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Advances in Monte Carlo Criticality Methods

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NUCLEAR ENGINEERING

Advances in MC Criticality Methods

- History & Concerns

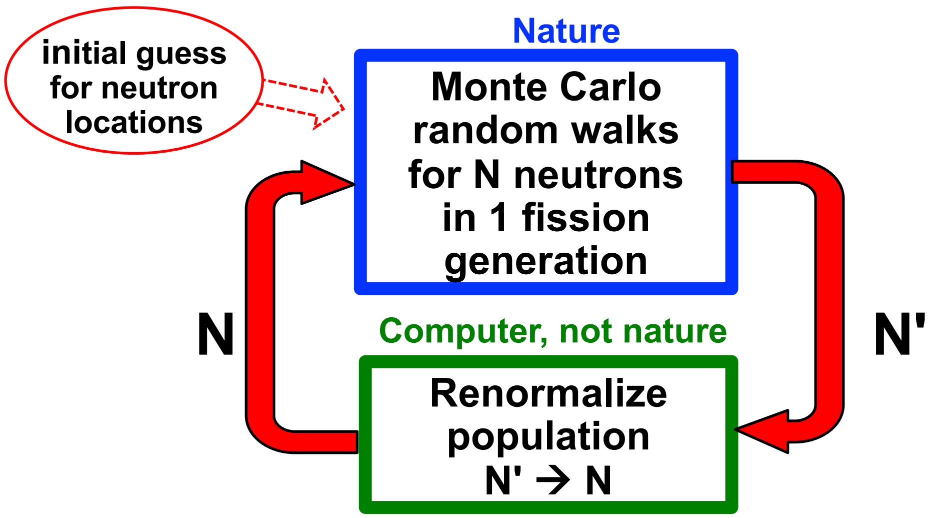
- Meshing
- Fission-Matrix
- Acceleration
- Convergence Testing
- Population Size Testing
- Automation

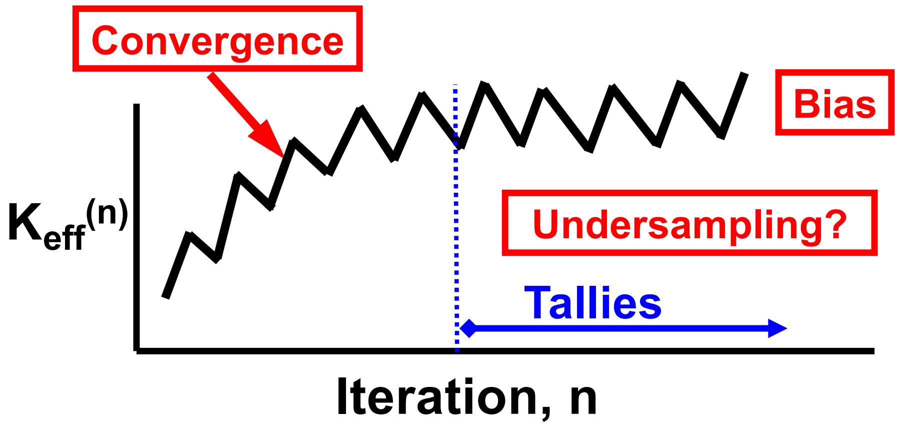
- Examples

- Conclusions

History
&
Concerns

MC Criticality Calculations - Concerns

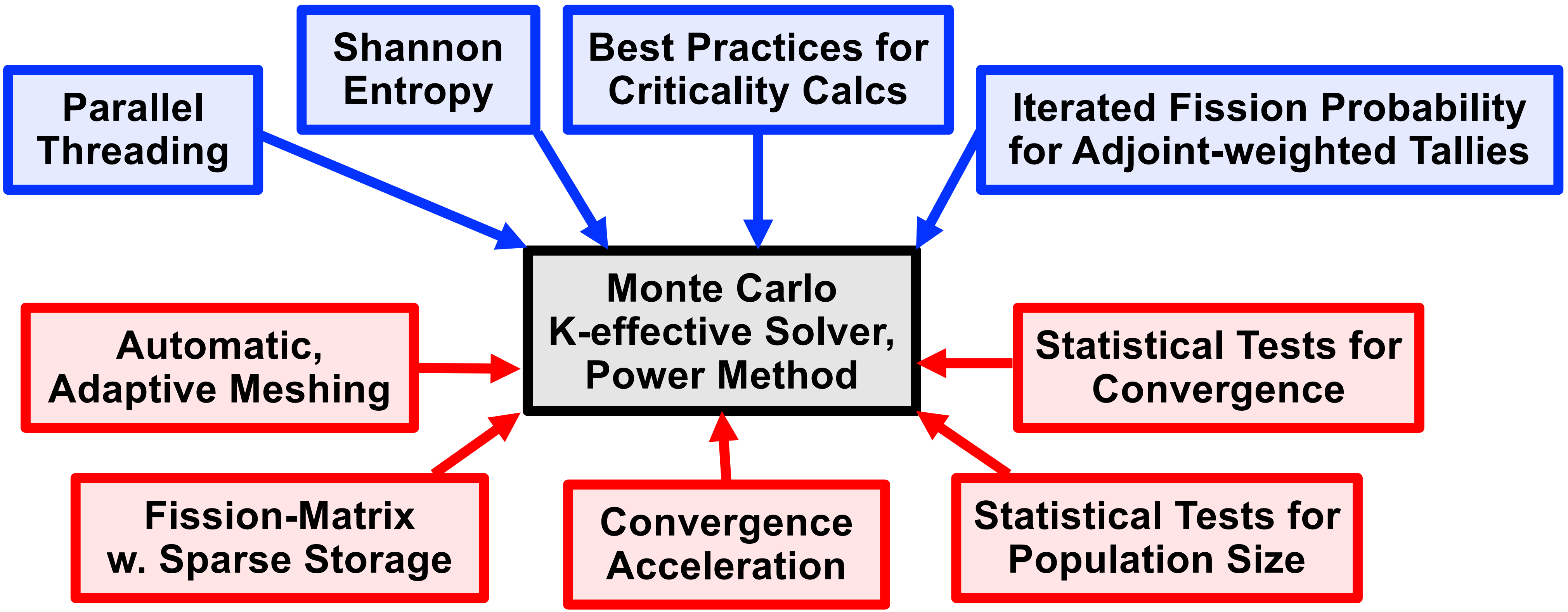




- **Bias in Keff**
  Nonconservative, ∝ -1 / (neutrons/cycle)
- **Bias in source shape**
  Too low in high-importance regions,
  Too high in low-importance regions
- **Undersampling/clustering**
  Not enough neutrons/cycle to cover space
- **Convergence**
  Source shape takes longer than keff
- **Underestimate statistics**
  Typically by 3-5x for local tallies

- **Best Practices**
  Source in all fissile regions.
  Examine H_{src} plot for convergence.
  >10k neuts/cycle (>100k big probs).
  A few 100 active cycles, or more

MC Criticality Calculations – History



1950s ➜ early MC codes:	**original methods,**	**black box**
2000s ➜ mcnp5, 6.1, 6.2:	**improvements,**	**blue boxes**
2010s ➜ mcnp6.3:	**advanced methods,**	**red boxes**

Automated Acceleration & Convergence Testing for MC Criticality

Enabling technology, automate & combine new methods

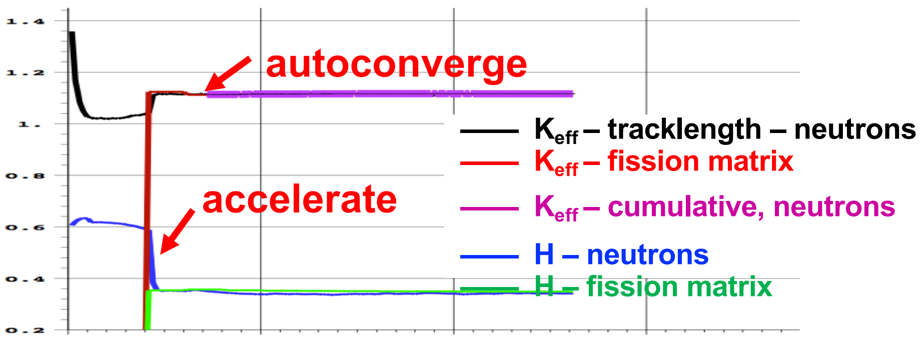
- **Automated, adaptive meshing**
  - Physics-based mesh used for Shannon entropy & fission-matrix
- **Fission-matrix with adaptive sparse storage**
  - Reference solution for global fission distribution
- **Accelerate convergence of neutron distribution**
  - Importance sampling of cycle sources, based on fission-matrix eigenfunction
- **Statistical tests for convergence**
  - 8 tests on metrics, 3 tests on distributions
  - Automatically begin active cycles & tallies
- **Population size tests**

Eliminate user burdens:

Before: Trial run, eye-ball entropy plots, judgement, fix input, re-run

Now: Fully automated,
faster convergence,
11 convergence checks
2 population size checks

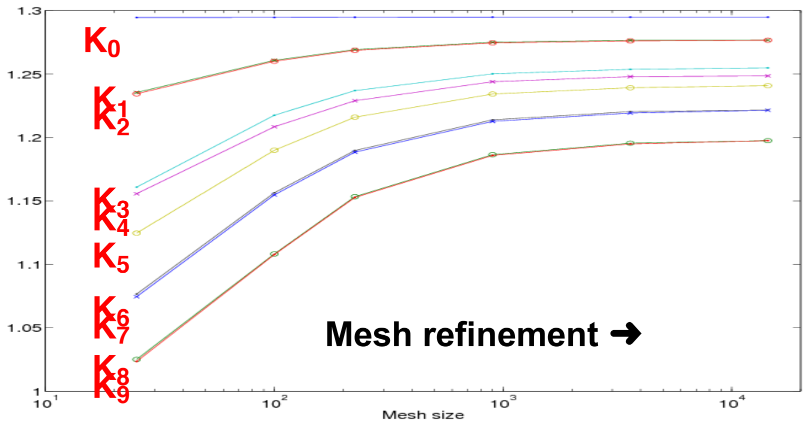
- **Quantitative evidence of convergence**
- **Enables parameter studies & coupled multiphysics**
- **Saves significant computer time & people time**
- **Easy to use – no user input needed**



Meshing,
Fission-Matrix,
Acceleration,
Convergence Testing,
Population Size Testing,
Automation

Meshing (1)

- **Since early-2000s, a mesh has been used for calculating Shannon entropy**
  – HSRC card or automatic meshing
  – Auto-mesh was crude, ad hoc (but works)
- **Today, mesh is used for:**
  – Shannon entropy
  – Fission-matrix
  – Convergence acceleration & testing
  – Population size tests
- **From MCD 2013, Sun Valley:**
  – Detailed solutions for higher eigenmodes
  – Mesh was refined until higher-mode eigenvalue spectrum converged



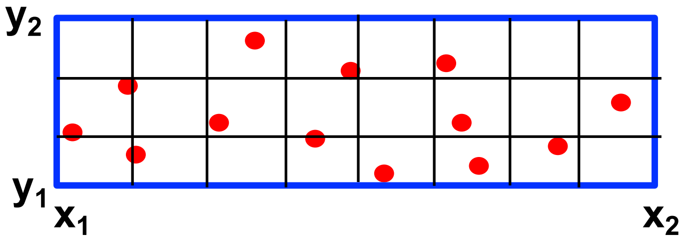
- **Today, for acceleration & convergence testing of global eigenfunction:**
  – Only need global solution for fundamental mode
  – Physics-based metric to automatically choose mesh resolution:

L_{Fiss} = RMS distance from birth to next-generation fission

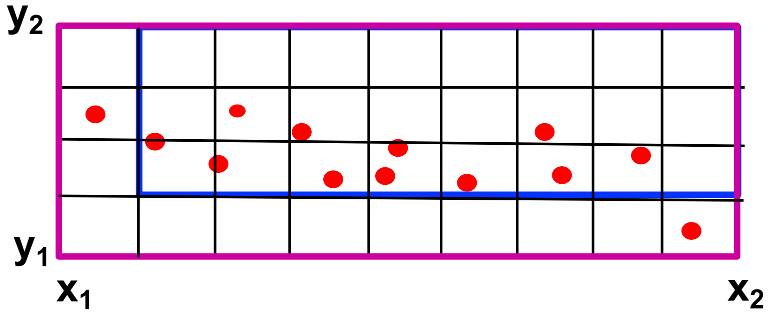
- **Mesh resolution**
  – For previous detailed analysis of higher-mode eigenfunctions,
  $\Delta\{x,y,z\} \sim .1 \cdot L_{Fiss}$ works best
  – For global convergence of fundamental eigenfunction,
  $\Delta\{x,y,z\} \sim L_{Fiss}$ works best

Meshing (2)

- **Cycle 1 – set initial mesh**
  - Compute L_{Fiss}
  - Bounding-box
  - Set n_X, n_Y, n_Z for mesh spacing of $\sim L_{fiss}$

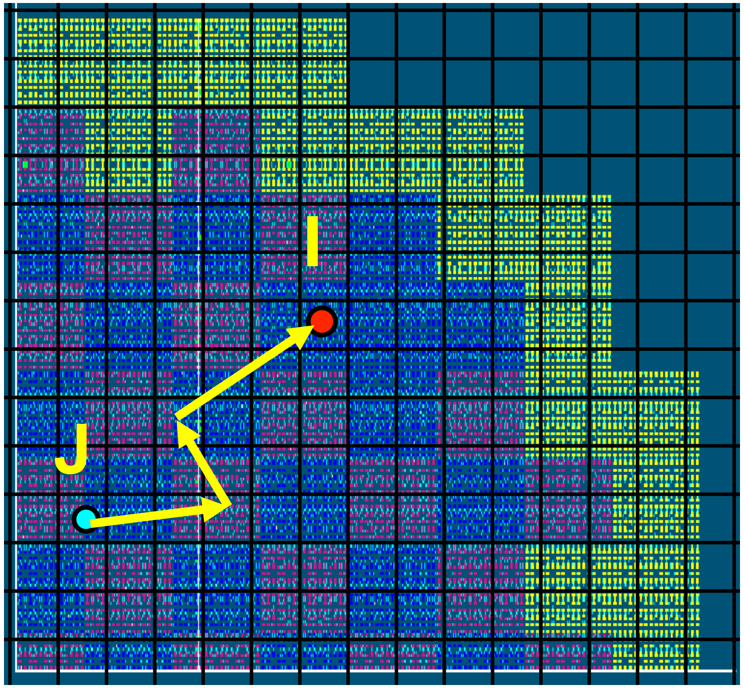


- **Later cycles**
  - Extend mesh if needed
  - Never shrink the mesh
  - Add same-size cells
  - Reallocate/reindex tallies for entropy, source, & fission-matrix



- **Initial mesh & later extensions are automated – no user input needed**
- **Mesh is used for tallying S_{neut}, H, F_{IJ}, & storing S_{FM}**
- **Meshing does not affect MC simulation or tallies**

Fission-Matrix



- Mesh
  - Does not have to be aligned with material or geometric boundaries
  - OK for underlying geometry to be hexagonal, spherical, cylindrical, ...
  - Must cover all fissionable regions
- Example

  100 x 100 x 100 mesh = 10^6 regions

  F is 10^6 x 10^6, 8 TB for full matrix

  10^{12} tallies for Green's function

  Adaptive, sparse-storage is necessary

- From neutron simulation in a cycle, tally $F(I \leftarrow J)$
  - Probability that neutron born in region J produces next-generation neutron in region I
  - Accumulate over all cycles (even inactive)
  - Estimate of point-to-point Green's functions
- For $n_x \cdot n_y \cdot n_z$ mesh
  - $N = n_x \cdot n_y \cdot n_z$ mesh cells
  - F-matrix is N • N, large & nonsymmetric
  - Adaptive sparse-storage is used for F-matrix
- Fission-matrix equation for fission neutron source:

$$S = 1/k \; F \bullet S$$

Given F, can solve for k & S.

Provides reference solution for acceleration & convergence testing

Accelerating Source Convergence

- **At the end of each cycle**
  - **S_{FM} is available – fission-matrix eigenfunction at end-of-block**
  - **S_{neuts} is available – actual neutron source at end-of-cycle**

- **During inactive cycles, can optionally use (S_{FM} / S_{neuts}) for importance sampling of the fission source, for each mesh region**
  - **Pushes neutron distribution toward F-matrix reference**
  - **Recomputed each cycle using S_{FM} from previous end-of-block, and S_{neuts} for current end-of-cycle**
  - **Works – typically reduces inactive cycles by 2-20 X**
  - **Further development under consideration:**
    - Investigate using $S_{FM}^{adjoint}$ for source importance sampling
    - Maybe coarsen the fission-matrix, to reduce statistical noise

Statistical tests for convergence

- **Slope test**
  - For a block of cycles (default = 10)

  - For result x from each cycle in block, compute least-squares slope & σ_{slope}

| slope(x) | < 0.0001 → pass, slope ~ 0

| slope(x) | < $t_{0.025}\,\sigma_{slope}$ → pass, slope ~ 0 within statistics

- **Metric tests, at end-of-block for convergence testing**

1. Slope $K_{tracklen}$
2. Slope $K_{collide}$
3. Slope K_{absorb}
4. Slope H, Shannon entropy
5. Slope H_X, entropy X marginal
6. Slope H_Y, entropy Y marginal
7. Slope H_Z, entropy Z marginal
8. H_{block} within 1% of H_{FM}

If Test 8 passes, strong evidence of convergence
If Test 8 fails, ignore it – might be low popsize

- **Distribution tests, at end-of-block for convergence testing**

9. Kolmogorov-Smirnov test at 95% level, S_{block} & S_{FM} have same distrib.

   For multi-D distributions, KS statistic depends on ordering. Take worst case KS statistic for many random permutations.

10. Chi-square 2-point test at 95% level, S_{block} & S_{FM} have same distrib.

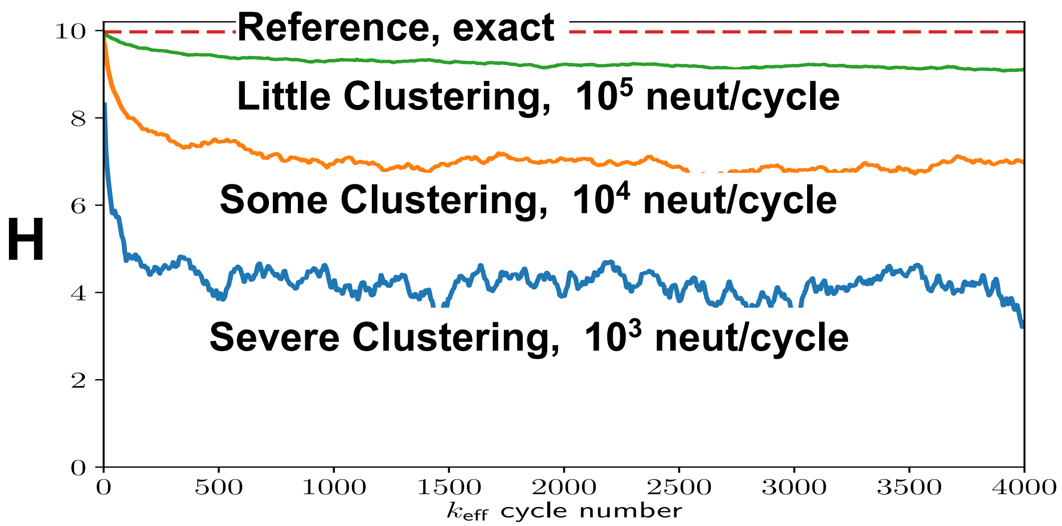
11. Relative entropy (Kullback-Liebler discrepancy) test at 95% level for S_{block} & S_{FM}

    If Test 11 passes, strong evidence of convergence
    If Test 11 fails, ignore it – might be low popsize

- **If convergence tests all pass, convergence is locked-in**
  - Tests continue for each block
  - Some tests may later fail (due to statistics), but convergence not rescinded
  - Start the tallies

Statistical tests for Population Size

- **From LA-UR-18-27656, Source renormalization leads to:**
  - **Bias in source shape**
    Too low in high-importance regions,
    Too high in low-importance regions
  - **Undersampling/clustering**
    Not enough neutrons/cycle to cover space



- **At the end of a block of cycles**
  - **S_{FM} is available – source from fission-matrix fundamental at end-of-block**
  - **S_{block} is available – neutron source accumulated in mesh during block**
  - **S_{FM} can be considered a reference solution**

- **If population size is large enough such that source renormalization bias is negligible,**

$S_{block} \sim S_{FM}$, **compare distributions using relative entropy**

$< H(S_{cycle}) >_{block} \sim H(S_{FM})$, **compare FM entropy to neutron entropy averaged over cycles in block**

Automated Methods

- **Cycle 1**
  - **Estimate L_{Fiss} & set initial mesh**

- **Initial cycles**
  - **Iterate until mesh and S_{neut} & F tallies are stable**
    - Automated, test that (*Δ* nonzero tallies) < 2%, 5%
  - **When S_{neut} & F tallies are stable, begin a block of cycles**

- **At each end-of-block of cycles (default = 10 cycles/block)**
  - **Solve F-matrix equations for S_{FM}, fundamental mode eigenfunction**
  - **Convergence tests**
    - **11 statistical tests must all pass for convergence**
    - **If converged, set active cycles to begin with next cycle, start population size tests after next block**
    - **If not converged, accelerate source convergence for each cycle by importance sampling with weights:**

$$S_{FM}(m) / S_{neut}(m), \quad m = \text{bin}$$

Examples

MCNP6.3 User Input

Extra MCNP input to activate new features:

```
kopts    fmat=        yes
         fmatconvrg=  yes
         fmataccel=   yes
```

kcode

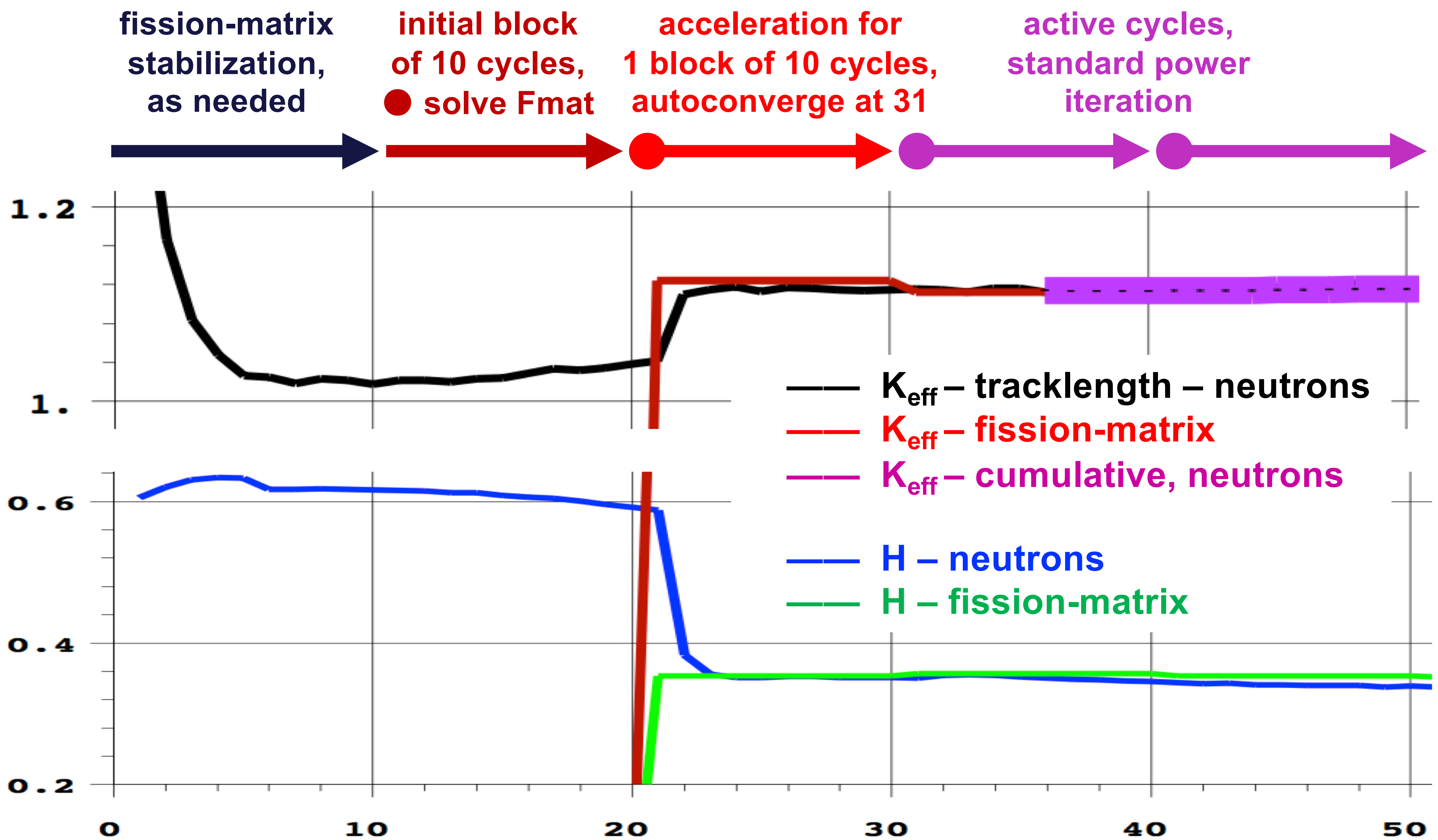
- Must use 10,000 or more neutrons/cycle
- 3rd entry ignored, number of inactive cycles
- Active cycles after convergence ($kcode_{4th\ entry} - kcode_{3rd\ entry}$)

Other Notes

- Another 1 or 2 input kopts entries are needed for
  - 1D or 2D problems (with infinite extent in 1 or 2 dimensions)
  - Precise Dominance Ratio calculations

Example: OECD-NEA Source Convergence Problem TEST4S

50,000 neuts/cycle, acceleration, auto-converge, k = 1.1165 (2)



MCNP6.3 Example – TEST4S

```
comment. -----------------------------------------------------------------------
comment. The MESH (adaptive, axis-aligned, cartesian) to be used for computing
comment. Shannon entropy, fission-matrix tallies (if used), and source
comment. convergence checking is initially defined by:
comment.     max mesh spacing for automesh =   1.0052E+01
comment.
comment.     total mesh cells = 3675
comment.
comment.     Xbins=   35    Xmin=-1.6861E+02    Xmax= 1.6856E+02    dx= 9.6334E+00
comment.     Ybins=   35    Ymin=-1.6856E+02    Ymax= 1.6857E+02    dy= 9.6323E+00
comment.     Zbins=    3    Zmin=-9.6460E+00    Zmax= 9.9571E+00    dz= 6.5344E+00
comment.
comment. the mesh will be automatically extended if necessary,
comment. preserving the original mesh cells and spacing.
comment. -----------------------------------------------------------------------
comment. -----------------------------------------------------------------------
comment.  FISSION MATRIX WILL BE COMPUTED to estimate dominance ratio,
comment.      based on fission sites only - not flights or collisions
comment.
comment.  The mesh for the fission matrix is the same as the entropy mesh,
comment.      using  3675  mesh bins for tallying fission neutrons
comment.
comment.      Fission matrix mesh will be extended if
comment.         any fission sites are found outside this mesh.
comment.
comment.      Fission matrix tallies will be reset after cycle   1
comment.      Fission matrix eigenfunction will be found every  10 cycles.
comment.
comment.      Fission matrix dimensions:  3675 x 3675
comment.
comment.      Compressed-row-storage is used for the fission matrix.
comment.         max number of nonzero entries:  13505625
comment.
comment.
comment.  FMATCONVRG option is being used.
comment.     Statistical tests on the neutron & fiss-matrix distributions
comment.     will be used to determine convergence & begin active cycles.
comment.     The 3rd entry on the KCODE card may be ignored.
comment.
comment.     Targets for statistical tests:
comment.       h_slope:    < 0.95 conf level,  or  < 0.0001
comment.       k_slope:    < 0.95 conf level,  or  < 0.0001
comment.       distribs:   < 0.95 conf level,  h_diff:  < 0.01
comment.
comment.
comment.  FMATACCEL option is being used.
comment.    Fission matrix will be used to ACCELERATE source convergence
comment.    of the neutron distribution during inactive cycles.
comment.    Importance-factor-limits:   min= 0.20,  max= 5.00
comment. -----------------------------------------------------------------------
```

L_{Fiss} ← (max mesh spacing)

Bounding Box & Initial Mesh

MCNP6.3 Example – TEST4S

```
cycle      k(col)        ctm    entropy    active      k(col)     std dev      chains
    1     1.35733        0.04   0.60521                                         35416
                                           extend H-mesh to:    36 x 35 x 4
    2     1.16857        0.10   0.62080                                         22433
                                           extend H-mesh to:    37 x 35 x 4
    3     1.08223        0.13   0.63109                                         17100
                                           dS=  3%, dF= 34%, shift window
                                           extend H-mesh to:    37 x 36 x 4
    4     1.05100        0.17   0.63410                                         13800
                                           dS=  2%, dF= 19%, shift window
                                           extend H-mesh to:    37 x 37 x 4
    5     1.02827        0.21   0.63348                                         11529
                                           dS=  1%, dF= 14%, shift window
                                           extend H-mesh to:    37 x 37 x 5
    6     1.02118        0.25   0.61732                                          9997
                                           dS=  0%, dF= 10%, shift window
    7     1.02018        0.29   0.61762                                          8746
                                           dS=  1%, dF=  9%, shift window
    8     1.02413        0.32   0.61845                                          7790
                                           dS=  0%, dF=  7%, shift window
    9     1.01974        0.37   0.61766                                          6974
                                           dS=  0%, dF=  7%, shift window
   10     1.01709        0.43   0.61656                                          6313
                                           dS=  1%, dF=  5%, shift window
   11     1.02129        0.48   0.61606                                          5815
                                           dS=  1%, dF=  5%, shift window
   12     1.01705        0.53   0.61452                                          5351
   13     1.02459        0.58   0.61263                                          4975
   14     1.02193        0.65   0.61214                                          4640
   15     1.02741        0.70   0.60894                                          4372
   16     1.03005        0.73   0.60600                                          4091
   17     1.03266        0.78   0.60435                                          3852
   18     1.03369        0.83   0.60065                                          3628
   19     1.03485        0.87   0.59622                                          3426
   20     1.03631        0.91   0.59177                                          3245
   21     1.04159        0.96   0.58774                                          3074

      fmatrix keff= 1.12401,   DR= 0.91098,   iters=    199
```

Source, fission-matrix, & mesh stabilization

Block of cycles

← from F-matrix solution

MCNP6.3 Example – TEST4S

```
fmatrix keff= 1.12400,  DR= 0.91098,  iters=   199

CONVERGENCE INFO & CHECKS:          (based on last  10 cycles)

  entropy for fmatrix eigenvector    =  0.35378
  entropy for neutron  last cycle    =  0.58774   dif=   66.13%
  relative entropy for last cycle    =  2.06900

  slope of keff (tracklen)     =  2.0E-03,  target:  < 5.3E-04   FAIL
  slope of keff (collide)      =  2.1E-03,  target:  < 5.3E-04   FAIL
  slope of keff (absorb)       =  2.0E-03,  target:  < 5.8E-04   FAIL
  slope of entropy             = -2.6E-03,  target:  < 4.3E-04   FAIL
  slope of entropy X marginal  = -2.1E-03,  target:  < 5.1E-04   FAIL
  slope of entropy Y marginal  = -2.1E-03,  target:  < 4.2E-04   FAIL
  slope of entropy Z marginal  =  8.7E-04,  target:  < 3.3E-04   FAIL
  entropy dif, neuts vs fmat   =  7.1E-01,  target:  < 1.0E-02   n/a
  Kolmo-Smirnov, distrib, stat =  6.8E-01,  target:  < 9.1E-02   FAIL
  Chi-square,    distrib, stat =  5.0E+04,  target:  < 5.1E+02   FAIL
  rel-h-block,   distrib, stat =  2.5E+00,  target:  < 5.1E-03   n/a

  ***** convergence tests were NOT passed *****

MISCELLANEOUS INFO & CHECKS:

  rmse        =    1.16    %
  fmat nnz=        11884,  0.09 %

                                       accelerate: Imin= 0.2, Imax= 4.7
22   1.10782      0.81   0.38309                                        2134
                                       accelerate: Imin= 0.2, Imax= 3.8
23   1.11376      0.85   0.35605                                        1499
                                       accelerate: Imin= 0.2, Imax= 3.2
24   1.11583      0.88   0.35129                                        1233
                                       accelerate: Imin= 0.2, Imax= 5.0
25   1.11726      0.92   0.35104                                        1077
                                       accelerate: Imin= 0.2, Imax= 3.4
```

MCNP6.3 Example – TEST4S

```
 31    1.11257       1.12    0.35069                                       680

      fmatrix keff= 1.11187,  DR= 0.91653,  iters=   138

      CONVERGENCE INFO & CHECKS:           (based on last  10 cycles)

        entropy for fmatrix eigenvector    =  0.35656
        entropy for neutron  last cycle    =  0.35069   dif=   -1.65%
        relative entropy for last cycle    =  0.00972

        slope of keff (tracklen)      =  4.2E-03,  target:  < 5.1E-03   PASS
        slope of keff (collide)       =  4.6E-03,  target:  < 4.9E-03   PASS
        slope of keff (absorb)        =  4.6E-03,  target:  < 4.9E-03   PASS
        slope of entropy              = -1.4E-02,  target:  < 1.6E-02   PASS
        slope of entropy X marginal   = -1.8E-02,  target:  < 1.9E-02   PASS
        slope of entropy Y marginal   = -1.8E-02,  target:  < 1.9E-02   PASS
        slope of entropy Z marginal   =  1.3E-03,  target:  < 1.6E-03   PASS
        entropy dif, neuts vs fmat    = -9.1E-04,  target:  < 1.0E-02   PASS
        Kolmo-Smirnov, distrib, stat =  2.5E-03,  target:  < 9.1E-02   PASS
        Chi-square,    distrib, stat =  9.0E+01,  target:  < 5.1E+02   PASS
        rel-h-block,   distrib, stat =  2.8E-03,  target:  < 5.1E-03   PASS

        ******************************************************************
        ******************************************************************
        ** FISSION SOURCE HAS CONVERGED, based on last      10   cycles  **
        **   Metrics:                                                    **
        **     slope of keff (tracklen)          is 0   (within uncert) **
        **     slope of keff (collide)           is 0   (within uncert) **
        **     slope of keff (absorb)            is 0   (within uncert) **
        **     slope of entropy                  is 0   (within uncert) **
        **     slope of entropy X marginal       is 0   (within uncert) **
        **     slope of entropy Y marginal       is 0   (within uncert) **
        **     slope of entropy Z marginal       is 0   (within uncert) **
        **     entropy dif, neuts vs fmat        is 0   (within uncert) **
        **   Distribution checks:                                        **
        **     Kolmo-Smirnov, distrib, stat,  neut vs fmat (within conf) **
        **     Chi-square,    distrib, stat,  neut vs fmat (within conf) **
        **     rel-h-block,   distrib, stat,  neut vs fmat (within conf) **
        ******************************************************************
        ******************************************************************
        Convergence is locked-in, even if some tests fail in future cycles

        Active cycles will begin with cycle =       32
        Active cycles will end   with cycle =      131
        Total active cycles to be run       =      100
```

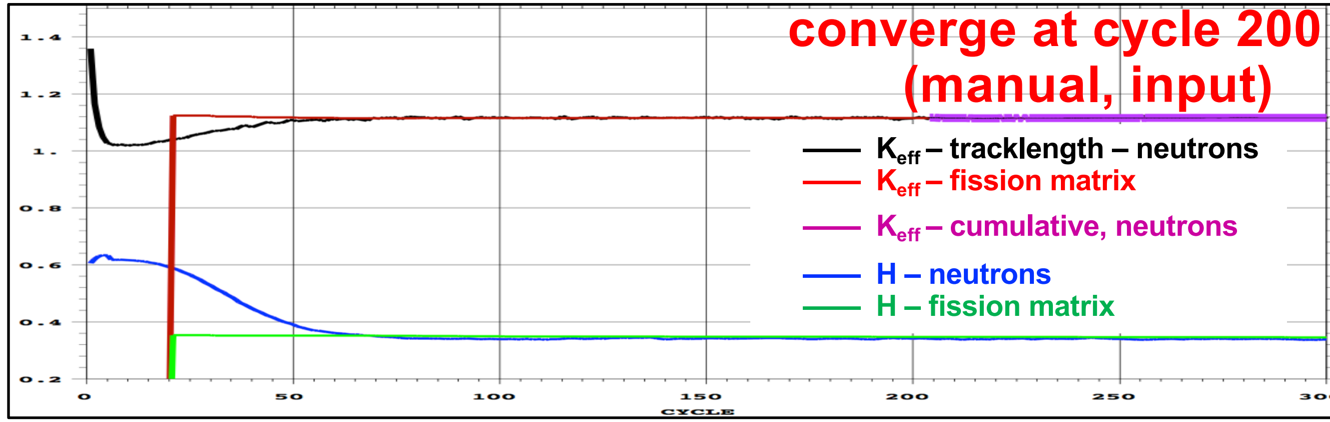
Dominance Ratio estimate

Quantitative Evidence For Convergence

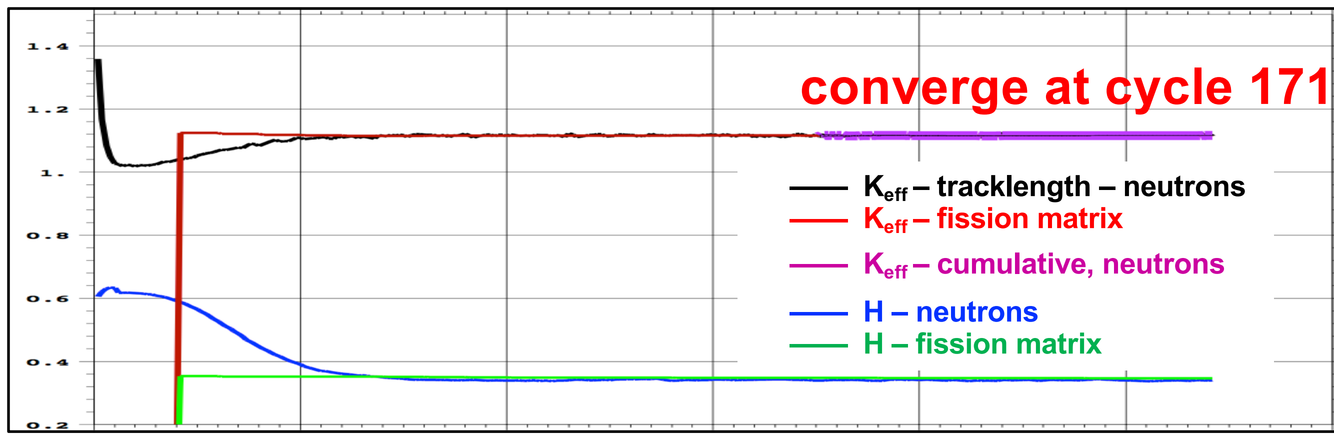
Quantitative Evidence For Convergence

MCNP6.3 Example – TEST4S

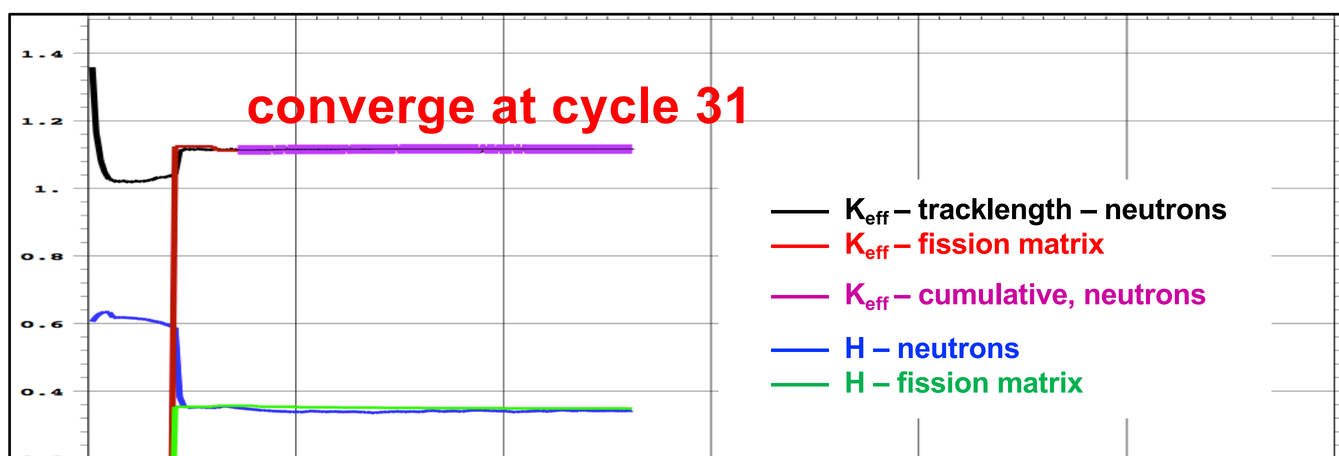
50,000 neuts/cycle
no acceleration
no auto-converge
k = 1.1164 (2)



50,000 neuts/cycle
no acceleration
auto-converge
k=1.1161 (2)



50,000 neuts/cycle
acceleration
auto-converge
k = 1.1165 (2)



Summary
&
Conclusions

Summary & Conclusions

- **Automation, user convenience, & correctness are major requirements**
- **Statistical testing for iteration convergence**
  - **No single statistical test is adequate, use many tests for robustness**
  - **Slope test is a powerful tool, can be applied to any metric vs cycle**
- **Statistical testing for population size**
  - **Very new, much potential for additional testing approaches**
- **Practical considerations**
  - **These methods work on a wide variety of application problems**
    - Correct results for every problem tested, never converged to a wrong answer
  - **Are the methods guaranteed to work correctly?**
    - Assumes a reasonable initial source guess, covering fissionable regions
    - Of course, contrived & devious problems can be constructed to break things
    - Fall-back is the conventional 1950s-style methods, which have not changed
  - **Significant advance in state-of-the-art for MC criticality**
    - Prevent user-errors related to iteration convergence
    - Quantitative convergence evidence for reviews & audits
    - Auto-convergence for routine work, parameter studies, multiphysics, …

References

- F.B. Brown (Ed.), (11 coauthors US, UK, FR), **"Statistical Tests for Diagnosing Fission Source Convergence and Undersampling in Monte Carlo Criticality Calculations",** final report from OECD-NEA-WPNCS Subgroup-6 (to be published by OECD-NEA in 2021)
- F.B. Brown, S.E. Carney, B.C. Kiedrowski, W.R. Martin, **"Fission Matrix Capability for MCNP, Part I - Theory",** Mathematics & Computation 2013, Sun Valley, ID, LA-UR-13-20429 (2013).
- S.E. Carney, F.B. Brown, B.C. Kiedrowski, W.R. Martin, **"Fission Matrix Capability for MCNP, Part II - Applications",** Mathematics & Computation 2013, Sun Valley, ID, LA-UR-13-20454 (2013).
- F.B. Brown, C.J. Josey, S. Henderson, W.R. Martin, **"Automated Acceleration and Convergence Testing for Monte Carlo Criticality Calculations",** ANS M&C 2019, Portland OR, LA-UR-19-20308 (2019)
- F.B. Brown, C.J. Josey, S. Henderson, W.R. Martin, **"Automated Acceleration and Convergence Testing for Monte Carlo Nuclear Criticality Safety Calculations",** ICNC 2019, Paris FR, LANL report LA-UR-19-20482 (2019)
- F.B. Brown, **“A Review of Best Practices for Monte Carlo Criticality Calculations”,** ANS NCSD 2009, Hanford WA, LA-UR-09-03136 (2009).
- F.B. Brown, **“Investigation of Clustering in MCNP6 Monte Carlo Criticality Calculations”,** Int. Conf. on Transport Theory, Monterey CA, Oct 2017, LA-UR-17-29261 (2017).
- F.B. Brown, W.R. Martin, **“Statistical Tests for Convergence in Monte Carlo Criticality Calculations”,** LA-UR-18-28764 (2018).
- F.B. Brown, C.J. Josey, **“Diagnostics for Undersampling and Clustering in Monte Carlo Criticality Calculations”,** LA-UR-18-27656 (2018).
- F.B. Brown, **“Monte Carlo Techniques for Nuclear Systems”**, LA-UR-16-29043 (2016).
- F.B. Brown, **"Advanced Computational Methods for Monte Carlo Calculations"**, LA-UR-18-20247 (2018)

Additional Examples

(as time permits)

MCNP6.3 Test Problems for Fission Matrix Based Automated Convergence & Acceleration of K-eigenvalue Problems

- VALIDATION_CRITICALITY benchmark suite
- Godiva – bare HEU sphere
- PWR2d – commercial PWR
- ATR – INL advanced test reactor
- AGN-201m – UNM research reactor
- C5G7 - 3D U-Mox benchmark, OECD-NEA
- Triga reactor
- ACRR – Sandia burst reactor, with FREC
- LCT-078-001 - Sandia critical experiment
- 3D PWR – Hoogenboom-Martin benchmark, OECD-NEA
- Whitesides problem – K-effective of the world model
- TEST4S – simplified Whitesides, OECD-NEA
- FPOOL – OECD-NEA source convergence benchmark 1

VALIDATION_CRITICALITY benchmark suite

- Standard MCNP validation suite since 2002 (Mosteller)
  - 31 ICSBEP Handbook problems, critical experiments
  - Run using ENDF/B-VII.1 nuclear data
  - Timing results include all I/O, input & xsec file processing, Monte Carlo random walks, printing results, etc. for all 31 problems

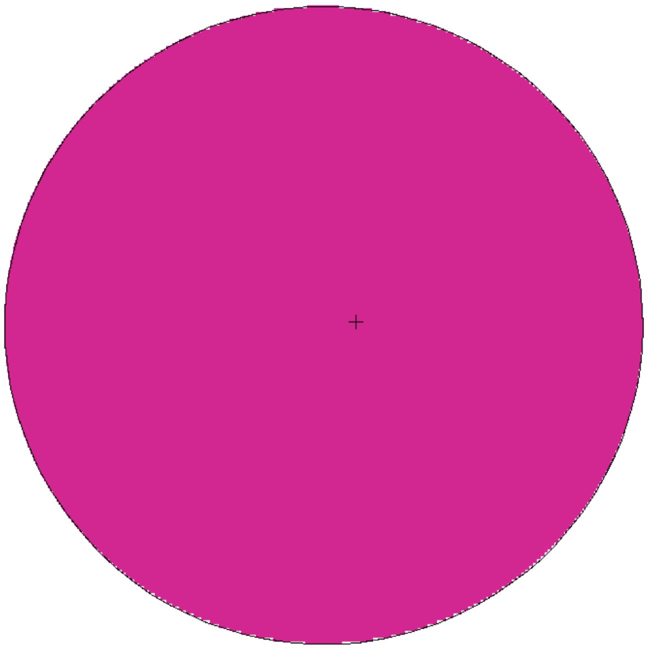
- Timing tests
  - 50,000 neutrons/cycle for all runs
  - For standard runs, 100 inactive cycles, 100 active cycles
  - For auto accelerate & converge, 100 active cycles

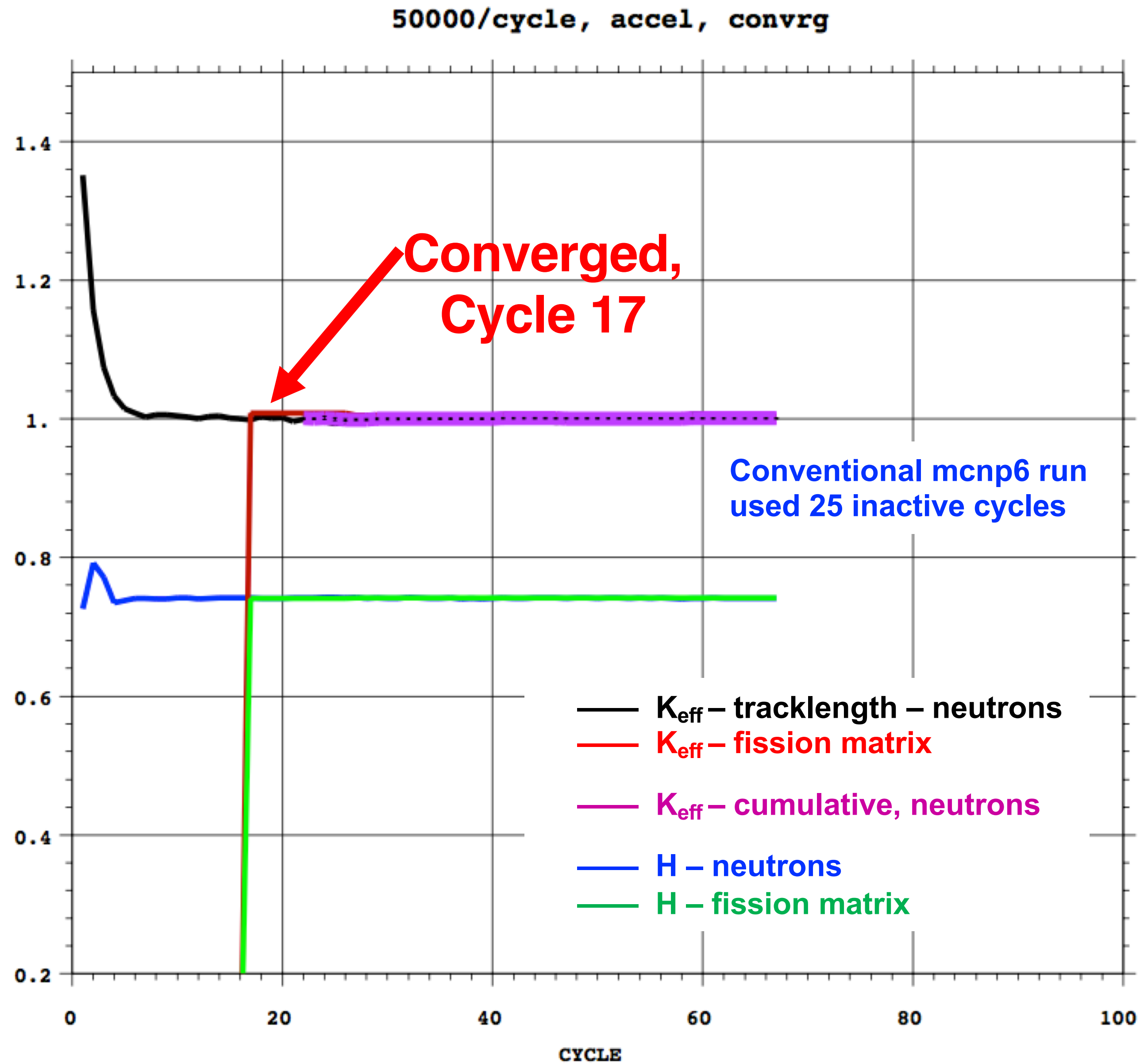
Standard run: 106 minutes

Auto accel & converge: 70 minutes

Godiva Problem

Bare HEU sphere

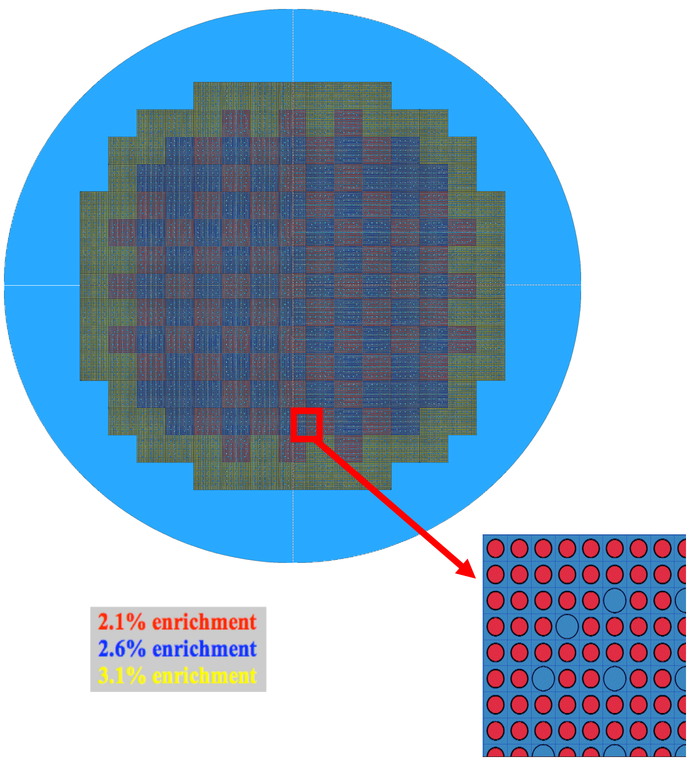


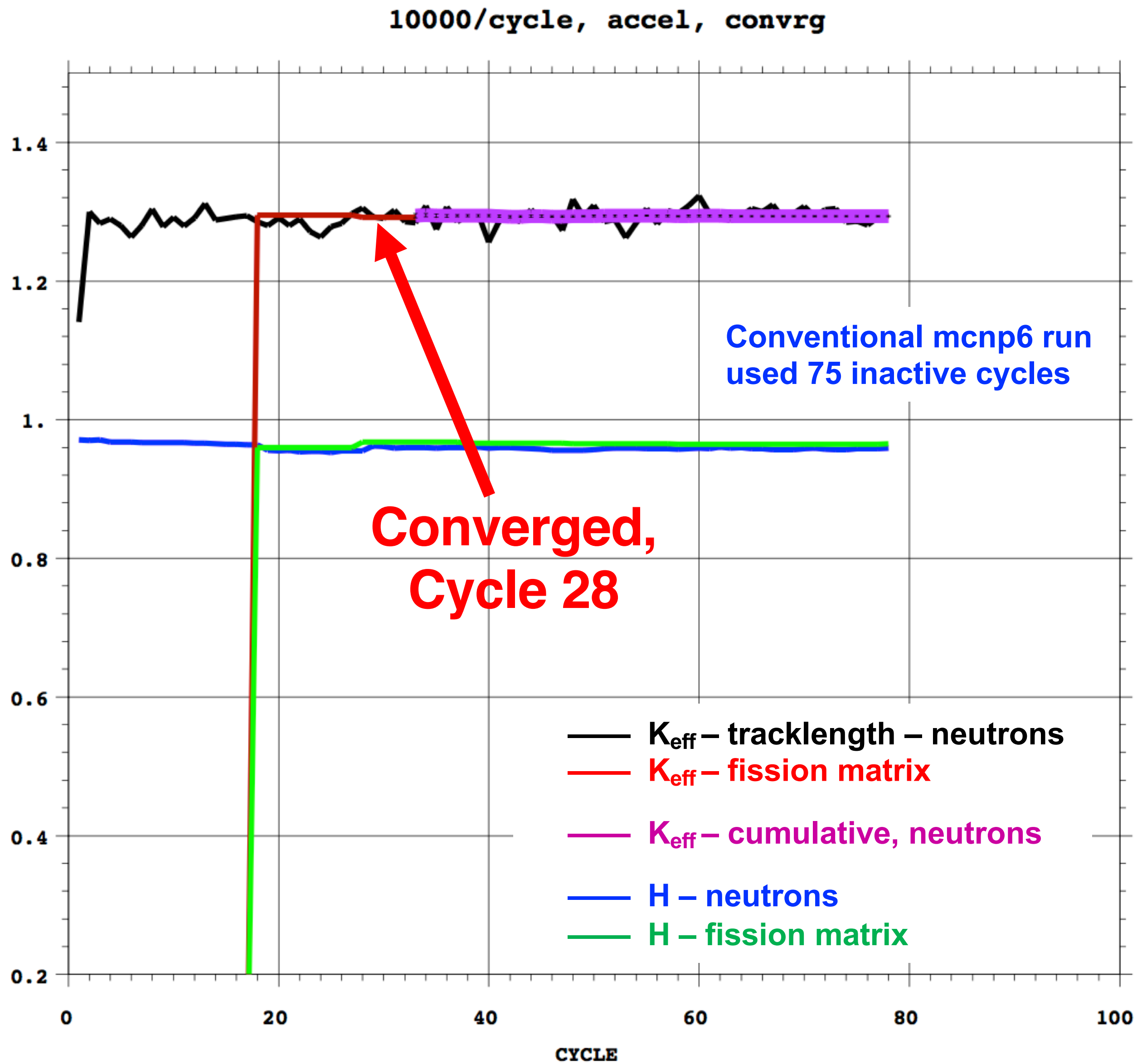


Whole-core 2D PWR Model

2D PWR (Nakagawa & Mori model)

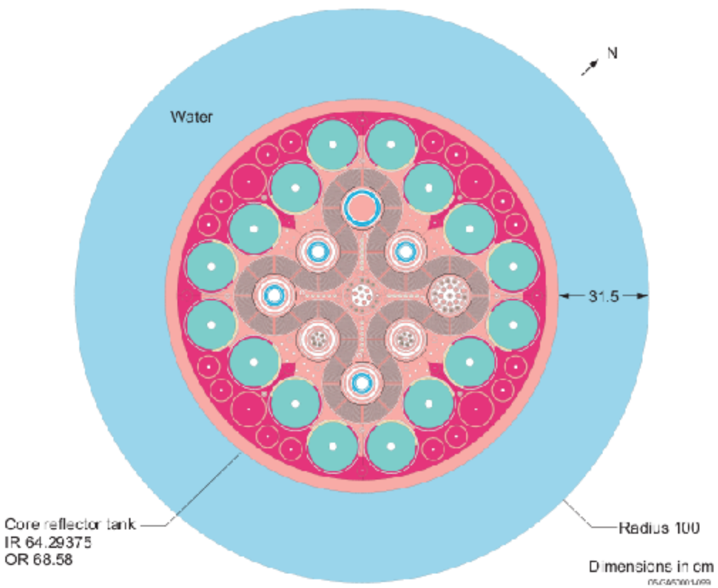
- 193 fuel assemblies:
  - 50,952 fuel pins with cladding
  - 4825 water tubes
- Each assembly:
  - Explicit fuel pins & rod channels
  - 17x17 lattice
  - Enrichments: 2.1%, 2.6%, 3.1%
- Calculations used whole-core model

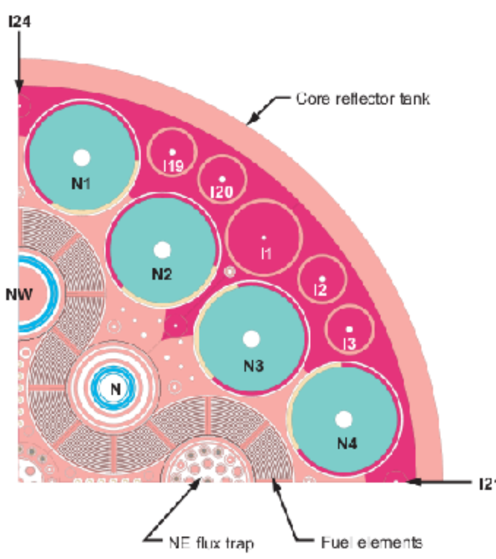


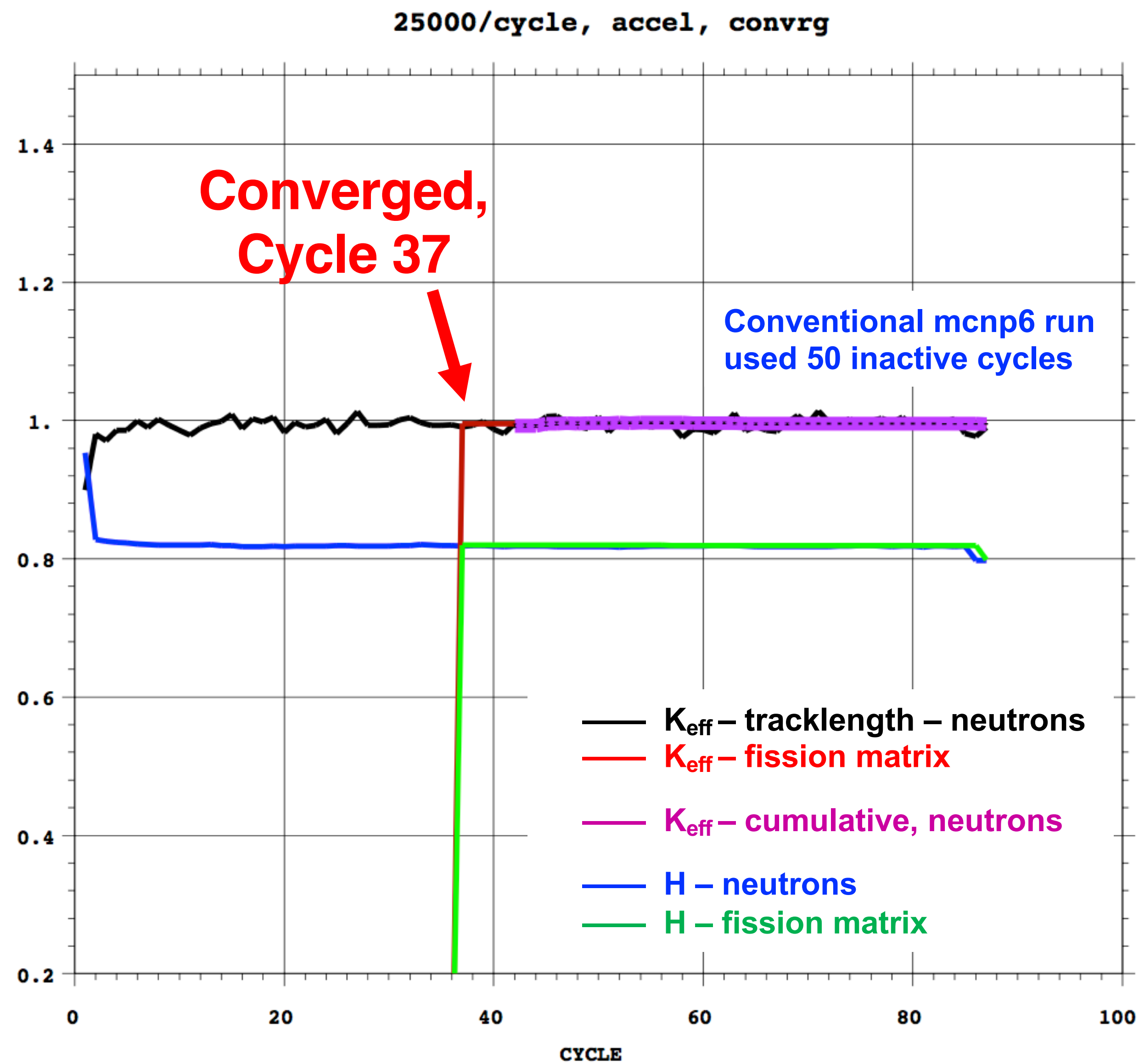


Advanced Test Reactor

"Serpentine Arrangement of Highly Enrichment Water-Moderated Uranium-Aluminide Fuel Plates Reflected by Beryllium"

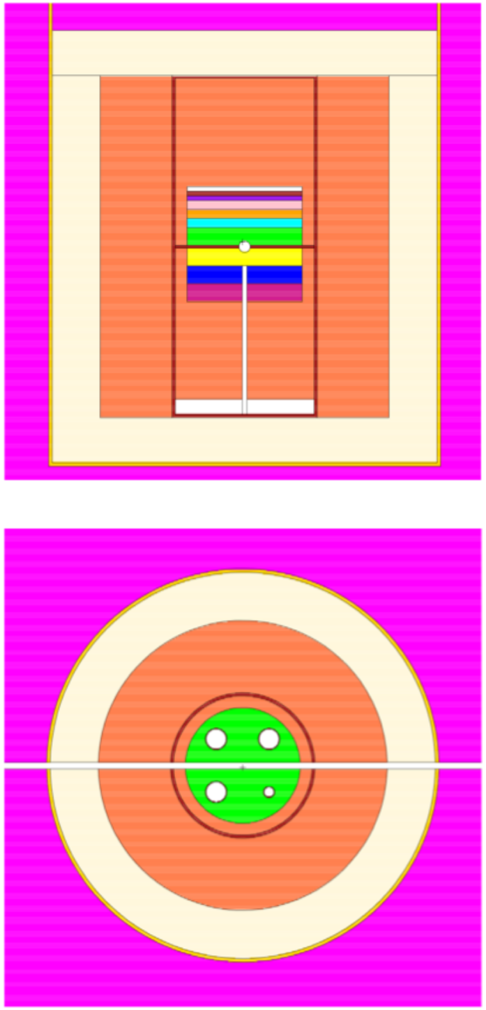


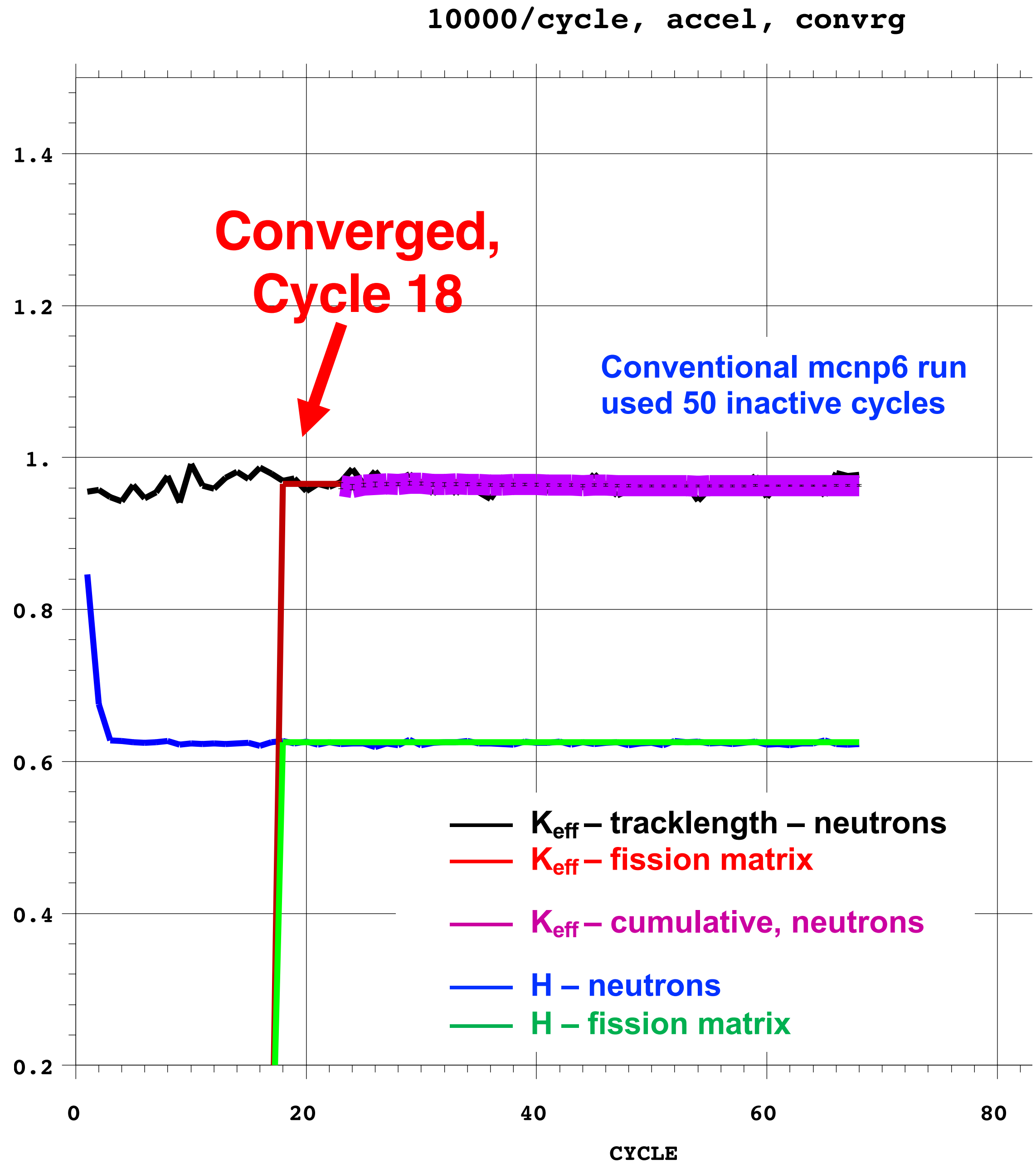




AGN-201 - Univ. New Mexico Research Reactor

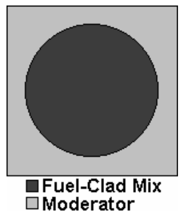
AGN
UNM Research Reactor





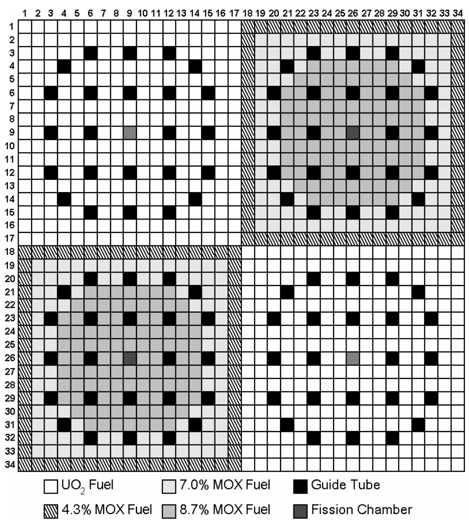
OECD-NEA Benchmark - C5G7

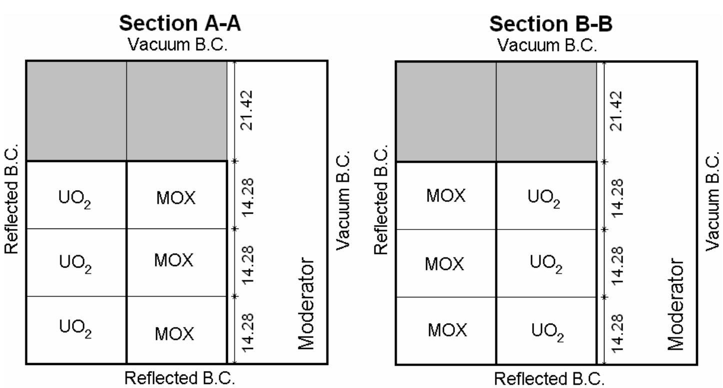
Figure 2. Fuel pin layout

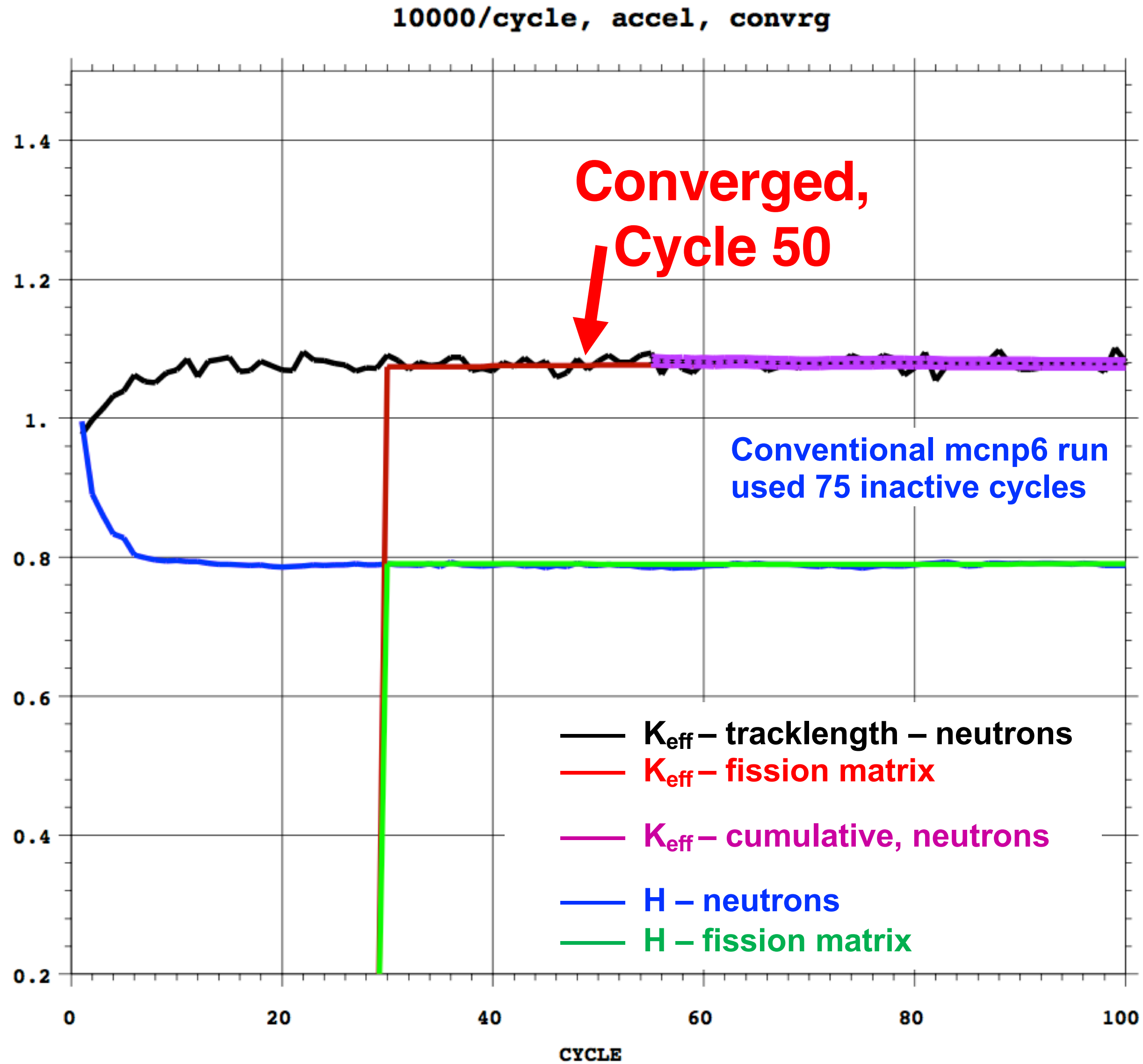


3D model

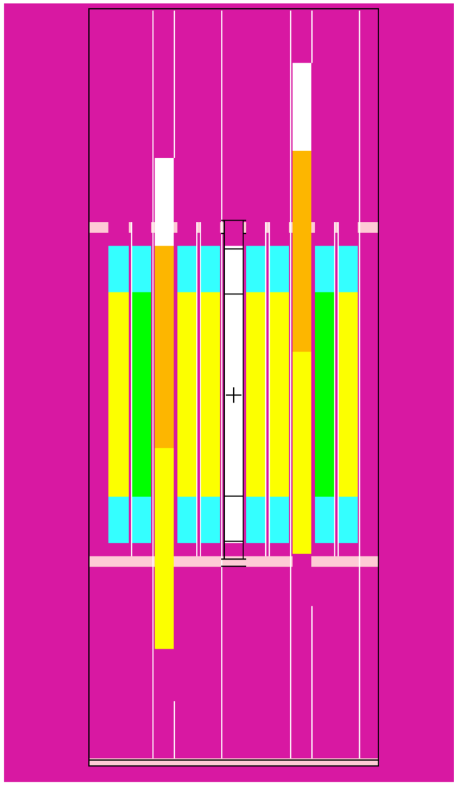
Figure 3. Benchmark fuel pin compositions and numbering scheme

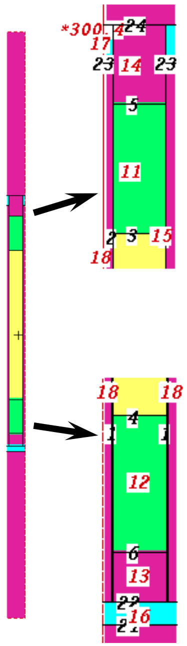


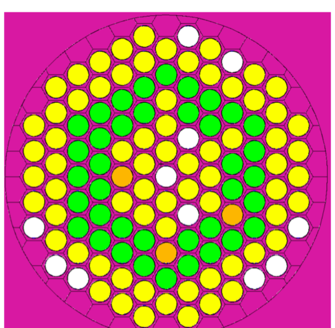


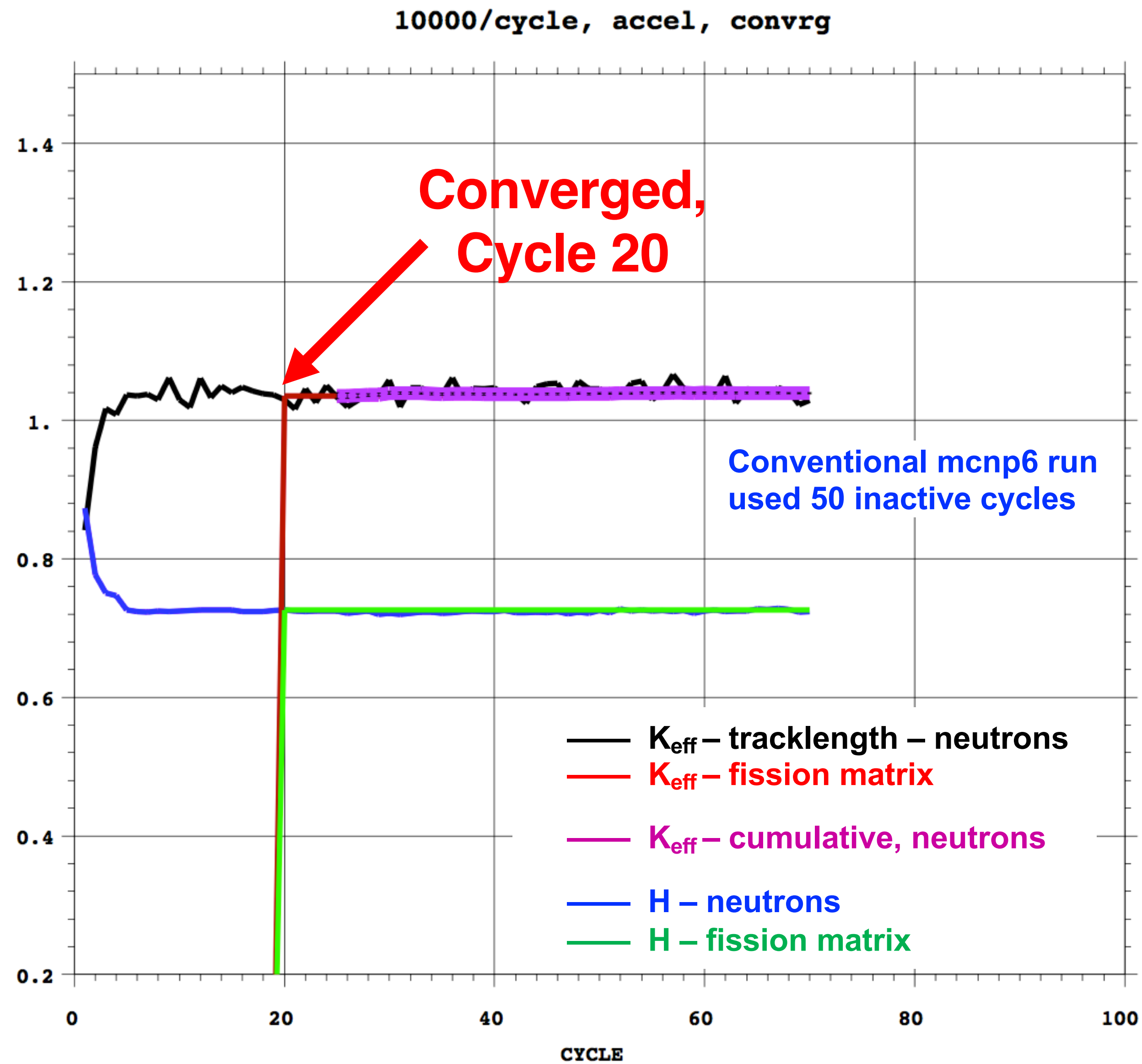


TRIGA Reactor



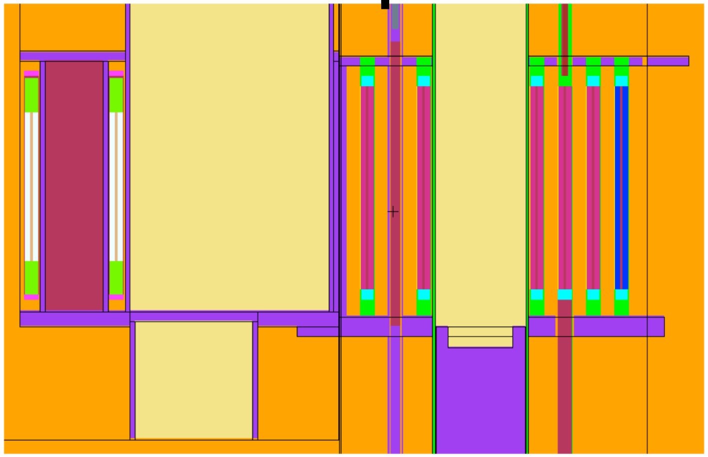




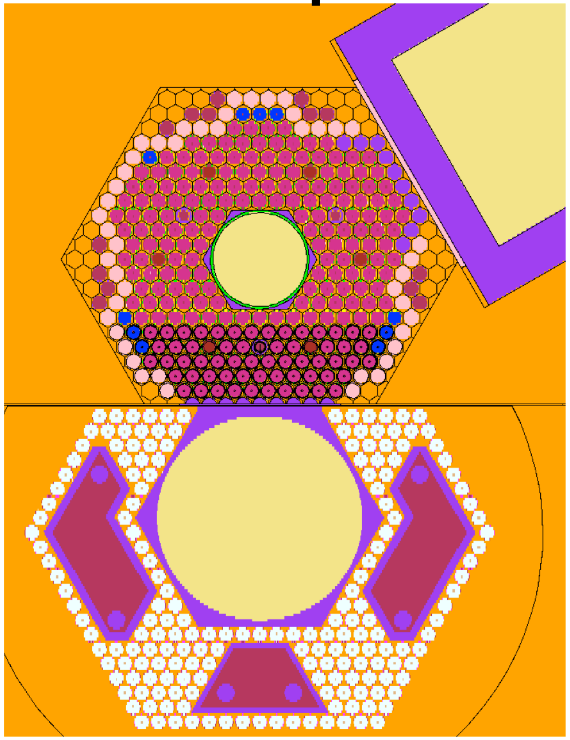


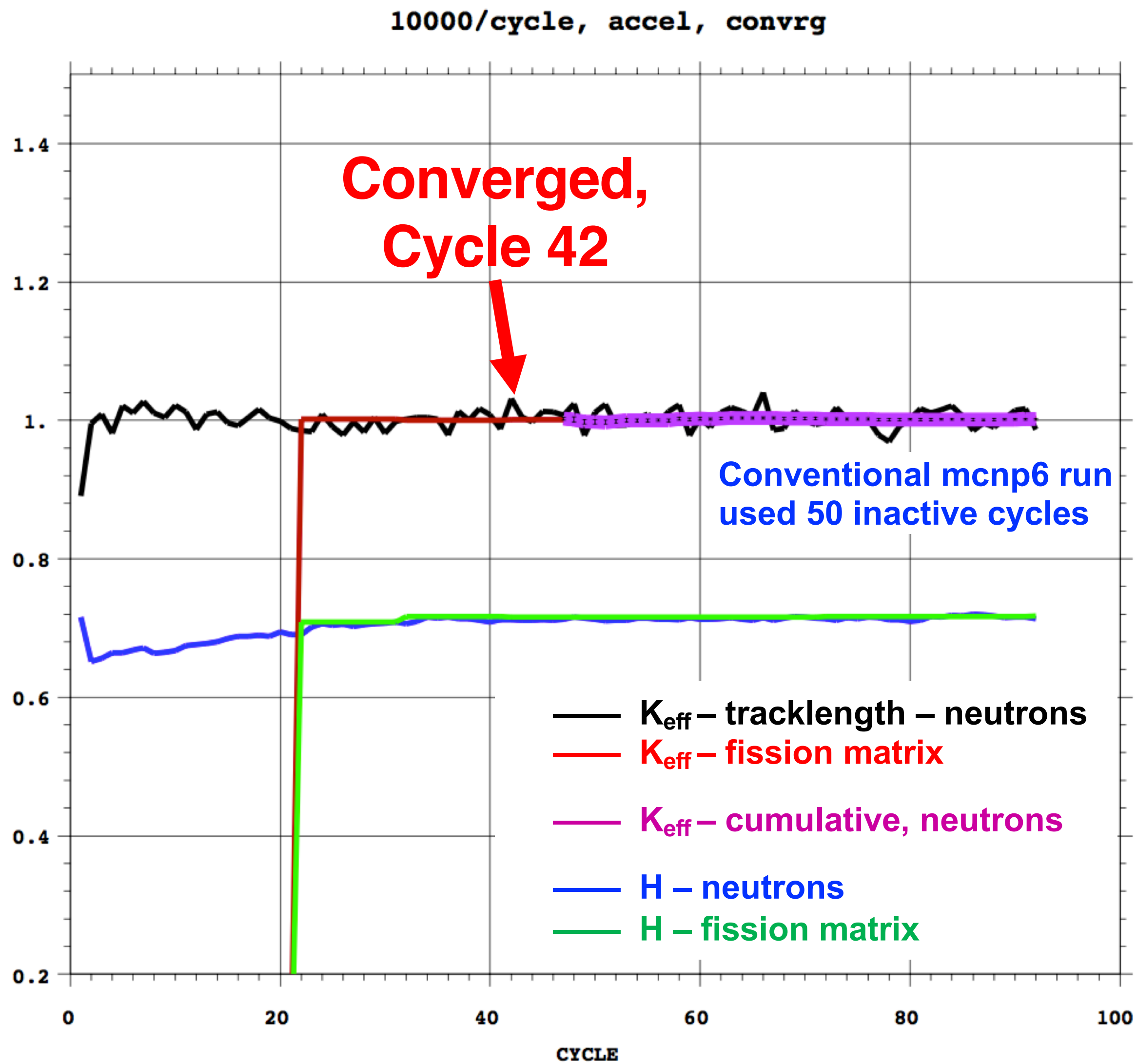
Sandia burst reactor - ACRR, with FREC

Y-Z plot



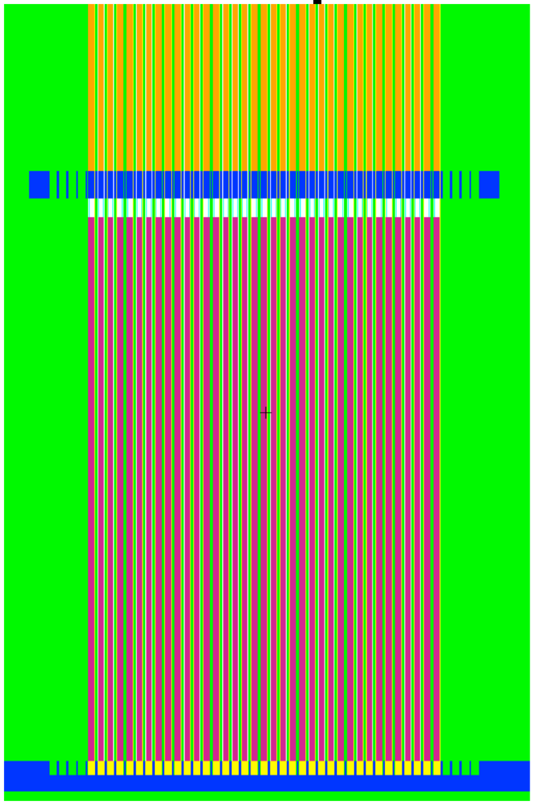
X-Y plot



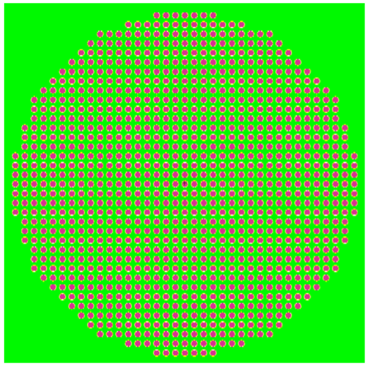


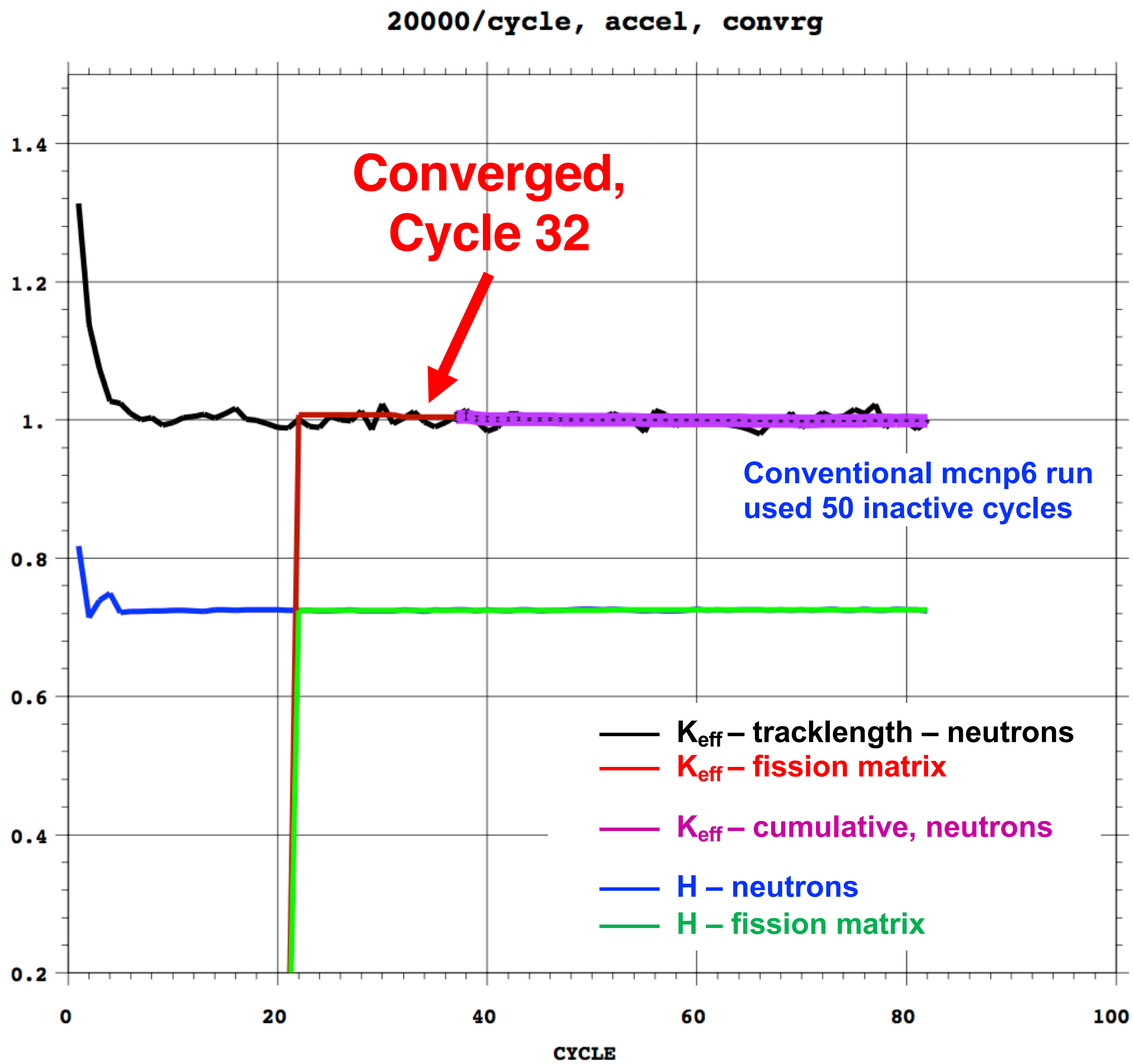
Sandia critical experiment – LCT-078-001, 1,057 rod assembly

Y-Z plot



X-Y plot





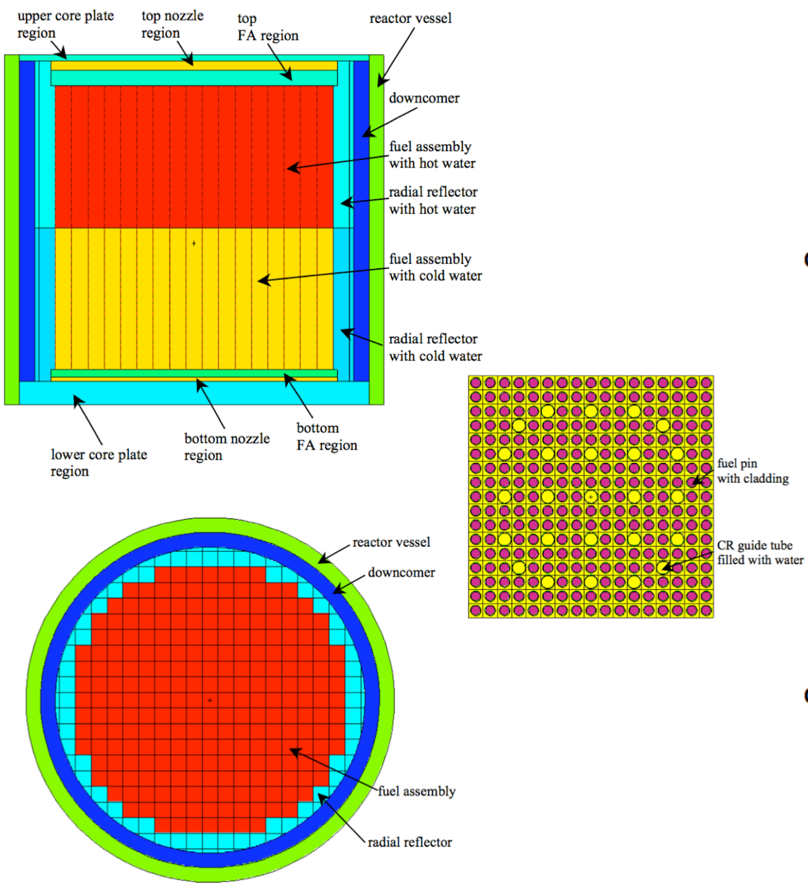
OECD-NEA "Hoogenboom-Martin Performance Benchmark"

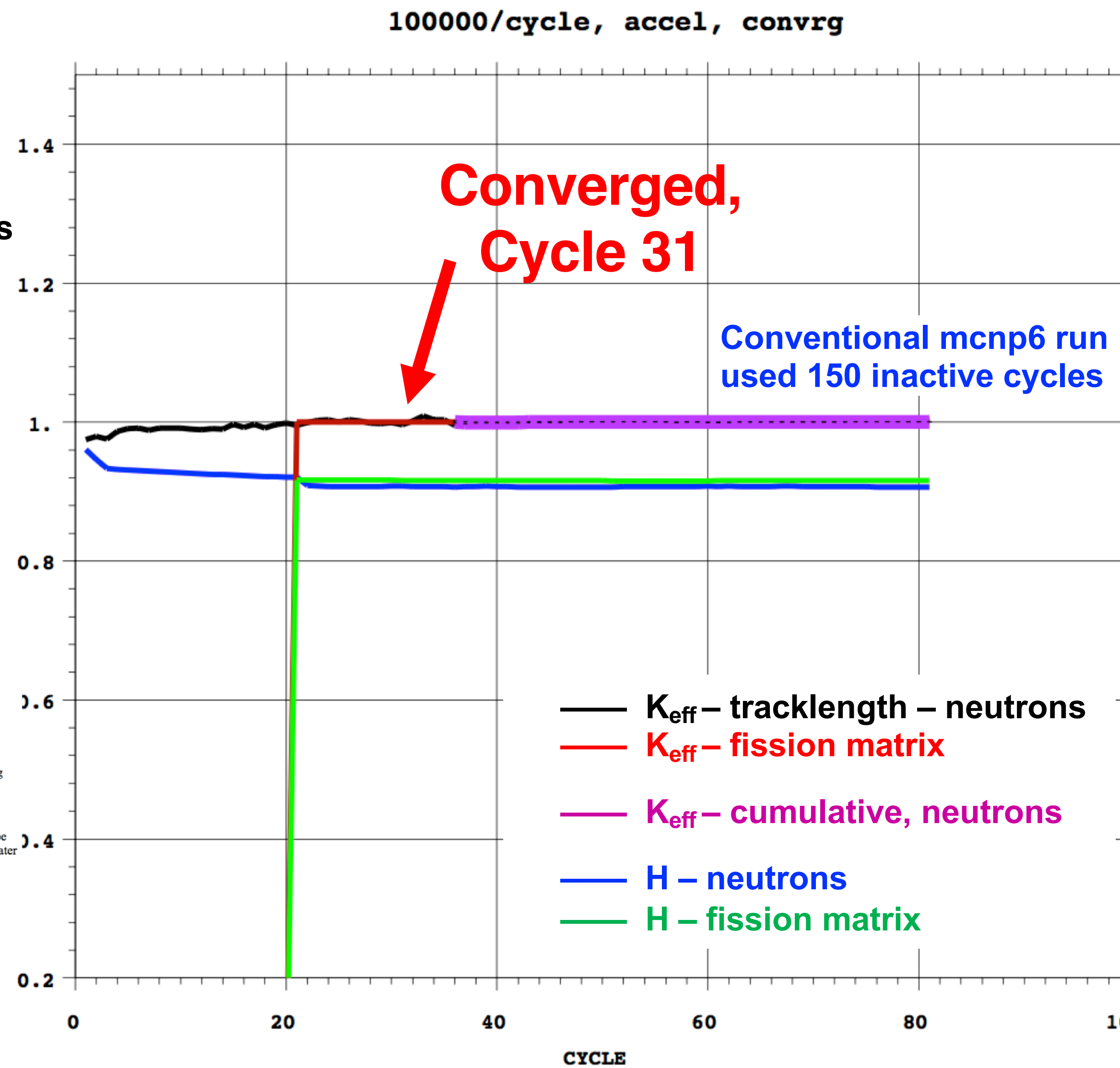
Reactor – full core, 3D

- **LWR model: 241 assemblies, 63,624 pins**
- **Fuel: 17 actinides + 16 FPs; borated water**
- **Detailed 3D MCNP model**

(63,624 pins) x (100 axial) = 6.3M pin powers

Runs easily on deskside computer



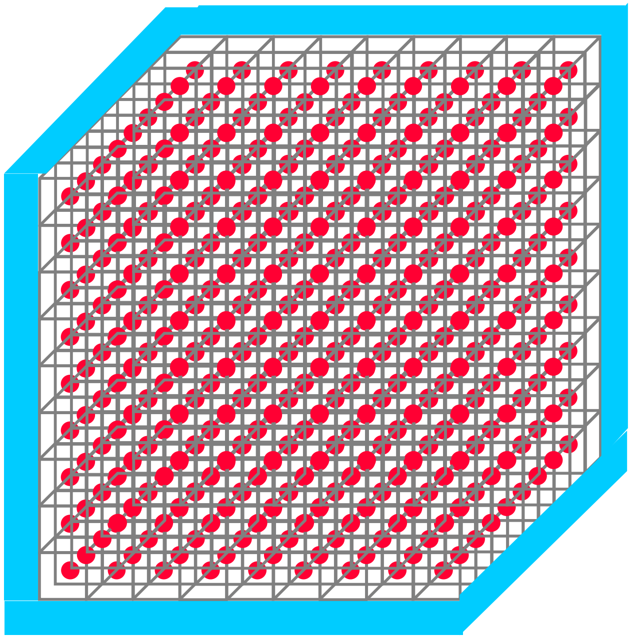


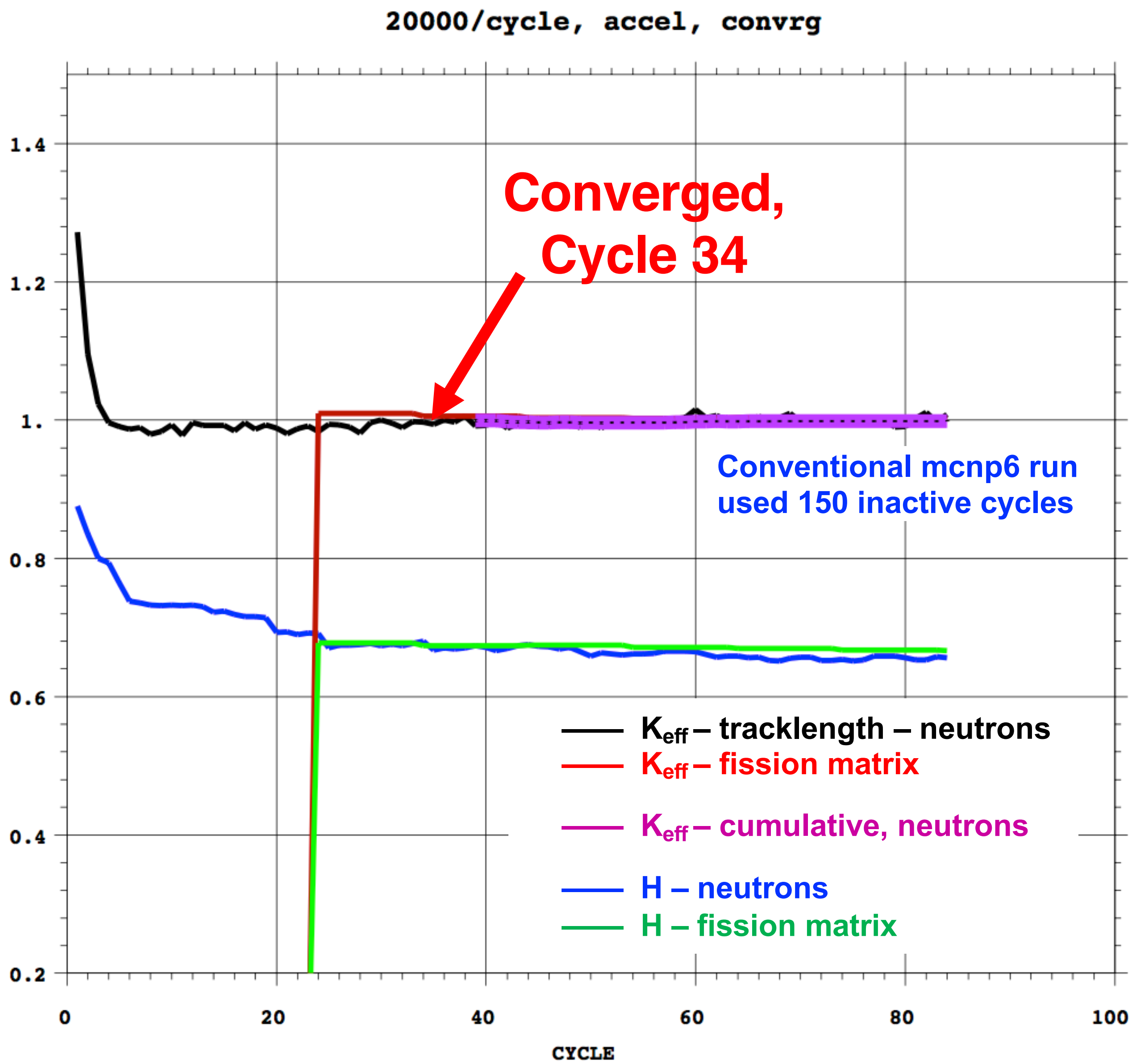
Whitesides' Model Problem – K-eff of the World

9 x 9 x 9 array of Pu-239 spheres
- 729 spheres
- Void between spheres
- Surrounded by 30 cm water
- Sphere radii ~ 4 cm
- Pitch = 60 cm
- Keff ~ 0.93

Replace center sphere of array by larger (critical) sphere

Should be supercritical - is it ?

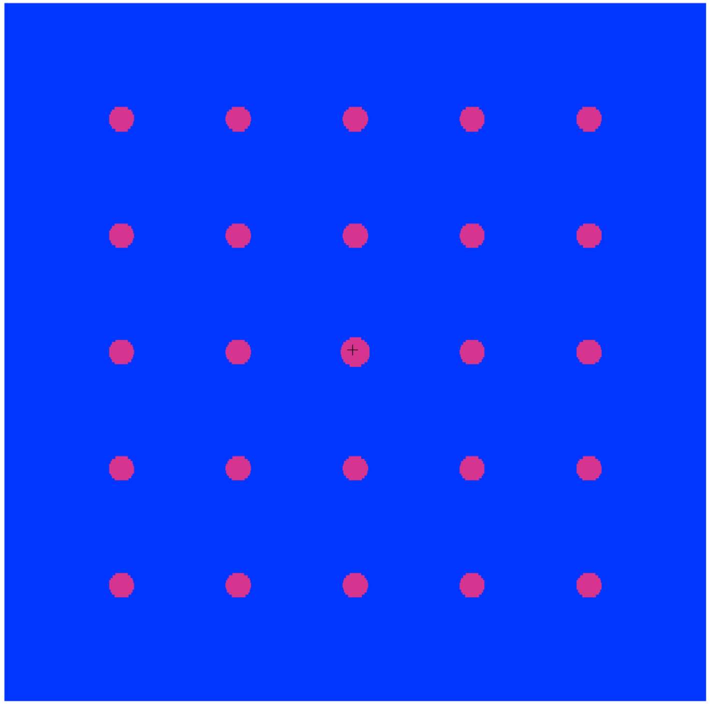


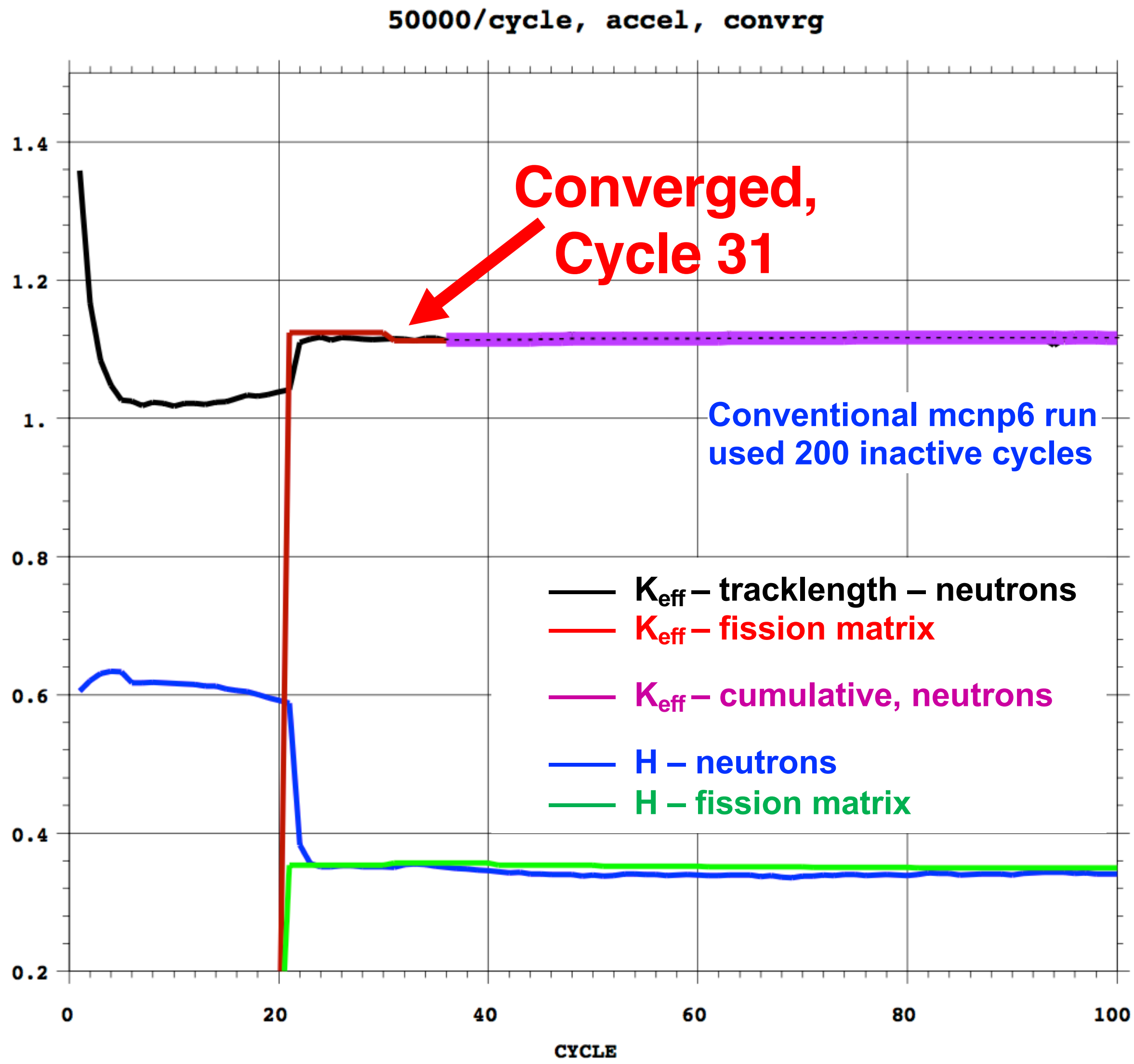


OECD-NEA Source Convergence Problem TEST4S

OECD-NEA source convergence benchmark

- Simplified version of Whitesides problem
- 5 x 5 array of HEU spheres
  - center sphere, R = 10 cm
  - others, R = 8.71 cm
  - pitch = 80 cm
  - air in between spheres
  - vacuum boundary conditions

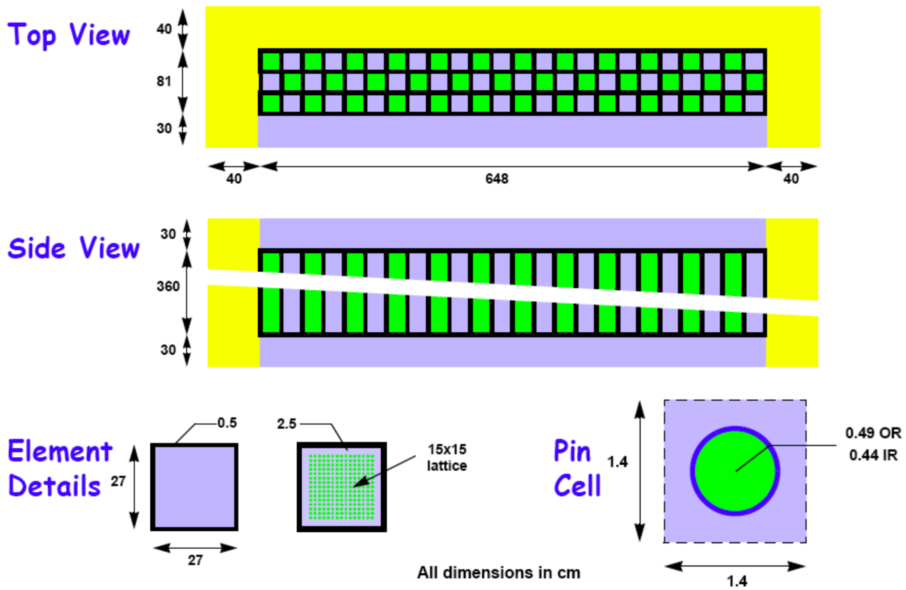




OECD-NEA Fuel Storage Pool

OECD-NEA-WPNCS Expert Group on Source Convergence

Benchmark 1



100k neuts/cycle