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# CRITICALITY SAFETY ANALYSIS OF THE H.B. ROBINSON SPENT FUEL POOL WITH 4.2% NOMINAL ENRICHMENT FUEL ASSEMBLIES

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Prepared by

L. D. Gerrald

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Prepared by: L. D. Gerrald, Licensing Specialist, Corporate Licensing — Date: 1/24/89

Concurred by: J. E. Pieper, Second-Party Reviewer — Date: 1/24/89

Approved by: C. W. Malody, Manager Corporate Licensing — Date: 1/24/89

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# CRITICALITY SAFETY ANALYSIS OF THE H. B. ROBINSON SPENT FUEL POOL WITH 4.2% NOMINAL ENRICHMENT FUEL ASSEMBLIES

## 1.0 INTRODUCTION

Criticality safety of 4.2% nominal enriched 15x15 fuel assemblies in the poisoned, high density spent fuel storage racks is conservatively demonstrated in accordance with NUREG-0800 and ANSI/ANS-57.2-1983.

The analysis includes conservative assumptions on the dimensional changes of the Boraflex absorber sheets.

Using results from a previous analysis of the unpoisoned spent fuel racks with 4.2% enriched fuel (5) and sensitivity analysis data reported here, it is also conservatively shown that the entire spent fuel pool (including poisoned and unpoisoned racks) meet the applicable criticality safety criteria.

## 2.0 SUMMARY

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

| | |
|---|---|
| Fuel Design: | As described in Section 3.0. |
| Rack Design: | As described in Section 4.0 (Poisoned Racks).<br>21-inch nominal center-to-center spacings (Unpoisoned Racks) |
| Fuel Handling: | At least 500 ppm dissolved boron during fuel handling and at least 7-inches edge-to-edge spacings for in-transit bundles will assure that no single fuel handling accident can cause criticality. |

The maximum k-eff for the high density spent fuel racks, including conservative allowances for uncertainties, will be 0.919.

The maximum k-eff for 4.20% nominal enriched assemblies in the unpoisoned racks or in-transit in the pool will be 0.930.

Thus, the spent fuel pool meets the 0.95 upper limit on k-eff.

## 3.0 FUEL DESIGN

The 15x15 assembly includes 204 fuel rods, 20 guide tubes and one instrument tube. Key bundle design parameters are listed in Table 1.

TABLE 1 FUEL DESIGN PARAMETERS

| | |
|---|---|
| Enrichment: | 4.20 ± 0.05 wt% U-235 |
| Pellet Diameter: | 0.3565 ± 0.0005" |
| Pellet Density: | 94.0 ± 1.5 %TD |
| Pellet Dish Volume: | 1.0 ± 0.3 vol% |
| Pellet Stack Length: | 132" enriched plus 6" natural at both ends |
| Clad ID: | 0.364 ± 0.0015" |
| Clad OD: | 0.424 ± 0.0020" |
| Rod Pitch: | 0.563" |
| Guide Tube ID: | 0.511 ± 0.0020" |
| Guide Tube OD: | 0.544 ± 0.0020" |

Each of the 204 fuel rods and 21 guide/instrument tubes per bundle were explicitly modeled. The modeled rods contained only enriched $UO_2$; no poisons such as $Gd_2O_3$ and no natural uranium at the ends of the pellet stack. Nominal parameters were assumed in the KENO model; tolerance effects were calculated using CASMO models.

The arrangement of the fuel rods and the instrument/guide tubes is shown in Figure 1.

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

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | F | F | F | F | F | F | F | F | F | F | F | F | F | F |
| F | F | F | F | F | F | F | F | F | F | F | F | F | F | F |
| F | F | G | F | F | G | F | F | F | G | F | F | G | F | F |
| F | F | F | F | F | F | F | G | F | F | F | F | F | F | F |
| F | F | F | F | G | F | F | F | F | F | G | F | F | F | F |
| F | F | G | F | F | F | F | F | F | F | F | F | G | F | F |
| F | F | F | F | F | F | F | F | F | F | F | F | F | F | F |
| F | F | F | G | F | F | F | I | F | F | F | G | F | F | F |
| F | F | F | F | F | F | F | F | F | F | F | F | F | F | F |
| F | F | G | F | F | F | F | F | F | F | F | F | G | F | F |
| F | F | F | F | G | F | F | F | F | F | G | F | F | F | F |
| F | F | F | F | F | F | F | G | F | F | F | F | F | F | F |
| F | F | G | F | F | G | F | F | F | G | F | F | G | F | F |
| F | F | F | F | F | F | F | F | F | F | F | F | F | F | F |
| F | F | F | F | F | F | F | F | F | F | F | F | F | F | F |

## 4.0 STORAGE RACK DESIGN

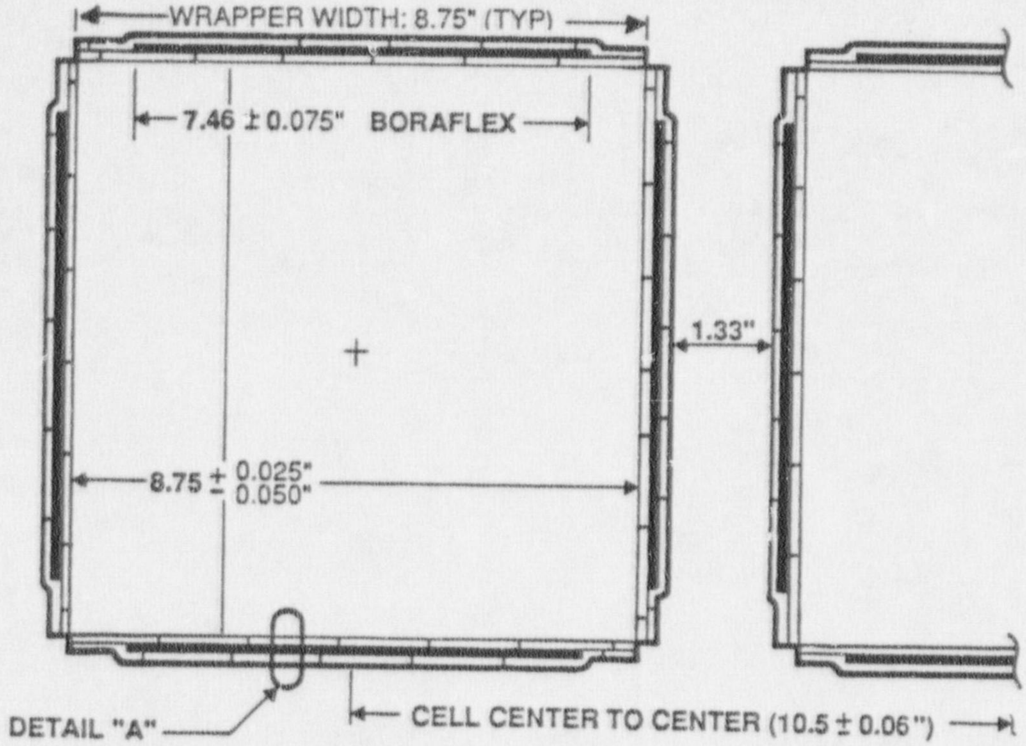
The key rack design parameters are listed in Table 2. The geometry of the unit cell in the rack is shown in Figure 2. Each cell is defined by walls of 304 stainless steel (SS) with 8.75"x8.75" nominal inner dimensions. Except as noted below, each cell has a sheet of Boraflex (secured by a 304SS "wrapper") at each of its four walls. Two Boraflex sheets with an intermediate water gap are between any pair of bundles in the rack. The perimeter cells in the rack do not contain Boraflex in the external wall.

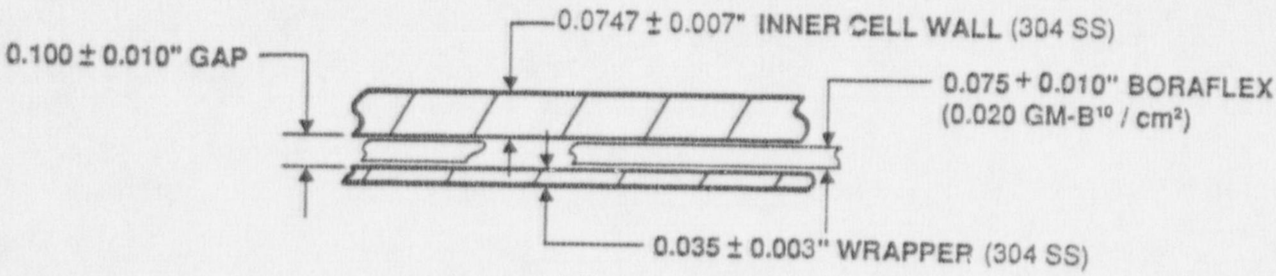
TABLE 2 SPENT FUEL STORAGE RACK DESIGN PARAMETERS

| | |
|---|---|
| Cell Pitch: | 10.5" ± 0.06" |
| Cell Inner Dimension: | 8.75" +0.025" / -0.050" |
| Boraflex Width: | 7.46" ± 0.075" |
| Boraflex Thickness: | 0.075" ± 0.010" |
| Boraflex Length: | 144.25" ± 0.25" |
| B-10 Areal Density in Boraflex: | 0.020 g B-10/$cm^2$ (minimum) |
| Cell Wall Thickness: | 0.0747" ± 0.007" |
| "Wrapper" Wall Thickness: | 0.035" ± 0.003" |
| Thickness of gap between cell wall and wrapper: | 0.100" ± 0.010" |

Nominal parameters were assumed in the KENO model except that the most reactive credible parameters were modeled for the Boraflex width, length, and B-10 density. Therefore, no uncertainty adjustment is needed for the above three parameters. Uncertainties associated with tolerances of all other parameters were calculated using CASMO.

The B-10 density modeled is 0.121 gm B-10 per cc which corresponds to an areal density of 0.020 g/cm$^2$ at a 0.065" Boraflex thickness. The Boraflex was modeled as B4C with the boron composed of 19.6 atom % B-10, balance B-11. Other Boraflex components such as hydrogen and silicon were conservatively neglected.




DETAIL "A"

FIGURE 2

H.B. ROBINSON SPENT FUEL RACKS
(POISONED, HIGH DENSITY) CELL DIMENSIONS

## 5.0 CALCULATION METHODS

The spent fuel racks were conservatively modeled using KENO-Va with 16-group cross sections prepared using BONAMI/NITAWL. The above codes and cross sections are part of the SCALE (1) system. Additional calculations on the effects of tolerances were performed using CASMO-3 (6). Methods validation data are in Section 8.0.

## 6.0 CALCULATION RESULTS

A copy of the the KENO and BONAMI models is included for reference in Section 7.0.

### 6.1 Nominal Parameters

As described earlier in Section 4.0, the "nominal" KENO model included the most reactive values for Boraflex width, length, and B-10 density. The Boraflex was assumed to be 140 inches long; the entire 4.25 inches of shrinkage was at the top and it was filled with water.

The KENO-Va result for an infinite planar array of finite length cells (with full water reflection) is 0.9082 ± 0.0039. Using CASMO-3 for the same model (except that the length is infinite) produced a 0.90684 value for k-inf; very close to the KENO value.

Replicate calculations using the same KENO model but with different cross sections yielded the following results:

- 27 Group Cross Sections (ENDF/B-4): 0.9028 ± 0.0035
- 123 Group Cross Sections (GAM-THERMOS): 0.9152 ± 0.0031

The above reference results agree well with the 16-group KENO results and with the CASMO results.

The spent fuel pool actually contains four modules of high density cells; three modules are a 12x8 cell array and one is a 10x8 cell array. The three 12x8 modules are arranged (with 1.0" nominal edge-to-edge spacing) to form a larger 12x24 array. This larger 12x24 array was modeled with the outer walls of all perimeter cells containing no Boraflex. The six faces of this larger array were reflected by 30 cm of water. The KENO result is 0.9070 ± 0.0033; not significantly different from the value for the infinite planar array. The

12x24 array is adjacent to the unpoisoned-low density storage racks. The bundle-bundle spacings within the low density racks and the bundle-bundle spacings between perimeter bundles in the two adjacent racks are adequate to assure negligible bundle-bundle interactions. The above statement is based on the following:

- The center-to-center spacing for bundles within the low density racks is 21 inches.

- The center-to-center spacing for adjacent bundles in the two racks is 14.5 inches.

- The minimum edge-to-edge spacing, based on a 8.445 inches bundle size, will be about 6 inches.

- Based on the data in Table 8.2 of Reference 5, which addresses 4.20% enriched bundles in the low density, unpoisoned spent fuel racks, the k-eff for two bundles spaced 6 inches edge-to-edge is not significantly different from the k-eff for a single bundle.

Since methods validation (benchmarking) data are provided for the 16 group cross sections and since the reactivity of the infinite planar array is greater than or equal to that for the finite array, the 0.9082 value for the infinite planar array of finite length cells will be used as the nominal k-eff.

The previous analysis (Reference 5) for 4.20% bundles in the unpoisoned spent fuel racks resulted in a k-inf of 0.917 ± 0.005. The 0.917 value is not significantly different from the 0.9082 value for the poisoned racks.

### 6.1 Sensitivity Analysis

In accordance with Sections 6.4.2.2.5 through 6.4.2.2.7 of ANSI/ANS-57.2-1983, maximum credible reactivity effects due to fissile loading, moderation, construction materials, fixed neutron absorbers, and spacings were calculated. The effects of various tolerances were calculated using CASMO. The cell pitch is affected as noted by certain changes in dimensions of rack components because only one parameter was altered per case.

The effect of eccentric bundle positioning was calculated using a KENO model of an infinite array of a 2x2 sub-array of cells with the bundles positioned as close as possible to the center of the sub-array. The resulting k-eff is 0.8974 +/- 0.0028; which is lower than the normal positioning, perhaps due in part to the larger spacings between sub-arrays caused by smaller spacings within sub-arrays. Therefore, the positioning effect was taken as negligible.

#### 6.1.1 Enrichment

Increasing the enrichment to 4.25% caused a 0.00212 rise in k-inf.

#### 6.1.2 Pellet Density

The nominal case has a 94.0% TD pellet and a 1.0 vol% dish. With a 95.5% TD pellet density, the k-inf increased by 0.00189.

#### 6.1.3 Pellet Dish

Decreasing the dish volume to 0.7 vol% caused a 0.00036 rise in k-inf.

#### 6.1.4 Boraflex Thickness

Decreasing the 0.075 inch nominal thickness by 0.010 inch caused a 0.00378 rise in k-inf. Since the Boraflex is centered in the 0.100" thick gap between the cell wall and the wrapper (see Figure 2) and since this gap thickness was not changed, the cell pitch was not changed in this case.

### 6.1.5 Cell Wall Thickness

Increasing the 304SS cell wall thickness by 0.007 inch caused a 0.00064 rise in k-inf. The cell pitch was increased by 0.014 inch by this change in cell wall thickness.

### 6.1.6 Wrapper Thickness

Decreasing the wrapper thickness by 0.003 inch caused a 0.00001 rise in k-inf. The cell pitch was decreased by 0.006 inch in this model.

### 6.1.7 Cell Inner Dimension

Increasing the 8.75-inch cell size to 8.775 inches caused a 0.00085 rise in k-inf. The cell pitch was increased by 0.025 inch in this model.

### 6.1.8 Cell Spacing

Reducing the nominal 1.33 inch edge-to-edge spacing between cell outer surfaces by the cell pitch tolerance (0.06") caused a 0.0056 rise in k-inf. The cell pitch was reduced by 0.06" in this model.

## 6.2 Final Result

The one-sided 95% Student's t value for the KENO standard deviation (0.0039) from 100 generations of 500 neutrons is 1.67. Therefore, the KENO uncertainty is 0.0065. Uncertainty sums were calculated as the square root of sums of squares. The total of the eight uncertainties in Section 6.1 is 0.0074. The bias uncertainty (Section 8.0) is 0.0096. The total uncertainty is 0.0138. Since the weighted average of the benchmark k-eff values is 1.0035 (Section 8.0), 0.0035 is subtracted to correct for bias.

The bias-corrected final result is:

k-eff = 0.9082 - 0.0035 + 0.0138 = 0.9185

There is at least 95% confidence that the k-eff of the racks will not exceed 0.919 when fully loaded with new fuel with zero poison content.

Performing the same analysis for the unpoisoned spent fuel racks:

- The only tolerance uncertainties are for the enrichment, fuel density, and pellet dish volume which sum to 0.0029.

- The KENO uncertainty is 0.0084.

- For conservatism, the bias will be taken as zero but the bias uncertainty will remain at 0.0096. The total uncertainty is 0.0131.

- Therefore, for the unpoisoned racks and for in-transit bundles, the bias-corrected final result is:

$$\text{k-eff} = 0.917 - 0 + 0.0131 = 0.930$$

The above 0.930 value demonstrates that <u>nominal</u> 4.20% enriched bundles are within the 0.95 upper limit for k-eff in the unpoisoned racks and in-transit in the pool.

Exposed fuel and that with poison rods will be even less reactive. Therefore, the system k-eff will be well below the 0.95 limit on k-eff.

The data in the table on page 20 of Reference 5 show that 500 ppm dissolved boron is adequate to assure safety at any single accident condition during fuel handling.

## 7.0 TYPICAL COMPUTER INPUT LISTINGS

### 7.1 Nominal KENO-Va Model

```
H.B. ROBINSON, 4.2
READ PARAMETERS
TME=290.0 GEN=103 NPG=500 LIB=41 TBA=2.0
FLX=YES FDN=YES XS1=YES NUB=YES PWT=YES
PLT=YES
END PARAMETERS
READ MIXT  SCT=1
MIX= 1
' UO2 IN INTERIOR ROD, 4.2% ENRICHED, 94% TD, 1.0 VOL%
     92501  9.6755E-04
     92801  2.1790E-02
      8016  4.5516E-02
MIX= 2
' UO2 IN EDGE ROD, 4.2% ENRICHED, 94% TD, 1.0 VOL%
     92502  9.6755E-04
     92802  2.1790E-02
      8016  4.5516E-02
MIX= 3
'  ZIRCALLOY
     40302  4.251812E-02
MIX= 4
'  WATER AT 20C
      8016  3.337967E-02
      1001  6.675933E-02
```

```
MIX= 5
'  BORAFLEX, 0.020 GM B-10/SQCM AT 0.065" THICKNESS
      5010  7.2838E-03
      5011  2.9878E-02
      6012  9.2905E-03
MIX= 6
'  304SS
     24304  1.742958E-02
     25055  1.736443E-03
     26304  5.935923E-02
     28304  7.718178E-03
END MIXT
READ GEOMETRY
UNIT 1
COM=" INTERIOR ROD                              "
CYLI  1 1 0.452755 2P182.88
CYLI  0 1 0.46228 2P182.88
CYLI  3 1 0.53848 2P182.88
CUBO  4 1 4P0.71501 2P182.88
UNIT 2
COM=" EDGE ROD                              "
CYLI  2 1 0.452755 2P182.88
CYLI  0 1 0.46228 2P182.88
CYLI  3 1 0.53848 2P182.88
CUBO  4 1 4P0.71501 2P182.88
UNIT 3
COM="  GUIDE TUBE                          "
CYLI  4 1 0.64897 2P182.88
CYLI  3 1 0.69088 2P182.88
CUBO  4 1 4P0.71501 2P182.88
```

```
UNIT 4
COM=" 15X15 BUNDLE                  "
ARRAY  1 2R-10.72515 -182.88
'  ADD WATER TO CELL INNER SURFACE (8.75"X8.75" CELL)
CUBO  4 1 4P11.1125 2P182.88
'  ADD 0.0747" STEEL WALL
CUBO  6 1 4P11.3022 2P182.88
UNIT 5
COM= "WRAPPER AT +/- Y SIDES OF +/- X SHEETS              "
' WRAPPER ENDS AT 8.75" (SAME AS CELL INNER DIMENSION)
CUBO  6 1 2P0.04445 2P0.8222 2P182.88
UNIT 6
COM= "WRAPPER AT +/- X SIDES OF +/- Y SHEETS              "
CUBO  6 1 2P0.8222 2P0.04445 2P182.88
UNIT 7
COM="  BORAFLEX SHEET AT + X SIDE OF CELL        "
'  WIDTH = 7.46" MINUS 0.075" = 7.385"
'  LENGTH = 140" (4" WATER AT TOP(+Z))
'  THICKNESS = 0.075", GAP= 0.100"
CUBO  5 1 2P0.09525 2P9.379 172.72 -182.88
'  ADD 4" WATER AT TOP
'  ALSO ADD WATER FOR 0.100" GAP BETWEEN STEEL (BORAFLEX CENTERED IN GAP)
CUBO  4 1 2P0.127 2P9.379 182.88 -182.88
'  ADD 0.035" STEEL WRAPPER AT +/- Y & AT +X
CUBO  6 1 0.2159 -0.127 2P9.4679 2P182.88
'  ADD WATER
CUBO  4 1 0.2159 -0.127 2P11.3022 2P182.88
HOLE  5 -0.08254 10.2902 0.0
HOLE  5 -0.08254 -10.2902 0.0
```

```
UNIT 8
COM="  BORAFLEX SHEET AT - X SIDE OF CELL        "
CUBO  5 1 2P0.09525 2P9.379 172.72 -182.88
CUBO  4 1 2P0.127 2P9.379 182.88 -182.88
CUBO  6 1 0.127 -0.2159 2P9.4679 2P182.88
CUBO  4 1 0.127 -0.2159 2P11.3022 2P182.88
HOLE  5 0.08254 10.2902 0.0
HOLE  5 0.08254 -10.2902 0.0
UNIT 9
COM="  BORAFLEX SHEET AT + Y SIDE OF CELL        "
CUBO  5 1 2P9.379 2P0.09525 172.72 -182.88
CUBO  4 1 2P9.379 2P0.127 2P182.88
CUBO  6 1 2P9.4679 0.2159 -0.127 2P182.88
CUBO  4 1 2P11.3022 0.2159 -0.127 2P182.88
HOLE  6 10.2902 -0.08254 0.0
HOLE  6 -10.2902 -0.08254 0.0
UNIT 10
COM="  BORAFLEX SHEET AT - Y SIDE OF CELL        "
CUBO  5 1 2P9.379 2P0.09525 172.72 -182.88
CUBO  4 1 2P9.379 2P0.127 2P182.88
CUBO  6 1 2P9.4679 0.127 -0.2159 2P182.88
CUBO  4 1 2P11.3022 0.127 -0.2159 2P182.88
HOLE  6 10.2902 0.08254 0.0
HOLE  6 -10.2902 0.08254 0.0
UNIT 11
COM="  0.3429X0.3429 CM WATER REGION AT CORNERS"
CUBO  4 1 4P0.17145 2P182.88
GLOBAL
UNIT 12
COM=" COMPLETE POISONED UNIT CELL          "
ARRAY 2 2R-11.6459 -182.88
' ADD WATER FOR 10.5" CENTERS
```

```
CUBO  4 1 4P13.335 2P182.88
' ADD WATER REFLECTION AT +/- Z
REPL  4 2 4R0.0 2R3.0 10
END GEOMETRY
READ ARRAY
ARA=1 NUX=15 NUY=15 NUZ=1
LOOP
2  1 15 1  1 15 1  1 1 1
1  2 14 1  2 14 1  1 1 1
3  3 6 3  3 13 10  1 1 1
3  10 13 3  3 13 10  1 1 1
3  8 8 1  4 12 8  1 1 1
3  5 11 6  5 11 6  1 1 1
3  3 13 10  6 10 4  1 1 1
3  4 12 4  8 8 1  1 1 1
END LOOP
ARA=2 NUX=3 NUY=3 NUZ=1
FILL
11 10 11
 8  4  7
11  9 11
END FILL
END ARRAY
READ START
NST=1
END START
READ BOUNDS
XYF=SPECULAR ZFC=VACUUM
END BOUNDS
READ BIAS
ID=500 2 11
END BIAS
```

```
READ PLOT
TTL="  YX SECTION, STORAGE CELL        "
PIC=MEDIA
NCH=" 12Z.BS"
XUL=-13.335 XLR=13.335 YUL=13.335 YLR=-13.335 ZUL=10.0 ZLR=10.0
UAX=1.0 VDN=-1.0 NAX=120 LPI=6 END
TTL="  YX SECTION, UPPER RIGHT QUADRANT          "
NCH=" 12Z.BS"
XUL=0.0 XLR=13.335 YUL=13.335 YLR=0.0 ZUL=10.0 ZLR=10.0
UAX=1.0 VDN=-1.0 NAX=120 LPI=6 END
TTL="  YX SECTION, LOWER RIGHT QUADRANT          "
NCH=" 12Z.BS"
XUL=0.0 XLR=13.335 YUL=0.0 YLR=-13.335 ZUL=10.0 ZLR=10.0
UAX=1.0 VDN=-1.0 NAX=120 LPI=6 END
TTL="  YX SECTION, LOWER LEFT QUADRANT          "
NCH=" 12Z.BS"
XUL=-13.335 XLR=0.0 YUL=0.0 YLR=-13.335 ZUL=10.0 ZLR=10.0
UAX=1.0 VDN=-1.0 NAX=120 LPI=6 END
TTL="  YX SECTION, UPPER LEFT QUADRANT          "
NCH=" 12Z.BS"
XUL=-13.335 XLR=0.0 YUL=13.335 YLR=0.0 ZUL=10.0 ZLR=10.0
UAX=1.0 VDN=-1.0 NAX=120 LPI=6 END
TTL="  YX SECTION AT +Y SIDE OF +X SHEET           "
NCH=" 12Z.BS"
XUL=11.0 XLR=11.75 YUL= 11.75 YLR=9.2 ZUL=10.0 ZLR=10.0
UAX=1.0 VDN=-1.0 NAX=120 LPI=6 END
TTL="  YX SECTION AT -Y SIDE OF +X SHEET           "
NCH=" 12Z.BS"
XUL=11.0 XLR=11.75 YUL=-9.2 YLR=-11.75 ZUL=10.0 ZLR=10.0
UAX=1.0 VDN=-1.0 NAX=120 LPI=6 END
END PLOT
END DATA
```

## 7.2 BONAMI Input

The self-shielded cross sections for U-235 and U-238 were prepared using the BONAMI input listed below.

```
' H. B. ROBINSON, 4.2
0$$ 16 15 18 17
 1$$ 0 2 6 2R1 0
2** 1.0-5 E
 T
 3$$ 3R1 3R2
 4$$ 92235 92238 8016 1Q3
 5** 9.67545E-04 2.17903E-02 4.55157E-02 1Q3
6$$ 1 2
8** F293.0
9** 1.11 1.19
10$$ 92501 92801 8016 92502 92802 801602
11$$ F0
 T
```

## 8.0 METHODS VALIDATION

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

Supplemental benchmarking was performed 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 a poisoned spent fuel storage rack analysis (i.e., all benchmark cases were arrays of bundles with boron-containing absorber sheets).

The results are listed in Table 3.

TABLE 3 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 of the calculated k-eff data are 1.00265 and 0.00490 respectively, assuming equal weight for each case. Using these unweighted data, the best estimates for the average bias and its uncertainty are 0.00265 and 0.00131, respectively.

Weighted estimates of the bias and its variance are preferred for these Monte Carlo benchmark results. The weight of each k-eff value is proportional to the reciprocal of its variance. Replicate calculations of the same KENO model and cross sections but with different random number sequences would be expected to produce results that are not identical but normally distributed per the average KENO statistics. If these replicate data were analysed, the true variance of the bias would be zero (the bias is fixed for all cases), but this would not be apparent from the unweighted analysis. In the following analysis of the benchmark data, the systematic error variance is separated from the random error variance.

The parameters below were estimated using the methods of Reference 4.

- Weighted average k-eff: 1.0035
- Random uncertainty: 0.00377
- Bias uncertainty: 0.00368
- Total uncertainty: 0.00526

The 95/95 value for the bias uncertainty is 0.0096. This value is pooled with other uncertainties, including the random error from the KENO calculation, to determine the upper limit on the system k-eff.

## 9.0 REFERENCES

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DISTRIBUTION

L. D. Gerrald (2)
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