LA-UR-06-5886

Approved for public release; distribution is unlimited.

Title: Investigation of Shannon Entropy for Characterizing Convergence of MCNP5 Eigenvalue Calculations

Author(s): Jesse Cheatham & Forrest Brown

Intended for: Final report on summer work, 2006

Investigation of Shannon Entropy for Characterizing Convergence of MCNP5 Eigenvalue Calculations

Jesse Cheatham & Forrest Brown
X-3 Monte Carlo Codes

Introduction

Determining source convergence in Monte Carlo eigenvalue calculations has been a significant challenge. While giving key information about the power distribution within a system, the nature of Monte Carlo calculations adds a significant amount of uncertainty about when an accurate distribution has been achieved. Until the introduction of Shannon entropy, the only way to gain confidence about a source distribution was through long runs.

Shannon entropy, originally taken from information theory, can be used as a metric to determine the convergence of a source distribution. This entropy is calculated by $-\sum_i p_i * Log_2(p_i)$ where p_i = (source particles in mesh cell i) / (total source particles). When the entropy value converges, then the source distribution is also converged. Shannon entropy is tallied by fixing the boundaries of a grid in the x, y, and/or z direction. Then, within these fixed boundaries, a number of meshes in the x, y, and/or z direction are specified that subdivide the fixed grid into that many sections in their corresponding dimension and are the location of the entropy tallies. At the end of each cycle, the entropy contribution from each mesh within the fixed grid boundary is added together to give the value for that cycle.

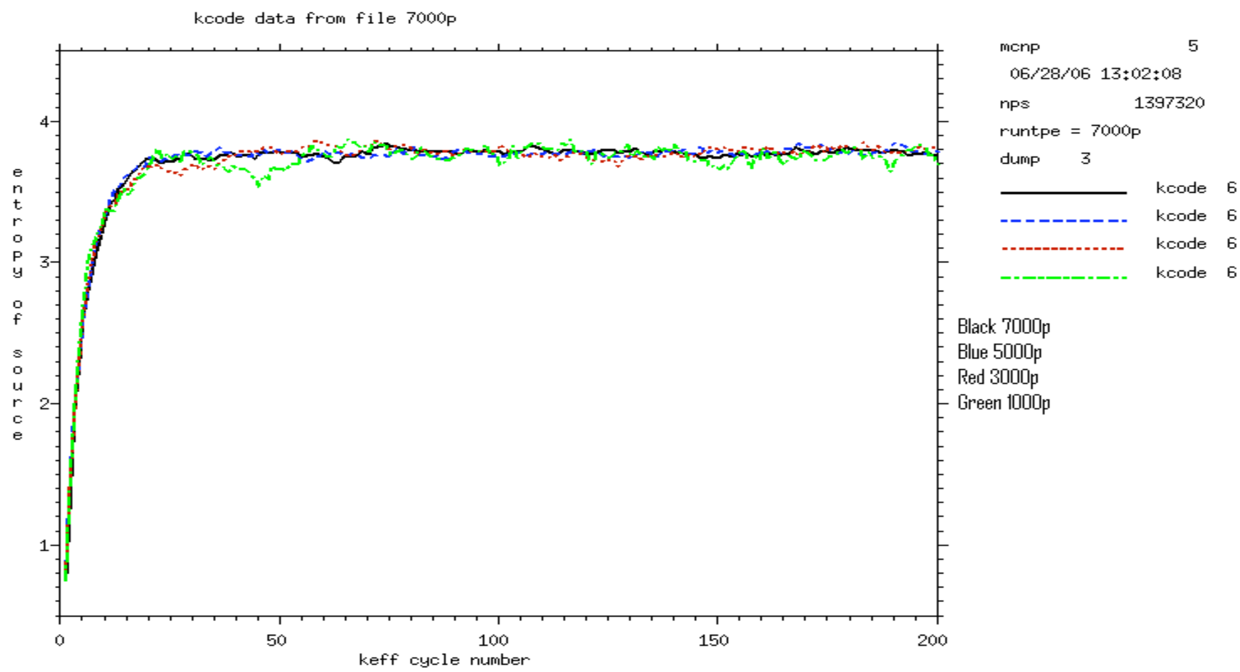
To scope aspects of this new tool, test problems bench3, test4s, triyyy and inp24 are used to determine characteristics of entropy convergence. By varying the particles per cycle (ppc) and the tallying grid meshes and size, it can be shown that too fine a mesh removes any useful information, changing ppc on a fixed mesh will still converge to the same answer, convergence takes longer in 3d than in 2d, and the default grid in MCNP5 works well for non infinite problems.

Discussion

To determine the aspects of the convergence of Shannon entropy, bench3, test4s, triyyy, and inp24 were used. (Details of these problems may be found in the appendix) First, these test problems were run with different numbers of particles per cycle (ppc) to determine confidently when the eigenvalue and Shannon entropy had converged. After this, the Shannon entropy grid was changed in size and mesh number to see the effect on convergence time.

Using inp24, it can be seen in Figure 1 that by changing the ppc of this problem on a 2d fixed grid does not change the final value of entropy that it converges too. In fact, the main difference is the noisiness in which convergence occurs.

Figure 1 – Varying ppc, inp24 in 2d



This feature of convergence shown in Figure 1 repeats itself in the other test problems as long as enough particles per cycle (ppc) are used so that under sampling does not occur. While no example of under sampling is given here, it is a problem in Monte Carlo methods where too few particles are used to describe a system, and the results give incorrect answers for that system.

After determining a ppc that will clearly show convergence, the Shannon entropy mesh number was altered. By fixing the boundary of the grid to include all fissionable regions, the number of meshes within those boundaries was increased. Figure 2 shows the change within bench3 as the number of meshes increases in the x direction increases radically with a fixed 2000 ppc in this 1d problem.

Figure 2 – Too many bins, bench3

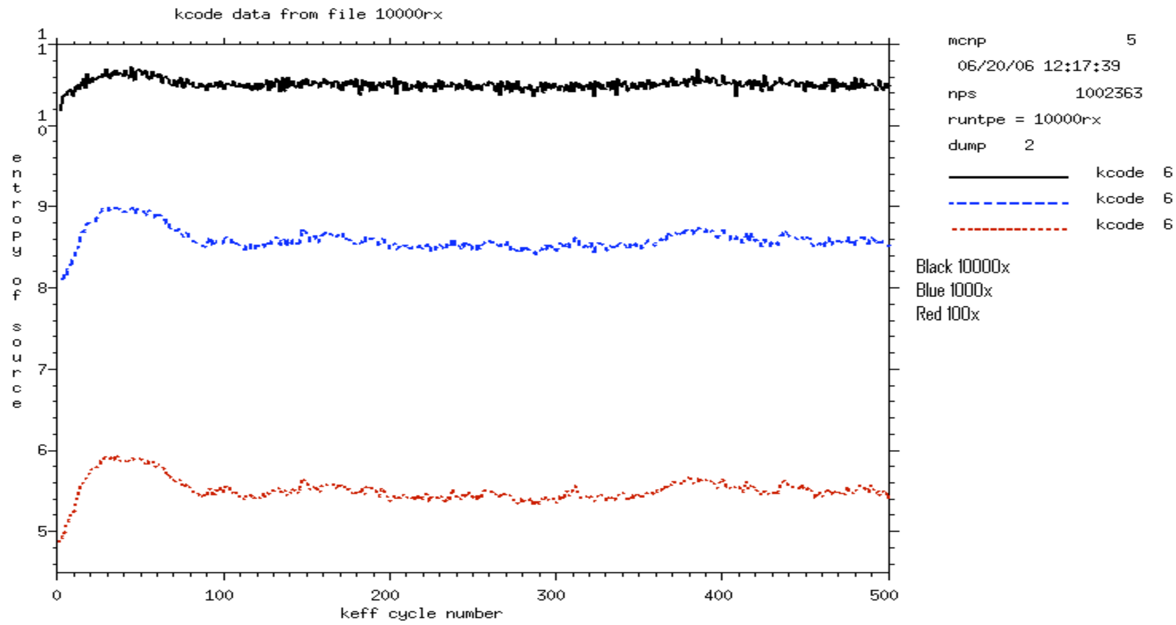
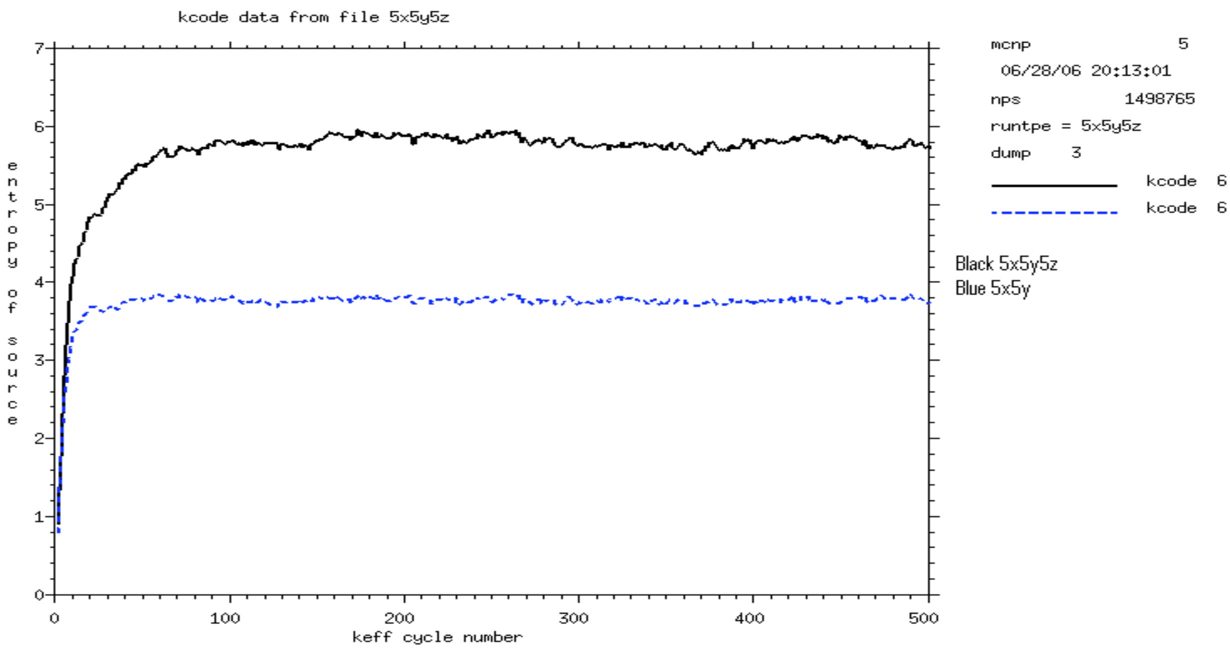


Figure 2 shows the change from 100, 1000, and 10000 meshes in the x direction. Each increase in mesh number shows a corresponding rise in entropy. This is due to the nature of the Shannon entropy calculation where more randomness in a distribution yields a higher value. It is worthy to note the similarities between the 100 and 1000 number of meshes runs. In all of the test problems run so far, slight changes in the number of meshes in one direction seem to only move the characteristics of the graphs up or down depending on the increase or decrease of meshes. This phenomenon only occurs as long as the number of meshes does not get too large as shown in the 10000 meshes case, where no information can be gleaned from this distribution as 1 particle per mesh is approached. When that extreme is reached, there will be no pertinent information that can be retrieved.

The relationship between the number of meshes and entropy convergence is an important interaction to note. While there seems to be a shift when varying the number of mesh cells in one dimension, if another dimension is added the results become significantly different. Figure 3 shows the change from the 2d grid to a 3d grid on problem inp24 with 3000 ppc.

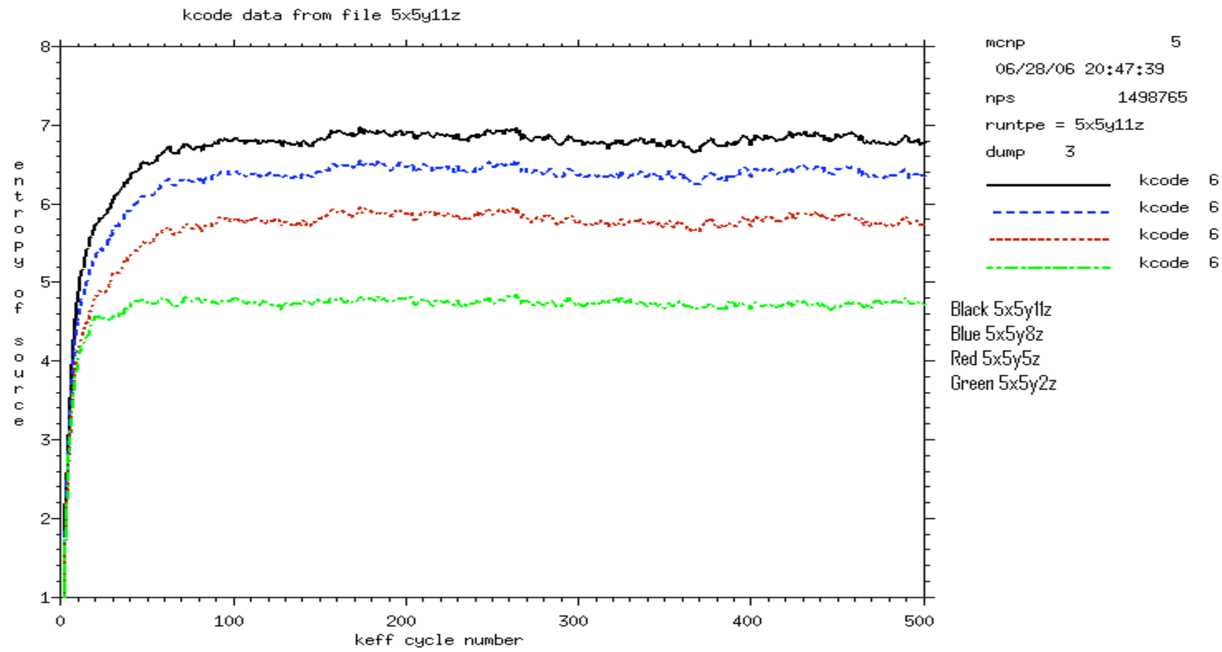
Figure 3 – 2d vs. 3d mesh, inp24



It becomes clear, when comparing the 5 meshes in the x, y and z direction (5x5y5z) and the 5 meshes in x and y and 1 in z (5x5y) that more cycles are required to converge the 3d grid. The higher dimensional grid is capturing more information and requires a longer time to finally level out to a set number. Another aspect to note is that the graphs no longer share similar characteristics as they do when varying one dimension.

Dimensional change leading to characteristic change in the entropy convergence can be seen in Figure 4. In this graph, only the z number of meshes was changed, showing the morphing from 2d to 3d, then the characteristic entropy rise with changing one dimension also with a fixed 3000 ppc.

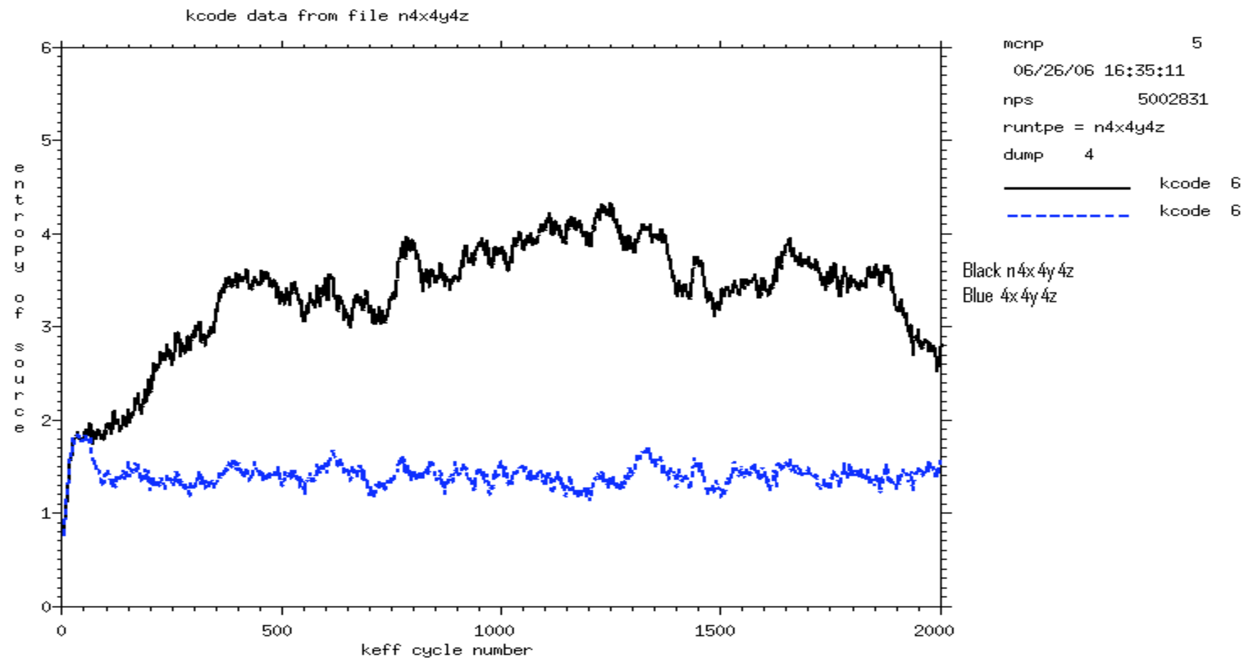
Figure 4 – Moving from 2d to 3d, inp24



There are clear similarities between Figure 3's two dimensional graph and the three dimensional graph with two meshes in the z direction. However, these characteristics morph into the 3d graph by the time that there are five z meshes, where the varying number of meshes to achieve the same characteristic phenomenon occurs.

There are some dangers in using a fixed grid though. As shown in Figure 5, the 1d grid (Blue) is morphed into a 3d grid (Black) by changing the boundaries in the y and z directions from 1e20 cm to something on the order of 100's of centimeters while keeping 2000 ppc. Particles coming into and leaving the Shannon entropy grid have a significant impact on convergence.

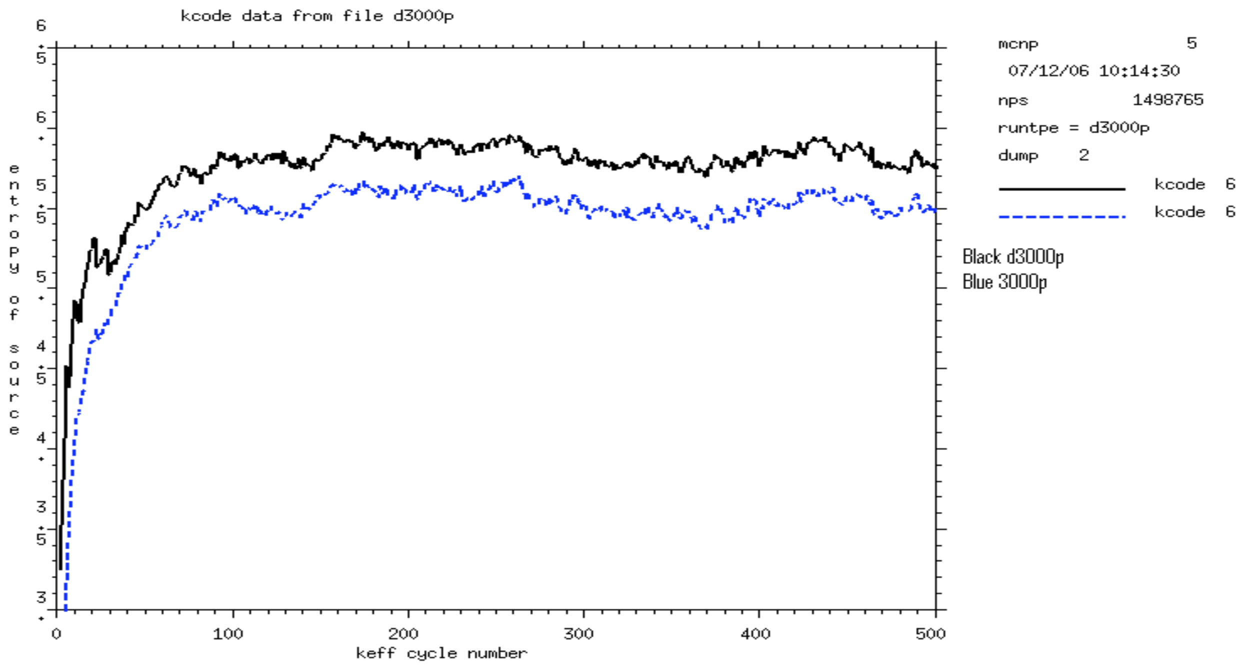
Figure 5 – Grid that doesn't cover all fissionable area, bench3



While it is clear to see convergence with the 1d grid (Blue), the 3d grid (Black) that does not cover all of the fissionable material gives no usable information about convergence. This clearly spells out the necessity to insure the boundaries of the grid cover all fissionable sites.

Instead of using a fixed grid, it is possible to use the default grid created by MCNP. The default grid changes by following the fissions sites and will remain the default size or get bigger to encompass the new information. Figure 6 shows the characteristics of the default grid and mesh created by MCNP.

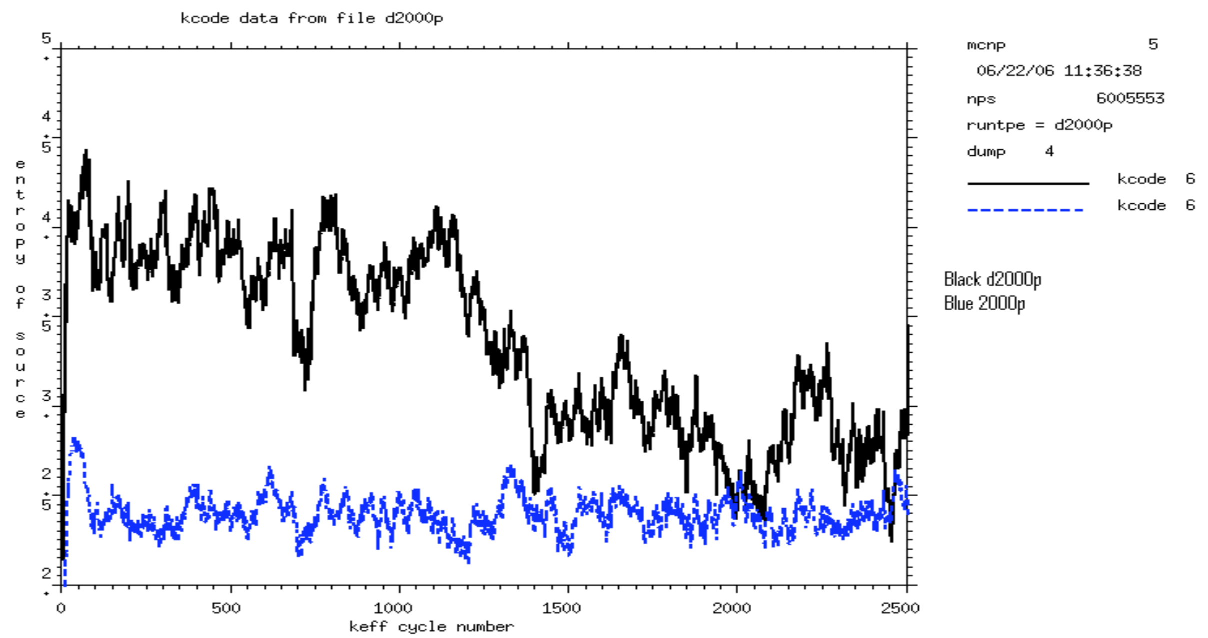
Figure 6 – Default grid vs. fixed grid, inp24 3d



It is worthy to note that in the first 80 cycles, the shape of the two graphs is different as the default grid (d3000p, Black) is reshaping and resizing itself. However, past 100 cycles, the two graphs mimic each other as a perturbation in only one dimension does. (Fixed grid (Blue) is 5x5x4, the default grid (Black) is 5x5x5 run with 3000 ppc each)

However, this default grid does not come without its own dangers. Figure 7 demonstrates what occurs when a default grid is attempted on a semi infinite problem. To try and encompass all of the fission sites, the actual grid continues to resize itself as particles drift farther away from what its original size estimate was. This continual reshaping seems to postpone any reasonable information about when the distribution has occurred. As shown in Figure 7, even after 2500 cycles at 2000 ppc, it is still not clear that the default run (in black) has converged while the run with the fixed grid (Blue) has.

Figure 7 – Default grid on a semi infinite slab, bench3



Conclusions

If a grid meshes get too fine, any information that could be yielded from this distribution will be wiped out. When the problem approaches the limit of 1 particle per bin/mesh, any valuable information about the distribution is lost since your results are the same per cycle. It is also essential that the fixed grid cover all fissionable areas as well. Otherwise particles will move in and out of the meshes giving unreliable results. While many different numbers of grid meshes will work within a fixed grid, it is best to keep the number small but reasonable.

Reasonable being for these test problems, no fewer than 4 meshes in one dimension, and most likely no more than 15. While you can use more meshes in one direction than 15, the results appear the same but at an elevated entropy value. It is best not to go below 20 particles per mesh.

The number of particles per cycle (ppc) that are run on a fixed grid and mesh number does not have an effect on the final value of the entropy that the problem converges. However, ppc does affect the noisiness in which the convergence takes place and therefore confidence in that convergence. As noted before, under sampling the problem will make this conclusion invalid.

When examining convergence in 2d and 3d problems, it is clear that the 3d problem convergence takes as many cycles, most of the time more, then the 2d convergence on that same problem. The longer time for 3d convergence is due to resolving more distribution information about the problem. There is also an implied equal or higher value of the entropy H that is converged to with the increased number of meshes being tallied against.

Use of the default grid generator in MCNP has proved to be a useful tool but has some slightly different characteristics then the afore mentioned fixed grid. Changing the ppc of the problem will actually change the number of meshes being tallied against. Therefore, there is not a guaranteed H value of convergence when the ppc is changed. The results will often be a perturbation of the entropy value higher or lower, depending on your ppc change, then your original default run ppc.

Another difference in the default runs will be that the grid boundaries are set by the first fission distribution and then expand from there. This can change the approach to convergence even with the same number of meshes in two default runs due to how the grid expands as fission points move about. Grid expansions also can lead to wrong answers if the problem is infinite in one direction. The grid will continually expand with each expansion changing the region that a mesh covers and therefore changing the answer. Infinite problems using the default grid do not appear to converge, so knowledge of the problem is essential before implementing the default grid.

One final note, while the results are not shown here, test4s and triyyy test problems were also run. They demonstrated the same characteristics as I have mentioned before. The only characteristic that test4s showed that was different was due to its special geometry characteristics. Being a grid of spheres in a 5 by 5 matrix, it was much more susceptible to changes in meshes in the x and y dimensions. The entropy value would move in drastic ways as the meshes either included all of a single sphere or contained only part of the sphere. These drastic differences in the dispersement of particles in a single mesh showed up as having different characteristics of convergence shape.

Appendix

References

X-5 Monte Carlo Team, “MCNP – A General Purpose Monte Carlo N-Particle Transport Code, Version 5,” LA-UR-03-1987, Los Alamos National Laboratory (April, 2003).

F.B. Brown, "Fundamentals of Monte Carlo Particle Transport," LA-UR-05-4983, Los Alamos National Laboratory (July 2005).

Test Problems

Bench3 – A one dimensional problem. Infinite in the y and z planes, while finite in the x. This models a chunk of fuel with water on both sides.

```
c -- OECD convergence benchmark #3, case 6
c
c   |            |             |            |
c   | 18 cm fuel | 20 cm water | 20 cm fuel |
c   |            |             |            |
c
c
  1   1  0.099486894    1 -2    imp:n=1   $ Fuel  region #1
 99   2  0.099987000    2 -3    imp:n=1   $ Water region
  2   1  0.099486894    3 -4    imp:n=1   $ Fuel  region #2
991   0                -1       imp:n=0
992   0                 4       imp:n=0

1    px    0.0
2    px   18.0
3    px   38.0
4    px   58.0

c kcode 2000 .9   35 500   50000 4j   -2.  $  -1.0
kcode 2000 1 35 1000 50000
c
c hsrc 10 0 58  1 -1e20 1e20  1 -1e20 1e20
hsrc 4 0 58 2 -5.2089e2 7.8489e02 1 -6.0044e02 9.4682e02
c
rand  gen=2 seed=123456789
sdef x=d1  y=0 z=0
si1  0 18.
sp1  0  1
c
m1    1001 5.9347e-2   7014 2.1220e-3   8016 3.7258e-2
     92235 7.6864e-5  92238 6.8303e-4
m2    1001 6.6658e-2   8016 3.3329e-2
mt1  lwtr
mt2  lwtr
```

Inp24 – A quarter core problem with reflective boundaries. This can be used to simulate a 2d and 3d problem.

```
testprob24 -- reflecting lattice.  15x15 at 3.75 w/o u-235 enrichment.
1    1 -10.182 -1 u=2
2    2 -.001 1 -2 u=2
3    3 -6.55 2 -3 u=2
4    4 -1.0 3 u=2
5    4 -1.0 -14:15 u=3
6    3 -6.55 14 -15 u=3
7    4 -1.0 -4 +5 -6 +7 u=1 lat=1 fill=-8:8 -8:8 0:0
     1 17r 2 14r 1 1 2 14r 1 1 2 2 3 2 2 3 2 2r 3 2 2
     3 2 2 1 1 2 6r 3 2 6r 1 1 2 3r 3
     2 4r 3 2 3r 1 1 2 2 3 2 8r 3 2 2
     1 1 2 14r 1 1 2 2r 3 2 2r 3 2 2r
     3 2 2r 1 1 2 14r 1 1 2 2 3 2 8r 3
     2 2 1 1 2 3r 3 2 4r 3 2 3r 1 1
     2 6r 3 2 6r 1 1 2 2 3 2 2 3
     2 2r 3 2 2 3 2 2 1 1 2 14r 1 1 2 14r 1 17r
8    0 -8     -10     -12 u=4 fill=1
9    5 -7.9 8:10 u=4
10   4 -1.0 -8     -10     +12 u=4
11   4 -1.0 -16 +9          u=5 lat=1 fill=0:6 0:0 0:0 4 3r 5 2r
12   0 +28 +29 -19 -17 +13 -18 fill=5
13   0 +28 -19 +17 -31 +13 -18 fill=5 (-11.5 23 0)
14   0 +28 -19 +31 -32 +13 -18 fill=5 (-23 46 0)
15   0 +28 -19 +32 -33 +13 -18 fill=5 (-69 69 0)
16   4 -1.0 +28 -19 +33 +13 -18
17   4 -1.0 +28 +29 -19 -24 +18
18   6 -7.9 (+28 +29 +19 -20 +23 -25):(+28 +29 -19 +23 -13)
     :(+28 +29 -19 +24 -25)
19   7 -7.088254305 (+28 +29 +20 -21 +22 -25):(+28 +29 -20 +22 -23)
20   0 -28:-29:+21:-22:+25

1    cz  .464693
2    cz  .483743
3    cz  .535940
4    px  .71501
5    px -.71501
6    py  .71501
7    py -.71501
8    px  11.0
9    px -11.0
10   py  11.0
12   pz  400.903
13   pz  34.0
14   cz  .652018
15   cz  .690118
16   px  12.0
17   py  12.0
18   pz  439.0
19   cz  82.25
20   cz  83.25
21   cz  116.35
22   pz  0.0
23   pz  33.0
24   pz  447.9
25   pz  485.9
*28  px  0.0
*29  py  0.0
31   py  35.0
32   py  58.0
33   py  81.0

imp:n 1 18r 0
nonu 1 18r 0
c   kcode 200 .7 1 3 4500 0
c   kcode 200 .7 10 50
```

```
c
kcode 3000 .7 20 500
c   kcode 500 .7 20 105  10000
c
c hsrc  5 0 82   5 0 82   5 34 440
c hsrc  100 0 82   100 0 82   1 -1e20 1e20
ksrc 1.5 1.5 217.4515
m1   92235 1.31964e20   92237 1.31964e20 92238 2.15905e22
m2    8016 1.00000000
m3   41093 1.
m4   1001 .666666667    8016 .333333333
m5   26058 -.68874500    5010. -.00178200    5011 -.00721800
m6   26058 -.69500000
m7   26058 .830266962    6012 .133437328
mt4  lwtr.01t
c    drxs
prdmp 2j -1
c   f6:n  8 12 13 14 15 $ heating in mat=0 cells kills mcnp4.2
c   sd6   1 4r
c
c    mesh  geom=rec ref= .1 .1 .1   origin= 0 0 -1000  imesh=81 iints=5
c          jmesh=81 jints=5  kmesh=2000 kints=1
c    wwg 6
c    wwge:n  1.e9
c    wwp:n  5 3 5 0 -1
c
print
fmesh4:n geom=xyz origin= 0 0 34
      imesh 82 iints 164 jmesh 82 jints 164 kmesh 440 kints 1
fm4   1. 0 -6 -8
c   mplot fmesh 4  freq 10
c
```

Test4s – A 5x5 matrix of spheres symmetrically spaced within the matrix grid.

```
OECD source convergence benchmark 4 with spheres
1 1 4.805e-2  -1  imp:n=1
2 1 4.805e-2  -2   imp:n=1
3 1 4.805e-2  -3  imp:n=1
4 1 4.805e-2  -4  imp:n=1
5 1 4.805e-2  -5  imp:n=1
6 1 4.805e-2  -6  imp:n=1
7 1 4.805e-2  -7  imp:n=1
8 1 4.805e-2  -8  imp:n=1
9 1 4.805e-2  -9  imp:n=1
10 1 4.805e-2  -10  imp:n=1
11 1 4.805e-2  -11  imp:n=1
12 1 4.805e-2  -12  imp:n=1
13 1 4.805e-2  -13  imp:n=1
14 1 4.805e-2  -14  imp:n=1
15 1 4.805e-2  -15  imp:n=1
16 1 4.805e-2  -16  imp:n=1
17 1 4.805e-2  -17  imp:n=1
18 1 4.805e-2  -18  imp:n=1
19 1 4.805e-2  -19  imp:n=1
20 1 4.805e-2  -20  imp:n=1
21 1 4.805e-2  -21  imp:n=1
22 1 4.805e-2  -22  imp:n=1
23 1 4.805e-2  -23  imp:n=1
24 1 4.805e-2  -24  imp:n=1
25 1 4.805e-2  -25  imp:n=1
c air
```

```
26 2 5.406e-5 26 -27 28 -29 30 -31 1 2 3 4 5 6 7 8 9
      10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 imp:n=1
999  0        -26:27:-28:29:-30:31  imp:n=0

1 s  80  80 0 8.71
2 s 160  80 0 8.71
3 s 240  80 0 8.71
4 s 320  80 0 8.71
5 s 400  80 0 8.71
6 s  80 160 0 8.71
7 s 160 160 0 8.71
8 s 240 160 0 8.71
9 s 320 160 0 8.71
10 s 400 160 0 8.71
11 s  80 240 0 8.71
12 s 160 240 0 8.71
13 s 240 240 0 10.0
14 s 320 240 0 8.71
15 s 400 240 0 8.71
16 s  80 320 0 8.71
17 s 160 320 0 8.71
18 s 240 320 0 8.71
19 s 320 320 0 8.71
20 s 400 320 0 8.71
21 s  80 400 0 8.71
22 s 160 400 0 8.71
23 s 240 400 0 8.71
24 s 320 400 0 8.71
25 s 400 400 0 8.71
26 px 0
27 px 480
28 py 0
29 py 480
30 pz -80
31 pz 80

c  kcode 10000 1.11  60 1060 20000
c  kcode 5000 1.11 10 160
kcode 2000 1.11 60 3000
c hsrc 5 70 470 5 70 470 1 -80 80
c hsrc 4 5.0332 4.7358e2 4 5.1877 4.7472e2 4 -1.1712e1 1.1694e1
ksrc 80 80 0
     80 80 0   80 80 0   80 80 0   80 80 0   80 80 0
     80 160 0  80 240 0  80 320 0  80 400 0
      160 80 0  160 160 0 160 240 0 160 320 0 80 400 0
      240 80 0  240 160 0 240 240 0 240 320 0 240 400 0
      320 80 0  320 160 0 320 240 0 320 320 0 320 400 0
      400 80 0  400 160 0 400 240 0 400 320 0 400 400 0
m1 92235 4.549e-2 92238 2.560E-3  $ enriched uranium metal
m2 7014 4.3250e-5   8016 1.0810e-5  $ air
c
c   use new mcnp rn generator
rand gen=3 seed=123456789 stride=12345 hist=1
c
mode n
prdmp 2j -1
c f4:n 1
c
c MESH GEOM=rec REF=1.e-6 1.e-6 1.e-6 ORIGIN=0 0 -80
c       IMESH    70 71 89 90 150 151 169 170 230 231 249 250
c                310 311 329 330 390 391 409 410 480
c     IINTS    1 1 5 1 1 1 5 1 1 1 5 1 1 1 5 1 1 1 5 1 1
c     JMESH    70 71 89 90 150 151 169 170 230 231 249 250
c              310 311 329 330 390 391 409 410 480
c     JINTS    1 1 5 1 1 1 5 1 1 1 5 1 1 1 5 1 1 1 5 1 1
```

```
c     KMESH    -10 -9 9 10 80
c     KINTS    1 1 5 1 1
c wwg
c  print
c  fmesh4:n geom=xyz  origin= 0 0 -100
c         imesh 480 iints 480 jmesh 480 jints 480 kmesh 100 kints 1
c   fm4    1. 0  -6 -8
c   mplot  fmesh 4   freq 5
```

Triyyy – A full core simulation

```
Watts Bar Unit #1, (1177 MWe), PWR, fuel at 900 K, everything else 600 K
C    Cell Card
C    u(2.1)o2 fuel bundle
1    1 -10.76      -1         u=1 imp:n=1 tmp=7.7556e-8 $ u(2.1)o2 fuel pellets
2    4 -0.01198    1 -4       u=1 imp:n=1 tmp=5.1704e-8 $ helium gas
3    5 -6.507      4 -5       u=1 imp:n=1 tmp=5.1704e-8 $ Zr-4 cladding
4    6 -0.647      5          u=1 imp:n=1 tmp=5.1704e-8 $ Water
5    0             -6   lat=1 u=21 fill= -8:8 -8:8 0:0
     1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
     1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
     1 1 1 1 1 2 1 1 2 1 1 2 1 1 1 1 1
     1 1 1 2 1 1 1 1 1 1 1 1 1 2 1 1 1
     1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
     1 1 2 1 1 2 1 1 2 1 1 2 1 1 2 1 1
     1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
     1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
     1 1 2 1 1 2 1 1 2 1 1 2 1 1 2 1 1
     1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
     1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
     1 1 2 1 1 2 1 1 2 1 1 2 1 1 2 1 1
     1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
     1 1 1 2 1 1 1 1 1 1 1 1 1 2 1 1 1
     1 1 1 1 1 2 1 1 2 1 1 2 1 1 1 1 1
     1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
     1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
     imp:n=1 $ lattice cell
6    0             -7              fill=21 u=22 imp:n=1
c   7    0             #6                   imp:n=0 $void
8    6 -0.647       -2        u=2 imp:n=1 tmp=5.1704e-8 $ water holio
10   5 -6.507      2 -3       u=2 imp:n=1 tmp=5.1704e-8 $ Zr-4 Cladding
11   6 -0.647      3          u=2 imp:n=1 tmp=5.1704e-8 $ Water
12   6 -0.647      7         u=22 imp:n=1 tmp=5.1704e-8
C    13   1 -10.76      -12        u=1 imp:n=1 $ Single Fuel Pellet
C
C
C    u(2.6)o2 fuel bundle
21   like 1 but mat=2         u=3 imp:n=1 tmp=7.7556e-8 $ u(2.6)o2 fuel pellets
22   like 2 but               u=3 imp:n=1 tmp=5.1704e-8 $ helium gas
23   like 3 but               u=3 imp:n=1 tmp=5.1704e-8 $ Zr-4 cladding
24   like 4 but               u=3 imp:n=1 tmp=5.1704e-8 $ water
29   0             -6   lat=1 u=25 fill= -8:8 -8:8 0:0
     3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
     3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
     3 3 3 3 3 2 3 3 2 3 3 2 3 3 3 3 3
     3 3 3 2 3 3 3 3 3 3 3 3 3 2 3 3 3
     3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
     3 3 2 3 3 2 3 3 2 3 3 2 3 3 2 3 3
     3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
     3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
     3 3 2 3 3 2 3 3 2 3 3 2 3 3 2 3 3
     3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
     3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
```

```
     3 3 2 3 3 2 3 3 2 3 3 2 3 3 2 3 3
     3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
     3 3 3 2 3 3 3 3 3 3 3 3 3 2 3 3 3
     3 3 3 3 3 2 3 3 2 3 3 2 3 3 3 3 3
     3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
     3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
     imp:n=1 $ lattice cell
30    0             -7    fill=25 u=26 imp:n=1
C   31    0              #57 #61 #50 #30 #6    imp:n=0 $void
32   6 -0.647        7        u=26 imp:n=1 tmp=5.1704e-8
C   33   like 13 but mat=2        u=3 imp:n=1  tmp=7.7556e-8 $ U(2.6)o2 single
f
C
C
C
C
C
C    u(3.1)o2 fuel bundle
41   like 1 but mat=3         u=5 imp:n=1 tmp=7.7556e-8 $ u(3.1)o2 fuel pellets
42   like 2 but               u=5 imp:n=1 tmp=5.1704e-8 $ helium gas
43   like 3 but               u=5 imp:n=1 tmp=5.1704e-8 $ Zr-4 cladding
44   like 4 but               u=5 imp:n=1 tmp=5.1704e-8 $ water
49   0             -6   lat=1 u=30 fill= -8:8 -8:8 0:0
     5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
     5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
     5 5 5 5 5 2 5 5 2 5 5 2 5 5 5 5 5
     5 5 5 2 5 5 5 5 5 5 5 5 5 2 5 5 5
     5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
     5 5 2 5 5 2 5 5 2 5 5 2 5 5 2 5 5
     5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
     5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
     5 5 2 5 5 2 5 5 2 5 5 2 5 5 2 5 5
     5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
     5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
     5 5 2 5 5 2 5 5 2 5 5 2 5 5 2 5 5
     5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
     5 5 5 2 5 5 5 5 5 5 5 5 5 2 5 5 5
     5 5 5 5 5 2 5 5 2 5 5 2 5 5 5 5 5
     5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
     5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
     imp:n=1 $ lattice cell
50    0             -7 fill=30 u=31 imp:n=1  tmp=5.1704e-8
C     51    0              #57 #61 #50 #30 #6    imp:n=0 $void
52   6 -0.647        7         u=31 imp:n=1  tmp=5.1704e-8
C    53   like 13 but mat=3    u=5  imp:n=1  tmp=7.7556e-8 $ individual
u(3.1)o2
C
C
C    Water Lattice
54   6 -0.647        -7 u=18             imp:n=1 tmp=5.1704e-8 $ water block
55   6 -0.647         7 u=18             imp:n=1 tmp=5.1704e-8 $ outer void?
C
C
C
C    u(2.6)o2 fuel bundle
C    61   like 1 but mat=2         u=6 imp:n=1 tmp=7.7556e-8 $ u(2.6)o2 fuel
pel
C    62   like 2 but               u=6 imp:n=1 tmp=5.1704e-8 $ helium gas
C    63   like 3 but               u=6 imp:n=1 tmp=5.1704e-8 $ Zr-4 cladding
C    64   like 4 but               u=6 imp:n=1 tmp=5.1704e-8 $ water
C    69   0             -6   lat=1 u=69 fill= -8:8 -8:8 0:0
C         6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
C     6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
C     6 6 6 6 6 7 6 6 7 6 6 7 6 6 6 6 6
C     6 6 6 7 6 6 6 6 6 6 6 6 6 7 6 6 6
```

```
c     6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
c     6 6 7 6 6 7 6 6 7 6 6 7 6 6 7 6 6
c     6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
c     6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
c     6 6 7 6 6 7 6 6 7 6 6 7 6 6 7 6 6
c     6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
c     6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
c     6 6 7 6 6 7 6 6 7 6 6 7 6 6 7 6 6
c     6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
c     6 6 6 7 6 6 6 6 6 6 6 6 6 7 6 6 6
c     6 6 6 6 6 7 6 6 7 6 6 7 6 6 6 6 6
c     6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
c     6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
c     imp:n=1 $ lattice cell
c    70    0             -7    fill=69 u=70 imp:n=1
c    C   31    0             #57 #61 #50 #30 #6    imp:n=0 $void
c    72   6 -0.647      7        u=70 imp:n=1  tmp=5.1704e-8
c    73   7 -2.5       -2          u=7 imp:n=1 tmp=5.1704e-8 $ boron insertion
c    74   5 -6.507      2 -3       u=7 imp:n=1 tmp=5.1704e-8 $ Zr-4 Cladding
c    75   6 -0.647      3          u=7 imp:n=1 tmp=5.1704e-8 $ Water
C
C
C    Lattice of lattices
C
80   0             -8 lat=1 u=80 fill= -7:7 -7:7 0:0
     18 18 18 18 31 31 31 31 31 31 31 18 18 18 18
     18 18 31 31 31 22 31 22 31 22 31 31 31 18 18
     18 31 31 26 22 26 22 26 22 26 22 26 31 31 18
     18 31 26 26 26 22 26 22 26 22 26 26 26 31 18
     31 31 22 26 22 26 22 26 22 26 22 26 22 31 31
     31 22 26 22 26 22 26 22 26 22 26 22 26 22 31
     31 31 22 26 22 26 22 26 22 26 22 26 22 31 31
     31 22 26 22 26 22 26 22 26 22 26 22 26 22 31
     31 31 22 26 22 26 22 26 22 26 22 26 22 31 31
     31 22 26 22 26 22 26 22 26 22 26 22 26 22 31
     31 31 22 26 22 26 22 26 22 26 22 26 22 31 31
     18 31 26 26 26 22 26 22 26 22 26 26 26 31 18
     18 31 31 26 22 26 22 26 22 26 22 26 31 31 18
     18 18 31 31 31 22 31 22 31 22 31 31 31 18 18
     18 18 18 18 31 31 31 31 31 31 31 18 18 18 18
     imp:n=1
81   0             -9 #83 fill=80 imp:n=1
82   6 -0.647    9 -10            imp:n=1  tmp=5.1704e-8
83   8 -7.92     10 -11           imp:n=1  tmp=5.1704e-8
84   0           11               imp:n=0

C    Surface Cards
1    rcc 0 0 -194.492 0 0 365     0.41   $ Fuel Pellet
2    rcc 0 0 -194.55  0 0 389.1   0.570  $ inner water hole
3    rcc 0 0 -194.55  0 0 389.1   0.610  $ outer water hole
4    rcc 0 0 -194.493 0 0 388.986 0.418  $ inner clad radius
5    rcc 0 0 -194.55  0 0 389.1   0.475  $ outer clad radius
6    RPP -.63 .63 -.63 .63 -194.55 194.55 $ pin pitch
7    RPP -10.71 10.71 -10.71 10.71 -194.55 194.55
8    RPP -10.75 10.75 -10.75 10.75 -194.55 194.55
9    RPP -161.25 161.25 -161.25 161.25 -194.55 194.55
10   rcc 0 0 -670    0 0 1340    220
11   rcc 0 0 -691.51 0 0 1383.02 241.51
12   rcc 0 0 -0.675  0 0 1.35    0.409    $ Single Fuel Pellet

C    Data Card
kcode 15000 1 50 300
c   kcode 1000 1 50 150
hsrc  15  -161.25 161.25  15 -161.25 161.25  1000 -196 196
sdef  x=d1 y=d2 z=d3
```

```
si1   -161 161
sp1   0  1
si2   -161 161
sp2   0  1
si3   -194 170
sp3   0  1
c
C    Cell Cards
m1   92235 0.00708764531189471 92238 0.326245688021439
     8016  0.666666666666667                   $ 2.1 w/o uo2
m2   92235 0.00877461880227359 92238 0.32455871453106
     8016  0.666666666666667                    $ 2.6 w/o uo2
m3   92235 0.0104613765675533  92238 0.32287195676578
     8016  0.666666666666667                    $ 3.1 w/o uo2
m4   2003  0.00000137          2004  0.99999863  $ He
m5   40000 0.640063438268831   50000 0.00651143472063538
     26054 0.0137029759428733  26056 0.214914195343355
     26057 0.00496586478613528 26058 0.000655868934017868
     24050 0.00497438196657179 24052 0.095816888500931
     24053 0.0108635928005591  24054 0.00269874515887573
     8016  0.00483261357721442                  $ Zr-4
m6   1001  2                   8016  1      $ H2O
mt6  lwtr
m7   5010 0.1592 5011 0.6408 6000 0.2   $ B4C
m8   26054 0.0380690450797349  26056 0.597065792489859
     26057 0.013795961635733   26058 0.00182210814056851
     24050 0.0078908996489140 6 24052 0.151995053237358
     24053 0.0172329992332606  24054 0.00428103980952579
     28058 0.0772272619352035  28060 0.0297429319615311
     28061 0.00129317095484918 28062 0.00411772856675659
     28064 0.00105495525264012 42000 0.0144577065941068
     25055 0.020198349171644   14028 0.018220033076712
     14029 0.000922558326664265 14030 0.000612404884937735
C                                                   $ SS316
C
c   Mesh tally for power   (flux*fission*Q)
fmesh104:n  geom=xyz  origin= -161.25 -161.25 -194.492
         imesh=161.25 iints=15  jmesh=161.25 jints=15 kmesh=170.508 kints=1
        out=cf
fm104  -1.0  0  -6 -8
c
c  Mesh tally for fast & thermal flux
fmesh204:n  geom=xyz  origin= -161.25 -161.25 -194.492
         imesh=161.25 iints=150 jmesh=161.25 jints=150 kmesh=170.508 kints=1
         emesh  .625e-6  20.
c
c  fmesh304:n  geom=xyz  origin= -161.25 -161.25 -194.492
c              imesh=161.25 iints=1  jmesh=161.25 jints=1 kmesh=170.508 kints=1
c             out=cf
c  fm304  -1.0  0  -6 -8
c
c  total fission energy
c
c   F7:N (1<5<6<80<81) (21<29<30<80<81) (41<49<50<80<81) T
c   sd7    1 1  1 1
c   c
c   F17:N 1 21 41  T
c   sd17    1 1  1 1
c   c
c   c
c   F14:N (1<5<6<80<81)
c   fm14  -1.0 1 -6 -8
c   sd14    1
c   c
c   F24:N  (21<29<30<80<81)
```

```
c   fm24  -1.0 2 -6 -8
c   sd24    1
c   c
c   F34:N  (41<49<50<80<81)
c   fm34  -1.0 3 -6 -8
c   sd34    1
c   c
c   F104:N (1<5<6<80[-7:7 -7:7 0:0]<81) T
c   fm104  -1.0 1 -6 -8
c   sd104   1  225r
c   c
c   F204:N (21<29<30<80[-7:7 -7:7 0:0]<81) T
c   fm204  -1.0 2 -6 -8
c   sd204   1  225r
c   c
c   prdmp j j j 2
c   print 98

C
6789112345678921234567893123456789412345678951234567896123456789712345678 98
```