX-10 Preliminary Safety Analysis Report (PSAR).

The accident conditions assessed in this paper assume a failure in the Primary Cooling System (PCS) piping leading to a loss of reactor pool water to the adjacent PCS pump room. The water loss from the pool will reduce the shielding above the core as well as any spent driver assemblies residing in the reactor pool interim storage rack. Subsequent failure of the service trench gate separating the reactor and service pools has also been assessed. This scenario leads to a reduction of water shielding over the spent driver assemblies residing in the service pool storage rack, and any molybdenum production assemblies in the service pool.

The radiation fields associated with these conditions have been calculated directly above the MX-10 pools and at occupied and potentially occupied areas including the reactor hall floor, service hall, and the control room, for each of the potential source terms.

2. Calculational Methods

Assessing the dose rates in the MX-10 facility under loss-of-pool-water accident conditions involves calculating (a) all potential source terms in both the reactor and service pools, and (b) the depth of water shielding remaining over the fuel assemblies following the postulated accident. The dose rates in typically occupied areas of the facility away from the pools result entirely from radiation scattering in the air and from surfaces above the pools. Accurate calculation of this scattered component requires a rigorous treatment. The following sections detail the modeling, calculational methods, and codes employed in the analysis.

2.1 Photon Source Terms

Four source terms were considered in the analysis: (a) a full service pool driver storage rack, (b) a single driver assembly residing in the reactor pool interim storage rack, (c) the shut-down reactor core, and (d) a single molybdenum production (target) assembly residing on the service pool disassembly table. In all cases, only the photon sources were considered as the neutron component is negligible.

All photon source terms were calculated using the ORIGEN-S isotope generation and depletion code.1) The photon spectra were generated in the ORIGEN-S default 18-energy-group structure. A fission power of 690kW and core residence time of 168 days was assumed for all spent driver assemblies.2) This burnup scenario results in spent driver fuel assemblies being discharged from the core at the rate of one every 14 days. The molybdenum production assembly fission power was assumed to be 250 kW, with a core residence time of 7 days.2) The initial fuel compositions were taken from the revision 2 reactor specifications report.3) The cross-section library used by ORIGEN-S was created using the SCALIAS-77 system.4) The library incoporated updated resonance-processed ENDF/B-IV cross-section data from the 27-neutron-group SCALE library for those isotopes present in the initial fuel composition, and flux weight factors calculated using the XSDRNPM-S lattice cell transport code.5)

The photon source strengths of the driver assemblies residing in the service pool spent storage rack were determined individually for ten assemblies, ranging in cooling time from 14 days to 140 days. Assemblies having longer cooling times contributed less than 5% to the dose rate above the pool and were therefore not included.

The single driver assembly residing in the reactor pool interim storage rack was conservatively assumed to have cooled for a minium time of 10 minutes prior to an accident condition occuring. Photon source terms were also generated for several cooling times ranging up to 7 days to allow an estimate of the change in the gamma fields from the interim rack assembly with time, since the source varies relatively quickly at short cooling times.

The moly target assembly in the service pool was assumed to have cooled for a minimum time of 2 hours. Photon sources were also calculated for longer cooling times of 6 and 24 hours to assess the initial decrease in the radiation fields with time. The core was conservatively assumed to consist entirely of nineteen driver assemblies. A single decay time for all core assemblies of 1 minute was assumed.

2.2 Pool Water Depths

The only shielding present above the spent fuel assemblies is that provided by the pool water. The water depths in the reactor and service pools were estimated for a postulated condition in which a PCS failure allows reactor pool water to flow into the pump room. Two subsequent scenarios were considered: (a) the service trench gate separating the reactor and service pool remains in place, and (b) the gate is assumed to fail, resulting in a loss of service pool water to the reactor pool.

The pump room size and position is such that the pool water level will equilibriate with the pump room water level before the pool drains to the level of the lowest possible pipe break. The equilibrium water height is dependent upon two factors: the elevation difference between the initial pool water level and the pump room floor, and the cross-sectional area of the pool and the PCS pump room. Using the fact that the water volume displacement from the pool is equal to that into the pump room, the change in water height is given by

$$\triangle H_1 = H_2 A_2 / A_1 \cdots\cdots (1)$$

where H refers to the change in water height, A is cross-sectional area, and the two subscripts refer to the pool and the pump room. At equilibrium, the height difference between the initial pool water level and the pump room floor $\triangle H_0$ is equal to the sum of the pool and pump room water level changes, so that equation (1) can be rewritten

$$\Delta H_0 = H_1(1 + A_1 / A_2) \cdots\cdots (2)$$

The pool and pump room areas and elevations were obtained from the architectural arrangement design drawings.[6],[7] The calculated pump room area did not account for equipment in the room, but included the primary heat exchanger plinth. The areas and elevations used in the calculations are provided in Table 1.

Table 1. Room Area and Elevation Specifications

Main Reactor Pool	
· Room Number	006
· Pool Area (cm^2)	$1.11 \times 10^{5*}$
· Floor Elevation (mm)	136,000
· Normal Water Elevation (mm)	145,500
· Accident Water Elevation (mm) (gate closed)	141,615
· Accident Water Elevation (mm) (gate open)	142,353
Service Pool	
· Room Number	008
· Pool Area (cm^2)	$1.15 \times 10^{5*}$
· Floor Elevation (mm)	140,500
· Normal Water Elevation (mm)	145,500
· Accident Water Elevation (mm)	142,353
Pump Room	
· Room Number	001
· Room Area Less HX Plinth (cm^2)	4.54×10^5
· HX Plinth Area (cm^2)	5.01×10^4
· HX Plinth Height (cm)	1.00×10^2
· Floor Elevation (mm)	140,500
· Flooded Elevation (mm) (gate closed)	141,162
· Flooded Elevation (mm) (gate open)	142,353

***Area includes sevice trench area up to gate**

The reduction in the reactor pool water level following a PCS pipe break, assuming the service pool gate remains intact, is calculated to be 389 cm. This results in a reactor pool water depth of 561 cm, and a depth above the service trench floor of 112 cm. Failure of the service gate will result in an additional 74 cm of water in the reactor pool. The service pool is reduced to a water depth of 185 cm.

2.3 Gamma Dose Rate Calculations

Gamma dose rate calculations over the reactor and service pools during the water-loss accident conditions were performed using QAD-CG,[8] a three-dimensional point kernel integration code. As QAD-CG uses a ray tracing analytical method, it is incapable of correctly calculating the scattered photon dose rates outside of the solid angle subtended by the source and pool walls. To assess the scattered radiation fields away from the pools, the Monte Carlo transport code MCNP[9] was used. Due to the cost in MCNP of transporting particles between media of highly differing densities, such as between the pool water and air, the QAD-CG results were used to determine an equivalent pool surface source for MCNP, so that source photons did not have to penetrate the water shielding. The MCNP surface sources were sized and normalized to produce fields above the pools which matched the QAD-CG results. A brief description of the QAD-CG and MCNP modeling follows.

2.3.1 QAD-CG Calculations

The driver and moly fuel assembly dimensions and compositions used in the QAD-CG calculations were based on the revsion 2 reactor physics specifications report.[3] The fuel assembly and shielding material compositions are listed in Table 2.

Table 2. QAD-CG Material Compositions

ELEMENT	ILMENITE CONCRETE (g/cm^3)	WATER (g/cm^3)	STEEL LINER (g/cm^3)	DRIVER ASSEMBLY (g/cm^3)	TARGET ASSEMBLY (g/cm^3)
H	0.008	0.112		0.060	0.067
C	0.019				
O	1.191	0.888		0.480	0.531
Mg	0.053				
Al	0.075			1.085	1.031
Si	0.122			0.035	
Ca	0.113				
Ti	0.513				
Fe	1.390		7.86		
Zr				0.071	0.110
U				0.853	0.069
TOTAL	3.484	1.00	7.86	2.584	1.808

The driver assemblies residing in the service pool spent fuel storage rack were modeled. The fuel assemblies were modeled in a 2×7 array with a 19.0-cm-square assembly pitch. The nearest assembly centreline to pool wall distance was 20.0 cm. The bottom of the fueled assembly region was modeled 12.8 cm from the pool floor. This rack position resulted in a 114.4 cm depth of water shielding above the active fuel region of the stored assemblies in the event of service pool water loss.

A recently discharged moly target assembly located in the service pool was modeled at a height of 1 metre from the pool bottom. As detailed information on the design of the disassembly table was not available at the time of these calculations, the height was conservatively based on the best estimates available.[10] The assembly was modeled lying on its side.

A recently discharged driver assembly located in the reactor pool interim storage rack was modeled with the top of the assembly at a height equal to the service trench floor. This resulted in a water shielding thickness above the assembly following a loss-of-pool-water accident of 112 cm with the service gate closed, and 185 cm in the event of a service pool trench gate failure.

The top of the nineteen driver assemblies modeled in the reactor core were positioned a distance of 150.6 cm from the pool floor, resulting in water shielding thickness of 411 cm and 485 cm for the closed and open gate scenarios, respectively.

2.3.2 MCNP Calculations

The model of the MX-10 facility used in the MCNP transport calculations is shown in Figule 1. The dimensions of pools, reactor hall and control room were obtained from recent architectural design drawings.[7),11),12)] The control room and reactor hall walls were approximated using cylindrical geometry to simplify input. The modeled cylindrical room diameters were set equal to the true room widths. The reactor and control room walls and ceilings were modeled as 15-cm-thick concrete. The ceiling in the rest of the MX-10 facility was modeled as steel.

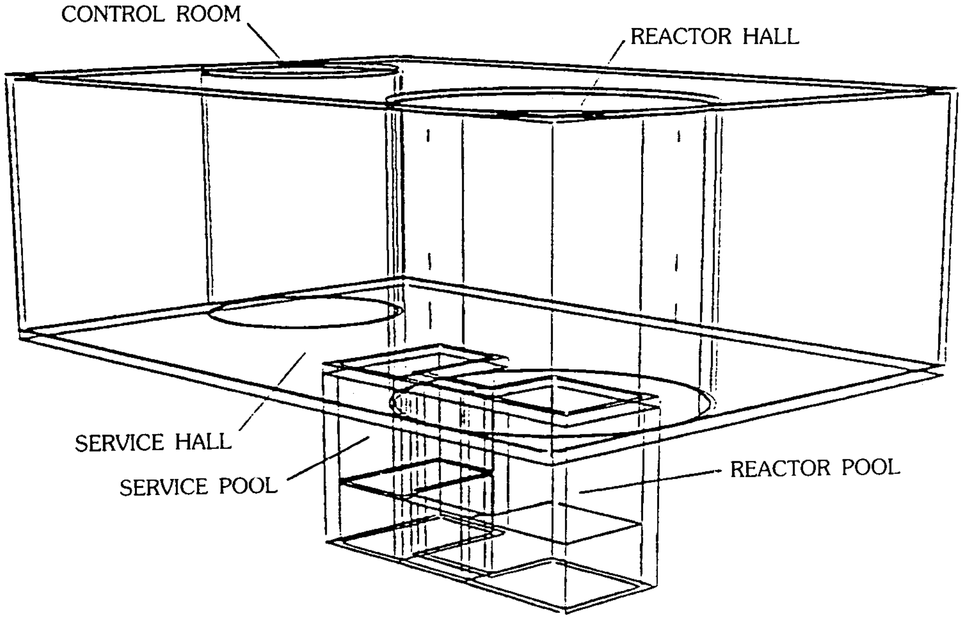

Fig.1 MCNP Model of the MAPLEX-10 Facility Used in Scattering Calculations

The surface source used in MCNP was given a cosine angular distribution to approximate the field divergence. The pool surface source areas were modeled as 1 m^2, which gave a good agreement between the QAD-CG and MCNP dose rate profiles vertically above each of the sources. The initial photon energy distributions used in MCNP were obtained using the ONEDANT Sn transport code[13] since QAD-CG provides no spectral information through shielding.

The NPS (Number of Particles Started) used in MCNP calculation was 20,000 and the computer time to perform the calculation by that NPS was 152 minutes in AECL-WNRE VAX computer system.

3. Results

The QAD-CG gamma dose rates above the main reactor pool during a low-water accident condition, for the open and closed service gate scenarios are given in Table 3, for the two reactor pool sources. The dose rates were calculated at several points ranging from the pool water level to the reactor hall ceiling along the assembly centrelines. The variation in dose rate for several driver assembly cooling times ranging from 10 minutes to 1 day is presented for the single assembly residing in the interim storage rack. A single decay time of 1 minute was assumed for the 19-driver assemblies modeled in the shut-down reactor core. Longer cooling times were not considered for the core as this contribution to the total dose rate above the pool is seen to be minimal for the lowest water level.

Table 3. QAD-CG Calculated Dose Rates over the Reactor Pool from Interim Driver Assembly and Core Sources(mrem/h)

SINGLE DRIVER ASSEMBLY RESIDING IN INTERIM RACK (SERVICE GATE CLOSED)				
Cooling Time	10 Minute	1 Hour	24 Hours	7 Days
Water Level	8.4239E+05*	4.5758E+05	9.8236E+04	6.0071E+04
Floor Level	3.8789E+04	2.1212E+04	4.5102E+03	2.7627E+03
1 Metre**	2.7906E+04	1.5259E+04	3.2430E+03	1.9866E+03
2 Metres	2.1036E+04	1.1502E+04	2.4436E+03	1.4970E+03
3 Metres	1.6422E+04	8.9788E+03	1.9071E+03	1.1684E+03
5 Metres	1.0804E+04	5.9069E+03	1.2541E+03	7.6840E+02
Ceiling	7.0724E+03	3.8664E+03	8.2064E+02	5.0282E+02
SINGLE DRIVER ASSEMBLY RESIDING IN INTERIM RACK (SERVICE GATE OPEN)				
Cooling Time	10 Minute	1 Hour	24 Hours	7 Days
Water Level	1.3567E+04	7.0365E+03	9.9073E+02	6.3043E+02
Floor Level	1.6350E+03	8.4706E+02	1.1861E+02	7.5482E+01
1 Metre**	1.1766E+03	6.0953E+02	8.5307E+01	5.4290E+01
2 Metres	8.8712E+02	4.5952E+02	6.4290E+01	4.0914E+01
3 Metres	6.9267E+02	3.5878E+02	5.0182E+01	3.1936E+01
5 Metres	4.5583E+02	2.3608E+02	3.3007E+01	2.1006E+01
Ceiling	2.9843E+02	1.5455E+02	2.1601E+01	1.3747E+01

REACTOR CORE INVENTORY OF 19 DRIVER ASSEMBLIES
(SERVICE GATE CLOSED)

Water Level	4.7264E+01	
Floor Level	1.1448E+01	
1 Metre**	9.1904E+00	
2 Metres	7.5403E+00	
3 Metres	6.2977E+00	
6 Metres	3.9771E+00	
Ceiling	3.0771E+00	

* Read as 8.4239×10^5
** Distances measured from floor elevation

The radiation fields above the service pool during a low-water accident condition are listed in Table 4, for distances ranging from the water level to the service hall ceiling. Additional cooling of the stored driver assemblies was not considered as the rate of decrease in the gamma field with time for decay times exceeding 14 days is relatively small. The dose rates from the single moly assembly residing on the service pool table are given for decay times ranging from 2 to 24 hours. The time dependence of the gamma dose rates at floor elevation above the reactor and service pools are plotted in Figure 2.

Table 4. QAD-CG Calculated Dose Rates over the Service Pool from Driver Assemblies and Moly Target Sources(mrem/h)

Molybdenum Target Assembly on Service Pool Table

Cooling Time	2 Hours	6 Hours	24 Hours
Water Level	3.7975E+06	1.9586E+06	9.3440E+05
Floor Level	1.4722E+05	7.6010E+04	3.6298E+04
1 Metre*	9.8815E+04	5.1020E+04	2.4365E+04
2 Metres	7.0880E+04	3.6596E+04	1.7476E+04
3 Metres	5.3305E+04	2.7524E+04	1.3144E+04
5 Metres	3.3283E+04	1.7185E+04	8.2065E+03
Ceiling	1.9285E+04	9.9575E+03	4.7551E+03

Driver Assembly Storage Rack with 10 Assemblies

Water Level	8.4322E+04
Floor Level	5.6173E+03
1 Metre*	3.8639E+03
2 Metres	2.8192E+03
3 Metres	2.1473E+03
5 Metres	1.3643E+03
Ceiling	8.6819E+02

*Distances measured from floor elevation

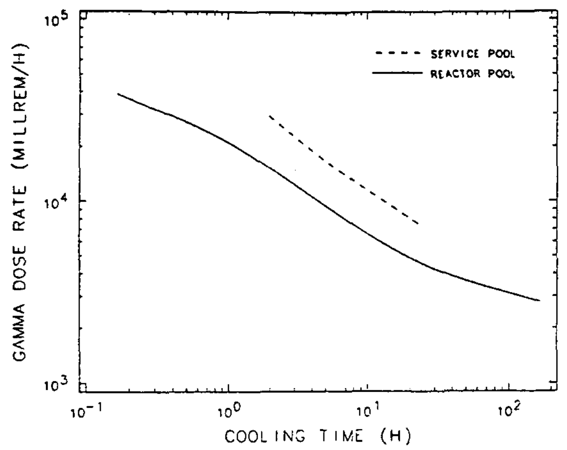

Fig.2 Dose Rates above Reactor and Service Pools as a Function of Cooling Time

The MCNP calculated gamma dose rates in the MX-10 facility at positions away from the reactor and service pools are provided in Table 5. The results are based on the shortest cooling time data calculated for the interim driver and moly target assemblies, namely 10 minutes and 2 hours, respectively. The core sources were not included in the scattering calculations due to their relatively minor importance. All detector points in the MCNP results presented were placed 1 metre above the floor.

Table 5. MCNP Calculated Gamma Dose Rates in the MX-10 Facility from Reactor and Service Pool Sources(mrem/h)

Reactor Pool Interim Storage Rack Driver Assembly

	Moly Target	Driver Rack
Adjacent Pool	4.8033E+02	1.6436E+01
9 Metres	3.8999E+02	1.2783E+01
12 Metres	1.8921E+02	6.5147E-00
Control Room	7.2755E-01	1.9405E-03

Service Pool Driver Assembly Rack and Moly Target

	Gate Closed	Gate Open
Reactor Hall (Max)	6.4637E+02	3.0448E+01
Reactor Hall (Min)	2.3457E+02	1.0271E+01
Outside Reactor Hall Wall	1.4858E-00	2.0800E-01
Control Room	2.9406E-03	1.0387E-04

The highest gamma field generated in the reactor hall during a loss-of-pool-water accident condition results from the single driver assembly residing in the interim storage rack. At a cooling time of 10 minutes, the peak dose rate in the hall exceeds 38 rem/h directly above the assembly when the service gate remains closed. Adjacent to the reactor pool, about 2 metress from the edge, the peak dose rate is about 646 mrem/h for the same condition. Applying the decay curve from Figure 2, this field is predicted to decrease to about 75 mrem/h after a 1 day cooling period, and 46 mrem/h after 7 days. These fields are reduced by a factor of about 20 when the service gate is open, owing to the extra water shielding from the service pool. The dose rate outside the reactor hall concrete wall is reduced to less than 2 mrem/h for the worst accident scenario considered.

Peak gamma dose rates in the service hall result from the moly target assembly residing on the pool table. The dose rate above the pool at floor elevation from a 2 hour cooled assembly exceeds 140 rem/h. At about 2 metres from the pool edge, this field is reduced to about 480 mrem/h. From Figure 2, this field is expected to decrease to about 120 mrem/h after 1 day. The dose rates adjacent to the service pool from the driver storage rack is calculated to be about 16 mrem/h.

The contribution of all potential source terms to the control room gamma dose rate is calculated to be less than 1 mrem/h for the most conservative scenario. The largest single contribution is from the moly target assembly. Excluding this source, the total control room dose rate will not be significantly different than normal background.

4. Discussion

This report has presented calculations of gamma dose rates in the MX-10 facility resulting from several potential loss-of-pool-water accident conditions. The major source terms which would be expected in the pools were analyzed in the assement. The dose rate calculations were performed using the combined results from analytical QAD-CG code and those of the Monte Carlo transport code MCNP.

The uncertainty of the QAD-CG results above the pools is expected to be better than 10% for the geometries analyzed. The Monte Carlo results vary in statistical accuracy depending on the number of particles tracked. The fields calculated in the reactor hall, where the particle flux and dose rates were highest, were generally better than 7% uncertainty. Similar accuracy was achieved in the service hall dose rates from the service pool sources. The dose rates in the control room were significantly lower, resulting in higher uncertainties of about 40%.

The dose rates in the MX-10 facility were found to be extremely high above the reactor and service pools in the event of low pool water conditions. The maximum fields away from the pools was over 600 mrem/h in the reactor hall, and about 480 mrem/h in the service hall. These dose rates arise entirely from radiation scattering above the pools. The gamma fields penetrating through the reactor hall and control room walls are extremely small. This is due to the fact that scattered photons lose most of their energy to the scattering medium. The maximum energy any scattered photon can have is 511 keV, giving them a very low shield penetration ability.

The highest single contributing source to the control room dose rate is the moly target assembly. The results were based on a conservative moly target position in the pool since the design was not finalized at the time of the calculations. A lower table height well significantly lower the resulting service hall and control room fields.

In all of these calculations, the effect of the bridge above each pool was not considered. Presence of a bridge will likely increase the dose rates adjacent to the pools, but have little affect on other locations. The effect will be local, and highly dependent on the bridge design and construction, which was unknown at the time of the current calculations.

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