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A NEW 3D REACTOR MODEL FOR CRITICALITY SAFETY ANALYSIS OF NIRR-1 USING SCALE 6.2.3

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ABSTRACT

Detailed 3D model was developed for the Nigeria Research Reactor (NIRR-1) recently converted to 12.5% enriched UO_2 core during the last quarter of 2018. The KENO3D module of SCALE 6.2.3 was used to visualize the geometry of the system before the criticality safety analysis was performed with the KENO-VI module of the code. This model consists of over 10 different units that are properly placed at their exact position on the global unit. The coordinate of each fuel pin was calculated using the radius of the circle and the pin angular positions. Several reactor physics parameters generated include k-effective values by generation run, the average k-effective, the neutron lifetime, the generation time, the average number of neutron per fission in the system, the average energy group at which fission occurs, and the energy of the average lethargy causing fission in the system. Some of this information was used to determine how fast or thermal the spectrum of the modeled system was. A plot of average k-effective versus the number of generation run was used to determine whether the calculations performed using the input prepared for the modeled NIRR-1 system has source convergence difficulties or not.

Keywords: k-effective, neutronics, fission, absorption, thermal, leakage, control

INTRODUCTION

The Nigeria Research Reactor 1 (NIRR-1) is a 31kW tank in pool type research reactor used mostly for neutron activation analysis and radioisotope production. It was converted from HEU to LEU fuel in the last quarter of 2018. The HEU fuel removed from this reactor was returned to the country of origin, China, in December, 2018 (Chakrov and Hanlon, 2018). The successful NIRR-1 core conversion, form the second Miniature Neutron Source Reactor (MNSR), outside China, converted to Low Enriched Uranium Fuel (LEU), after the similar one in Ghana called GHARR-1 was converted to LEU in 2017 (Chakrov and Hanlon, 2018). The new LEU core of NIRR-1 consists of the same number of pins in the fuel cage as in the HEU core of the system (See Yahaya et al, 2017). The number of dummy pins in the core increased by twelve with a corresponding decreased, in the number of active fuel pins. The dimension of the pins as well as the fuel cage in the LEU core is exactly the same with that of the HEU core. Detail description of NIRR-1 system can be found in the 2005 Fuel safety analysis report (see FSAR, 2005) for the HEU core of the system as well as in several other publications (see Yahaya et al, 2017, Ibikunle et al, 2016, Salawu, 2013 & Jonah and Balogun, 2005); as the similar document for the LEU core is yet to be made available for public consumptions by the regulatory agency. The fuel element in the LEU core is made of 12.5% enriched Uranium dioxide with a cladding material made of Zirconium alloy. In this work detailed three dimensional model of the Miniature Neutron Source Reactor (MNSR) was developed for criticality safety analysis of the systems, using the resent version of the SCALE code system called SCALE 6.2.3. This computer software is widely-used around the world for nuclear safety analysis and design and it was developed, maintained, tested, and managed in the United State of America (Rearden and Jessee Eds, 2016). The KENO-VI module of SCALE used to perform this analysis is a three-dimensional (3D) Monte Carlo criticality transport computer code, with a very flexible geometry package capable of modeling accurately, any volume that can be constructed using quadric equation, with features such as geometry intersections, body rotations, hexagonal and dodecahedral arrays, and array boundaries (Rearden and Jessee Eds, 2016). It is normally used to calculate the following type of data for three dimensional system: k-effective, neutron lifetime, generation time, energy-dependent leakages, energy- and region-dependent absorptions, fissions, the system mean-free-path, the region-dependent mean-free-path, average neutron energy, flux densities, fission densities, reaction rate tallies, mesh tallies, source convergence diagnostics, problem dependent continuous energy temperature treatments, parallel calculations, restart capabilities, etc (Rearden and Jessee Eds, 2016). The KENO3D rendering of the KENOVI geometry model of each component in the system form the best geometry of NIRR-1 ever produced. The core of the modeled system consists of 354 pins of equal dimension arranged in ten concentric circles with one central control rod. Four of these pins were the tie rods located equally spaced on the eighth concentric circle, while the dummy pins were arranged on the tenth circle. The remaining three hundred and thirty three active fuel pins were arranged on the concentric circles with radial pitch ranging from 10.58 to 11.47cm (FSAR, 2005).

Methodology

The criticality safety analysis for NIRR-1 system was performed in this work using one of the SCALE control module for the enhanced criticality safety analysis for three dimensional (3-D) systems called KENO-VI. Using ENDF/B-VII (i.e. v7-238) cross section library, this module within the SCALE code, automatically activated other modules needed to generate a problem dependent cross sections and calculated the neutron multiplication factor for the modeled 3-D system. The material compositions of the designed system were aluminum, light water, Beryllium, Cadmium, Stainless steel, 12.5% UO_2 fuel material and Zirconium alloy. The model consists of thirteen different units arranged at their exact location on the global Unit; the fourteenth unit. The first unit was made of the active fuel regions of the system with the zirconium alloy as the cladding material, while the second unit was the 9 mm long zirconium plug, placed on both end of the first unit, to produce the NIRR-1 fuel pin; the third unit. The control rod of NIRR-1 system was produced in the model as the fourth unit while the fifth and the sixth unit represented the inner and the outer irradiation channels respectively. Unit seven was the fission chamber, and the bottom beryllium was produced as unit eight. The control rod and the guide tube in the system were combined together as unit nine. The tenth, eleventh and the twelfth unit were used to form the system dummy pins and the tie rods respectively. The thirteenth unit was made of radial beryllium and the aluminum tank where each of the other units (i.e. from unit one to unit twelve) were arranged at their exact positions in the tank, using the SCALE HOLE command. This command was also used to arrange the three hundred and thirty five active fuel pins (unit three) in the LEU system, in ten concentric circles, to produce the NIRR-1 fuel cage whose picture is shown in figure 1. The dimension of the x- and y- coordinate of each pin on each concentric circle, that was used to place the pins at their exact position were calculated using the radius of the circles as well as the pin angular positions. The top view of the modeled fuel cage is shown in figure 2.

Fig. 1: Picture of a typical MNSR Fuel cage.

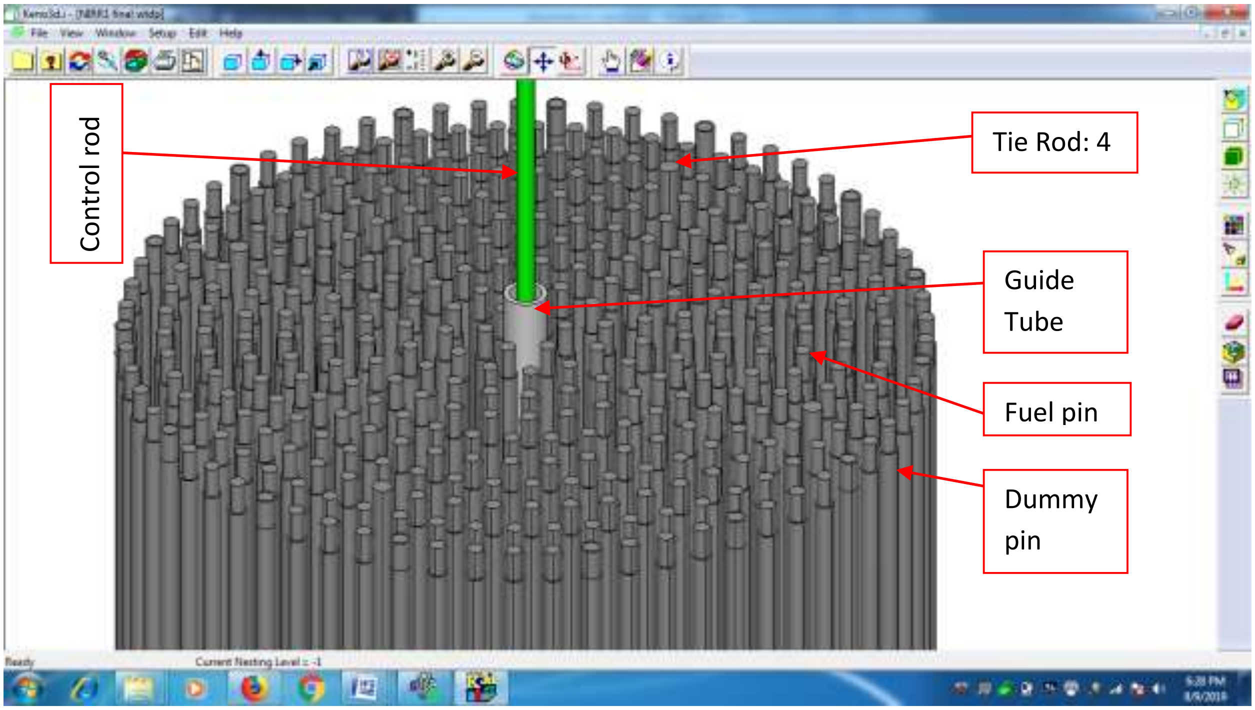
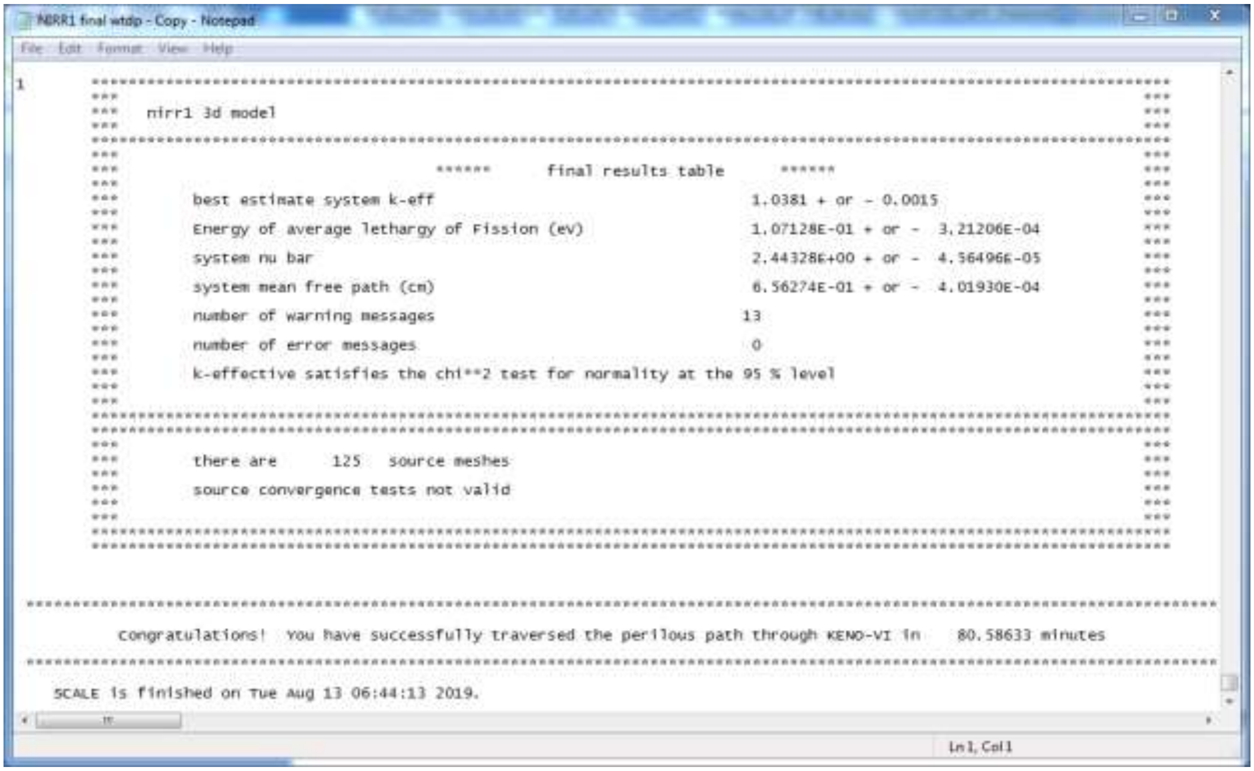


Fig. 2: The top view of the modeled NIRR-1 fuel cage



```
1       *******************************************************************************************************************
        ***                                                                                                             ***
        ***   nirr1 3d model                                                                                            ***
        ***                                                                                                             ***
        *******************************************************************************************************************
        ***                                                                                                             ***
        ***                                 ******      final results table      ******                                 ***
        ***                                                                                                             ***
        ***          best estimate system k-eff                                   1.0381 + or - 0.0015                  ***
        ***                                                                                                             ***
        ***          Energy of average lethargy of Fission (eV)                   1.07128E-01 + or -  3.21206E-04       ***
        ***                                                                                                             ***
        ***          system nu bar                                                2.44328E+00 + or -  4.56496E-05       ***
        ***                                                                                                             ***
        ***          system mean free path (cm)                                   6.56274E-01 + or -  4.01930E-04       ***
        ***                                                                                                             ***
        ***          number of warning messages                                  13                                     ***
        ***                                                                                                             ***
        ***          number of error messages                                     0                                     ***
        ***                                                                                                             ***
        ***          k-effective satisfies the chi**2 test for normality at the 95 % level                              ***
        ***                                                                                                             ***
        ***                                                                                                             ***
        *******************************************************************************************************************
        *******************************************************************************************************************
        ***                                                                                                             ***
        ***          there are      125   source meshes                                                                 ***
        ***                                                                                                             ***
        ***          source convergence tests not valid                                                                 ***
        ***                                                                                                             ***
        ***                                                                                                             ***
        *******************************************************************************************************************
        *******************************************************************************************************************


 ****************************************************************************************************************************

         Congratulations!  You have successfully traversed the perilous path through KENO-VI in    80.58633 minutes

 ****************************************************************************************************************************

   SCALE is finished on Tue Aug 13 06:44:13 2019.
```

Table 1: The final result table of a successful SCALE run

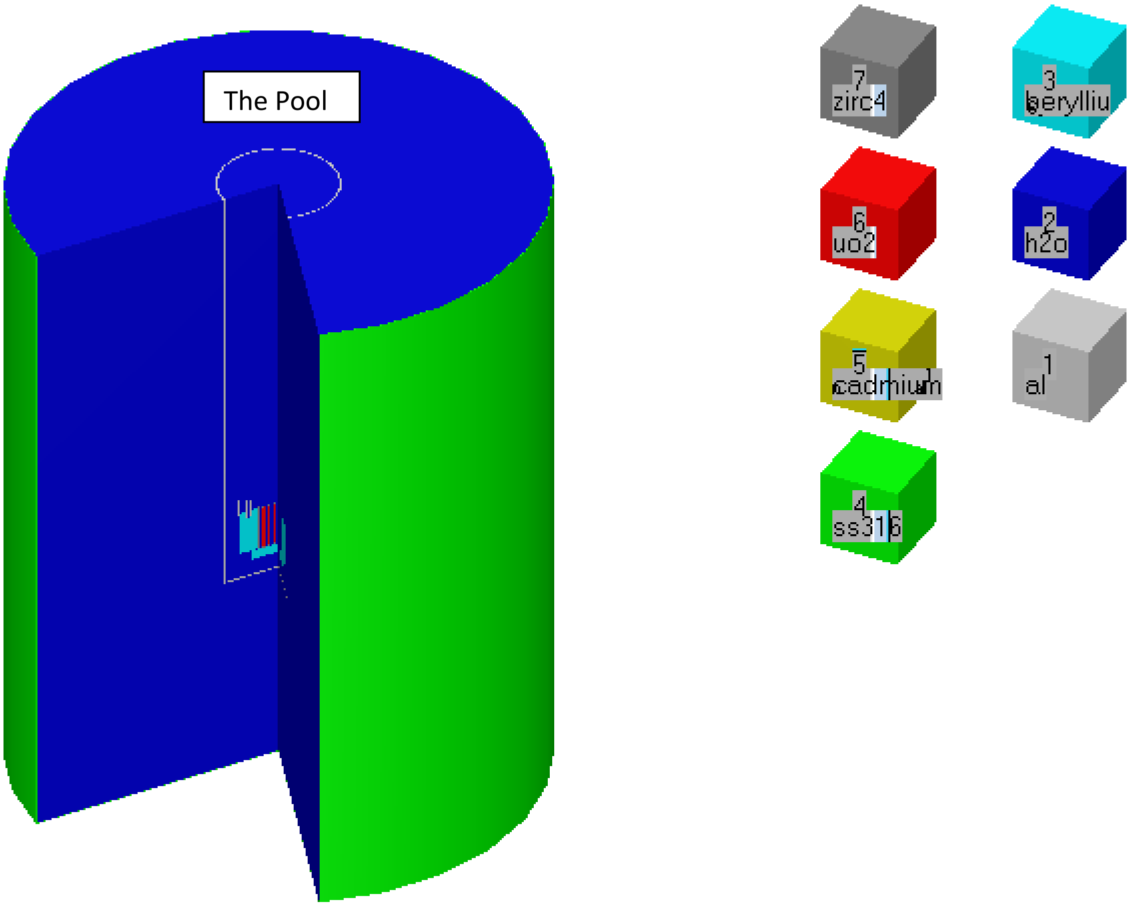


Fig. 3: Geometry and material composition of different components in NIRR-1 system.

Lastly, unit fourteen was the reactor pool in which unit twelve, the aluminum tank and the other entire reactor component inside it, were placed to produce the model for the NIRR-1 system. Note that the four support shoes, welded to the bottom of the vessel on which the core components are mounted could not be modeled due to lack of information concerning their geometry and material composition. The same is true for the three regulatory rods on the NIRR-1 core. The neutron multiplication factor was calculated by simply clicking the run button or the "run in background" option in the run menu of the Fulcrum user interface of SCALE 6.2.3. The input prepared for the system run successfully with chi-square test for normality, satisfied at the 95% level. The final result table conveying this message is shown in table 1. Several reactor physics parameters generated include the effective neutron multiplication factor (k-effective), values of k-effective by generation run as well as the average k-effective, the neutron lifetime, the generation time, the average number of neutron per fission in the system, the average energy group at which fission occurs, and the energy of the average lethargy causing fission in the system.

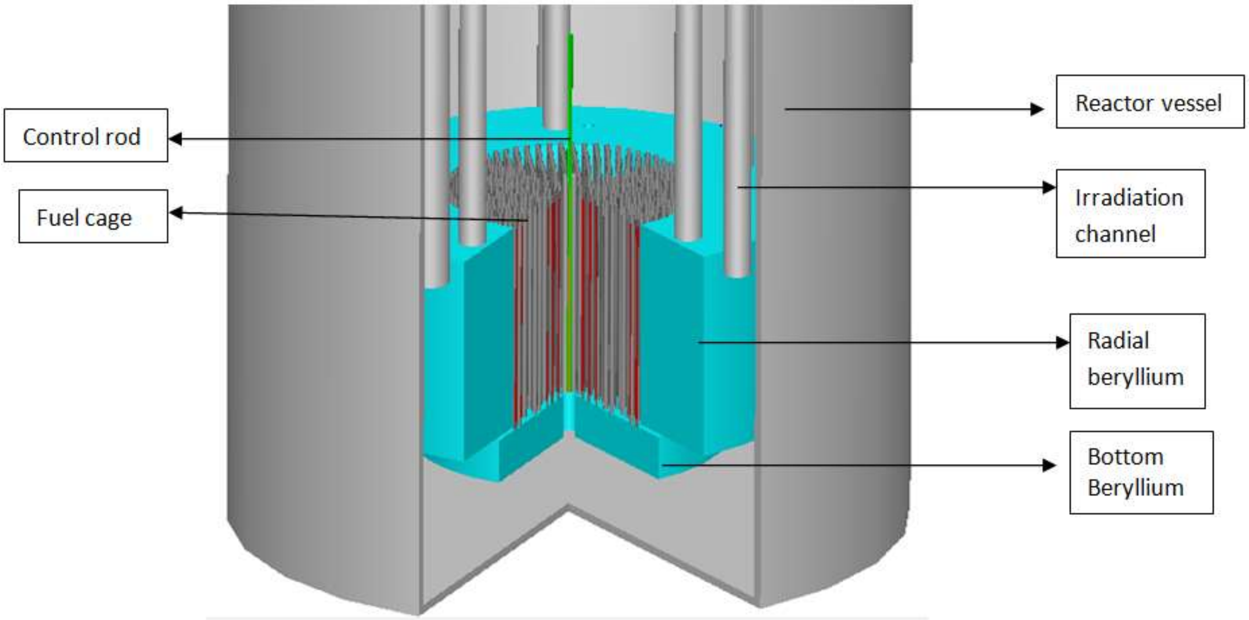


Fig. 4a: The arrangement of core component in NIRR-1 vessels with control rod at fully inserted position.

RESULT AND DISCUSSION

The modeled fuel cage of the Nigeria Research Reactor 1 (NIRR-1) is as shown in Figure 2. The control rod, the tie rods and the fuel pins were clearly shown in the figure except the dummy pins that cannot be differentiated from the fuel pins because its shape, dimension and material composition are the same with that of the cladding material of the fuel meat.

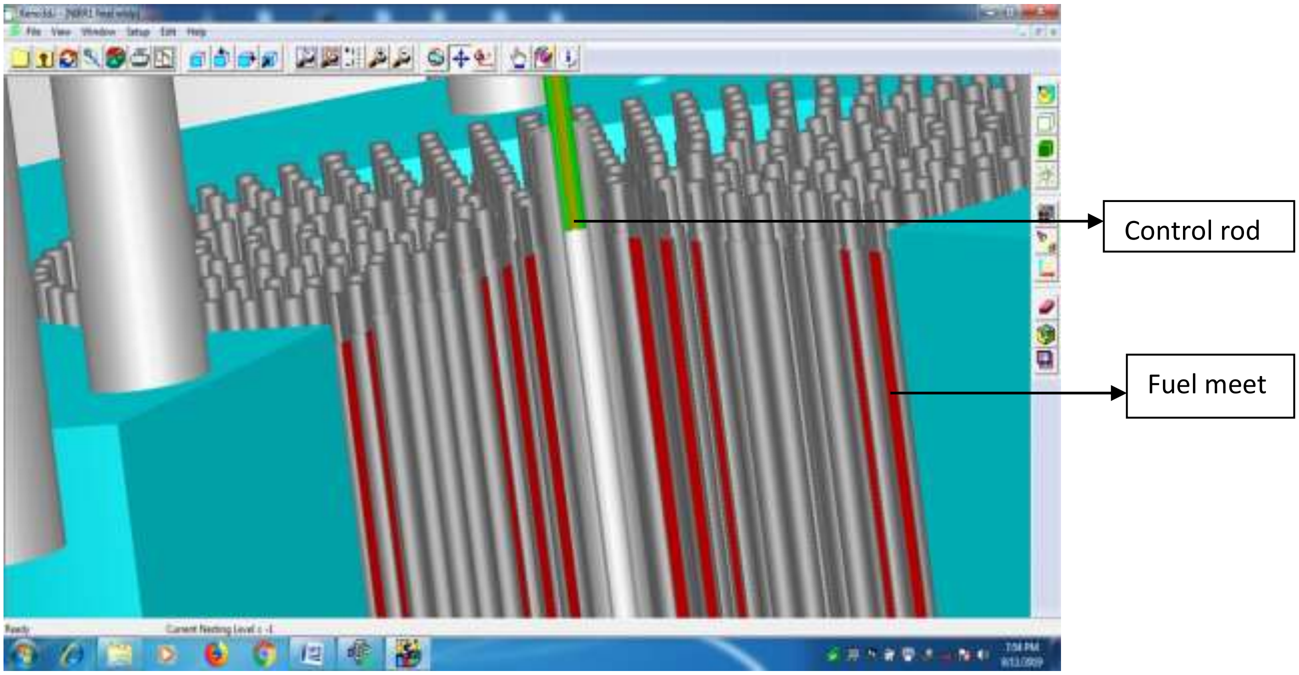
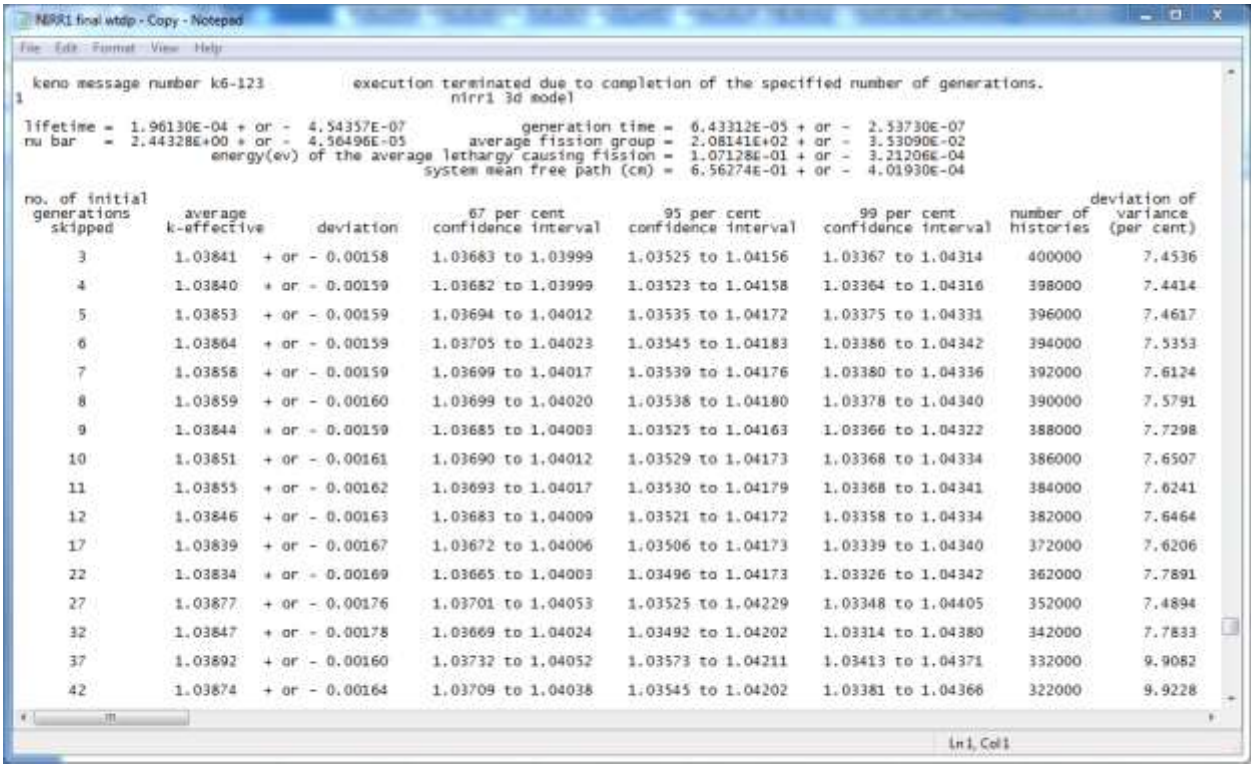


Figure 4b: The control rod at fully withdrawn position.

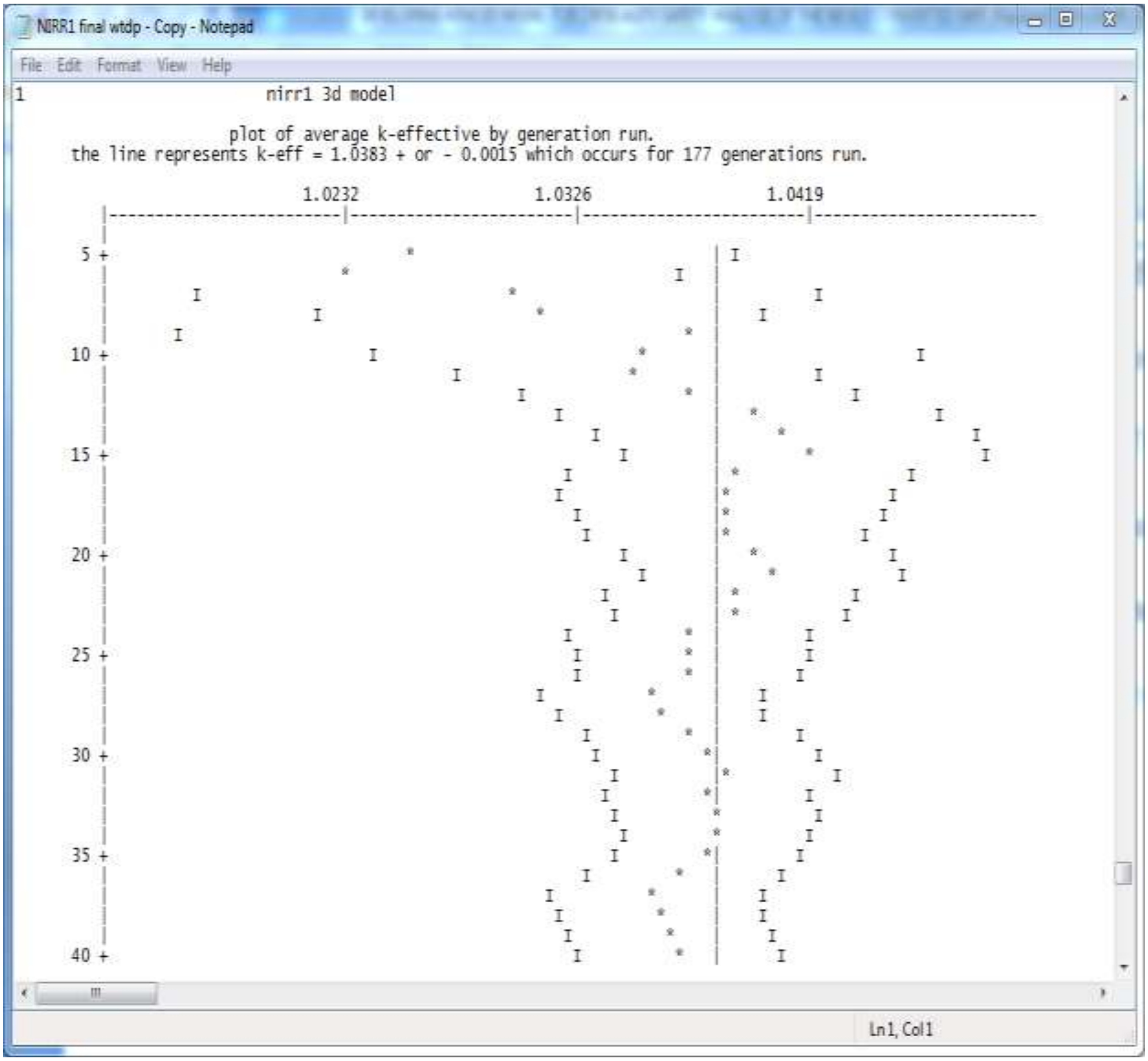
Table 2: Summaries of some calculated values for the system



```
 keno message number k6-123         execution terminated due to completion of the specified number of generations.
1                                                      nirr1 3d model

 lifetime =  1.96130E-04 + or -  4.54357E-07            generation time =  6.43312E-05 + or -  2.53730E-07
 nu bar   =  2.44328E+00 + or -  4.56496E-05       average fission group =  2.08141E+02 + or -  3.53090E-02
                    energy(ev) of the average lethargy causing fission =  1.07128E-01 + or -  3.21206E-04
                                         system mean free path (cm) =  6.56274E-01 + or -  4.01930E-04

 no. of initial                                                                                                   deviation of
  generations      average                        67 per cent          95 per cent          99 per cent      number of   variance
   skipped       k-effective      deviation    confidence interval  confidence interval  confidence interval  histories  (per cent)

       3           1.03841    + or - 0.00158   1.03683 to 1.03999   1.03525 to 1.04156   1.03367 to 1.04314    400000      7.4536

       4           1.03840    + or - 0.00159   1.03682 to 1.03999   1.03523 to 1.04158   1.03364 to 1.04316    398000      7.4414

       5           1.03853    + or - 0.00159   1.03694 to 1.04012   1.03535 to 1.04172   1.03375 to 1.04331    396000      7.4617

       6           1.03864    + or - 0.00159   1.03705 to 1.04023   1.03545 to 1.04183   1.03386 to 1.04342    394000      7.5353

       7           1.03858    + or - 0.00159   1.03699 to 1.04017   1.03539 to 1.04176   1.03380 to 1.04336    392000      7.6124

       8           1.03859    + or - 0.00160   1.03699 to 1.04020   1.03538 to 1.04180   1.03378 to 1.04340    390000      7.5791

       9           1.03844    + or - 0.00159   1.03685 to 1.04003   1.03525 to 1.04163   1.03366 to 1.04322    388000      7.7298

      10           1.03851    + or - 0.00161   1.03690 to 1.04012   1.03529 to 1.04173   1.03368 to 1.04334    386000      7.6507

      11           1.03855    + or - 0.00162   1.03693 to 1.04017   1.03530 to 1.04179   1.03368 to 1.04341    384000      7.6241

      12           1.03846    + or - 0.00163   1.03683 to 1.04009   1.03521 to 1.04172   1.03358 to 1.04334    382000      7.6464

      17           1.03839    + or - 0.00167   1.03672 to 1.04006   1.03506 to 1.04173   1.03339 to 1.04340    372000      7.6206

      22           1.03834    + or - 0.00169   1.03665 to 1.04003   1.03496 to 1.04173   1.03326 to 1.04342    362000      7.7891

      27           1.03877    + or - 0.00176   1.03701 to 1.04053   1.03525 to 1.04229   1.03348 to 1.04405    352000      7.4894

      32           1.03847    + or - 0.00178   1.03669 to 1.04024   1.03492 to 1.04202   1.03314 to 1.04380    342000      7.7833

      37           1.03892    + or - 0.00160   1.03732 to 1.04052   1.03573 to 1.04211   1.03413 to 1.04371    332000      9.9082

      42           1.03874    + or - 0.00164   1.03709 to 1.04038   1.03545 to 1.04202   1.03381 to 1.04366    322000      9.9228
```

Figure 3 shows the reactor pool and other reactor components; with the legend showing the material composition of each component. The enlarged image of the lower section of the reactor vessel, showing clearly the geometry of the core components with control rod at fully inserted position and at fully withdrawn position, after the removal of the moderator, is shown in figure 4a and figure 4b respectively

The values of the calculated best estimate effective neutron multiplication factor (k effective) at the two locations of the control rod (CR) are 1.0381 ± 0.0015 and 1.0426 ± 0.0014 respectively. These values correspond to the calculated k-effective values with the minimum standard deviation at the two location of the CR. The values are higher than what was expected for a critical system because we couldn't modeled the four reactivity regulators in the system due to lack of sufficient information about their geometry and material compositions at the time of this research. The energy of the average lethargy causing fission (EALF) in the system was calculated to be approximately 0.107eV. This value shows that the modeled system is a thermal reactor. The mean free path and the average number of neutron per fission in the system (i.e. nu bar) were calculated to be approximately 0.656cm and 2.44 respectively. Table 2 shows values of some of the parameters calculated for the system such as lifetime, average fission group, and Energy of Average Lethargy causing fission. This information further confirm the spectrum of the modeled system which was quite soft as indicated by the relatively long life time of 0.196 milliseconds and the very low value of EALF. This table also shows some portion of the calculated k-effective values for the system versus number of initial generation skipped, average k-effective values and its associated deviation, the number of histories used in calculating the average k-effective and the limit of k-effective for the 67, 95, and 99% confidence intervals. Careful examination of the average k-effective values shows that they are relatively stable or constant in the modeled system. Figure 5a is a plot of these average values versus generation run. It shows that the modeled system does not have very serious source convergence difficulties as the source appears to be fairly converged. This is indicated by the fair stability observed in the average k-effective and by the slight variance in the k-effective near the end of the plot as shown in figure 5b.



```
1                           nirr1 3d model

                        plot of average k-effective by generation run.
      the line represents k-eff = 1.0383 + or - 0.0015 which occurs for 177 generations run.

                                1.0232                   1.0326                    1.0419
         |--------------------------|-------------------------|------------------------|------------------------
         |
       5 +                                 *                                 | I
         |                          *                                    I   |
         |          I                                 *                      |          I
         |                       I                       *                   |    I
         |        I                                                *         |
      10 +                             I                             *       |                      I
         |                                      I                   *        |          I
         |                                             I                  *  |              I
         |                                                  I                |   *                    I
         |                                                      I            |      *                     I
      15 +                                                         I         |         *                   I
         |                                                   I               | *                   I
         |                                                  I                |*                 I
         |                                                    I              |*                 I
         |                                                     I             |*              I
      20 +                                                         I         |   *               I
         |                                                           I       |     *              I
         |                                                       I           | *            I
         |                                                        I          | *           I
         |                                                   I            *  |         I
      25 +                                                    I           *  |         I
         |                                                    I           *  |        I
         |                                               I            *      |    I
         |                                                  I          *     |    I
         |                                                     I          *  |        I
      30 +                                                      I           *|          I
         |                                                        I          |*           I
         |                                                       I          *|         I
         |                                                        I          *          I
         |                                                         I         *         I
      35 +                                                        I         *|        I
         |                                                     I         *   |      I
         |                                                I           *      |    I
         |                                                  I          *     |    I
         |                                                   I          *    |     I
      40 +                                                    I          *   |      I
```

Fig. 5a: Average k-effective by generation run

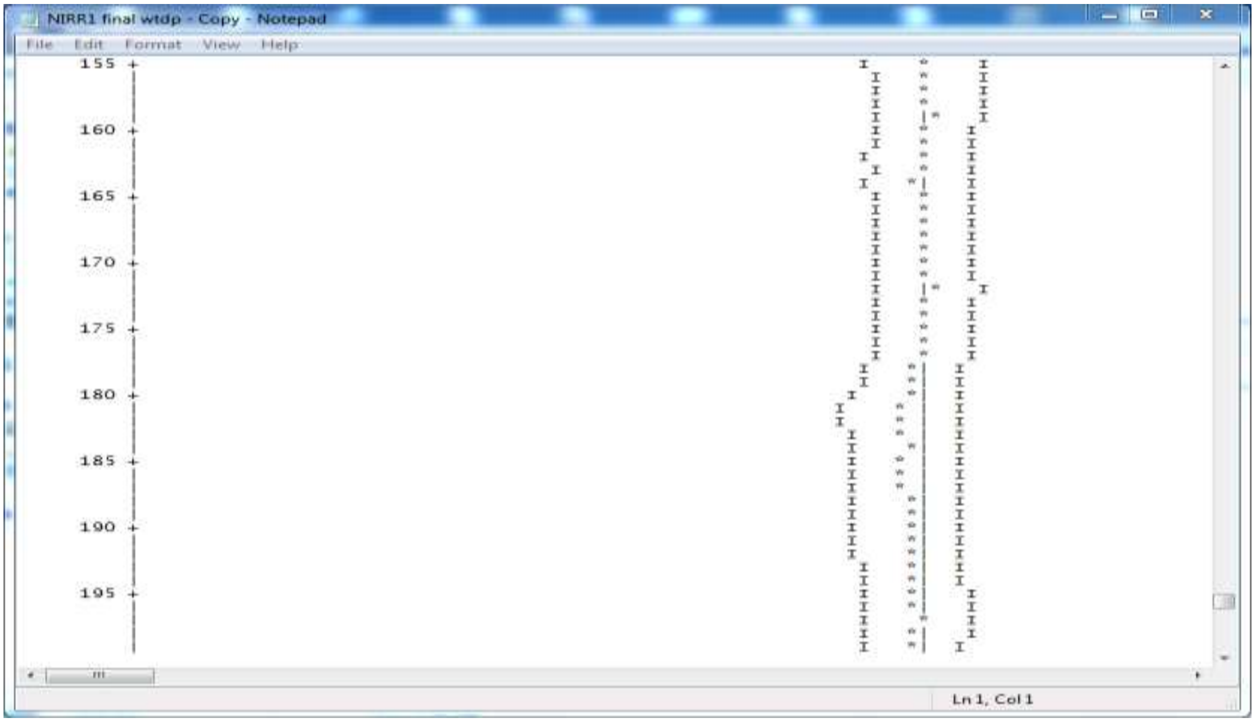
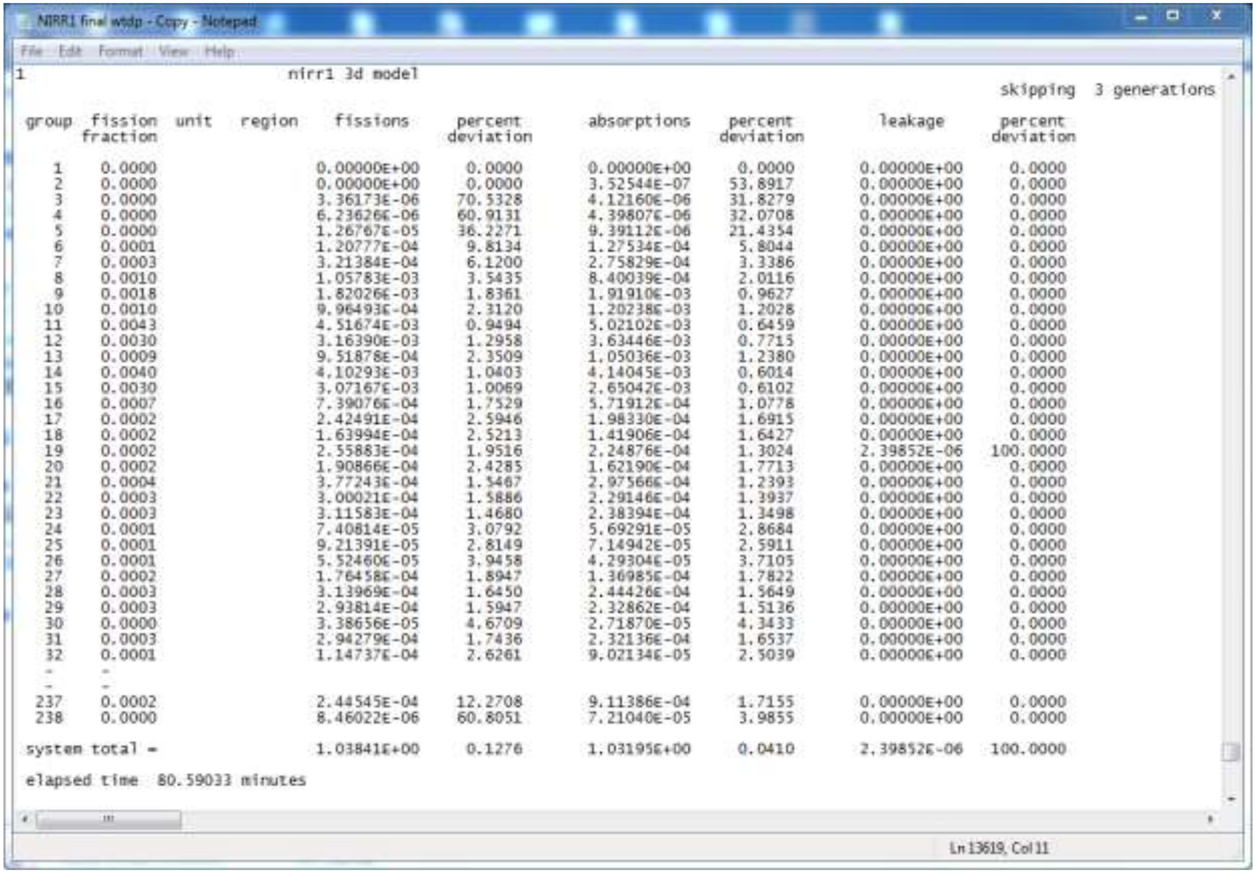
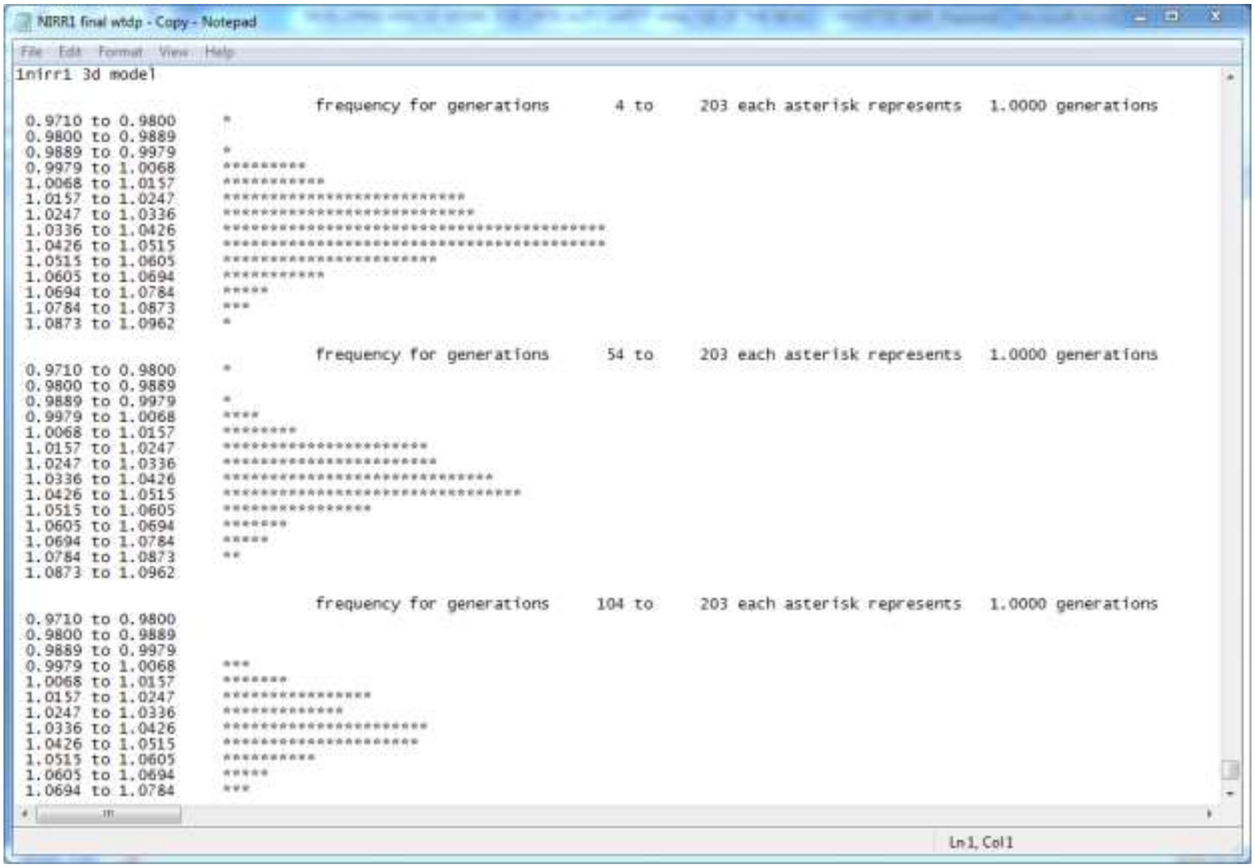


Fig. 5b: The lower section of the average k-effective by generation run

Table 3: Fission, absorption, leakage and their percentage deviation



```
1                          nirr1 3d model
                                                                                        skipping  3 generations

 group  fission  unit   region     fissions      percent       absorptions    percent        leakage      percent
        fraction                                 deviation                    deviation                   deviation

    1    0.0000                  0.00000E+00     0.0000       0.00000E+00     0.0000       0.00000E+00     0.0000
    2    0.0000                  0.00000E+00     0.0000       3.52544E-07    53.8917       0.00000E+00     0.0000
    3    0.0000                  3.36173E-06    70.5328       4.12160E-06    31.8279       0.00000E+00     0.0000
    4    0.0000                  6.23626E-06    60.9131       4.39807E-06    32.0708       0.00000E+00     0.0000
    5    0.0000                  1.26767E-05    36.2271       9.39112E-06    21.4354       0.00000E+00     0.0000
    6    0.0001                  1.20777E-04     9.8134       1.27534E-04     5.8044       0.00000E+00     0.0000
    7    0.0003                  3.21384E-04     6.1200       2.75829E-04     3.3386       0.00000E+00     0.0000
    8    0.0010                  1.05783E-03     3.5435       8.40039E-04     2.0116       0.00000E+00     0.0000
    9    0.0018                  1.82026E-03     1.8361       1.91910E-03     0.9627       0.00000E+00     0.0000
   10    0.0010                  9.96493E-04     2.3120       1.20238E-03     1.2028       0.00000E+00     0.0000
   11    0.0043                  4.51674E-03     0.9494       5.02102E-03     0.6459       0.00000E+00     0.0000
   12    0.0030                  3.16390E-03     1.2958       3.63446E-03     0.7715       0.00000E+00     0.0000
   13    0.0009                  9.51878E-04     2.3509       1.05036E-03     1.2380       0.00000E+00     0.0000
   14    0.0040                  4.10293E-03     1.0403       4.14045E-03     0.6014       0.00000E+00     0.0000
   15    0.0030                  3.07167E-03     1.0069       2.65042E-03     0.6102       0.00000E+00     0.0000
   16    0.0007                  7.39076E-04     1.7529       5.71912E-04     1.0778       0.00000E+00     0.0000
   17    0.0002                  2.42491E-04     2.5946       1.98330E-04     1.6915       0.00000E+00     0.0000
   18    0.0002                  1.63994E-04     2.5213       1.41906E-04     1.6427       0.00000E+00     0.0000
   19    0.0002                  2.55883E-04     1.9516       2.24876E-04     1.3024       2.39852E-06   100.0000
   20    0.0002                  1.90866E-04     2.4285       1.62190E-04     1.7713       0.00000E+00     0.0000
   21    0.0004                  3.77243E-04     1.5467       2.97566E-04     1.2393       0.00000E+00     0.0000
   22    0.0003                  3.00021E-04     1.5886       2.29146E-04     1.3937       0.00000E+00     0.0000
   23    0.0003                  3.11583E-04     1.4680       2.38394E-04     1.3498       0.00000E+00     0.0000
   24    0.0001                  7.40814E-05     3.0792       5.69291E-05     2.8684       0.00000E+00     0.0000
   25    0.0001                  9.21391E-05     2.8149       7.14942E-05     2.5911       0.00000E+00     0.0000
   26    0.0001                  5.52460E-05     3.9458       4.29304E-05     3.7105       0.00000E+00     0.0000
   27    0.0002                  1.76458E-04     1.8947       1.36985E-04     1.7822       0.00000E+00     0.0000
   28    0.0003                  3.13969E-04     1.6450       2.44426E-04     1.5649       0.00000E+00     0.0000
   29    0.0003                  2.93814E-04     1.5947       2.32862E-04     1.5136       0.00000E+00     0.0000
   30    0.0000                  3.38656E-05     4.6709       2.71870E-05     4.3433       0.00000E+00     0.0000
   31    0.0003                  2.94279E-04     1.7436       2.32136E-04     1.6537       0.00000E+00     0.0000
   32    0.0001                  1.14737E-04     2.6261       9.02134E-05     2.5039       0.00000E+00     0.0000
    -    -
    -    -
  237    0.0002                  2.44545E-04    12.2708       9.11386E-04     1.7155       0.00000E+00     0.0000
  238    0.0000                  8.46022E-06    60.8051       7.21040E-05     3.9855       0.00000E+00     0.0000

 system total =                  1.03841E+00     0.1276       1.03195E+00     0.0410       2.39852E-06   100.0000

 elapsed time  80.59033 minutes
```



```
1nirr1 3d model

                                   frequency for generations       4 to     203 each asterisk represents   1.0000 generations
  0.9710 to 0.9800     *
  0.9800 to 0.9889
  0.9889 to 0.9979     *
  0.9979 to 1.0068     *********
  1.0068 to 1.0157     ***********
  1.0157 to 1.0247     **************************
  1.0247 to 1.0336     ***************************
  1.0336 to 1.0426     *****************************************
  1.0426 to 1.0515     *****************************************
  1.0515 to 1.0605     ***********************
  1.0605 to 1.0694     ***********
  1.0694 to 1.0784     *****
  1.0784 to 1.0873     ***
  1.0873 to 1.0962     *

                                   frequency for generations      54 to     203 each asterisk represents   1.0000 generations
  0.9710 to 0.9800     *
  0.9800 to 0.9889
  0.9889 to 0.9979     *
  0.9979 to 1.0068     ****
  1.0068 to 1.0157     ********
  1.0157 to 1.0247     **********************
  1.0247 to 1.0336     ***********************
  1.0336 to 1.0426     *****************************
  1.0426 to 1.0515     ********************************
  1.0515 to 1.0605     ****************
  1.0605 to 1.0694     *******
  1.0694 to 1.0784     *****
  1.0784 to 1.0873     **
  1.0873 to 1.0962

                                   frequency for generations     104 to     203 each asterisk represents   1.0000 generations
  0.9710 to 0.9800
  0.9800 to 0.9889
  0.9889 to 0.9979
  0.9979 to 1.0068     ***
  1.0068 to 1.0157     *******
  1.0157 to 1.0247     ****************
  1.0247 to 1.0336     *************
  1.0336 to 1.0426     **********************
  1.0426 to 1.0515     *********************
  1.0515 to 1.0605     **********
  1.0605 to 1.0694     *****
  1.0694 to 1.0784     ***
```

Fig. 6: Frequency of the calculated k-effective by generation run

Table 3 shows the fission fraction for each group and the fission production, absorptions, and leakage with their associated percent deviation. Note that energy group 33 through 236 was removed in order to show the totals at the end of the table. From the values presented in the system total, 99.9998% of the neutrons were absorbed and 0.002% leaked from the system. Figure 6 is a frequency distributions plot that indicates the number of generations in which k-effective is within a specified interval based on the upper and lower limits values of the calculated k-effective for all generation. Even though the distributions are not perfectly symmetrical and bell shaped as expected, this statistical analysis of the calculated k-effective is still fairly good.

CONCLUSION

A very detailed three dimensional model has been developed for NIRR-1 system and this model can be used for criticality safety analysis of any Miniature Neutron Source Reactor (MNSR) with little or no modification to the geometry and material composition of the system. Several Reactor physics parameters generated for the system include k-effective values by generation run as well as the average k-effective, the neutron lifetime, the generation time, the average number of neutron per fission in the system, the average energy group at which fission occurs, and the energy of the average lethargy causing fission in the system. Some of these values indicate that the spectrum of the model system is thermal.

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