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CRITICALITY SAFETY ANALYSIS ST. LUCIE NEW FUEL STORAGE VAULT WITH 4.5% ENRICHED 14x14 FUEL ASSEMBLIES

MARCH 1987

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ADVANCED NUCLEAR FUELS CORPORATION

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1.0 SUMMARY

The criticality safety of the new fuel storage vault with 4.5% enriched 14x14 bundles is assessed 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. Bundle-Bundle Spacing Within Racks - 21" nominal (center-center) (14" minimum bundle pitch is acceptable)
3. Loading Arrangement - Rows 5 and 6 of 10x10 array locked out
4. Dissolved boron (greater than or equal to 1720 ppm) in water during fuel movements in normally flooded systems unless 4" (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 2.0.

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 2.0.

Table 2.0
Bundle Parameters

Parameter	Design Value	Model Value
Enrichment (wt% U-235)	4.50 (max.)	4.50
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

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

Figure 2.0 Rod Arrangement

3.0 STORAGE RACK GEOMETRY

The new fuel vault contains a 10x10 array of storage cells on a 21 inches nominal square pitch. Rows 5 and 6 have been designated as unavailable for fuel bundle storage and are physically locked out of service. Therefore, the racks modeled contained only 80 bundles. The racks were modeled in accordance with Figure 9.1-1 of the FSAR. The racks were modeled with concrete reflection (30 cm thick) at the four walls, the floor, and at the top of the racks (14 feet above the floor). The modeled spacings between the edge of the racks and the walls are 40.5 inches (north), 37.5 inches (south), 31.5 inches (east), and 36.0 inches (west).

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_{inf} and k_{eff}, were calculated using KENO-Va, a three dimensional Monte Carlo code, or using XSDRNPM, a one dimensional discrete ordinates transport code.

The 16 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.

Evidence of methods verification is presented later in this document.

5.0 MODERATION AND SPACING EFFECTS

To assure safety at all credible accident conditions, the following effects were assessed.

1. The effect of removing fuel rods from a fully flooded bundle; i.e., increase the water/fuel volume ratio (Vw/Vf) within the bundle.

2. Achieve optimum interspersed moderation within the racks.

3. Effect of bundle-bundle spacing within the racks.

4. Fuel handling accidents resulting in two or more bundles placed closely together at fully flooded and reflected conditions.

5.1 Removal of Fuel Rods (Fully Flooded)

Generic models with Vw/Vf ratio s in the range of 2.03 to 4.0 were calculated. The nominal dimensions for the pellet and clad were used with a variable rod pitch to yield the desired Vw/Vf.

The calculation sequence for each Vw/Vf case was:

1. Prepare self-shielded cross sections using BONAMI/NITAWL.

2. Perform cell weighting of the unit rod cell using XSDRNPM.

3. Using the cell weighted (homogeneous) cross sections from step 2, model an infinite length bundle surrounded by 30 cm of water. The bundle and the water reflector were modeled as concentric cylindrical regions.

The results are in Table 5.1.

Table 5.1
Single Full Water Reflected Bundle System
Full Water Density, Infinite Length Bundle
Moderation Effects (Fuel Rod Removal)
(XSDRNPM Results)

Vw/Vf	k_{eff}
2.03 (nom.)	0.888
2.5	0.903
3.0	0.910
3.5	0.911
4.0	0.907

The optimum Vw/Vf is near 3.5. Since the bundle is relatively small (7.98 inch surface-surface or 8.12 inch across homogeneous cells), the neutron leakage is adequate to maintain the fully flooded k_{eff} well below 0.95 with any number of removed fuel rods.

5.2 Optimum Interspersed Moderation Within Racks

For these cases, the nominal bundle design and the nominal rack design parameters were modeled.

The water within and between the bundles in the rack was modeled as uniform in the range zero to 100 volume percent. Infinite and finite systems were modeled. The infinite system results were used to estimate the optimum interspersed water density. The finite system was then modeled with water densities near the estimated optimum. The calculation sequence for each water density was:

1. Prepare self-shielded cross sections using BONAMI/NITAWL.

2. Perform cell weighting of the unit rod cell using XSDRNPM.

3. Model an infinite array of infinite length bundles on 21 inch centers. As described before, the fuel and moderation were concentric cylindrical regions.

The k_{inf} results for the rod lattice and for the bundle lattice (21 inch centers) are listed in Table 5.2a.

Table 5.2a
Infinite System Data (Zero Leakage)
Interspersed Moderation Effects
(XSDRNPM Results)

Water Density (Vol%)	k_{inf} (Rod Lattice)	k_{inf} (Bundle Lattice) (21" Centers)
0 (normal)	0.7534	0.7534
1	0.7784	1.0480
3	0.8204	1.3344
5	0.8617	1.3874
8	0.9240	1.3294
10	0.9640	1.2563
12	1.0020	1.1749
15	1.0546	1.0543
20	1.1300	0.8858
40	1.3172	0.6548
60	1.4080	0.7131
80	1.4571	0.8063
100	1.4838	0.8901

The above data indicate that an infinite array of infinite length bundles is adequately subcritical at all interspersed water densities greater than 20 percent and also with zero interspersed moderation. Although the optimum water density for an infinite system is near 5 percent, leakage effects in a finite system will typically result in higher optimum water densities and lower k_{eff}'s.

The actual finite system was explicitly modeled using KENO-Va. The parameters modeled for the fuel and for the racks were given in Sections 2.0 and 3.0.

The results for low density interspersed moderation conditions are listed in Table 5.2b.

Table 5.2b
Finite System Data (New Fuel Racks)
Interspersed Moderation Effects
Moderation Between Rack Edge and Walls (Reflector Not Close-Fitted)
(KENO-Va Results)

Water Density (Vol%)	k_{eff}
5	0.903 ± 0.0041
8	0.963 ± 0.0047
10	0.961 ± 0.0049
12	0.942 ± 0.0044
20	0.800 ± 0.0045

Interpolated Data Below (Polynomial Regression)

5.0	0.9031
5.5	0.9187
6.0	0.9318
6.5	0.9426
7.0	0.9511
7.5	0.9576
8.0	0.9620
8.5	0.9646
9.0	0.9655
9.5	0.9648
10.0	0.9626
10.5	0.9590
11.0	0.9542
11.5	0.9483
12.0	0.9414
13.0	0.9253
14.0	0.9067
15.0	0.8866
16.0	0.8662
17.0	0.8463
18.0	0.8280
19.0	0.8122
20.0	0.8000

The KENO calculations (finite system) were performed using 83 (typical) generations of 300 neutrons. To establish the 95 percent upper limit on the Monte Carlo calculations, the appropriate one-sided "Student" t (80 degrees of freedom) is 1.66. Using the highest interpolated k_{eff} (9 percent water) and the highest KENO standard deviation (0.0049), the 95 percent upper limit is:

$$k_{eff}\ (95\%\ \text{UL}) = 0.9655 + 1.66 * 0.0049 = 0.9736$$

Since the k_{eff} is less than 0.98 with 95 percent confidence, the system is demonstrated to be adequately subcritical at optimum moderation.

5.3 Rack Spacing Effects (Bundle-Bundle Spacing)

The peak k_{eff} with low density interspersed moderation will change little if any with credible changes in bundle-bundle spacings. However, the optimum interspersed water density will tend to increase with decreasing bundle-bundle spacings.

The effect of bundle-bundle spacings on the reactivity of an infinite array of flooded infinite length bundles was assessed as described in Section 5.2 (infinite system) except that the bundle-bundle spacing was decreased and also the water density was fixed at 100 percent. The results are in Table 5.3.

Table 5.3
Infinite System Data (Zero Leakage)
Fully Flooded State
Bundle Spacing Effects
(XSDRNPM Results)

Bundle Spacing (Center-Center) (inches)	Bundle Spacing (Edge-Edge) (inches)	k_{inf}
21 (nominal)	12.88	0.890
18	9.88	0.894
14	5.88	0.930
12	3.88	1.024
8.12	0.00	1.484

An explicit KENO-Va model of the 14 inch center-center spacing condition resulted in a k_{inf} of 0.938 ± 0.0060. Thus, the KENO and XSDRNPM results are statistically identical.

An infinite array of flooded infinite length bundles is adequately subcritical (k_{eff} less than 0.95) at all bundle pitches greater than 14 inches. No credible combination of dimensional tolerances, eccentric positioning, or accident condition would result in a pitch approaching 14 inches. Therefore, the flooded state is acceptable.

5.4 Fuel Handling Accidents

As shown in Table 5.2a, an infinite array of edge-edge bundles (infinite rod lattice) is adequately subcritical for all interspersed water densities less than 10 percent.

It was also shown that an infinite array of flooded bundles is adequately subcritical if the bundle pitch is at least 14 inches.

Close placement of two flooded bundles was also explicitly modeled using KENO-Va. This covers potential accidents at the Fuel Inspection Elevator, Upender and the Fuel Transfer Tube, as well as generic cases such as dropping a bundle or moving a bundle next to another flooded bundle.

Finite bundle arrays with various spacings were modeled. In each case, the array was reflected by 30 cm of full density water. The KENO Va results are in Table 5.4.

Table 5.4
Fuel Handling Accidents
Fully Flooded, Full Water Reflection
(KENO-Va Results)

Bundle Array	Bundle-Bundle Spacing (Inches Edge-Edge)	k_{eff}
1x1		0.897 ± 0.0057
2x1	0	1.016 ± 0.0061
2x1	2.0	0.992 ± 0.0056
2x1	4.0	0.920 ± 0.0053

It is seen that two closely placed bundles may become critical if flooded and reflected. About four inches of water between two adjacent bundles is adequate to assure safety.

Full flooding and close placement of bundles represent two independent and improbable accident conditions in the new fuel vault. Since either condition alone has been shown to be acceptable, the new fuel vault is adequately subcritical.

In other systems which are normally flooded and which may accidentally allow close placement of bundles, additional controls are required. Assurance of dissolved boron (1720 ppm minimum) in these locations during fuel movement will lower the maximum credible k_{eff} by about 0.20, resulting in reactivities far below the 0.95 limit.

6.0 METHODS VERIFICATION

Supplemental benchmarking of the methods employed in this analysis were performed. Critical experiments documented in references 2-5 were modeled using methods identical to those of this report. The critical experiments include bundle arrays with variable bundle-bundle spacings, and with and without neutron absorber rods/plates between the bundles.

6.1 Reference 2 Experiments

Reference 2 experiments include a 3x3 array of 14x14 bundles. The rods contain 2.46 percent enriched UO_2 pellets on a 1.636 cm square pitch. Five of the experiments were selected for this benchmark. These cases contain little, if any, dissolved boron in the moderator (water), and include the effects of neutron absorbers. The other cases, not selected for benchmarking, include effects such as dissolved boron content and slight temperature changes.

The critical moderator height was determined in these experiments. The reported k_{eff}'s were normalized to a constant moderator height for each of the two classes of experiments. Therefore, the observed k_{eff}'s are not all unity. The data are in Table 6.1.

Table 6.1
Benchmark Results
Data of Reference 2

Case Number	k_{eff} (Observed)	k_{eff} (Calculated)	k_{eff} (95% UL)
2321	1.0030 ± 0.0009	0.997 ± 0.005	1.007
2317	1.0083 ± 0.0012	1.004 ± 0.004	1.012
2378	1.0000 ± 0.0010	1.009 ± 0.005	1.019
2396	1.0001 ± 0.0019	1.004 ± 0.004	1.012
2420	0.9997 ± 0.0015	1.002 ± 0.004	1.010
Average	1.0022 ± 0.0016	1.0032 ± 0.0019	1.0120

The 95 percent upper limit on the calculated k_{eff}, which is the parameter used in judging acceptability, exceeds the observed k_{eff} in every case. The average of the individual biases (calculated minus observed) is 0.00098 ± 0.0028.

6.2 Reference 3 Data

Reference 3 includes data on experiments using 2.35 and 4.31 percent enriched UO_2 rods in a 1x3 bundle array. Only the 4.31 percent enriched cases were selected for this benchmark. These cases were either 8x13 bundles (2.54 cm rod pitch) or 16x12 bundles (1.892 cm pitch). The critical separation between the bundles was determined with various neutron absorbers between the bundles and with various spacings to a thick steel wall.

In these cases, the observed k_{eff}'s are all 1.000.

Table 6.2
Benchmark Data From Reference 3

Rod Pitch (cm)	Distance to Steel Wall (cm)	Neutron Absorbers	k_{eff}
2.54	0		0.999 ± 0.006
2.54	6.6		1.001 ± 0.005
2.54	26.16		1.012 ± 0.005
1.892	6.6		0.999 ± 0.004
1.892	13.21		0.998 ± 0.004
1.892	54.05		1.008 ± 0.005
1.892	1.96	Boroflex	1.003 ± 0.004
1.892	1.96	Boral	0.997 ± 0.005
Average			1.0021

The average bias is 0.0021 ± 0.0019. The 95 percent upper limit on the KENO k_{eff} exceeds the observed value in each case.

6.3 Reference 4 Data

A single, undermoderated 22x22 array of 4.742 percent enriched rods with various patterns of 25 "water holes" (removed fuel rods) was tested to determine the critical moderator height. Since the bundle modeled contains guide tubes, the reference 4 data are useful to verify the methods, particularly the homogeneous representation of the bundle.

Three cases were calculated using KENO with explicit modeling and homogeneous modeling.

Table 6.3
Reference 4 Data
KENO with Hansen-Roach Cross Sections

Case	k_{eff} (Explicit)	k_{eff} (Homogeneous)
1670	0.995 ± 0.0054	1.002 ± 0.0055
1674	0.996 ± 0.0054	1.001 ± 0.0054
1680	1.000 ± 0.0051	1.005 ± 0.0063
Average	0.997	1.0027

The bias is -0.00017 ± 0.0015 for all six cases.

The homogeneous model results appear to be about 0.005 higher than the explicit model results, but this bias is not significant. All results agree very well with the observed k_{eff} of unity.

6.4 Reference 5 Data

The rod design here is identical to that of the reference 4 data:

Table 6.4a
Fuel Design Parameters

Rod Diameter (cm)	0.79
Enrichment (% U-235)	4.742
UO_2 Density (%TD)	94.71
Fuel Length (cm)	90
Clad	Aluminum
Clad ID/OD (cm)	0.82/0.94

Four flooded 18x18 bundles were placed in a 2x2 array spaced by various thicknesses of various between-bundle moderators. These moderators included air, water, expanded polystyrene, polyethylene powder (low density), and polyethylene balls (higher density).

These experiments were modeled using the SCALE system as documented in reference 6. Selected cases were modeled here for comparison.

These experiments are useful in validating the optimum moderation calculations. Experimental data with low density moderation within and between bundles are not available.

The three cases selected had a 10 cm spacing between bundles. This spacing was filled with either air, polystyrene, or polyethylene powder. The corresponding hydrogen densities were 0, 0.0022, and 0.0464 gm/cc, respectively. The water densities to yield these H densities are 0, 1.97 and 41.47 percent, respectively.

Table 6.4b
Reference 5 Data
Low Density Moderation Between Bundles
KENO Results

H Density (gm/cc)	k_{eff} (16 Group)	k_{eff} (27 Group)
0	1.012 ± 0.0046	0.985 ± 0.0053
0.0022	1.012 ± 0.0059	
0.0464	1.036 ± 0.0045	1.024 ± 0.0050

For the three 16-group cases, the bias is 0.020 ± 0.008.

The results presented, agree well with the complete result set of reference 6. The 16 group (Hansen-Roach) results appear to be slightly conservative.

These results indicate that the low density moderation results are accurate or perhaps slightly conservative.

6.5 Acceptability Limit

Pooling data from references 2, 3 and 4 (flooded cases), the average and standard deviation of the systematic bias are 0.0011 and 0.0011, respectively. Clearly, there is no significant systematic bias. Based on the limited replication of the low moderation cases (reference 5), and the complete results in reference 6, the bias at this condition will be conservatively set equal to that for the flooded cases.

Using the criteria of ANSI/ANS-8.17-1984 (and other similar documents), the maximum allowable, calculated k_{eff} is established as follows.

$$\text{LIMIT} = A - B - C - D$$

The terms are defined below.

LIMIT:	Maximum acceptable k_{eff}.
A:	Mean k_{eff} from appropriate benchmarks. The assigned value is 1.0011.
B:	An allowance for uncertainties in parameter A. The assigned value is 0.0011.
C:	An allowance for uncertainty in k_{eff} calculations. This allowance is variable, and is included in the final k_{eff} result; i.e., the 95 percent upper limit statement. Therefore, the acceptability limit is not adjusted, and C is set to zero.

D: An arbitrary margin to ensure subcriticality. This is set to 0.05, except for optimum moderation conditions where the value is 0.02.

Therefore, the acceptability limit is 0.95, or 0.98 (optimum moderation).

It should be noted that allowances B and C are often pooled before applying a confidence level multiplier (usually about 2.0).

In this format:

$$\text{LIMIT} = A - D - K * B + C$$

where K is the confidence level multiplier.

Since the KENO standard deviation is typically 0.003-0.006, the sum of squares is dominated by the KENO variance. The limits calculated by the two methods are very close. The ANS/ANSI format is more conservative by 0-0.0004 for typical KENO standard deviations.

7.0 REFERENCES

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(3) S. R. Bierman and E. D. Clayton, "Criticality Experiments with Subcritical Clusters of 2.35 wt% and 4.31 wt% U-235 Enriched UO_2 Rods in Water with Steel Reflecting Walls," NUREG/CR-1784 (PNL-3602), January 1981.

(4) J. C. Manaranche, et. al., "Critical Experiments with Lattices of 4.75% wt% U-235 Enriched UO_2 Rods in Water," ANS Trans, Vol. 28, pp. 302-303.

(5) J. C. Manaranche, et. al., "Dissolution and Storage Experimental Program with $U(4.75)O_2$ Rods," ANS Trans, Vol. 33, pp. 362-364.

(6) A. M. Hathout, et. al., "SCALE System Cross Section Validation for Criticality Safety Analysis," ANS Trans, Vol. 35, pp. 281-283.