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FINAL REPORT CRITICALITY SAFETY ANALYSIS D.C. COOK NEW FUEL STORAGE VAULT WITH 5.0 PERCENT ENRICHED 17X17 FUEL

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D.C. COOK NEW FUEL STORAGE VAULT
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1.0 INTRODUCTION

The criticality safety of 5.0 percent enriched 17x17 fuel assemblies in the new fuel storage vault is conservatively demonstrated in accordance with NUREG-0800 and ANSI/ANS-57.3-1983.

2.0 SUMMARY

The spent fuel storage racks meet the applicable criticality safety criteria subject to the limits and controls listed below.

- Fuel Design: As specified in Section 3.0.
- Storage Rack Design: As described in Section 4.0.
- Fuel Handling: Unless covered by a specific analysis, all in-transit bundles shall be maintained at least 12 inches edge-edge from all other bundles.

3.0 FUEL DESIGN

The nominal bundle design parameters assumed in this evaluation are listed in Table 1.

TABLE 1

FUEL DESIGN PARAMETERS

Parameter	Design Value	Model Value
Enrichment (wt% U-235)	5.0 (max.)	5.0
Pellet Diameter (inch)	0.3030	0.3030
Pellet Density (%TD)	94.0 ± 1.5	95.0
Pellet Dish (Vol%)	1.0	0
Pellet Stack Length (inch)	144	144 (min.)
Clad ID/OD (inch)	0.310/0.360	0.310/0.360
Inst. Guide Tube ID/OD (inch)	0.448/0.480	0.448/0.480[1]
Number of Inst. Guide Tubes	25	25[1]
Rod Pitch (inch)	0.496	0.496[1]

1 The tabulated values were used in explicit models of the nominal design. As described in Section 7.1, sensitivity studies were performed with generic bundle designs which had different values for the noted parameters.

The arrangement of the rod types in the bundle is shown in Figure 1.

FIGURE 1
ROD ARRANGEMENT WITHIN BUNDLE
KEY: F = FUEL ROD; G = GUIDE TUBE; I = INSTRUMENT TUBE

ROW/COL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
2	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
3	F	F	F	F	F	G	F	F	G	F	F	G	F	F	F	F	F
4	F	F	F	G	F	F	F	F	F	F	F	F	F	G	F	F	F
5	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
6	F	F	G	F	F	G	F	F	G	F	F	G	F	F	G	F	F
7	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
8	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
9	F	F	G	F	F	G	F	F	I	F	F	G	F	F	G	F	F
10	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
11	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
12	F	F	G	F	F	G	F	F	G	F	F	G	F	F	G	F	F
13	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
14	F	F	F	G	F	F	F	F	F	F	F	F	F	G	F	F	F
15	F	F	F	F	F	G	F	F	G	F	F	G	F	F	F	F	F
16	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
17	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F

4.0 SYSTEM GEOMETRY

The racks were modeled using nominal dimensions. The array descriptions below, such as "MxN", imply M units in the east-west direction and N units in the north-south direction.

Bundles are stored in a 2x4 array of banks with a 9x2 array of bundles per bank. Since room is available for an additional 1x4 array of banks to the east of the 2x4 array, a 3x4 bank array was modeled for these calculations. The bundles are on 21 inch centers within the banks. The banks are on 234"x64.5" centers. Concrete reflection was applied at the four walls, the floor, and at 12 feet above the floor. The fuel length was 12 feet. Uniformly interspersed water with a density in the range 0 to 1.0 gm/cc was within and between the bundles.

5.0 CALCULATION METHODS

All computer codes and cross sections used in this evaluation are part of the SCALE[1] system which has been extensively benchmarked against data from critical experiments.

Sixteen group cross sections were prepared using BONAMI/NITAWL.

K_{eff} or k_{inf} calculations were performed using KENO-Va or XSDRNPM.

5.1 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 experiments were selected particularly to establish the calculational bias for the poisoned spent fuel storage rack analysis but virtually identical results have been obtained in previous calculations for non-poisoned experiments.

The results are listed in Table 2.

TABLE 2
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

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.

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. The KENO results are for 83 or 103 generations of neutrons. Thus, the 1.66 multiplier is conservative.

For reference, the bias-corrected results are reported in Table 3.

TABLE 3
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

The 95 percent 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 conservatively.

All k_{eff} results in this report have not been bias-corrected, unless otherwise stated. Therefore, these results would tend to be conservative by about 0.0027.

6.0 CALCULATION RESULTS

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

The KENO-Va results are listed in Table 4.

TABLE 4
NEW FUEL RACKS
3X4 BANK ARRAY, 5.0% ENRICHED FUEL
INTERSPERSED MODERATION EFFECTS
KENO-Va RESULTS

Interspersed Water Density (Vol%)	k_{eff}
2.5	0.8771 ± 0.0045
5	0.8794 ± 0.0045
7.5	0.8530 ± 0.0048
10	0.8316 ± 0.0043
100	0.9359 ± 0.0039

The fully flooded result is actually that for a single bundle surrounded by 30 cm of water. As will be shown in Section 7.2, flooded bundles on 21-inch centers are effectively isolated; i.e., the bundle-bundle interactions are negligible.

The k_{inf} for an infinite array of infinite length fuel rods with zero interspersed moderation is 0.8340 using XSDRNPM. The finite system reactivity would be less than this value.

The peak reactivity occurs at full flooding. If all cells had been on 21-inch centers without banking and spacing between banks, the peak reactivity would have been higher at it would occur with low density interspersed moderation.

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

The one-sided 95 percent upper limit on the bias-corrected peak k_{eff} is:

k_{eff} (95% UL) = 0.9359 - 0.00265 + 1.66 * SQRT(0.0039**2 + 0.0049**2) = 0.9333 + 1.66 * 0.0063 = 0.9437.

7.0 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 vault are in Section 6.0. Other moderation effects are covered in Section 7.1.

3. Bundle-Bundle Spacing - Spacing effects due to dimensional tolerances, eccentric positioning, etc. and those due to bundle handling accidents are covered in Section 7.2.

7.1 Moderation Effects (Full Flooding)

The nominal bundle design (264 fuel rods and 25 instrument/guide tubes) is composed as follows:

TABLE 5
FUEL ZONE COMPOSITION
NOMINAL DESIGN VALUES

Material	Volume %
UO_2	26.77
Pellet-Clad Gap	1.25
Clad (Zr)	10.59
Moderation (water)	61.38
Total	99.99

The average water/fuel volume ratio (Vw/Vf) is 2.29. If the entire 17x17 array was fuel rods, the Vw/Vf would be 2.00. 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 gap dimensions but with clad OD and pitch values to yield the designed Vw/Vf and the bundle-average clad volume. The calculation sequence was as follows.

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

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 8.432"x8.432"xinfinite 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.

TABLE 6
GENERIC BUNDLE CHARACTERISTICS

Vw/Vf	Clad OD (cm)	Pitch (cm)	Total Fuel Rods	Removed Fuel Rods
2.0	0.92376	1.26516	278.3	-14.3 (14.3 rods in guide tubes)
2.29	0.92426	1.31814	264.0	0.0 (nominal)
2.50	0.92462	1.35443	254.7	9.3
3.0	0.92548	1.43816	234.9	29.1
3.5	0.92634	1.51729	217.9	46.1
4.0	0.92720	1.59249	203.2	60.8

Listed in Table 7 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 30 cm of water.

TABLE 7
FUEL ROD REMOVAL EFFECTS (GENERIC RODS/BUNDLES)
XSDRNPM RESULTS (INFINITE LENGTH RODS/BUNDLES)

Vw/Vf	Rod k_{inf}	FWR Bundle k_{eff}
2.0	1.5038	0.9256
2.29	1.5163	0.9373
2.5	1.5231	0.9438
3.0	1.5311	0.9528
3.5	1.5305	0.9553
4.0	1.5251	0.9536

The Table 7 results indicate a peak k_{eff} near 0.955 assuming that fuel rods are withdrawn in the optimum sequence.

Given the conservative model used in these calculations, the fact that about 10-20 optimally removed rods are required to achieve a 0.95 k_{eff}, and the subcriticality with any number of removed rods, 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 (264 fuel rods, 25 instrument/guide tubes, 12 feet long) flooded and reflected with full density water is 0.9359 ± 0.0039.

A single flooded bundle was also modeled using the homogeneous (cell-weighted) cross sections. The KENO-Va results from a cylindrical model (as in XSDRNPM) and from a cuboidal model are 0.9388 ± 0.0039 and 0.9305 ± 0.0036, respectively. Therefore, the cross sections (heterogeneous-homogeneous) and the codes (KENO-XSDRNPM) agree very well.

7.2 Bundle Spacing Effects

An infinite array of generic bundles with the nominal Vw/Vf (2.29) were modeled with XSDRNPM. The system modeled was fully flooded. The infinite length bundles were spaced as indicated in Table 8.

TABLE 8
BUNDLE SPACING EFFECTS
INFINITE X INFINITE BUNDLE ARRAY
FULLY FLOODED
XSDRNPM RESULTS

Center-Center Spacing (inch)	Edge-Edge Spacing (inch)	k_{inf}
12	3.568	1.0931
14	5.568	0.9839
16	7.568	0.9517
18	9.568	0.9420
20	11.568	0.9388
21	12.568	0.9382

An infinite array of bundles is acceptable with all center-center spacings greater than about 16-18 inches. The storage cell guides form a 9.0"x9.0" square. If four bundles were brought together at the near edges of their contiguous guides, these bundles would be on 20.432 inch centers. Therefore, no credible combination of dimension tolerances and eccentric positioning could result in spacings approaching 18 inches or less.

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.

8.0 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

```
DC COOK, NEW FUEL RACKS, 5.0% ENR, 10% INTERSPERSED WATER
READ PARAMETERS
TME=290.0 GEN=103 NPG=500 LIB=41 TBA=3.0
FLX=YES FDN=YES XS1=YES NUB=YES PWT=YES
END PARAMETERS
READ MIXT  SCT=1
MIX= 1
'  FUEL PELLET
   92235  1.175834E-03
   92238  2.205852E-02
    8016  4.646871E-02
MIX= 2
,  CLAD
 40302  4.251812E-02
MIX= 3
'  10
      8016  3.337967E-03
      1001  6.675933E-03
```

```
MIX=4
'  REG CONCRETE
      8016  4.607448E-02
      1C01  1.374186E-02
     26000  3.472435E-04
     13027  1.745493E-03
     20040  1.520656E-03
     14028  1.662057E-02
     11023  1.747307E-03
END MIXT
READ GEOMETRY
UNIT  1
COM="   FUEL ROD                       '
CYLI  1 1 0.38481 2P182.88
CYLI  0 1 0.3937 2P182.88
CYLI  2 1 0.4572 2P182.88
CUBO  3 1 4P0.62992 2P182.88
UNIT  2
COM="  GUIDE TUBE                                  "
CYLI  3 1 0.56896 2P182.88
CYLI  2 1 0.6096 2P182.88
CUBO  3 1 4P0.62992 2P182.88
UNIT  3
COM="  BUNDLE ON 21 INCHX21 INCH CENTERS             "
ARRAY 1 2*-10.70864 -182.88.0
CUBO  3 1 4P26.67 2P182.88
UNIT 4
COM=" THIS IS A 9X2 BANK OF BUNDLES
ARRAY 2 -240.03 -53.34 -182.88
' BANK SPACINGS (BUNDLE C-C): X=66", Y=54"
' 31.92272CM OF C-C SPACING IN UNIT 4
' ADD 67.85864CM AT +/- X, 52.61864CM AT +/- Y
CUBO  3 1 2P307.88864 2P105.95864 2P182.88
```

```
GLOBAL
UNIT 6
ARRAY 3 3R0.0
' ADD CONCRETE REFLECTOR AT ALL 6 FACES
REPL  4 2 6R5.0 6
END GEOMETRY
READ ARRAY
ARA=1 NUX=17 NUY=17 NUZ=1
LOOP
1  1 17 1  1 17 1  1 1 1
2  6 12 3  3 15 12  1 1 1
2  4 14 10  4 14 10  1 1 1
2  3 15 3  6 12 3  1 1 1
END LOOP
ARA=2 NUX=9 NUY=2 NUZ=1
FILL F3 END FILL
ARA=3 NUX=3 NUY=4 NUZ=1
FILL F4 END FILL
END ARRAY
READ START
NST=1
'  CONSERVATIVE START
XSM= 897.0 XSP=950.0 YSM=212.0 YSP=424.0 ZSM=180.0 ZSP=185.76
END START
READ BOUNDS
ALL=VACUUM
END BOUNDS
READ BIAS
ID=301 2 7
END BIAS
END DATA
```

9.0 REFERENCES

(1) "SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation," NUREG/CR-0200.

(2) M.N. Baldwin, et al, "Critical Experiments Supporting Close Proximity 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.

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