OAK RIDGE National Laboratory

Tutorial: Using ORIGAMI for Detailed Spent Fuel Assembly Analysis in Safeguards Applications

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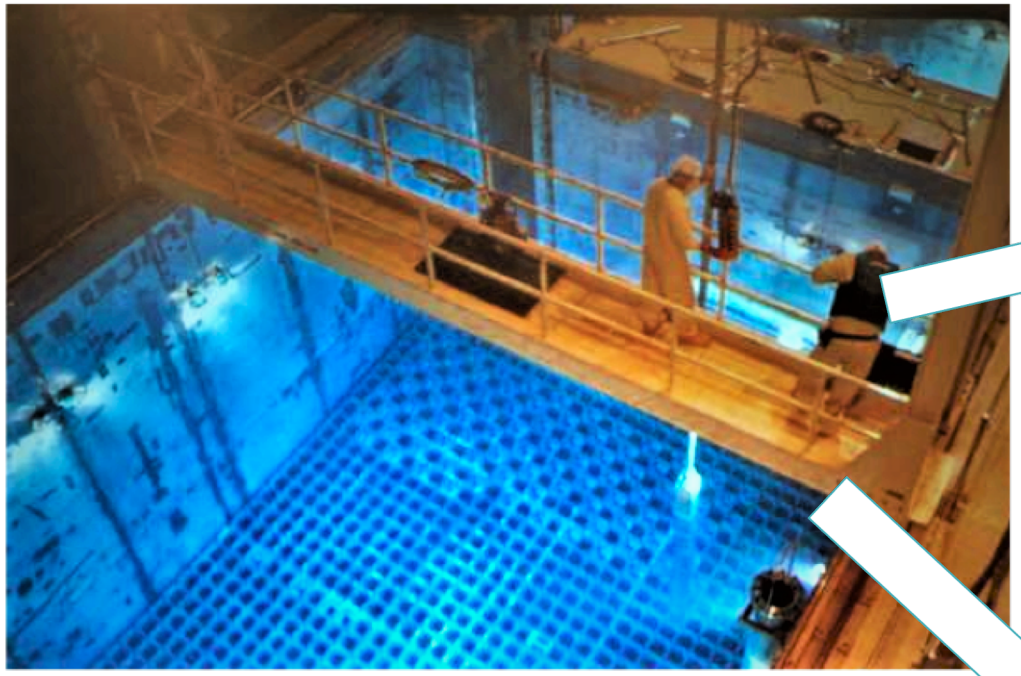
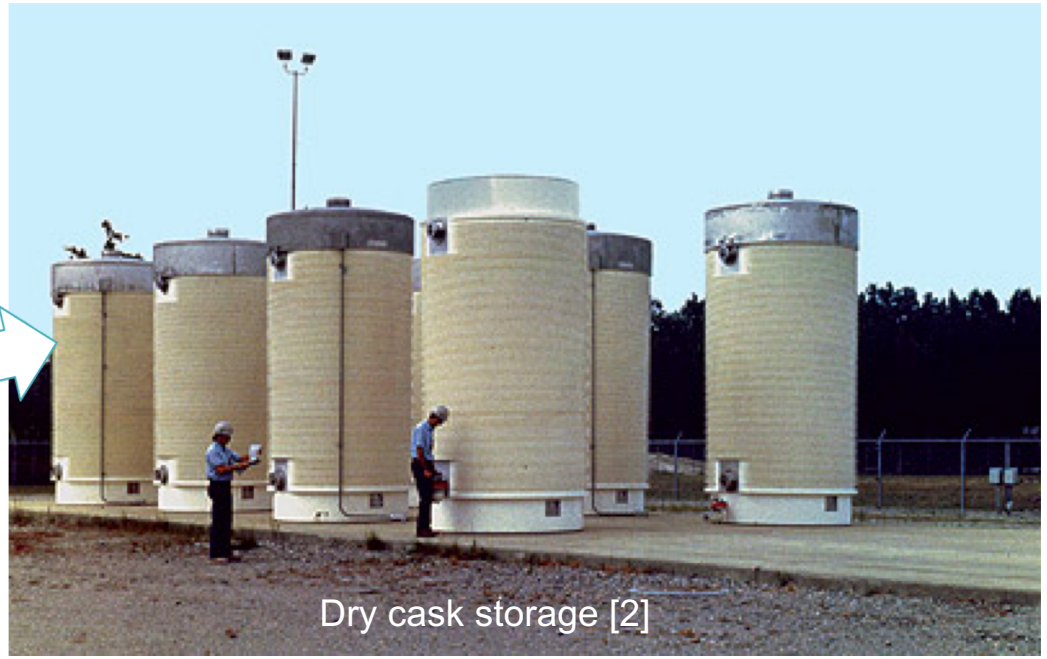
Outline

- Background of spent fuel safeguards
- Introduction to ORIGEN and **ORIG**en **A**sse**M**bly **I**sotopics (ORIGAMI)
- ORIGAMI: descriptions and features
- ORIGAMI tutorial problems

Spent fuel Safeguards

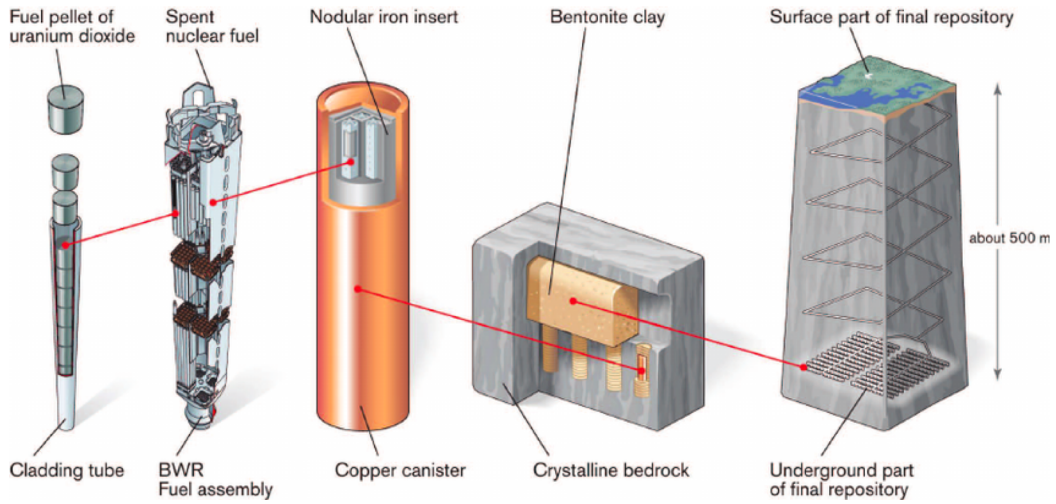


Spent fuel storage pool [1]



Dry cask storage [2]

Partial defect tests are required before spent fuel assemblies being transferred to “difficult-to-access” storage.



Encapsulation and final disposal [3]

[1]: https://www.linkedin.com/pulse/performance-improvement-case-study-1-outage-duration-todd-mccann
[2]: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/dry-cask-storage.html
[3]https://www.researchgate.net/publication/260877239_The_Use_of_Clay_as_an_Engineered_Barrier_in_Radioactive-Waste_Management_-_A_Review/figures?lo=1

Overview of ORIGEN

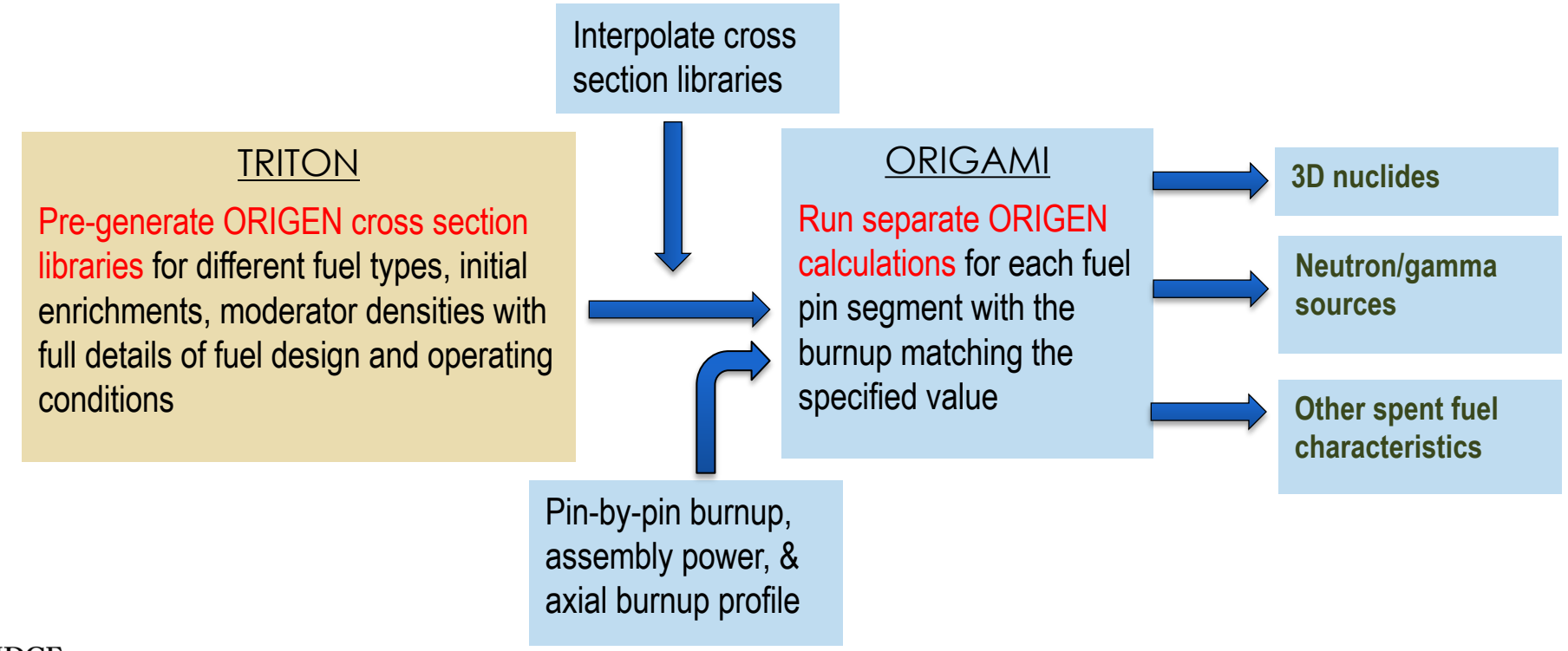
- Oak Ridge Isotope Generation code in SCALE
- Irradiation and decay simulation code
- Explicit simulation of nuclides in database
  - 176 actinides
  - 1151 fission products
  - 910 structural activation nuclides
- Explicit simulation of all pathways from neutron transmutation, fission, and decay
  - ORIGEN tracks 2237 isotopes
  - Includes all nuclides with half-lives > 1 ms
  - Accurately represents the evaluated nuclear data
  - Many physics codes track a small subset of isotopes

Key Capabilities of ORIGEN

- Spent nuclear fuel characterization
  - Nuclide concentrations (atoms and mass)
  - Activities
  - Decay heat
  - Radiation emission rates and spectra (neutron and gamma)
  - Radiotoxicity
- Source terms for accident analyses (operating reactors, spent fuel handling, storage, etc.)
- Structural material activation (in-core, ex-core)
- Fuel cycle analysis (e.g., material feed and removal processing)
- ORIGEN data enable comprehensive isotopic characterization of fuel over a large time scale, including repository analysis

ORIGAMI: an automated ORIGEN interface for 3D fuel assembly burnup calculation

- A customized user interface of ORIGEN for 3-D assembly burnup calculations.
- Pre-generated cross-section libraries are interpolated to produce accuracies similar to full SCALE/TRITON depletion simulations.
- Can generate nuclide compositions and decay heat for each axial node of each fuel pin based on specified burnup values.
- Accepts different compositions, enrichments, burnup, cross-section libraries for each fuel rod.



ORIGAMI Capabilities

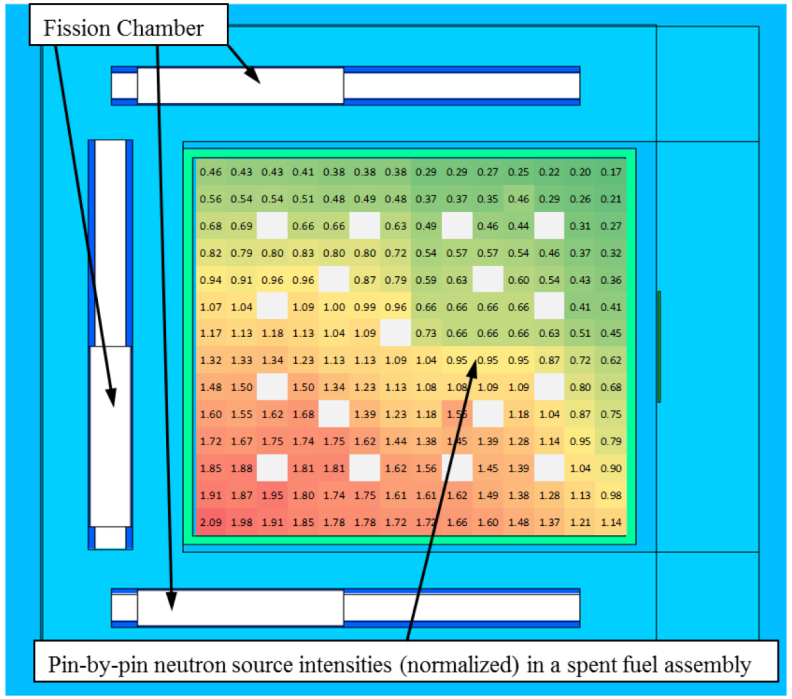
- Enable 3D ORIGEN calculations on a spent fuel assembly
- Input capabilities
  - Account for assembly radial and axial burnup distributions
  - Account for axial moderator density variations
  - Can assign different initial fuel composition (e.g., enrichment, Gd) and ORIGEN library for each pin
  - Assign different power levels on each pin segment
  - Convenient Fulcrum interface
- Output capabilities
  - Complete f71 file and SCALE StdComp mix file
  - Material cards and neutron/gamma source terms for each pin segment, which can be directly used for MCNP and KENO transport models
  - Decay heat for each axial segment of the assembly

Why is high-fidelity spent fuel modeling and simulation needed?

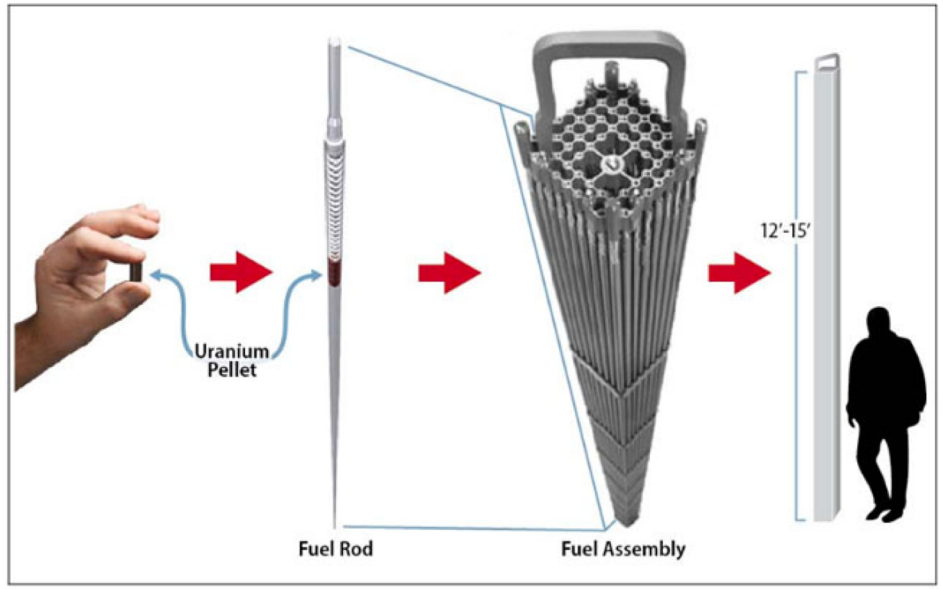
- Detailed nuclide compositions and spatial distribution are needed for 3D NDA modeling and simulation, in order to quantify instrument performance.
- Calculations provide a) correlations between measured data and the quantities of interest not directly measured and b) verification of measurements since the actual assembly inventories cannot be measured.

28.2	27.8	27.5	27.3	27.1	27.0	26.9	25.4	25.3	25.0	24.6	24.0	23.2	22.3
29.6	29.5	29.7	29.1	28.8	29.2	28.7	27.1	27.4	26.8	28.3	26.0	24.8	23.6
31.0	31.4		31.3	31.1		30.7	29.0		28.8	28.3		26.5	24.8
32.1	32.2	32.8	32.5	32.8	32.5	31.5	29.6	30.3	30.2	29.3	28.7	27.2	25.8
33.2	33.4	34.0	34.2		33.4	32.4	30.1	30.9		30.7	29.7	28.1	26.7
34.3	34.9		35.0	34.5	34.0	34.0	30.9	30.9	31.3	31.2		28.2	27.4
35.1	35.2	35.7	34.9	34.4	34.9		31.8	31.0	30.9	30.9	30.7	29.3	27.9
36.2	36.3	36.8	35.9	35.2	34.9	35.0	34.4	33.8	33.6	33.5	33.3	31.7	30.3
37.0	37.7		37.8	37.0	35.8	35.0	34.7	34.8	35.2	35.1		32.8	30.9
37.7	38.0	38.7	38.8		37.3	35.9	35.5	38.3		36.0	34.8	32.9	31.4
38.5	38.7	39.4	39.0	39.2	38.6	37.2	36.8	37.6	37.3	36.2	35.4	33.6	32.1
39.2	39.9		39.8	39.5		38.6	38.2		37.7	37.0		34.8	32.9
39.7	39.8	40.2	39.4	39.1	39.3	38.4	38.2	38.5	37.5	36.9	36.6	35.0	33.6
40.3	40.0	39.7	39.4	39.1	38.8	38.5	38.6	38.3	37.8	37.2	36.5	35.5	34.6

Pin-by-pin burnup map of a 14x14 spent fuel assembly [1]



Neutron source distribution in the MCNP model for the CIPN detector [1]



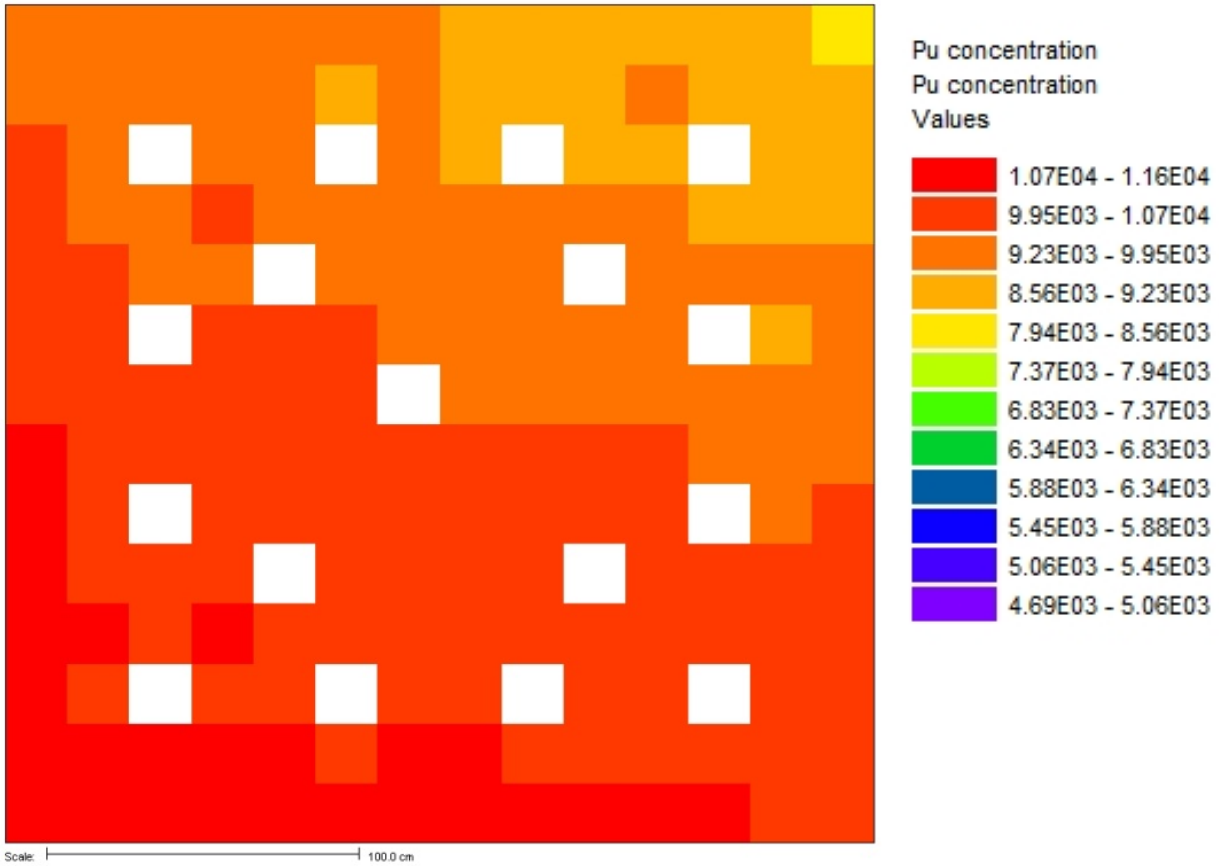
A fuel assembly [2]

[1] J. Hu, I. C. Gauld, J. Banfield and S. Skutnik, "Developing Spent Fuel Assembly Standards for Advanced NDA Instrument Calibration – NGSI Spent Fuel Project," ORNL/TM-2013/576, Oak Ridge National Laboratory, 2014.
[2]: http://modernsurvivalblog.com/nuclear/spent-nuclear-fuel-pools-are-full/

ORIGAMI results: radial Pu distribution

28.2	27.8	27.5	27.3	27.1	27.0	26.9	25.4	25.3	25.0	24.6	24.0	23.2	22.3
29.6	29.5	29.7	29.1	28.8	29.2	28.7	27.1	27.4	26.8	28.3	26.0	24.8	23.6
31.0	31.4		31.3	31.1		30.7	29.0		28.8	28.3		26.5	24.8
32.1	32.2	32.8	32.5	32.8	32.5	31.5	29.6	30.3	30.2	29.3	28.7	27.2	25.8
33.2	33.4	34.0	34.2		33.4	32.4	30.1	30.9		30.7	29.7	28.1	26.7
34.3	34.9		35.0	34.5	34.0	34.0	30.9	30.9	31.3	31.2		28.2	27.4
35.1	35.2	35.7	34.9	34.4	34.9		31.8	31.0	30.9	30.9	30.7	29.3	27.9
36.2	36.3	36.8	35.9	35.2	34.9	35.0	34.4	33.8	33.6	33.5	33.3	31.7	30.3
37.0	37.7		37.8	37.0	35.8	35.0	34.7	34.8	35.2	35.1		32.8	30.9
37.7	38.0	38.7	38.8		37.3	35.9	35.5	38.3		36.0	34.8	32.9	31.4
38.5	38.7	39.4	39.0	39.2	38.6	37.2	36.8	37.6	37.3	36.2	35.4	33.6	32.1
39.2	39.9		39.8	39.5		38.6	38.2		37.7	37.0		34.8	32.9
39.7	39.8	40.2	39.4	39.1	39.3	38.4	38.2	38.5	37.5	36.9	36.6	35.0	33.6
40.3	40.0	39.7	39.4	39.1	38.8	38.5	38.6	38.3	37.8	37.2	36.5	35.5	34.6

Operator-provided pin-by-pin burnup (GWd/tU) map [1]



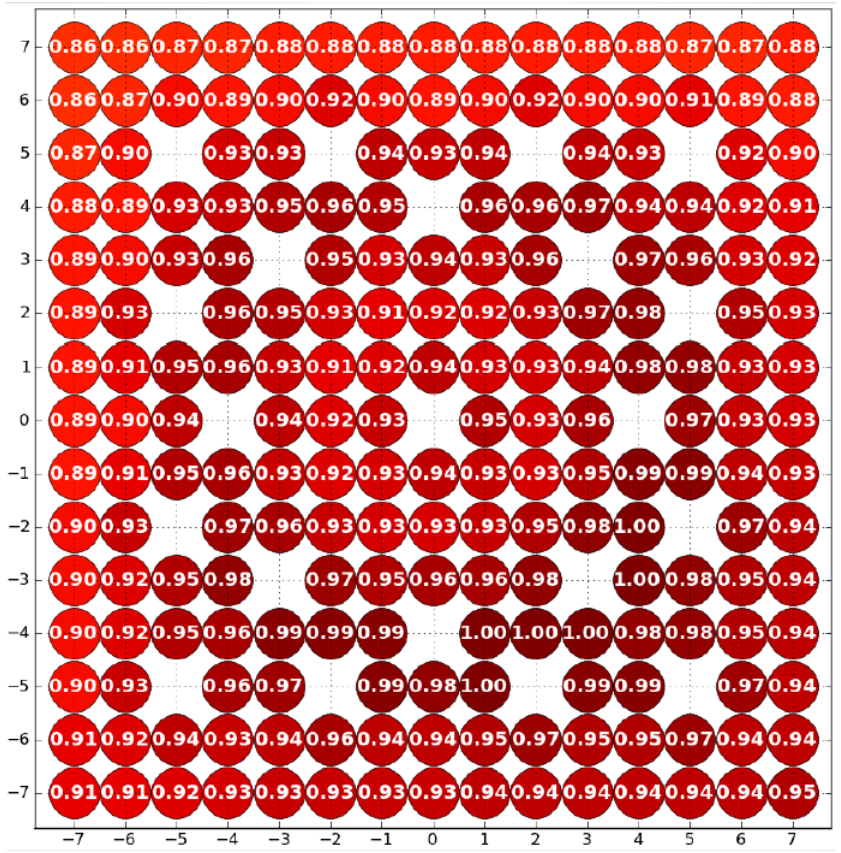
Pu content (g/MTU) in each Pin [1]

[1] J. Hu, I. C. Gauld, J. Banfield and S. Skutnik, "Developing Spent Fuel Assembly Standards for Advanced NDA Instrument Calibration – NGSI Spent Fuel Project," ORNL/TM-2013/576, Oak Ridge National Laboratory, 2014.

ORIGAMI results: radial Cs-137 distribution

0.86	0.86	0.86	0.87	0.87	0.88	0.88	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
0.86	0.87	0.9	0.88	0.89	0.91	0.89	0.88	0.89	0.91	0.89	0.89	0.91	0.88	0.88
0.87	0.9		0.92	0.93		0.94	0.93	0.94		0.94	0.93		0.92	0.89
0.87	0.89	0.93	0.93	0.95	0.96	0.95		0.96	0.96	0.96	0.94	0.94	0.91	0.9
0.88	0.9	0.93	0.96		0.95	0.92	0.94	0.93	0.96		0.97	0.96	0.92	0.91
0.89	0.92		0.96	0.95	0.92	0.9	0.91	0.91	0.93	0.96	0.98		0.95	0.92
0.89	0.9	0.95	0.96	0.93	0.91	0.91	0.94	0.93	0.92	0.94	0.98	0.98	0.93	0.92
0.89	0.9	0.94		0.94	0.91	0.93		0.94	0.92	0.96		0.97	0.93	0.92
0.89	0.9	0.95	0.96	0.93	0.91	0.92	0.94	0.93	0.92	0.95	0.99	0.98	0.94	0.93
0.89	0.93		0.97	0.96	0.93	0.92	0.92	0.93	0.95	0.98	0.99		0.96	0.94
0.89	0.91	0.95	0.97		0.97	0.95	0.96	0.95	0.98		1	0.98	0.95	0.94
0.9	0.91	0.95	0.96	0.98	0.99	0.98		0.99	1	1	0.98	0.98	0.95	0.94
0.9	0.93		0.96	0.97		0.98	0.98	0.99		0.99	0.98		0.97	0.94
0.9	0.91	0.94	0.93	0.94	0.96	0.94	0.94	0.95	0.97	0.95	0.95	0.97	0.94	0.94
0.91	0.91	0.91	0.92	0.93	0.93	0.93	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.95

(a) Given burnup distribution (input) [1]



(b) Calculated Cs-137 distribution (output) [1]

[1] J. Hu, et al., "Spent Fuel Modeling and Simulation using ORIGAMI for Advanced NDA Instrument Testing," in ANS M&C 2015, Nashville, TN, 2015.

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ORIGAMI Problem 1:

Express form using Fulcrum [1]:

A point model

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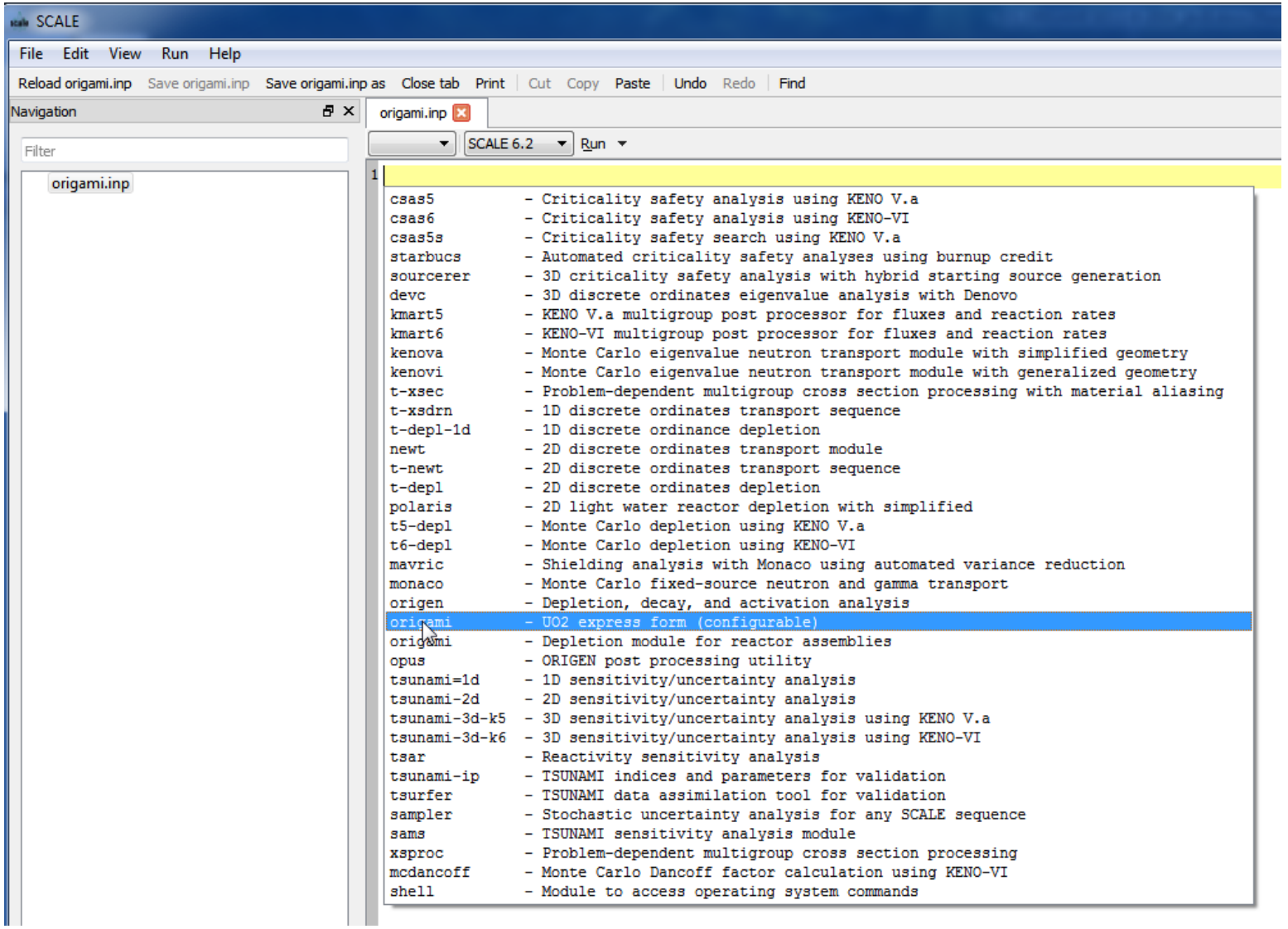
U.S. DEPARTMENT OF ENERGY

[1] W. Wieselquist, H. Liljenfeldt, ORIGAMI Spent Fuel Characterization, Scale Users' Group Workshop, ORNL, 2017

Problem 1: a point model using Fulcrum express form

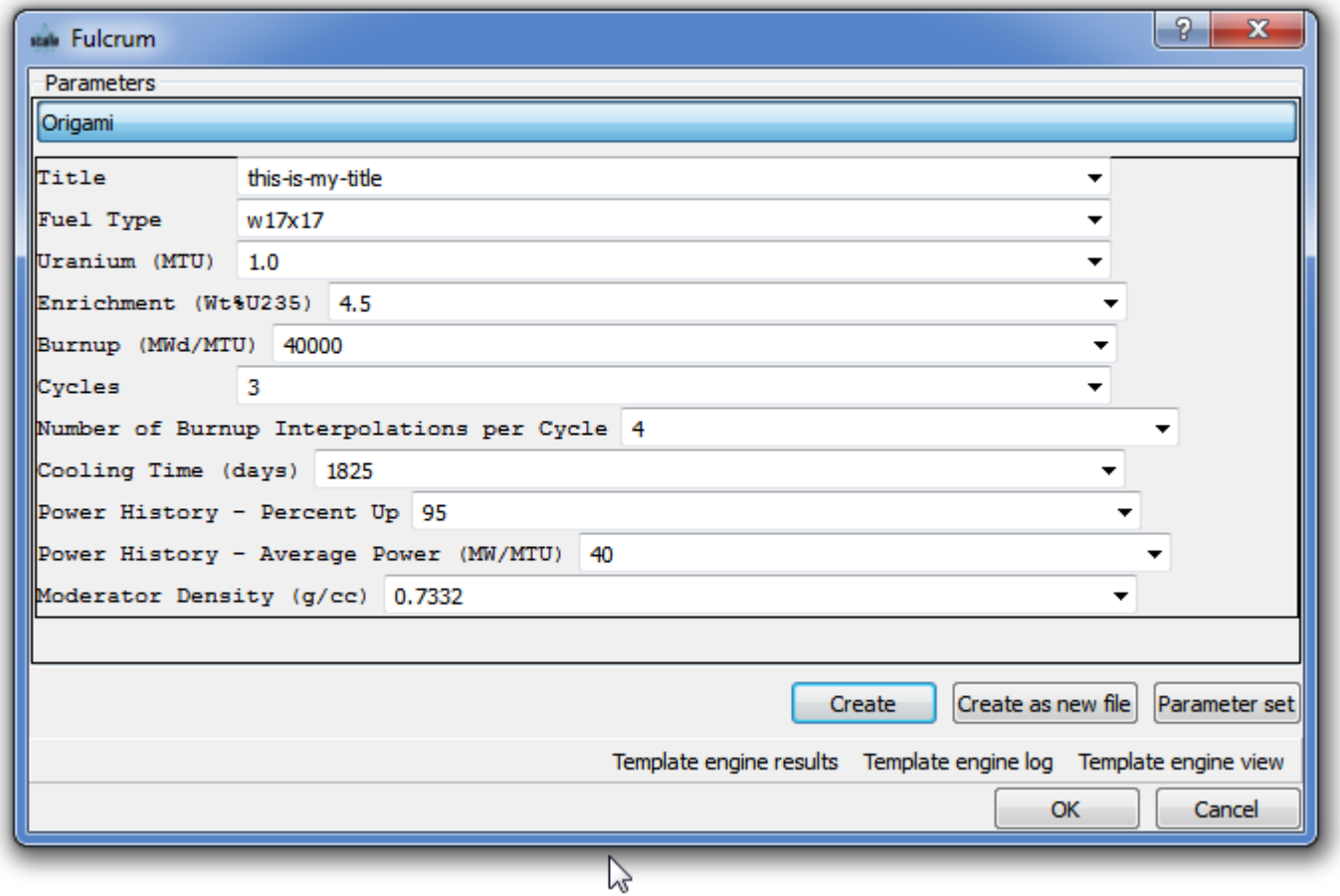
- Use Fulcrum express form to build a single-point model
- One fuel composition: 4.5% UO2
- One radial and one axial node
- Three uniform cycles with constant irradiation power
- 5 year final cooling time.

ORIGAMI "Express Form"



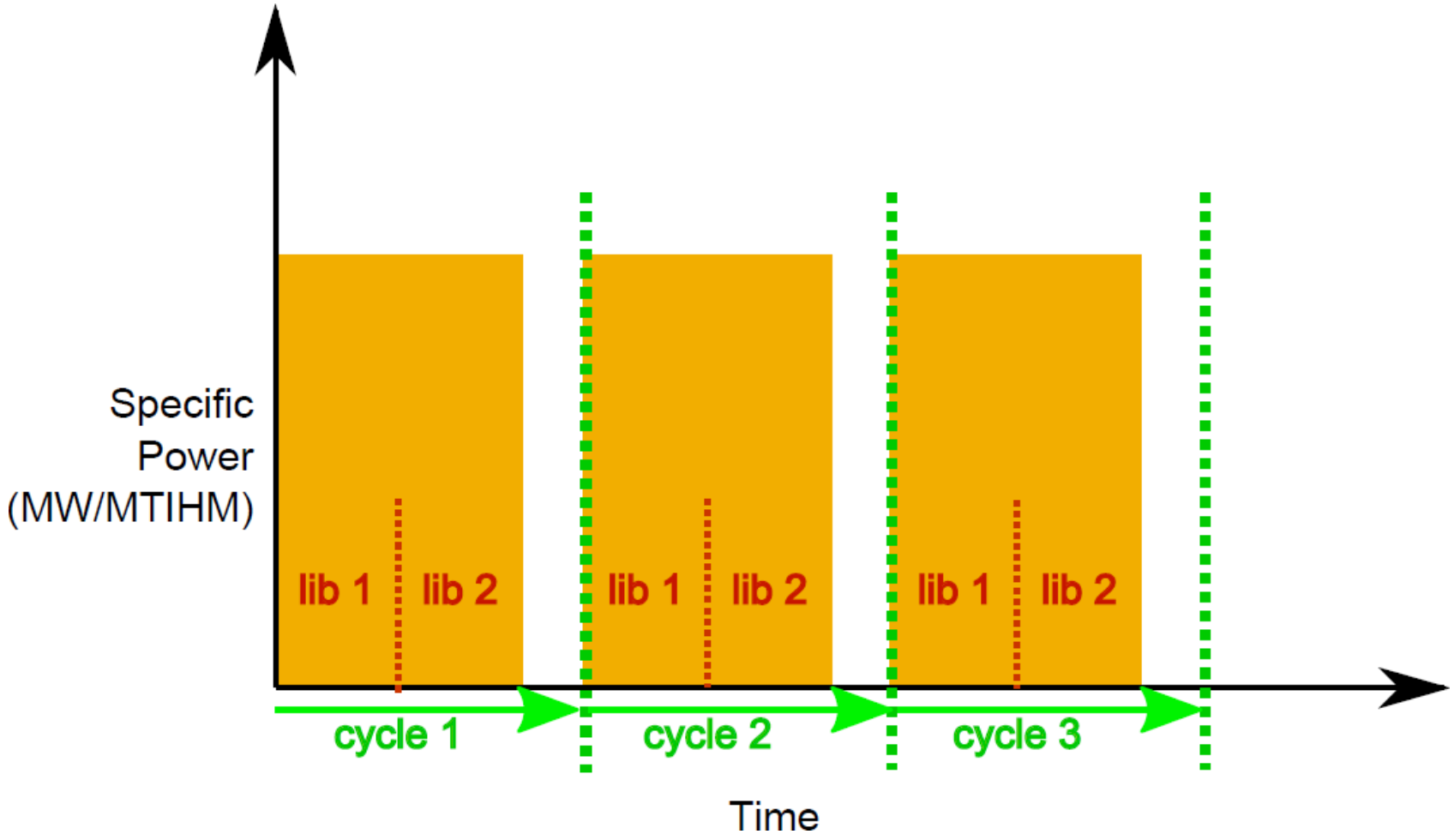
- create empty file (origami.inp)
- CTRL+SPACE inside empty file
- choose "origami – UO2 express form (configurable)

ORIGAMI "Express Form" (cont.)



- window will appear
- click "Create"
- click "OK"

Controlling Cross Section Interpolation (libraries per cycle)



ORIGAMI "Express Form" (cont.)

origami.inp*

document | SCALE 6.2 | Run

```
=origami

  title="this-is-my-title"
  options{ mtu=1.0 ft71=all}
  libs=[ "w17x17" ]
  fuelcomp{
    uox(fuel){ enrich=4.5 }
    mix(1){ comps=[ fuel=100 ] }
  }
  modz=[ 0.7332 ]
  pz=[ 1.0 ]
  hist[
    cycle{ power=40 burn=333.33 nlib=4 down=16.67 }
    cycle{ power=40 burn=333.33 nlib=4 down=16.67 }
    cycle{ power=40 burn=333.33 nlib=4 down=0 }
    cycle{ down=1825 }
  ]

end
```

- This is a valid ORIGAMI input!
- click Run

ORIGAMI "Express Form" (cont.)

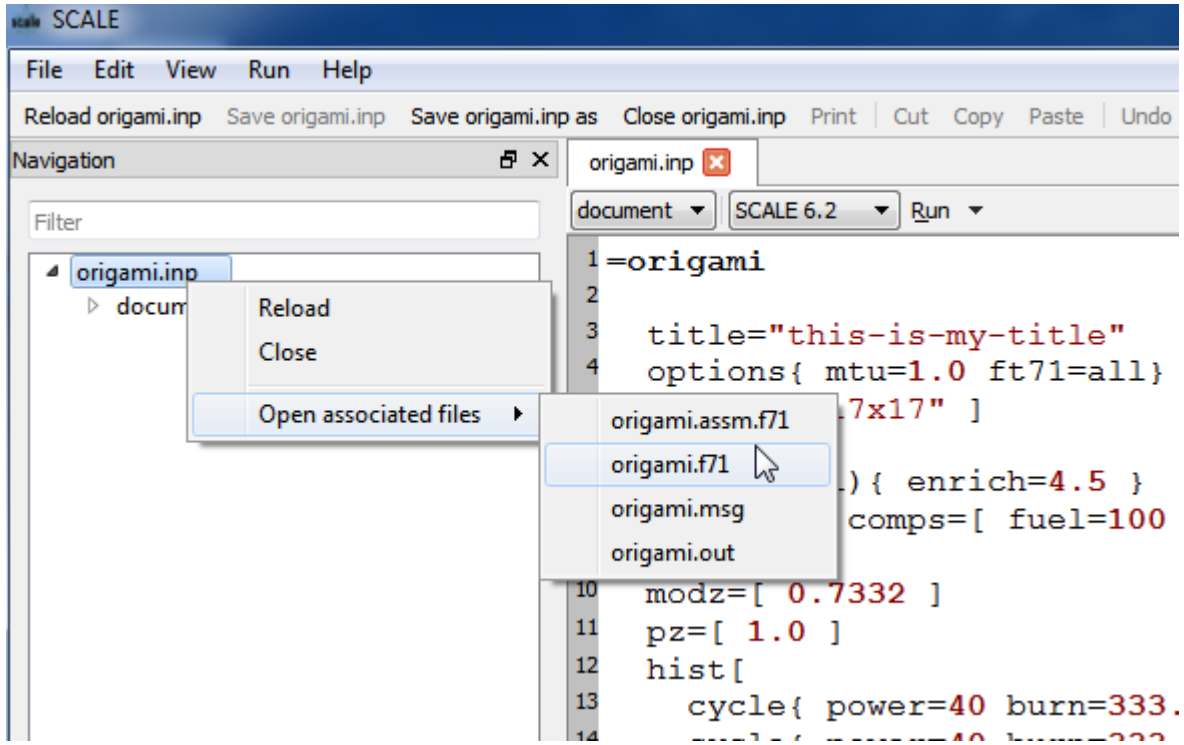
Wed Feb 17 17:13:11 2016 | Wed Feb 17 17:19:44 2016

```
 9  *                                                                      *
10  *                     Reactor and Nuclear Systems Division             *
11  *                       Oak Ridge National Laboratory                  *
12  *                                                                      *
13  *                          http://scale.ornl.gov                       *
14  *                           scalehelp@ornl.gov                         *
15  *                                                                      *
16  ************************************************************************
17  ************************************************************************
18
19                  Job Information
20                  ---------------
21       Job started on PC0091974 on Wed 17/02/2016 17:19:44
22       Working directory: C:\Users\ww5\AppData\Local\Temp\scale.ww5.13016
23       Input file name  : C:\Users\ww5\Desktop\origami.inp
24       Output file name : C:\Users\ww5\Desktop\origami.out
25       SCALE executable : C:\SCALE-6.2/bin/scale
26
27  ************************************************************************
28
29
30 Now depleting axial zone: 001, pin: 01-01
31
32
33 Scale job C:/Users/ww5/Desktop/origami.inp is finished.
34 Output is stored in C:\Users\ww5\Desktop\origami.out
35
36 Process finished with 0 return code; ran in 13 secs, finished at Wed Feb 17 17:19:57 2016
```

ORIGAMI takes a little while…

- performs by default 10 substeps
  - depletion equal length
  - decay rule of 3s
- nlib=4 would require 4 cases in ORIGEN
- the input has (4+4+4)*10=120 depletion solves and (1+1+0+1)*10=30 decay solves.

ORIGAMI "Express Form" (cont.)



- ORIGAMI produces .f71 and .assm.f71 by default
- open .f71
  - right-click on origami.inp in navigation pane
  - open associated files
  - origami.f71

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ORIGAMI Problem 2:

An example of safeguards application:

A 3 x 3 lattice model

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Problem 2: A 3 x 3 lattice model

- 3 x 3 lattice with a guide tube
- Two different fuel compositions
- Radial power (burnup) profile
- Three axial nodes with axial power profile
- Three non-uniform cycles
- Request neutron/gamma emission spectra after 5-year cooling time

An example

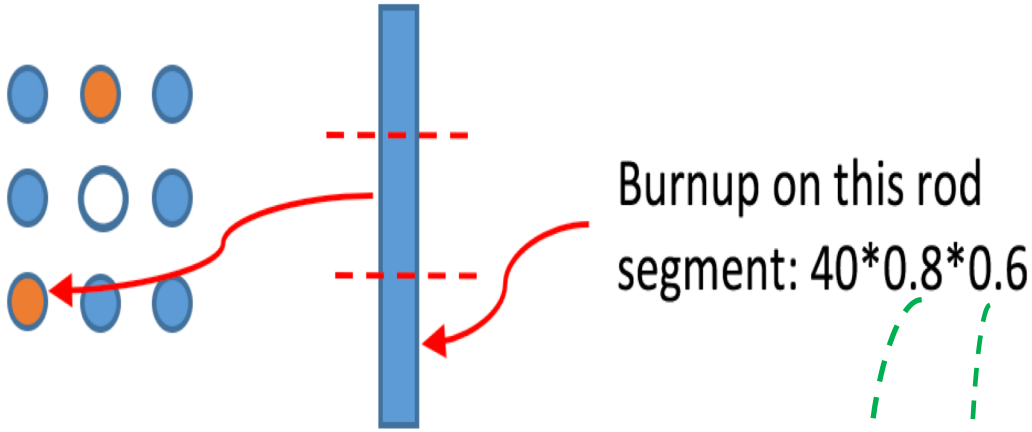
```
=origami
 title= 'multi-pin; multi-library'
 options{ mtu=0.45 decayheat=yes mcnp=yes relnorm=no}
 nonfuel= [ cr=3.5 fe=6.3 ]

 fuelcomp{
  uox(fuel_2pct){ enrich=2 dens=10.42 }
  uox(fuel_4pct){ enrich=4 dens=10.45 }
  mix(1){ comps[fuel_2pct=100] }
  mix(2){ comps[fuel_4pct=97.0 Gd2O3=3.0 ]} }
 compmap=[ 1  2  1
           1  0  1
           2  1  1 ]

 libs=[ w17x17  w17x17_Gd ]
 libmap=[ 1  2  1
          1  0  1
          2  1  1 ]

 pxy=[ 0.9  1.1  0.9
       1.2  0    1.2
       0.8  1.1  0.9 ]
 pz=[ 0.6 1.0 0.5 ]
 meshz=[  0 120  240  360 ]
 modz=[ 0.75 0.73 0.71 ]

 hist[
   cycle{ power=30  burn=500  nlib=4  down=45 }
   cycle{ power=50  burn=300  nlib=4  down=45 }
   cycle{ power=25  burn=400  nlib=4  down=1825 }
 ]
 ggrp=[ 10e6 2e6 1e6 0.01]
 ngrp=[ 20e6 1e6 1e5 0.025 ]
end
```



Lib1

Lib2*

Radial power/burnup profile

Axial power/burnup profile

Assembly avg. burnup:
40 GWd/MTU

Lib2*, not included in the SCALE package; need to be generated by the user for the Gd rods

ORIGAMI Output Files

*_AxialDecayHeat

```
 2.78253E+02
 5.89804E+02
 2.17135E+02
```

*_ MCNP_matls.inp

```
C  Axial zone: 03, Pin: 008
C  Zone mass (grams):  2.144858E+04
m803    1001   -8.598225E-09
           1002   -6.035635E-10
           1003   -2.526046E-08
           2003   -8.794443E-09
           2004   -3.262135E-06
           3006   -2.660487E-17
           3007   -7.905803E-18
           4009   -5.885097E-13
           5010   -6.966128E-17
           5011   -4.479028E-15
```

*_ MCNP_neutron.inp

```
C  Neutron source for axial zone 03, pin 001
C  Total intensity (n/sec):  5.2826E+05
SI103         H   2.5000E-08  1.0000E-01  1.0000E+00  2.0000E+01
SP103         D   1.1249E-02  2.5571E-01  7.3304E-01
```

Much more info in the main output file "*.out"

```
=============================================================================================
=   Nuclide concentrations in grams, actinides for case 'axial zone: 001, pin: 03-01' (#6)
=   multi-pin; multi-library
---------------------------------------------------------------------------------------------
  (relative cutoff; integral of concentrations over time >   1.00E-04 % of integral of all
.
                1290.000d   1290.093d   1290.278d   1290.834d   1292.503d   1297.510d   131
  u-234      1.8117E+00  1.8117E+00  1.8117E+00  1.8118E+00  1.8119E+00  1.8122E+00  1.81
  u-235      6.6208E+01  6.6208E+01  6.6208E+01  6.6208E+01  6.6208E+01  6.6209E+01  6.62
  u-236      5.0132E+01  5.0132E+01  5.0132E+01  5.0132E+01  5.0133E+01  5.0133E+01  5.01
  u-238      1.7853E+04  1.7853E+04  1.7853E+04  1.7853E+04  1.7853E+04  1.7853E+04  1.78
  np-237     6.2240E+00  6.2248E+00  6.2263E+00  6.2307E+00  6.2425E+00  6.2679E+00  6.29
  pu-238     2.7486E+00  2.7491E+00  2.7500E+00  2.7527E+00  2.7589E+00  2.7694E+00  2.78
  pu-239     9.3958E+01  9.3987E+01  9.4044E+01  9.4197E+01  9.4530E+01  9.4935E+01  9.50
  pu-240     4.6659E+01  4.6659E+01  4.6659E+01  4.6659E+01  4.6659E+01  4.6659E+01  4.66
  pu-241     2.4857E+01  2.4856E+01  2.4856E+01  2.4854E+01  2.4848E+01  2.4832E+01  2.47
  pu-242     1.2514E+01  1.2514E+01  1.2514E+01  1.2514E+01  1.2514E+01  1.2515E+01  1.25
  am-241     9.5200E-01  9.5231E-01  9.5292E-01  9.5475E-01  9.6025E-01  9.7675E-01  1.02
  am-243     2.3990E+00  2.3995E+00  2.4002E+00  2.4008E+00  2.4010E+00  2.4010E+00  2.40
  cm-242     2.9934E-01  2.9937E-01  2.9941E-01  2.9925E-01  2.9771E-01  2.9156E-01  2.73
  cm-244     9.0308E-01  9.0315E-01  9.0316E-01  9.0314E-01  9.0301E-01  9.0254E-01  9.01
  cm-245     4.8234E-02  4.8234E-02  4.8234E-02  4.8234E-02  4.8234E-02  4.8234E-02  4.82
------------
  totals     1.8163E+04  1.8163E+04  1.8163E+04  1.8163E+04  1.8163E+04  1.8163E+04  1.81
```

Import ORIGAMI results into MCNP detector models

```
C   Fuel assembly lattice
900 0 -12 13 -14 15 lat=1 imp:n=1 u=70 fill=-7:6 -7:6 0:0
       44 45 46 47 48 49 50 50 49 48 47 46 45 44
       37 38 39 40 41 42 43 43 42 41 40 39 38 37
       32 33 51 34 35 51 36 36 51 35 34 51 33 32
       25 26 27 28 29 30 31 31 30 29 28 27 26 25
       19 20 21 22 51 23 24 24 23 51 22 21 20 19
       13 14 51 15 16 17 18 18 17 16 15 51 14 13
        1  2  3  4  5 10 51 11 12  5  4  3  2  1
        1  2  3  4  5  6  7  8  9  5  4  3  2  1
       13 14 51 15 16 17 18 18 17 16 15 51 14 13
       19 20 21 22 51 23 24 24 23 51 22 21 20 19
       25 26 27 28 29 30 31 31 30 29 28 27 26 25
       32 33 51 34 35 51 36 36 51 35 34 51 33 32
       37 38 39 40 41 42 43 43 42 41 40 39 38 37
       44 45 46 47 48 49 50 50 49 48 47 46 45 44
c 901 0    -100           imp:n=1 fill=70
```

```
m147
      90230   2.933E-09
      90232   4.284E-09
      91231   5.646E-10
      92233   5.496E-09
      92234   2.286E-05
      92235   6.968E-03
      92236   1.770E-03
      92238   2.970E-01
      93236   5.379E-10
```

```
sdef cel d10 pos 0 0 0 rad d2 ext d3 axs d4
      erg=d101 par=1
si10 l 2001:402:403:601
sp10 1
c
si2 0 0.4096
sp2 -21 1
c extent of the source
si3 -182.88 182.88
sp3 0 1
c axis of the source
si4 l 0 0 1
sp4 1
c
c neutron spectrum
c total neutron emission: 5.475684E+07 n/s/0.1MTU
SI101    H   1.00E-04
             1.00E-03 1.00E-02 3.00E-02 6.00E-02 1.00E-01 2.00E-01
             4.00E-01 6.00E-01 8.00E-01 1.00E+00 2.00E+00 3.00E+00
             4.00E+00 5.00E+00 6.00E+00 7.00E+00 8.00E+00 9.00E+00
             1.00E+01 1.20E+01 1.40E+01 1.60E+01 1.80E+01 2.00E+01
SP101    D   0
             6.19E+02 1.95E+04 8.42E+04 1.88E+05 3.30E+05 1.09E+06
             2.83E+06 3.29E+06 3.49E+06 3.53E+06 1.58E+07 1.11E+07
             6.53E+06 3.35E+06 1.64E+06 8.02E+05 3.81E+05 1.77E+05
             8.06E+04 5.20E+04 9.93E+03 1.82E+03 3.21E+02 5.52E+01
```

OAK RIDGE National Laboratory

ORIGAMI Problem 3:

Detailed form using Fulcrum:

A 2 x 2 lattice model

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

[1] W. Wieselquist, H. Liljenfeldt, ORIGAMI Spent Fuel Characterization, Scale Users' Group Workshop, ORNL, 2017

Problem 3: A 2 x 2 lattice model using detailed form

- 2 x 2 lattice
- Two different fuel compositions
- Radial power (burnup) profile
- One long cycle with constant power
- Ten axial nodes with axial power profile
- Nonfuel components

ORIGAMI input from scratch

origami.inp

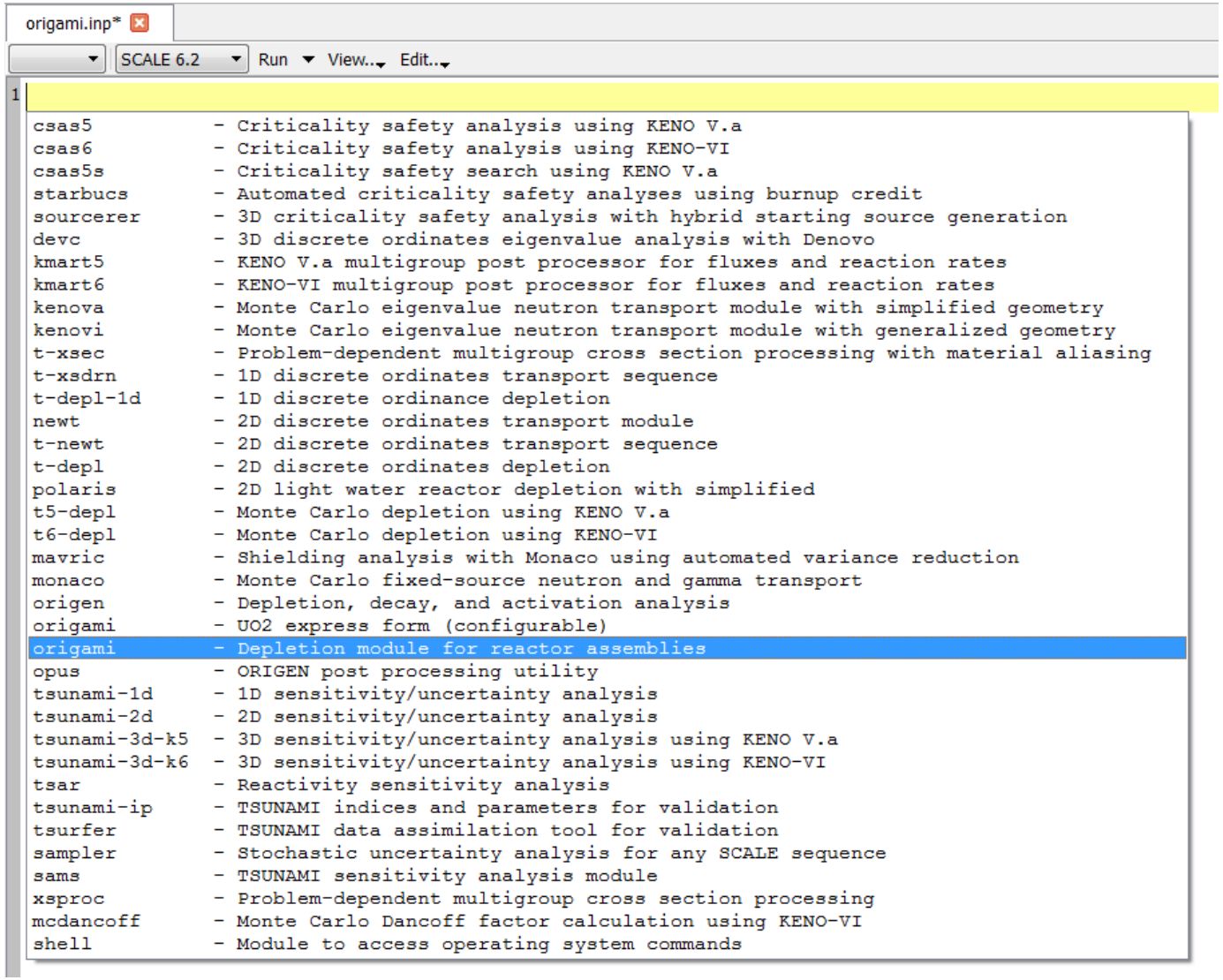
document | SCALE 6.2 | Run | View... | Edit...

```
1 =origami
2   libs=[ "w15x15" ]
3   fuelcomp{
4     uox(fuel){ enrich=4.5 }
5     mix(1){ comps=[ fuel=100 ] } }
6   hist[ cycle{ power=40 burn=1500 down=3650 } ]
7 end
```

- **`Libs`** – reactor library
- **`fuelcomp`** – declare mixtures (single mixture problems use 1)
- **`hist`** – operating history

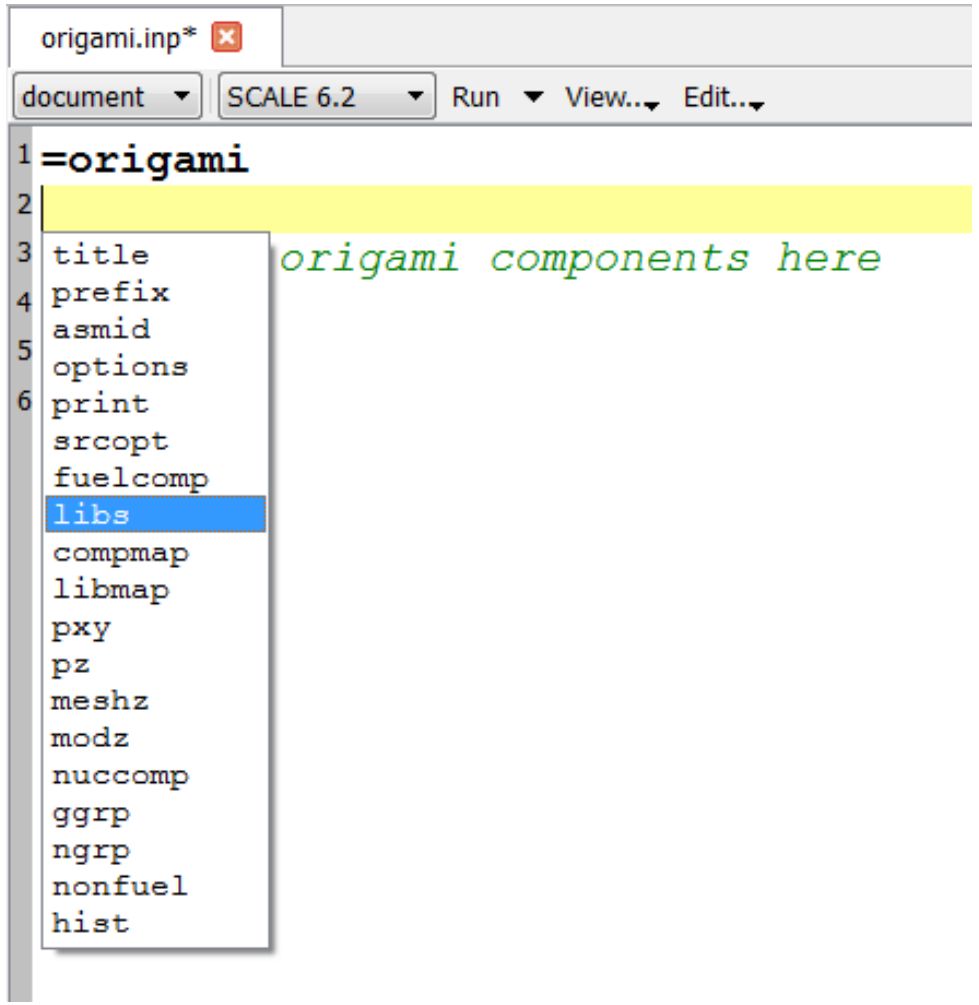
This is all that is needed to run ORIGAMI.

ORIGAMI input from scratch (cont.)



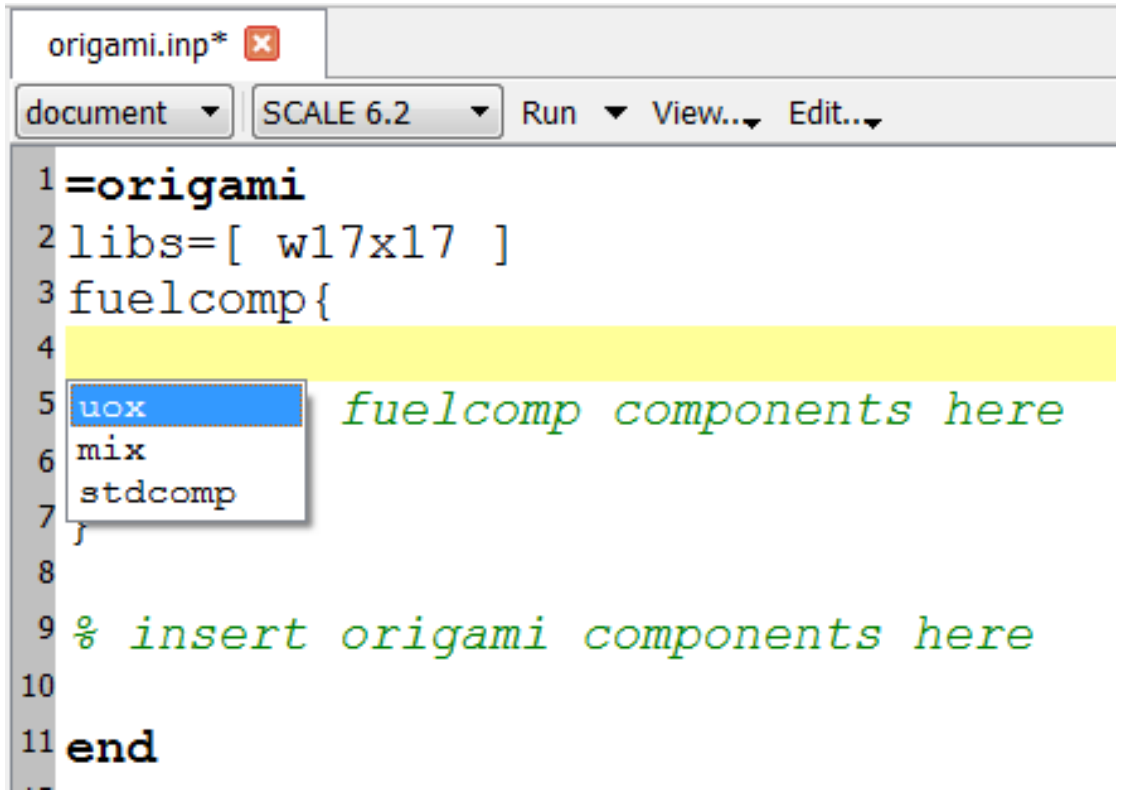
- Create new input file
- CTRL + SPACE and select origami **(not UO2 express form)**

ORIGAMI input from scratch (cont.)



- Put marker inside of origami sequence
- CTRL + SPACE and select libs
- Repeat for fuelcomp

ORIGAMI input from scratch (cont.)



- Put marker inside of fuelcomp sequence
- CTRL + SPACE and select uox
- Repeat for mix

ORIGAMI input from scratch (cont.)

origami.inp*

document | SCALE 6.2 | Run | View... | Edit...

```
=origami
libs=[ w17x17 ]
fuelcomp{
uox(fuel){

  enrich=5.0

}
mix(1){ comps[ fuel=100.0 ] }

% insert fuelcomp components here

}
hist[

cycle
% insert cycles here

]

% insert origami components here

end
```

- Put marker outside fuelcomp but inside origami
- CTRL + SPACE and select hist
- Repeat for cycle **(inside hist)**

ORIGAMI input from scratch (cont.)

origami.inp*

document | SCALE 6.2 | Run | View... | Edit...

```
=origami
libs=[ w17x17 ]
fuelcomp{
uox(fuel){

  enrich=5.0

}
mix(1){ comps[ fuel=100.0 ] }

% insert fuelcomp components here

}
hist[
cycle{ power=40 burn=365 down=31 }


% insert cycles here

]

% insert origami components here

end
```

Final input should look something like this.

Or cleaned up:

origami.inp

document | SCALE 6.2 | Run | View... | Edit...

```
=origami
libs=[ w17x17 ]
fuelcomp{ uox(fuel){enrich=5.0} mix(1){ comps[ fuel=100.0 ] }}
hist[ cycle{ power=40 burn=365 down=31 }]
end
```

File is ready to run.

Results will be per MTU

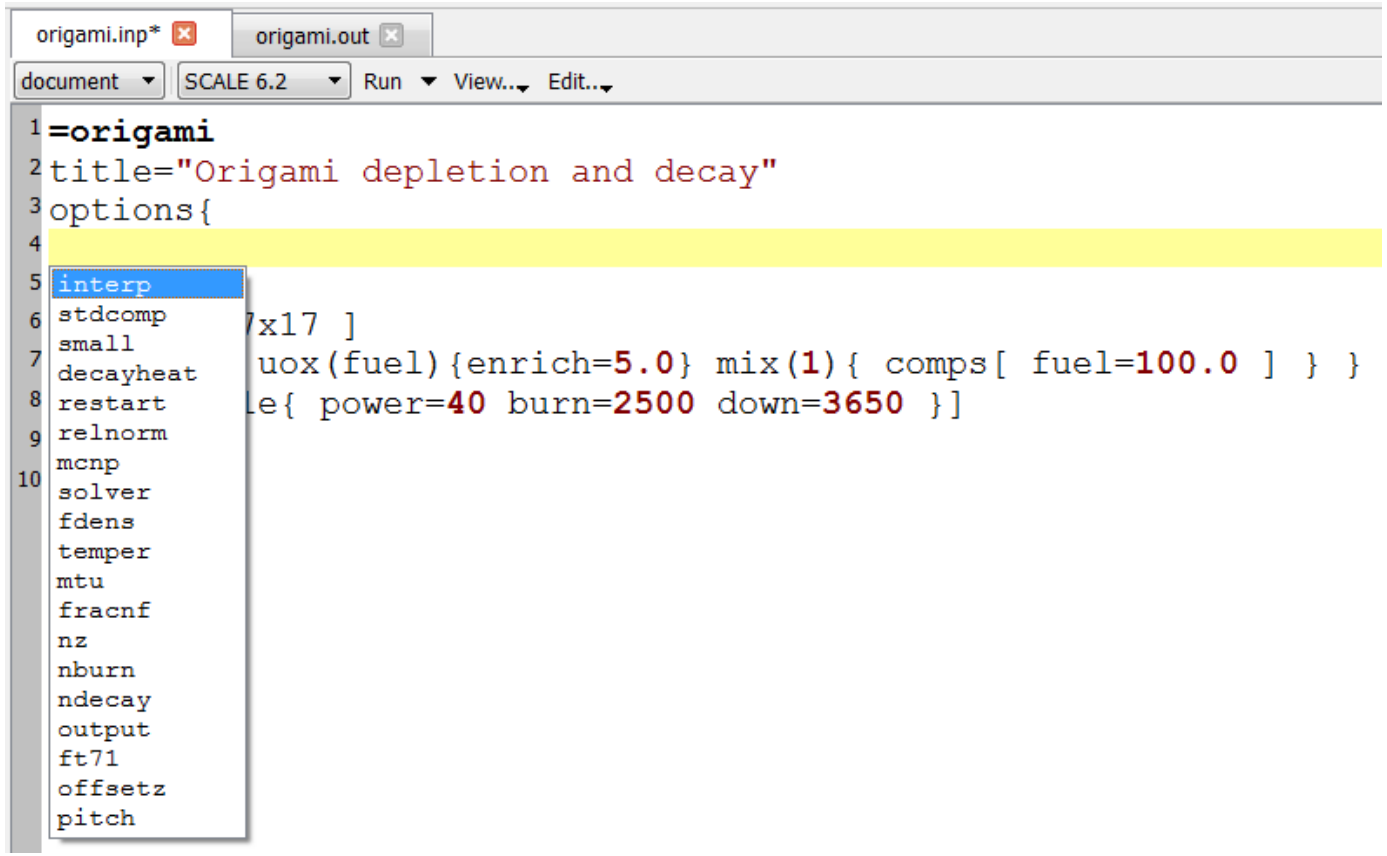
```


Now depleting axial zone: 001, pin: 01-01


Scale job C:/SCALE-6.2/henrik/temp/origami.inp is finished.
Output is stored in C:\SCALE-6.2\henrik\temp\origami.out

Process finished with 0 return code; ran in 3 secs, finished at Wed Oct 19 10:24:53 2016
```

ORIGAMI input: Options

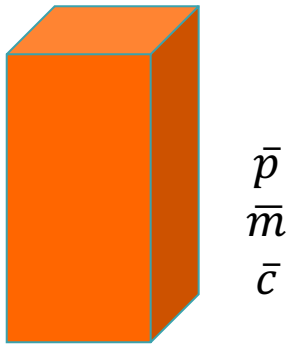


miscellaneous input

- **`mtu`**
  - metric tons of initial heavy metal (not just U)
  - used to convert to power in MW
  - DEFAULT: 1 MTU
- **`ft71`**
  - flag to write f71 file last/cycle/all
- **other options**
  - **`stdcomp`** write SCALE StdComp blocks
  - **`decayheat`** write file with axial decay heat

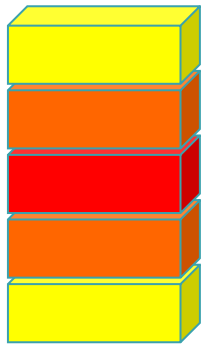
ORIGAMI spatial variation

- power shape → axial & radial → $p(z)\times p(x,y)$
- moderator density → axial only → $m(z)$
- fuel composition → radial only → $c(x,y)$



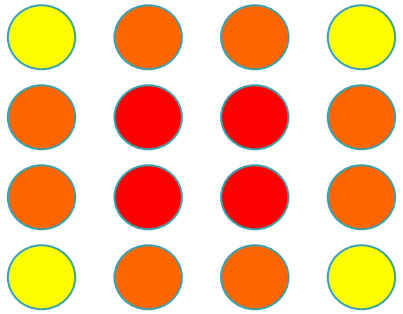
$\bar{p}$
$\bar{m}$
$\bar{c}$

0D assembly



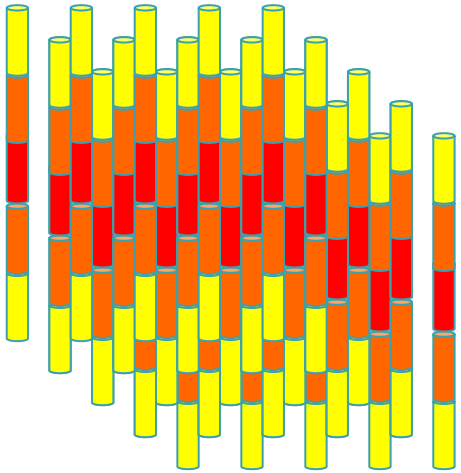
$p(z)$
$m(z)$
$\bar{c}$

1D assembly



$p(x,y)$
$\bar{m}$
$c(x,y)$

2D assembly

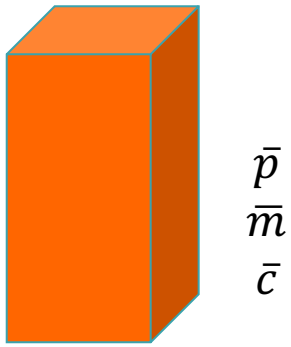


$p(x,y)\times p(z)$
$m(z)$
$c(x,y)$

3D assembly

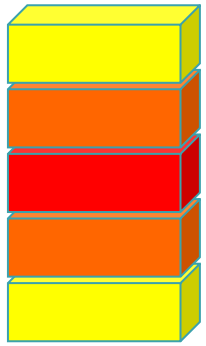
ORIGAMI spatial variation

- limitations
  - *no time-dependence*
  - *axially-dependent compositions really needed for BWRs*



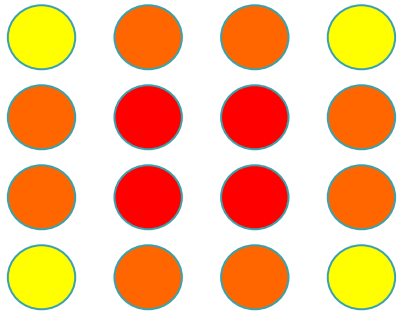
$\bar{p}$
$\bar{m}$
$\bar{c}$

0D assembly



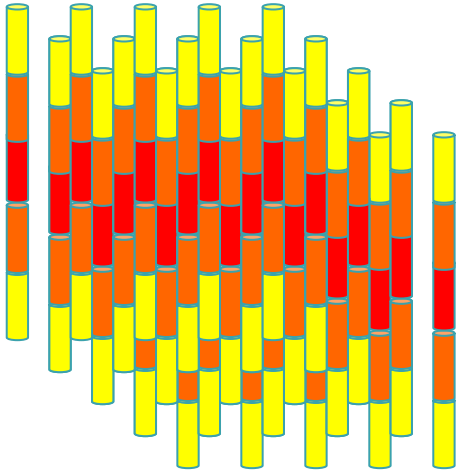
$p(z)$
$m(z)$
$\bar{c}$

1D assembly



$p(x,y)$
$\bar{m}$
$c(x,y)$

2D assembly



$p(x,y)\times p(z)$
$m(z)$
$c(x,y)$

3D assembly

ORIGAMI Input: Radial and axial distributions

origami.inp* | origami.f71

document | SCALE 6.2 | Run | View.. | Edit..

```
=origami
title="Origami depletion and decay 2x2 fuel array"
libs=[ w17x17 w15x15 ]
libmap=[ 1 2
         2 1 ]
fuelcomp{
    uox(fuel){enrich=5.0}
    mix(1){ comps[ fuel=100.0 ] }
    uox(fuel2){enrich=4.0}
    mix(2){ comps[ fuel2=100.0 ] }
}
compmap=[ 2 1
          1 2 ]
hist[ cycle{ power=20 burn=2500 down=3650 }]
pxy=[ 0.80 1.00
      1.00 0.80 ]
pz=[ 0.2 0.5 0.8 1.0 1.1 1.15 1.2 0.9 0.6 0.3 ]
end
```

Axial and radial power distribution

- **`pxy, pz`**
  - power shape (unitless)
  - renormalized by default
- All zones same cool time
- All axial nodes same material and reactor libraries

ORIGAMI Input: modz and meshz

origami.inp

document | SCALE 6.2 | Run | View... | Edit...

```
=origami
title="Origami depletion and decay 2x2 fuel array"
options{ decayheat=yes stdcomp=yes }
libs=[ w17x17 w15x15 ]
libmap=[ 1 2
         2 1 ]
fuelcomp{
    uox(fuel){enrich=5.0}
    mix(1){ comps[ fuel=100.0 ] }
    uox(fuel2){enrich=4.0}
    mix(2){ comps[ fuel2=100.0 ] }
}
compmap=[ 2 1
          1 2 ]
hist[ cycle{ power=20 burn=2500 down=3650 }]
pxy=[ 0.80 1.00
      1.00 0.80 ]
pz=    [ 0.20 0.50 0.80 1.00 1.10 1.15 1.20 0.90 0.60 0.30 ]
modz=  [ 0.75 0.74 0.73 0.72 0.71 0.70 0.69 0.68 0.67 0.66 ]
meshz= [ 0  10   50   100  150  200  250  300  350  360  370 ]
end
```

- **meshz** - used to evaluate non-uniform axial nodes.
  - **pz** +1 number of entries
- **modz** - used to evaluate changing moderator density
  - Same number of entries as **pz**
  - Requires moderator density interpolation in reactor library or will always use same value.

ORIGAMI Input: Non-fuel components

origami.inp

document | SCALE 6.2 | Run | View... | Edit...

```
=origami
title="Origami depletion and decay 2x2 fuel array"
options{ decayheat=yes stdcomp=yes }
libs=[ w17x17 w15x15 ]
libmap=[ 1 2
         2 1 ]
fuelcomp{
    uox(fuel){enrich=5.0}
    mix(1){ comps[ fuel=100.0 ] }
    uox(fuel2){enrich=4.0}
    mix(2){ comps[ fuel2=100.0 ] }
}
compmap=[ 2 1
          1 2 ]
hist[ cycle{ power=20 burn=2500 down=3650 }]
pxy=[ 0.80 1.00
      1.00 0.80 ]
pz=    [ 0.20 0.50 0.80 1.00 1.10 1.15 1.20 0.90 0.60 0.30 ]
modz=  [ 0.75 0.74 0.73 0.72 0.71 0.70 0.69 0.68 0.67 0.66 ]
meshz= [ 0  10   50   100  150  200  250  300  350  360  370 ]
nonfuel[ zirc4=200 co=0.02 ]
end
```

- **nonfuel** is given in kg per MTU
  - Give value pairs of standard compositions (i.e. Zirc4), nuclides (i.e. zr-94) or elements (Zr)
  - Can be used to activate cladding, top and bottom nozzles, spacers, fuel channels, control rods/blades, etc.

ORIGAMI Input: Sources

origami.inp*

document | SCALE 6.2 | Run | View... | Edit...

```
=origami
title="Origami depletion and decay 2x2 fuel array"
options{ decayheat=yes stdcomp=yes }
libs=[ w17x17 w15x15 ]
libmap=[ 1 2
         2 1 ]
fuelcomp{
    uox(fuel){enrich=5.0}
    mix(1){ comps[ fuel=100.0 ] }
    uox(fuel2){enrich=4.0}
    mix(2){ comps[ fuel2=100.0 ] }
}
compmap=[ 2 1
          1 2 ]
hist[ cycle{ power=20 burn=2500 down=3650 }]
pxy=[ 0.80 1.00
      1.00 0.80 ]
pz=    [ 0.20 0.50 0.80 1.00 1.10 1.15 1.20 0.90 0.60 0.30 ]
modz=  [ 0.75 0.74 0.73 0.72 0.71 0.70 0.69 0.68 0.67 0.66 ]
meshz= [ 0  10   50   100  150  200  250  300  350  360  370 ]
nonfuel[ zirc4=200 co=0.02 ]
srcopt{
    sublib=all
    brem_medium=uo2
    alphan_medium=case
    print=no
}
ggrp=[  3.0E+06 2.5E+06 2.0E+06 1.5E+06 1.0E+06 0.7E+06 0.4E+06 ]
ngrp=[ 20.0E+06 6.4E+06 3.0E+06 1.8E+06 1.4E+06 0.9E+06 0.4E+06 0.1E+06 ]
end
```

- **scropt** – options for neutron and gamma sources
- **ggrp, ngrp** – gamma/neutron group structure
  - Given as boundaries in descending order

ORIGAMI Input: Print

origami.inp

document | SCALE 6.2 | Run | View... | Edit...

```
=origami
title="Origami depletion and decay 2x2 fuel array"
options{ decayheat=yes stdcomp=yes }
libs=[ w17x17 w15x15 ]
libmap=[ 1 2 2 1 ]
fuelcomp{uox(fuel){ enrich=5.0} mix(1){ comps[ fuel= 100.0 ] }
         uox(fuel2){enrich=4.0} mix(2){ comps[ fuel2=100.0 ] } }
compmap=[ 2 1 1 2 ]
hist[ cycle{ power=20 burn=2500 down=3650 }]
pxy=[ 0.80 1.00 1.00 0.80 ]
pz=    [ 0.20 0.50 0.80 1.00 1.10 1.15 1.20 0.90 0.60 0.30 ]
modz=  [ 0.75 0.74 0.73 0.72 0.71 0.70 0.69 0.68 0.67 0.66 ]
meshz= [ 0  10   50   100  150  200  250  300  350  360  370 ]
nonfuel[ zirc4=200 co=0.02 ]
srcopt{ sublib=all brem_medium=uo2 alphan_medium=case print=no}
ggrp=[  3.0E+06 2.5E+06 2.0E+06 1.5E+06 1.0E+06 0.7E+06 0.4E+06 ]
ngrp=[ 20.0E+06 6.4E+06 3.0E+06 1.8E+06 1.4E+06 0.9E+06 0.4E+06 0.1E+06 ]
print{
    nuc{
        sublibs=[ lt ac fp ]
        total=yes
        units=[ grams watts curies ]
    }
}
nuccomp=[ 8016 92234 92235 92236 92238 93237 94238 94239 94240 94241 94242
          95241 95243 42095 43099 44101 45103 47109 55133 60143 60145 62147
          62149 62150 62151 62152 63151 63153 64155 ]
end
```

- print – sets what is shown in the output for last time step
  - Select between nuclides (nuc) or element (ele)
  - Sublibs, can be light elements (lt), actinides (ac), fission products (fp) or all.
  - total = yes will print the total concentration for each output unit type