Gamma Dose Measurements in ZPPR-15

Nuclear Science and Engineering Division

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ABSTRACT

Gamma doses were measured in the Zero Power Plutonium Reactor (ZPPR) to provide data for validation of calculations of gamma heating in important reactor components. Stainless steel-encapsulated LiF thermoluminescent dosimeters (TLDs) were irradiated in two configurations in ZPPR-15B and one configuration in ZPPR-15D to provide gamma heating data for the Integral Fast Reactor design in the mid-1980s.

The ZPPR-15 experimental records were used to develop detailed as-built Monte Carlo models for the gamma dose measurements in ZPPR-15B and ZPPR-15D. These Monte Carlo models can be converted to deterministic models for calculations with deterministic codes.

The reported uncertainty in the published gamma dose measurements is just the statistical uncertainty in the TLD readout. In addition to this statistical uncertainty in the TLD readout, several corrections and other factors contribute to the total uncertainty for the gamma dose measurements. The total uncertainty for the gamma dose measurements can be significantly larger than the published statistical uncertainty for the TLD readout. All known contributions to the total uncertainty were analyzed, and a total uncertainty was derived for the ZPPR-15 gamma dose measurements.

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1 Introduction

Gamma doses were measured in several ZPPR critical experiment programs. Those measurements were used to validate calculations of gamma heating in important reactor components. Reference 1 provides a general description of the Zero Power Plutonium Reactor (ZPPR) facility. Gamma doses were measured with thermoluminescent dosimeters in ZPPR-15B and ZPPR-15D.

A thermoluminescent dosimeter (TLD) consists of a thermoluminescent material in a capsule. The thermoluminescent material contains a number of electron or hole traps which are stable at room temperature [2,3]. Some of these traps are filled when ionizing radiation creates electrons or holes in thermoluminescent material. When the irradiated thermoluminescent material is subsequently heated, the electrons or holes are released from the trapping centers by thermal ionization. Ionized carriers move through the thermoluminescent material until electron-hole annihilation occurs. Electron-hole annihilation is accompanied by emission of a photon. Measurement of the number and intensity of photons emitted as a result of the annihilation provides an estimate of the radiation dose received by the thermoluminescent material during irradiation.

There are several thermoluminescent materials and potential capsule materials. The choices of thermoluminescent material, capsule material and capsule thickness were important considerations for TLD measurements. Stainless steel-encapsulated ${}^7\text{LiF}$ thermoluminescent dosimeters were the standard TLDs used to measure gamma doses at ZPPR when ZPPR-15 was constructed. The Li in the LiF was enriched to approximately 99.993% ${}^7\text{Li}$ because ${}^6\text{Li}(n,\alpha)$ reactions obscure the gamma contribution to the measured dose. TLD will refer either to the LiF thermoluminescent material inside the capsule or to the LiF material plus the stainless steel capsule for convenience in this report.

Two types of TLDs were used in the ZPPR-15 experiments. The first type was a stainless steel cylindrical capsule with a diameter of 12.7 mm and height of 6.35 mm, which could contain up to five LiF disks. Each capsule contained two LiF disks for the ZPPR-15 experiments. The recorded measurement was the average of these two disks. The dimensions of the LiF disks are not listed in available reports, but for realistic capsule wall thicknesses, it is likely that each LiF disk was a circular disk or chip with a diameter of ~ 10 mm and a thickness of approximately 0.5 – 1.0 mm. The capsules containing the LiF disks were placed in cavities in special tunnel sodium plates, i.e., sodium plates with a 12.7 mm cavity, which replaced normal sodium plates at selected locations in the assembly. TLDs containing LiF disks were used in the core and blanket of ZPPR-15. A TLD drawer was created by replacing one sodium plate in the standard drawer at the desired location by a sodium tunnel plate containing a TLD.

The second type of TLD was a stainless steel cylindrical capsule with an outer diameter of 3.175 mm and height of 12.7 mm that contained one LiF rod. The rod had a 1 mm square cross section and height of 6 mm. The thickness of the capsule wall was 0.035 in or 0.889 mm, and the steel was Type 304 stainless steel. This second type was sandwiched between normal material plates beyond the radial blanket during gamma dose measurements.

TLDs had been used at ZPPR since the ZPPR-2 program in the early 1970s, so it is likely that TLD designs were standardized by the time the ZPPR-15 TLD measurements were performed in 1985 – 1986. Type 304 stainless steel was widely used at ZPPR, so it is probable that the

capsule for the first type of TLD also consisted of Type 304 stainless steel. The capsule wall thickness was a very important parameter for TLD measurements because the thickness of the capsule wall determined whether electron equilibrium was established in the TLD. A steel capsule with a 0.035 inch wall thickness was used for TLD measurements at ZPPR and ZPR-9 in the 1970s, so it is probable that the capsule wall thickness for the first type of TLD was 0.035 inches or 0.889 mm.

2 TLD Measurements

Gamma doses were measured with TLDs in ZPPR-15B loadings 115, 122 and 133 (L115, L122 and L133) as part of the ZPPR-15B shield experiment and in ZPPR-15D loading 202 (L202). ZPPR-15B L115 served as a reference configuration for the ZPPR-15B TLD measurements. Two separate shield configurations were built in ZPPR-15B. ZPPR-15B L122 was the stainless steel-sodium (SSNA) configuration for the TLD measurements. ZPPR-15B L133 was the boron carbide-sodium (BCNA) configuration for the TLD measurements.

The TLD irradiations were performed such that the integrated power was approximately 300 watt-hours. The actual irradiation time from reactor startup to reactor shutdown was about 90 – 100 minutes according to the ZPPR-15 reactor logbook. The reactor power for the TLD irradiations in ZPPR-15B L115, L122 and L133 was ~1200 W, and the reactor power for the TLD irradiation in ZPPR-15D L202 was ~250 W according to the logbook. For an integrated power of 300 watt-hours, the irradiation time in ZPPR-15B L115, L122 and L133 at peak reactor power must have been much less than one hour. For operational and experimental reasons, a short irradiation at high power would be preferable to a long irradiation at low power. A long irradiation at low power has a negative impact on cost and schedules. In addition, a long irradiation at low power requires a larger correction and associated uncertainty for radioactive decay during the irradiation period. The TLDs were removed from the reactor approximately 20 hours after reactor shutdown.

All TLDs were located in half 1 of the ZPPR matrix for the ZPPR-15 TLD measurements except for four drawers in half 2 of ZPPR-15D L202. Each of those four drawers in half 2 of ZPPR-15D L202 contained multiple TLDs in order to measure the intra-drawer (or intra-cell) dose distribution in four types of ZPPR-15D unit cells (see Figures 2.5 and 2.6).

Figure 2.1 shows the matrix map for half 1 of ZPPR-15B L122, and Figure 2.2 shows the matrix map for half 1 of ZPPR-15B L133. Note that a matrix map shows the drawer master loaded in each matrix tube (see Ref. 1 for details regarding drawer masters and matrix maps). The projection on the left side in Figures 2.1 and 2.2 was a simulated radial shield constructed to obtain reaction rate measurements in a shield environment. The available plate inventory and the 77 x 77 size of the ZPPR matrix limited the simulated shield to one side of the core.

The rows in the 77 x 77 ZPPR matrix were numbered from 111 to 187 in half 1, the stationary half, and from 211 to 287 in half 2, the movable half. Rows 111 and 211 were at the top of the matrix; rows 187 and 287 were at the bottom of the matrix. The columns in the ZPPR matrix were numbered from 11 to 87 in both halves, but the order of the columns was reversed in half 2. An observer standing between the halves and facing half 1 would see column 11 of half 1 on the left. Column 11 of half 2 would be behind the observer's left shoulder. If the observer turns around and faces half 2, the observer would see column 87 on the left and column 11 on the right. These are the views shown in the matrix maps presented below. The reverse order

of the columns in half 2 allowed the column numbers to align when the matrix halves were brought together. For example, matrix location 145-33 in half 1 would be directly aligned with matrix location 245-33 in half 2 when the matrix halves touch. Note that 145-33 refers to row 45, column 33 in half 1 and 245-33 refers to row 45, column 33 in half 2 in the standard ZPPR convention for matrix locations. The Z-axis was parallel with the long axis of the matrix tubes with positive Z values in half 1. This numbering convention provided a standard right-handed coordinate system for analysis purposes.

The X-axis in ZPPR-15 was the line between rows 58 and 59, and the corresponding Y-axis was the line between columns 48 and 49. Note that row 59 was designated as 159 in half 1 of ZPPR and as 259 in half 2 of ZPPR. In ZPPR-15B L115, there were 24 TLDs distributed between the core center and the radial reflector in columns 22 – 48 in row 159 and 20 TLDs distributed between the core center and radial blanket in rows 139 – 158 in column 48. In ZPPR-15B L122 and L133, TLDs were placed in the outer core, radial blanket and shield on one side of the Y-axis and in the outer core, radial blanket and radial reflector on the other side of the Y-axis. All TLDs in ZPPR-15B L122 and L133 were located in row 159.

In ZPPR-15D L202, 20 TLDs were placed in the core and radial blanket in row 159, and 20 TLDs were placed in the core and radial blanket in column 48.

The light blue cells in Figures 2.1 and 2.2 are the radial reflector drawers, and the dark blue cells in these figures are the radial blanket drawers. The dark green cells inside the radial blanket are core drawers containing two columns of Pu-U-Mo fuel plates (DCF drawers), and the white cells inside of the radial blanket are core drawers containing one Pu-U-Mo fuel column (SCF drawers). The brown cells inside of the radial blanket are matrix tubes containing control rods and narrow core drawers. The orange cells at various locations are detector drawers. The other colored cells on the left side of Figures 2.1 and 2.2 are components of the simulated shield. The empty cells outside of the radial reflector and shield are empty matrix tubes.

The small numbers in the core, radial blanket, radial reflector and shield cells are abbreviations for the drawer master identifiers in the matrix tubes. Each drawer master identified a specific configuration of plates in a drawer (see Ref. 1). For example, “101” is the abbreviation for “15-0-101,” the full identifier for that particular drawer type. The numbers in the top row of each matrix map figure are the column numbers in the ZPPR matrix, and the numbers in the first column of each matrix map figure are the row numbers (shortened from 1nn or 2nn to nn where the “1” designates half 1 and “2” designates half 2) in the ZPPR matrix. Empty rows and columns of the matrix were omitted in Figures 2.1 and 2.2.

ZPPR-15B L115 was similar to L122 and L133 except that there was no simulated shield in L115. Consequently, the radial reflector thickness was uniform around the core and radial blanket.

Figure 2.3 shows the matrix map for half 1 of ZPPR-15D L202. The interpretation of the cell colors is identical to the description for ZPPR-15B L122 and L133 with two additions. The salmon-colored cells in Figure 2.3 are drawers containing HEU fuel plates in place of Pu-U-Mo fuel plates. The orange cells in row 159 and column 48 are core cells where TLDs were placed. There were also TLDs in three blanket cells in row 159 and in column 48.

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Figure 2.1 ZPPR-15B Loading 122 - Half 1 - Core Matrix Map

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Figure 2.2 ZPPR-15B Loading 133 - Half 1 - Core Matrix Map

Figure 2.3 ZPPR-15D Loading 202 - Half 1 - Core Matrix Map

Table 2.1 gives the measured gamma doses in row 159 of ZPPR-15B L115, and Table 2.2 gives the measured gamma doses in column 48 of ZPPR-15B L115. Table 2.3 gives the measured gamma doses in row 159 in the core, radial blanket and shield on the shield side of ZPPR-15B L122, and Table 2.4 gives the measured gamma doses in row 159 in the core, radial blanket and radial reflector on the opposite side of ZPPR-15B L122. Table 2.5 gives the measured gamma doses in row 159 in the core, radial blanket and shield on the shield side of ZPPR-15B L133, and Table 2.6 gives the measured gamma doses in row 159 in the core, radial blanket and radial reflector on the opposite side of ZPPR-15B L133. Table 2.7 gives the measured gamma doses in row 159 of ZPPR-15D L202, and Table 2.8 gives the measured gamma doses in column 48 of ZPPR-15D L202.

Columns 1 and 2 of Tables 2.1 – 2.8 show the row and column, respectively, where the TLD was located. Column 3 of these tables shows the column numbers in the drawer that specify the TLD position in the drawer. Columns 4 – 6 of Tables 2.1 – 2.8 show the coordinates of the TLD in the overall ZPPR matrix. Column 7 of these tables shows the measured dose rate, and column 8 of the tables shows the reported statistical uncertainties for the measured values. In all cases, the reported statistical uncertainty for the measurement was 2%. The estimated reactor power was one watt in all cases. Since the integrated power for the TLD irradiations was approximately 300 watt-hours, the one watt estimated reactor power for the published TLD values corresponds to normalized values. **All doses in the tables are in units of millirads/second where 1 rad = 0.01 Gy.**

The usable interior width in a drawer was 2 in. The ZPPR staff divided this space into sixteen 1/8th inch columns for reporting purposes. These drawer columns were labeled with letters A – P with A on the left as the observer faces the drawer. The two letters shown in the “Cell Location” column, i.e., column 3, of the tables below are the drawer columns that either contain or bound the TLD location. For example, JK means that either the TLD was placed between columns J and K in the drawer or that the sodium tunnel plate containing the TLD was in those columns. The columns labeled “Row” and “Column” in the tables below are the row and column of the ZPPR matrix containing the TLD.

The X-, Y- and Z-coordinates shown in all tables are the coordinates of the TLD location relative to an origin at the lower left corner of the interface between matrix halves. $Z = 0.0$ is at the interface between matrix halves, and the positive Z-axis is parallel to the long axis of the matrix tubes in half 1. $X = 0.0$ is at the left side of column 11 in half 1, and $Y = 0.0$ is at the bottom of row 187. Consequently, the origin corresponds to the position at the lower left corner of the interface between half 1 and half 2 for an observer facing half 1. **All dimensions and positions in all tables are in centimeters.**

Table 2.1 Gamma Dose in ZPPR-15B Loading 115 – Row 159

Row	Column	Cell Location	X, cm	Y, cm	Z, cm	Dose Rate, mrd/s ^a	σ_{stat} , % ^b
159	48	JK	207.7987	157.4063	7.6200	0.6843	2.0
159	47	JK	202.2742	157.4063	7.6200	0.6855	2.0
159	46	JK	196.7497	157.4063	7.6200	0.6897	2.0
159	45	JK	191.2252	157.4063	7.6200	0.6924	2.0
159	44	JK	185.7007	157.4063	7.6200	0.6728	2.0
159	43	JK	180.1762	157.4063	7.6200	0.7038	2.0
159	42	JK	174.6517	157.4063	7.6200	0.6867	2.0
159	41	JK	169.1272	157.4063	7.6200	0.6690	2.0
159	40	JK	163.6027	157.4063	7.6200	0.6631	2.0
159	39	JK	158.0782	157.4063	7.6200	0.6565	2.0
159	38	JK	152.5537	157.4063	7.6200	0.6339	2.0
159	37	JK	147.0292	157.4063	7.6200	0.6528	2.0
159	36	JK	141.5047	157.4063	7.6200	0.6334	2.0
159	35	JK	135.9802	157.4063	7.6200	0.6181	2.0
159	34	JK	130.4557	157.4063	7.6200	0.5377	2.0
159	33	JK	124.9312	157.4063	7.6200	0.4876	2.0
159	32	JK	119.4067	157.4063	7.6200	0.3821	2.0
159	31	HI	113.2472	157.4063	7.6200	0.1587	2.0
159	30	HI	107.7227	157.4063	7.6200	0.0948	2.0
159	29	HI	102.1982	157.4063	7.6200	0.0665	2.0
159	28	HI	96.67367	157.4063	7.6200	0.0419	2.0
159	26	HI	85.62467	157.4063	7.6200	0.0316	2.0
159	24	HI	74.57567	157.4063	7.6200	0.0198	2.0
159	22	HI	63.52667	157.4063	7.6200	0.0094	2.0

- Dose rate is in units of millirads/second. The estimated reactor power is one watt.
- This is the statistical uncertainty in the TLD readout. The total uncertainty is determined in Section 3.

Table 2.2 Gamma Dose in ZPPR-15B Loading 115 – Column 48

Row	Column	Cell Location	X, cm	Y, cm	Z, cm	Dose Rate, mrd/s ^a	σ_{stat} , % ^b
158	48	JK	207.7987	162.9308	7.6200	0.6926	2.0
157	48	JK	207.7987	168.4553	7.6200	0.6971	2.0
156	48	JK	207.7987	173.9798	7.6200	0.7034	2.0
155	48	JK	207.7987	179.5043	7.6200	0.6893	2.0
154	48	JK	207.7987	185.0288	7.6200	0.7017	2.0
153	48	JK	207.7987	190.5533	7.6200	0.6883	2.0
152	48	JK	207.7987	196.0778	7.6200	0.7005	2.0
151	48	JK	207.7987	201.6023	7.6200	0.6752	2.0
150	48	JK	207.7987	207.1268	7.6200	0.6622	2.0
149	48	JK	207.7987	212.6513	7.6200	0.6581	2.0
148	48	JK	207.7987	218.1758	7.6200	0.6534	2.0
147	48	JK	207.7987	223.7003	7.6200	0.6530	2.0
146	48	JK	207.7987	229.2248	7.6200	0.6184	2.0
145	48	JK	207.7987	234.7493	7.6200	0.6052	2.0
144	49	JK	213.3232	240.2738	7.6200	0.5283	2.0
143	48	JK	207.7987	245.7983	7.6200	0.4777	2.0
142	48	JK	207.7987	251.3228	7.6200	0.3623	2.0
141	48	HI	207.1637	256.8473	7.6200	0.1609	2.0
140	48	HI	207.1637	262.3718	7.6200	0.0976	2.0
139	48	HI	207.1637	267.8963	7.6200	0.0694	2.0

- Dose rate is in units of millirads/second. The estimated reactor power is one watt.
- This is the statistical uncertainty in the TLD readout. The total uncertainty is determined in Section 3.

Table 2.3 Gamma Dose in ZPPR-15B Loading 122 – Shield – Row 159

Row	Column	Cell Location	X, cm	Y, cm	Z, cm	Dose Rate, mrd/s ^a	σ_{stat} , %
159	36	JK	141.5047	157.4063	7.6200	0.6285	2.0
159	35	JK	135.9802	157.4063	7.6200	0.6163	2.0
159	34	JK	130.4557	157.4063	7.6200	0.5056	2.0
159	33	JK	124.9312	157.4063	7.6200	0.4578	2.0
159	32	JK	119.4067	157.4063	7.6200	0.3536	2.0
159	31	HI	113.2472	157.4063	7.6200	0.1539	2.0
159	30	HI	107.7227	157.4063	7.6200	0.0950	2.0
159	29	HI	102.1982	157.4063	7.6200	0.0673	2.0
159	28	HI	96.67367	157.4063	7.6200	0.0428	2.0
159	27	HI	91.14917	157.4063	7.6200	0.0366	2.0
159	26	HI	85.62467	157.4063	7.6200	0.0313	2.0
159	25	HI	80.10017	157.4063	7.6200	0.0258	2.0
159	24	HI	74.57567	157.4063	7.6200	0.0199	2.0
159	23	HI	69.05117	157.4063	7.6200	0.0152	2.0
159	22	HI	63.52667	157.4063	7.6200	0.0110	2.0
159	21	HI	58.00217	157.4063	7.6200	0.0069	2.0
159	20	HI	52.47767	157.4063	7.6200	0.0044	2.0
159	19	HI	46.95317	157.4063	7.6200	0.0034	2.0
159	18	HI	41.42867	157.4063	7.6200	0.0025	2.0
159	17	HI	35.90417	157.4063	7.6200	0.0020	2.0
159	16	HI	30.37967	157.4063	7.6200	0.0016	2.0
159	15	HI					
159	14	HI	19.33067	157.4063	7.6200	0.0006	2.0
159	13	HI					
159	12	HI	8.28167	157.4063	7.6200	0.0003	2.0

- Dose rate is in units of millirads/second. The estimated reactor power is one watt.
- This is the statistical uncertainty in the TLD readout. The total uncertainty is determined in Section 3.

Table 2.4 Gamma Dose in ZPPR-15B Loading 122 – Normal Reflector – Row 159

Row	Column	Cell Location	X, cm	Y, cm	Z, cm	Dose Rate, mrd/s ^a	σ_{stat} , %
159	61	FG	278.3472	157.4063	7.6200	0.6370	2.0
159	62	FG	283.8717	157.4063	7.6200	0.6313	2.0
159	63	FG	289.3962	157.4063	7.6200	0.5159	2.0
159	64	FG	294.9207	157.4063	7.6200	0.4584	2.0
159	65	FG	300.4452	157.4063	7.6200	0.3481	2.0
159	66	HI	306.6047	157.4063	7.6200	0.1577	2.0
159	67	HI	312.1292	157.4063	7.6200	0.0944	2.0
159	68	HI	317.6537	157.4063	7.6200	0.0684	2.0
159	69	HI	323.1782	157.4063	7.6200	0.0442	2.0
159	70	HI					
159	71	HI					
159	72	HI	339.7517	157.4063	7.6200	0.0252	2.0
159	73	HI					
159	74	HI					
159	75	HI					
159	76	HI	361.8497	157.4063	7.6200	0.0056	2.0

- Dose rate is in units of millirads/second. The estimated reactor power is one watt.
- This is the statistical uncertainty in the TLD readout. The total uncertainty is determined in Section 3.

Table 2.5 Gamma Dose in ZPPR-15B Loading 133 – Shield – Row 159

Row	Column	Cell Location	X, cm	Y, cm	Z, cm	Dose Rate, mrd/s ^a	σ_{stat} , %
159	36	JK	141.5047	157.4063	7.6200	0.6429	2.0
159	35	JK	135.9802	157.4063	7.6200	0.6321	2.0
159	34	JK	130.4557	157.4063	7.6200	0.5155	2.0
159	33	JK	124.9312	157.4063	7.6200	0.4862	2.0
159	32	JK	119.4067	157.4063	7.6200	0.3578	2.0
159	31	HI	113.2472	157.4063	7.6200	0.1531	2.0
159	30	HI	107.7227	157.4063	7.6200	0.0942	2.0
159	29	HI	102.1982	157.4063	7.6200	0.0634	2.0
159	28	HI	96.67367	157.4063	7.6200	0.0356	2.0
159	27	HI	91.14917	157.4063	7.6200	0.0257	2.0
159	26	HI	85.62467	157.4063	7.6200	0.0156	2.0
159	25	HI	80.10017	157.4063	7.6200	0.0139	2.0
159	24	HI	74.57567	157.4063	7.6200	0.0082	2.0
159	23	HI	69.05117	157.4063	7.6200	0.0044	2.0
159	22	HI	63.52667	157.4063	7.6200	0.0024	2.0
159	21	HI	58.00217	157.4063	7.6200	0.0014	2.0
159	20	HI	52.47767	157.4063	7.6200	0.0008	2.0
159	19	HI	46.95317	157.4063	7.6200	0.0005	2.0
159	18	HI	41.42867	157.4063	7.6200	0.0004	2.0
159	17	HI	35.90417	157.4063	7.6200	0.0003	2.0
159	16	HI	30.37967	157.4063	7.6200	0.0003	2.0
159	15	HI					
159	14	HI	19.33067	157.4063	7.6200	0.0002	2.0
159	13	HI					
159	12	HI	8.28167	157.4063	7.6200	0.0001	2.0

- Dose rate is in units of millirads/second. The estimated reactor power is one watt.
- This is the statistical uncertainty in the TLD readout. The total uncertainty is determined in Section 3.

Table 2.6 Gamma Dose in ZPPR-15B Loading 133 – Normal Reflector – Row 159

Row	Column	Cell Location	X, cm	Y, cm	Z, cm	Dose Rate, mrd/s ^a	σ_{stat} , %
159	61	FG	278.3472	157.4063	7.6200	0.6603	2.0
159	62	FG	283.8717	157.4063	7.6200	0.6265	2.0
159	63	FG	289.3962	157.4063	7.6200	0.5300	2.0
159	64	FG	294.9207	157.4063	7.6200	0.4870	2.0
159	65	FG	300.4452	157.4063	7.6200	0.3633	2.0
159	66	HI	306.6047	157.4063	7.6200	0.1561	2.0
159	67	HI	312.1292	157.4063	7.6200	0.0946	2.0
159	68	HI	317.6537	157.4063	7.6200	0.0668	2.0
159	69	HI	323.1782	157.4063	7.6200	0.0435	2.0
159	70	HI					
159	71	HI					
159	72	HI	339.7517	157.4063	7.6200	0.0270	2.0
159	73	HI					
159	74	HI					
159	75	HI					
159	76	HI	361.8497	157.4063	7.6200	0.0059	2.0

- Dose rate is in units of millirads/second. The estimated reactor power is one watt.
- This is the statistical uncertainty in the TLD readout. The total uncertainty is determined in Section 3.

Table 2.7 Gamma Dose in ZPPR-15D Loading 202 – Row 159

Row	Column	Cell Location	X, cm	Y, cm	Z, cm	Dose Rate, mrd/s ^a	σ_{stat} , %
159	48	JK	207.7987	157.4063	7.6200	0.9012	2.0
159	47	JK	202.2742	157.4063	7.6200	0.8750	2.0
159	46	JK	196.7497	157.4063	7.6200	0.8849	2.0
159	45	JK	191.2252	157.4063	7.6200	0.9346	2.0
159	44	JK	185.7007	157.4063	7.6200	0.8879	2.0
159	43	JK	180.1762	157.4063	7.6200	0.9650	2.0
159	42	JK	174.6517	157.4063	7.6200	0.9395	2.0
159	41	IJ	168.8097	157.4063	7.6200	1.1490	2.0
159	40	IJ	163.2852	157.4063	7.6200	1.1105	2.0
159	39	JK	158.0782	157.4063	7.6200	0.6374	2.0
159	38	JK	152.5537	157.4063	7.6200	0.5851	2.0
159	37	JK	147.0292	157.4063	7.6200	0.5660	2.0
159	36	HI	140.8697	157.4063	7.6200	0.7696	2.0
159	35	IJ	135.6627	157.4063	7.6200	0.9598	2.0
159	34	HI	129.8207	157.4063	7.6200	0.6101	2.0
159	33	IJ	124.6137	157.4063	7.6200	0.7167	2.0
159	32	HI	118.7717	157.4063	7.6200	0.4305	2.0
159	31	HI	113.2472	157.4063	7.6200	0.1527	2.0
159	30	HI	107.7227	157.4063	7.6200	0.0936	2.0
159	29	HI	102.1982	157.4063	7.6200	0.0690	2.0

- a. Dose rate is in units of millirads/second. The estimated reactor power is one watt.
- b. This is the statistical uncertainty in the TLD readout. The total uncertainty is determined in Section 3.

Table 2.8 Gamma Dose in ZPPR-15D Loading 202 – Column 48

Row	Column	Cell Location	X, cm	Y, cm	Z, cm	Dose Rate, mrd/s ^a	σ_{stat} , %
158	48	JK	207.7987	162.9308	7.6200	0.9362	2.0
157	48	JK	207.7987	168.4553	7.6200	0.8970	2.0
156	48	JK	207.7987	173.9798	7.6200	0.9166	2.0
155	48	JK	207.7987	179.5043	7.6200	0.8396	2.0
154	48	JK	207.7987	185.0288	7.6200	0.8438	2.0
153	48	JK	207.7987	190.5533	7.6200	0.8812	2.0
152	48	JK	207.7987	196.0778	7.6200	0.9457	2.0
151	48	IJ	207.4812	201.6023	7.6200	1.2120	2.0
150	48	IJ	207.4812	207.1268	7.6200	1.1500	2.0
149	48	JK	207.7987	212.6513	7.6200	0.6152	2.0
148	48	JK	207.7987	218.1758	7.6200	0.5387	2.0
147	48	JK	207.7987	223.7003	7.6200	0.5122	2.0
146	48	HI	207.1637	229.2248	7.6200	0.6924	2.0
145	48	IJ	207.4812	234.7493	7.6200	0.8809	2.0
144	48	HI	207.1637	240.2738	7.6200	0.5391	2.0
143	48	IJ	207.4812	245.7983	7.6200	0.7459	2.0
142	48	HI	207.1637	251.3228	7.6200	0.4249	2.0
141	48	HI	207.1637	256.8473	7.6200	0.1482	2.0
140	48	HI	207.1637	262.3718	7.6200	0.0972	2.0
139	48	HI	207.1637	267.8963	7.6200	0.0664	2.0

- Dose rate is in units of millirads/second. The estimated reactor power is one watt.
- This is the statistical uncertainty in the TLD readout. The total uncertainty is determined in Section 3.

There were strong heterogeneity effects in the ZPPR-15 drawers, so gamma dose distributions within drawer types were measured by placing multiple TLDs in drawers at several locations. Available reports do not list the locations for intra-drawer TLD measurements in ZPPR-15B. For ZPPR-15D L202, the intra-drawer measurements were performed at four locations in half 2. Table 2.9 gives the matrix locations and drawer masters for the intra-drawer TLD measurements in half 2 of ZPPR-15D L202.

**Table 2.9 Locations and Drawer Types for Intra-Cell Gamma Dose Measurements in ZPPR-15D
Loading 202**

Location	Drawer Master
256-48	15-0-941
251-48	15-0-940
248-48	15-0-942
246-48	15-0-939

Figure 2.4 shows the intra-drawer dose measurement in ZPPR-15B. Figure 2.5 shows the intra-drawer dose measurements in the double fuel column (DCF) drawers in ZPPR-15D; Figure 2.6 shows the intra-drawer dose measurements in the single fuel column (SCF) drawers in ZPPR-15D. Note that Figures 2.4 – 2.6 are the original figures produced by the ZPPR staff.

Figure 2.4 Intra-Drawer Gamma Dose Measurement in ZPPR-15B

Figure 2.5 Intra-Drawer Gamma Dose Distribution in ZPPR-15D – Double and Single Fuel Column Cells.

Figure 2.6 Intra-Drawer Gamma Dose Distribution in ZPPR-15D – Single Fuel Column Cells

3 TLD Uncertainties

Various uncertainties and corrections are relevant to determining the final measured dose rates and total uncertainties for the TLD measurements.

3.1 Correction for Non-Equilibrium Irradiation Conditions

In a real reactor application, the reactor is running at steady state for a prolonged period, and the quantity of interest is the gamma dose at selected locations under steady state irradiation conditions. In the ideal TLD experimental measurement in ZPPR, the TLDs would be inserted, irradiated and removed while ZPPR was operating at the desired power level under steady state conditions. This ideal TLD measurement was not possible at ZPPR.

Real TLD irradiations in ZPPR were necessarily performed under non-equilibrium conditions. The TLDs were inserted into ZPPR while the reactor was shut down. The reactor was brought to the desired power, and TLDs were irradiated for the desired time. In the ZPPR-15 TLD measurements, the integrated reactor power was approximately 300 watt-hours. The reactor was then shutdown, and the TLDs were removed after a 20-hour delay.

If the TLDs were removed from the reactor immediately after shutdown, they would miss the contribution from gammas produced by the decay of longer-lived fission products. The importance of leaving irradiated TLDs in the reactor for some time period after shutdown was measured in ZPPR and in ZPR-9.

In ZPPR-2 the E1 and E2 experiments were performed to measure the non-equilibrium effect. In the E1 experiment, the TLDs were removed 44 hours after shutdown. In the E2 experiment, the TLDs were removed 30 minutes after irradiation. The E1/E2 ratio was in the 1.05 – 1.10 range, depending upon the radial and axial position of the TLD in the assembly (Ref. 5, pp. 181 – 183).

The non-equilibrium effect was also measured in ZPR-9/27, the Fast Test Reactor – Engineering Mockup Critical (FTR-EMC) program in ZPR-9. TLDs were removed from the reactor in three batches at approximately 2.5 hours, 6.5 hours and 18 hours after irradiation. During the reactor run, an ionization chamber that was sensitive to gammas was located in the back drawer at matrix position S-17/18 [6]. The ionization chamber current was recorded on a strip chart recorder for the period before the run, during the run and for 16 hours after shutdown. The rate of gamma decay at the ionization chamber location was assumed to be representative of the remainder of the reactor. The strip chart recording was used to derive fractional corrections for the TLDs. The corrections for the three retrieval times were approximately 1.6% $\pm$ 0.3% for 2.5 h – 18 h, 1.0% $\pm$ 0.3% for 6.5 h – 18 h, and 0.5% $\pm$ 0.3% for 18 h – ∞ (Ref. 6, pp. 130 – 131).

The TLDs were removed from ZPPR-15 after 20 hours of post-irradiation decay in the reactor, so the uncertainty in the non-equilibrium correction for the ZPPR-15 TLD measurements is $\sim$ 0.3%.

One conclusion from the FTR-EMC experiments in ZPR-9 was that the background radiation contribution to the measured TLD dose prior to reactor startup was negligible. It is assumed that this conclusion is applicable to the TLD irradiations in ZPPR-15.

3.2 Correction for Shine

At the end of the TLD irradiation, the reactor was shut down, and the two halves of the reactor were separated. The TLDs remained in the reactor for approximately 20 hours prior to removal. The 20-hour post-shutdown residence corrected for the non-equilibrium irradiation conditions discussed in Section 3.1. In principle, this shutdown configuration also allowed TLDs in the low-flux regions in half 1 to be affected by shine from the high-flux region at the center of the core in half 2 since the TLDs were relatively close to the fronts of the drawers.

The shine effect was mitigated by the presence of the personnel shields placed between the two halves. The personnel shields were mounted on tracks and were placed between matrix halves after the halves were separated to reduce the dose received by personnel working on the machine (e.g. inserting or removing drawers when the reactor was shut down). The shield for each half in ZPR-9 was a 20.32 cm sandwich of steel, benelex, boral and lead which attenuated

post-irradiation gammas by a factor of approximately 15 – 20. The ZPPR personnel shields would have been at least as thick as the ZPR-9 shields because the larger cores in ZPPR would have resulted in larger doses than the doses received by personnel working between matrix halves of ZPR-9.

The contribution of shine was measured in the ZPR-9 FTR-EMC experiments. Background dosimeters were taped to the personnel shields and to various locations on the platform and matrix tubes to measure the effects of shine during the post-irradiation period before the TLDs were removed from the reactor. No consistent shine effect was measured in the FTR-EMC experiments [6]. The personnel shields mitigated the shine effect in ZPPR-15 in the same way that the ZPR-9 shields mitigated the shine effect in the FTR-EMC experiments, so there is no correction for shine and no associated uncertainty for the TLD measurements in ZPPR-15.

3.3 Correction for Electron Equilibrium Effects

The operation of a TLD is based on cavity ionization theory [3,4]. For gamma dose measurements in TLDs, one assumption of cavity ionization theory is that electron equilibrium is established. For electron equilibrium to be established, the amount of energy entering the cavity equals the amount of energy removed from the cavity. This means that each electron entering the cavity is balanced by another electron of approximately the same energy leaving the cavity.

The thickness of the capsule walls or sleeve surrounding the LiF is important. If the sleeve is too thick, scattering of the gamma flux introduces an unnecessary error. If the sleeve is too thin, the measured dose in the cavity will be lower than it would be if electron equilibrium existed. Theoretical and experimental studies were performed at Argonne to determine the preferred cavity wall material and corresponding wall thickness to establish electron equilibrium for use with the LiF thermoluminescent material. For LiF with a stainless steel sleeve, analysis of the FTR-EMC configuration in ZPR-9 led to the conclusion that the capsule sleeve thickness was sufficient to establish electron equilibrium and, consequently, that the measured dose in the TLD corresponds to the gamma ray energy deposited in a small stainless steel sample at the TLD location subject to gamma spectrum effects and fast neutron sensitivity to be discussed below. The FTR-EMC experiments were performed more than 10 years before ZPPR-15 was built, so it is reasonable to assume that the capsule and TLD designs were standardized at ZPPR by the mid-1980s.

3.4 Variation in Individual TLDs

The thermoluminescent materials were purchased from standard commercial suppliers. The initial thermoluminescent materials purchased for ZPPR operations in the early 1970s were 1 x 1 x 6 mm LiF rods, which had a one-sigma variation of ~5.8% in sensitivity to gamma irradiation due to normal variations in the manufacturing process. Testing of subsequent batches of rods showed intra-batch variations in sensitivity of 3.5% – 8% due to manufacturing variations.

In the early 1970s, ANL experimenters developed an intra-batch sensitivity selection method which significantly reduced the statistical variation in batches of TLDs used for experiments at ZPPR, ZPR-6 and ZPR-9. In this method, a purchase lot of TLD rods was divided into a number of individual batches. The second step was to inspect the TLD rods and to remove any over-sized or under-sized rods and any rods with visible chips or cracks. The remaining rods in each

batch were then exposed to a given gamma dose, measured and sorted according to sensitivity. The final set for each batch was obtained by removing any rods with sensitivities falling outside of a $\pm 5\%$ tolerance band about the average measured sensitivity for the batch.

At the end of the selection process, the intra-batch variation in sensitivity for a batch of TLD rods was reduced to $\sim 2.5\%$. It would have been possible to repeat the process to further reduce the variation, but available documents state that this was not done.

The one-sigma variation in sensitivity for a batch of TLDs is assumed to be 2.5% .

3.5 Calibration Uncertainty

For absolute gamma dose measurements, it was necessary to calibrate the TLDs by exposing at least a subset of them to a known gamma field. In a typical calibration procedure, a gamma source was suspended a fixed distance above a group of TLDs in a large high-bay building. The TLDs were suspended above ground level to reduce the problem of backscattered gammas. The TLDs were exposed to a fixed gamma dose, e.g., 30 rads, stored for 24 hours, and then read. This provided the calibration required for absolute gamma dose measurements. Relative or normalized gamma dose measurements would not require the calibration procedure.

The distance between the TLDs and the gamma source, the irradiation time, post-irradiation storage time and the readout procedure could be carefully controlled and generally made minor contributions to the calibration uncertainty. One uncertainty for the calibration measurements was the uncertainty in the gamma source strength. According to the available documents, the gamma source used at ZPPR was a 0.804 Curie ^{60}Co source. The uncertainty in the source strength for this source was listed as $\pm 2\%$ in available documents, so a calibration source uncertainty of 2% is assumed.

There are additional calibration uncertainties related to sample uniformity and to the readout procedure. The ZPPR staff assigned a 5% uncertainty to the ZPPR-2 TLD calibration data but did not quantify the individual components. The ZPR-9 staff also included a 5% uncertainty attributed to the sample uniformity and readout procedure without further quantifying those individual components [6]. The ZPPR staff later developed a method to reduce the variation in intra-batch sensitivity for a batch of TLD rods to approximately 2.5% , which would likely reduce the 5% uncertainty attributed to the sample uniformity and readout procedure.

Aside from any contribution from counting statistics, the uniformity of the calibration samples and the uncertainty related to the readout procedure are the principal components of the calibration data uncertainty. It is assumed here that the 5% uncertainty assigned to the ZPPR-2 TLD calibration data by the ZPPR staff refers to the same calibration uncertainty as the 5% uncertainty assigned to sample uniformity and readout procedure by the ZPR-9 staff.

Assuming a 5% uncertainty for the sample uniformity and readout procedure (calibration data) and a 2% uncertainty in the ^{60}Co source strength, the combined uncertainty is $\sim 5.39\%$. Reducing the variation in intra-batch sensitivity would reduce the total uncertainty below 5.39% , but the reduction cannot be quantified accurately since the contributions from the individual components are not known accurately.

A total calibration uncertainty of $\sim 5.4\%$ is assumed for this analysis.

3.6 Variations in Gamma Ray Spectrum

A TLD consists of a stainless steel capsule or sleeve ($Z \approx 26$) surrounding LiF ($Z \approx 8.2$) which does not represent a matched cavity dosimeter. Gamma ray energy absorption coefficients and mass stopping powers are different for the sleeve and cavity material (LiF). Both of these energy-dependent parameters can induce systematic errors whose magnitude depends upon the difference between the ^{60}Co spectrum used for calibration and the ZPPR assembly gamma ray spectrum, which depends strongly on the TLD location in the assembly.

Based upon theoretical and experimental work performed at ANL in the early 1970s, the maximum error due to the mismatch between the calibration spectrum and the local spectrum in the assembly was estimated to be $\pm 10\%$ in the fueled core region(s) where the gamma spectrum is relatively hard.

In the reflector region where the local gamma spectrum is much softer than the calibration spectrum, the measured dose was estimated to be less than the true dose by up to $30\% \pm 15\%$. The uncertainty in this value arises from the uncertainty in the calculated gamma spectrum in the reflector.

It is likely that the error in the blanket was intermediate between the error in the core and the error in the reflector/shield because the gamma spectrum softens gradually between the core and the shield.

These values were derived for the ZPR-9 FTR-EMC experiments [6], but the ZPR-9 FTR-EMC configurations are sufficiently similar to ZPPR-15 that these values should apply to the ZPPR-15 TLD measurements as well.

3.7 Dose-Response Curve and Dose Dependence

In the ideal case the dose-response curve is linear up to the saturation point at which all traps are filled. The response curve for LiF is linear up to 1000 rads; beyond 1000 rads the response is supralinear. The dose rate dependence at doses up to 10^{10} rad/sec is negligible according to observations (see Ref. 4, p. 174).

3.8 Reproducibility

Assessment by ANL experimenters in the early 1970s was that it is possible to obtain 2% – 3% reproducibility for a given dosimeter and from dosimeter to dosimeter within the same batch (see Ref. 4, pp. 174 – 175). No later assessments have been found, so reproducibility is assumed to be 3% for the ZPPR-15 shielding experiments.

3.9 Stability, Past History and Electronic Drift

LiF shows some evidence of fading over time; the amount of fading is less than 10% per month. It is possible to correct for this effect if the TLD readout always occurs at a fixed time after irradiation. Note that “read” and “readout” refer to measuring the photons emitted when the TLD is heated under controlled conditions after irradiation.

LiF response shows sensitivity to past irradiation history, particularly pre- and post-irradiation parameters. The LiF response decreases if the LiF has been exposed previously to irradiation greater than about 10^4 rads.

There could also be some drift in the electronics for long readout periods, but it was possible to correct for this drift. If reference TLDs are read out with the initial calibration data, interspersing readouts of the reference TLDs that were given comparable calibration doses on the day of the run with readouts from the TLDs irradiated in the subsequent experiment provides a correction for any electronic drift.

It is assumed that the experimenters corrected for the effects associated with stability, irradiation history and electronic drift because these effects were recognized by ANL experimenters in the early 1970s. The TLD measurements were performed in ZPPR-15 in 1985 and 1986.

3.10 Response to Fast Neutrons

TLDs are sensitive to both gammas and fast neutrons, so the dose measured by a TLD includes a contribution from fast neutrons [3,4,6]. Elastic scattering of fast neutrons in the TLD produces recoil nuclei, and slowing down of these recoil nuclei creates electron-hole pairs similar to those created by gamma interactions in the TLD. The net effect is that elastic scattering of fast neutrons contributes to the total number of filled electron or hole traps in LiF and, consequently, to the number and intensity of photons detected when the TLD is readout.

Any experimental determination of the magnitude of the neutron contribution is complicated for two reasons. First, the neutrons are always accompanied by gammas, and the gammas may make the dominant contribution to the TLD response. Second, the magnitude of the neutron contribution depends upon the neutron spectrum. The importance of the neutron contribution decreases as the neutron spectrum softens from the core to the reflector.

There were limited experimental and analytical studies of the fast neutron effect performed at ANL and elsewhere in the 1960s and early 1970s. The general conclusion of the reports produced at ANL at that time is that more work was needed, but there is no evidence that the fast neutron issue was studied in any detail at ANL after the early 1970s.

In a comparison of measured and calculated neutron contributions [7] to the measured dose, the calculated and measured curves had similar shapes, but the measured values were lower than the calculated values by an order of magnitude. The likely explanations of the reduced neutron contributions were a) reduced ability of low-energy recoil ions (nuclei) to produce ionization and b) the higher probability of recombination as the ionization density increases, which is a greater issue for the recoil ion produced by neutron scattering than for an electron produced by a gamma interaction. For the same dose produced by gammas and fast neutrons, the thermoluminescent output will be significantly greater for the gammas than for the neutrons.

The contribution of fast neutrons to the measured dose in TLDs was assessed for the FTR-EMC critical experiments in ZPR-9. Calculations indicated that the fast neutron contribution ranged from $10\% \pm 5\%$ of the observed dose at the center of the core to $0.5\% \pm 0.5\%$ in the shield for the FTR-EMC experiments [6]. The ZPPR staff reported that the neutron contribution for the ZPPR-15 experiments is approximately 20% of the measured dose and is a function of position.

3.11 Total Corrections and Uncertainty for ZPPR-15 TLD Measurements

Table 3.1 summarizes the corrections and uncertainties for the TLD measurements in ZPPR-15.

After discussion with a former ZPPR staff member [9], the measured doses listed in Tables 2.1 – 2.8 are believed to include all of the corrections listed in Table 3.1 except for the contribution from fast neutron sensitivity, i.e., the response to fast neutrons. The ZPPR-15 report listing the TLD measured values for ZPPR-15 explicitly states that the published values include both the gamma contribution and the neutron contribution.

The measured doses in Tables 2.1 – 2.8 include the fast neutron contribution. Based upon the assessment by the ZPPR staff, the correction for fast neutron sensitivity is -20.0% in the center of the core and -0.5% in the reflector. The correction in the outer core and blanket is probably between -5.0% and -10.0% with the correction decreasing for locations further from the core center. Determining a more precise value for the correction as a function of position is possible in principle but difficult in practice. Whether the effort to determine the fast neutron sensitivity correction is worthwhile depends upon the accuracy of shielding calculations in general. If shielding calculations are accurate to 10% – 20%, it might be worthwhile to attempt to determine the fast neutron correction more accurately. If the inherent accuracy of shielding calculations is in the 50% – 100% range, refining the fast neutron sensitivity correction slightly is likely not worth the effort.

Table 3.1 Corrections and Uncertainties for Gamma Dose Measurements in ZPPR-15

Source	Magnitude, %		Type	Location
	Correction	Uncertainty		
Statistical uncertainty in measurement	0.0	2.0	Random	Everywhere
Non-equilibrium irradiation conditions	0.5	0.3	Systematic	Everywhere
Shine	0.0	0.0		
Electron equilibrium effects	0.0	0.0		
TLD variation	0.0	2.5	Random	Everywhere
Calibration uncertainty	0.0	5.4	Systematic	Everywhere
Spectrum variation – core	0.0	10.0	Systematic	Core
Spectrum variation – blanket ^a		12.5	Systematic	Blanket
Spectrum variation – reflector and shield	30.0	15.0	Systematic	Reflector and shield
Dose response and dose dependence	0.0	0.0		
Reproducibility	0.0	3.0	Random	Everywhere
Stability/history/drift	0.0	0.0		
Fast neutron sensitivity – core	-20.0	5.0	Systematic	Core
Fast neutron sensitivity – blanket ^a		2.5	Systematic	Blanket
Fast neutron sensitivity – reflector and shield	-0.5	0.5	Systematic	Reflector and shield
Total – Core		13.2		
Total – Blanket		14.5		
Total – Reflector and Shield		16.5		

- a. Documents list values for the core and reflector but do not list explicit values for the blanket. The value for the blanket is assumed to be intermediate between the core and reflector values.

The uncertainties for individual TLD measurements must be combined correctly if the gamma doses are normalized to a specific measured value such as the largest value in a table. It is not valid to simply divide all of the measured values and uncertainties in a table by a selected reference value from that table because that selected reference value is itself uncertain. The correct procedure for determining the uncertainty for a normalized ratio is the following (see Ref. 8, Section V.E):

1. Consider x with uncertainty σ_x , y with uncertainty σ_y , and the desired ratio $R = x/y$.
2. Define $S_x = \sigma_x/x$, $S_y = \sigma_y/y$, and $S_R = \sigma_R/R$.
3. Then $S_R = \sqrt{(S_x)^2 + (S_y)^2}$

S_R is the correct relative uncertainty for any ratio such as normalization in which S_x and S_y are independent.

4 Gamma Dose Calculations

4.1 As-Built MCNP Models

As-built MCNP models have been created for the gamma dose measurements in ZPPR-15. However, it would be very difficult to calculate the gamma doses measured in ZPPR-15 by Monte Carlo. The actual TLDs are either 1 x 1 x 6 mm square rods or ~10 mm diameter x ~0.5 mm thick disks. Each individual TLD occupies a negligible fraction of the assembly volume, so very few neutrons or photons will encounter any given TLD during normal particle tracking. Consequently, the statistical uncertainties in TLDs will be very large for direct Monte Carlo calculations.

In ZPPR-15B L122 and L133, there were 23 TLDs in the outer core, radial blanket and shield on the left side of half 1 and 10 TLDs on the X-axis in the outer core, radial blanket and radial reflector on the right side of half 1. All TLDs in loadings 122 and 133 were located in row 159.

In ZPPR-15D L202, there were 20 TLDs placed in the core and radial blanket along row 159. In addition, TLD measurements were performed at 20 locations in the core along column 48 in ZPPR-15D L202.

In principle, it might be possible to use splitting/Russian roulette, weight windows and other variance reduction techniques to improve the Monte Carlo statistics for TLDs at one or two locations, but those variance reduction techniques will also make the Monte Carlo statistics worse at all other TLD locations.

Another problem with any direct Monte Carlo calculation of the TLD measurements is that the flux falls significantly between the inner core, radial blanket, radial reflector and shield, which exacerbates the problem of obtaining meaningful statistics for the TLD measurements.

The combination of the negligible volumes of individual TLDs, the large number of TLDs in the core and blanket, and the large reduction in flux between the inner core, radial blanket, radial reflector and shield makes any direct Monte Carlo calculation of the fluxes or reaction rates in the TLDs very difficult.

Monte Carlo calculations with point detectors and other next event estimators would also be very difficult for ZPPR-15 as-built models. Next event estimators can work well in models with large, homogeneous regions because it is relatively straightforward to compute the contribution to a next event estimator under those circumstances. However, as-built models of ZPPR-15 do not contain any large, homogeneous regions. Instead, each matrix tube in an as-built model contains many individual cells with thicknesses ranging from ~0.1 mm to ~10 mm, and there may be many matrix tubes between the location of the particle and the location of the next event estimator.

Consider a scattering event at point (x_1, y_1, z_1) and a point detector at point (x_2, y_2, z_2) . The point detector estimator assumes that after the collision at (x_1, y_1, z_1) the scattered particle travels directly to the point detector and makes a contribution to the point detector estimator score. This means it is necessary to compute the distance through every cell or region between (x_1, y_1, z_1) and (x_2, y_2, z_2) , to compute the appropriate cross section in each of those cells and then to compute the optical path length through each of those cells. This process is repeated for each point detector at each collision. For a few detectors in a model with large, homogeneous regions, next event estimators can work very well. For an as-built ZPPR-15 model with many

thousands of very small cells and many locations of interest, e.g., TLD locations, computing the TLD doses with next event estimators such as point detectors would require very large computer resources.

It is likely that the most practical way to perform meaningful calculations of the ZPPR-15 TLD measurements is to convert the as-built MCNP models of the TLD configurations to deterministic models for the calculations.

5 Summary

Stainless steel encapsulated LiF TLDs were irradiated in ZPPR-15B L115, ZPPR-15B L122, ZPPR-15B L133 and ZPPR-15D L202 to measure gamma doses at various locations in the core, radial blanket, radial reflector and simulated shield of ZPPR-15. These gamma dose measurements were described, and the measured gamma doses were provided.

In addition to the statistical uncertainty in the measurements, various corrections and other factors that contribute to the total uncertainty for the gamma dose measurements were discussed. All of the known contributions to the total uncertainty were detailed, and a total uncertainty was derived for the gamma dose measurements.

As-built MCNP models were created for the gamma dose measurements in ZPPR-15 loadings 115, 122, 133 and 202. Because each TLD occupies a negligible volume in a ZPPR-15 assembly, it is necessary to convert the MCNP models to deterministic models to compute meaningful gamma doses for comparison with the measured values.

6 References

1. R. M. Lell, M. A. Smith and Z. Zhong, "ZPPR-15 Criticality Measurements," Argonne National Laboratory, ANL-VTR-51, April 2020.
2. G. F. Knoll, Radiation Detection and Measurement, Third Edition, John Wiley & Sons, Inc., 2000.
3. T. J. Yule, "Evaluation of Thermoluminescent Materials and Techniques for Determining Gamma Heating in Fast Reactors," Applied Physics Division Annual Report, July 1, 1970 to June 30, 1971, Argonne National Laboratory, ANL-7910, January 1972.
4. G. G. Simons and T. J. Yule, "Gamma-Ray Heating Measurements in Zero-Power Fast Reactors with Thermoluminescent Dosimeters," Nuclear Science and Engineering, Vol. 53, pp. 162 – 175 (1974).
5. G. G. Simons and A. P. Olson, "Analyses and Measurements of Gamma-Ray Heating in the Demonstration Benchmark Plutonium-Fueled Critical Assembly," Nuclear Science and Engineering, Vol. 53, pp. 176 – 196 (1974).
6. G. S. Stanford, W. R. Robinson, G. G. Simons, T. J. Yule and T. S. Huntsman, "Gamma-Ray Heating by Thermoluminescent Dosimetry in FTR Engineering Mockup Shielding Experiment," Applied Physics Division Annual Report, July 1, 1971 to June 30, 1972, Argonne National Laboratory, ANL-8010, pp. 129 – 132.
7. C. L. Wingate, E. Tochilin and N. Goldstein, "Response of Lithium Fluoride to Neutrons and Charged Particles," Proc. Intern. Conf. Luminescence Dosimetry, Stanford University, 1965, U.S. Atomic Energy Commission, Division of Technical Information, 1967.
8. Yardley Beers, Introduction to the Theory of Error, Second Edition, Addison-Wesley Publishing Company, 1957.
9. R. W. Schaefer, Personal Communication.

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