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REVALIDATION STUDIES OF MARK 16 EXPERIMENTS: J70 (U)

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Applied Technology Section
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INTRODUCTION AND SUMMARY

The MGBS-TGAL combination of the J70 criticality modules[1] was validated for Mark 16 lattices by H. K. Clark as reported in DPST-83-1025 [2]. Unfortunately, the records of the calculations reported can not be retrieved and the descriptions of the modeling used are not fully provided in DPST-83-1025. The report does not describe in detail how to model the experiments and how to set up the input. The computer output for the cases reported in the memorandum can not be located in files.

The MGBS-TGAL calculations reported in DPST-83-1025 have been independently reperformed to provide retrievable record copies of the calculations, to provide a detailed description and discussion of the methodology used, and to serve as a training exercise for a novice criticality safety engineer. The current results reproduce Clark's reported results to within about 0.01% or better. A procedure to perform these and similar calculations is given in this report, with explanation of the methodology choices provided. The procedure is described by providing two detailed examples. Results are summarized in Table 2. Finally, copies of the computer output have been made via microfiche and will be maintained in APG files.

DISCUSSION

KOKO-MGBS-TGAL

MGBS and TGAL are modular computer codes, described in DPSTM-86-700-3 [1], used at SRS to perform criticality calculations. MGBS provides 12-group and 2-group multigroup diffusion parameters and macroscopic cross sections, primarily for arrays of materials in water. TGAL employs macroscopic cross sections, diffusion parameters such as provided by MGBS, and lattice description parameters to perform one-dimensional transverse buckling searches, which are combined by KOKO to generate the reactivity parameter, K_{eff}, for the lattice. In addition to the original cross section formulation in MGBS, an alternate formulation has been provided in MGBS and is commonly used for criticality analyses.

TGAL solves the one-dimensional two-group steady-state diffusion equation analytically for slab, cylindrical, and spherical geometries. The diffusion equation solution is effective for regions containing fissionable material, moderator, and structural material. For thin, strong absorbing regions, TGAL can apply the collision probability method since diffusion theory is not accurate in strong absorbing regions. The cadmium sheets in a couple of the experiments analyzed here are such regions.

The MGEX record is expected when the EXPT option is specified for the MGBS module. From data provided in the MGEX record, KOKO writes the input records for MGBS and TGAL for a heterogeneous cell with equal pitch sizes in a regular array. It should be pointed out that a lattice with different pitch sizes can not be modeled just by records created by KOKO directly from the MGEX record. The TGAL records generated by the MGEX input record must be modified to match the lattice geometry desired.

DESCRIPTIONS OF THE MARK 16 EXPERIMENTS

The Mark 16 experiments[3] modeled by Clark were subcritical lattices in water. The lattices were generally 2 x 3, 2 x 4, 3 x 3, and 4 x 4 arrays of Mark 16 fuel, frequently with assemblies in contact within rows and rows separated by as much as several inches

of water. For several experiments, aluminum-clad cadmium sheets were inserted between rows. No targets were inserted in the fuel assemblies. The Mark 16 dimensions as modeled are shown in Figure 12. Ribs in the assemblies are indirectly modeled, consistent with Clark's practice. Clark included the volume of the ribs in the outer cladding of the inner and middle fuel tubes, maintaining total aluminum volume.

Table 2 indicates each experimental lattice modeled. Three different fuel compositions were modeled, corresponding to Oralloy, and $^{236}U/^{235}U$ ratios of 0.19 and 0.74, as shown in Table 1. The aluminum content of each fuel region was calculated by KOKO using standard formulas and densities of uranium and aluminum as discussed in DPSTM-86-700-3. The experiments involved measuring κ^2, the square of the inverse relaxation length, for various subcritical arrays of these lattices when moderated and fully reflected with H_2O. The measured κ^2 values were used by the experimenters to determine K_{eff}[3].

PROCEDURE

Clark reported MGBS-TGAL calculations for the arrays indicated in Table 2. However, the file copies of the computer output are not retrievable and the descriptions of the calculations provided in DPST-83-1025 did not detail the methods and input data used. An explicit modeling of several lattices in MGBS and TGAL input records did not produce the same results as reported by Clark. He indicated the driver module KOKO was used to generate the MGBS and TGAL input data via the MGEX record.

The MGBS-TGAL combination via the MGEX record under KOKO can directly provide calculations only for uniform fuel lattice arrays with equal pitch in both dimensions (x and y coordinates). To perform calculations for arrays with different pitches between rows of assemblies than between assemblies in a row, a multistep procedure must be used to accurately model the arrays.

A general procedure using the MGBS-TGAL module combination under KOKO to determine the effective multiplication factor (K_{eff}) corresponding to a subcritical experiment has been established. In the following text, upper case `Courier` type designates the invariant portion of the record names, and lower case `Courier` type designates the user-specified portion of the record names. Note that detailed directions to create the KOKO input records are provided in DPSTM-86-700-3. The procedure is as follows:

1. Create the following input records corresponding to the uniform array for the experiment:

   ```
   INPUT.KOKO.?jobname
   INPUT.KOKO.MGEX.?name
   ```

   where `?jobname` is the job dataset name and `?name` is the study designation name. In the `INPUT.KOKO.?jobname` record, specify execution of MGBS-TGAL with the EXPT option.

2. Execute KOKO (J70 JOSHUA system).

3. Copy the following input records generated by KOKO to the user data set:

   ```
   INPUT.MGBS.CONTROL.?name.?n
   INPUT.MGBS.TYPE.?name.?n
   INPUT.MGBS.RADII.?name
   ```

```
INPUT.TGAL.?jobname
INPUT.TGAL.BTCH.?name.?btch number
INPUT.TGAL.CMBN.?name
```

4. Modify `INPUT.TGAL.BTCH.?name.?btch number` records to match the lattice geometry desired. Note that this record requires dimensions in centimeters. (The `INPUT.TGAL.BTCH.?name.?btch number` record is required for each dimension explicitly modeled.)

5. Modify the `INPUT.KOKO.?jobname` record to specify execution of MGBS-TGAL without the EXPT option.

6. Execute KOKO.

7. Record the lattice K_{eff} from the KOKO output.

EXAMPLES

To demonstrate the general procedure, preparation of input records and problem execution two cases are provided here as examples.

- 2 x 4 array in water (a row of 4 assemblies in contact separated from an identical row by 2.3") with ^{236}U to ^{235}U atom ratio = 0.19.
- 4 x 4 array in water (4 rows of 4 assemblies at 3.838" pitch within row, rows separated by 1.3" of water with an aluminum clad cadmium sheet between rows) with ^{236}U to ^{235}U atom ratio = 0.19.

The arrays are shown in Figures 13 and 16.

I. 0.19 Ratio, 2 x 4 Mark 16 Array (6.00" x 3.70")

The physical configuration of the Mark 16 array is illustrated in Figure 13. Figure 14 shows the uniform lattice model used to generate basic diffusion and macroscopic parameters via the MGEX record. TGAL uses these basic parameters to solve the two-group diffusion equations for the lattice model of the physical array in Figure 13. The different pitch sizes and different number of material regions along the x- and y-directions are shown in the one-dimensional slab models in Figure 15. The input records are provided in Figures 1 to 5. Letters and numbers denoted in outlined italics in the input records are the input data.

Following the general procedure described above, the `INPUT.KOKO.?jobname` record specifying execution of MGBS and TGAL with the EXPT option and the `INPUT.KOKO.MGEX.?name` record are set up as shown in Figures 1 and 2. The job name (SYLN4777) and study designation name (MK16M) provide linkage between the input records and with the job execution and are arbitary choices of the user. The MGEX input record shown in Figure 2 is expected if the EXPT option is specified for MGBS in the `INPUT.KOKO.?jobname` record. Parameter choices for the MGEX record are detailed in Reference 1. The first page of the `INPUT.KOKO.MGEX.?name` record specifies the dimensional and material content information for each region in a fuel assembly and the second page specifies the cell and lattice dimensions and axial buckling. The assembly dimensions are as indicated in Figure 12. The axial buckling data are from the κ^2 values

provided by Clark (Ref. 2) and given in Table 2. As can be seen in the last column of the second page in Figure 2, the negative value of the measured value (κ^2) is used as the axial buckling. The basis for this usage is provided in the Appendix. The third page of the record specifies the isotopic compositions of the materials. Note that water, as the moderator, need not be included in the material composition listing since KOKO assumes water is the material #1 for the MGEX record.

Figure 1. Computer input record for Case I (INPUT.KOKO.?jobname)

```
INPUT.KOKO.SYLN4777

MX16M  DESIGNATION (NAME) FOR STUDY
       JOBNAME FOR DATA SET WITH PREVIOUS OUTPUT RECORDS
    2  NUMBER OF PROGRAMS (MODULES)
    3  NUMBER OF LINES OF COMMENTS. MAY BE 0.
    0  NUMBER OF BATCHES (APPLIES ONLY TO GLASS, MGBS(SLEN
       OR EXPT)-TGAN(ABBR OR EXPT), TGAN(    ), ANSN OR KENO
       WHEN PRECEDED BY HRXN). MAY BE 0.
    2  1 TO PRINT INPUT RECORDS; 2 TO PRINT COMPUTED INPUT
       RECORDS AS WELL; 3 TO READ & PRINT AMPX LIBRARY ALSO:

OPTIONAL INPUT RECORDS ARE--  INPUT.KOKO
.ADBN.?NAME.?N,        .ANSN.?NAME.?N,        .GLSS.?NAME.?N,
.MGEX.?NAME.?N,        .SLEN.?NAME.?N,        .TWTR.?NAME.?N, OR
.DISL.?NAME.,          .PADJ.?NAME.?N,        .TSLA.?NAME.
                       PROGRAM    OPTION
                        MGBS       EXPT
                        TGAL       EXPT



PAGE        1


INPUT.KOKO.SYLN4777

1   ANALYSIS OF TWO DPST-83-1025 ARRAYS
2   1. 0.19 236/235 RATIO 2 X 4 ARRAY ON 6.0 X 3.7 IN PITCH
3   2. MGBS-TGAL WITH ALTERNATE MGBS C.X.



LASTPAGE        2
```

Figure 2. Computer input record for Case I (INPUT.KOKO.MGEX.?name)

```
INPUT.KOKO.MGEX.MK16M.1

12 NO. OF REGIONS INSIDE FUEL O.D.   FOR EACH REGION TYPE INDEX
& RADIUS(CM) OR DIA(IN) ARE REQUIRED.  THE DIMENSIONAL LIMIT FOR
MGBS IS 22 REGIONS.  MODERATOR IS TYPE 1.  SLIGHTLY ENRICHED UR-
ANIUM OR THORIUM MUST BE TYPE 2 FOR RESONANCE INTEGRAL FOR HETE-
ROGENEOUS LATTICE DUE TO HELLSTRAND OR WEITMAN TO BE REQUESTED.
REGION   INDEX  DIMENSION        REGION   INDEX  DIMENSION
1        1      1.7180           2        2      1.7980
3        3      2.0240           4        2      2.1010
5        1      2.5900           6        2      2.6500
7        4      2.8760           8        2      2.9520
9        1      3.4340          10        2      3.4940
11       5      3.6400          12        2      3.7000


PAGE       1


INPUT.KOKO.MGEX.MK16M.1

1  NUMBER OF LATTICES (NO. CELLS + RADII FROM P 1 < 51)
COLUMN 1 IS CELL RADIUS (CM) OR CELL DIA (IN) OR PITCH (IN)
COLUMN 2 IS LATTICE DIA OR WIDTH OR -NO. RODS. (0 FOR DIM SRCH)
COLUMN 3 IS HT, LNGTH, AXIAL BCKLNG, OR BIAS(KEFF)--FOR DIM SRCH
COLUMN 4 IS HT, AXIAL BCKLNG, OR CONC (FOR A DIMENSION SEARCH) :
3.70000E 00     7.40000E 00     1.48000E 01     -.12950E-02


PAGE       2


INPUT.KOKO.MGEX.MK16M.1

2   PITCH INDEX(0, 2 OR 3)  |  2  UNITS INDEX, 0 FOR CM, >0 FOR
33  REMAINING ITEMS         |     IN (1 FOR DIA, 2 FOR PITCH)
REMAINING ITEMS ARE DENSITY & COMPOSITION FOR METAL OR OXIDE
TYPES.  ORDER IS DENSITY, NEGATIVE ELEMENT INDEX, ISOTOPIC COM-
POSITION (WT% U233, U234, U235, U236, U238 FOR U; PU239, PU240,
PU241, PU242 FOR PU), WEIGHT FRACTION OF ELEMENT, ETC., DENSITY,
ETC.  FOR DIMENSION SEARCH THESE MUST BE FOLLOWED BY DELTA KEFF:
ELEMENT   O, U,PU,TH,AL,ZR,FE,CR,NI, B,CD,GD,PB, C,BE
INDEX     5, 6, 7, 8, 9,10,11,12,13,14,15,16,17,18,19
2.70000E 00  -.90000E 01  1.00000E 00  4.24000E 01  -.60000E 01
0.00000E 00  1.40000E-02  7.42000E-01  1.45000E-01  9.90000E-02
0.00000E 00  -.90000E 01  0.00000E 00  1.02000E 02  -.60000E 01
0.00000E 00  1.50000E-02  7.28000E-01  1.54000E-01  1.03000E-01
0.00000E 00  -.90000E 01  0.00000E 00  1.04000E 02  -.60000E 01
0.00000E 00  1.40000E-02  7.62000E-01  1.30000E-01  9.40000E-02
0.00000E 00  -.90000E 01  0.00000E 00

LASTPAGE       3
```

Upon execution, KOKO generates MGBS and TGAL input records based on the KOKO-MGEX input record for a uniform array. KOKO generates one TGAL.BTCH record with two cases and specifies each case with two regions (fuel cell and water regions) for this lattice. The procedure requires that two TGAL.BTCH records be used, to model different material regions and dimensions for each of the x- and y-directions of the lattice model in Figure 15. Note that KOKO automatically sets up the lattices specified by the MGEX record as a lattice with 1000 cm of H_2O on each side and also represents the lattice as reflected about the center in each direction. The following input records generated by KOKO (described in detail in DPSTM-86-700-3) must be copied to the user data set:

```
INPUT.MGBS.CONTROL.MK16M.1
INPUT.MGBS.CONTROL.MK16M.2
INPUT.MGBS.RADII.MK16M.1
INPUT.MGBS.TYPE.MK16M.1
INPUT.MGBS.TYPE.MK16M.2
INPUT.MGBS.TYPE.MK16M.3
INPUT.MGBS.TYPE.MK16M.4
INPUT.MGBS.TYPE.MK16M.5
INPUT.TGAL.SYLN4777
INPUT.TGAL.BTCH.MK16M.1
INPUT.TGAL.CMBN.MK16M
```

Then, the `INPUT.TGAL.BTCH.MK16M.1` record, which models both x and y dimensions uniformly, is modified to match the x-direction (within row) regions of the equivalent lattice in Figure 15. The number-of-cases parameter, shown in boldfaced italics in Figure 3, is changed from 2 to 1, and results in the y-direction region descriptions being eliminated from this record. The x-direction (within row) regions are correctly modeled. The modified parameter is shown in boldfaced italics in Figure 3.

A similar, but different record, `INPUT.TGAL.BTCH.MK16M.2`, is then created to include the water region (between rows) of the equivalent lattice for the y-direction illustrated in Figure 15. The created input record is shown in Figure 4. In addition, the `INPUT.KOKO.?jobname` record is modified to specify the KOKO execution of the MGBS-TGAL combination without the EXPT option. The revised KOKO input record is shown in Figure 5. Then, KOKO is executed. The resulting effective multiplication factor, K_{eff}, is shown in Table 2.

II. <u>0.19 Ratio, 4 x 4 Mark 16 Array with Aluminum-Clad Cadmium Sheets between Rows</u> (5.00" x 3.838")

Figure 16 shows the physical configuration of the 4 x 4 Mark 16 fuel assembly array with cadmium poison plates.

Following the general procedure, `INPUT.KOKO.?jobname` and `INPUT.KOKO.MGEX.?name` records are set up for a uniform lattice model of the 4 x 4 physical array, which is shown shown in Figure 17. The input records are shown in Figures 6 and 7. As shown in Figure 7, aluminum metal and cadmium material compositions are also provided to generate additional MGBS records for the two materials in the aluminum clad cadmium plate between the rows of fuel assemblies as shown in Figure 16. These materials will be referenced in step 4 of the general procedure.

Figure 3. Computer input record for Case I (INPUT.TGAL.BTCH.?name.?btch number)

```
INPUT.TGAL.BTCH.MK16M.1

0       NUMBER OF LINES OF COMMENTS
1       NUMBER OF CASES PER BATCH
2       NUMBER OF REGIONS(NR)  (DIMENSIONS IN CM)
1.00000    FAST INNER ALBEDO        1.00000   SLOW INNER ALBEDO
-1.00000   FAST OUTER ALBEDO       -1.00000   SLOW OUTER ALBEDO
0       GEOMETRY INDEX. 0=SLAB, 1=CYLINDER, 2=SPHERE, 3=SLAB
        & CYLINDER, 4=SLAB & SPHERE, 5=CYLINDER & SPHERE, 6=
        ALL THREE. (3-6 ONLY IF SEARCH INDEX(L) > 0).
-1      TYPE OF SEARCH(K). 0 FOR KEFF, > 0 FOR THICKNESS OF
        REGION N=K MODULO NR+1 (MAY NOT BE A TRANSMISSION
        REGION; LARGEST INTEGER IN K/(NR+1) IS INDEX OF
        OTHER REGION CHANGED TO COMPENSATE), < 0 FOR TRANS-
        VERSE BUCKLING.
0       L. IF > 0, THICKNESS SEARCH IS MADE FOR ALL MIXTURES
        IN REGION N. K MUST THEREFORE BE > 0. ONLY ONE CASE
        SHOULD BE SPECIFIED FOR THIS BATCH. EXPECTS BIAS.
0       ODD FOR ITERATION TRACE; ALSO CONTROLS SEARCH MESH.
0.000   DELTA KEFF (IF.NE.0, CRITICAL AND CORRESPONDING SUB-
        CRITICAL SEARCHES ARE MADE.)


PAGE        1



INPUT.TGAL.BTCH.MK16M.1

              1   CASE NUMBER
0.0000         KEFF (DEFAULTS TO UNITY. MINUS TO REQUEST BIAS)
0.00000E 00    TRANSVERSE BUCKLING (OR PROBLEM NOS.    0     0 )
0.00000E 00    INNER RADIUS
|--THE ENCLOSED APPLY ONLY TO VOID REGIONS. 0 FOR INFINITY.--|
|INTERNAL >     0.0000E 00  HEIGHT OR NEGATIVE DIAMETER       |
|   TO ---->    0.0000E 00  LENGTH                            |
|  UNIT   >     0.0000    0.0000  FAST, SLOW REFLECTOR ALBEDO.|
|EXTERNAL-->    0.0000  INTER. PROB.      0.00  REFL. AREA/UNIT|:
REGION     MIXTURE     TYPE(1=F,0=T)       THICKNESS
1          1              1            1.87960E 01
2          2              1            1.00000E 03


LASTPAGE        2
```

Figure 4. Revised computer input record for Case I (INPUT.TGAL.BTCH.?name.?btch number)

```
INPUT.TGAL.BTCH.MK16M.2

0         NUMBER OF LINES OF COMMENTS
1         NUMBER OF CASES PER BATCH
3         NUMBER OF REGIONS(NR)   (DIMENSIONS IN CM)
1.00000     FAST INNER ALBEDO          1.00000   SLOW INNER ALBEDO
-1.00000    FAST OUTER ALBEDO         -1.00000   SLOW OUTER ALBEDO
0        GEOMETRY INDEX. 0=SLAB, 1=CYLINDER, 2=SPHERE, 3=SLAB
         & CYLINDER, 4=SLAB & SPHERE, 5=CYLINDER & SPHERE, 6=
         ALL THREE. (3-6 ONLY IF SEARCH INDEX(L) > 0).
-1       TYPE OF SEARCH(K). 0 FOR KEFF, > 0 FOR THICKNESS OF
         REGION N=K MODULO NR+1 (MAY NOT BE A TRANSMISSION
         REGION; LARGEST INTEGER IN K/(NR+1) IS INDEX OF
         OTHER REGION CHANGED TO COMPENSATE), < 0 FOR TRANS-
         VERSE BUCKLING.
0        L. IF > 0, THICKNESS SEARCH IS MADE FOR ALL MIXTURES
         IN REGION N. K MUST THEREFORE BE > 0. ONLY ONE CASE
         SHOULD BE SPECIFIED FOR THIS BATCH. EXPECTS BIAS.
0        ODD FOR ITERATION TRACE; ALSO CONTROLS SEARCH MESH.
0.000    DELTA KEFF (IF.NE.0, CRITICAL AND CORRESPONDING SUB-
         CRITICAL SEARCHES ARE MADE.)


PAGE       1



INPUT.TGAL.BTCH.MK16M.2

           1   CASE NUMBER
0.0000     KEFF (DEFAULTS TO UNITY. MINUS TO REQUEST BIAS)
0.00000E 00   TRANSVERSE BUCKLING (OR PROBLEM NOS.    0     0 )
0.00000E 00   INNER RADIUS
|--THE ENCLOSED APPLY ONLY TO VOID REGIONS. 0 FOR INFINITY.--|
|INTERNAL >     0.0000E 00  HEIGHT OR NEGATIVE DIAMETER       |
|   TO ---->    0.0000E 00  LENGTH                            |
|  UNIT   >     0.0000     0.0000  FAST, SLOW REFLECTOR ALBEDO.|
|EXTERNAL-->    0.0000  INTER. PROB.      0.00  REFL. AREA/UNIT|:
REGION      MIXTURE      TYPE(1=F,0=T)        THICKNESS
1           2               1             2.92100E 00
2           1               1             9.39800E 00
3           2               1             1.00000E 03



LASTPAGE       2
```

Figure 5. Revised computer input record for Case I (INPUT.KOKO.?jobname)

```
INPUT.KOKO.SYLN4777

MX16M    DESIGNATION (NAME) FOR STUDY
         JOBNAME FOR DATA SET WITH PREVIOUS OUTPUT RECORDS
    2    NUMBER OF PROGRAMS (MODULES)
    3    NUMBER OF LINES OF COMMENTS. MAY BE 0.
    0    NUMBER OF BATCHES (APPLIES ONLY TO GLASS, MGBS(SLEN
         OR EXPT)-TGAN(ABBR OR EXPT), TGAN(    ), ANSN OR KENO
         WHEN PRECEDED BY HRXN). MAY BE 0.
    2    1 TO PRINT INPUT RECORDS; 2 TO PRINT COMPUTED INPUT
         RECORDS AS WELL; 3 TO READ & PRINT AMPX LIBRARY ALSO:

OPTIONAL INPUT RECORDS ARE--  INPUT.KOKO
.ADBN.?NAME.?N,        .ANSN.?NAME.?N,        .GLSS.?NAME.?N,
.MGEX.?NAME.?N,        .SLEN.?NAME.?N,        .TWTR.?NAME.?N, OR
.DISL.?NAME.,          .PADJ.?NAME.?N,        .TSLA.?NAME.
                       PROGRAM    OPTION
                       MGBS
                       TGAL


PAGE       1


INPUT.KOKO.SYLN4777

1   ANALYSIS OF TWO DPST-83-1025 ARRAYS
2   1. 0.19 236/235 RATIO 2 X 4 ARRAY ON 6.0 X 3.7 IN PITCH
3   2. MGBS-TGAL WITH ALTERNATE MGBS C.X.




LASTPAGE       2
```

Figure 6. Computer input record for Case II (INPUT.KOKO.?jobname)

```
INPUT.KOKO.SLC34777

MX16-C2  DESIGNATION (NAME) FOR STUDY
         JOBNAME FOR DATA SET WITH PREVIOUS OUTPUT RECORDS
      2  NUMBER OF PROGRAMS (MODULES)
      3  NUMBER OF LINES OF COMMENTS. MAY BE 0.
      0  NUMBER OF BATCHES (APPLIES ONLY TO GLASS, MGBS(SLEN
           OR EXPT)-TGAN(ABBR OR EXPT), TGAN(    ), ANSN OR KENO
           WHEN PRECEDED BY HRXN). MAY BE 0.
      2   1 TO PRINT INPUT RECORDS; 2 TO PRINT COMPUTED INPUT
           RECORDS AS WELL; 3 TO READ & PRINT AMPX LIBRARY ALSO:

OPTIONAL INPUT RECORDS ARE--  INPUT.KOKO
.ADBN.?NAME.?N,        .ANSN.?NAME.?N,        .GLSS.?NAME.?N,
.MGEX.?NAME.?N,        .SLEN.?NAME.?N,        .TWTR.?NAME.?N, OR
.DISL.?NAME.,          .PADJ.?NAME.?N,        .TSLA.?NAME.
                    PROGRAM   OPTION
                    MGBS      EXPT
                    TGAL      EXPT



PAGE        1


INPUT.KOKO.SLC34777

1 ANALYSIS OF TWO DPST-83-1025 ARRAYS
2 1. 0.19 236/235 RATIO 4 X 4 CD ARRAY 5.0 X 3.838IN PITCH
3 2. MGBS-TGAL WITH ALTERNATE MGBS CROSS SECTIONS



LASTPAGE        2
```

Figure 7. Computer input record for Case II (INPUT.KOKO.MGEX.?name)

```
INPUT.KOKO.MGEX.MK16-C2.1

12 NO. OF REGIONS INSIDE FUEL O.D.   FOR EACH REGION TYPE INDEX
& RADIUS(CM) OR DIA(IN) ARE REQUIRED.  THE DIMENSIONAL LIMIT FOR
MGBS IS 22 REGIONS.  MODERATOR IS TYPE 1.  SLIGHTLY ENRICHED UR-
ANIUM OR THORIUM MUST BE TYPE 2 FOR RESONANCE INTEGRAL FOR HETE-
ROGENEOUS LATTICE DUE TO HELLSTRAND OR WEITMAN TO BE REQUESTED.
REGION INDEX  DIMENSION      REGION   INDEX  DIMENSION
1        1        1.7180          2        2        1.7980
3        3        2.0240          4        2        2.1010
5        1        2.5900          6        2        2.6500
7        4        2.8760          8        2        2.9520
9        1        3.4340          10       2        3.4940
11       5        3.6400          12       2        3.7000


PAGE       1


INPUT.KOKO.MGEX.MK16-C2.1

1  NUMBER OF LATTICES (NO. CELLS + RADII FROM P 1 < 51)
COLUMN 1 IS CELL RADIUS (CM) OR CELL DIA (IN) OR PITCH (IN)
COLUMN 2 IS LATTICE DIA OR WIDTH OR -NO. RODS. (0 FOR DIM SRCH)
COLUMN 3 IS HT, LNGTH, AXIAL BCKLNG, OR BIAS(KEFF)--FOR DIM SRCH
COLUMN 4 IS HT, AXIAL BCKLNG, OR CONC (FOR A DIMENSION SEARCH) :
3.83800E 00     1.53520E 01     1.53520E 01     -.95000E-03


PAGE       2


INPUT.KOKO.MGEX.MK16-C2.1

2   PITCH INDEX(0, 2 OR 3)  |  2  UNITS INDEX, 0 FOR CM, >0 FOR
39  REMAINING ITEMS         |     IN (1 FOR DIA, 2 FOR PITCH)
REMAINING ITEMS ARE DENSITY & COMPOSITION FOR METAL OR OXIDE
TYPES.  ORDER IS DENSITY, NEGATIVE ELEMENT INDEX, ISOTOPIC COM-
POSITION (WT% U233, U234, U235, U236, U238 FOR U; PU239, PU240,
PU241, PU242 FOR PU), WEIGHT FRACTION OF ELEMENT, ETC., DENSITY,
ETC.  FOR DIMENSION SEARCH THESE MUST BE FOLLOWED BY DELTA KEFF:
ELEMENT   O, U,PU,TH,AL,ZR,FE,CR,NI, B,CD,GD,PB, C,BE
INDEX     5, 6, 7, 8, 9,10,11,12,13,14,15,16,17,18,19
2.70000E 00  -.90000E 01  1.00000E 00  4.24000E 01  -.60000E 01
0.00000E 00  1.40000E-02  7.42000E-01  1.45000E-01  9.90000E-02
0.00000E 00  -.90000E 01  0.00000E 00  1.02000E 02  -.60000E 01
0.00000E 00  1.50000E-02  7.28000E-01  1.54000E-01  1.03000E-01
0.00000E 00  -.90000E 01  0.00000E 00  1.04000E 02  -.60000E 01
0.00000E 00  1.40000E-02  7.62000E-01  1.30000E-01  9.40000E-02
0.00000E 00  -.90000E 01  0.00000E 00  8.64200E 00  -.15000E 02
1.00000E 00  2.70000E 00  -.90000E 01  1.00000E 00


LASTPAGE       3
```

The following records generated by the execution of KOKO were copied to the user data set:

```
INPUT.MGBS.CONTROL.MK16-C2.1
INPUT.MGBS.CONTROL.MK16-C2.2
INPUT.MGBS.CONTROL.MK16-C2.3
INPUT.MGBS.RADII.MK16-C2.1
INPUT.MGBS.TYPE.MK16-C2.1
INPUT.MGBS.TYPE.MK16-C2.2
INPUT.MGBS.TYPE.MK16-C2.3
INPUT.MGBS.TYPE.MK16-C2.4
INPUT.MGBS.TYPE.MK16-C2.5
INPUT.MGBS.TYPE.MK16-C2.6
INPUT.MGBS.TYPE.MK16-C2.7
INPUT.TGAL.SLC34777
INPUT.TGAL.BTCH.MK16-C2.1
INPUT.TGAL.CMBN.MK16-C2
```

The TGAL.BTCH record created by KOKO provides TGAL input for both dimensions in the x and y directions, but the allowed indexing specifies the same number of regions in each dimension. To correctly and efficiently input the required TGAL data, a `INPUT.TGAL.BTCH.?name.?btch number` record is used for each dimension. The total number of TGAL batch cases remains as 2. If desired, multiple MGBS-TGAL cases can be run with a single set of records by specifying all materials in the MGEX record and creating TGAL batch cases for each dimension of each array. The TGAL.CMBN record then specifies how those cases are to be combined.

Among the records generated by the KOKO run, the `INPUT.TGAL.BTCH.MK16-C2.1` record is modified to include only the x-direction regions corresponding to the one-dimensional slab model shown in Figure 18. The modified record is shown in Figure 8 with the changed parameters denoted in boldfaced italics. The `INPUT.TGAL.BTCH.MK16-C2.2` record is created to include water moderator and cadmium poison regions between the rows of fuel assemblies in the y-direction as illustrated in Figure 18. This record contains 11 different material regions in the y-direction for the one-directional slab model, which is consistent with Figure 18. The created input record is shown in Figure 9. The strong absorber (Cd) region, where the diffusion approximation is not valid, is characterized by transmission and collision probabilities by specifying `type = 0` in the third column of the second page of Figure 9. Note that the aluminum cladding of the cadmium plate is modeled normally since it is a region of low absorption. The `INPUT.KOKO.?jobname` record is modified to specify the KOKO execution of MGBS-TGAL combination without the EXPT option as shown in Figure 10. Then, KOKO is executed to get the K_{eff} result as shown in Table 2.

The examples provided used the standard alternate MGBS cross sections. To specify the original MGBS cross sections rather than the alternate MGBS cross sections, one modification is required in the TGAL record (before step 5 in the general procedure). The parameter for `ORIGINAL MGBS XSECS AND TGAN SOLUTION`, the fourth entry parameter of the `INPUT.TGAL.?jobname` record, should be changed to 0 from 1, which is the default number created by the KOKO-MGEX run. The modified parameter is shown in boldfaced italics in Figure 11. The results in Table 2 include K_{eff} values for the formulations of both cross sections.

Figure 8. Computer input record for Case II (INPUT.TGAL.BTCH.?name.?btch number)

```
INPUT.TGAL.BTCH.MK16-C2.1

0       NUMBER OF LINES OF COMMENTS
1       NUMBER OF CASES PER BATCH
2       NUMBER OF REGIONS(NR)  (DIMENSIONS IN CM)
1.00000   FAST INNER ALBEDO          1.00000    SLOW INNER ALBEDO
-1.00000  FAST OUTER ALBEDO         -1.00000    SLOW OUTER ALBEDO
0       GEOMETRY INDEX. 0=SLAB, 1=CYLINDER, 2=SPHERE, 3=SLAB
        & CYLINDER, 4=SLAB & SPHERE, 5=CYLINDER & SPHERE, 6=
        ALL THREE. (3-6 ONLY IF SEARCH INDEX(L) > 0).
-1      TYPE OF SEARCH(K). 0 FOR KEFF, > 0 FOR THICKNESS OF
        REGION N=K MODULO NR+1 (MAY NOT BE A TRANSMISSION
        REGION; LARGEST INTEGER IN K/(NR+1) IS INDEX OF
        OTHER REGION CHANGED TO COMPENSATE), < 0 FOR TRANS-
        VERSE BUCKLING.
0       L. IF > 0, THICKNESS SEARCH IS MADE FOR ALL MIXTURES
        IN REGION N. K MUST THEREFORE BE > 0. ONLY ONE CASE
        SHOULD BE SPECIFIED FOR THIS BATCH. EXPECTS BIAS.
0       ODD FOR ITERATION TRACE; ALSO CONTROLS SEARCH MESH.
0.000   DELTA KEFF (IF.NE.0, CRITICAL AND CORRESPONDING SUB-
        CRITICAL SEARCHES ARE MADE.)



PAGE        1



INPUT.TGAL.BTCH.MK16-C2.1

            1   CASE NUMBER
0.0000        KEFF (DEFAULTS TO UNITY. MINUS TO REQUEST BIAS)
0.00000E 00   TRANSVERSE BUCKLING (OR PROBLEM NOS.    0     0 )
0.00000E 00   INNER RADIUS
|--THE ENCLOSED APPLY ONLY TO VOID REGIONS. 0 FOR INFINITY.--|
|INTERNAL >     0.0000E 00    HEIGHT OR NEGATIVE DIAMETER       |
|   TO ---->    0.0000E 00    LENGTH                            |
|  UNIT   >     0.0000  0.0000   FAST, SLOW REFLECTOR ALBEDO.   |
|EXTERNAL-->    0.0000   INTER. PROB.      0.00  REFL. AREA/UNIT |:
REGION      MIXTURE      TYPE(1=F,0=T)        THICKNESS
1             1             1                   1.94970E 01
2             2             1                   1.00000E 03



LASTPAGE        2
```

Figure 9. Revised computer input record for Case II (INPUT.TGAL.BTCH.?name.?btch number)

```
INPUT.TGAL.BTCH.MK16-C2.2

0       NUMBER OF LINES OF COMMENTS
1       NUMBER OF CASES PER BATCH
11      NUMBER OF REGIONS(NR)  (DIMENSIONS IN CM)
1.00000     FAST INNER ALBEDO          1.00000     SLOW INNER ALBEDO
-1.00000    FAST OUTER ALBEDO          -1.00000    SLOW OUTER ALBEDO
0       GEOMETRY INDEX. 0=SLAB, 1=CYLINDER, 2=SPHERE, 3=SLAB
        & CYLINDER, 4=SLAB & SPHERE, 5=CYLINDER & SPHERE, 6=
        ALL THREE. (3-6 ONLY IF SEARCH INDEX(L) > 0).
-1      TYPE OF SEARCH(K). 0 FOR KEFF, > 0 FOR THICKNESS OF
        REGION N=K MODULO NR+1 (MAY NOT BE A TRANSMISSION
        REGION; LARGEST INTEGER IN K/(NR+1) IS INDEX OF
        OTHER REGION CHANGED TO COMPENSATE), < 0 FOR TRANS-
        VERSE BUCKLING.
0       L. IF > 0, THICKNESS SEARCH IS MADE FOR ALL MIXTURES
        IN REGION N. K MUST THEREFORE BE > 0. ONLY ONE CASE
        SHOULD BE SPECIFIED FOR THIS BATCH. EXPECTS BIAS.
0       ODD FOR ITERATION TRACE; ALSO CONTROLS SEARCH MESH.
0.000   DELTA KEFF (IF.NE.0, CRITICAL AND CORRESPONDING SUB-
        CRITICAL SEARCHES ARE MADE.)

PAGE        1


INPUT.TGAL.BTCH.MK16-C2.2

            1   CASE NUMBER
0.0000        KEFF (DEFAULTS TO UNITY. MINUS TO REQUEST BIAS)
0.00000E 00   TRANSVERSE BUCKLING (OR PROBLEM NOS.    0     0 )
0.00000E 00   INNER RADIUS
|--THE ENCLOSED APPLY ONLY TO VOID REGIONS. 0 FOR INFINITY.--|
|INTERNAL >     0.0000E 00  HEIGHT OR NEGATIVE DIAMETER         |
|   TO ---->    0.0000E 00  LENGTH                              |
|  UNIT   >     0.0000    0.0000  FAST, SLOW REFLECTOR ALBEDO.  |
|EXTERNAL-->    0.0000  INTER. PROB.      0.00      REFL. AREA/UNIT|:
REGION      MIXTURE     TYPE(1=F,0=T)       THICKNESS
1             3               0               3.81000E-02
2             4               1               3.17500E-01
3             2               1               1.12014E 00
4             1               1               9.74852E 00
5             2               1               1.12014E 00
6             4               1               3.17500E-01
7             3               0               7.61999E-02
8             4               1               3.17500E-01
9             2               1               1.12014E 00
10            1               1               9.74852E 00
11            2               1               1.00000E 03

LASTPAGE        2
```

Figure 10. Revised computer input record for Case II (INPUT.KOKO.?jobname)

```
INPUT.KOKO.SLC34777

MX16-C2   DESIGNATION (NAME) FOR STUDY
          JOBNAME FOR DATA SET WITH PREVIOUS OUTPUT RECORDS
       2  NUMBER OF PROGRAMS (MODULES)
       3  NUMBER OF LINES OF COMMENTS. MAY BE 0.
       0  NUMBER OF BATCHES (APPLIES ONLY TO GLASS, MGBS(SLEN
          OR EXPT)-TGAN(ABBR OR EXPT), TGAN(    ), ANSN OR KENO
          WHEN PRECEDED BY HRXN). MAY BE 0.
       2  1 TO PRINT INPUT RECORDS; 2 TO PRINT COMPUTED INPUT
          RECORDS AS WELL; 3 TO READ & PRINT AMPX LIBRARY ALSO:

          OPTIONAL INPUT RECORDS ARE--  INPUT.KOKO
.ADBN.?NAME.?N,        .ANSN.?NAME.?N,        .GLSS.?NAME.?N,
.MGEX.?NAME.?N,        .SLEN.?NAME.?N,        .TWTR.?NAME.?N, OR
.DISL.?NAME.,          .PADJ.?NAME.?N,        .TSLA.?NAME.
                    PROGRAM    OPTION
                      MGBS
                      TGAL




PAGE        1



INPUT.KOKO.SLC34777

1   ANALYSIS OF TWO DPST-83-1025 ARRAYS
2   1. 0.19 236/235 RATIO 4 X 4 CD ARRAY 5.0 X 3.838IN PITCH
3   2. MGBS-TGAL WITH ALTERNATE MGBS CROSS SECTIONS



LASTPAGE        2
```

Figure 11. Computer input record specifying original MGBS cross sections (INPUT.TGAL.?jobname)

```
INPUT.TGAL.SYLN4777

MK16M   NAME ASSIGNED TO STUDY
   0    NUMBER OF BATCHES OF CASES (IF 0, WILL COUNT BATCHES)
   0    NUMBER OF MIXTURES (IF 0, WILL COUNT MIXTURES)
   0    0 FOR ORIGINAL MGBS XSECS AND TGAN SOLUTION (NO KEFF
        SEARCH); 1 FOR KOKO-TYPE ADJUSTMENT AND KEFF SEARCH;
        2 FOR SIGMA-TR=1/(3*D); 3 FOR XSECS MULTIPLIED BY D
        RATIO; 4 FOR ORIGINAL MGBS XSECS AND KEFF SEARCH
   1    >0 TO PRINT INPUT RECORDS
   0    0 TO REQUEST DIFFUSION CONSTANTS ASSOCIATED WITH
        TRANSVERSE LEAKAGE BE 1/(3*SIGMA-TR) AS IN TGAN. IF
        1, BUCKLING DEPENDENT TRANSPORT THEORY EXPRESSION
        WILL BE USED. CONSTANTS MAY BE READ (SEE BELOW)

        REMAINING INPUT DATA IS CONTAINED IN
        INPUT.TGAL.BTCH.?NAME.?BATCH-NUMBER
        AND OPTIONALLY IN
        INPUT.XSEC.DCST.?NAME.?MIXTURE-NUMBER
        OUTPUT.XSEC.?NAME.?MIXTURE-NUMBER
        INPUT.TGAL.KEFF.?NAME
        INPUT.TGAL.CMBN.?NAME
```

RESULTS

The procedure outlined in the previous section has been used to calculate K_{eff} for each of the cases provided by Clark[2]. The results are provided in Table 2. Calculations with both alternate and original MGBS cross sections are included as was done by Clark. Note that the present results deviate from Clark's results by only ± 0.0001 (about 0.01 %) for 4 cases among the 30 cases delineated in Table 2. That deviation may be due to different computer systems (e.g., different compilers or different intrinsic math libraries) from that used by Clark. That deviation is insignificant in demonstrating that the described technique is equivalent to Clark's technique.

Convergence to the wrong root in transverse buckling searches may occur, especially in a multi-region problem such as a fuel assembly array with cadmium sheets inserted between rows. This happened in the 4 x 4 (5.0" x 3.70") array with an aluminum clad cadmium sheet between rows using the original MGBS cross section option (microfiche job number 5258 in Table 3). In this situation, a non-zero positive value of a transverse buckling in the `INPUT.TGAL.BTCH.?name.?btch number` record may be entered (default value = 0.0). It serves as the initial guess to get correct convergence in a transverse buckling search. Different initial guesses do not affect the final result.

For information, the effect of including or not including the aluminum in the ribs as part of the fuel cladding was examined and found to be negligibly small. Modeling the ribs as added aluminum in the cladding yields K_{eff} about 0.5 % less than modeling without considering the ribs. That is intuitively expected since including the ribs in the cladding reduces the total volume of moderator within the assembly and reduced moderator is generally expected to reduce the reactivity for arrays such as considered here.

Lastly, the job record number for each calculation is shown in Table 3 to keep track of the microfiche outputs. The microfiche will be maintained in APG files for future retrieval and reference.

CONCLUSION

Clark's results have been independently reproduced. A technique has been demonstrated to prepare the KOKO input records and execute KOKO as intended by Clark for criticality calculations.

REFERENCES

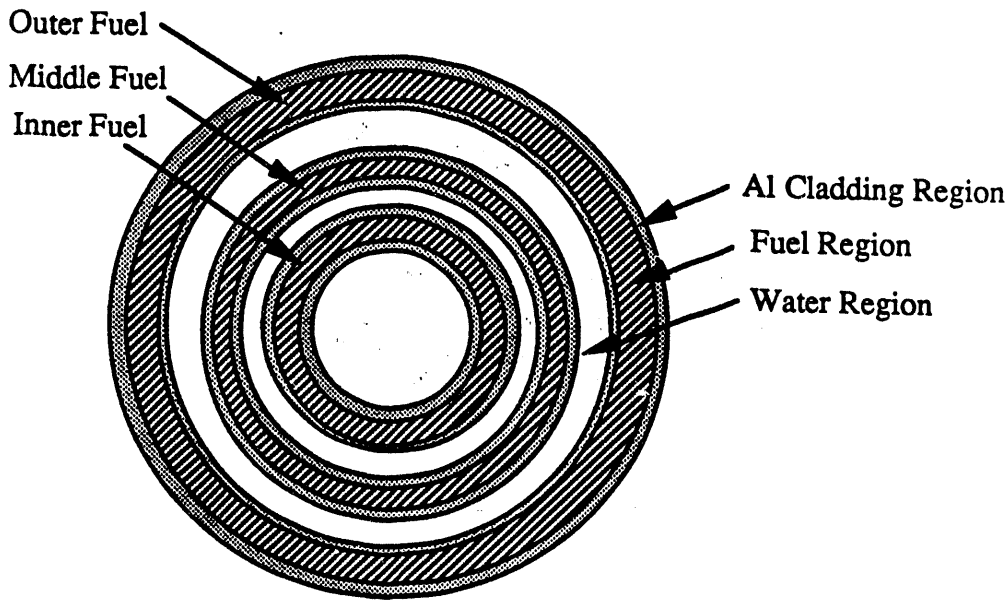
1. H. K. Clark, "User's Manual, Joshua Nuclear Criticality Safety Modules", DPSTM-86-700-3, March, 1987.

2. H. K. Clark, "Correlations with Mark 16 Experiments", DPST-83-1025, November 29, 1983.

3. R. L. Currie, "Nuclear Safety Measurements Using Special Mark 16 Fuel Tubes", DPST-70-462, September 15, 1970.

4. J. J. Duderstadt and L. J. Hamilton, Nuclear Reactor Analysis, John Wiley & Sons, Inc., New York, 1976.

5. S. Glasstone and M. C. Edlund, The Elements of Nuclear Reactor Theory, D. Van Nostrand Company, Inc., New York, 1952.



Inner Fuel Inner Cladding I. D.	1.718 inch
Inner Fuel Inner Cladding O. D.	1.798 inch
Inner Fuel I. D.	1.798 inch
Inner Fuel O. D.	2.024 inch
Inner Fuel Outer Cladding I. D.	2.024 inch
Inner Fuel Ouer Cladding O. D.	2.101 inch
Middle Fuel Inner Cladding I. D.	2.590 inch
Middle Fuel Outer Cladding O. D.	2.650 inch
Middle Fuel I. D.	2.650 inch
Middle Fuel O. D.	2.876 inch
Middle Fuel Outer Cladding I. D.	2.876 inch
Middle Fuel Outer Cladding O. D.	2.952 inch
Outer Fuel Inner Cladding I. D.	3.434 inch
Outer Fuel Inner Cladding O. D.	3.494 inch
Outer Fuel I. D.	3.494 inch
Outer Fuel O. D.	3.640 inch
Outer Fuel Outer Cladding I. D.	3.640 inch
Outer Fuel Outer Cladding O. D.	3.700 inch

Figure 12. Detailed dimensions of Mark 16 fuel assembly[2] used in the input record, `INPUT.KOKO.MGEX.?name` (note that ribs are accounted for using equivalent diameter.).

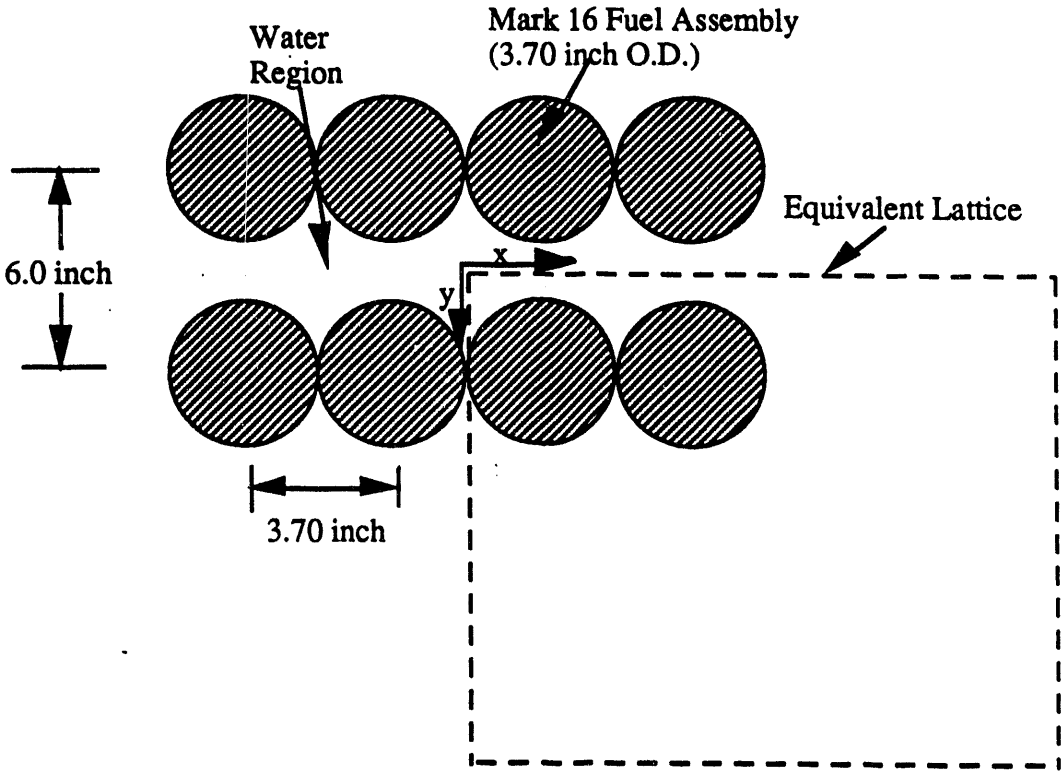


Figure 13. 2 x 4 Mark 16 array (6.00" x 3.70").

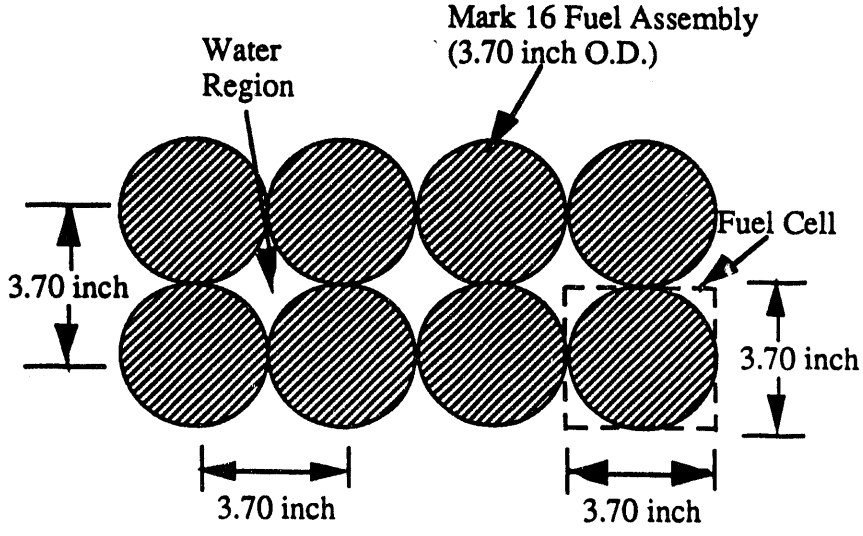
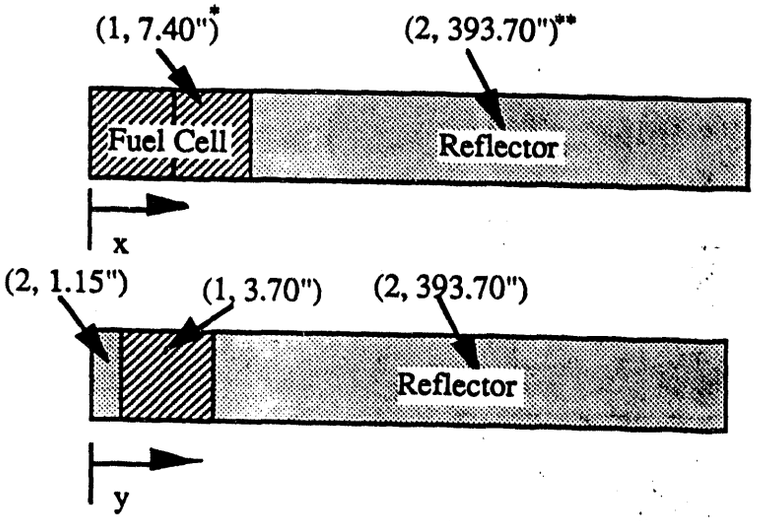


Figure 14. Uniform lattice model of 2 x 4 Mark 16 fuel assembly array as modeled in `INPUT.KOKO.MGEX.MK16M.1` record.



Region Number	Materials
1	Fuel Cell
2	Water

* The first number in parenthesis indicates region number and the second thickness of each region in inch.

** 393.70 inch (=1000 cm) corresponds to large value of reflector thickness. (1000 cm is standard value provided by KOKO.)

Figure 15. Slab model for equivalent lattice of 2 x 4 Mark 16 array (dotted rectangle in Figure 13) for transverse buckling search as modeled in `INPUT.TGAL.BTCH.MK16M.1` and `INPUT.TGAL.BTCH.MK16M.2`.

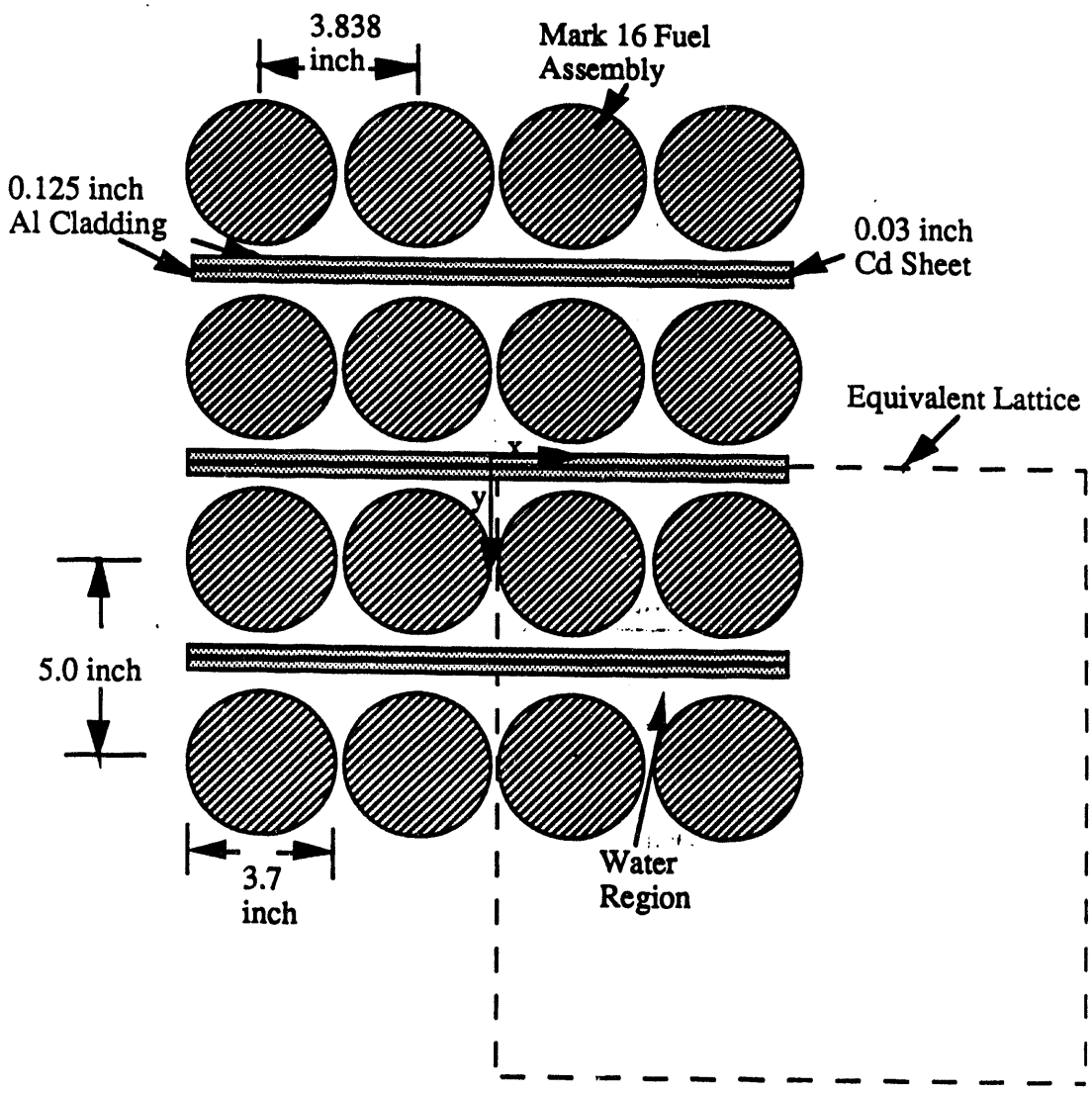


Figure 16. 4 x 4 Mark 16 fuel assembly array with Al clad Cd sheets between rows.

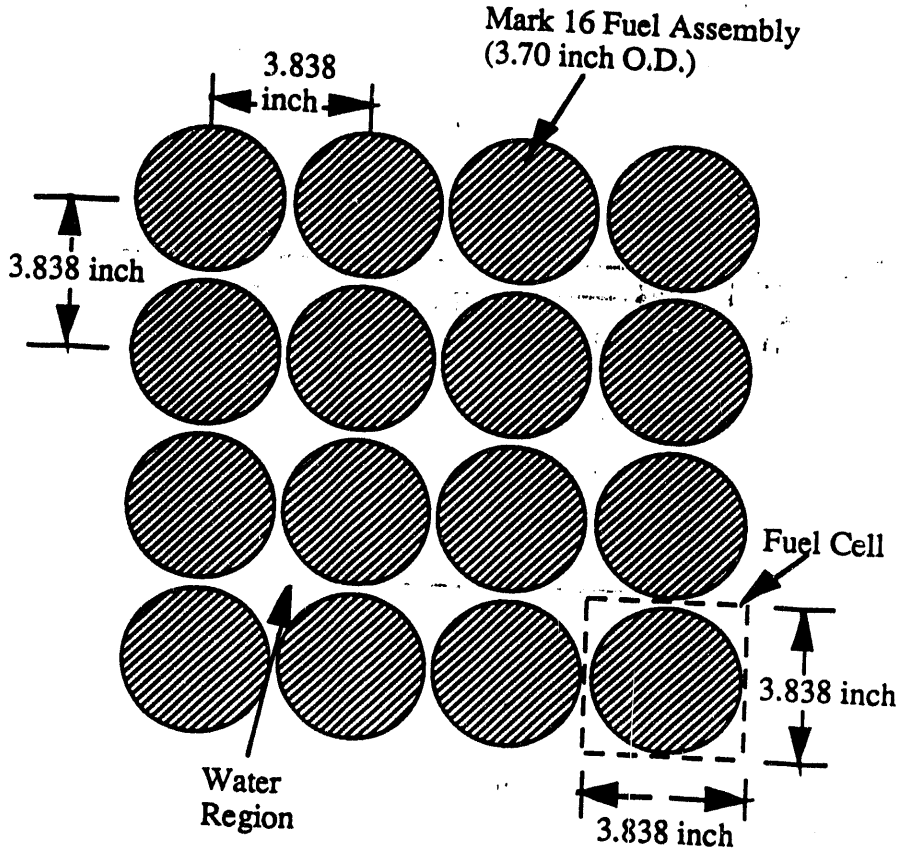
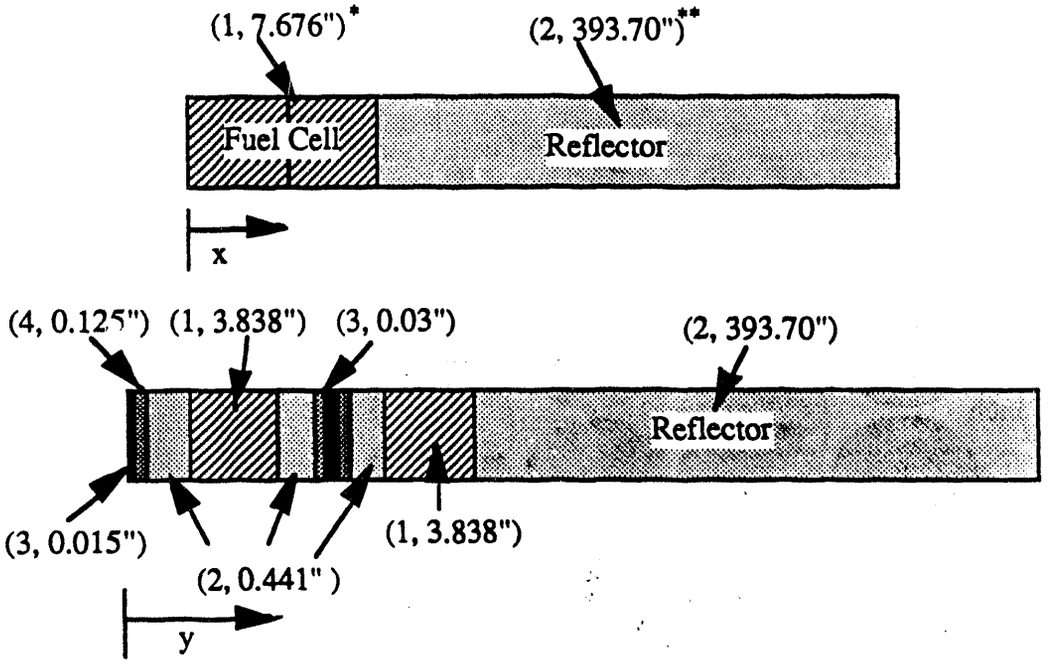


Figure 17. Uniform lattice model of 4 x 4 Mark 16 fuel assembly array as modeled in `INPUT.KOKO.MGEX.MK16-C2.1` record.



Region Number	Materials
1	Fuel Cell
2	Water
3	Cadmium
4	Aluminium

* The first number in parenthesis indicates region number and the second thickness of each region in inch.

** 393.70 inch (=1000 cm) corresponds to large value of reflector thickness.

Figure 18. Slab model for equivalent lattice of 4 x 4 Mark 16 assemblies with Al clad Cd sheets (dotted rectangle in Figure 16) for transverse buckling search as modeled in `INPUT.TGAL.BTCH.mk16-c2.1` and `INPUT.TGAL.BTCH.mk16-c2.2`.

Table 1. Material densities and Uranium isotope compositions of Mark 16 assembly

Atom Ratio of U^{236}/U^{235} = 0.19						
Materials	Density * in gm U^{235}/ft	Isotope Composition				
		U^{233}	U^{234}	U^{235}	U^{236}	U^{238}
Inner Fuel	INFO Deleted	0.0	0.014	0.742	0.145	0.099
Middle Fuel		0.0	0.015	0.728	0.154	0.103
Outer Fuel		0.0	0.014	0.762	0.130	0.094

Atom Ratio of U^{236}/U^{235} = 0.74						
Materials	Density in gm U^{235}/ft	Isotope Composition				
		U^{233}	U^{234}	U^{235}	U^{236}	U^{238}
Inner Fuel	INFO Deleted	0.0	0.016	0.480	0.357	0.147
Middle Fuel		0.0	0.016	0.480	0.357	0.147
Outer Fuel		0.0	0.016	0.480	0.357	0.147

Atom Ratio of U^{236}/U^{235} = 0.0 (Oralloy)						
Materials	Density in gm U^{235}/ft	Isotope Composition				
		U^{233}	U^{234}	U^{235}	U^{236}	U^{238}
Inner Fuel	INFO Deleted	0.0	0.010	0.920	0.0	0.070
Middle Fuel		0.0	0.010	0.920	0.0	0.070
Outer Fuel		0.0	0.010	0.920	0.0	0.070

* Density of Aluminium cladding material is 2.7 gm/cm^3.

• Note that aluminum component of U-Al fuel region is calculated by KOKO using inputted geometry, standard formulas, and uranium and aluminum densities.

• Density of cadmium sheet was taken as 8.642 gm/cm^3, the value specified in Reference 1 for the predefined TGAN macroscopic cross section set.

Table 2. MGBS-TGAL results for various arrays and fuel compositions of Mark 16 assembly

Atom Ratio of U^{236}/U^{235}	Fuel Assembly Arrays [a]	K^2 , cm^2	K_{eff}	
			Original MGBS[b]	Alternate MGBS[c]
0.19	2 x 3 (3.700" x 3.700")	5.350×10^{-4}	1.0637 (1.0637)[d]	1.0464 (1.0464)[d]
	2 x 3 (3.838" x 3.838")	3.400×10^{-4}	1.0712 (1.0712)	1.0563 (1.0563)
	2 x 3 (4.187" x 4.187")	3.350×10^{-4}	1.0765 (1.0765)	1.0664 (1.0664)
	2 x 4 (4.536" x 4.536")	-4.500×10^{-4}	1.0695 (1.0695)	1.0641 (1.0641)
0.74	2 x 3 (4.187" x 4.187")	9.700×10^{-4}	1.0584 (1.0584)	1.0471 (1.0471)
0.0 (Oralloy)	2 x 2 (3.700" x 3.700")	1.520×10^{-3}	1.0766 (1.0766)	1.0512 (1.0512)
	2 x 2 (3.838" x 3.838")	1.360×10^{-3}	1.0884 (1.0883)	1.0664 (1.0664)
	2 x 2 (4.187" x 4.187")	8.900×10^{-4}	1.0897 (1.0897)	1.0732 (1.0732)
	2 x 2 (4.536" x 4.536")	1.250×10^{-3}	1.0798 (1.0798)	1.0671 (1.0671)
0.19	**2 x 4 (6.000" x 3.700")[e]**	1.295×10^{-3}	1.0789 (1.0789)	1.0629 (1.0629)
	3 x 3 (6.000" x 3.700")	9.100×10^{-4}	1.0793 (1.0793)	1.0617 (1.0618)
	3 x 3 (6.000" x 3.838")	1.010×10^{-3}	1.0968 (1.0968)	1.0842 (1.0842)
0.0 (Oralloy)	3 x 3 (7.500" x 3.700")	1.950×10^{-3}	1.0947 (1.0947)	1.0758 (1.0758)
0.19 (with Cd sheets)	4 x 4 (5.000" x 3.700")	8.000×10^{-4}	1.0806 (1.0806)	1.0771 (1.0772)
	4 x 4 (5.000" x 3.838")	9.500×10^{-4}	1.0945 (1.0946)	1.0983 (1.0983)

[a] No. of rows x No. of assemblies per row (Pitch of rows in inch x Pitch in row in inch)

[b] MGBS-TGAL combination with original MGBS cross sections.

[c] MGBS-TGAL combination with alternate MGBS cross sections.

[d] The number in parentheses is H. K. Clark's result (DPST-83-1025)
(Underlined values (4 cases) indicate the cases with differences between HKC results and current calculations.)

[e] The example cases are indicated by boldfaced letter.

Table 3. Job number list of microfiche output files

Atom Ratio of U^{236}/U^{235}	Fuel Assembly Arrays[a]	κ^2 , cm^2	Microfiche Job Number	
			Original MGBS[b]	Alternate MGBS[c]
0.19	2 x 3 (3.700" x 3.700")	5.350×10^{-4}	0054	5878
	2 x 3 (3.838" x 3.838")	3.400×10^{-4}	0078	5752
	2 x 3 (4.187" x 4.187")	3.350×10^{-4}	0083	6224
	2 x 4 (4.536" x 4.536")	-4.500×10^{-4}	0084	6384
0.74	2 x 3 (4.187" x 4.187")	9.700×10^{-4}	0094	9624
0.0 (Oralloy)	2 x 2 (3.700" x 3.700")	1.520×10^{-3}	1600	9679
	2 x 2 (3.838" x 3.838")	1.360×10^{-3}	1622	9746
	2 x 2 (4.187" x 4.187")	8.900×10^{-4}	1642	9774
	2 x 2 (4.536" x 4.536")	1.250×10^{-3}	1653	9806
0.19	2 x 4 (6.000" x 3.700")	1.295×10^{-3}	5124	5111
	3 x 3 (6.000" x 3.700")	9.100×10^{-4}	5282	5281
	3 x 3 (6.000" x 3.838")	1.010×10^{-3}	5194	5189
0.0 (Oralloy)	3 x 3 (7.500" x 3.700")	1.950×10^{-3}	5223	5214
0.19 (with Cd Sheets)	4 x 4 (5.000" x 3.700")	8.000×10^{-4}	5258	5249
	4 x 4 (5.000" x 3.838")	9.500×10^{-4}	5266	5262

[a] No. of rows x No. of assemblies per row (Pitch of rows in inch x Pitch in row in inch)

[b] MGBS-TGAL combination with original MGBS cross sections.

[c] MGBS-TGAL combination with alternate MGBS cross sections.

APPENDIX

• Relationship of Measured Parameter κ^2 to Axial Buckling B_z^2 of an Array

The thermal neutron flux distribution in an exponential pile[4,5] is determined by the steady-state diffusion equation.

$$\nabla^2\Phi(x, y, z) + B_m^2\Phi(x, y, z) = 0 \qquad (A.1)$$

where $B_m^2 < B_g^2$ for a subcritical system and $B_m^2 = B_g^2$ for a critical system.

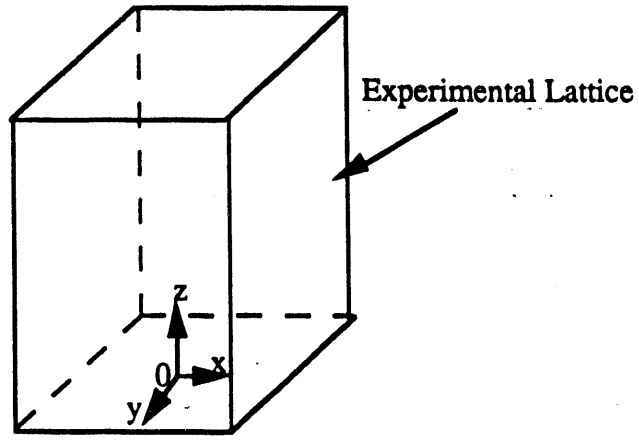


Figure A.1. Rectangular parallelepiped block in the Cartesian coordinate system.

Assuming that the function Φ is separable under the Cartesian coordinate system in Figure A.1,

$$\Phi(x, y, z) = \phi_1(x)\,\phi_2(y)\,\phi_3(z) \qquad (A.2)$$

After substituting equation A.2 into equation A.1 and dividing the resulting equation by $\phi_1\phi_2\phi_3$, the terms in ϕ_1, ϕ_2, and ϕ_3 may then be set equal to the constants, $-B_x^2$, $-B_y^2$, and κ^2, respectively.

$$\begin{aligned}
\frac{1}{\phi_1}\frac{d^2}{dx^2}\phi_1 &= -B_x^2 \\
\frac{1}{\phi_2}\frac{d^2}{dy^2}\phi_2 &= -B_y^2 \\
\frac{1}{\phi_3}\frac{d^2}{dz^2}\phi_3 &= \kappa^2
\end{aligned} \qquad (A.3)$$

Substituting equation A.3 into equation A.1, B_m^2 becomes

$$B_m^2 = B_x^2 + B_y^2 - \kappa^2 \qquad (A.4)$$

Boundary conditions for the rectangular block in Figure A.1 are given as

$$\phi_1(x = \pm a/2) = 0 \qquad \text{(A.5)}$$

$$\phi_2(y = \pm b/2) = 0 \qquad \text{(A.6)}$$

$$\phi_3(z=0)=\phi_{30} \text{ and } \phi_3(z=c)=0 \qquad \text{(A.7)}$$

where a, b, and c in equations A.5, A.6, and A.7 are the physical dimensions including the extrapolated distances along the x-, y-, and z-directions.

Applying the boundary conditions (equations A.5 to A.7) to the separated equation A.3, the fundamental functional form for the neutron flux in the exponential experiment becomes

$$\Phi(x, y, z)=\phi_1(x)\ \phi_2(y)\ \phi_3(z)$$
$$= A\cos(B_x x)\cos(B_y y)\sinh\kappa(c-z) \qquad \text{(A.8)}$$

where

$$B_x=\frac{\pi}{a} \text{ and } B_y=\frac{\pi}{b} \qquad \text{(A.9)}$$

At distances not too near the top of the rectangular block in Figure A.1 ($z < c$), the z-direction function is approximated as

$$\phi_3(z) \approx Ce^{-\kappa z} \qquad \text{(A.10)}$$

where C is a constant and κ is the determinable parameter from the exponential experiment.

The inverse value of κ in equation A.10 corresponds to the relaxation length of the neutrons, that is, the distance within which the neutron flux falls off by a factor of e in the z-direction.

Substituting equation A.9 into equation A.4, the material buckling B_m^2 becomes

$$B_m^{\,2}=\left(\frac{\pi}{a}\right)^2+\left(\frac{\pi}{b}\right)^2-\kappa^2 \qquad \text{(A.11)}$$

For the rectangular block shown in Figure A.1, the geometrical buckling B_g^2 is given as

$$B_g^{\,2} = B_x^{\,2} + B_y^{\,2} + B_z^{\,2} \qquad \text{(A.12)}$$

For a critical system ($B_m^2 = B_g^2$), comparison of equations A.11 and A.12 shows that

$$B_z^{\,2} = -\kappa^2 \qquad \text{(A.13)}$$

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