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ADVANCED NUCLEAR FUELS CORPORATION

FINAL REPORT
CRITICALITY SAFETY ANALYSIS
MILLSTONE-2 NEW FUEL STORAGE VAULT
AND TRANSFER CARRIAGE
WITH 5.0 PERCENT ENRICHED
14x14 FUEL ASSEMBLIES

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FINAL REPORT
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WITH 5.0 PERCENT ENRICHED 14X14 FUEL ASSEMBLIES

1.0 SUMMARY

The criticality safety of the new fuel storage vault and transfer carriage with 5.0 percent enriched 14x14 bundles is demonstrated in accordance with NUREG-0800 and ANSI/ANS-57.3-1983.

The subject system meets the applicable criticality safety criteria subject to the limits and controls given below.

1) Fuel Design: As specified in Section 2.0.

2) System Design: As described in Section 3.0.

3) If fuel assemblies are stored with plastic wrapping, the bottom of the wrapping shall be open to assure free drainage.

4) Five hundred (500) ppm (minimum) dissolved Boron in water during fuel movements in normally flooded systems unless four inch (minimum) edge-edge bundle spacing (two bundles) is assured at all credible accident conditions.

2.0 FUEL PARAMETERS

The key bundle design parameters used in these calculations are listed in Table 2.1.

The bundle is a 14x14 design with five guide tubes. Since the guide tubes are much larger than the fuel rods, the bundle may be more easily visualized as a 7x7 array of two cell types. Type 'F' is a 2x2 fuel rod array and Type 'G' is a single guide tube. Using this 7x7 description, the bundle is composed as shown in Figure 2.1.

Table 2.1
Bundle Parameters

Parameter	Design Value	Model Value
Enrichment (wt% U-235)	5.0 (max.)	5.0
Pellet Diameter (inch)	0.3700	0.3700
Pellet Density (%TD)	94.0	95.0
Pellet Dish Volume (%)	1.0	0
Active Fuel Length (inch)	136.7	136.7 (min.)
Clad ID/OD (inch)	0.378/0.440	0.378/0.440
Rod Pitch (inch)	0.5800	0.5800
Gd/Boron Content	Variable	None
Fuel Rods Per Bundle	176	176
Guide Tube ID/OD (inch)	1.035/1.115	1.035/1.115

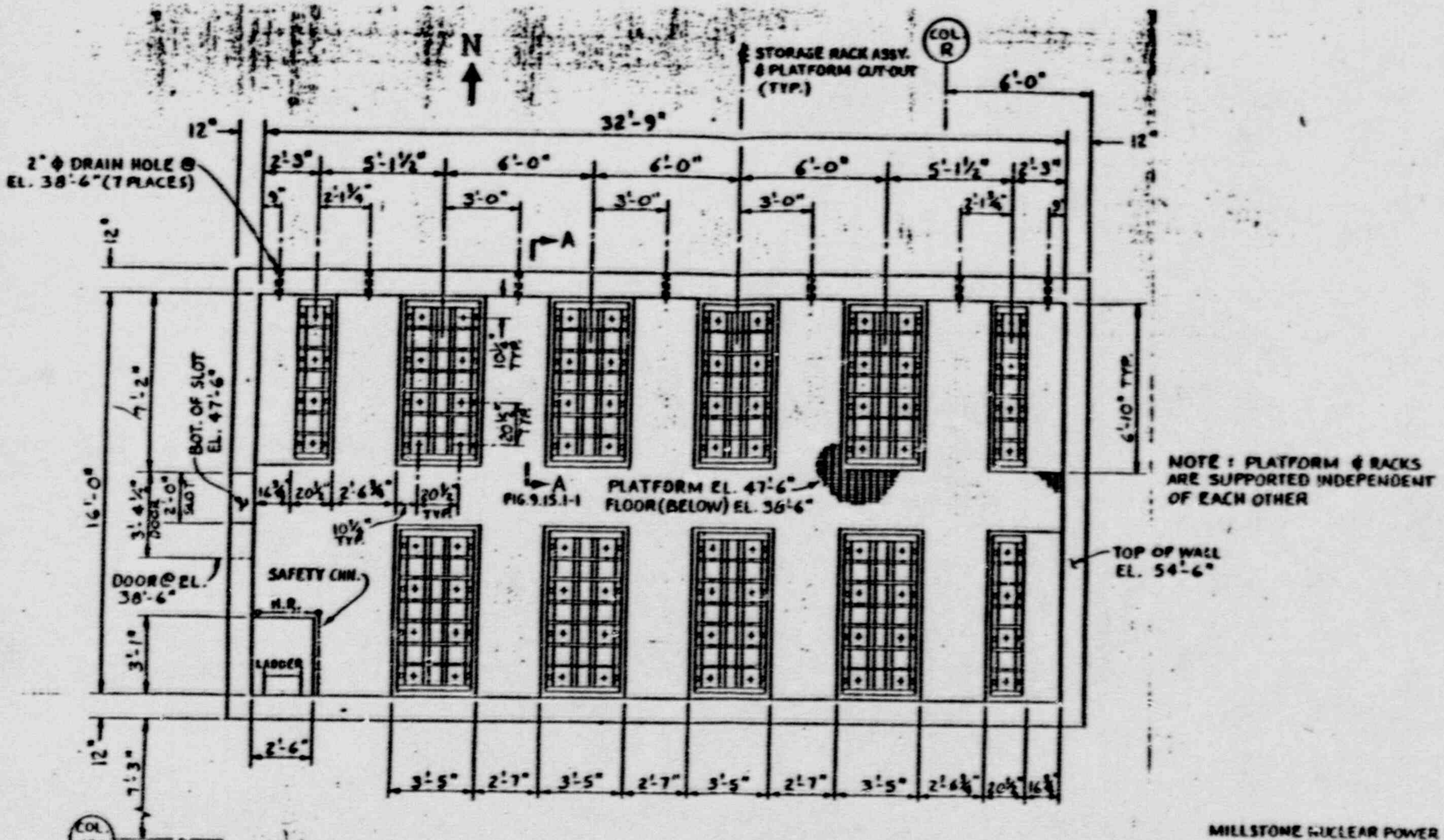
Figure 2.1

Rod Arrangement

Row/Col	1	2	3	4	5	6	7
1	F	F	F	F	F	F	F
2	F	G	F	F	F	G	F
3	F	F	F	F	F	F	F
4	F	F	F	G	F	F	F
5	F	F	F	F	F	F	F
6	F	G	F	F	F	G	F
7	F	F	F	F	F	F	F

Key: F = 2x2 Fuel Rod Array

G = Guide Tube



NOTE: PLATFORM & RACKS ARE SUPPORTED INDEPENDENT OF EACH OTHER

PLAN OF NEW FUEL STORAGE RACKS

MILLSTONE NUCLEAR POWER STATION
MILLSTONE UNIT NO. 2

FIG. 9.8-1

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4a

3.0 STORAGE RACK GEOMETRY

The coordinate system used is:

X: East-West (East is +)
Y: North-South (North is +)
Z: Vertical (Up is +)

Multiple dimensions and array descriptions are listed in the order X, Y, Z. The racks were modeled in accordance with Figure 9.8-1 of the FSAR.

The vault was modeled as a room 32'-9"x16'x11'4.7". The vault was reflected with 30 cm of concrete at all six faces.

This close-fitted reflection at the top and bottom is conservative relative to the actual bundle positioning and the vault height. All 76 storage locations were filled with the subject fuel design.

There are eight 2x4 modules and three 1x4 modules of storage cells.

The bundles are spaced 20.5 inches center-center within modules. The edge-edge module-module spacing modeled is 31 inches (X) and 28 inches (Y).

All materials of construction were neglected in the model. All neutron absorptions occur in the fuel, the moderator, or the reflector. This is a conservative model.

4.0 CALCULATION METHODS

All computer codes and cross sections are part of the SCALE[1] system.

The neutron multiplication factors, k_{eff} or k-inf, were calculated using XSDRNPM, a one-dimensional discrete ordinates transport code, or KENO-Va, a three-dimensional Monte Carlo code.

Sixteen group (Hansen-Roach) cross sections were used with resonance corrections by BONAMI/NITAWL.

All codes and cross sections have been extensively benchmarked against critical experiment data.

4.1 METHODS VERIFICATION

The SCALE codes and cross sections have been extensively benchmarked against data from critical experiments.

Supplemental benchmarking was performed immediately before the calculations reported here. The experiments selected are described in References 2 and 3.

The results are listed in Table 4.1.

The average and standard deviation are 1.00265 and 0.00490, respectively.

The 95 percent upper limit (UL) on the KENO k_{eff} is calculated by pooling the KENO variance and the bias variance.

Table 4.1
Benchmark Calculation Results from KENO-Va
16 Group Cross Sections

Case No.	Calculated k_{eff}
	Reference 2 Experiments
2378	1.00395 ± 0.00376
2384	1.00037 ± 0.00306
2388	0.99886 ± 0.00341
2420	1.00038 ± 0.00367
2396	0.99443 ± 0.00360
2402	1.00694 ± 0.00283
2411	1.01223 ± 0.00286
2407	1.00647 ± 0.00332
2414	1.00967 ± 0.00327
	Reference 3 Experiments
9	1.00092 ± 0.00487
10	1.00181 ± 0.00412
11	0.99786 ± 0.00413
12	0.99885 ± 0.00487
31	1.00442 ± 0.00421

For example, the 95 percent UL k_{eff} for Case 2378 is calculated below.
k_{eff} (95% UL) = 1.00395 - 0.00265 + 1.66 * sqrt(3.76E-3**2 + 4.90E-3**2)
= 1.00130 + 0.01025 = 1.01155

The 1.66 multiplier is the one-sided Student t (5%) with about 80 degrees of freedom.

For reference, the bias-corrected results are reported in Table 4.2.

The 95% upper limit (UL), which is the parameter used in judging acceptability, exceeds 1.0 in every case after bias correction. The average 95% UL is 1.0102.

Therefore, the results remain conservative.

All results in this report have <u>not</u> been bias-corrected, unless otherwise stated. Therefore, these results would tend to be conservative by about 0.0027.

Table 4.2
Bias-Corrected Benchmark Results

Case No.	k_{eff}	k_{eff} (95% UL)
2378	1.00130 ± 0.00376	1.01155
2384	0.997716 ± 0.00306	1.00731
2388	0.996206 ± 0.00341	1.00612
2420	0.997726 ± 0.00367	1.00789
2396	0.991776 ± 0.00360	1.00187
2402	1.00429 ± 0.00283	1.01368
2411	1.00958 ± 0.00286	1.01900
2407	1.00382 ± 0.00332	1.01364
2414	1.00702 ± 0.00327	1.01680
9	0.998266 ± 0.00487	1.00973
10	0.999156 ± 0.00412	1.00978
11	0.995206 ± 0.00413	1.00584
12	0.996196 ± 0.00487	1.00766
31	1.00177 ± 0.00421	1.01249

5.0 CALCULATION RESULTS

The racks were conservatively modeled with uniform interspersed moderation and with concrete reflection. The input for a typical KENO run is attach for reference.

The KENO-Va results are listed in Table 5.1.

The fully flooded result is actually that for a single bundle surrounded by 30 cm of water. As will be shown in Section 6.2, flooded bundles on 20.5 inches centers are effectively isolated (i.e., the bundle-bundle interactions are negligible.

The peak reactivity occurs at full flooding. The 95% upper limit on the peak k_{eff} is:

k_{eff} (95% UL) = 0.9045 - 0.00265 + 1.66 * SQRT(0.0038**2+0.0049**2) = 0.9121

Therefore, the system meets the 0.95 limit on k_{eff}.

If the iron/steel structural members of the rack had been modeled, the k_{eff} would have been lower than that reported here.

Table 5.1
New Fuel Racks
5.0% Enriched Fuel
Interspersed Moderation Effects
KENO-Va Results

Interspersed Water Density (Vol%)	k_{eff}
1	0.7095 ± 0.0047
2.5	0.7139 ± 0.0035
5	0.8566 ± 0.0032
7.5	0.8158 ± 0.0034
100	0.9045 ± 0.0038

6.0 SENSITIVITY STUDIES

The key parameters controlling reactivity are:

1) Fuel enrichment: The enrichment is fixed at the maximum credible value (5.0%).

2) Moderation: Data on interspersed moderation effects within the new fuel storage are in Section 5.0.

Other moderation effects are covered in Section 6.1.

3) Bundle-Bundle Spacing: Spacing effects due to dimensional tolerances, eccentric positioning and those due to bundle handling accidents are covered in Section 6.2.

6.1 Moderation Effects (Full Flooding)

The nominal bundle design (176 fuel rods and 5 guide tubes) is composed as follows:

The average water/fuel volume ratio (Vw/Vf) is 2.03. If the entire 14x14 array was fuel rods, the Vw/Vf would be 1.71. Since reactivity may be changed if fuel rods are removed from the bundle, generic bundle designs with Vw/Vf ratios in the range 2.0-4.0 were evaluated. The generic bundles were modeled with the nominal pellet and clad dimensions but with a pitch selected to yield the desired Vw/Vf. This is a conservative model since the zircaloy of the guide tubes is not in the model. Reference data for models with all zircaloy included are also provided. The calculation sequence was as follows:

1) Self-shielded 16 group cross sections were generated using BONAMI/NITAWL.

Table 6.1
Fuel Zone Composition
Nominal Design Values

Material	Volume %
UO_2	28.70
Pellet-Clad Gap	1.25
Clad (zirc)	11.66
Moderation (water)	58.39
Total	100.00

2) Cell-weighted cross sections were generated using an XSDRNPM model of an infinite rod array.

3) These cell-weighted cross sections were used to simulate a 8.12"x8.12"x infinite bundle in KENO-Va or XSDRNPM models of bundles in an infinite array or a single bundle with full water reflection.

Generic bundle characteristics are listed in Table 6.2.

Listed in Table 6.3 are XSDRNPM results for generic rods/bundles. The results include the k-inf for an infinite rod lattice (cell-weighting run) and the k_{eff} for a single bundle with full water reflection (FWR). The bundle was modeled as a 12.0834 cm radius cylinder (infinite length) surrounded by a 30 cm of water.

The Table 6.3 results indicate a peak k_{eff} (conservative model) near 0.934 assuming that fuel rods are withdrawn in the optimum sequence.

Table 6.2
Generic Bundle Characteristics

Vw/Vf	Clad OD (cm)	Pitch (cm)	Total Fuel Rods	Removed Fuel Rods
			Guide Tube Zr in Model	
2.0	1.13148	1.54689	177.8	-1.8
2.03	1.13162	1.55465	176.0	0 (nominal)
2.5	1.1335	1.65629	155.1	20.9
3.0	1.1355	1.75889	137.5	38.5
3.5	1.13752	1.85585	123.5	52.5
4.0	1.13952	1.94796	112.1	63.9
			No Guide Tube Zr in Model	
2.0	1.1176	1.53894	177.8	-1.8
2.03	1.1176	1.54667	176.0	0 (Nominal)
2.50	1.1176	1.64778	155.1	20.9
3.0	1.1176	1.74987	137.5	38.5
3.5	1.1176	1.84631	123.5	52.5
4.0	1.1176	1.93797	112.1	63.9

Table 6.3
Fuel Rod Removal Effects (Generic Rods/Bundles)
XSDRNPM Results (Infinite Length Rods/Bundles)

Vw/Vf	Rod k-inf	FWR Bundle k_{eff}
		Guide Tube Zr in Model
2.0	1.5086	0.9062
2.5	1.5252	0.9219
3.0	1.5298	0.9286
3.5	1.5279	0.9296
4.0	1.5210	0.9267
		No Guide Tube Zr in Model
2.0	1.5102	0.9103
2.03	1.5119	0.9117
2.5	1.5268	0.9262
3.0	1.5314	0.9329
3.5	1.5295	0.9340
4.0	1.5226	0.9311

Safety of a single bundle is assured with any credible number of fuel rods removed (or added). The KENO result for an explicit model of a single bundle (176 fuel rods, 5 guide tubes, 136.7" long) flooded and reflected with full density water is 0.9045 ± 0.0038.

A single flooded bundle was also modeled using the conservative homogeneous (cell-weighted) cross sections in KENO-Va; Result: 0.9054 ± 0.0035.

Therefore, the cross sections (heterogeneous-homogeneous) and the codes (KENO-XSDRNPM) agree very well.

6.2 Bundle Spacing Effects

An infinite array of generic bundles with the nominal Vw/Vf (2.03) were modeled with XSDRNPM. The system modeled was fully flooded. The guide tube Zr was not in the model. The infinite length bundles were spaced as indicated in Table 6.4.

An infinite array of bundles is acceptable with all center-center spacing greater than about 15 inches. No credible combination of dimension tolerances and eccentric positioning could result in spacings approaching 15" or less.

Two closely-placed bundles (flooded, full water reflection) were also modeled to determine the effect of fuel handling accidents. The results are in Table 6.5.

Table 6.4
Bundle Spacing Effects
Infinite x Infinite Bundle Array
Fully Flooded
XSDRNPM Results

Center-Center Spacing (inch)	Edge-Edge Spacing (inch)	k-inf
20.5	12.38	0.9128
20	11.88	0.9131
18	9.88	0.9158
16	7.88	0.9244
14	5.88	0.9525
12	3.88	1.0481
10	1.88	1.3218
8.12	0	1.5119

Table 6.5
Two Closely Placed Bundles
Flooded, Full Water Reflection
Zero Boron
KENO-Va Results (Explicit Model)

Edge-edge Spacing (inch)	k_{eff}
0	1.0379 ± 0.0053
4	0.9270 ± 0.0052
8	0.9041 ± 0.0049
12	0.9002 ± 0.0054

Criticality can result if two bundles are brought together in a flooded system. Since a minimum spacing between bundles has been specified and since flooding of the vault is an independent and very unlikely occurrence, no single accident condition in the new fuel vault can result in criticality.

The four-inch minimum edge-edge spacing is met by two bundles on the transfer carriage. If an in-transit bundle could be brought closer than four inches to a bundle on the carriage, then 500 ppm (minimum) dissolved boron will be required.

For fuel handling in normally flooded systems, a minimum dissolved boron content is specified to assure safety if bundles are accidentally brought together. The effect of boron on the k_{eff} of two edge-edge bundles is shown in Table 6.6. The reflector water (30 cm thick) also contained the indicated boron content.

The specified 500 ppm (minimum) will assure criticality safety at any single credible accident condition during fuel handling.

Table 6.6
Dissolved Boron Effects
Two Edge-Edge Bundles
Flooded, Full Water Reflection
KENO-Va Results (Explicit Model)

PPM Boron	k_{eff}
0	1.0409 ± 0.0045
500	0.9371 ± 0.0037
1000	0.8739 ± 0.0030
1500	0.8247 ± 0.0038

7.0 KENO INPUT LISTING

The new fuel vault model, including compositions and geometry, is in the listing below. The water density was changed for other runs reported in Section 6.0.

```
MILLSTONE 14x14, 5.0% ENR, NEW FUEL RACKS, 5% WATER
READ PARAMETERS
TME=290.0 GEN=103 NPG=500 LIB=41 TBA=2.0
FLX=YES FDN=YES XS1=NO NUB=YES PWT=YES
END PARAMETERS
READ MIXT  SCT=1
MIX= 1
'  FUEL PELLET, 5.0% ENR
    92235  1.175834E-03
    92238  2.205852E-02
     8016  4.646871E-02
MIX= 2
    40302  4.251812E-02
MIX= 3
'  5% WATER
     8016 1.6690-3
     1001 3.3380-3
MIX= 4
'  CONCRETE
     8016  4.607448E-02
     1001  1.374186E-02
    13027  1.745493E-03
    20040  1.520656E-03
    26000  3.472435E-04
    14028  1.662057E-02
    11023  1.747307E-03
 END MIXT
 READ GEOMETRY
```

```
UNIT  1
'  FUEL ROD
CYLINDER  1 1 0.4699 2P173.609
CYLINDER  0 1 0.48006 2P173.609
CYLINDER  2 1 0.5588 2P173.609
CUBOID  3 1 4P0.7366 2P173.609
UNIT  2
'   GUIDE TUBE, 1.035"ID/1.115"OD
COM=' UNIT 2 IS GUIDE TUBE'
CYLI  3 1 1.31445 2P173.609
CYLI  2 1 1.41605 2P173.609
CUBO  3 1 4P1.4732 2P173.609
UNIT 3
COM=" 2X2 ARRAY OF FUEL RODS                    "
ARRAY 1 2R-1.4732 -173.609
UNIT 4
COM="  THIS IS THE BUNDLE        "
ARRAY 2 2R-10.3124 -173.609
'  ADD MODERATION FOR 20.5" CENTERS
CUBO  3 1 4P26.035 2P173.609
UNIT 5
COM=" THIS IS A 1X4 ARRAY OF CELLS        "
ARRAY 3 -26.035 -104.14 -173.609
UNIT 6
COM=" MODERATION FOR 6 FEET C-C BETWEEN 2X4 MODULES        "
'  E-E SPACING = 72" -41" = 31"
CUBO  3 1 2P39.37 2P104.14 2P173.609
UNIT 7
COM=" MODERATION FOR 61.5 INCH C-C SPACING (1X4 - 2X4)          "
'  E-E SPACING = 61.5-20.5 - 10.25 = 30.75"
CUBO  3 1 2P39.0525 2P104.14 2P173.609
```

```
UNIT 8
COM=" RACKS AT NORTH END OF ROOM            "
ARRAY 4 -456.565 -104.14 -173.609
'  ADD MODERATION TO WALL AT EAST-WEST AND TO ROOM CENTER AT N-S
CUBO  3 1 2P499.11 104.14 -139.7 2P173.609
UNIT 9
COM=" RACKS AT SOUTH END OF ROOM            "
ARRAY 5 -326.39 -104.14 -173.609
'  ADD MODERATION TO WALL AT EAST-WEST AND TO ROOM CENTER AT N-S
CUBO  3 1 2P499.11 139.7 -104.14 2P173.609
GLOBAL
UNIT 10
ARRAY 6 3R0.0
'  ADD 30 CM CONCRETE REFLECTION
REPL  4 2 6R5.0 6
END GEOMETRY
READ ARRAY
ARA=1 NUX=2 NUY=2 NUZ=1
FILL F1 END FILL
ARA=2 NUX=7 NUY=7 NUZ=1
LOOP
3  1 7 1  1 7 1  1 1 1
2  2 6 4  2 6 4  1 1 1
2  4 4 1  4 4 1  1 1 1
END LOOP
ARA=3 NUX=1 NUY=4 NUZ=1
FILL F4 END FILL
ARA=4 NUX=15 NUY=1 NUZ=1
FILL 5 7 5 5 6 5 5 6 5 5 6 5 5 7 5 END FILL
ARA=5 NUX=13 NUY=1 NUZ=1
FILL 5 5 6 5 5 6 5 5 6 5 5 7 5 END FILL
ARA=6 NUX=1 NUY=2 NUZ=1
FILL 9 8 END FILL
END ARRAY
```

```
READ BOUNDS
ALL=VACUUM
END BOUNDS
READ START
NST=1
END START
READ BIAS
ID=301 2 7 END BIAS
END DATA
```

8.0 REFERENCES

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2. M.N. Baldwin, et.al., "Critical Experiments Supporting Close Proxim Water Storage of Power Reactor Fuel", BAW-1484-7, July 1979.

3. S.R. Bierman, B.M. Durst, and E.D. Clayton, "Critical Separation Between Subcritical Clusters of 4.31% Enriched UO_2 Rods in Water with Fixed Neutron Poisons," NUREG/CR-0073, May 1978.