ZPR-3 ASSEMBLY 59:
A CYLINDRICAL ASSEMBLY OF PLUTONIUM METAL AND GRAPHITE WITH A THICK LEAD REFLECTOR

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1.0 DETAILED DESCRIPTION

1.1 Overview of Experiments

Over a period of 30 years, more than a hundred Zero Power Reactor (ZPR) critical assemblies were constructed at Argonne National Laboratory. The ZPR facilities, ZPR-3, ZPR-6, ZPR-9 and ZPPR, were all fast critical assembly facilities. The ZPR critical assemblies were constructed to support fast reactor development, but data from some of these assemblies are also well suited for nuclear data validation and to form the basis for criticality safety benchmarks. A number of the Argonne ZPR/ZPPR critical assemblies have been evaluated as ICSBEP and IRPhEP benchmark experiments.

Of the three classes of ZPR assemblies, engineering mockups, engineering benchmarks and physics benchmarks, the last group tends to be most useful for criticality safety. Because physics benchmarks were designed to test fast reactor physics data and methods, they were as simple as possible in geometry and composition. The principal fissile species was ^{235}U or ^{239}Pu. Fuel enrichments ranged from 9% to 95%. Often there were only one or two main core diluent materials, such as aluminum, graphite, iron, sodium or stainless steel. The cores were reflected (and insulated from room return effects) by one or two layers of materials such as depleted uranium, lead or stainless steel. Despite their more complex nature, a small number of assemblies from the other two classes would make useful criticality safety benchmarks because they have features related to criticality safety issues, such as reflection by soil-like material.

ZPR-3 Assembly 58 (ZPR-3/58) was constructed to study a persistent discrepancy between calculated and measured central reactivity worths. Assembly 58 was followed by Assembly 59 which was a continuation of Assembly 58 with the depleted uranium reflector replaced by a lead reflector. Assemblies 58 and 59 were continuations of a series of benchmark physics assemblies (Assemblies 48, 49, 50, 53 and 54) with relatively simple core geometry and composition to facilitate analysis.

Lead was used as the reflector in ZPR-3/59 to completely eliminate ^{238}U from the assembly. Conversion of reactivity from the natural measurement units to units that can be compared to calculations, e.g., pcm, requires β_{eff}. In 1969 some measurements at Los Alamos had raised questions about the delayed neutron parameters for ^{238}U. Replacing the depleted uranium reflector in ZPR-3/58 with a lead reflector in ZPR-3/59 eliminated the ^{238}U delayed neutron data as a possible source of error for the discrepancy between calculated and measured central reactivity worths.

Loading of ZPR-3 Assembly 58 began in late October 1969. The last configuration in ZPR-3/58 was loaded in late November 1969 and was immediately followed by the transition to Assembly 59. The ZPR-3/59 core consisted of Pu-Al plates and graphite plates loaded into stainless steel drawers which were inserted into the central square stainless steel tubes of a 31 x 31 matrix on a split table machine. The core unit cell consisted of two columns of 0.125 in.-wide (3.175 mm) Pu-Al alloy plates and fourteen columns of 0.125 in.-wide graphite plates. The graphite plates were included to produce a softer neutron spectrum that would be more characteristic of a large power reactor.

The length of each fuel column was 11 in. (279.4 mm) in half 1 of the core and 9 in. (228.6 mm) in half 2. The core was followed by a 12 in. (304.8 mm) lead axial reflector in each half. The core asymmetry was driven by the fact that the lead used in the reflector in Assembly 59 was only available in 4 in. (101.6 mm) blocks and by the numbers of front drawers of different lengths in the ZPR-3 inventory. The average thickness of the lead radial reflector was approximately 13.5 in. (342.9 mm). The length of the radial reflector was 24 in. (609.6 mm) in half 1 and 20 in. (508.0 mm) in half 2. The assembly geometry approximated a right circular cylinder as closely as the square matrix tubes allowed.

According to the logbook, loading records for ZPR-3/59 and other internal documents, the reference critical configuration was loading 6 which achieved criticality on December 8, 1969. Subsequent loadings in the ZPR-3/59 program were very similar but less clean for criticality because there were modifications made to accommodate reactor physics measurements other than criticality. Accordingly, ZPR-3/59 loading 6 was selected as the only configuration for this benchmark. As documented below, it was determined to be acceptable as a criticality safety benchmark experiment.

For the ZPR-3/59 core plus radial and axial lead reflectors, 0.03% of the fissions occur in the thermal energy range, 52.26% of the fissions occur in the intermediate energy range, and 47.71% of the fissions occur in the fast energy range. Consequently, ZPR-3/59 is classed as intermediate spectrum with a significant fast component.

A very accurate transformation to a simplified model is needed to make any ZPR assembly a practical criticality safety benchmark. There is simply too much geometric detail in an exact (as-built) model of a ZPR assembly, even a clean core such as ZPR-3/59 loading 6. The transformation must reduce the detail to a practical level without masking any of the important features of the critical experiment. And it must do this without increasing the total uncertainty far beyond that of the original experiment. Such a transformation is described in Section 3. It was obtained using a pair of continuous-energy Monte Carlo calculations. First, the critical configuration was modeled in full detail – every plate, drawer, matrix tube, and air gap was modeled explicitly. Then the region-wise compositions and volumes from the detailed as-built model were used to construct a homogeneous, three-dimensional (XYZ) model of ZPR-3/59 that conserved the mass of each nuclide and volume of each region. The simple model is the criticality safety benchmark model. The difference in calculated k_{eff} values between the as-built three-dimensional model and the homogeneous RZ benchmark model was used to adjust the measured excess reactivity of ZPR-3/59 loading 6 to obtain the k_{eff} for the benchmark model. Uncertainties associated with this simplification, which go beyond Monte Carlo statistical uncertainties, were included in the k_{eff} uncertainty of the benchmark model. The net difference in k_{eff} and each of the effects that contributes to it are small.

1.2 Description of Experimental Configuration

A lot of details must be presented to describe precisely the as-built assembly. Also, it is useful to define some jargon (to be shown in italics) to facilitate the presentation. For those unfamiliar with ZPR assemblies, the task of absorbing this may be tedious if not a bit overwhelming. In fact, the task of modeling the exact plate-by-plate loading would be unreasonable to do by hand. In practice, the information contained in this section was accumulated in an electronic database and processed into models using computer programs. Readers interested only in using the benchmark model need not be concerned with any of these details, since Section 3 contains a complete specification of the criticality safety benchmark model.

1.2.1 The ZPR-3 Facility - The ZPR-3 fast critical facility was a horizontal split-table type machine consisting of a large, cast-steel bed supporting two tables or carriages, one stationary and the other movable. Details of the ZPR-3 facility are given in the hazard evaluation report for the facility.[a] A pictorial view of the ZPR-3 facility is shown in Figure 1-1. Each table was 100 in. (2.54 m)[b] wide and 67 in. (1.70 m) long. Stainless steel square tubes, nominally 2 in. (51 mm) on a side (inside dimension), 0.040 inches (1 mm) thick, and 33.5 in. (851 mm) long, were stacked horizontally on each table to form a 31-row and 31-column square "honeycomb" matrix. Each 31 x 31 array of matrix tubes was pressed tightly together and clamped in place on its table by steel structural members.

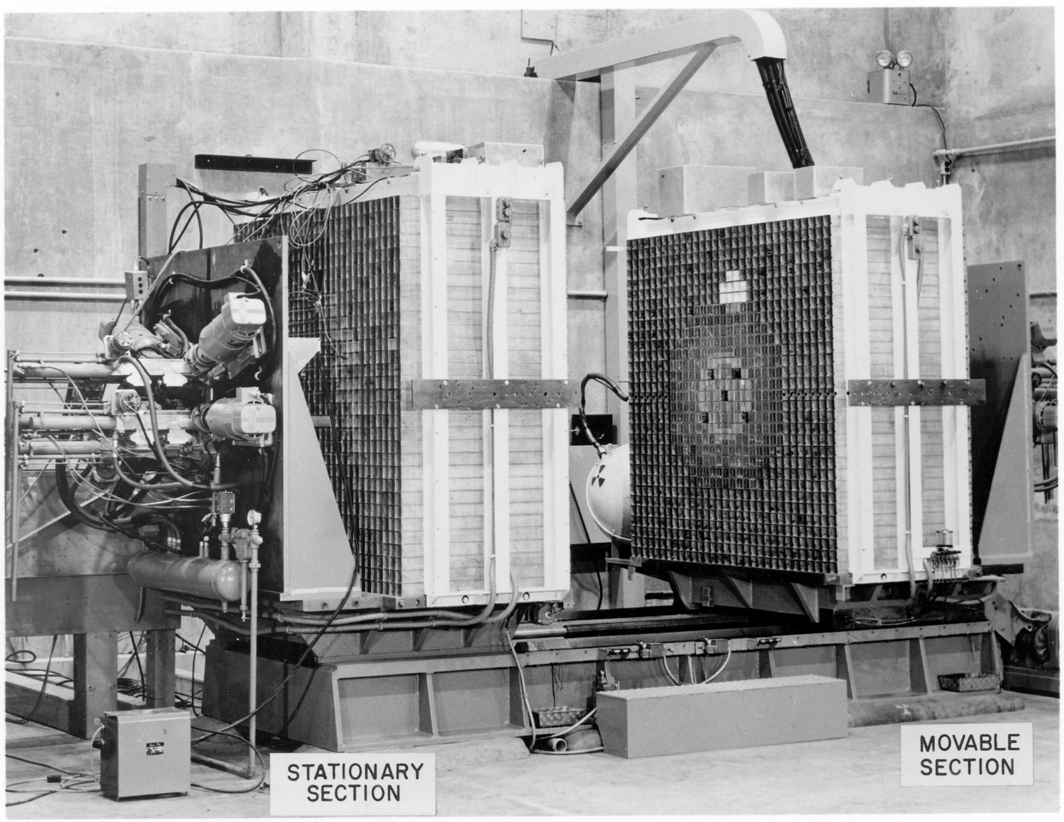

Figure 1-1. View of the ZPR-3 Facility.

The matrix pitch was measured in November 1959. The reported pitch values were 2.1835 in. (55.461 mm) in the horizontal direction and 2.1755 in. (55.258 mm) in the vertical direction.[c]

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[a] R. O. Brittan *et al*, "Hazard Evaluation Report on the Fast Reactor Zero Power Experiment ZPR-III," Argonne National Laboratory Report ANL-6408, October 1961.
[b] Almost all of the data sources give dimensions in English units and some also give metric equivalents. We display the metric equivalent in parentheses when practical, as a courtesy to international readers.
[c] L. H. Berkes, ZPR-3 Hot Constants Memo, March 31, 1960.

Except during reactor operation, the tables were separated by 5 feet (1.5 m). For reactor operation, the movable table was driven against the stationary table with a nut and lead screw mechanism, forming a cubical 31 x 31 matrix array, 67 inches (1.7 m) on a side.[a]

A *matrix position* is specified by three parameters: matrix half (S or M), row letter (A-Z and AA-EE starting from the top), and column number (1 – 31 starting from the left looking from the movable half towards the stationary half). For example, the central position in the movable half is M-P/16. Because column numbers for both halves start from the same side of the machine, the row and column numbers in the stationary and movable tables of the machine align when the tables are brought together. For example, the matrix positions designated as row N, column 15 in the stationary and movable halves (S-N/15 and M-N/15) are directly aligned when the movable table touches the stationary table.

The stationary and movable matrix halves are sometimes designated as half 1 and half 2, respectively, in ZPR documents. That convention is retained here.

During startup, a neutron source had to be present in each half of any ZPR-3 loading that did not contain an inherent source in the core (e.g., ^{240}Pu). Figure 1-1 provides a partial view of the movable half's spherical source pig (shielded container) and the source transport tube connecting the pig to matrix row P. The source pig is the light sphere at the lower center of Figure 1-1. It is between the movable half and the wall and is partially hidden by the movable half. There was a corresponding pig and tube for the stationary half. The safety documents, which were based on uranium fuel, required the presence of drawers in ZPR-3/59 that could accommodate a source tube.[b]

A steel back plate, roughly 30 inches (762 mm) behind the matrix tubes on each table, supported control rod drives. The drives were mounted on the outboard side of the plate and were connected to control rods by steel shafts that projected through holes in the plate.

ZPR-3 had no system to cool the matrix loading until plutonium fuel came into use. Then, because of the heat load that plutonium fuel presented, a rudimentary forced-air cooling system was devised. It consisted of a blower with filtered exhaust, hoses (similar to a clothes dryer exhaust hose) and two plena. The face of each plenum matched the stepwise-cylindrical outline of a matrix loading of core plus approximately one row of radial blanket. Except when back drawers were being loaded, one plenum covered the central portion of the back end of the movable half. A hose connected the plenum to the blower, which sucked air through the air gap between the top of each core drawer and the top of its matrix tube. When the matrix halves were closed, air was sucked from the back of the stationary half, through the core matrix tubes in both halves. When the halves were separated, the second plenum was attached temporarily to the interface side of the stationary-half matrix and this plenum was connected by a second hose to the single blower.[c]

A small number of thermocouples were in the ZPR-3 matrix to monitor the core temperature. Before plutonium fuel was used at ZPR-3, there was only one thermocouple per half. Five more thermocouples per half were added when plutonium fuel came into use. Each thermocouple, and its electrical lead, was installed in the small, axial interstitial gap that existed where the rounded corners of four matrix tubes met.[b] No record of the axial and radial locations of these thermocouples has been found. The logbook entries for critical configurations usually include measured temperatures. The logbook entries for critical ZPR-3/59 loadings list twelve temperatures which is consistent with six thermocouples per half.

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[a] Slight misalignment of the matrix bundles was unavoidable, resulting in a small (approximately 1 mm) gap at the interface when the tables were driven to the closed position.
[b] J. M. Gasidlo, Private Communication, April 2, 2009.
[c] J. M. Gasidlo, Private Communication, April 10, 2009.

The matrix machine was near (approximately 2 m from) a corner of a large cell (room), approximately 45 feet by 42 feet and 30 feet tall (14 × 13 × 9 m).

The desired average composition was achieved by loading the matrix with drawers containing rectangular plates of different materials such as plutonium, depleted uranium, graphite, etc. A specific plate-loading pattern in a drawer is called a *drawer master*. The plates were bare material or had a cladding or, in the case of uranium, may have had a protective coating. Figure 1-2 shows a matrix tube, drawer and related hardware. Figure 1-3 shows a typical loaded ZPR drawer although the drawer shown was not used in ZPR-3/59.

There were usually many plate sizes available for a given material and a limited number of plates of any one size. Consequently, there were often several drawer masters that had essentially the same composition, differing only in the plate sizes used. The number of similar drawer masters was increased by the fact that drawers for the stationary and movable halves had different (opposite, mirror image) drawer masters.

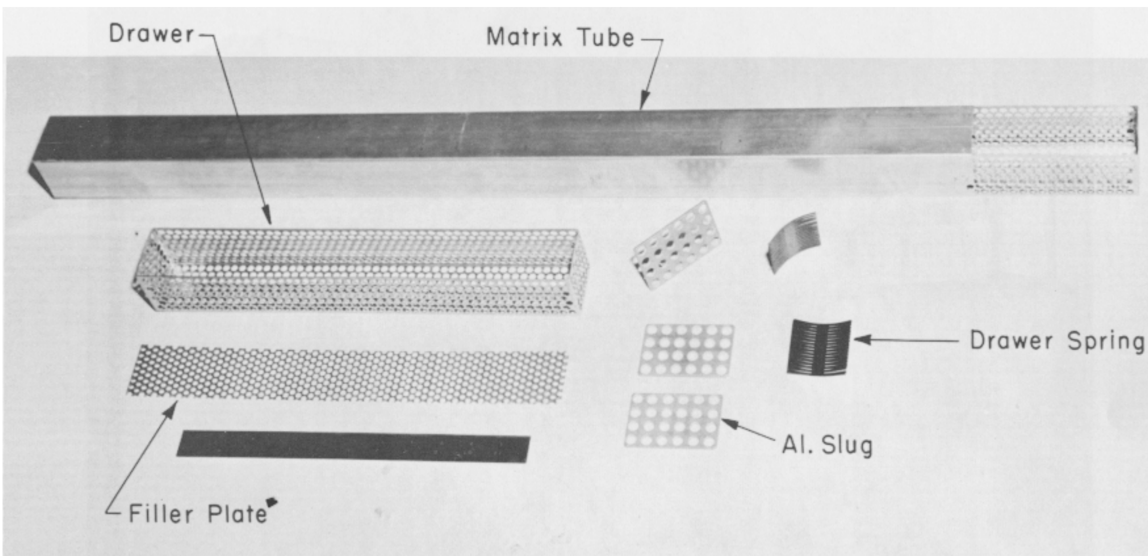

Figure 1-2. Typical ZPR-3 Drawer.

The specification of which drawer master was in each matrix position is known as a *matrix loading map*. In ZPR-3/59 a matrix position in the core region of half 1 had two drawers, a *front drawer* and a *back drawer.* The front drawers in half 1 were adjacent to the matrix interface between halves. A matrix position in the core region of half 2 only contained a front drawer because the front drawer was long enough to include the 9 in. core and the 12 in. axial reflector. The radial reflector was loaded directly into the matrix tubes except for the six drawers designed to accommodate a source tube and the three detector drawers in the radial reflector.

The ZPR-3 drawers themselves can be categorized as either normal drawers or control drawers. Each normal drawer had 2 inch-tall (51 mm) front, back, and side walls, and a 2 inch-wide bottom wall. Most normal drawers in the ZPR-3 inventory consisted of approximately 0.03-inch-thick (0.8-mm), highly perforated Type 304 stainless steel wall material. The rest of the normal drawers in the inventory had approximately 0.04-inch-thick unperforated aluminum walls. Each normal front drawer had a tab at the front edge of each side wall. There were corresponding notches in the side walls of the matrix tubes. The tabs fit in the notches to provide positive seating of the drawer in the tube, with the front of the drawer flush with the front of the matrix tube. Each normal back drawer had a handle extending from its back wall, which allowed the drawer to be extracted from the back of the matrix tube.

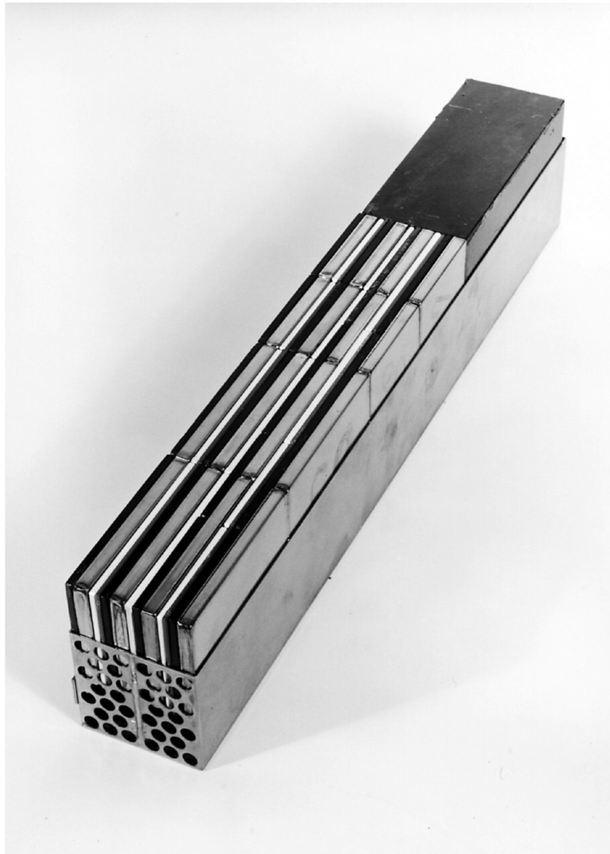

Figure 3. Typical Loaded ZPR Drawer.[a]

All drawers used in ZPR-3/58 and ZPR-3/59 were stainless steel drawers. Figure 1-2 shows a perforated drawer. Drawings of the drawers in the ZPR-3 inventory are not available. The ZPR-3 staff did not record any details regarding those drawers except the dimensions and masses of the drawer components (front plate, back plate, bottom and sides) in available records because such details were far beyond their needs or the needs of analysts of that era. The masses of the drawer components include the effects of perforations as well as the tabs on the front drawers which matched the notches in the matrix tubes.

The only type of operational control rod used in ZPR-3 was the *dual-purpose* (DP) control rod, so-called because it was a drawer that contained a core unit cell that could be driven in and out along a matrix tube to adjust reactivity. For ZPR-3/59, there were five DP rods in each half. Four DP rods per half were designated as safety rods, and the remaining DP rod per half was used as a control rod.

The control drawer itself was basically like a normal drawer but had some special features. Because the DP control drawer had to be strong enough to undergo rapid acceleration and deceleration, it was made of unperforated Type 304 stainless steel with twice the wall thickness (0.063 in. = 1.6 mm) of normal-drawer walls. To minimize the possibility of a DP drawer binding in the matrix tube through which it moved, the DP drawer width was made 0.063 in. (1.6 mm) less than that of a normal drawer. A consequence of these two design features was that the width of the plate loading had to be 1/8 inch (3.2 mm) less than the normal 2-inch wide (51 mm) plate loading. Only fifteen 1/8 in. plate columns could be loaded into a DP drawer. To act as a

[a] The plates are elevated above the bottom of the drawer in this photograph.

single rigid body, a DP drawer not only had to be thick walled, it had to be at least as long as the combination of a normal front drawer and back drawer. The DP drawer's nominal length was 32 inches (813 mm) which is nearly as long as that of a matrix tube. Finally, the design included a wall at 15 ¼ in. dividing the drawer into front and back compartments. This helped stiffen the drawer, but more importantly, it allowed the drawer's plate loading to be locked in place more effectively, with springs inserted at the back of each compartment.[a]

The full details of a ZPR-3 loading are not contained in published reports because of their complexity. Instead, it was usual to give details of a representative drawer master for each region, the matrix loading map in terms of representative drawer masters, and the average composition for each material region. However, the detailed description of ZPR-3/59 was archived in loading records.

1.2.2 The Matrix and Drawer Loading Data - Figures 1-4 and 1-5 are matrix loading diagrams for the stationary half and movable half, respectively, of the reference ZPR-3/59 critical core configuration. Note that matrix column 1 is on the left side of Figure1-4 but on the right side of Figure 1-5. This implies that the views are looking from the matrix interface towards the half being shown. These are the views fuel handlers had when installing front drawers into the matrix. The nearly cylindrical boundaries of the core and radial reflector regions are shown.

Some of the matrix tubes in row P contained a small hole in the side walls through which a source tube could pass. In cases where the source tube was required, the plate loadings in the source tube locations were adjusted to make space for the source tube. Safety documents required the presence of the source tube drawers, which had side wall holes aligning with the matrix tube side wall holes, even if an external neutron source was not needed. ZPR-3/59 was such a case, since the ^{240}Pu in its fuel plates provided an inherent neutron source. In ZPR-3/59, the source drawers were present in the six matrix locations 1-P-24, 1-P-25, 1-P-26, 2-P-24, 2-P-25 and 2-P-26. Note that 1-P-24 is equivalent to S-P/24 and 2-P-24 is equivalent to M-P/24. The original loading records for ZPR-3/59 used the 1-P-24 convention for identifying matrix positions.

The source drawers are designated by "201" in Figures 1-4 and 1-5. The drawers designated by "203" and "205" in Figures 1-4 and 1-5 were detector drawers. There was a one inch square channel in the axial direction to accommodate a detector in each detector drawer. The drawer master figures show the channel, but they do not show any details of the actual detector in the channel.

In order for the drawer master numbers to remain legible in Figures 1-4 and 1-5, these figures only show the last part of the drawer master identifier. The full identifier for drawer master 100 in Figure 1-4 is 59-1-100, and the full identifier for drawer master 100 in Figure 1-5 is 59-2-100. In the general case, a drawer master identifier for ZPR-3/59 would be 59-x-yyy. The first part of the identifier, 59, designates the assembly. The second part of the identifier, x, is 1 for half 1 and 2 for half 2. The third part of the identifier, yyy, designates the specific plate loading pattern for that drawer master.

Drawer masters 59-1-203 and 59-1-205 in Figure 1-4 and drawer master 59-2-205 in Figure 1-5 were detector drawers. The loading records clearly show the detector drawers in matrix positions 1-A-1 (Figure 1-4) and 2-EE-1 (Figure 1-5). Drawer master 59-1-401 in matrix position 1-U-16 was a DP control drawer that contained radial reflector material rather than core material.

The matrix tube array was 31 x 31. The dimensions of each unit cell, i.e., matrix position, in the array in Figures 1-4 and 1-5 are 2.1835 in. x 2.1755 in.

[a] J. M. Gasidlo, Private Communication, April 7, 2009.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
A	205																														
B																															
C																															
D																															
E																															
F													200	200	200	200	200	200	200												
G											200	200	200	200	200	200	200	200	200	200	200										
H										200	200	200	200	200	200	200	200	200	200	200	200	200									
I									200	200	200	200	200	200	200	200	200	200	200	200	200	200	200								
J								200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200							
K							200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200						
L							200	200	200	200	200	200	200	200	100	100	102	200	200	200	200	200	200	200	200						
M						200	200	200	200	200	200	200	102	100	100	100	100	100	200	200	200	200	200	200	200	200					
N						200	200	200	200	200	200	200	400	100	100	100	100	100	400	200	200	200	200	200	200	200					
O						200	200	200	200	200	200	102	100	100	100	100	100	100	100	102	200	200	200	200	200	200					
P						200	200	200	200	200	200	100	100	100	100	100	100	100	100	100	200	200	200	201	201	201					
Q						200	200	200	200	200	200	100	100	100	100	100	100	100	100	102	200	200	200	200	200	200					
R						200	200	200	200	200	200	200	400	100	100	100	100	100	400	200	200	200	200	203	200	200					
S						200	200	200	200	200	200	200	200	100	100	100	100	100	200	200	200	200	200	200	200	200					
T							200	200	200	200	200	200	200	200	102	100	102	200	200	200	200	200	200	200	200						
U							200	200	200	200	200	200	200	200	200	401	200	200	200	200	200	200	200	200	200						
V								200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200							
W									200	200	200	200	200	200	200	200	200	200	200	200	200	200	200								
X										200	200	200	200	200	200	200	200	200	200	200	200	200									
Y											200	200	200	200	200	200	200	200	200	200	200										
Z													200	200	200	200	200	200	200												
AA																															
BB																															
CC																															
DD																															
EE																															

Figure 1-4. ZPR-3/59 Loading 6 Core Layout – Half 1 (Stationary Half).

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
A																															
B																															
C																															
D																															
E																															
F													200	200	200	200	200	200	200												
G											200	200	200	200	200	200	200	200	200	200	200										
H										200	200	200	200	200	200	200	200	200	200	200	200	200									
I									200	200	200	200	200	200	200	200	200	200	200	200	200	200	200								
J								200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200							
K							200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200						
L							200	200	200	200	200	200	200	200	102	100	100	200	200	200	200	200	200	200	200						
M						200	200	200	200	200	200	200	200	100	100	100	100	100	102	200	200	200	200	200	200	200					
N						200	200	200	200	200	200	200	400	100	100	100	100	100	400	200	200	200	200	200	200	200					
O						200	200	200	200	200	200	100	100	100	100	100	100	100	100	102	200	200	200	200	200	200					
P						201	201	201	200	200	200	100	100	100	100	100	100	100	100	100	200	200	200	200	200	200					
Q						200	200	200	200	200	200	102	100	100	100	100	100	100	100	100	200	200	200	200	200	200					
R						200	200	200	200	200	200	200	400	100	100	100	100	100	400	200	200	200	200	200	200	200					
S						200	200	200	200	200	200	200	103	100	100	100	100	100	200	200	200	200	200	200	200	200					
T							200	200	200	200	200	200	200	200	102	400	102	200	200	200	200	200	200	200	200						
U							200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200						
V								200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200							
W									200	200	200	200	200	200	200	200	200	200	200	200	200	200	200								
X										200	200	200	200	200	200	200	200	200	200	200	200	200									
Y											200	200	200	200	200	200	200	200	200	200	200										
Z													200	200	200	200	200	200	200												
AA																															
BB																															
CC																															
DD																															
EE																															205

Figure 1-5. ZPR-3/59 Loading 6 Core Layout – Half 2 (Movable Half).

ZPR-3/58 (PU-MET-INTER-003) and ZPR-3/59 (PU-MET-INTER-004) were companion assemblies. The core unit cell and core compositions are essentially identical in these two assemblies. The thick depleted uranium radial and axial reflectors in ZPR-3/58 were replaced by thick lead radial and axial reflectors in ZPR-3/59. Table 1.1 shows a comparison of some of the key parameters in these two assemblies.

Table 1.1. Comparison of ZPR-3/58 and ZPR-3/59 Core and Reflector Parameters

Parameter	ZPR-3/58	ZPR-3/59
Number of fueled drawers	156	117
Number of reflector drawers	542	580
Reflector	Depleted uranium	Lead
Number of 1/8x2x1 in. PANN[(a)] plates	329	309
Number of 1/8x2x2 in. PANNplates	416	411
Number of 1/8x2x3 in. PANNplates	337	309
Number of 1/8x2x1 in. PANI plates	129	40
Number of 1/8x2x2 in. PANI plates	243	54
Number of 1/8x2x3 in. PANI plates	111	41
Mass of ^{239}Pu + ^{241}Pu, kg	101.833	76.054
Core radius, cm	27.5843	23.8325
Core height, cm	50.9684	50.9697
Core volume, liters	121.836	90.950
Reflector volume, liters	1073.307	1103.547

(a) There were two types of Pu-Al plates. Pu-Al No Nickel (PANN) plates did not have a nickel coating on the Pu-Al fuel meat. Pu-Al NIckel (PANI) plates did have a nickel coating on the Pu-Al fuel meat. Both types of Pu-Al plates had stainless steel cladding.

Figure 1-6 shows the predominant stationary-half (half 1) normal core drawer master (59-1-100) used in ZPR-3/59 loading 6 matrix positions. The numbers in the drawer master descriptions indicate the dimensions in inches. Figure 1-7 shows the predominant movable half (half 2) drawer master (59-2-100) used in loading 6. The normal front drawers used in half 1 were ~15 in. (381 mm) long, and the normal front drawers used in half 2 were ~21 in. (533.4 mm) long. With the exceptions of the source drawers, the detector drawer (59-1-205) in 1-A-1, the detector drawer (59-1-203) in 1-R-24 and the detector drawer (59-2-205) in 2-EE-1, each of the radial blanket matrix positions in both matrix halves consisted of lead blocks loaded directly into the matrix tube.

For the loading 6 core region in the movable half (half 2), there were drawer masters analogous to those shown in half 1. The half 2 drawer masters are the mirror images, reflected about the X=1.0 plane, of their corresponding stationary-half drawer masters. This resulted in like columns of plates aligning when the two halves of the matrix were brought together. Any given drawer master, and the matrix loading maps depicted in Figures 1-4 and 1-5, show the view from the matrix interface towards the matrix half being described, implying that columns that physically align across the halves when the matrix is closed are on opposite sides (in the X-direction) in these masters and maps.

The drawer itself is not shown in any of the drawer masters.

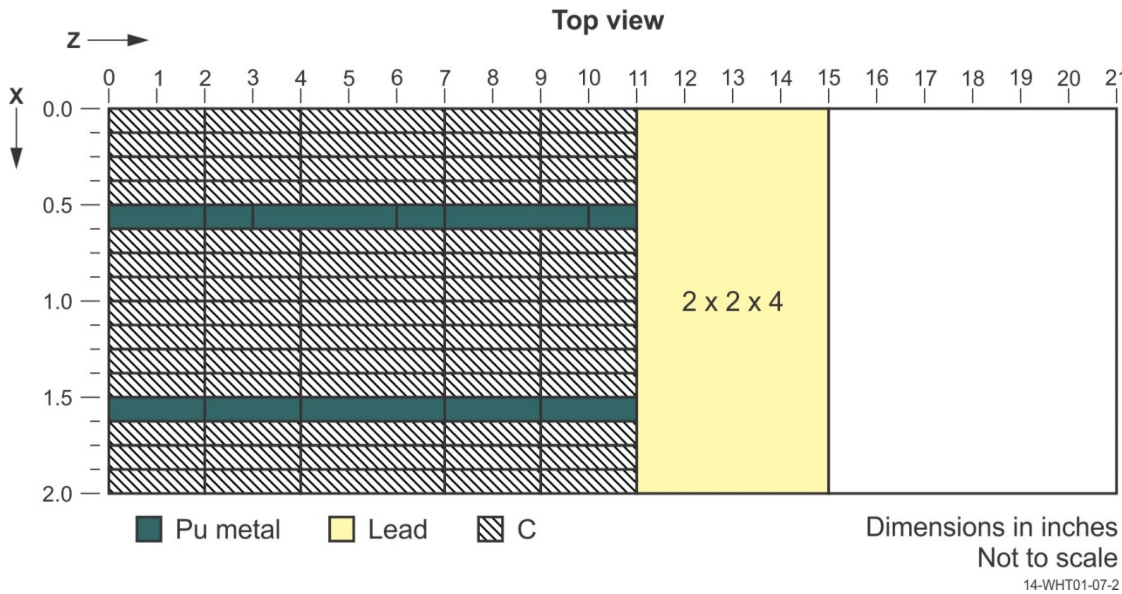

Figure 1-6. Loading Pattern for ZPR-3/59 Normal Core Drawer Master 59-1-100.

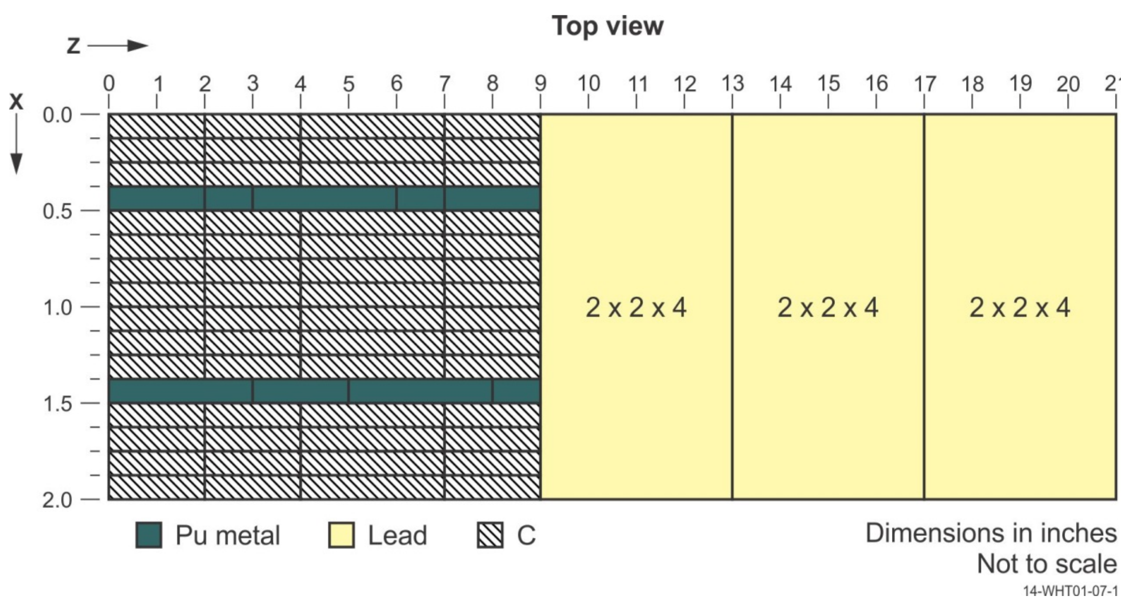

Figure 1-7. Loading Pattern for ZPR-3/59 Normal Drawer Master 59-2-100.

Figures 1-8 – 1-11 show different views of the matrix tube.

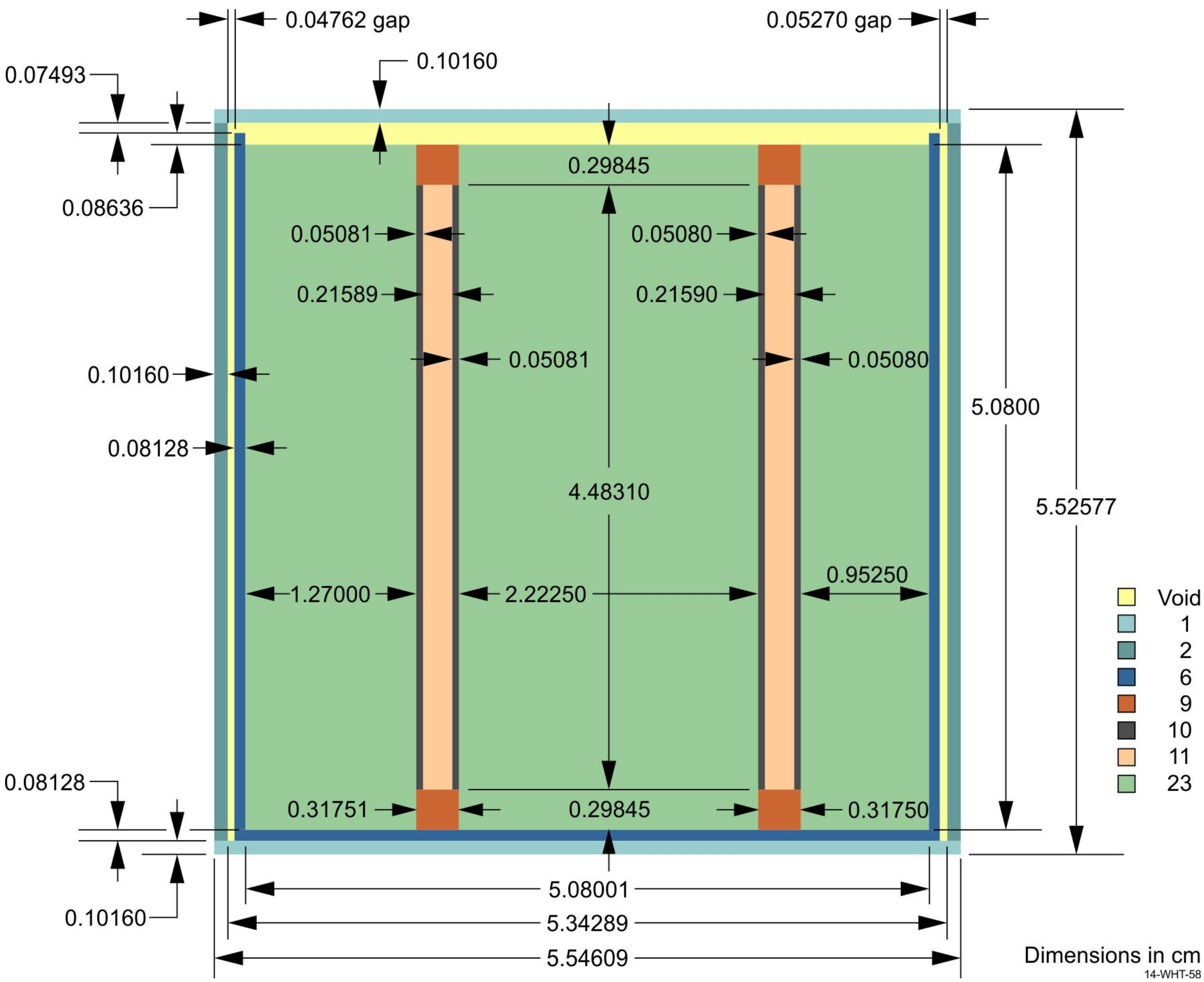

Figure 1-8. Cross-Sectional View of Core Drawer and Matrix Tube.

Figure 1-8 shows a cross-sectional (X-Y) view of a core drawer and matrix tube. The dimensions in Figure 1-8 are centimeters. The color code on the right side of Figure 1-8 corresponds to the following materials:

1. Top and bottom of matrix tube.
2. Sides of matrix tube. Because of the notches in the first inch of the sides of the matrix tubes to accommodate the drawer tabs, the composition of the first inch of the top and bottom of the matrix tube differed from the composition of the first inch of the sides of the matrix tube. After the first inch, the same composition applies to all four sides of the matrix tube.
6. Drawer sides and bottom.
9. Clad on the top and bottom of the Pu-Al plates.
10. Clad on the sides of the Pu-Al plates.
11. Pu-Al fuel meat.
23. Graphite plates.

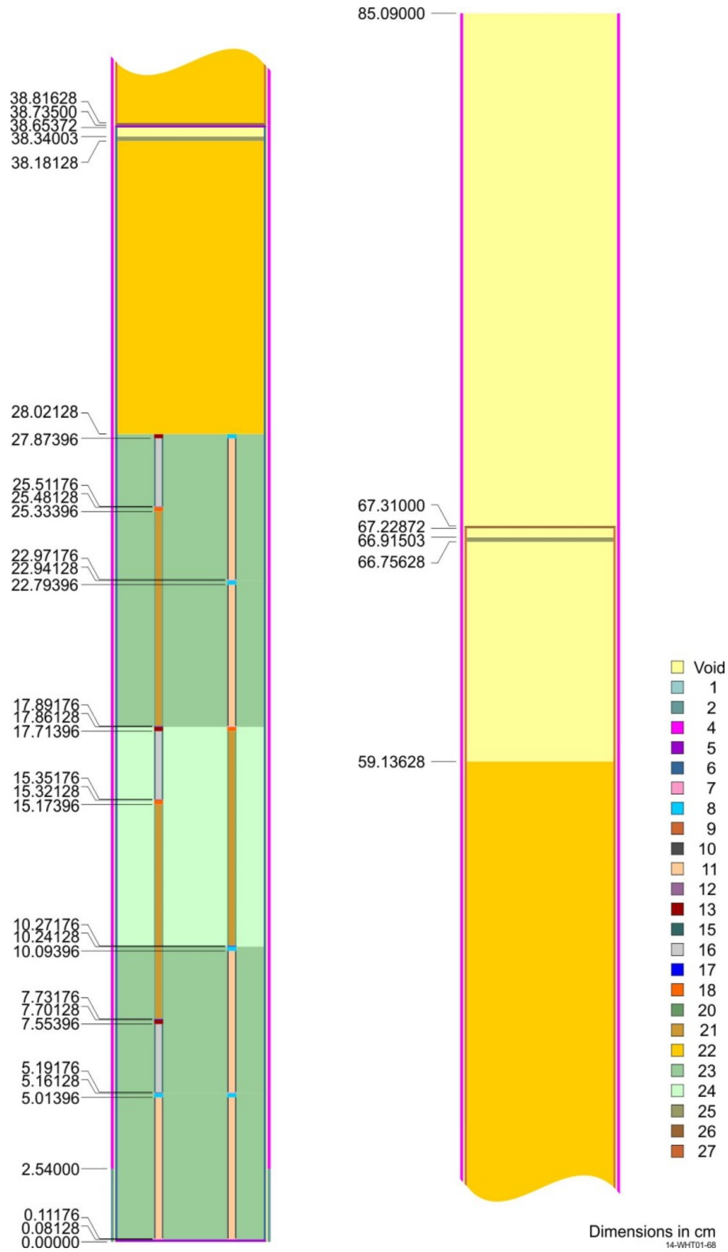

Figure 1-9. Axial View of Core Drawer and Matrix Tube.

Figure 1-9 shows an axial (X-Z) view of a core drawer and matrix tube. The dimensions in Figure 1-9 are centimeters. The color code on the right side of Figure 1-9 corresponds to the following materials:

1. First inch of matrix tube.
2. First inch of matrix tube.
4. Matrix tube beyond first inch.
5. Front and back plates of front drawer.
6. Bottom and sides of front drawer.
7. Clad for 1/8x2x2 in. PANN Pu-Al plate.

8. Clad for 1/8x2x2 in. PANN Pu-Al plate.
9. Clad for 1/8x2x2 in. PANN Pu-Al plate.
10. Clad for 1/8x2x2 in. PANN Pu-Al plate.
11. Pu-Al fuel meat for 1/8x2x2 in. PANN Pu-Al plate.
12. Clad for 1/8x2x1 in. PANN Pu-Al plate.
13. Clad for 1/8x2x1 in. PANN Pu-Al plate.
14. Clad for 1/8x2x1 in. PANN Pu-Al plate.
15. Clad for 1/8x2x1 in. PANN Pu-Al plate.
16. Pu-Al fuel meat for 1/8x2x1 in. PANN Pu-Al plate.
17. Clad for 1/8x2x3 in. PANN Pu-Al plate.
18. Clad for 1/8x2x3 in. PANN Pu-Al plate.
19. Clad for 1/8x2x3 in. PANN Pu-Al plate.
20. Clad for 1/8x2x3 in. PANN Pu-Al plate.
21. Pu-Al fuel meat for 1/8x2x3 in. PANN Pu-Al plate.
22. Lead plate.
23. ZPR-3 graphite plate.
24. ZPR-3 graphite plate.
25. Spring at back of drawer.
26. Front and back plates of back drawer.
27. Bottom and sides of back drawer.

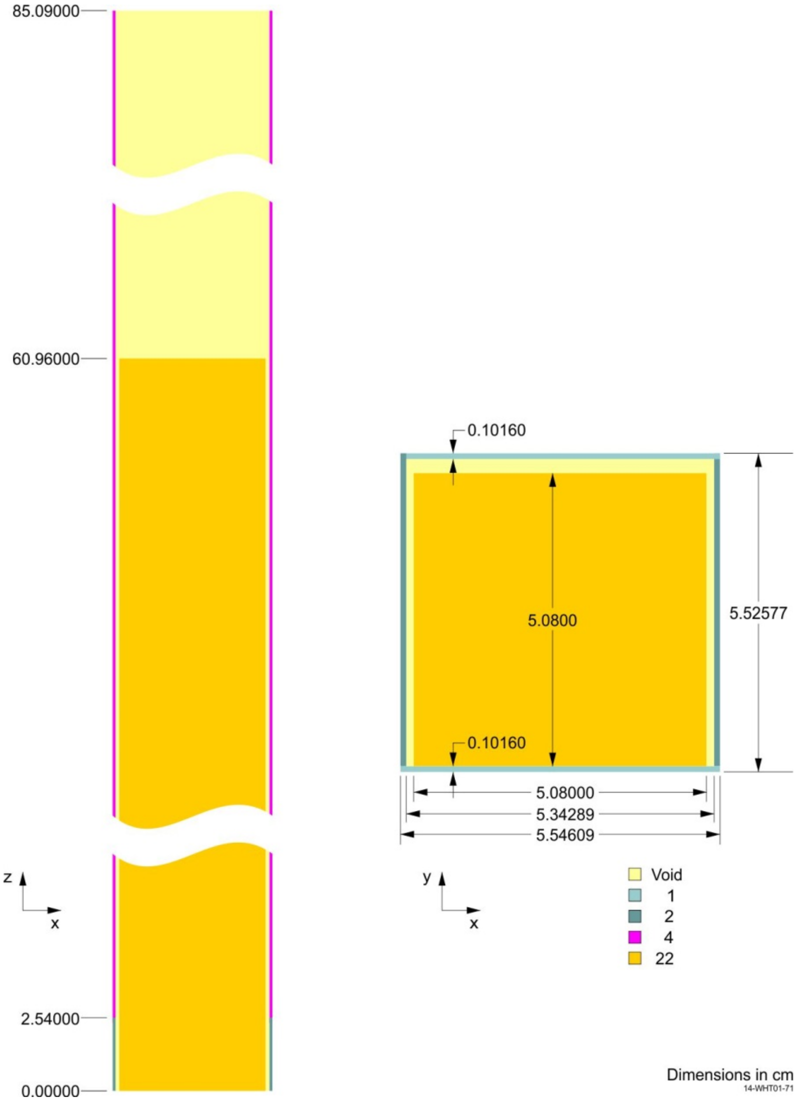

Figure 1-10. Lead Block in Matrix Tube.

Figure 1-10 shows a lead reflector block loaded directly into a matrix tube. The dimensions in Figure 1-10 are centimeters. The color code on the right side of Figure 1-10 corresponds to the following materials:

1. First inch of matrix tube.
2. First inch of matrix tube.
4. Matrix tube beyond first inch.
22. Lead plate.

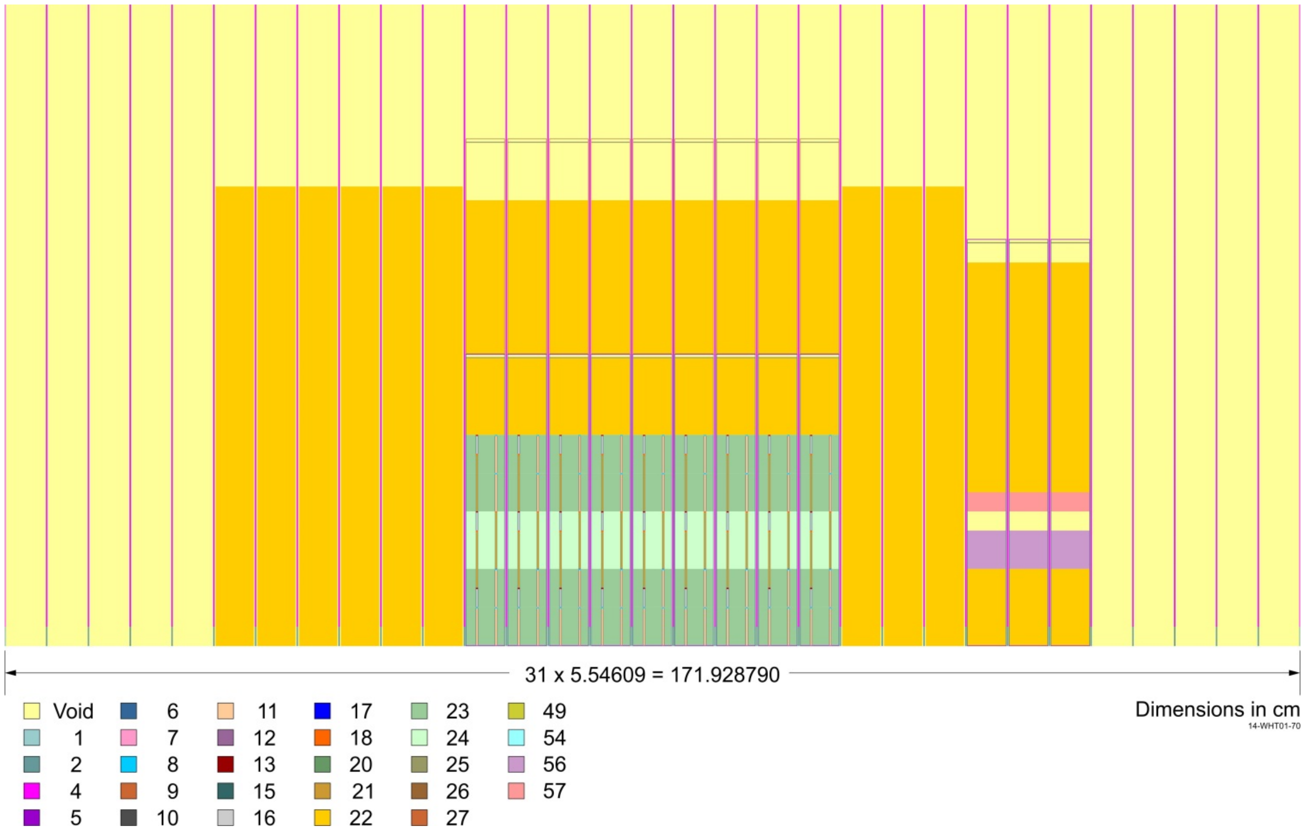

Figure 1-11. Axial View of Core.

Figure 1-11 shows an axial (X-Z) view of half 1 of the core. The outermost three drawers in the radial reflector on the right side of the core are the source drawers in row P. The color code below Figure 1-11 corresponds to the following materials:

1. First inch of matrix tube.
2. First inch of matrix tube.
4. Matrix tube beyond first inch.
5. Front and back plates of front drawer.
6. Bottom and sides of front drawer.
7. Clad for 1/8x2x2 in. PANN Pu-Al plate.
8. Clad for 1/8x2x2 in. PANN Pu-Al plate.
9. Clad for 1/8x2x2 in. PANN Pu-Al plate.
10. Clad for 1/8x2x2 in. PANN Pu-Al plate.
11. Pu-Al fuel meat for 1/8x2x2 in. PANN Pu-Al plate.
12. Clad for 1/8x2x1 in. PANN Pu-Al plate.
13. Clad for 1/8x2x1 in. PANN Pu-Al plate.
14. Clad for 1/8x2x1 in. PANN Pu-Al plate.
15. Clad for 1/8x2x1 in. PANN Pu-Al plate.
16. Pu-Al fuel meat for 1/8x2x1 in. PANN Pu-Al plate.
17. Clad for 1/8x2x3 in. PANN Pu-Al plate.
18. Clad for 1/8x2x3 in. PANN Pu-Al plate.
19. Clad for 1/8x2x3 in. PANN Pu-Al plate.
20. Clad for 1/8x2x3 in. PANN Pu-Al plate.

21. Pu-Al fuel meat for 1/8x2x3 in. PANN Pu-Al plate.
22. Lead plate.
23. ZPR-3 graphite plate.
24. ZPR-3 graphite plate.
25. Spring at back of drawer.
26. Front and back plates of back drawer.
27. Bottom and sides of back drawer.
49. Steel drawer component.
54. Aluminum plate.
56. Lead plates.
57. Lead plates.

It should be noted that Figures 1-8, 1-9, 1-10 and 1-11 were derived from the as-built model of ZPR-3/59 loading 6. They are included here to clarify the core geometry. The numbers for the color code are the relevant material numbers for that model and correspond to the materials that were in the corresponding locations in ZPR-3/59 loading 6. Some Pu-Al clad numbers are listed for completeness although they do not show up in the views shown in these figures.

Detailed matrix loading maps for the stationary and movable halves of ZPR-3/59 loading 6 are shown in Figures 1-4 and 1-5. More precisely, Figures 1-4 and 1-5 show the front drawer matrix loadings, respectively, for half 1 and half 2. There was a back drawer behind each normal core drawer in half 1. It is believed that an "axial reflector" back drawer would have been placed behind each radial reflector source drawer in half 1 to make the radial reflector loading nominally the same length as that in a normal radial reflector position. The lack of available loading records indicating this was done is not considered a contra-indication, since record keeping for back drawers was not rigorous.

There were no back drawers behind the DP control rods, the detector drawers, the source tube drawers in half 2 or any of the core drawers in half 2. The DP control rod drawer was long enough to accommodate both the core and the full length of the axial reflector, and a shaft connects the back of the DP drawer to the control rod drive, so there were no back drawers behind the DP drawers. The cables that project from the backs of the detector drawers preclude back drawers in the detector locations, and the core drawers and source tube drawers in half 2 were long enough to contain either the core plus axial reflector or the radial reflector.

The lead blocks in the radial reflector were loaded directly into the matrix tubes without drawers, so there were no back drawers in the radial reflector except for the source tube locations. The exterior dimensions of a matrix tube were 2.1835 in. x 2.1755 in., and the matrix tube thickness was 0.040 in. Consequently, the interior dimensions of the matrix tube were 2.1035 in. x 2.0955 in. For a 2 in. x 2 in. lead block in the matrix tube, the nominal air gap between the block and the inner wall of the matrix tube would be 0.05175 in., and the nominal air gap between the top of the block and the interior surface of the top of the matrix tube would have been 0.0955 in.

The front drawer lengths in half 1 and half 2 were 15.25 in. and 21.25 in., respectively. The length of the back drawers used behind core drawers in half 1 and behind source tube drawers was 11.25 in.

Table 1.2 and Table B.1 in Appendix B are used to define completely the drawer masters used in ZPR-3/59 loading 6. Table 1.2 and Table B.1 give the multi-character drawer master identifiers that appear on the archived drawer master diagrams. Table 1.2 also gives the role of the drawer master, the length of the drawer into which the plates were loaded, and how many matrix positions had the drawer master in ZPR-3/59 loading 6. Drawers of lengths 15.25 in. and 21.25 in. are front drawers, while drawers of length 11.25 in. are back drawers. The "partial" designation for drawer master 59-2-103 means that drawer contained half core material and half radial reflector material in the core axial region.

Table 1.2. Drawer Identification and Type Data.

Drawer Master Identifier	Role of Drawer	Drawer Length (inches)	Number in ZPR-3/59 Loading 6
59-1-100	Normal Core	15.25	47
59-2-100	Normal Core	21.25	47
59-1-102	Normal Core	15.25	7
59-2-102	Normal Core	21.25	6
59-2-103	Normal Core (Partial)	21.25	1
59-1-400	DP Control Rod-Core	32.50	4
59-1-401	DP Control Rod-Radial Reflector	32.50	1
59-2-400	DP Control Rod-Core	32.50	5
59-1-200	Radial Reflector	24.00[(a)]	286
59-2-200	Radial Reflector	20.00[(a)]	287
59-1-201	Radial Reflector-Source Drawer	15.25	3
59-2-201	Radial Reflector-Source Drawer	21.25	3
59-1-203	Radial Reflector-BF_3 Counter	21.25	1
59-1-205	BF_3 Counter	21.25	1
59-2-205	BF_3 Counter	21.25	1

(a) Length of plate column loaded directly into matrix tube; no drawer used for this master.

Table B.1 in Appendix B provides the drawer plate loading description for each drawer master used in ZPR-3/59 loading 6. Some explanation is needed to interpret properly those descriptions. This is provided here by explaining the data for drawer master 59-1-100, the first drawer described in Table B.1 That portion of Table B.1 is reproduced here as Table 1.3. All dimensions and locations in Table 1.3 and Table B.1 are in inch units.

There is a header row starting the description of each drawer master in Table B.1. The header in the extraction shown in Table 1.3 has the three-field identifier 59-1-100, where the three fields indicate Assembly 59, Half 1 (stationary half), and Master 100, respectively. Referring back to Table 1.2, it can be seen that this is a normal core drawer loading in a 15.25-inch-long drawer and that there were 47 drawers loaded using this master.

Each remaining row for the drawer master describes a contiguous block of identical plates. The row gives a) the plate name and nominal dimensions, b) the starting position of the block, c) the number of plates in the block in each direction, and d) a rotation code (spatial orientation) for the block of plates. The plate name portion of the plate ID gives an approximate indication of the plate material. A full composition description is given in Section 1.3.

Unless otherwise noted for a specific case, the first dimension for any plate, drawer or other rectangular object is the X-dimension, the second dimension is the Y-dimension and the third dimension is the Z-dimension. For example, for a plate with listed dimensions of 1/8 x 2 x3 in., 1/8 in. is the X-dimension, 2 in. is the Y-dimension and 3 in. is the Z-dimension. This applies throughout the document.

Most plates were loaded with the standard orientation, designated by rotation code 1. Consider, for example, the 1/8x2x3 in. Pu-Al plate in the drawer master in Table 1.3. The standard orientation is that the first plate dimension (1/8 in.) is in the X-direction, the second plate dimension (2 in.) is in the Y-direction and the third plate dimension (3 in.) is in the Z-direction. In fact, all plates in this drawer master had the standard orientation, but there are cases in Table B.1 with other code values. A rotation code of 4 corresponds to rotating the plate 90 degrees about the X-axis. A rotation code of 5 corresponds to rotating the plate 90 degrees about the Z-axis. A rotation code of 6 means the plate is rotated 90 degrees about the Y-axis. A rotation code of 2 means the plate is rotated 90 degrees about the Z-axis and 90 degrees about the Y-axis.

It should be noted that the numbers of decimal places in the starting locations in Table 1.3 and Table B.1 do not mean that those locations were known that accurately. Rather, it reflects the fact that some ZPR plate types had thicknesses of 0.0625 in. (1/16 in.), so the code that produces these tables must accommodate more than three decimal places for some assemblies. Thus, despite the displayed precision, the locations shown in Table 1.3 and Table B.1 are just nominal locations.

Table 1.3. Drawer Plate Loading Description for ZPR-3/59 Loading 6.[(a)]

Plate ID (dimension in inches)	Starting X Location	Starting Y Location	Starting Z Location	X #	Y #	Z #	Rotation
Drawer Master 59-1-100							
Graphite (coated) (1/8x2x2)	0.0000	0.0000	0.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	2.0000	4	1	1	1
Graphite (coated) (1/8x2x3)	0.0000	0.0000	4.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	7.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	9.0000	4	1	1	1
Pu-Al - No Ni (1/8x2x2)	0.5000	0.0000	0.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.5000	0.0000	2.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x3)	0.5000	0.0000	3.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.5000	0.0000	6.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x3)	0.5000	0.0000	7.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.5000	0.0000	10.0000	1	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	0.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	2.0000	7	1	1	1
Graphite (coated) (1/8x2x3)	0.6250	0.0000	4.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	7.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	9.0000	7	1	1	1
Pu-Al - No Ni (1/8x2x2)	1.5000	0.0000	0.0000	1	1	2	1
Pu-Al - No Ni (1/8x2x3)	1.5000	0.0000	4.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x2)	1.5000	0.0000	7.0000	1	1	2	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	0.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	2.0000	3	1	1	1
Graphite (coated) (1/8x2x3)	1.6250	0.0000	4.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	7.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	9.0000	3	1	1	1
Lead (2x2x4)	0.0000	0.0000	11.0000	1	1	1	1

(a) All dimensions and locations are in inch units.

Figure 1-12 provides pictorial representations of the information given in Table 1.3. (Figure1-12 is a duplicate of Figure 1-6 above and is reproduced here for the convenience of the reader.) Figure 1-12 presents an X-Z view, i.e., looking down at the top of this drawer master, and shows the columns of plates. The drawer itself is not shown – only its plate contents. The origin of the drawer master coordinate system is at the front lower left corner of the space inside the drawer, which is near the upper left corner of the figure. The X-axis is along the drawer width and is divided in eighth-inch units from zero to two inches (16 eighths). The Z-axis is along the drawer length and goes from zero to 15 inches in inch units.[a] The Y-axis is transverse to the page, pointing towards the viewer, and the range encompassing the plate loading is 0 – 2 inches.

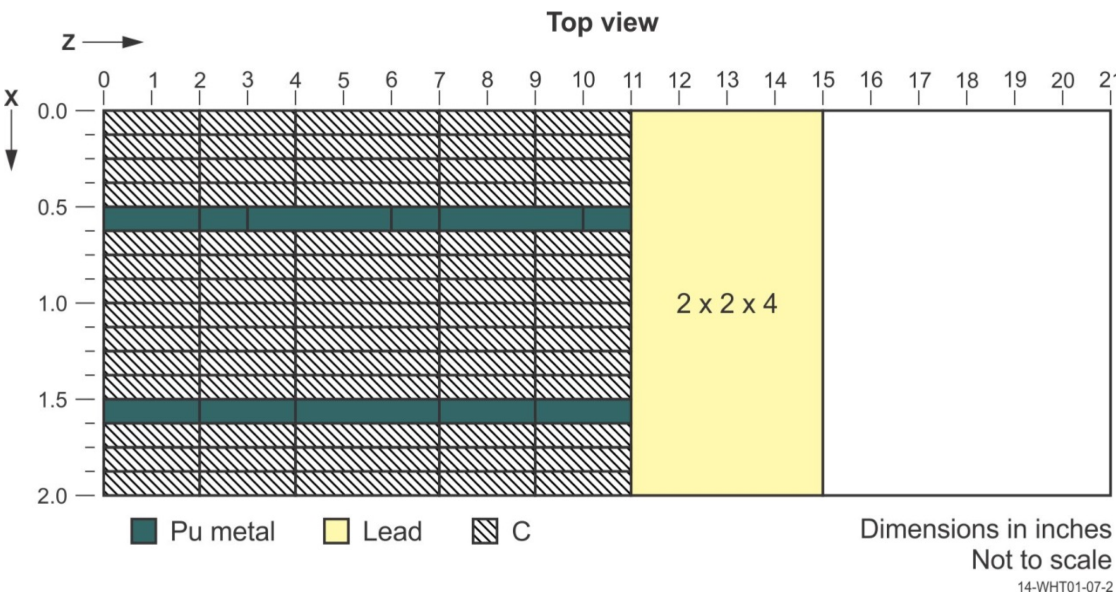

Figure 1-12. Loading Pattern for ZPR-3/59 Drawer Master 59-1-100.

Line 1 of Table 1.3 specifies a block of four 1/8x2x2 in. graphite plates contiguous in the X-direction starting at Z = 0.0 in., so this block spans the space from X = 0.0 to X = 0.5 in. Lines 2 – 5 also specify blocks of four graphite plates of dimensions 1/8x2x2 in., 1/8x2x3 in., 1/8x2x2 in. and 1/8x2x2 in., respectively, contiguous in the X-direction. The axial starting positions of these four blocks are Z = 2.0 in., Z = 4.0 in., Z = 7.0 in. and Z = 9.0 in., respectively.

The following six lines specify a column of six Pu-Al plates. There were two types of Pu-Al plates in the ZPR-3 inventory. Both types were clad in stainless steel. One type also had a nickel coating around the Pu-Al alloy and was designated as PANI (Plutonium-Aluminum NIckel coated). The other type did not have a nickel coating around the Pu-Al alloy and, consequently, was designated as PANN (Plutonium-Aluminum No Nickel). The column of Pu-Al plates at X = 0.5 in. consisted of six PANN plates of dimensions 1/8x2x2 in., 1/8x2x1 in., 1/8x2x3 in., 1/8x2x1 in., 1/8x2x3 in. and 1/8x2x1 in., respectively.

Lines 12 – 16 of Table 1.3 specify five blocks of graphite plates of lengths 1/8x2x2 in., 1/8x2x2 in., 1/8x2x3 in., 1/8x2x2 in., and 1/8x2x2 in., respectively. The axial starting positions of these five blocks are Z = 0.0 in., Z = 2.0 in., Z = 4.0 in., Z = 7.0 in., and Z = 9.0 in., respectively. Each block consists of seven graphite plates contiguous in the X-direction and occupies the space from X = 0.625 in. to X = 1.5 in.

[a] Note that the coordinate convention for ZPR assemblies is unusual in that the Z direction is horizontal, not vertical.

Lines 17 – 19 of Table 1.3 specify a column of Pu-Al plates starting at X = 1.5 in. In the axial direction, this column consists of two contiguous 1/8x2x2 in. PANN plates, one 1/8x2x3 in. PANN plate, and two contiguous 1/8x2x2 in. PANN plates in that order.

Lines 20 – 24 of Table 1.3 specify five blocks of graphite plates of lengths 1/8x2x2 in., 1/8x2x2 in., 1/8x2x3 in., 1/8x2x2 in., and 1/8x2x2 in., respectively. The axial starting positions of these five blocks are Z = 0.0 in., Z = 2.0 in., Z = 4.0 in., Z = 7.0 in., and Z = 9.0 in., respectively. Each block consists of three graphite plates contiguous in the X-direction and occupies the space from X = 1.625 in. to X = 2.0 in.

Line 25 of Table 1.3 specifies one 2x2x4 in. lead block starting at Z = 11.0 in. which constitutes the first four inches of the lead axial reflector. This completes the specification of plates in drawer master 59-1-100.

For ease of loading plates, the inside length of a drawer was slightly greater than the length of the plate loading. After loading the plates, a small retainer spring was pressed between the end of the plate loading and the back of the drawer. This spring pushed all of the plate columns forward against the front of the drawer, eliminating any gaps and preventing further movement of plates within the drawer. Tables B.1 and 1.3 do not show this spring, just as they do not show the drawer itself.

There were a few drawer masters where the distance between the back of the drawer and the end of the plate loading needed to mock up the back portion of the assembly was much greater than a spring's thickness. The principal example is axial reflector back drawers in half 1. Because each 11.25 in. back drawer contained only 8 in. of lead, the remaining 3 in. of each back drawer was loaded with perforated aluminum plates. A spring was then pressed between the end of the aluminum plates and the back of the drawer to keep the lead plates at the front of the drawer. The choice of a low density of material that is relatively transparent to neutrons made the reactivity effect of this scheme minimal. Perforated aluminum plates were also used to eliminate the free space in the back of each DP control drawer.

In using these loading data, one must keep in mind the difference between the convention for identifying matrix positions in the two halves and the convention for viewing drawer masters in the two halves. It was noted in Section 1.2.1 that, for both halves, the matrix column number (essentially the X-coordinate) is counted from the left when looking from the movable half towards the stationary half. In contrast, the origin of the drawer master coordinates is at the left edge of the plates when looking from the matrix interface (Z=0) towards the matrix half that contains the drawer. The perspective is the same in both conventions for the stationary half but opposite for the movable half.

1.2.3 Measurement Technique and Excess Reactivity - Excess reactivity is the system reactivity when all control elements are in their most reactive positions. Excess reactivities in ZPR-3/59 were measured with a calibrated control rod. No information concerning the method used to calibrate the control rods in ZPR-3/59 is available. However, for other ZPR-3 assemblies from the same period, control rods were calibrated by inverse kinetics and by a technique referred to as the rod bump method by the experimenters (see Section 2.1 of MIX-COMP-FAST-003 for a description of the rod bump method).

The reference critical configuration had DP control drawer #5, which was in matrix position 2-U-16 in half 2, withdrawn 1.83 in. when the reactor was at the reference power level. The other nine DP drawers were fully inserted.

The excess reactivity for ZPR-3/59 loading 6 was determined by the experimenters to be 0.080 %Δk/k from the control rod calibration curves. Although the actual reactivity measurement was in units of inhours, that original measurement is not available. The 0.080 %Δk/k is the value listed by the experimenters in their final report for ZPR-3/59 (see Ref. 1, p. 13).

1.3 Description of Material Data

Composition data presented here were taken from several sources. Some of the composition data were taken from the electronic plate material library (ADEN library). These data are essentially the same as those in the most recent issue of a ZPR/ZPPR working document referred to informally as the "hot constants memo." That issue was first released in 1983, after all of the other ZPR facilities were shut down, and was updated periodically until the shutdown of ZPPR.

Earlier versions of the hot constants memo—from ZPR-3, from the early period of ZPR-6&9, and the final (1978) version from ZPR-6&9—were consulted to resolve ambiguities about material description details, to infer which "lot" of material could have been used in ZPR-3/59 and to supply data missing from the ADEN library. Specifically, it was necessary to consult documents that predate the ADEN library because the graphite plates used in ZPR-3/59 were eliminated from the plate inventory in the early 1980s. Consequently, the graphite plates used in ZPR-3/59 are not listed in the last ZPPR hot constants memo or the ADEN library. Data for those graphite plates were taken from the last ZPR-3 hot constants memo issued prior to loading ZPR-3/59 and from the ZPR-6 hot constants memo. Appendix A of the published ZPR-3/48 document ANL-7759 also has relevant composition and geometry details. In the case of ambiguities, preference was given to the data source closest in time to the date of the experiment.

The original documentation on most of the inventory used in ZPR-3/59 has been lost. The hot constants memos (and the ADEN library) give average compositions by batch or lot, which are what are given in the tables below. The memos do not give uncertainties, and the issue of estimating composition uncertainties and impurities is addressed in Section 2.

This section also contains material dimensions, some details of which were not presented in Section 1.2. Details such as the wall thickness of each face of plate cladding are easier to present and to find as part of the plate and drawer descriptions in this section. Available data on wall thicknesses of cladding and drawers were collected in the 1980s and put into an electronic cladding library. That is the source of such data presented here. **In all tables in this section, dimensions are provided in units of inches.**

The plate outer dimensions given below are the nominal values from the hot constants memos. The compositions given below are derived from the ADEN library, supplemented as described above.

Most masses and weight percents in the inventory are time invariant, with the only significant exceptions being those for ^{241}Pu and ^{241}Am. The Pu and Am data displayed in the tables of this section correspond to January 1, 1977, the decay date used in generating the ADEN library. This date is approximately 7.06 years after the criticality date for ZPR-3/59 loading 6. Given the 14.29 year half-life of ^{241}Pu, the 1977 ^{241}Pu masses are too small for ZPR-3/59. It was simply convenient to use the ADEN library to generate the tables in this section. The data-processing codes used to produce the as-built and benchmark models adjust material compositions such that ^{241}Pu and ^{241}Am concentrations in the as-built and benchmark models correspond to the actual concentrations of those nuclides on the dates of the experiments.

For each plate type and size, e.g., the 1/8 x 2 x 3 in. Pu-Al plates, the masses and compositions recorded in the hot constants memos and the ADEN library are the average values for all of the plates of that type and size in the fuels database. The masses shown in Tables 1.4 and 1.5 are those average values. The same considerations apply to the nominal mass and composition values listed below for other types of plates.

ZPR-3/59 used most of the Pu-Al plate inventory, so ZPR-3/59 contained PANN plates of dimensions 1/8x2x1 in., 1/8x2x2 in., and 1/8x2x3 in. as well as PANI plates of dimensions 1/8x2x1 in., 1/8x2x2 in., and 1/8x2x3 in. Again, PANI plates had a nickel coating around the Pu-Al alloy while PANN plates had no nickel coating around the Pu-Al alloy. The exact Pu-Al plate width is 0.123 in., the height is 1.975 in., and the actual length exceeds the nominal length by 0.003 in. The fuel meat is 0.085 in. wide, 1.765 in. high and shorter than the nominal plate length by 0.07 in. (see ANL-7759, Appendix A and BNL-15746, Vol. I, Section 1.1, Table II). The front, top, back and side thicknesses of the cladding are 0.012 in., 0.0955 in., 0.0203 in. and 0.012 in., respectively. The bottom cladding thickness is the same as the top cladding thickness. Plate design and fabrication techniques made the front and back faces of the plate clearly distinguishable.[a] The position of the serial number on each Pu-Al plate would also ensure consistent orientation of the Pu-Al plates when they were loaded in drawers.

Fuel and clad masses and outer dimensions for the Pu-Al plates are given in Tables 1.4 and 1.5. Each Pu-Al fuel plate was weighed before and after cladding, and these masses were recorded in a database. The masses shown in Tables 1.4 and 1.5 are the average values for the given plate type and size, as derived from this database. Similarly, samples from each melt were analyzed when the fuel was cast, and these data were used to derive the aluminum and plutonium isotopic mass distributions in Table 1.4.

Table 1.4. Standard Pu-Al Fuel Composition.

Plate ID	Nominal Size(a) (inches)	^{238}Pu Mass(g)	^{239}Pu Mass(g)	^{240}Pu Mass(g)	^{241}Pu(b) Mass(g)	^{242}Pu Mass(g)	^{241}Am(b) Mass(g)	Al Mass (g)
PANN (1/8x2x1)	0.125x2.0x1.0	-----	30.6992	1.4589	0.0557	-----	0.0666	0.3647
PANN (1/8x2x2)	0.125x2.0x2.0	-----	65.5924	3.1217	0.1200	-----	0.1435	0.7703
PANN (1/8x2x3)	0.125x2.0x3.0	-----	98.9824	4.7161	0.2076	0.0049	0.2482	1.1584
PANI (1/8x2x1)	0.125x2.0x1.0	0.0009	30.5292	1.4481	0.0644	0.0237	0.0803	0.3848
PANI (1/8x2x2)	0.125x2.0x2.0	0.0004	65.3517	3.0555	0.1400	0.0301	0.1747	0.8205
PANI (1/8x2x3)	0.125x2.0x3.0	0.0017	98.8135	4.6821	0.1837	0.0600	0.2291	1.2508

(a) Outer clad dimensions.
(b) Masses of ^{241}Pu and ^{241}Am correspond to January 1, 1977.

Table 1.5. Stainless Steel Cladding Mass and Composition for Standard Pu-Al Fuel.

Plate ID	Clad Mass (g)	Composition, wt.%									
		C	Si	P	S	Cr	Mn	Fe	Ni	Cu	Mo
PANN (1/8x2x1)	8.76	0.068	0.479	0.023	0.023	18.485	1.712	69.717	8.900	0.274	0.320
PANN (1/8x2x2)	16.80	0.065	0.482	0.024	0.018	18.452	1.726	69.702	8.929	0.280	0.321
PANN (1/8x2x3)	24.76	0.065	0.477	0.024	0.020	18.455	1.696	69.701	8.965	0.279	0.319
PANI (1/8x2x1)	10.41	0.058	0.423	0.019	0.019	16.359	1.508	61.806	19.270	0.250	0.288
PANI (1/8x2x2)	20.21	0.059	0.426	0.020	0.020	16.368	1.509	61.846	19.223	0.247	0.282
PANI (1/8x2x3)	29.78	0.057	0.426	0.024	0.017	16.387	1.511	61.914	19.130	0.248	0.285

The apparent difference in composition between the clad on the PANN plates and the clad in the PANI plates actually reflects the presence of the nickel coating on the PANI plates. Inventory records do not distinguish the mass of nickel in the coating from the mass of nickel in the clad and do not list the thickness of the nickel coating. However, based on the differences in clad mass and composition shown in Table 1.5, it is likely that the mass of the nickel coating ranges from about 1.5 g for the 1/8x2x1 in. PANI plates to about 4 g for the 1/8x2x3 in. PANI plates.

ZPR-3 acquired new graphite plates in the mid-1960s. The number of graphite plates required for ZPR-3/59 makes it clear that the new plates were used for this assembly. These plates were coated with a mixture of TiO_2 and Teflon. The mass of the coating was about 0.20 g for the 1/8x2x3 in. plates and about 0.13 g for the

[a] J. A. Morman, Private Communication, March 20, 2014.

1/8x2x2 in. plates. The thickness of the coating and the percentages of TiO_2 and Teflon in the coating are not known. The uncertainty regarding the composition of the coating is addressed in Section 2. The hot constants memo states that the plates contained less than 0.05% impurities and less than 70 ppm hydrogen. No further information regarding impurities is available. Table 1.6 shows the mass and composition for the graphite plates used in ZPR-3/59.

Table 1.6. Mass and Composition for the Graphite Plates.

Plate ID	Graphite (1/8x2x2)	Graphite (1/8x2x3)
Nominal Size	0.125x2x2	0.125x2x3
Number of Plates	5674	1622
C Mass, g	12.88	19.42

Very little direction information is available concerning the lead blocks used in ZPR-3/59. Internal experiment planning documents show that the experimenters were still considering other possible reflectors for Assembly 59 as they were planning the Assembly 58 program. The lead blocks are not listed in any of the hot constants memos issued before or after the Assembly 59 program. It seems likely that the lead blocks were acquired specifically for ZPR-3/59. The fact that they are not listed in any subsequent hot constants memo suggests that they were eliminated from the inventory shortly after the end of the ZPR-3/59 program.

The lead blocks used in ZPR-3/59 consisted almost entirely of 2 x 2 x 4 in. blocks. The few odd sizes required for detector drawers and source tube drawers were probably machined from the 2 x 2 x 4 in. blocks. Table 1.7 shows the sizes of the lead blocks used in ZPR-3/59. The issue of the composition of the lead blocks is addressed in Section 2.3.

Table 1.7. Lead Plates and Blocks used in ZPR-3/59.

Plate Size, in.	Number
2 x 2 x 4	3504
2 x 1 x 4	2
1.875 x 2 x 4	27
1.875 x 2 x 2	10
1.875 x 2 x 3	1
2 x 1.125 x 2	3
2 x 1.125 x 1	3
2 x 0.875 x 4	3
2 x 1.125 x 3	3
2 x 0.875 x 4	3
2 x 1 x 1	1
2 x 2 x 4, 1.25 in. axial hole	10
1.875 x 2 x 1	1

For the ten 2 x 2 x 4 in. blocks with an axial hole, the hole extended all the way through the block. These block were used in the detector drawers, and a counter filled the axial void in the column of blocks.

Perforated aluminum plates were placed in the backs of the back drawers and DP control rod drawers to eliminate free space and to keep the lead plates in the axial reflector pushed to the fronts of the drawers.

Table 1.8 shows the masses and compositions of these aluminum plates. No impurities in the aluminum are specified in the hot constants memos. Plates designated AL45 were perforated to reduce the plate density to approximately 45% of the density of solid aluminum metal.

Table 1.8. Masses and Compositions of the Perforated Aluminum Plates.

Plate ID	AL45 (1/8x2x1)	AL45 (1/8x2x2)	AL45 (1/8x2x3)
Nominal Size	0.125x2x1	0.125x2x2	0.125x2x3
Number of Plates	18	90	543
Al Mass, g	4.55	9.13	14.01

Slightly different compositions for the Type 304 stainless steel drawers and matrix tubes are given in different documents. These are shown in Table 1.9. Only the first composition totals to 100 wt.%. The stainless steel compositions listed in Table 1.9 differ from current (2014) standard specifications for Type 304 stainless steel and may differ from the standard specifications for this steel in the early 1950s when the drawers and matrix tubes were fabricated. The compositions listed in Table 1.9 are the values reported by the experimenters and are the values used by ZPR-3 personnel for planning and analysis of experiments.

Table 1.9. Element Wt.% Data for Type 304 Stainless Steel Drawers and Matrix Tubes.

Source	Component	Fe	Cr	Ni	Mn	Si	Total
ANL-7759, Appendix A[(a)]	plate-drawer-tube average	73.4	17.0	8.4	0.75	0.45	100.0
ZPR-3 Hot Constants[(b)]	plate-drawer-tube average	71.4	17.0	8.4	0.74	0.44	98.0
ZPR-3 Hot Constants[(b)]	matrix tubes	72.0	16.9	7.8	0.7	0.50	97.9
ZPR-3 Hot Constants[(b)]	drawers	70.0	17.4	9.6	1.5	0.36	98.9

(a) A. M. Broomfield *et al*, "ZPR-3 Assemblies 48, 48A, and 48BThe Study of a Dilute Plutonium-fueled Assembly and Its Variants," Argonne National Laboratory Report ANL-7759, December 1970.

(b) W. P Murphy and R. Rowberry, ZPR-3 Hot Constants Memo, July 14, 1966.

The masses and dimensions of the stainless steel drawer components and of the matrix tubes that are given explicitly in Appendix A of ANL-7759 are shown in Table 1.10. The ZPR-3 hot constants memos give no drawer component dimensions but give the same masses. Explicit data are not given in either reference for drawer back plates or the DP compartment divider, but values can be inferred. The mass is per inch of length in the Z-direction for the matrix tube and for drawer bottom + sides. The normal drawer components had smaller masses than the DP drawer components because the DP drawer walls were twice as thick and were unperforated, while the normal drawers were perforated. The first dimension in Table 1.10 is the X-dimension (width), the second dimension in Table 1.10 is the Y-dimension (height), and the third dimension in Table 1.10 is the Z-dimension (thickness or length).

Table 1.10. Mass and Dimensions of Stainless Steel Drawer and Matrix Components.

Plate ID	DP Front Plate	DP Bottom + Sides[(a)]	Normal Front Plate	Normal Bottom + Sides[(a)]	Matrix Tube[(a,b)]
Outside Dimensions (in.)	2.001x2.063x0.063	2.001x2.063x1 (0.063 wall)	2.064x2.035x0.032	2.064x2.035x1 (0.032 wall)	2.1835x2.1755x1 (0.040 wall)
Mass (g)	31.00	48.44	9.85	10.36	44.64

(a) Mass per inch of length for bottoms+sides of drawers and for the matrix tube.
(b) The mass per inch for the first inch of the matrix tube was 27.483 g because of the notches at the front of the matrix tube to accommodate the tabs on the front drawers.

The matrix tube is just a hollow rectangular stainless steel tube with exterior dimensions of 2.1835 in. x 2.1755 in. x 33.5 in. (5.54609 cm x 5.52577 cm x 85.09 cm) and a wall thickness of 0.040 in (0.1016 cm). The notches in the front to accommodate the tabs in drawer fronts reduced the mass per inch for the first inch of the matrix tube to 27.843 g/in.

Table 1.10 lists the exterior dimensions of the components of normal and DP drawers. Normal front drawers in half 1 were 15.25 in. long, normal front drawers in half 2 were 21.25 in. long, back drawers were 11.25 in. long, and DP drawers were 32.5 in. long. The normal drawer front plate, back plate, bottom and sides were 0.032 in. (0.8128 mm) thick. The DP drawer front plate, bottom and sides were 0.063 in. (0.16002 cm) thick. The masses in Table 1.10 for the components of normal drawers include the effects of any perforations in the drawers. There were no perforations in the DP drawers.

There was a retainer spring at the back of each drawer to keep the plates pushed to the front of the drawer. The retainer springs were made of mild steel. The mass by element for a spring is: 9.862 g Fe, 0.097 g C. One retainer spring was used at the back of each normal front or back drawer. To prevent any plate shifting under acceleration or deceleration of the DP control rod drawers, as many retainer springs as possible (up to four) were pressed into the gap at the back of each of the two compartments of each DP drawer.[a]

Each DP drawer is divided into two compartments by a small plate at Z = 15.25 in., and each DP drawer is connected to a control rod drive by a shaft attached to the back of the drawer. No further information has been discovered regarding the dimensions or compositions of these components. The divider plate was represented in the as-built ZPR-3/59 model by a 1.75 x 2.0 x 0.0625 in. steel plate containing 0.006 g C, 0.071 g Si, 5.620 g Cr, 0.440 g Mn, 21.246 g Fe, 3.356 g Ni, 0.012 g Cu and 0.003 g Mo. The DP control rod drive shaft was represented in the as-built ZPR-3/59 model by a column of 0.25 x 2 x 1 in. steel plates containing 0.030 g C, 0.170 g Si, 11.677 g Cr, 0.954 g Mn, 44.258 g Fe, 5.437 g Ni, 0.130 g Cu and 0.260 g Mo per plate.

[a] J. M. Gasidlo, Private Communication, April 9, 2009.

1.4 Temperature Data

The thermocouple readings were not recorded in the logbook for loading 6. The first assembly loading for which thermocouple readings are available is loading 16. This issue is discussed in Section 2. No measured temperature coefficient for ZPR-3/59 has been found.

1.5 Supplemental Experimental Measurements

A list of experiments performed in ZPR-3/59 is given below.

- Criticality.
- Central fission rate ratios.
- Fission rate distributions.
- Cf source worth and traverses.
- Small sample worths.
- Foil activations.
- Doppler sample worth.

This list was compiled from the loading records and logbook. Only the criticality measurement has been evaluated.

2.0 EVALUATION OF EXPERIMENTAL DATA

The reactivity effects of many of the uncertainties discussed below were quantified using TWODANT[a] (two-dimensional S_N code) RZ models of the benchmark. The radial boundaries preserved the area of each region in the X-Y plane of the X-Y-Z geometry as-built model. Axial boundaries preserved the volumes of the core, radial reflector, lower axial reflector, upper axial reflector and the small volume between the axial reflector regions in half 1 which consists of the retainer spring and back plate of the front drawer plus the front plate of the back drawer. The calculations used cross sections derived from ENDF/B-VII.0 data using the Argonne cross section processing code MC^2-3.[b] The eigenvalue convergence criterion was 10^{-7}, which allowed any non-negligible effect (> $10^{-4}\Delta k$) to be computed explicitly with a pair of TWODANT calculations. The uncertainties are displayed in units of %Δk (100 times the change in k_{eff}). For consistency in accounting, they are displayed to four decimal places, even though that level of precision is not always justified on physical grounds.

The uncertainties affecting criticality have been divided into three broad categories. They are uncertainties associated with 1) measurement technique, 2) geometry, and 3) compositions. Each category is considered in turn and then the combined experimental uncertainty is presented. Other adjustments to the measured excess reactivity are also identified. Each uncertainty estimate is one standard deviation.

2.1 Measurement Technique Uncertainties

Excess reactivities in ZPR-3/59 were measured with calibrated control rods. Exact details regarding the calibration technique are not available although it is likely that inverse kinetics and possibly the rod bump method were used (see Section 2.1 of MIX-COMP-FAST-003 for a discussion of the rod bump method). The reference critical configuration had DP control drawer #5 in matrix position 2-U-16 withdrawn 1.83 inches when the reactor was at the reference power level. All other DP drawers were fully inserted. The reported excess reactivity for ZPR-3/59 loading 6 was 0.080 %Δk/k. No associated uncertainty was listed. However, any realistic uncertainty associated with the excess reactivity would be dominated by the geometry and composition uncertainties for ZPR-3/59. A typical value for a ZPR-3 assembly would be approximately 0.0060 %Δk, and that value will be assumed here.

There also are a few uncertainty contributions associated with the core temperature. It was acknowledged, in an internal report,[c] that the thermocouple average was not the true core average, although it was a reliable parameter to measure changes in the true core-average temperature. It was also stated there that ten thermocouples (5 in each half) were used for averaging, but the logbook generally has temperatures from twelve thermocouples.

The thermocouple readings for loading 6 were not recorded in the logbook. The first loading for which the thermocouple readings are available is loading 16. The thermocouple readings listed in the logbook for loading 16 at the time the controlling DP rods were at the reported critical positions are:

TC 1 – 22.1 °C,
TC 2 – 32.1 °C,
TC 3 – 32.7 °C,
TC 4 – 31.0 °C,

[a] R. E. Alcouffe, F. W. Brinkley, D. R. Marr, and R. D. O'Dell, "User's Guide for TWODANT: A Code Package for Two-Dimensional, Diffusion-Accelerated, Neutral-Particle Transport," LA-10049-M, Revised February 1, 1990.
[b] W. S. Yang et al, "Neutronics Modeling and Simulation of SHARP for Fast Reactor Analysis," Nuclear Science and Technology, **42**, No. 5, pp 520-545, October 2010..
[c] W. G. Davey and R. L. McVean, Private Communication, March 1969.

TC 5 – 23.5 °C,
TC 6 – 35.5 °C,
TC 7 – 34.8 °C,
TC 8 – - ,
TC 9 – 32.8 °C,
TC 10 – 37.0 °C,
TC 11 – 36.5 °C,
TC 12 – 31.7 °C.

Although these are not the true thermocouple readings for ZPR-3/59 loading 6, they are representative of the recorded temperatures and temperature ranges in ZPR-3/58 and ZPR-3/59 loadings. These temperature readings are adequate for present purposes because any effect of temperature uncertainty in ZPR-3/59 is small compared to the effects of some composition uncertainties discussed in Section 2.3, particularly the effects of the hydrogen impurity in the graphite and the uncertainty in the matrix tube mass.

One reading, TC 1, is clearly an inlet temperature, since it is always in the 19 °C - 23 °C range in logbook entries, and would not have been included in an average to represent the core. It is likely that TC 5 was the other thermocouple not considered representative of the core temperature, since its temperatures are most different from (lower than) those of the other entries. These thermocouple (excluding TC 1 and TC 5) readings have an average value of 33.8 °C and the readings ranged from 31.0 °C to 37.0 °C. Treating the uncertainty in the true core temperature as a Type B uncertainty characterized by this range, the standard uncertainty is the range divided by √12, which equals 1.73 °C.

No measured temperature coefficient has been found for ZPR-3/59, so the Argonne cross section processing codes discussed above were used with the TWODANT model to compute a temperature coefficient for ZPR-3/59. The computed temperature coefficient for ZPR-3/59 was -2.490 x 10^{-3} %Δk/°C. Using this temperature coefficient with the 1.73 °C temperature uncertainty yields a reactivity uncertainty of ±0.0043 %Δk.

The uncertainty in the calibration of the thermocouples, which is a systematic uncertainty, is estimated to be 0.5 °C. This converts to ±0.0012 %Δk. When added in quadrature with the ±0.0043 %Δk averaging uncertainty from above, the combined uncertainty is ±0.0045 %Δk.

The final core temperature issue is that the temperature distribution in the core changed when the matrix halves closed. It took significant time to establish the new asymptotic distribution and, "in those days," sufficient time was not always allowed.[a] Startup of loading 6, the reference critical configuration, occurred at 11:00, and shutdown occurred at 17:33 according to the logbook. For this startup, the asymptotic temperature uncertainty effect is assumed to be less than 0.0010 %Δk. Any uncertainty in this value is negligible compared to geometry and composition uncertainties, so further effort to quantify this uncertainty is not warranted. When the 0.0010 %Δk asymptotic temperature uncertainty is added in quadrature to the 0.0045 %Δk combined uncertainty for assembly temperature and thermocouple calibration, the total temperature uncertainty is 0.0046 %Δk.

Estimates of the configuration reproducibility uncertainty are not available. In ZPR-3/56B (see MIX-COMP-FAST-004, Section 2.1), ±2.5 inhours[b] (Ih) or ±0.0024 %Δk was adopted as a reasonable 1σ estimate of the reproducibility uncertainty based on repeated measurements. Because of the similarities between ZPR-3/56B and the configuration being evaluated here in terms of equipment, experimental

[a] J. M. Gasidlo, Private Communication, April 9, 2009.
[b] An inhour (Ih) is a unit of reactivity and is defined as the amount of positive reactivity corresponding to an asymptotic power rise with a time constant or period of one hour. Reactivity is rarely (if ever) reported in inhours today, but the inhour was a common unit for measuring and reporting reactivity during the period when ZPR-3 operated.

techniques and materials, it seems reasonable to adopt ±0.0024 %Δk as the 1σ estimate of the reproducibility for ZPR-3/59. This uncertainty is small relative to uncertainties related to geometry and composition, so further refinement of the worth of the reproducibility uncertainty does not seem to be worthwhile.

The conversion from the natural measurement units, inhours (Ih), to units of k_{eff} requires knowledge of the delayed neutron kinetics parameters, particularly β_{eff}. The estimated uncertainty in the reactivity conversion factor is 5%. The 5% uncertainty for β_{eff} was chosen for several reasons. First, measurements of β_{eff} were difficult, so they were only performed in a limited number of ZPR or ZPPR assemblies. In the limited number of cases where the measured values were compared with calculated values, the result was consistent with about 5% uncertainty. Second, calculations of β_{eff} for different configurations in the same experimental program are also consistent with about 5% uncertainty. Finally, 5% uncertainty in β_{eff} is consistent with a wide range of ICSBEP benchmarks. This uncertainty is normally applied to the measured excess reactivity which usually was reported in units of inhours for ZPR assemblies.

If, for simplicity, the 5% uncertainty in the conversion factor is applied to the uncertainties related to excess reactivity, temperature and reproducibility, the contribution of the uncertainty in the reactivity conversion is approximately 0.0040 %Δk for excess reactivity uncertainty, 0.0002 %Δk for the temperature uncertainty and 0.0001 %Δk for the reproducibility uncertainty. These values are negligible compared to the geometry and composition uncertainties, so further refinement of the reactivity conversion uncertainty is not worthwhile.

2.2 Geometry Uncertainties

Because the matrix halves were not perfectly aligned, there was a small gap between the two halves, even at the nominal full closure position. There could also be a small gap because of uncertainty in the actual position of the movable half at full closure relative to the position indicated by the instruments. Typically, the actual physical gap varied from 0 to 30 mils (0.0 – 0.8 mm). As-built and benchmark models do not include an interface gap because of its small, non-uniform and imprecisely known size. Consequently, a gap correction is derived here in conjunction with the gap uncertainty analysis, and the correction is applied to the calculated k_{eff} in Section 3.5.

No measured gap coefficient of reactivity has been located, so the worth of the gap was computed by continuous energy Monte Carlo as the difference between k_{eff} for the as-built model with no gap and k_{eff} for the as-built model with a small gap between the halves. The computed gap worth for ZPR-3/59 loading 6 with an average gap of 0.4 mm is 0.0690 ± 0.0040 %Δk based on one billion (10^9) histories for each configuration. The estimated 1σ uncertainty in the gap width is 0.1 mm, making the total uncertainty in both the gap worth and the gap closure correction ± 0.0177 %Δk.

Besides the interface gap, there are three issues regarding the exact location of materials. One is the possibility that the drawer fronts might not have been flush with the front edge of the matrix tubes. Care was taken to make the drawers flush with the matrix, and the drawer-tab — matrix-tube-notch design feature made that easy for fuel handlers. Another issue is the possibility that the plate columns might not have been all the way forward against the drawer front. This problem was minimized by taking care to do this when loading the plates in drawers, by using springs to hold the plates there, and by inserting the drawer tabs into the matrix tube notches slowly. These two issues are assumed to be covered by the interface gap uncertainty.

The third issue to consider is deviations from nominal dimensions for plates, drawers, and matrix tubes. Deviations in the dimensions that affect the precise X- and Y-positions of materials within the unit cell are too small to impact k_{eff} significantly. The dimensions that determine the volumes over which the material masses are distributed can have an effect. The plate lengths, drawer front thickness, and the length of front drawers affect the axial positions of materials, similar to the interface gap effect. It is estimated that the uncertainties in these dimensions collectively have no larger effect than 50% of the interface gap effect; accordingly, an uncertainty of 0.0345 %Δk was assigned.

A deviation from the nominal average spacing between matrix tubes also would affect the region volumes. At the ZPR-3 facility, measurements were made of the average spacing with the matrix filled. The average pitch was measured in 1959 to be 2.1835 inches wide and 2.1755 inches high. These were reported as typical values, and it was noted that the values may change with assembly loading.[a] It is estimated that the error in these measurements is ±1 mil, i.e., ±0.001 in. (see ICSBEP benchmark IEU-MET-FAST-012, Section 2.2). The implied change in reactivity was estimated by computing the resulting change in k_{eff} using TWODANT calculations of the benchmark model with the nominal matrix pitch and with the matrix pitch increased and decreased by 1 mil (0.0254 mm). Compositions were adjusted to preserve mass when the matrix pitch was changed. The estimated reactivity effect is ± 0.0643 %Δk.

One final consideration with regard to axial-positioning uncertainties relates to the actual positions of the DP rods, which were fully inserted for the benchmark configuration. This uncertainty, negligibly small compared to the uncertainty components discussed above, is included in the measurement uncertainties provided in Section 2.1.

An adjustment and an uncertainty are needed for room return of neutrons to the assembly. The assembly description above encompasses only the matrix tubes and their contents. An upper bound for the room return effect was computed by expanding the as-built model to include the table, back plate and supporting structures on the sides and top (see Figure 1 above) and the surrounding room. The room return was computed as the difference between two continuous energy Monte Carlo calculations for as-built models with and without the added structures. The computed result is 0.5910 ± 0.0103 %Δk which is treated as an adjustment to the measured reactivity. The associated uncertainty is assumed to be 25% of the computed value, i.e., ± 0.1478 %Δk, so the total uncertainty associated with room return is 0.1482 %Δk. The effect of room return will be included in the adjustments discussed in Section 3.1.

2.3 Composition Uncertainties

A bit of history about the materials inventory records is needed to appreciate the extent and limitations of the information available on the compositions used in ZPR-3/59. The material inventory for Argonne's ZPR facilities was accumulated over a period of more than three decades, starting in the mid-1950s. The procurement acceptance process required thorough documentation on dimensions, masses, composition, etc. of the various core components. Information needed for day-to-day operations was extracted and compiled in working documents known informally as "hot constants memos." These memos give batch or lot average values of dimensions, masses, and weight percents of constituents but no uncertainties. The original documentation on most of the inventory used in ZPR-3/59 has been lost, but the hot constants documents are available. Consequently, indirect evidence and estimates were used to quantify many of the composition uncertainties. Compositions given in these hot constants documents are used directly. That is, weight fractions are not adjusted or renormalized to sum to 100%.

The composition uncertainty for a component is treated in two parts, the uncertainty in total mass and the uncertainty in the weight percents of the constituents. Since these two sources of uncertainty are independent, they are added in quadrature. The reactivity effect of the composition uncertainty was determined by computing the change in k_{eff} using the TWODANT model of the benchmark. In some cases sensitivity coefficients computed with this model were used, and in other cases the specific perturbation was calculated explicitly.

[a] L. H. Berkes, ZPR-3 Hot Constants Memo, March 31, 1960.

The details of the mass measurements are unknown. For the plates and most of the drawers it is assumed that measurements of masses were within 0.01 g of actual value for plates of up to tens of grams and within 1 g for larger plates weighing kilograms, i.e., the uncertainty in weighing was 0.1%. The working standard used to calibrate the scale is taken to have an uncertainty of 0.05%, which is a systematic uncertainty. The uncertainty in weighing could be statistical, but since no details of the process are available, we assume this to be a systematic uncertainty, making a total uncertainty in mass of 0.15%. Mass uncertainty assumptions made for other items are specified as needed.

ZPR-3/59 was built using a very limited number of materials. The only materials which could contribute in a significant way to the composition uncertainties are the Pu-Al plates, lead plates, graphite plates, stainless steel drawers, and the stainless steel matrix. Masses and compositions for all of these materials are known reasonably well.

The uncertainty in the total plutonium mass in the Pu-Al plates was computed to be 0.0744% based on analysis of a database of mass and composition information for the Pu-Al plates. With the exception of ^{241}Pu decay uncertainty, all relative uncertainties for the Pu-Al plates were derived from the same database. Increasing the plutonium (plus americium) mass in the Pu-Al plates by this amount in the TWODANT model increased k_{eff} by 0.0312 %Δk.

The relative uncertainty in the ^{239}Pu weight percent was computed to be 0.0262% for the Pu-Al plates. In the TWODANT model, the ^{239}Pu concentration was increased by this amount and mass was preserved by decreasing just the ^{240}Pu concentration (a simplification justified by the very small size of the other isotopic concentrations). The resulting change in k_{eff} is 0.0108 %Δk for the Pu-Al plates.

Now, the weight percent of ^{238}Pu, ^{241}Pu and ^{242}Pu in the assembly, before decaying ^{241}Pu, was less than 2%. The only isotope besides ^{239}Pu whose uncertainty would be expected to impact k_{eff} appreciably is ^{240}Pu. The relative uncertainty in the ^{240}Pu weight percent is 0.1019% for the Pu-Al plates. Modification of the ^{240}Pu weight percent led to a calculated effect on k_{eff} of 0.0020 %Δk for the Pu-Al plates. The combined uncertainty in k_{eff} due to the uncertainties in the original weight percents of the remaining three isotopes is assumed to be no larger than the ^{240}Pu values, i.e., it is taken to be ±0.0020 %Δk for the Pu-Al plates. In principal, the total uncertainty in the Pu isotopic fractions could be reduced using the constraint that the sum of these fractions was unity. Because this uncertainty component does not make a significant contribution to the total uncertainty in the system reactivity, further analysis appears unwarranted.

Some of the ^{241}Pu that was in the fuel plates when they were manufactured decayed by the time ZPR-3/59 was built. ZPR-3/59 loading 6 was made critical on December 8, 1969 and the half-life of ^{241}Pu is 14.29 years.[a] The numbers in the inventory database are normalized to January 1, 1977. The estimated uncertainty in the decay constant is 1%. Increasing the decay constant increases the ^{241}Am mass and decreases the ^{241}Pu mass. Increasing the decay constant by 1% increases k_{eff} by 0.0008 %Δk for ZPR-3/59 loading 6.

Trace impurities in the plutonium fuel are known only to be small (approximately 0.2 wt.%) and are assumed to have a negligible effect on the total plutonium mass uncertainty. The quadrature sum of all the plutonium uncertainty effects, i.e., mass, weight percents and decay constant, is 0.0332 %Δk. This uncertainty is dominated by the plutonium mass uncertainty.

The uncertainty in the mass of aluminum in the Pu-Al fuel was also computed in the same way as the plutonium mass uncertainty. The computed aluminum mass uncertainty is 0.2560%. Changing the core region aluminum atom density by this amount changes k_{eff} by 0.0010 %Δk.

[a] E. M. Baum et al, "Nuclides and Isotopes – Chart of Nuclides," Seventeenth Edition, Revised 2009, Knolls Atomic Power Laboratory.

The assumed 0.15% uncertainty in the mass of the graphite plates was calculated to have a 0.0422 %Δk effect.

These plates are listed in the ZPR-3 hot constants memo as being 100% C. The graphite plates would have been nuclear grade graphite similar to CP-2 graphite. Table 2.1 shows the results of an analysis of CP-2 graphite performed by Evans Analytical Group for Idaho National Laboratory in 2012.[a]

[a] Table 2.1 was provided by J. D. Bess of Idaho National Laboratory.

Table 2.1. Measured Impurities in CP-2 Graphite.[a]

Element	Concentration [ppm wt]	Element	Concentration [ppm wt]
Li	0.67	Pd	<0.05
Be	<0.05	Ag	<0.05
B	0.35	Cd	<0.05
C	Matrix	In	<0.05
N	-	Sn	<0.05
O	-	Sb	<0.05
F	<0.1	Te	<0.05
Na	<0.05	I	<0.01
Mg	0.06	Cs	<0.05
Al	2.2	Ba	<0.05
Si	70	La	<0.05
P	0.65	Ce	<0.05
S	45	Pr	<0.05
Cl	0.45	Nd	<0.05
K	<0.1	Sm	<0.01
Ca	160	Eu	<0.01
Sc	<0.01	Gd	<0.01
Ti	12	Tb	<0.01
V	120	Dy	<0.01
Cr	<0.5	Ho	<0.01
Mn	0.02	Er	<0.01
Fe	6.2	Tm	<0.01
Co	<0.01	Yb	<0.01
Ni	1.4	Lu	<0.01
Cu	0.15	Hf	<0.01
Zn	<0.05	Ta	<100
Ga	<0.01	W	<0.05
Ge	<0.05	Re	<0.01
As	<0.05	Os	<0.01
Se	<0.05	Ir	<0.01
Br	<0.1	Pt	<0.01
Rb	<0.05	Au	<0.1
Sr	1.2	Hg	<0.1
Y	<0.05	Tl	<0.05
Zr	0.34	Pb	<0.05
Nb	<0.05	Bi	<0.05
Mo	<0.05	Th	<0.05
Ru	<0.05	U	<0.05
Rh	<0.01		

(a) Equivalent boron content (EBC) impurity = 0.9176 [ppm wt]

For the samples measured, the EBC impurity varied between 0 and 2ppm.[a] The EBC impurity uncertainty will be treated as bounding with a 2 ppm upper limit. The calculated worth of this uncertainty is 0.0055/√3 or 0.0032 %Δk.

The graphite plates were coated with a mixture of titanium oxide and Teflon. The titanium oxide gave the coating a white color. Many types of ZPR plates had small colored stripes painted on one edge to expedite identification, and the titanium oxide would have served that function. It is not known whether the titanium oxide also had a protective function. The hot constants memo does not indicate the percentages of titanium oxide and Teflon in the coating. For modeling purposes, it was assumed that the coating consisted of 50 wt.% titanium oxide and 50 wt.% Teflon. A reasonable range for the Teflon content is between 25 wt.% and 75 wt.% with the balance being titanium oxide which makes the uncertainty in the Teflon content 25 wt.%. This is treated as a bounding uncertainty with a uniform probability distribution. The calculated worth of the Teflon uncertainty is 0.0356/√3 or 0.0206 %Δk.

The hot constants memo states that the graphite plates contained less than 70 ppm hydrogen. It is not known whether this value reflected a range of measured values or a detection limit. The coating would have inhibited changes in the hydrogen content of the plates due to humidity in the atmosphere. It was assumed that the average hydrogen content in the graphite plates was 35 ppm with a 35 ppm uncertainty which is treated as a bounding uncertainty with uniform probability distribution. The computed worth of the 35 ppm hydrogen uncertainty is 0.1150/√3 or 0.0664 %Δk.

The quadrature sum of the uncertainties related mass, impurities, coating composition and hydrogen content for the graphite plates is 0.0814 %Δk.

The fact that the lead plates used in the ZPR-3/59 axial and radial reflectors are not listed in any hot constants memo indicates that they were acquired specifically for the ZPR-3/59 program and were eliminated from the ZPR-3 inventory shortly after the end of that program. No records regarding the acquisition or disposition of the lead have been found.

However, the experimenters were sensitive to the effects of impurities and would have purchased lead that met ASTM standards.[b] ASTM standard B29-55 (Reapproved 1966) was the governing standard for lead during the relevant time period. The highest purity lead listed in the 1971 ASTM standard is corroding lead, and it was assumed here that corroding lead was purchased to minimize impurities. Table 2.2 shows the composition range for corroding lead as listed in the 1971 ASTM standard.

Table 2.2. Composition of Corroding Lead.

Element	Minimum wt.%	Maximum wt.%	Midpoint wt.%
Ag	0	0.0015	0.00075
Cu	0	0.0015	0.00075
As, Sb, Sn	0	0.002	0.001
Zn	0	0.001	0.0005
Fe	0	0.002	0.001
Bi	0	0.05	0.025
Pb	99.94	100	99.971

[a] J. D. Bess, Personal Communication, May 6, 2014.
[b] 1971 Annual Book of ASTM Standards, Part 7, Standard B29-55 (Reapproved 1966).

The assumed 0.15% uncertainty in the mass of the lead plates was calculated to have a 0.0433 %Δk effect. To calculate the effects of the impurities, the midpoint composition in column 4 of Table 2.2 was computed with all impurities present and without the impurities, i.e., the uncertainty of the impurities was assumed to be 100%. The calculations were performed with MCNP5-1.60 with ENDF/B-VII.1 nuclear data. Each calculation was run for one billion (10^9) histories. The computed worth of the impurities was 0.0020 ± 0.0040 %Δk which is unimportant compared to the effect of the mass uncertainty.

It is not certain that corroding lead was used in ZPR-3/59, so the effects of substituting common desilvered lead for corroding lead was examined. Common desilvered lead is another form of lead listed in 1971 ASTM standard B29-55. Table 2.3 shows the composition range for common desilvered lead as listed in the 1971 ASTM standard.

Table 2.3. Composition of Common Desilvered Lead.

Element	Minimum wt.%	Maximum wt.%	Midpoint wt.%
Ag	0	0.002	0.001
Cu	0	0.0025	0.00125
As, Sb, Sn	0	0.005	0.0025
Zn	0	0.002	0.001
Fe	0	0.002	0.001
Bi	0	0.15	0.075
Pb	99.85	100	99.91825

The computed worth of replacing corroding lead with common desilvered lead was 0.0030 ± 0.0040 %Δk which is unimportant compared to the effect of the mass uncertainty.

The quadrature sum of the uncertainties related mass, impurities and type of lead for the lead plates is 0.0436 %Δk.

The stainless steel components in this assembly are the front drawers, back drawers, matrix tubes and the Pu-Al cans. These components are made of Type 304 stainless steel. Rigorously, the uncertainties for all the components are uncorrelated and therefore should be evaluated separately. The uncertainty effect was computed for each separable assembly component (matrix tubes, front drawers, back drawers and Pu-Al cans) and then those results were added in quadrature.

It is estimated that the mass of the matrix tubes is uncertain by 2% and the masses of the other stainless steel components are uncertain by 0.15%. The calculated effect of changing the matrix tube mass by 2% yielded an uncertainty in k_{eff} of 0.1299 %Δk. The effects of 0.15% mass changes in the front drawers and back drawers are 0.0018 %Δk for the front drawers and 0.0001 %Δk for the back drawers. The effects of 0.15% mass change in the Pu-Al cans is 0.0011 %Δk.

Table 1.9 in Section 1.3 shows multiple sets of weight percent data for the stainless steel drawers and matrix tubes. From reading ZPR-3 reports written for later ZPR-3 assemblies, it is clear that stainless steel weight percent differences of the magnitudes shown in Table 1.9 were not considered significant. It appears that the average composition shown in the first data row of Table 1.9 was used for all Type 304 stainless steel components in calculations at that time. In contrast, the hot constants compositions for drawers and matrix tubes were used in the benchmark models presented in Section 3 because these component-specific compositions are believed to be more accurate.

It can be seen that all the other compositions in the table have weight percents that do not account for one to two percent of the composition. Comparing the first two compositions, it can be seen that the only significant difference is a 2 percentage point higher Fe wt.% in the first composition, which is why only the first composition does not have a deficit in total wt.%. It is not known whether the Fe weight percent was adjusted arbitrarily or for well founded reasons. Consequently, the Fe wt.% uncertainties for matrix tubes and drawers are being treated here as Type B, where the range is the difference between the Fe wt.% in the first average composition and the Fe wt.% in the matrix or drawer composition. The standard uncertainty is this range divided by $\sqrt{12}$. With the Fe wt.% adjustment issue covered by this uncertainty, it seems most consistent to compute the Fe contributions to the matrix and drawer composition biases for the as-built model using the hot constants average composition (second row of Table 1.9), which is consistent with the matrix and drawer compositions in having unadjusted Fe.

Table 2.4 gives the estimated wt.% uncertainty for each element in the Type 304 stainless steel compositions. To put these values in perspective, representative weight percents, specifically the average composition from ANL-7759, are shown in parentheses. The uncertainty for each of the major elements was taken to be 0.2 wt.%, and the uncertainty for Mn in the stainless steel was taken to be 0.075 wt.% (or 10% of the nominal value) for consistency with previous ZPR evaluations. The uncertainty for silicon was assumed to be one half of the last significant figure provided in ANL-7759,[a] due to round-off error.

Table 2.4. Type 304 Stainless Steel Weight percent Uncertainty Data.

Element	Wt.% Uncertainty	Representative Wt.% Values
Fe	Matrix 0.4 Drawers 1.0 All else 0.2	73.4
Cr	0.2	17.0
Ni	0.2	8.4
Mn	0.075	0.75
Si	0.005	0.45

The k_{eff} uncertainty contributions due to the weight percent uncertainty for the elements comprising the stainless steel were computed by perturbing the reference TWODANT model using the data in Table 2.4. The results by element and component category are given in Table 2.5. In all of the perturbations, the reference steel mass in the core was preserved by reducing the atom density of the Fe element in proportion to the modification made to the other element.

[a] A. M. Broomfield *et al*, "ZPR-3 Assemblies 48, 48A, and 48B: The Study of a Dilute Plutonium-fueled Assembly and Its Variants," Argonne National Laboratory Report ANL-7759, December 1970.

Table 2.5. Contribution from the Stainless Steel Wt.% Uncertainty to the k_{eff} Uncertainty (%Δk).

Element	Matrix	Pu-Al Cans	Front Drawers	Back Drawers
Fe	0.0049	0.0001	0.0008	<0.0001
Cr	0.0031	0.0004	0.0006	<0.0001
Ni	0.0060	0.0003	0.0011	0.0001
Mn	0.0002	0.0021	0.0005	<0.0001
Si	0.0009	0.0001	0.0001	<0.0001
Quadrature Sum	0.0084	0.0021	0.0016	0.0001

The quadrature sum of the steel mass and composition uncertainties for the matrix is 0.1302 %Δk. The quadrature sums for the front drawers and back drawers are 0.0024 %Δk and 0.0002 %Δk, respectively. The quadrature sum for the Pu-Al cans is 0.0024 %Δk. The quadrature sum of all the steel wt.% uncertainties is 0.1303 %Δk, which is totally dominated by the uncertainty in the mass of the matrix tubes.

2.4 Humidity

A very small adjustment and uncertainty due to the presence of humidity in the air was derived for an earlier ZPR assembly. This was done by comparing calculations with the assembly gaps filled by dry air and by saturated air. The calculated effect, 0.0001% Δk, is assumed to apply to this assembly and will be included simply as an uncertainty.

2.5 Combined Uncertainties and Final k_{eff}

All of the uncertainties discussed in the previous sections are collected in Table 2.6. The uncertainties in the measurement technique are not important. The uncertainties in the composition category are significantly larger than those in the measurement technique category. The main sources of uncertainty were found to be the matrix interface gap, nominal plate and drawer dimensions, matrix tube pitch, plutonium mass in plates, hydrogen content of graphite plates and matrix tube mass. These uncertainties are not correlated.

After including the total uncertainty from Table 2.6, the excess reactivity was 0.0800 ± 0.1798 %Δk, so the experimental k_{eff} is 1.000800 ± 0.001798. The estimated uncertainty is larger than the excess reactivity, yet there is no doubt that the assembly was slightly supercritical. The uncertainty estimates are believed to be reasonable. Treating the uncertainties as if they were 1σ of a normal distribution should be acceptable for the purposes of the benchmark models.

ZPR-3/59 loading 6 has been determined to be an acceptable criticality safety benchmark experiment.

Table 2.6. Summary of Uncertainties in the Experimental k_{eff} for ZPR-3/59 Loading 6.

Source of Uncertainty	Uncertainty in Excess Reactivity, %Δk
Measurement Technique	
Excess Reactivity	0.0060
Inhour to Δk Conversion	0.0040
Temperature Uncertainty	0.0045
Asymptotic Temperature	0.0010
Reproducibility	0.0024
Subtotal	**0.0089**
Geometry	
Matrix Interface Gap	0.0177
Nominal Plate, Drawer Dimensions	0.0345
Matrix Tube Pitch	0.0643
Subtotal	**0.0751**
Composition	
Plutonium	0.0332
Al in Pu-Al Plates	0.0010
Lead Plates	0.0436
Graphite Plates	0.0814
Steel in Matrix Tubes	0.1302
Steel in Drawers	0.0024
Steel in Cans	0.0024
Humidity	0.0001
Subtotal	**0.1631**
Total	**0.1798**

3.0 BENCHMARK SPECIFICATIONS

3.1 Description of Model

Recall from Section 2.1 that the measurement for which we actually have records was establishment of a critical state for the described assembly with DP Rod #5 withdrawn 1.83 inches and all the other DP (fueled) controls fully inserted. Full insertion of DP Rod #5 resulted in a small excess reactivity of 0.080 %Δk. The total of all uncertainties in this excess reactivity value, which are summarized in Table 2.6, is 0.1798 %Δk. Thus, the experimental k_{eff} = 1.0008 ± 0.0018.

As described in earlier sections, several "modeling" adjustments need to be applied to this experimental k_{eff} to make the conditions consistent with the as-built model of ZPR-3/59 loading 6. These adjustments consist of a) neglect of structure beyond the matrix tubes and all their contents, i.e., room return (see Section 2.2), b) neglect of the matrix interface gap (see Section 2.2), c) neglect of moisture, i.e., hydrogen, in the graphite plates (see Section 2.3), d) neglect of impurities in the lead, e) the neglect of the drawer portions beyond the axial reflector lead, f) neglect of graphite impurities and g) adjustment of the temperature to the benchmark value. These adjustments acknowledge that the model we call "as-built" actually models some slightly idealized conditions.

The portions of the axial reflector back drawers and the DP drawers (and drive shafts) beyond the lead axial reflector have been removed from the benchmark model. The removed portions primarily consisted of perforated aluminum plates in steel drawers and were isolated from the core by the thick lead reflector. As a result, the matrix region behind the axial reflector consists of completely empty matrix tubes. The computed worth of this simplification, -0.0480 %Δk, is treated as a bias. The associated uncertainty is assumed to 50% of the computed worth or 0.0240 %Δk.

A reasonable estimate of the EBC impurity for the graphite plates is 1 ppm. The computed worth of this impurity is 0.0022 %Δk.

The Δk for each model idealization and the net Δk are summarized in Table 3.1. Adjustments for room return, the interface gap, hydrogen in the graphite plates, neglect of impurities in lead and neglect of drawer portions beyond the axial blanket were addressed in Sections 2 and 3.1. The 0.080 %Δk excess reactivity actually corresponds to a temperature of 40 °C or 313 K. Initially, ZPR-3 had no active cooling system because none was needed until ZPR-3 acquired an inventory of plutonium plates. When the plutonium plates were acquired, a rudimentary cooling system was devised for the matrix tubes (see Section 1.2.1). This cooling system did provide some cooling, but average core temperatures were significantly higher than 20 °C. It became the practice to adjust reported excess reactivities to a standard temperature of 40 °C or 313 K[a], and the 0.080 %Δk excess reactivity corresponds to this temperature. The computed temperature coefficient is -2.49 x 10^{-3} %Δk/°C. If the uncertainty of this value is assumed to be 25%, the adjustment to 293 K is 0.0498 ± 0.0124 %Δk.

The net adjustment is -0.6350 %Δk. This is an unusually large adjustment, but it is due almost entirely to neglecting room return. Generally, the reflector in a ZPR assembly effectively isolates the core from room return. However, capture in lead is very low, so neutrons reflected by surrounding structures have a better chance of reaching the core drawers with a lead reflector relative to reflected neutrons with the more typical depleted uranium reflector used in most ZPR-3 assemblies.

[a] R. E. Kaiser et. al., "Experimental Results for ZPR-3 Assemblies 53 and 54," Argonne National Laboratory Report ANL-7882, page 17.

Application of this net adjustment to the experimental k_{eff} yields a value of 0.9944 ± 0.0023, and is referred to as the as-built model k_{eff}. This is basically an experimental result with some calculational adjustments. It is the k_{eff} we aspire to reproduce with calculations of the as-built model.

Table 3.1. Model Biases to Experimental k_{eff}.[(a,b)]

Model Bias	%Δk
Room return neglected	-0.5910 ± 0.1482
No interface gap	+0.0690 ± 0.0177[(c)]
No moisture in graphite	-0.1150 ± 0.0664[(c)]
Omit EBC impurity in graphite	0.0022 ± 0.0032[(c)]
Omit lead impurities	-0.0020 ± 0.0040
Omit drawer beyond axial reflector	-0.0480 ± 0.0240
Adjust temperature to 20 °C	0.0498 ± 0.0124
Net Bias	-0.6350 ± 0.1507

(a) Resulting from experimental features either altered or neglected in the as-built model.
(b) Biases for aluminum spacers and moisture (hydrogen) in graphite were computed with ENDF/B-VII.0 data. The biases for the interface gap, room return and lead impurities were computed with ENDF/B-VII.1 data.
(c) These uncertainties have been included in the experiment uncertainty (see Table 2.6). To avoid double counting, they are omitted from the uncertainty in the net bias.

Even the most casual perusal of Section 1 makes it clear that the as-built model of ZPR-3/59 is much too complicated to be a practical criticality safety benchmark model without a great amount of simplification. Fortunately, it is possible to eliminate virtually all of the complexity, yielding a simple benchmark model, without losing any of the essential physics. Furthermore, this can be done without compromising the high accuracy of the experiment.

This was accomplished by computing the transformation from the detailed as-built experiment model to the simple benchmark model using MCNP5. Note that the term "transformation" will be used repeatedly throughout Section 3 and will, in all cases, refer to both the simplification of the model from the as-built platewise heterogeneous experiment model to the homogeneous benchmark model, and also the correction of k_{eff} to account for these simplifications. MCNP5 eigenvalue calculations were made for the as-built model and for the benchmark model. The k_{eff} correction is simply the difference in k_{eff} between the benchmark and as-built models.

The modeling of all the experimental detail was made tractable by the development of the BLDVIM computer code[a] to generate a VIM input file.[b] BLDVIM reads an electronic database containing a description of the ZPR plate and drawer inventory, the assembly drawer masters, and the matrix loading map. The code and

[a] R. W. Schaefer, R. D. McKnight and P. J. Collins, "Lessons Learned from Applying VIM to Fast Reactor Critical Experiments," *Proceedings of the Nuclear Criticality Technology Safety Workshop*, San Diego, CA, pp. 129-136, LA-13439-C (1995).
[b] R. N. Blomquist, R. M. Lell and E. M. Gelbard, "VIM – A Continuous Energy Monte Carlo Code at ANL," A Review of the Theory and Application of Monte Carlo Methods, Proceedings of a Seminar-Workshop, Oak Ridge, TN, April 21-23, 1980, ORNL/RSIC-44, p. 31, August 1980.

database were rewritten for UNIX-based workstations, at which time the values of Avogadro's number and the atomic masses were made to conform to the values recommended by the ICSBEP. The resulting as-built VIM input file was then converted to an as-built MCNP5 input file.

Development of a practical benchmark model of any ZPR assembly starts from an as-built model. Ideally, every geometric and compositional detail of the experimental configuration would be included as faithfully as possible in the as-built model. In reality, details that are both difficult/cumbersome to model and obviously insignificant to k_{eff} are simplified. One example is that perforated drawer walls are replaced with solid walls having the equivalent average density. Another example is that the cladding is smeared into the small clearance gaps between the cladding and the "meat" of a fuel plate for clad plutonium plates.

In addition, the scope of the as-built model is limited to the matrix and its contents, and minor but non-negligible details within the as-built model scope were omitted. The matrix interface gap and room return were discussed in Section 2. The worths derived in Section 2 for the interface gap and room return are included as adjustments to the benchmark k_{eff}.

It needs to be kept in mind that, compared to what the as-built model does include, these deficiencies are few and unimportant. The deficiencies were identified here for completeness and should be kept in perspective. The as-built model is extremely detailed; it represents explicitly every plate, every drawer wall and matrix tube wall, etc.

A benchmark model of ZPR-3/59 loading 6 was generated in exactly the same way as was used for previous ZPR benchmarks. The key features retained in the benchmark model are the region-averaged compositions and region volumes. The geometric model is an RZ model that preserves the areas of the X-Y boundaries of the core, reflector and empty matrix tubes in the as-built model. Axial dimensions of each region conserve the region volumes. Note that since axial regions in the as-built model core have been defined at fuel plate boundaries (which may vary between different matrix positions due to differences in thicknesses of drawer fronts of normal and DP drawers), the axial extent which conserves the region volume may be "non-physical", i.e., it may not correspond exactly to any actual fuel-plate boundary. Masses of the constituents within these regions are then homogenized to produce the region-averaged compositions, thereby conserving material masses within each region. The VIM output edits for the as-built model included the region-average compositions, which were extracted to construct the benchmark model.

The simplification (afforded by the benchmark model) that yielded by far the greatest elimination of detail was the smearing of plates, drawers, and matrix tubes into homogeneous mixtures. The plate heterogeneity effects, which require much effort to capture accurately in effective homogenized cross sections in a deterministic modeling approach, are included in the Monte Carlo-calculated Δk of the transformation.

This transformation process has been used previously with success. Loadings from the ZPPR-21 assembly were transformed into simple benchmarks for the criticality safety assessment of Pu-U-Zr fuel treatment at Argonne's Fuel Conditioning Facility (FCF). Using sensitivity calculations and generalized-least-squares fitting, it was shown[a] that the results from this plate critical assembly are consistent with those from the homogeneous assemblies Jezebel and Godiva.

The homogeneous RZ benchmark model resulting from the transformation of the as-built platewise heterogeneous ZPR-3/59 loading 6 model is defined in the remainder of the section. Only one critical configuration was evaluated, so Case 1 is ZPR-3/59 loading 6.

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[a] D. N. Olsen, P. J. Collins and S. G. Carpenter, "Experiments of IFR Fuel Criticality in ZPPR-21," *ICNC '91 International Conference on Criticality Safety*, Oxford, UK, September 9-13, 1991.

3.2 Dimensions

Figure 3-1 shows the benchmark RZ model for Case 1, i.e., ZPR-3/59 loading 6. The boundary conditions are reflecting along the left side (R = 0.0 cm) and vacuum along the bottom (Z = -85.09 cm), top (Z = 85.09 cm) and right side (R = 96.8226 cm). Table 3.2 provides the same dimension information. It should be noted that the number of decimal places shown in Figure 3-1 and Table 3.2 does not mean that those dimensions were known that accurately. Rather, the values in the figure and table reflect the conversion from units of inches to units of centimeters.

The drawer gap shown in Figure 3-1 and listed in Table 3.2 is not a void. This gap is the space between the back of the last reflector plate in the front drawer and the front of the first reflector plate in the back drawer. The drawer gap actually consists of the spring at the back of the front drawer, the back plate of the front drawer, the associated drawer sides and bottom of the front drawer, and the front plate of the back drawer.

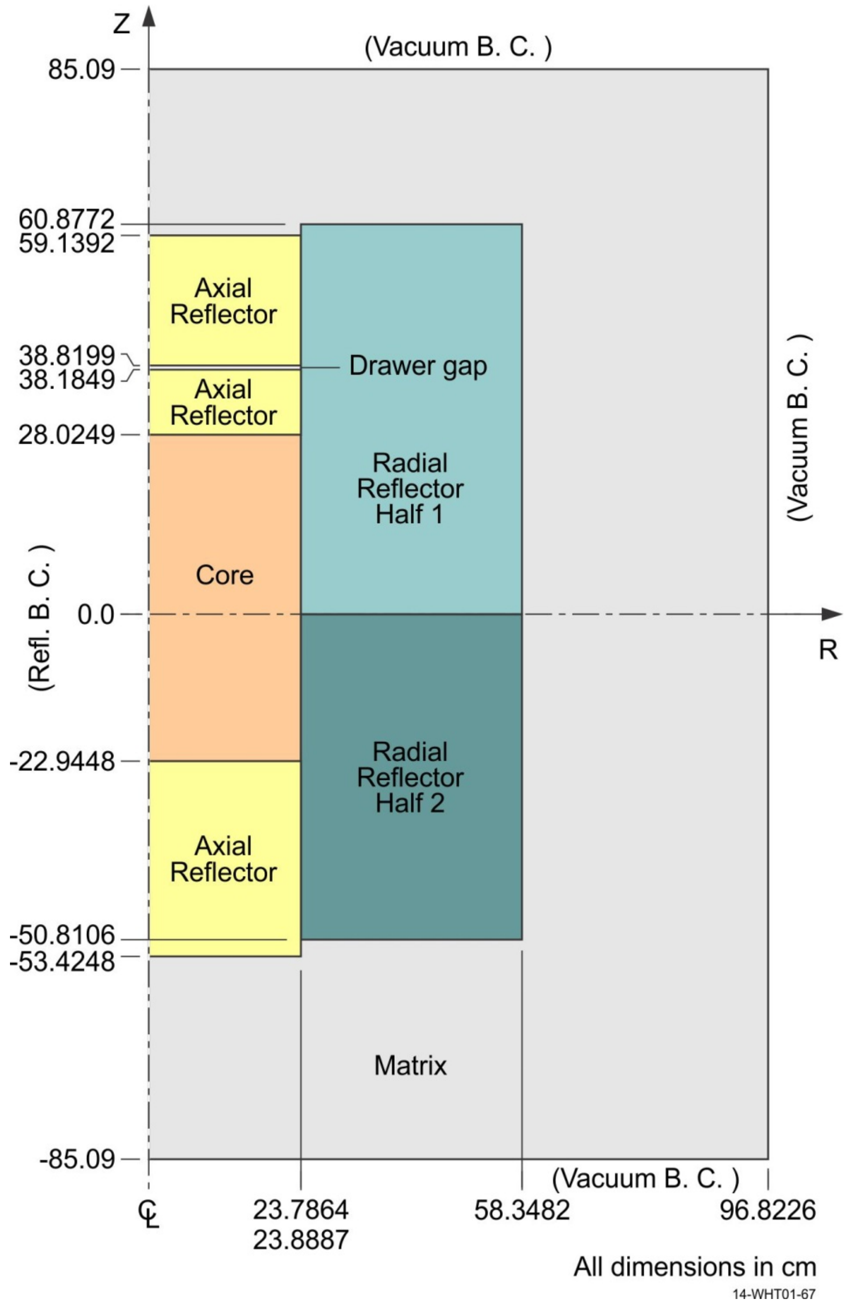

Figure 3-1. Case 1 (ZPR-3/59 Loading 6) Benchmark Model.

Table 3.2. Benchmark- Model Region Dimensions.

Region	Inner Radius (cm)	Outer Radius (cm)	Lower Height (cm)	Upper Height (cm)
Core – Half 2	0.0	23.8887	-22.9448	0.0
Core – Half 1	0.0	23.7864	0.0	28.0249
Axial Reflector - 1	0.0	23.8887	-53.4248	-22.9448
Axial Reflector - 2	0.0	23.7864	28.0249	38.1849
Drawer Gap	0.0	23.7864	38.1849	38.8199
Axial Reflector - 3	0.0	23.7864	38.8199	59.1392
Radial Reflector– Half 2	23.8887	58.3482	-50.8106	0.0
Radial Reflector- Half 1	23.7864	58.3482	0.0	60.8772
Matrix[(a)]	0.0	96.8226	-85.0900	85.0900

(a) The matrix fills the remaining space that is not occupied by the core, axial reflector, drawer gap and radial reflector.

The regions listed as "Axial Reflector – 1", "Axial Reflector – 2" and "Axial Reflector – 3" in Table 3.2 all have the same composition ("Axial Reflector" in Table 3.3). They are just shown as "Axial Reflector" in Figure 3-1 to avoid any uncertainty concerning whether the three axial reflector regions have different compositions.

The core radius is slightly smaller in half 1 (upper half, $Z > 0$) than the core radius in half 2 (lower half, $Z < 0$) because there was a partial fuel element present in half 2 that was not present in half 1 (compare Figures 1-4 and 1-5).

3.3 Material Data

Table 3.3 contains the region-dependent composition data for the benchmark model of Case 1 (ZPR-3/59 loading 6).

For the convenience of readers whose computer codes require total atom densities, the total atom densities for the benchmark compositions in Table 3.3 are:

1) Core - 7.087767E-02 at/b-cm,
2) Axial Reflector - 3.564809E-02 at/b-cm,
3) Radial Reflector-Half 1 - 3.384438E-02 at/b-cm,
4) Radial Reflector-Half 2 - 3.380632E-02 at/b-cm,
4) Drawer Gap - 2.410944E-02 at/b-cm,
5) Matrix - 6.197100E-03 at/b-cm.

Table 3.3. Compositions of the Benchmark Model Regions
of Case 1 (atoms/barn-cm).

Nuclide	1 – Core	2 - Axial Reflector	3 - Radial Reflector – Half 1
^{240}Pu	9.95365E-05	0.00000E+00	0.00000E+00
^{241}Pu	5.72562E-06	0.00000E+00	0.00000E+00
^{239}Pu	2.10081E-03	0.00000E+00	0.00000E+00
^{238}Pu	3.73187E-09	0.00000E+00	0.00000E+00
^{242}Pu	1.79101E-07	0.00000E+00	0.00000E+00
^{241}Am	3.29312E-06	0.00000E+00	0.00000E+00
Cr	1.91426E-03	1.46684E-03	1.11212E-03
Ni	8.56174E-04	6.20786E-04	4.55197E-04
Fe	7.44997E-03	5.89311E-03	4.53786E-03
Al	2.20421E-04	0.00000E+00	0.00000E+00
O	8.96044E-05	0.00000E+00	0.00000E+00
C	5.77309E-02	0.00000E+00	0.00000E+00
Mo	4.34689E-06	0.00000E+00	0.00000E+00
^{55}Mn	1.13224E-04	7.20937E-05	4.39192E-05
Cu	5.70933E-06	0.00000E+00	0.00000E+00
Pb	0.00000E+00	2.75143E-02	2.76345E-02
Ti	4.47813E-05	0.00000E+00	0.00000E+00
Si	9.55959E-05	7.46598E-05	6.07818E-05
^{19}F	1.43132E-04	0.00000E+00	0.00000E+00
Nuclide	**4 - Radial Reflector – Half 2**	**5 - Drawer Gap**	**6 – Matrix**
Cr	1.10431E-03	3.17537E-03	1.10960E-03
Ni	4.51668E-04	1.46192E-03	4.53554E-04
Fe	4.50718E-03	1.88265E-02	4.52968E-03
C	0.00000E+00	2.94049E-04	0.00000E+00
^{55}Mn	4.34331E-05	2.11494E-04	4.34957E-05
Pb	2.76393E-02	0.00000E+00	0.00000E+00
Si	6.04244E-05	1.40104E-04	6.07700E-05
^{19}F	1.21690E-05	0.00000E+00	0.00000E+00

3.4 Temperature Data

The benchmark temperature is 293 K (20 °C).

3.5 Experimental and Benchmark-Model k_{eff}

The last adjustment to the measured result is the transformation from the as-built model conditions to the benchmark model conditions. The transformation Δk (bias) from the as-built configuration to the benchmark model that was described in Section 3.1 was calculated using the MCNP5 Monte Carlo code. The individual k_{eff} values and the transformation Δk for ZPR-3/59 loading 6 are shown in Table 3.4. The uncertainties shown are just the statistical standard deviations from MCNP5. It is noted that this transformation Δk is relatively large compared with the transformation for many of the other ANL ZPR benchmark assemblies. This results from the larger core unit cell heterogeneity effects, which, in turn, are due to the softer spectrum in this assembly.

Table 3.4. Eigenvalues for Transformation from As-Built Model to RZ Benchmark Model for Case 1.

	As-Built Model k_{eff}	RZ Benchmark Model k_{eff}	Transformation Δk (bias)
MCNP5 (ENDF/B-VII.1)	0.99684 ± 0.00009	0.97472 ± 0.00009	-0.02212 ± 0.00013

An estimate of the total uncertainty in the transformation Δk from the as-built platewise heterogeneous critical-assembly model to the homogeneous RZ model is needed. Since there are no significant geometric approximations in the as-built model and there are no cross section processing approximations associated with either model, the only sources of uncertainty added to the original experimental uncertainty come from Monte Carlo statistical precision and the sensitivity of the calculated Δk values to uncertainties in basic cross section data.

To test the sensitivity of the calculated Δk values to uncertainties in basic cross section data, the transformation was computed with ENDF/B-V.2, -VI.0, -VII.0 and -VII.1 for ZPR-3/58 (PU-MET-INTER-003). The differences in the transformation relative to ENDF/B-VII.1 were -99 ± 10 pcm for ENDF/B-V.2, 1 ± 10 pcm for ENDF/B-VI.0 and 59 ± 10 pcm for ENDF/B-VII.0. Based on the range of these values, the uncertainty in the transformation is taken to be 99 pcm or 0.00099. Adding in quadrature to this the 0.006% uncertainty due to the Monte Carlo statistics yields a total uncertainty in the transformation Δk of ±0.099 %Δk. The same uncertainty is assumed here. This uncertainty estimate is believed to be realistic and still sufficiently small for criticality safety benchmark purposes.

The experimental and benchmark model k_{eff} values are summarized in Table 3.5. The data in Table 3.5 are in units of k_{eff}. The experimental k_{eff}, shown in the first row, is the value arrived at in Section 2.5 and reiterated in Section 3.1. The adjusted experimental k_{eff}, shown in the second row, was obtained in Section 3.1 by adding the experimental k_{eff} from the first row and the net bias from Table 3.1. The third row contains the transformation Δk from Table 3.4. The transformation Δk is the difference between the final benchmark model k_{eff} and the as-built model k_{eff}. Its assigned uncertainty is dominated by the impact of cross section data uncertainties on the transformation calculation. The transformation Δk includes all of the differences between the benchmark model and the as-built experiment except for those listed in Table 3.1. Adding the transformation Δk to the adjusted experimental k_{eff} yields the benchmark model k_{eff} shown in the last row of the table. It is the k_{eff} against which k_{eff} results calculated using the benchmark model should be compared.

Table 3.5. Experimental and Benchmark-Model Eigenvalues.[a]

	Case 1 – ZPR-3/59 Loading 6
Experimental k_{eff}	1.0008 ± 0.0018
Adjusted Experimental k_{eff}	0.9944 ± 0.0023
Monte Carlo Transformation of Model	-0.0221 ± 0.0010
Benchmark Model k_{eff}	0.9723 ± 0.0025

(a) Each uncertainty estimate is one standard deviation.

4.0 RESULTS OF SAMPLE CALCULATIONS

Results of sample calculations of the benchmark models are given in Table 4.1 for Case 1, ZPR-3/59 loading 6. These results are based on accumulating 1800 generations with 50,000 neutrons per generation for a total of 90,000,000 histories after skipping 100 initial generations to converge the source. More details of the calculations, including input listings, are given in Appendix A.

Table 4.1. Sample Calculation Results for Case 1, ZPR-3/59 Loading 6.

	MCNP5 (Continuous Energy ENDF/B-VII.1)
Case 1	0.97472 ± 0.00009

Calculations with ENDF/B-VII.1 data are approximately 0.24 %Δk (~1σ) above the benchmark value.

5.0 REFERENCES

1. J. M. Stevenson, J. M. Gasidlo, V. C. Rogers, G. G. Simons and R. O. Vosburgh, "Experimental Results for ZPR-3 Assemblies 58 and 59," Argonne National Laboratory, ANL-7695, April 1970.

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 MCNP Input Listings

The MCNP5 code was used with the ENDF/B-VII.1 continuous energy cross sections for all nuclides. The calculation used 90 million histories, with 50000 neutron histories per generation and 1800 active generations after skipping 100 generations.

MCNP5 ENDF/B-VII.1 Input Listing, Table 4.1.

```
PU-MET-INTER-004 - ZPR-3/59 L006 - Benchmark Model - VII.1 XS
1     1  7.087767E-02  -1   7  -8  imp:n=1 $ core - H2 - lower
2     1  7.087767E-02 -15   8  -9  imp:n=1 $ core - H1 - upper
3     2  3.564809E-02  -1   5  -7  imp:n=1 $ axial refl-lower
4     2  3.564809E-02 -15   9 -10  imp:n=1 $ axial refl-upper 1
5     5  2.410944E-02 -15  10 -11  imp:n=1 $ drawer gap
6     2  3.564809E-02 -15  11 -12  imp:n=1 $ axial refl-upper 2
7     6  6.197100E-03  -1   4  -5  imp:n=1 $ matrix-lower 1
8     6  6.197100E-03 -15  12 -14  imp:n=1 $ matrix-upper 1
9     4  3.380632E-02   1  -2   6  -8  imp:n=1 $ radial refl-lower
10    3  3.384438E-02  15  -2   8 -13  imp:n=1 $ radial refl-upper
11    6  6.197100E-03   1  -2   4  -6  imp:n=1 $ matrix-lower 2
12    6  6.197100E-03  15  -2  13 -14  imp:n=1 $ matrix-upper 2
13    6  6.197100E-03   2  -3   4 -14  imp:n=1 $ matrix-radial
14    0               (3:-4:14)  imp:n=0 $ external void

1     cz     23.8887
2     cz     58.3482
3     cz     96.8226
4     pz    -85.0900
5     pz    -53.4248
6     pz    -50.8106
7     pz    -22.9448
8     pz      0.0000
9     pz     28.0249
10    pz     38.1849
11    pz     38.8199
12    pz     59.1392
13    pz     60.8772
14    pz     85.0900
15    cz     23.7864

mode  n
kcode   50000  1.0  100  1900  2500000
sdef   erg=d1 rad=d2 ext=d3 pos 0 0 0.0 axs 0 0 1
sp1    -2
si2    0.0  23.78
si3    -22.9  28.0
m001        $ N=7.087767E-02 Core
       94240.80c  9.95365E-05
       94241.80c  5.72562E-06
       94239.80c  2.10081E-03
       94238.80c  3.73187E-09
       94242.80c  1.79101E-07
       95241.80c  3.29312E-06
       24050.80c  8.31746E-05
       24052.80c  1.60394E-03
       24053.80c  1.81874E-04
       24054.80c  4.52722E-05
       28058.80c  5.82857E-04
       28060.80c  2.24515E-04
       28061.80c  9.75953E-06
       28062.80c  3.11176E-05
       28064.80c  7.92475E-06
       26054.80c  4.35451E-04
       26056.80c  6.83565E-03
       26057.80c  1.57865E-04
```

```
       26058.80c  2.10089E-05
       13027.80c  2.20421E-04
        8016.80c  8.96044E-05
        6000.80c  5.77309E-02
       42092.80c  6.42036E-07
       42094.80c  4.01218E-07
       42095.80c  6.91156E-07
       42096.80c  7.25061E-07
       42097.80c  4.15563E-07
       42098.80c  1.05151E-06
       42100.80c  4.20344E-07
       25055.80c  1.13224E-04
       29063.80c  3.94800E-06
       29065.80c  1.76133E-06
       22046.80c  3.69446E-06
       22047.80c  3.33173E-06
       22048.80c  3.30128E-05
       22049.80c  2.42267E-06
       22050.80c  2.31967E-06
       14028.80c  8.81614E-05
       14029.80c  4.47867E-06
       14030.80c  2.95583E-06
        9019.80c  1.43132E-04
m002         $ N=3.564809E-02 Axial reflector
       24050.80c  6.37342E-05
       24052.80c  1.22905E-03
       24053.80c  1.39364E-04
       24054.80c  3.46908E-05
       28058.80c  4.26901E-04
       28060.80c  1.64441E-04
       28061.80c  7.14815E-06
       28062.80c  2.27914E-05
       28064.80c  5.80431E-06
       26054.80c  3.44452E-04
       26056.80c  5.40716E-03
       26057.80c  1.24875E-04
       26058.80c  1.66186E-05
       25055.80c  7.20937E-05
       82204.80c  3.85200E-04
       82206.80c  6.63095E-03
       82207.80c  6.08066E-03
       82208.80c  1.44175E-02
       14028.80c  6.88535E-05
       14029.80c  3.49781E-06
       14030.80c  2.30848E-06
m003         $ N=3.384438E-02 Radial reflector-H1
       24050.80c  4.83216E-05
       24052.80c  9.31834E-04
       24053.80c  1.05663E-04
       24054.80c  2.63016E-05
       28058.80c  3.09884E-04
       28060.80c  1.19367E-04
       28061.80c  5.18879E-06
       28062.80c  1.65441E-05
       28064.80c  4.21330E-06
       26054.80c  2.65238E-04
       26056.80c  4.16367E-03
       26057.80c  9.61573E-05
       26058.80c  1.27968E-05
       25055.80c  4.39192E-05
       82204.80c  3.86883E-04
       82206.80c  6.65991E-03
       82207.80c  6.10722E-03
       82208.80c  1.44805E-02
       14028.80c  5.60548E-05
       14029.80c  2.84763E-06
       14030.80c  1.87937E-06
m004         $ N=3.380632E-02 Radial reflector-H2
       24050.80c  4.79823E-05
       24052.80c  9.25290E-04
       24053.80c  1.04920E-04
```

```
       24054.80c  2.61169E-05
       28058.80c  3.07482E-04
       28060.80c  1.18441E-04
       28061.80c  5.14856E-06
       28062.80c  1.64159E-05
       28064.80c  4.18064E-06
       26054.80c  2.63445E-04
       26056.80c  4.13552E-03
       26057.80c  9.55071E-05
       26058.80c  1.27102E-05
       25055.80c  4.34331E-05
       82204.80c  3.86950E-04
       82206.80c  6.66107E-03
       82207.80c  6.10829E-03
       82208.80c  1.44830E-02
       14028.80c  5.57252E-05
       14029.80c  2.83088E-06
       14030.80c  1.86832E-06
m005        $ N=2.410944E-02 Drawer gap
       24050.80c  1.37970E-04
       24052.80c  2.66061E-03
       24053.80c  3.01692E-04
       24054.80c  7.50975E-05
       28058.80c  9.95230E-04
       28060.80c  3.83361E-04
       28061.80c  1.66644E-05
       28062.80c  5.31335E-05
       28064.80c  1.35315E-05
       26054.80c  1.10041E-03
       26056.80c  1.72741E-02
       26057.80c  3.98934E-04
       26058.80c  5.30907E-05
        6000.80c  2.94049E-04
       25055.80c  2.11494E-04
       14028.80c  1.29208E-04
       14029.80c  6.56387E-06
       14030.80c  4.33202E-06
m006        $ N=6.197100E-03 Matrix
       24050.80c  4.82121E-05
       24052.80c  9.29723E-04
       24053.80c  1.05423E-04
       24054.80c  2.62420E-05
       28058.80c  3.08766E-04
       28060.80c  1.18936E-04
       28061.80c  5.17006E-06
       28062.80c  1.64844E-05
       28064.80c  4.19810E-06
       26054.80c  2.64760E-04
       26056.80c  4.15616E-03
       26057.80c  9.59839E-05
       26058.80c  1.27737E-05
       25055.80c  4.34957E-05
       14028.80c  5.60439E-05
       14029.80c  2.84707E-06
       14030.80c  1.87901E-06
totnu
phys:n   20.0   0.0
ctme     99000.0
```

APPENDIX B: Drawer Plate Loading Description for ZPR-3/59 Loading 6

Table B.1 provides the drawer plate loading description for each drawer master used in ZPR-3/59 loading 6. Interpretation of the drawer plate loading descriptions in this table was provided previously in Section 1.2.2.

Table B.1. Drawer Plate Loading Description for ZPR-3/59 Loading 6.[a]

Plate ID (dimensions in inches)	Starting X Location	Starting Y Location	Starting Z Location	X #	Y #	Z #	Rotation
Drawer Master 59-1-100							
Graphite (coated) (1/8x2x2)	0.0000	0.0000	0.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	2.0000	4	1	1	1
Graphite (coated) (1/8x2x3)	0.0000	0.0000	4.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	7.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	9.0000	4	1	1	1
Pu-Al - No Ni (1/8x2x2)	0.5000	0.0000	0.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.5000	0.0000	2.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x3)	0.5000	0.0000	3.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.5000	0.0000	6.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x3)	0.5000	0.0000	7.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.5000	0.0000	10.0000	1	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	0.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	2.0000	7	1	1	1
Graphite (coated) (1/8x2x3)	0.6250	0.0000	4.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	7.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	9.0000	7	1	1	1
Pu-Al - No Ni (1/8x2x2)	1.5000	0.0000	0.0000	1	1	2	1
Pu-Al - No Ni (1/8x2x3)	1.5000	0.0000	4.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x2)	1.5000	0.0000	7.0000	1	1	2	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	0.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	2.0000	3	1	1	1
Graphite (coated) (1/8x2x3)	1.6250	0.0000	4.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	7.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	9.0000	3	1	1	1
Lead (2x2x4) ZPR-3	0.0000	0.0000	11.0000	1	1	1	1
Drawer Master 59-2-100							
Graphite (coated) (1/8x2x2)	0.0000	0.0000	0.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	2.0000	3	1	1	1
Graphite (coated) (1/8x2x3)	0.0000	0.0000	4.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	7.0000	3	1	1	1
Pu-Al - No Ni (1/8x2x2)	0.3750	0.0000	0.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.3750	0.0000	2.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x3)	0.3750	0.0000	3.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.3750	0.0000	6.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x2)	0.3750	0.0000	7.0000	1	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	0.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	2.0000	7	1	1	1
Graphite (coated) (1/8x2x3)	0.5000	0.0000	4.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	7.0000	7	1	1	1
Pu-Al - No Ni (1/8x2x3)	1.3750	0.0000	0.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x2)	1.3750	0.0000	3.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x3)	1.3750	0.0000	5.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	1.3750	0.0000	8.0000	1	1	1	1

Graphite (coated) (1/8x2x2)	1.5000	0.0000	0.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	2.0000	4	1	1	1
Graphite (coated) (1/8x2x3)	1.5000	0.0000	4.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	7.0000	4	1	1	1
Lead (2x2x4) ZPR-3	0.0000	0.0000	9.0000	1	1	3	1
Drawer Master 59-1-102							
Graphite (coated) (1/8x2x2)	0.0000	0.0000	0.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	2.0000	4	1	1	1
Graphite (coated) (1/8x2x3)	0.0000	0.0000	4.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	7.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	9.0000	4	1	1	1
Pu-Al - Ni Clad (1/8x2x2)	0.5000	0.0000	0.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x1)	0.5000	0.0000	2.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x3)	0.5000	0.0000	3.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x1)	0.5000	0.0000	6.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x3)	0.5000	0.0000	7.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x1)	0.5000	0.0000	10.0000	1	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	0.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	2.0000	7	1	1	1
Graphite (coated) (1/8x2x3)	0.6250	0.0000	4.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	7.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.6250	0.0000	9.0000	7	1	1	1
Pu-Al - Ni Clad (1/8x2x2)	1.5000	0.0000	0.0000	1	1	2	1
Pu-Al - Ni Clad (1/8x2x3)	1.5000	0.0000	4.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x2)	1.5000	0.0000	7.0000	1	1	2	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	0.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	2.0000	3	1	1	1
Graphite (coated) (1/8x2x3)	1.6250	0.0000	4.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	7.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.6250	0.0000	9.0000	3	1	1	1
Lead (2x2x4) ZPR-3	0.0000	0.0000	11.0000	1	1	1	1
Drawer Master 59-2-102							
Graphite (coated) (1/8x2x2)	0.0000	0.0000	0.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	2.0000	3	1	1	1
Graphite (coated) (1/8x2x3)	0.0000	0.0000	4.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	7.0000	3	1	1	1
Pu-Al - Ni Clad (1/8x2x2)	0.3750	0.0000	0.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x1)	0.3750	0.0000	2.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x3)	0.3750	0.0000	3.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x1)	0.3750	0.0000	6.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x2)	0.3750	0.0000	7.0000	1	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	0.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	2.0000	7	1	1	1
Graphite (coated) (1/8x2x3)	0.5000	0.0000	4.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	7.0000	7	1	1	1
Pu-Al - Ni Clad (1/8x2x3)	1.3750	0.0000	0.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x2)	1.3750	0.0000	3.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x3)	1.3750	0.0000	5.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x1)	1.3750	0.0000	8.0000	1	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	0.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	2.0000	4	1	1	1
Graphite (coated) (1/8x2x3)	1.5000	0.0000	4.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	7.0000	4	1	1	1
Lead (2x2x4) ZPR-3	0.0000	0.0000	9.0000	1	1	3	1

Drawer Master 59-2-103							
Lead (2x1x4) ZPR-3	0.0000	0.0000	0.0000	1	1	2	5
Lead (2x1x1) ZPR-3	0.0000	0.0000	8.0000	1	1	1	5
Graphite (coated) (1/8x2x2)	1.0000	0.0000	0.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.0000	0.0000	2.0000	3	1	1	1
Graphite (coated) (1/8x2x3)	1.0000	0.0000	4.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.0000	0.0000	7.0000	3	1	1	1
Pu-Al - Ni Clad (1/8x2x3)	1.3750	0.0000	0.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x2)	1.3750	0.0000	3.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x3)	1.3750	0.0000	5.0000	1	1	1	1
Pu-Al - Ni Clad (1/8x2x1)	1.3750	0.0000	8.0000	1	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	0.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	2.0000	4	1	1	1
Graphite (coated) (1/8x2x3)	1.5000	0.0000	4.0000	4	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	7.0000	4	1	1	1
Lead (2x2x4) ZPR-3	0.0000	0.0000	9.0000	1	1	3	1
Drawer Master 59-1-200							
Lead (2x2x4) ZPR-3	0.0000	0.0000	0.0000	1	1	6	1
Drawer Master 59-2-200							
Lead (2x2x4) ZPR-3	0.0000	0.0000	0.0000	1	1	5	1
Drawer Master 59-1-201							
Lead (2x2x4) ZPR-3	0.0000	0.0000	0.0000	1	1	1	1
Lead (2x1.125x2) ZPR-3	0.0000	0.0000	4.0000	1	1	1	1
Lead (2x1.125x1) ZPR-3	0.0000	0.0000	7.0000	1	1	1	1
Lead (2x0.875x4) ZPR-3	0.0000	1.1250	4.0000	1	1	1	1
Lead (2x2x4) ZPR-3	0.0000	0.0000	8.0000	1	1	3	1
Al-45% Void (1/8x2x1)	0.0000	0.0000	20.0000	1	2	1	5
Drawer Master 59-2-201							
Lead (2x2x4) ZPR-3	0.0000	0.0000	0.0000	1	1	1	1
Lead (2x1.125x3) ZPR-3	0.0000	0.0000	4.0000	1	1	1	1
Lead (2x0.875x4) ZPR-3	0.0000	1.1250	4.0000	1	1	1	1
Lead (2x2x4) ZPR-3	0.0000	0.0000	8.0000	1	1	3	1
Al-45% Void (1/8x2x1)	0.0000	0.0000	20.0000	1	2	1	5
Drawer Master 59-1-203							
Lead (2x2x4) ZPR-3	0.0000	0.0000	0.0000	1	1	1	1
Lead (2x2x4) 1.25" axial hol	0.0000	0.0000	4.0000	1	1	4	1
Al-45% Void (1/8x2x1)	0.0000	0.0000	20.0000	1	2	1	5
Drawer Master 59-1-205							
Lead (2x2x4) ZPR-3	0.0000	0.0000	0.0000	1	1	2	1
Lead (2x2x4) 1.25" axial hol	0.0000	0.0000	8.0000	1	1	3	1
Al-45% Void (1/8x2x1)	0.0000	0.0000	20.0000	1	2	1	5
Drawer Master 59-2-205							
Lead (2x2x4) ZPR-3	0.0000	0.0000	0.0000	1	1	2	1
Lead (2x2x4) 1.25" axial hol	0.0000	0.0000	8.0000	1	1	3	1
Al-45% Void (1/8x2x1)	0.0000	0.0000	20.0000	1	2	1	5
Drawer Master 59-1-300							
Lead (2x2x4) ZPR-3	0.0000	0.0000	0.0000	1	1	2	1
Al-45% Void (1/8x2x3)	0.0000	0.0000	8.0000	1	2	1	5
Drawer Master 59-1-400							
Graphite (coated) (1/8x2x2)	0.0000	0.0000	0.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	2.0000	3	1	1	1
Graphite (coated) (1/8x2x3)	0.0000	0.0000	4.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	7.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	9.0000	3	1	1	1

Pu-Al - No Ni (1/8x2x2)	0.3750	0.0000	0.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.3750	0.0000	2.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x3)	0.3750	0.0000	3.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.3750	0.0000	6.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x3)	0.3750	0.0000	7.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.3750	0.0000	10.0000	1	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	0.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	2.0000	7	1	1	1
Graphite (coated) (1/8x2x3)	0.5000	0.0000	4.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	7.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	9.0000	7	1	1	1
Pu-Al - No Ni (1/8x2x2)	1.3750	0.0000	0.0000	1	1	2	1
Pu-Al - No Ni (1/8x2x3)	1.3750	0.0000	4.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x2)	1.3750	0.0000	7.0000	1	1	2	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	0.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	2.0000	3	1	1	1
Graphite (coated) (1/8x2x3)	1.5000	0.0000	4.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	7.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	9.0000	3	1	1	1
Lead (1.875x2x4) ZPR-3	0.0000	0.0000	11.0000	1	1	1	1
DP rod retainer spring (1.75x2	0.0000	0.0000	15.0000	1	1	1	1
DP rod retainer spring (1.75x2	0.0000	0.0000	15.0625	1	1	1	1
DP drawer divider plate (1.75x	0.0000	0.0000	15.1250	1	1	1	1
Lead (1.875x2x4) ZPR-3	0.0000	0.0000	15.1875	1	1	2	1
Al-45% Void (1/8x2x3)	0.0000	0.0000	23.1875	8	1	1	1
Al-45% Void (1/8x2x3)	1.0000	0.0000	23.1875	7	1	1	1
Al-45% Void (1/8x2x3)	0.0000	0.0000	26.1875	8	1	1	1
Al-45% Void (1/8x2x3)	1.0000	0.0000	26.1875	7	1	1	1
Al-45% Void (1/8x2x3)	0.0000	0.0000	29.1875	8	1	1	1
Al-45% Void (1/8x2x3)	1.0000	0.0000	29.1875	7	1	1	1
Drawer Master 59-1-401							
Lead (1.875x2x4) ZPR-3	0.0000	0.0000	0.0000	1	1	3	1
Lead (1.875x2x3) ZPR-3	0.0000	0.0000	12.0000	1	1	1	1
DP rod retainer spring (1.75x2	0.0000	0.0000	15.0000	1	1	1	1
DP rod retainer spring (1.75x2	0.0000	0.0000	15.0625	1	1	1	1
DP drawer divider plate (1.75x	0.0000	0.0000	15.1250	1	1	1	1
Lead (1.875x2x1) ZPR-3	0.0000	0.0000	15.1875	1	1	1	1
Lead (1.875x2x4) ZPR-3	0.0000	0.0000	16.1875	1	1	2	1
Al-45% Void (1/8x2x2)	0.0000	0.0000	24.1875	8	1	1	1
Al-45% Void (1/8x2x2)	1.0000	0.0000	24.1875	7	1	1	1
Al-45% Void (1/8x2x3)	0.0000	0.0000	26.1875	8	1	1	1
Al-45% Void (1/8x2x3)	1.0000	0.0000	26.1875	7	1	1	1
Al-45% Void (1/8x2x3)	0.0000	0.0000	29.1875	8	1	1	1
Al-45% Void (1/8x2x3)	1.0000	0.0000	29.1875	7	1	1	1
Drawer Master 59-2-400							
Graphite (coated) (1/8x2x2)	0.0000	0.0000	0.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	2.0000	3	1	1	1
Graphite (coated) (1/8x2x3)	0.0000	0.0000	4.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	0.0000	0.0000	7.0000	3	1	1	1
Pu-Al - No Ni (1/8x2x2)	0.3750	0.0000	0.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.3750	0.0000	2.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x3)	0.3750	0.0000	3.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	0.3750	0.0000	6.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x2)	0.3750	0.0000	7.0000	1	1	1	1

Graphite (coated) (1/8x2x2)	0.5000	0.0000	0.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	2.0000	7	1	1	1
Graphite (coated) (1/8x2x3)	0.5000	0.0000	4.0000	7	1	1	1
Graphite (coated) (1/8x2x2)	0.5000	0.0000	7.0000	7	1	1	1
Pu-Al - No Ni (1/8x2x3)	1.3750	0.0000	0.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x2)	1.3750	0.0000	3.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x3)	1.3750	0.0000	5.0000	1	1	1	1
Pu-Al - No Ni (1/8x2x1)	1.3750	0.0000	8.0000	1	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	0.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	2.0000	3	1	1	1
Graphite (coated) (1/8x2x3)	1.5000	0.0000	4.0000	3	1	1	1
Graphite (coated) (1/8x2x2)	1.5000	0.0000	7.0000	3	1	1	1
Lead (1.875x2x4) ZPR-3	0.0000	0.0000	9.0000	1	1	1	1
Lead (1.875x2x2) ZPR-3	0.0000	0.0000	13.0000	1	1	1	1
DP rod retainer spring (1.75x2	0.0000	0.0000	15.0000	1	1	1	1
DP rod retainer spring (1.75x2	0.0000	0.0000	15.0625	1	1	1	1
DP drawer divider plate (1.75x	0.0000	0.0000	15.1250	1	1	1	1
Lead (1.875x2x2) ZPR-3	0.0000	0.0000	15.1875	1	1	1	1
Lead (1.875x2x4) ZPR-3	0.0000	0.0000	17.1875	1	1	1	1
Al-45% Void (1/8x2x2)	0.0000	0.0000	21.1875	8	1	1	1
Al-45% Void (1/8x2x2)	1.0000	0.0000	21.1875	7	1	1	1
Al-45% Void (1/8x2x3)	0.0000	0.0000	23.1875	8	1	1	1
Al-45% Void (1/8x2x3)	1.0000	0.0000	23.1875	7	1	1	1
Al-45% Void (1/8x2x3)	0.0000	0.0000	26.1875	8	1	1	1
Al-45% Void (1/8x2x3)	1.0000	0.0000	26.1875	7	1	1	1
Al-45% Void (1/8x2x3)	0.0000	0.0000	29.1875	8	1	1	1
Al-45% Void (1/8x2x3)	1.0000	0.0000	29.1875	7	1	1	1
Connecting Shaft for DP Drawers							
Stainless Steel (1/4x2x1)	0.9225	0.0000	0.0000	1	1	1	1

(a) All dimensions and locations are in inch units.

APPENDIX C: As-Built MCNP Model for ZPR-3/59 Loading 6

An as-built MCNP model for ZPR-3/59 loading 6 is provided here (pmi004ab.txt).