Covariance Matrix Generation at ANL

Nuclear Engineering Division

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Introduction

Since the advent of the nuclear power industry, experiments have been performed at various research facilities throughout the world dealing with specific physics and criticality issues. To archive and evaluate this vast quantity of highly specific (and expensive to produce) information in a single standardized format, two separate international projects have been initiated; they are the International Reactor Physics Experiment Evaluation Project (IRPhEP) and the International Criticality Safety Benchmark Evaluation Project (ICSBEP).

Uncertainties from these evaluated benchmark reports can be used to generate covariance matrices, which in turn, can be used to make gross data adjustments to nuclear cross sections to better fit experimentally measured integral data from these experiments.

This report discusses the generation of covariance matrices using a computer program developed at Argonne National Laboratory (ANL). Previously, covariance matrices were generated at ANL using Excel spreadsheets. However, the spreadsheet method was hands-on, thus it was cumbersome and very time consuming.

The computer program sample case, which will be discussed below, is based on the eight ANL ZPR-3 critical experiments shown in Table 1. This series of ZPR-3 experiments were performed at ANL-West, now named Idaho National Laboratory (INL), in the mid 1950's through the early 1970's.

Table 1. ICABEP Identification Name and ZPR-3 Experiment Name.

ICSBEP ID Name	ICSBEP Name Abbreviation	ZPR-3 Experiment
IEU-MET-FAST-015	IMF-015	ASSEMBLY 6F
IEU-MET-FAST-016	IMF-016	ASSEMBLY 11
IEU-COMP-FAST-004	ICF-004	ASSEMBLY 12
HEU-MET-FAST-055	HMF-055	ASSEMBLY 23
IEU-MET-FAST-012	IMF-012	ASSEMBLY 41
MIX-COMP-FAST-003	MCF-003	ASSEMBLY 48
MIX-COMP-FAST-003	MCF-003	ASSEMBLY 48B
MIX-COMP-FAST-004	MCF-004	ASSEMBLY 56B

Upon evaluating critical experiments from a series of several ANL machines (ZPR-3, ZPR-6, ZPR-9 and ZPPR) and renaming uncertainties that are the same (but with different descriptions), the distinct uncertainties shown in Table 2 were obtained. It turns out that there were a total of 62 uncorrelated uncertainty types identified that can be grouped in three broad uncertainty classes (Measurement Technique, Geometry and Composition). Because of the varying makeup of these assemblies, most of these uncertainty types (48 out of 62) are composition related.

Table 2. Distinct Uncertainty Class, Type and Weighting Matrices for ANL Critical Assemblies.

Number	Uncertainty Class	Uncertainty Type	Uncertainty Abbreviation	Weighting Matrix No.
1	MT ¹	Excess Reactivity	EXCESS	1
2	MT	Inhours to Δk	INHOUR	1
3	MT	Temperature	TEMP	1
4	MT	Reproducibility	REPRO	1
5	Geom ²	Room Return	RM RET	1
6	Geom	13 Unknown Reflector Positions	13 UNKN	1
7	Geom	Matrix Interface Gap	I GAP	1
8	Geom	Matrix Tube Pitch	PITCH	1
9	Geom	Missing Axial Reflector Drawer	MISSING	1
10	Geom	Nominal Plate, Drawer Dimensions	DIMENS	1
11	Geom	Aluminum Perforations	AL PERF	1
12	Geom	Uranium Axial Distribution	UAXIAL	1
13	Geom	PSR Axial Position	PSR AX	1
14	Geom	PSR Blades	PSR BLD	1
15	Comp ³	Aluminum in Core	AL CORE	1
16	Comp	Aluminum in Pu-Al Plates	AL PUAL	1
17	Comp	Aluminum in Matrix Tubes	AL MATX	1
18	Comp	Aluminum Drawers	AL DWR	1
19	Comp	Aluminum in Reflectors	AL REFL	1
20	Comp	Autorod Blade	AUTOROD	1
21	Comp	Beryllium	BE	1
22	Comp	Beryllium Oxide in Reflectors	BEOREF	1
23	Comp	Beryllium Oxide in SP-100 rods	BEO SP	1
24	Comp	Depleted Lithium Plates in core	DEP LI	1
25	Comp	Lithium Hydride in Shield	LIH SHD	1
26	Comp	Graphite	GRAPH	1
27	Comp	Graphite in Ax/Rad Refl.	C REFL	1
28	Comp	Molybdenum in Pu-U-Mo Plates	MO PUU	2
29	Comp	Nickel	NI	1
30	Comp	Niobium	NB	1
31	Comp	Rhenium	RH	1
32	Comp	Sand	SAND	1
33	Comp	Sodium	SODIUM	1
34	Comp	Sodium Carbonate	NAC	1
35	Comp	Tungsten	W	1
36	Comp	Zirconium	ZR	1
37	Comp	Hydrogen in Zirconium	H ZR	1
38	Comp	Steel Plates in the Core	SS CORE	1
39	Comp	Steel in the Cans	SS CAN	1
40	Comp	Steel in Drawers	SS DWR	1
41	Comp	Steel in Matrix Tubes	SS MAT	1

42	Comp	Steel in Reflectors	SS REF	1
43	Comp	Steel in Shield	SS SHD	1
44	Comp	Iron Oxide Plates	FEO	1
45	Comp	Enriched Uranium	ENR U	1
46	Comp	Depleted Uranium in Pu-U-Mo Plates	DU PUU	2
47	Comp	Depleted Uranium in Core	DU CORE	1
48	Comp	Depleted Uranium in Reflectors	DU REF	1
49	Comp	Depleted Uranium in Blanket	DU BLK	1
50	Comp	Depleted Uranium in Shield	DU SHD	1
51	Comp	Depleted Uranium Oxide Plates	DUO	1
52	Comp	Plutonium	PU	2
53	Comp	PSR Blades	PSR	1
54	Comp	“Control” Boron Carbide	C B4C	1
55	Comp	Polyethylene in core	POLY C	1
56	Comp	Borated Polyethylene in reflector	BPOLY R	1
57	Comp	Borated Polyethylene in shield	BPOLY S	1
58	Comp	Kel-F on core fuel	KELF C	1
59	Comp	Kel-F on core DU fuel	KELF DU	1
60	Comp	Kel-F on core BeO plates	KELF BE	1
61	Comp	Kel-F on reflector BeO plates	KELF R	1
62	Comp	Humidity	HUMID	1

¹ MT = Measurement Technique, ² Geom = Geometry, ³ Comp = Composition

Also shown in Table 2 are the “common” weighting matrices associated with each uncertainty type; these matrices and matrix assignments are discussed below.

There are a total of 496 (8 x 62) possible uncertainty entries from the ANL benchmark calculations. However, because of the diverse nature of these ANL assemblies, many entries in this overall uncertainty matrix are zero.

Code Mathematical Basis

In probability theory and statistics, covariance is a measure of how much two variables change together. A perfect correlation gives a 1.0 value, whereas no correlation gives a 0.0 value. The procedure used to determine covariance factors between sets of data has been set forth separately by both Ivanova and Ishikawa, References 1 and 2. In Ishikawa’s report there are two types of errors, “common” and “independent”, whereas Ivanova uses the equivalent terms “systematic” and “random”. Covariance factors involve only “common” or “systematic” errors. In this report, we follow the mathematical terminology as described by Ishikawa.

According Equation 7 of Ishikawa’s report, the covariance factor ($\rho_{A,B}$) for data from assembly A and assembly B is defined as the sum over all uncertainty types “i” (see Table 6) of the common fractional uncertainty for assembly A ($\sigma_{\text{Common},i} / \sigma_{\text{Total}}$) times the common fractional uncertainty for assembly B ($\sigma_{\text{Common},i} / \sigma_{\text{Total}}$); mathematically, this relationship is

$$\rho_{A,B} = \sum_i \frac{\sigma_{Common,A,i}}{\sigma_{Total,A}} * \frac{\sigma_{Common,B,i}}{\sigma_{Total,B}}$$

Notice that in the above equation that the numerators are common (or systematic) uncertainties, and therefore do not include any random uncertainties. In this analysis, common uncertainties are defined as the published uncertainties times a common factor between the two uncertainty types. For example, uranium plates that come from the same fuel “melt” will have a common factor of 1.0, whereas, plates from two different manufactures (or melts) will have a common factor of 0.0.

Sample Calculation

The two input common-factor matrices for the sample problem input are shown in Figures 1 and 2. The common matrices that will be used for each uncertainty type were shown in Table 2. These common-factor matrices are actually symmetric, but in the code, only the lower half of the covariance matrix cells are calculated; the corresponding symmetric cell value is automatically inserted.

Figure 1 common factors were used for most uncertainty types, but plutonium-related uncertainties were assumed to use the Figure 2 values. As seen from Figure 1, uncertainties are “in-common” with all other experiments within the ZPR-3 structure. Most of the plates were made at ANL and the only mass differences occur because of plate sizing. Thus, there are 1’s everywhere in the lower half of the matrix. As seen from Figure 2, the varying weighting terms attempted to distinguish plutonium-containing plates from various vendors.

Common #1	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	1	0	0	0	0	0	0	0
ZPR3 11	1	1	0	0	0	0	0	0
ZPR3 12	1	1	1	0	0	0	0	0
ZPR3 23	1	1	1	1	0	0	0	0
ZPR3 41	1	1	1	1	1	0	0	0
ZPR3 48	1	1	1	1	1	1	0	0
ZPR3 48B	1	1	1	1	1	1	1	0
ZPR3 56B	1	1	1	1	1	1	1	1

Figure 1. ZPR-3 Common Matrix Number 1.

Common #2	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	1	0	0	0	0	0	0	0
ZPR3 11	0	1	0	0	0	0	0	0
ZPR3 12	0	0	1	0	0	0	0	0
ZPR3 23	0	0	0	1	0	0	0	0
ZPR3 41	0	0	0	0	1	0	0	0
ZPR3 48	0	0	0	0	0	1	0	0
ZPR3 48B	0	0	0	0	0	0.75	1	0
ZPR3 56B	0	0	0	0	0	0	0	1

Figure 2. ZPR-3 Common Matrix Number 2.

Shown below is an input deck for calculating covariances for the eight ANL critical experiments using the ZPR-3 machine. The comments in **red** describe the various input parameters.

Start of sample problem script and input. The executable load module is named "cov2.x".

```
#!/bin/sh
#
RAJOBNAME=covariance
RABADGE=23921
RAOUTPUT=output
RAROUTE=cwd
# RAMESSAGES=VERBOSE
RALINES=120000
RATIME=4
RADATASIZE=40
RAMEM=6
. RASHELL
set -x
cp /home/nehome3/b23921/icsbep/covariance/cov2.x cov2
IFBOMB
ls -al
cov2 << 'EOF' >> output
Title card
Covariances for ANL ZPR3 Experiments
```

The following six input numbers (6I6 format) are:

Number of Experiments (8)
 Number of Uncertainties (62)
 Measurement Types (4)
 Geometry Types (10)
 Composition Types (48)
 Number of Matrix Commons (4)

8 62 4 10 48 4

The next 7 lines are the 62 uncertainty name abbreviations given in Table 2 (10A8 format).

EXCESS INHOUR TEMP REPRO RM RET 13 UNKN I GAP PITCH MISSING DIMENS
 AL PERF UAXIAL PSR AX PSR BLD AL CORE AL PUAL AL MATX AL DWR AL REFL AUTOROD
 BE BEOREF BEO SP DEP LI LIH SHD GRAPH C REFL MO PUU NI NB
 RH SAND SODIUM NAC W ZR H ZR SS CORE SS CAN SS DWR
 SS MATX SS REF SS SHD FEO ENR U DU PUU DU CORE DU REF DU BLK DU SHD
 DUO PU PSR C B4C POLY C BPOLY R BPOLY S KELF C KELF DU KELF BE
 KELF R HUMID

End of abbreviated uncertainty names.

The next series of lines are the uncertainties for the 8 ZPR-3 experiments from the benchmark documents. The first line gives the abbreviated ICSBEP experiment name, the experiment name and the number of non-zero uncertainty entries for that experiment. For example, the first experiment is "ZPR-3 Assembly 6F", with an abbreviated ICSBEP name of "IMF-015", has "17" non-zero entries; the 17 uncertainties with abbreviated type-names then follow.

IMF-015	ZPR3/6F	17
EXCESS	6.20E-03	
INHOUR	2.00E-04	
TEMP	1.50E-03	
REPRO	3.40E-03	
RM RET	1.00E-03	
I GAP	1.45E-02	
PITCH	4.10E-02	
DIMENS	2.77E-02	
AL CORE	4.40E-03	
AL DWR	9.00E-04	
SS CORE	9.00E-04	
SS MATX	3.10E-02	
ENR U	7.84E-02	
DU CORE	5.31E-02	
KELF C	1.20E-03	
KELF DU	1.00E-02	
HUMID	1.00E-04	
IMF-016	ZPR3/11	15
EXCESS	5.40E-03	
INHOUR	2.00E-04	
TEMP	1.90E-03	
REPRO	3.40E-03	
RM RET	9.00E-04	
I GAP	1.06E-02	
PITCH	2.54E-02	
DIMENS	1.91E-02	
SS DWR	3.00E-04	

SS MATX	1.20E-03	
ENR U	7.29E-02	
DU CORE	8.80E-02	
KELF C	2.00E-04	
KELF DU	9.60E-03	
HUMID	1.00E-04	
ICF-004	ZPR3/12	16
EXCESS	5.20E-03	
IN HOUR	4.00E-04	
TEMP	3.60E-03	
REPRO	3.40E-03	
RM RET	3.10E-03	
I GAP	1.16E-02	
PITCH	3.29E-02	
DIMENS	2.25E-02	
GRAPH	6.20E-03	
SS DWR	4.00E-04	
SS MATX	1.60E-02	
ENR U	7.25E-02	
DU CORE	6.12E-02	
KELF C	6.00E-04	
KELF DU	1.93E-02	
HUMID	1.00E-04	
HMF-055	ZPR3/23	15
EXCESS	1.10E-03	
IN HOUR	6.70E-03	
TEMP	2.20E-03	
RM RET	2.00E-02	
I GAP	5.00E-02	
PITCH	1.02E-01	
DIMENS	5.00E-02	
UAXIAL	1.21E-01	
AL CORE	9.30E-03	
SS DWR	5.00E-04	
SS MATX	4.20E-02	
ENR U	7.82E-02	
DU REF	5.03E-02	
KELF C	1.10E-02	
HUMID	1.00E-04	
IMF-012	ZPR3/41	17
EXCESS	9.00E-04	
IN HOUR	7.00E-03	
TEMP	4.10E-03	
RM RET	8.00E-03	
I GAP	5.00E-02	
PITCH	3.00E-02	
DIMENS	5.00E-02	
AL PERF	4.00E-02	
UAXIAL	1.23E-01	
AL CORE	1.50E-03	
SS CORE	1.20E-03	

SS MATX	7.80E-03	
ENR U	7.33E-02	
DU CORE	4.64E-02	
DU REF	2.60E-02	
KELF C	8.00E-04	
HUMID	1.00E-04	
MCF-003	ZPR3/48	21
EXCESS	1.00E-03	
IN HOUR	3.00E-03	
TEMP	6.50E-03	
REPRO	2.50E-03	
RM RET	1.60E-03	
I GAP	2.00E-02	
PITCH	3.18E-02	
DIMENS	2.00E-02	
AL PUAL	6.00E-04	
GRAPH	2.30E-03	
MO PUU	2.00E-04	
SODIUM	1.30E-03	
SS CAN	5.00E-04	
SS DWR	4.00E-04	
SS MATX	8.80E-03	
DU PUU	7.10E-03	
DU CORE	2.50E-02	
DU BLK	3.39E-02	
PU	3.05E-02	
KELF C	1.90E-03	
HUMID	1.00E-04	
MCF-003	ZPR3/48B	21
EXCESS	2.00E-03	
IN HOUR	5.00E-03	
TEMP	6.50E-03	
REPRO	2.50E-03	
RM RET	1.60E-03	
I GAP	2.00E-02	
PITCH	3.18E-02	
DIMENS	2.00E-02	
AL PUAL	5.00E-04	
GRAPH	2.30E-03	
MO PUU	2.00E-04	
SODIUM	1.30E-03	
SS CAN	5.00E-04	
SS DWR	4.00E-04	
SS MATX	8.80E-03	
DU PUU	7.30E-03	
DU CORE	2.50E-02	
DU BLK	3.39E-02	
PU	2.85E-02	
KELF C	1.90E-03	
HUMID	1.00E-04	
MCF-004	ZPR3/56B	21

EXCESS	6.00E-04
IN HOUR	3.10E-03
TEMP	3.60E-03
REPRO	2.40E-03
RM RET	9.35E-02
I GAP	1.92E-02
PITCH	3.21E-02
DIMENS	1.92E-02
MO PUU	4.00E-04
NI	1.55E-02
SODIUM	2.40E-03
NAC	5.70E-03
SS CAN	2.90E-03
SS DWR	1.30E-03
SS MATX	8.30E-03
FEO	3.70E-03
DU PUU	1.37E-02
DUO	1.71E-02
PU	4.36E-02
KELF C	7.00E-04
HUMID	1.00E-04

End of uncertainty inputs for each experiment; zero values are automatically inserted for all other uncertainty types.

The next series of inputs are the common matrices. In this sample calculation there are two 8x8 common matrices named C1 and C2. For each common matrix there are 8 vertical components (V1-V8).

1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	C1 V1
1.0000	1.0000					
0.0000	1.0000	1.0000	1.0000	1.0000	1.0000	C1 V2
1.0000	1.0000					
0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	C1 V3
1.0000	1.0000					
0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	C1 V4
1.0000	1.0000					
0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	C1 V5
1.0000	1.0000					
0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	C1 V6
1.0000	1.0000					
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	C1 V7
1.0000	1.0000					
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	C1 V8
0.0000	1.0000					
1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	C2 V1
0.0000	0.0000					
0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	C2 V2
0.0000	0.0000					
0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	C2 V3
0.0000	0.0000					
0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	C2 V4
0.0000	0.0000					
0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	C2 V5
0.0000	0.0000					

```

0.0000  0.0000  0.0000  0.0000  0.0000  1.0000  C2 V6
0.7500  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  C2 V7
1.0000  0.0000
0.0000  0.0000  0.0000  0.0000  0.0000  0.0000  C2 V8
0.0000  1.0000

```

End of common matrices.

The last input grouping defines which common matrix goes with each uncertainty type (12I6 format). In this example there are 62 input values. For example, most uncertainty types use common matrix “1”, while plutonium-related uncertainty types 28, 46 and 52 use common matrix number “2”.

```

1  1  1  1  1  1  1  1  1  1  1  1
1  1  1  1  1  1  1  1  1  1  1  1
1  1  1  2  1  1  1  1  1  1  1  1
1  1  1  1  1  1  1  1  1  2  1  1
1  1  1  2  1  1  1  1  1  1  1  1
1  1

```

End of input file (EOF)

EOF

IFBOMB

The “COVAR” output file contains plot able covariance matrix data for each uncertainty type plus cumulative values for the measurement, geometry, composition and total summations.

cp COVAR /home/nehome3/b23921/icsbep/covariance/COVAR

ls -al

Results

Shown in Figures 3-6 are the calculated covariance matrices for the three major grouping (Measurement Technique, Geometry and Composition) plus the overall (Total) covariance matrix. This data was obtained from the output COVAR dataset for the sample case.

Measurement	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	4.1E-03	3.5E-03	4.1E-03	5.0E-04	6.6E-04	3.2E-03	4.1E-03	1.4E-03
ZPR3 11	3.5E-03	3.1E-03	3.6E-03	4.7E-04	6.7E-04	3.3E-03	4.0E-03	1.4E-03
ZPR3 12	4.1E-03	3.6E-03	4.5E-03	7.5E-04	1.2E-03	5.2E-03	6.1E-03	2.1E-03
ZPR3 23	5.0E-04	4.7E-04	7.5E-04	1.2E-03	1.6E-03	2.5E-03	3.6E-03	1.3E-03
ZPR3 41	6.6E-04	6.7E-04	1.2E-03	1.6E-03	2.2E-03	4.0E-03	5.3E-03	1.8E-03
ZPR3 48	3.2E-03	3.3E-03	5.2E-03	2.5E-03	4.0E-03	1.2E-02	1.4E-02	5.0E-03
ZPR3 48B	4.1E-03	4.0E-03	6.1E-03	3.6E-03	5.3E-03	1.4E-02	1.7E-02	5.9E-03
ZPR3 56B	1.4E-03	1.4E-03	2.1E-03	1.3E-03	1.8E-03	5.0E-03	5.9E-03	2.2E-03

Figure 3. Measurement Covariance Matrix for ZPR-3 Benchmark Assemblies.

Geometry	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	2.1E-01	1.3E-01	1.8E-01	2.8E-01	1.7E-01	2.8E-01	2.8E-01	1.7E-01
ZPR3 11	1.3E-01	7.8E-02	1.1E-01	1.7E-01	1.1E-01	1.7E-01	1.7E-01	1.1E-01
ZPR3 12	1.8E-01	1.1E-01	1.6E-01	2.4E-01	1.4E-01	2.4E-01	2.4E-01	1.6E-01
ZPR3 23	2.8E-01	1.7E-01	2.4E-01	7.4E-01	6.6E-01	3.8E-01	3.8E-01	3.0E-01
ZPR3 41	1.7E-01	1.1E-01	1.4E-01	6.6E-01	7.3E-01	2.5E-01	2.6E-01	1.8E-01
ZPR3 48	2.8E-01	1.7E-01	2.4E-01	3.8E-01	2.5E-01	3.8E-01	3.9E-01	2.4E-01
ZPR3 48B	2.8E-01	1.7E-01	2.4E-01	3.8E-01	2.5E-01	3.9E-01	3.9E-01	2.5E-01
ZPR3 56B	1.7E-01	1.1E-01	1.6E-01	3.0E-01	1.8E-01	2.4E-01	2.5E-01	7.9E-01

Figure 4. Geometry Covariance Matrix for ZPR-3 Benchmark Assemblies.

Composition	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	7.9E-01	7.8E-01	8.0E-01	3.3E-01	4.3E-01	2.1E-01	2.1E-01	2.0E-02
ZPR3 11	7.8E-01	9.2E-01	8.5E-01	2.4E-01	4.5E-01	2.7E-01	2.7E-01	7.6E-04
ZPR3 12	8.0E-01	8.5E-01	8.4E-01	2.9E-01	4.4E-01	2.3E-01	2.3E-01	1.1E-02
ZPR3 23	3.3E-01	2.4E-01	2.9E-01	2.6E-01	2.1E-01	2.8E-02	2.8E-02	1.5E-02
ZPR3 41	4.3E-01	4.5E-01	4.4E-01	2.1E-01	2.7E-01	1.0E-01	1.0E-01	3.2E-03
ZPR3 48	2.1E-01	2.7E-01	2.3E-01	2.8E-02	1.0E-01	6.0E-01	5.5E-01	2.2E-02
ZPR3 48B	2.1E-01	2.7E-01	2.3E-01	2.8E-02	1.0E-01	5.5E-01	5.9E-01	2.3E-02
ZPR3 56B	2.0E-02	7.6E-04	1.1E-02	1.5E-02	3.2E-03	2.2E-02	2.3E-02	2.1E-01

Figure 5. Composition Covariance Matrix for ZPR-3 Benchmark Assemblies.

Total	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	1.0E+00	9.1E-01	9.8E-01	6.0E-01	6.0E-01	4.9E-01	4.9E-01	1.9E-01
ZPR3 11	9.1E-01	1.0E+00	9.6E-01	4.1E-01	5.6E-01	4.4E-01	4.5E-01	1.1E-01
ZPR3 12	9.8E-01	9.6E-01	1.0E+00	5.3E-01	5.9E-01	4.7E-01	4.8E-01	1.8E-01
ZPR3 23	6.0E-01	4.1E-01	5.3E-01	1.0E+00	8.6E-01	4.1E-01	4.1E-01	3.2E-01
ZPR3 41	6.0E-01	5.6E-01	5.9E-01	8.6E-01	1.0E+00	3.5E-01	3.6E-01	1.8E-01
ZPR3 48	4.9E-01	4.4E-01	4.7E-01	4.1E-01	3.5E-01	1.0E+00	9.5E-01	2.7E-01
ZPR3 48B	4.9E-01	4.5E-01	4.8E-01	4.1E-01	3.6E-01	9.5E-01	1.0E+00	2.8E-01
ZPR3 56B	1.9E-01	1.1E-01	1.8E-01	3.2E-01	1.8E-01	2.7E-01	2.8E-01	1.0E+00

Figure 6. Total (Overall) Covariance Matrix for ZPR-3 Benchmark Assemblies.

As seen from Figure 3-6, most of the overall covariance is due to composition related uncertainties. It is also noticed from Figure 6 that ZPR3 Assembly 56B is relatively uncorrelated with the other ZPR-3 experiments. This ZPR3 Assembly 56B difference is most likely due to the relatively large amounts of plutonium, nickel, sodium, sodium carbonate, and depleted uranium oxide in this experiment relative to the other ZPR-3 experiments.

Finally, shown in the Appendix are all non-zero covariance matrices for each uncertainty type. There are a total of 62 uncertainty types given in Table 2, but only 33 have non-zero covariance matrices. (Recall from above that the 62 uncertainty types were deduced from a series of ANL machines, not just ZPR-3.)

References

- 1) Tatiana Ivanova, et. al., "Towards validation of criticality calculations for systems with MOX powders," Annals of Nuclear Energy, 36 (2009) 305-309.
- 2) M. Ishikawa, "How to Determine Error Matrix of Integral Data, Appendix A," Draft, November 25, 2011 . **(MORE definition is needed for this reference.)**

Appendix: Supplementary Figures

This Appendix contains ancillary figures related to the generation and interpretation of Figures 3-6. As mentioned previously, there are a total of 62 uncertainty types, but only 33 have non-zero covariance matrices. The 33 non-zero covariance matrices follow in Figures A1-A33. Included in the figure titles are the abbreviated uncertainty type names from Table 2.

As will be seen from Figures A1-A33, there are relatively few uncertainty types that have significant covariance matrices. The most important covariance matrices, in figure order, are: pitch (Figure A7), axial uranium (A10), core enriched uranium (A24), core depleted uranium (A26), blanket depleted uranium (A28) and core plutonium (A30).

EXCESS	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	3.0E-03	2.5E-03	2.7E-03	3.0E-04	2.8E-04	8.0E-04	1.6E-03	2.9E-04
ZPR3 11	2.5E-03	2.0E-03	2.2E-03	2.4E-04	2.3E-04	6.6E-04	1.3E-03	2.3E-04
ZPR3 12	2.7E-03	2.2E-03	2.4E-03	2.6E-04	2.5E-04	7.1E-04	1.4E-03	2.5E-04
ZPR3 23	3.0E-04	2.4E-04	2.6E-04	2.9E-05	2.8E-05	7.9E-05	1.6E-04	2.8E-05
ZPR3 41	2.8E-04	2.3E-04	2.5E-04	2.8E-05	2.6E-05	7.5E-05	1.5E-04	2.7E-05
ZPR3 48	8.0E-04	6.6E-04	7.1E-04	7.9E-05	7.5E-05	2.1E-04	4.3E-04	7.6E-05
ZPR3 48B	1.6E-03	1.3E-03	1.4E-03	1.6E-04	1.5E-04	4.3E-04	8.7E-04	1.6E-04
ZPR3 56B	2.9E-04	2.3E-04	2.5E-04	2.8E-05	2.7E-05	7.6E-05	1.5E-04	2.7E-05

Figure A1. ZPR-3 Benchmark Covariance Matrix Due to Excess Reactivity (EXCESS).

INHOUR	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	3.1E-06	3.0E-06	6.6E-06	5.8E-05	7.0E-05	7.7E-05	1.3E-04	4.8E-05
ZPR3 11	3.0E-06	2.8E-06	6.2E-06	5.5E-05	6.7E-05	7.3E-05	1.2E-04	4.5E-05
ZPR3 12	6.6E-06	6.2E-06	1.4E-05	1.2E-04	1.5E-04	1.6E-04	2.7E-04	1.0E-04
ZPR3 23	5.8E-05	5.5E-05	1.2E-04	1.1E-03	1.3E-03	1.4E-03	2.4E-03	8.9E-04
ZPR3 41	7.0E-05	6.7E-05	1.5E-04	1.3E-03	1.6E-03	1.7E-03	2.9E-03	1.1E-03
ZPR3 48	7.7E-05	7.3E-05	1.6E-04	1.4E-03	1.7E-03	1.9E-03	3.2E-03	1.2E-03
ZPR3 48B	1.3E-04	1.2E-04	2.7E-04	2.4E-03	2.9E-03	3.2E-03	5.4E-03	2.0E-03
ZPR3 56B	4.8E-05	4.5E-05	1.0E-04	8.9E-04	1.1E-03	1.2E-03	2.0E-03	7.2E-04

Figure A2. ZPR-3 Benchmark Covariance Matrix Due to the Conversion of Inhours to Δk (INHOUR).

Temp	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	1.8E-04	2.1E-04	4.5E-04	1.4E-04	3.1E-04	1.3E-03	1.3E-03	4.1E-04
ZPR3 11	2.1E-04	2.5E-04	5.3E-04	1.7E-04	3.7E-04	1.5E-03	1.5E-03	5.0E-04
ZPR3 12	4.5E-04	5.3E-04	1.1E-03	3.6E-04	7.8E-04	3.2E-03	3.2E-03	1.1E-03
ZPR3 23	1.4E-04	1.7E-04	3.6E-04	1.2E-04	2.5E-04	1.0E-03	1.0E-03	3.4E-04
ZPR3 41	3.1E-04	3.7E-04	7.8E-04	2.5E-04	5.4E-04	2.2E-03	2.2E-03	7.3E-04
ZPR3 48	1.3E-03	1.5E-03	3.2E-03	1.0E-03	2.2E-03	9.0E-03	9.1E-03	3.0E-03
ZPR3 48B	1.3E-03	1.5E-03	3.2E-03	1.0E-03	2.2E-03	9.1E-03	9.1E-03	3.0E-03
ZPR3 56B	4.1E-04	5.0E-04	1.1E-03	3.4E-04	7.3E-04	3.0E-03	3.0E-03	9.8E-04

Figure A3. ZPR-3 Benchmark Temperature Covariance Matrix (TEMP).

REPRO	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	9.1E-04	8.6E-04	9.6E-04	0.0E+00	0.0E+00	1.1E-03	1.1E-03	6.3E-04
ZPR3 11	8.6E-04	8.1E-04	9.0E-04	0.0E+00	0.0E+00	1.0E-03	1.0E-03	5.9E-04
ZPR3 12	9.6E-04	9.0E-04	1.0E-03	0.0E+00	0.0E+00	1.2E-03	1.2E-03	6.6E-04
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	1.1E-03	1.0E-03	1.2E-03	0.0E+00	0.0E+00	1.3E-03	1.3E-03	7.6E-04
ZPR3 48B	1.1E-03	1.0E-03	1.2E-03	0.0E+00	0.0E+00	1.3E-03	1.4E-03	7.7E-04
ZPR3 56B	6.3E-04	5.9E-04	6.6E-04	0.0E+00	0.0E+00	7.6E-04	7.7E-04	4.3E-04

Figure A4. ZPR-3 Benchmark Reproducibility Covariance Matrix (REPRO).

RM RET	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	7.84E-05	6.66E-05	2.56E-04	8.72E-04	4.03E-04	2.06E-04	2.08E-04	7.18E-03
ZPR3 11	6.66E-05	5.66E-05	2.18E-04	7.41E-04	3.42E-04	1.75E-04	1.77E-04	6.10E-03
ZPR3 12	2.56E-04	2.18E-04	8.39E-04	2.85E-03	1.32E-03	6.75E-04	6.82E-04	2.35E-02
ZPR3 23	8.72E-04	7.41E-04	2.85E-03	9.70E-03	4.48E-03	2.29E-03	2.32E-03	7.99E-02
ZPR3 41	4.03E-04	3.42E-04	1.32E-03	4.48E-03	2.07E-03	1.06E-03	1.07E-03	3.69E-02
ZPR3 48	2.06E-04	1.75E-04	6.75E-04	2.29E-03	1.06E-03	5.43E-04	5.48E-04	1.89E-02
ZPR3 48B	2.08E-04	1.77E-04	6.82E-04	2.32E-03	1.07E-03	5.48E-04	5.54E-04	1.91E-02
ZPR3 56B	7.18E-03	6.10E-03	2.35E-02	7.99E-02	3.69E-02	1.89E-02	1.91E-02	6.58E-01

Figure A5. ZPR-3 Benchmark Matrix Room Return Covariance Matrix. (RM RET).

I GAP	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	1.65E-02	1.14E-02	1.39E-02	3.16E-02	3.65E-02	3.74E-02	3.78E-02	2.14E-02
ZPR3 11	1.14E-02	7.85E-03	9.60E-03	2.18E-02	2.52E-02	2.58E-02	2.61E-02	1.48E-02
ZPR3 12	1.39E-02	9.60E-03	1.17E-02	2.67E-02	3.08E-02	3.16E-02	3.19E-02	1.81E-02
ZPR3 23	3.16E-02	2.18E-02	2.67E-02	6.06E-02	7.00E-02	7.17E-02	7.24E-02	4.10E-02
ZPR3 41	3.65E-02	2.52E-02	3.08E-02	7.00E-02	8.08E-02	8.28E-02	8.37E-02	4.73E-02
ZPR3 48	3.74E-02	2.58E-02	3.16E-02	7.17E-02	8.28E-02	8.48E-02	8.57E-02	4.85E-02
ZPR3 48B	3.78E-02	2.61E-02	3.19E-02	7.24E-02	8.37E-02	8.57E-02	8.66E-02	4.90E-02
ZPR3 56B	2.14E-02	1.48E-02	1.81E-02	4.10E-02	4.73E-02	4.85E-02	4.90E-02	2.77E-02

Figure A6. ZPR-3 Benchmark Matrix Interface Gap Covariance Matrix (IGAP).

PITCH	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	1.3E-01	7.7E-02	1.1E-01	1.8E-01	6.2E-02	1.7E-01	1.7E-01	1.0E-01
ZPR3 11	7.7E-02	4.5E-02	6.5E-02	1.1E-01	3.6E-02	9.8E-02	9.9E-02	5.9E-02
ZPR3 12	1.1E-01	6.5E-02	9.5E-02	1.5E-01	5.2E-02	1.4E-01	1.4E-01	8.6E-02
ZPR3 23	1.8E-01	1.1E-01	1.5E-01	2.5E-01	8.6E-02	2.3E-01	2.4E-01	1.4E-01
ZPR3 41	6.2E-02	3.6E-02	5.2E-02	8.6E-02	2.9E-02	7.9E-02	8.0E-02	4.7E-02
ZPR3 48	1.7E-01	9.8E-02	1.4E-01	2.3E-01	7.9E-02	2.1E-01	2.2E-01	1.3E-01
ZPR3 48B	1.7E-01	9.9E-02	1.4E-01	2.4E-01	8.0E-02	2.2E-01	2.2E-01	1.3E-01
ZPR3 56B	1.0E-01	5.9E-02	8.6E-02	1.4E-01	4.7E-02	1.3E-01	1.3E-01	7.8E-02

Figure A7. ZPR-3 Benchmark Matrix Tube Pitch Covariance Matrix (PITCH).

DIMENSION	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	6.01E-02	3.91E-02	5.16E-02	6.04E-02	6.97E-02	7.14E-02	7.22E-02	4.08E-02
ZPR3 11	3.91E-02	2.55E-02	3.36E-02	3.93E-02	4.54E-02	4.65E-02	4.70E-02	2.66E-02
ZPR3 12	5.16E-02	3.36E-02	4.42E-02	5.18E-02	5.98E-02	6.12E-02	6.19E-02	3.50E-02
ZPR3 23	6.04E-02	3.93E-02	5.18E-02	6.06E-02	7.00E-02	7.17E-02	7.24E-02	4.10E-02
ZPR3 41	6.97E-02	4.54E-02	5.98E-02	7.00E-02	8.08E-02	8.28E-02	8.37E-02	4.73E-02
ZPR3 48	7.14E-02	4.65E-02	6.12E-02	7.17E-02	8.28E-02	8.48E-02	8.57E-02	4.85E-02
ZPR3 48B	7.22E-02	4.70E-02	6.19E-02	7.24E-02	8.37E-02	8.57E-02	8.66E-02	4.90E-02
ZPR3 56B	4.08E-02	2.66E-02	3.50E-02	4.10E-02	4.73E-02	4.85E-02	4.90E-02	2.77E-02

Figure A8. ZPR-3 Benchmark Nominal Plate Drawer Dimensions Covariance Matrix (DIMENSION).

AL PERF	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.2E-02	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A9. ZPR-3 Benchmark Aluminum Perforations Covariance Matrix (AL PERF).

U AXIAL	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	3.6E-01	4.2E-01	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	4.2E-01	4.9E-01	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A10. ZPR-3 Benchmark Axial Uranium Covariance Matrix (U AXIAL).

AL CORE	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	1.5E-03	0.0E+00	0.0E+00	1.8E-03	3.3E-04	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	1.8E-03	0.0E+00	0.0E+00	2.1E-03	3.9E-04	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	3.3E-04	0.0E+00	0.0E+00	3.9E-04	7.3E-05	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A11. ZPR-3 Benchmark Aluminum in Core Covariance Matrix (AL CORE).

AL PUAL	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7.6E-05	6.4E-05	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	6.4E-05	5.4E-05	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A12. ZPR-3 Benchmark Aluminum in Pu-Al Plates Covariance Matrix (AL PUAL).

AL DWR	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	6.3E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A13. ZPR-3 Benchmark Aluminum Drawers Covariance Matrix (AL DWR).

GRAPHITE	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	3.4E-03	0.0E+00	0.0E+00	1.9E-03	2.0E-03	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	1.9E-03	0.0E+00	0.0E+00	1.1E-03	1.1E-03	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	2.0E-03	0.0E+00	0.0E+00	1.1E-03	1.1E-03	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A14. ZPR-3 Benchmark Graphite Covariance Matrix (GRAPHITE).

MO PUU	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	8.5E-06	6.4E-06	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	6.4E-06	8.7E-06	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.2E-05

Figure A15. ZPR-3 Benchmark Molybdenum in Pu-U-Mo Plate Covariance Matrix (MO PUU).

NI	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.8E-02

Figure A16. ZPR-3 Benchmark Nickel Covariance Matrix (NI).

SODIUM	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.6E-04	3.6E-04	3.9E-04
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.6E-04	3.7E-04	4.0E-04
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.9E-04	4.0E-04	4.3E-04

Figure A17. ZPR-3 Benchmark Sodium Covariance Matrix (SODIUM).

NA C	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.4E-03

Figure A18. ZPR-3 Benchmark Sodium Carbonate Covariance Matrix (NA C).

SS CORE	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	6.3E-05	0.0E+00	0.0E+00	0.0E+00	5.4E-05	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	5.4E-05	0.0E+00	0.0E+00	0.0E+00	4.7E-05	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A19. ZPR-3 Benchmark Steel Plates in Core Covariance Matrix (SS CORE).

SS CAN	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.3E-05	5.4E-05	1.8E-04
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.4E-05	5.4E-05	1.9E-04
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.8E-04	1.9E-04	6.3E-04

Figure A20. ZPR-3 Benchmark Steel in the Cans Covariance Matrix (SS CAN).

SS DWR	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	6.3E-06	9.4E-06	6.2E-06	0.0E+00	1.5E-05	1.5E-05	2.8E-05
ZPR3 12	0.0E+00	9.4E-06	1.4E-05	9.2E-06	0.0E+00	2.2E-05	2.2E-05	4.2E-05
ZPR3 23	0.0E+00	6.2E-06	9.2E-06	6.1E-06	0.0E+00	1.4E-05	1.4E-05	2.8E-05
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	1.5E-05	2.2E-05	1.4E-05	0.0E+00	3.4E-05	3.4E-05	6.6E-05
ZPR3 48B	0.0E+00	1.5E-05	2.2E-05	1.4E-05	0.0E+00	3.4E-05	3.5E-05	6.6E-05
ZPR3 56B	0.0E+00	2.8E-05	4.2E-05	2.8E-05	0.0E+00	6.6E-05	6.6E-05	1.3E-04

Figure A21. ZPR-3 Benchmark Steel in the Drawers Covariance Matrix (SS DWR).

SS MATX	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	7.5E-02	2.8E-03	4.1E-02	5.7E-02	1.2E-02	3.5E-02	3.6E-02	2.0E-02
ZPR3 11	2.8E-03	1.0E-04	1.5E-03	2.1E-03	4.4E-04	1.3E-03	1.3E-03	7.2E-04
ZPR3 12	4.1E-02	1.5E-03	2.2E-02	3.1E-02	6.6E-03	1.9E-02	1.9E-02	1.1E-02
ZPR3 23	5.7E-02	2.1E-03	3.1E-02	4.3E-02	9.2E-03	2.7E-02	2.7E-02	1.5E-02
ZPR3 41	1.2E-02	4.4E-04	6.6E-03	9.2E-03	2.0E-03	5.7E-03	5.7E-03	3.2E-03
ZPR3 48	3.5E-02	1.3E-03	1.9E-02	2.7E-02	5.7E-03	1.6E-02	1.7E-02	9.2E-03
ZPR3 48B	3.6E-02	1.3E-03	1.9E-02	2.7E-02	5.7E-03	1.7E-02	1.7E-02	9.3E-03
ZPR3 56B	2.0E-02	7.2E-04	1.1E-02	1.5E-02	3.2E-03	9.2E-03	9.3E-03	5.2E-03

Figure A22. ZPR-3 Benchmark Steel in the Matrix Tube Covariance Matrix (SS MATX).

FEO	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.0E-03

Figure 23. ZPR-3 Benchmark Iron Oxide Plates Covariance Matrix (FEO).

ENR U	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	4.8E-01	4.2E-01	4.7E-01	2.7E-01	2.9E-01	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	4.2E-01	3.7E-01	4.1E-01	2.3E-01	2.5E-01	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	4.7E-01	4.1E-01	4.6E-01	2.6E-01	2.8E-01	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	2.7E-01	2.3E-01	2.6E-01	1.5E-01	1.6E-01	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	2.9E-01	2.5E-01	2.8E-01	1.6E-01	1.7E-01	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A24. ZPR-3 Benchmark Enriched Uranium Covariance Matrix (ENR U).

DU PUU	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.1E-02	1.1E-02	1.2E-02
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.1E-02	1.2E-02	1.3E-02
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.2E-02	1.3E-02	1.4E-02

Figure A25. ZPR-3 Benchmark Depleted Uranium in the Pu-U-Mo Plates Covariance Matrix (DU PUU).

DU CORE	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	2.2E-01	3.5E-01	2.7E-01	0.0E+00	1.2E-01	1.7E-01	1.7E-01	0.0E+00
ZPR3 11	3.5E-01	5.4E-01	4.2E-01	0.0E+00	1.9E-01	2.7E-01	2.7E-01	0.0E+00
ZPR3 12	2.7E-01	4.2E-01	3.3E-01	0.0E+00	1.5E-01	2.1E-01	2.1E-01	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	1.2E-01	1.9E-01	1.5E-01	0.0E+00	7.0E-02	9.6E-02	9.7E-02	0.0E+00
ZPR3 48	1.7E-01	2.7E-01	2.1E-01	0.0E+00	9.6E-02	1.3E-01	1.3E-01	0.0E+00
ZPR3 48B	1.7E-01	2.7E-01	2.1E-01	0.0E+00	9.7E-02	1.3E-01	1.4E-01	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A26. ZPR-3 Benchmark Depleted Uranium in the Core Covariance Matrix (DU CORE).

DU REF	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	6.1E-02	3.7E-02	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	3.7E-02	2.2E-02	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A27. ZPR-3 Benchmark Depleted Uranium in the Reflectors Covariance Matrix (DU REF).

DU BLK	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.4E-01	2.5E-01	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.5E-01	2.5E-01	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A28. ZPR-3 Benchmark Depleted Uranium in the Blanket Covariance Matrix (DU BLK).

DUO	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.2E-02

Figure A29. ZPR-3 Benchmark Depleted Uranium Oxide Plates Covariance Matrix (DUO).

PU	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.0E-01	1.4E-01	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.4E-01	1.8E-01	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.4E-01

Figure A30. ZPR-3 Benchmark Plutonium Covariance Matrix (PU).

KELF C	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	1.1E-04	1.8E-05	6.0E-05	5.8E-04	4.8E-05	2.9E-04	3.0E-04	6.4E-05
ZPR3 11	1.8E-05	2.8E-06	9.4E-06	9.1E-05	7.6E-06	4.6E-05	4.7E-05	1.0E-05
ZPR3 12	6.0E-05	9.4E-06	3.1E-05	3.0E-04	2.6E-05	1.6E-04	1.6E-04	3.4E-05
ZPR3 23	5.8E-04	9.1E-05	3.0E-04	2.9E-03	2.5E-04	1.5E-03	1.5E-03	3.3E-04
ZPR3 41	4.8E-05	7.6E-06	2.6E-05	2.5E-04	2.1E-05	1.3E-04	1.3E-04	2.8E-05
ZPR3 48	2.9E-04	4.6E-05	1.6E-04	1.5E-03	1.3E-04	7.7E-04	7.7E-04	1.7E-04
ZPR3 48B	3.0E-04	4.7E-05	1.6E-04	1.5E-03	1.3E-04	7.7E-04	7.8E-04	1.7E-04
ZPR3 56B	6.4E-05	1.0E-05	3.4E-05	3.3E-04	2.8E-05	1.7E-04	1.7E-04	3.7E-05

Figure A31. ZPR-3 Benchmark Kel-F on Core Fuel Covariance Matrix (KELF C).

KELF DU	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	7.8E-03	7.1E-03	1.6E-02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 11	7.1E-03	6.4E-03	1.4E-02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 12	1.6E-02	1.4E-02	3.3E-02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 23	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 41	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 48B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ZPR3 56B	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Figure A32. ZPR-3 Benchmark Kel-F on Core Depleted Uranium Fuel Covariance Matrix (KELF DU).

HUMID	ZPR3 6F	ZPR3 11	ZPR3 12	ZPR3 23	ZPR3 41	ZPR3 48	ZPR3 48B	ZPR3 56B
ZPR3 6F	7.8E-07	7.4E-07	8.3E-07	4.4E-07	5.0E-07	1.3E-06	1.3E-06	7.7E-07
ZPR3 11	7.4E-07	7.0E-07	7.8E-07	4.1E-07	4.8E-07	1.2E-06	1.2E-06	7.2E-07
ZPR3 12	8.3E-07	7.8E-07	8.7E-07	4.6E-07	5.3E-07	1.4E-06	1.4E-06	8.1E-07
ZPR3 23	4.4E-07	4.1E-07	4.6E-07	2.4E-07	2.8E-07	7.2E-07	7.2E-07	4.3E-07
ZPR3 41	5.0E-07	4.8E-07	5.3E-07	2.8E-07	3.2E-07	8.3E-07	8.4E-07	4.9E-07
ZPR3 48	1.3E-06	1.2E-06	1.4E-06	7.2E-07	8.3E-07	2.1E-06	2.1E-06	1.3E-06
ZPR3 48B	1.3E-06	1.2E-06	1.4E-06	7.2E-07	8.4E-07	2.1E-06	2.2E-06	1.3E-06
ZPR3 56B	7.7E-07	7.2E-07	8.1E-07	4.3E-07	4.9E-07	1.3E-06	1.3E-06	7.5E-07

Figure A33. ZPR-3 Benchmark Humidity Covariance Matrix (HUMID).

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