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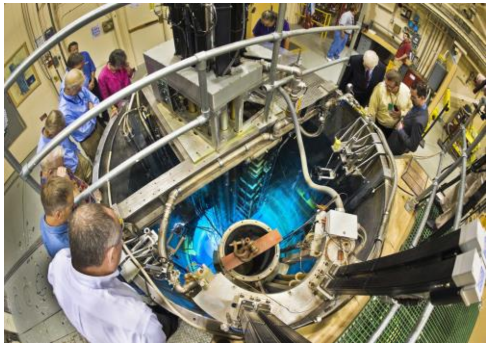

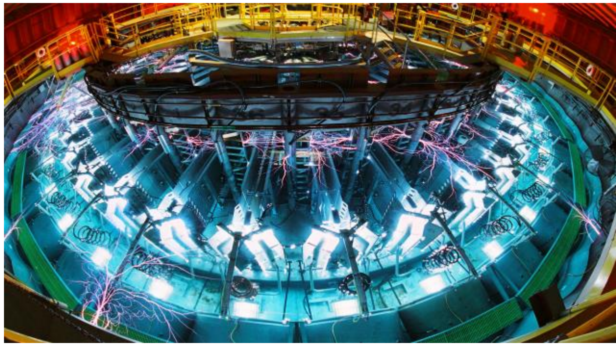

Characterization of ACPR Spent Fuel

By: Richard Vega

8/13/13

TA-V LEADING NUCLEAR TECHNOLOGIES

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Background and Motivation

Figure 1. HC-3 container from the Legacy experiment (left) , and questionable container labeled "ACPR fuel" (right).

- One of the Corporate Storage Bunkers is shut down due to a HC-3 occurrence in March 2013.
- There are several containers in this bunker labeled "ACPR fuel."
- Unknowns about the ACPR fuel in the containers:
  - ❖ Irradiation history
  - ❖ Position in the ACPR core
  - ❖ Radionuclide inventories
  - ❖ Clad or no clad?
- In order to determine the HC-3 sum of fractions, the radionuclide inventories must be determined.

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Solution to the Problem

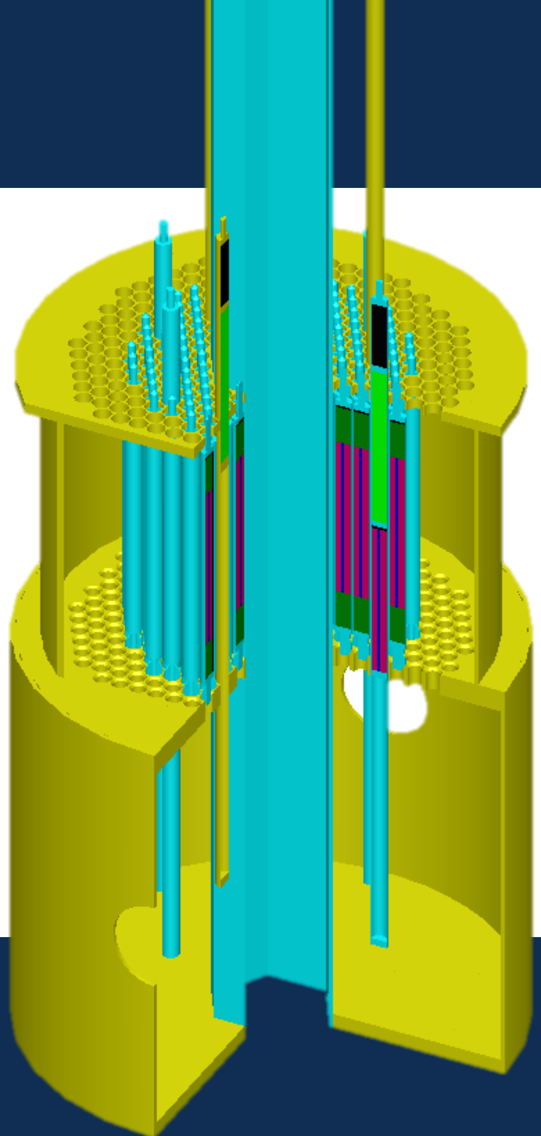

Figure 2. KENOVI model of the ACPR.

- Model the ACPR reactor and use Monte Carlo simulation codes to calculate the burnup in the fuel.
- Codes used:
  - ❖ SCALE 6.1: TRITON coupling of KENOVI and ORIGEN-S
  - ❖ Serpent 2 Beta
- Documents used for model parameters:
  - ❖ ACPR SAR [1]
  - ❖ ACRR DSA [2]
  - ❖ MCNP/MCNPX Model of the Annular Core Research Reactor [3]
  - ❖ SCALE Standard Compositions Library [4]
- Documents still needed:
  - ❖ ACPR energy release logs

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Assumptions and Conditions

- Validity of the steady state approximation to pulse power.
  - ❖ Common practice to determine source terms
  - ❖ Confirmed over relatively short time spans (months)
- Determination of the steady state power level without the energy release logs.
  - ❖ One case representing 4 pulse per day for each pulse height.
  - ❖ ACPR SAR statement of burnup: "Through the year 1972, the ACPR had accumulated a total of only 13.2 MWd of operation." [1]
- The irradiation time was varied from 1 year to 10 years.
- The fuel temperature was set at the maximum measured temperature for each pulse height. The sixth case used 737 °C to be conservative.

Table 1. ACPR pulse characteristics (left) and corresponding steady state power levels (right).

Reactivity ($)	FWHM (msec)	Maximum Measured Temperature (°C)	Energy Release (MJ)
2.50	10.6	435	42
3.00	8.0	518	55
3.50	6.3	602	68
4.00	5.3	678	82
4.42	4.6	737	92

Bounding Case	Steady State Power Level (kW)
Four 42 MJ pulses per day	1.944
Four 55 MJ pulses per day	2.546
Four 68 MJ pulses per day	3.148
Four 82 MJ pulses per day	3.796
Four 92 MJ pulses per day	4.259
SAR statement of burnup	7.885

Pulse vs. Steady State

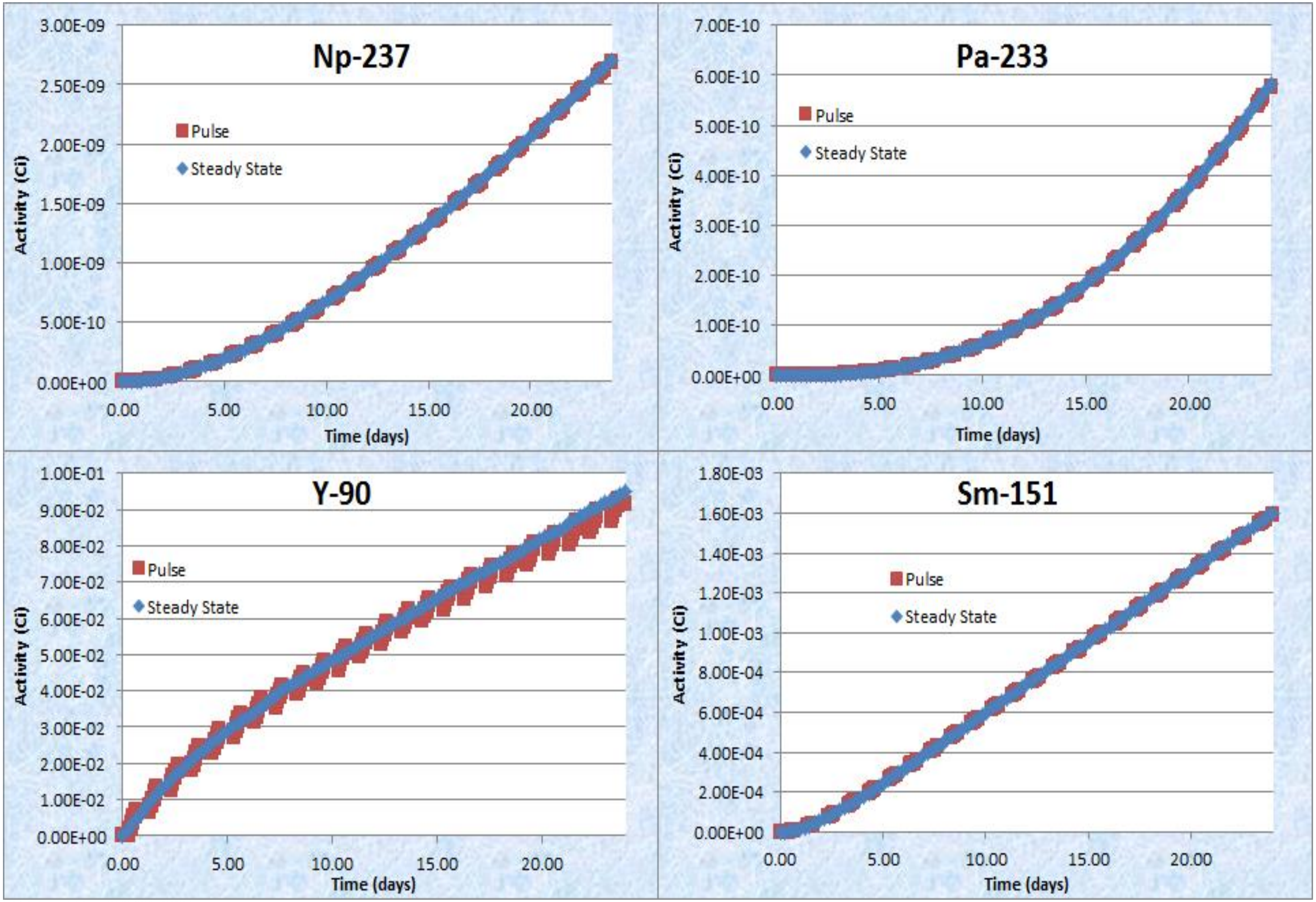
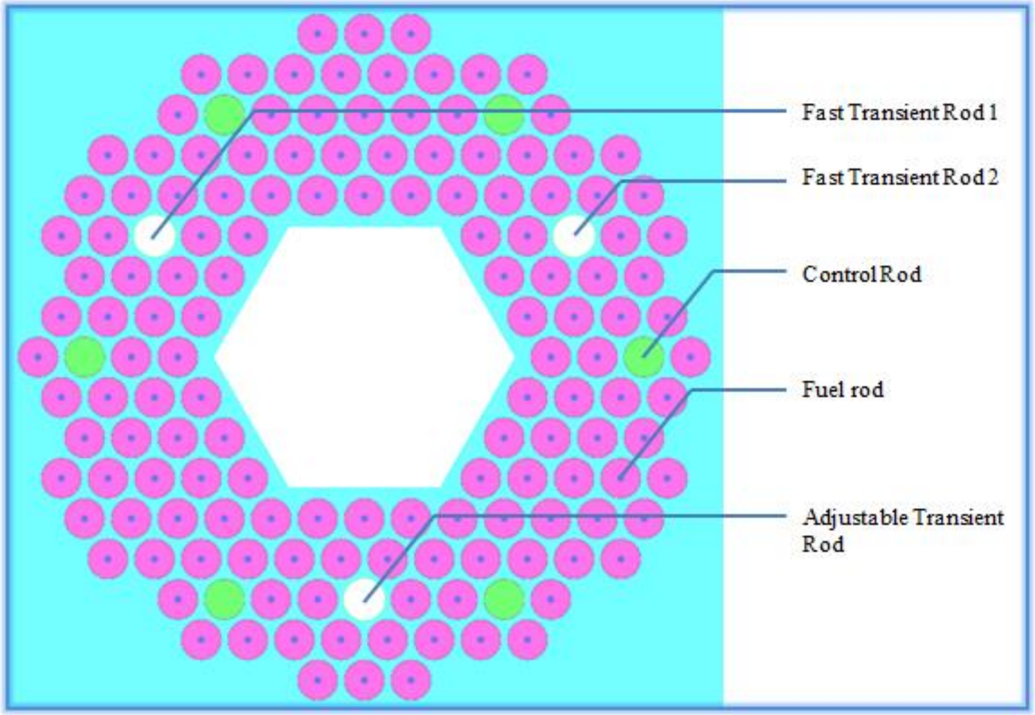


Figure 3. Activities as a function of time for both puling power and steady state power.

Fuel Pin Geometry and Core Layout



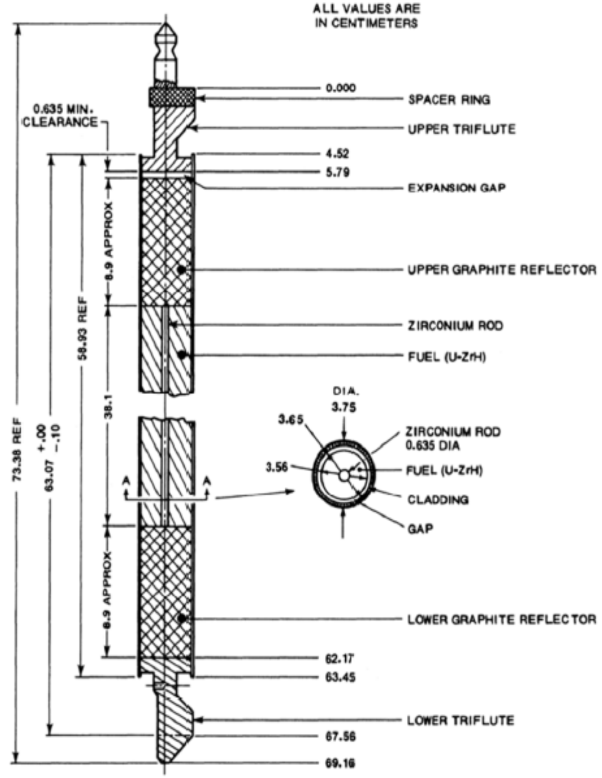


Figure 4. ACPR core layout (above), comparison of the fuel rod as modeled to the description given in the SAR [1] (upper right), and the internals of a TRIGA fuel rod, taken from General Atomics [5] (right).

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Control Rods & Transient Rods

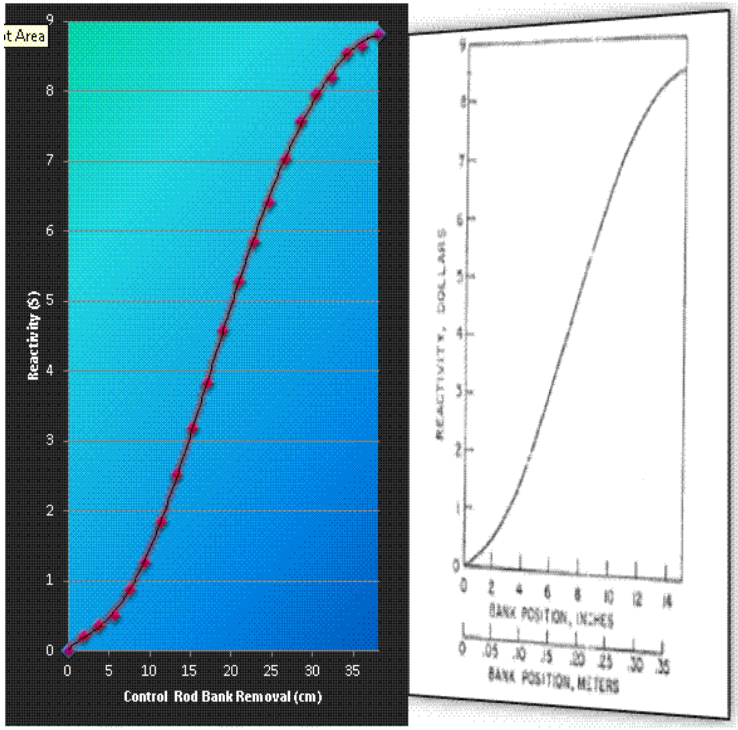

Figure 5. Comparison of the calculated integral control rod worth curve (left) with the same curve given in the ACPR SAR [1].

- Control rods are fuel followed and are moved together as a bank with a stroke of 38.1 cm.
- Transient rods are void followed:
  - ❖ Fast transient rods: 76.2 cm poison region with a stroke of 91.4 cm.
  - ❖ Adjustable transient rod: 38.1 cm poison region with a stroke of 42 cm.
- The control rods were modeled at the position that caused criticality, just as they would be during a pulse. This position was 53.8% removed.
- The transient rods were modeled 100 % removed from the core.

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All values taken from the ACPR SAR. [1]

Burnup Model

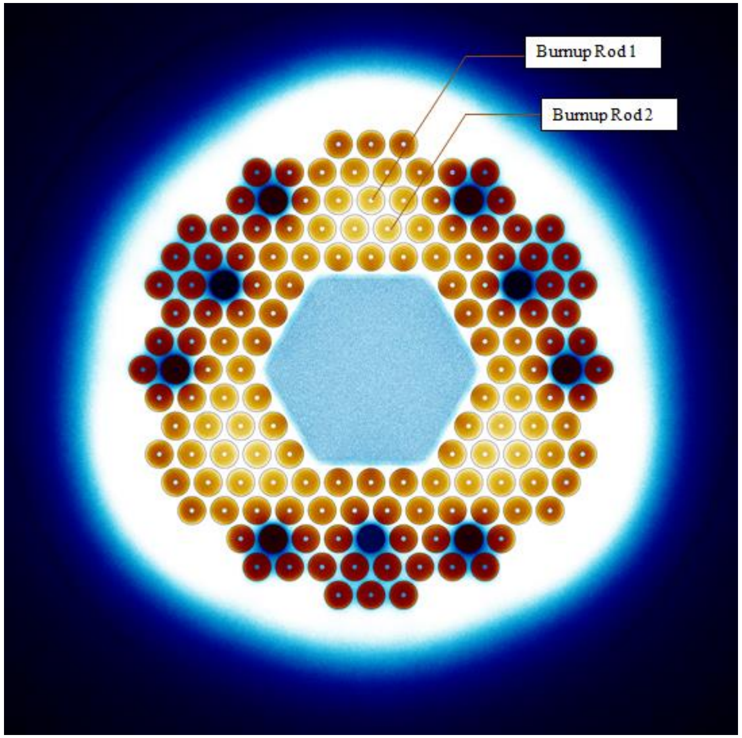

Figure 6. Thermal flux/fission rate density profile of the ACPR core.

- The fuel material in the two highest pin powers were tracked separately.
- Isotope inventories tracked: ^{241}Am, ^{242m}Am, ^{243}Am, ^{242}Cm, ^{245}Cm, ^{137}Cs, ^{154}Eu, ^{3}H, ^{166m}Ho, ^{85}Kr, ^{59}Ni, ^{237}Np, ^{233}Pa, ^{147}Pm, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{151}Sm, ^{90}Sr, ^{99}Tc, ^{228}Th, ^{230}Th, ^{234}U, ^{236}U, and ^{90}Y.
- Originally, the calculation was performed in order to determine a worst case scenario, so the fuel was burned for the full 10 year reactor lifetime.
- More data points have since been generated for lesser irradiation periods.
- Each case is followed by a decay period giving the final composition on January 1 2014.

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Results

- The burnup for the worst case scenario remained below 1 %.
- The maximum burnup occurred in the second row from the irradiation cavity.
- Serpent 2 burnup results were generated for comparison to ORIGEN-S.
- The calculated activities can be used to determine the HC-3 sum of fractions for an ACPR fuel element.

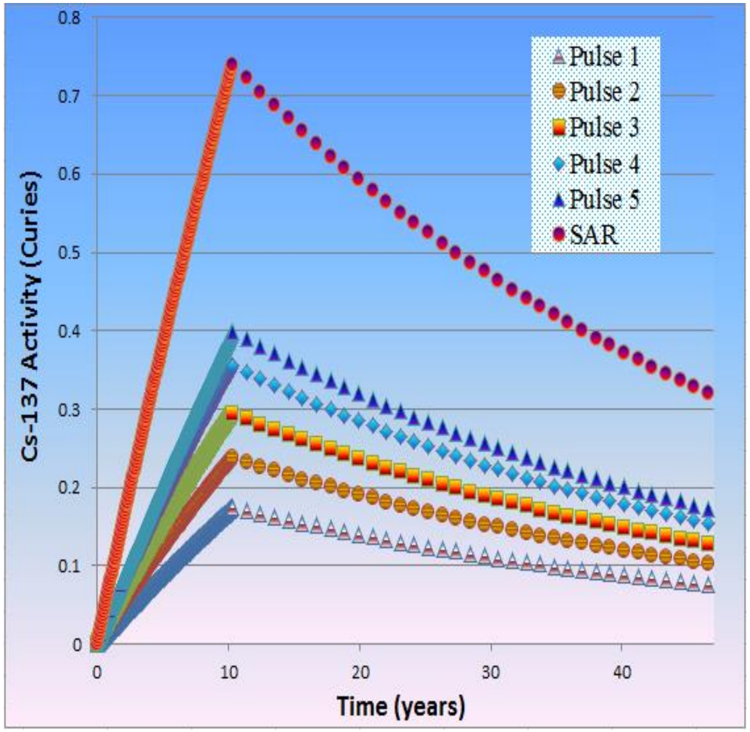

Figure 7. Activity of Cs-137 as a function of time to illustrate the relative magnitudes of the six cases.

Table 2. Burnup after 10 years at each of the six steady state power levels considered.

Bounding Case	Maximum Burnup (% ^{235}U removed)
Case 1: Four 42 MJ pulses per day	0.160
Case 2: Four 55 MJ pulses per day	0.213
Case 3: Four 68 MJ pulses per day	0.239
Case 4: Four 82 MJ pulses per day	0.293
Case 5: Four 92 MJ pulses per day	0.346
Case 6: SAR statement of burnup	0.612

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HC-3 Sum of Fractions

Table 3. HC-3 contributions for ten years at each of the six power levels considered.

Nuclide	HC3 Threshold (Ci)	Case 1 (Ci)	Fraction	Case 2 (Ci)	Fraction	Case 3 (Ci)	Fraction	Case 4 (Ci)	Fraction	Case 5 (Ci)	Fraction	Case 6 (Ci)	Fraction
Am-241	2.890E+00	3.060E-08	1.059E-08	7.839E-08	2.713E-08	1.676E-07	5.800E-08	3.250E-07	1.124E-07	4.996E-07	1.729E-07	3.165E-06	1.095E-06
Am-242m	3.220E+00	6.243E-13	1.939E-13	2.228E-12	6.920E-13	6.349E-12	1.972E-12	1.579E-11	4.904E-12	2.851E-11	8.855E-12	3.321E-10	1.031E-10
Am-243	2.920E+00	3.737E-16	1.280E-16	6.612E-16	2.264E-16	1.513E-15	5.180E-16	3.941E-15	1.350E-15	7.533E-15	2.580E-15	1.581E-13	5.414E-14
Cm-242	2.350E+01	5.149E-13	2.191E-14	1.837E-12	7.816E-14	5.231E-12	2.226E-13	1.302E-11	5.539E-13	2.351E-11	1.000E-12	2.738E-10	1.165E-11
Cm-245	2.820E+00	3.866E-23	1.371E-23	6.980E-23	2.475E-23	1.197E-22	4.246E-23	2.255E-22	7.997E-23	3.746E-22	1.328E-22	1.429E-20	5.067E-21
Cs-137	6.040E+01	7.867E-02	1.302E-03	1.033E-01	1.710E-03	1.277E-01	2.115E-03	1.544E-01	2.556E-03	1.733E-01	2.868E-03	3.210E-01	5.314E-03
Eu-154	2.250E+02	4.110E-07	1.827E-09	7.051E-07	3.134E-09	1.078E-06	4.790E-09	1.570E-06	6.979E-09	1.974E-06	8.774E-09	6.780E-06	3.014E-08
H-3	1.660E+04	8.008E-05	4.824E-09	1.051E-04	6.334E-09	1.301E-04	7.838E-09	1.574E-04	9.480E-09	1.767E-04	1.064E-08	3.281E-04	1.977E-08
Ho-166m	1.020E+02	1.518E-13	1.488E-15	2.204E-13	2.160E-15	3.015E-13	2.956E-15	4.039E-13	3.960E-15	4.882E-13	4.787E-15	1.282E-12	1.256E-14
Kr-85	3.330E+04	2.399E-03	7.205E-08	3.149E-03	9.455E-08	3.894E-03	1.169E-07	4.706E-03	1.413E-07	5.282E-03	1.586E-07	9.784E-03	2.938E-07
Np-237	5.360E+00	1.206E-08	2.251E-09	1.632E-08	3.044E-09	2.060E-08	3.843E-09	2.564E-08	4.784E-09	2.928E-08	5.462E-09	5.918E-08	1.104E-08
Pa-233	2.980E+03	1.206E-08	4.048E-12	1.632E-08	5.476E-12	2.060E-08	6.913E-12	2.564E-08	8.605E-12	2.928E-08	9.825E-12	5.918E-08	1.986E-11
Pm-147	2.400E+03	2.050E-05	8.541E-09	2.687E-05	1.120E-08	3.324E-05	1.385E-08	4.020E-05	1.675E-08	4.510E-05	1.879E-08	8.357E-05	3.482E-08
Pu-238	2.620E+00	7.376E-08	2.815E-08	1.342E-07	5.120E-08	2.165E-07	8.265E-08	3.396E-07	1.296E-07	4.443E-07	1.696E-07	1.630E-06	6.222E-07
Pu-239	2.400E+00	5.906E-04	2.461E-04	7.945E-04	3.310E-04	1.002E-03	4.175E-04	1.233E-03	5.137E-04	1.403E-03	5.846E-04	2.592E-03	1.080E-03
Pu-240	2.400E+00	1.836E-06	7.652E-07	3.538E-06	1.474E-06	6.027E-06	2.511E-06	9.576E-06	3.990E-06	1.286E-05	5.359E-06	4.388E-05	1.828E-05
Pu-241	1.320E+02	1.740E-07	1.318E-09	4.463E-07	3.381E-09	9.537E-07	7.225E-09	1.848E-06	1.400E-08	2.843E-06	2.154E-08	1.801E-05	1.364E-07
Pu-242	2.560E+00	1.185E-14	4.631E-15	4.165E-14	1.627E-14	1.154E-13	4.507E-14	2.811E-13	1.098E-13	4.965E-13	1.939E-13	5.843E-12	2.282E-12
Sm-151	3.040E+03	3.333E-03	1.096E-06	4.365E-03	1.436E-06	5.384E-03	1.771E-06	6.490E-03	2.135E-06	7.271E-03	2.392E-06	1.325E-02	4.358E-06
Sr-90	2.590E+01	7.345E-02	2.836E-03	9.643E-02	3.723E-03	1.193E-01	4.604E-03	1.442E-01	5.566E-03	1.618E-01	6.246E-03	2.996E-01	1.157E-02
Tc-99	7.610E+02	2.951E-05	3.877E-08	3.873E-05	5.089E-08	4.792E-05	6.297E-08	5.792E-05	7.611E-08	6.498E-05	8.539E-08	1.204E-04	1.582E-07
Th-228	2.890E+00	5.016E-09	1.736E-09	7.137E-09	2.470E-09	9.710E-09	3.360E-09	1.273E-08	4.403E-09	1.522E-08	5.265E-09	2.815E-08	9.740E-09
Th-230	2.844E+00	9.369E-12	3.294E-12	1.177E-11	4.140E-12	1.414E-11	4.971E-12	1.680E-11	5.908E-12	1.870E-11	6.575E-12	3.275E-11	1.151E-11
U-234	1.320E+01	2.879E-08	2.181E-09	3.511E-08	2.660E-09	4.133E-08	3.131E-09	4.831E-08	3.660E-09	5.333E-08	4.040E-09	9.027E-08	6.839E-09
U-235	1.460E+01	1.154E-04	7.902E-06	1.153E-04	7.900E-06	1.153E-04	7.897E-06	1.152E-04	7.891E-06	1.152E-04	7.889E-06	1.149E-04	7.867E-06
U-236	1.430E+01	8.584E-07	6.003E-08	1.134E-06	7.928E-08	1.410E-06	9.862E-08	1.713E-06	1.198E-07	1.928E-06	1.348E-07	3.570E-06	2.496E-07
U-238	1.540E+01	7.192E-05	4.670E-06	7.192E-05	4.670E-06	7.192E-05	4.670E-06	7.192E-05	4.670E-06	7.192E-05	4.670E-06	7.188E-05	4.668E-06
Y-90	1.767E+03	7.349E-02	4.159E-05	9.647E-02	5.460E-05	1.193E-01	6.752E-05	1.442E-01	8.161E-05	1.618E-01	9.158E-05	2.996E-01	1.696E-04
Ni-63*	5.240E+03	2.235E-03	4.266E-07	2.980E-03	5.687E-07	3.740E-03	7.137E-07	4.573E-03	8.726E-07	5.180E-03	9.886E-07	9.576E-03	1.828E-06
Fe-55*	2.410E+03	7.957E-06	3.302E-09	1.058E-05	4.392E-09	1.333E-05	5.531E-09	1.626E-05	6.748E-09	1.844E-05	7.651E-09	3.406E-05	1.413E-08
Co-60*	2.900E+02	2.693E-07	9.285E-10	3.533E-07	1.218E-09	4.451E-07	1.535E-09	5.361E-07	1.849E-09	6.059E-07	2.089E-09	1.123E-06	3.873E-09
Ni-59*	1.270E+04	2.411E-05	1.899E-09	3.215E-05	2.531E-09	4.035E-05	3.177E-09	4.929E-05	3.881E-09	5.588E-05	4.400E-09	1.033E-04	8.130E-09
Sum of fractions			0.44%		0.58%		0.72%		0.87%		0.98%		1.82%

Code Comparison

- Things to note about the code comparison:
  - ❖ The major contributors to the HC-3 sum of fractions agree to within a fraction of a percent.
  - ❖ The agreement becomes better as the atom density rises above non-negligible amounts.

Table 4. Serpent and SCALE atom density comparison.

Nuclide	Atom Density on January 1, 2014 (atoms/barn cm)		Serpent/SCALE
	Serpent	SCALE	
Am241	6.12384E-12	6.33300E-12	0.967
Am242m	2.32810E-16	2.16500E-16	1.075
Am243	4.99171E-18	5.39900E-18	0.925
Cm242	6.07810E-19	5.64100E-19	1.077
Cm245	5.02218E-25	5.64600E-25	0.890
Cs137	4.42608E-08	4.45400E-08	0.994 ←
Eu154	2.88483E-13	2.68700E-13	1.074
H3	4.43488E-17	1.86500E-11	0.000
Ho166m	7.63451E-17	7.10300E-18	10.748
Kr85	3.39044E-10	4.85500E-10	0.698
Np237	6.00419E-10	5.84500E-10	1.027
Pa233	2.06812E-17	2.01300E-17	1.027
Pu238	6.79241E-13	6.55700E-13	1.036
Pu239	2.87265E-07	2.87900E-07	0.998 ←
Pu240	1.30397E-09	1.33100E-09	0.980
Pu241	1.15145E-12	1.19100E-12	0.967
Pu242	9.65333E-15	1.01100E-14	0.955
Sm151	5.47240E-09	5.50200E-09	0.995
Sr90	3.95464E-08	3.97900E-08	0.994 ←
Th230	1.17664E-14	1.13600E-14	1.036
U234	1.05533E-10	1.02000E-10	1.035
U236	3.84302E-07	3.85800E-07	0.996
U235	3.73602E-04	3.73600E-04	1.000
U238	1.48402E-03	1.48400E-03	1.000
Y90	1.00312E-11	1.00900E-11	0.994 ←

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Worst Case Scenario vs. Reality

- With data for lesser years of irradiation, a more realistic estimate of the HC-3 sum of fractions can be determined.
- Data is currently being generated for irradiation periods ranging from 1 - 10 years.

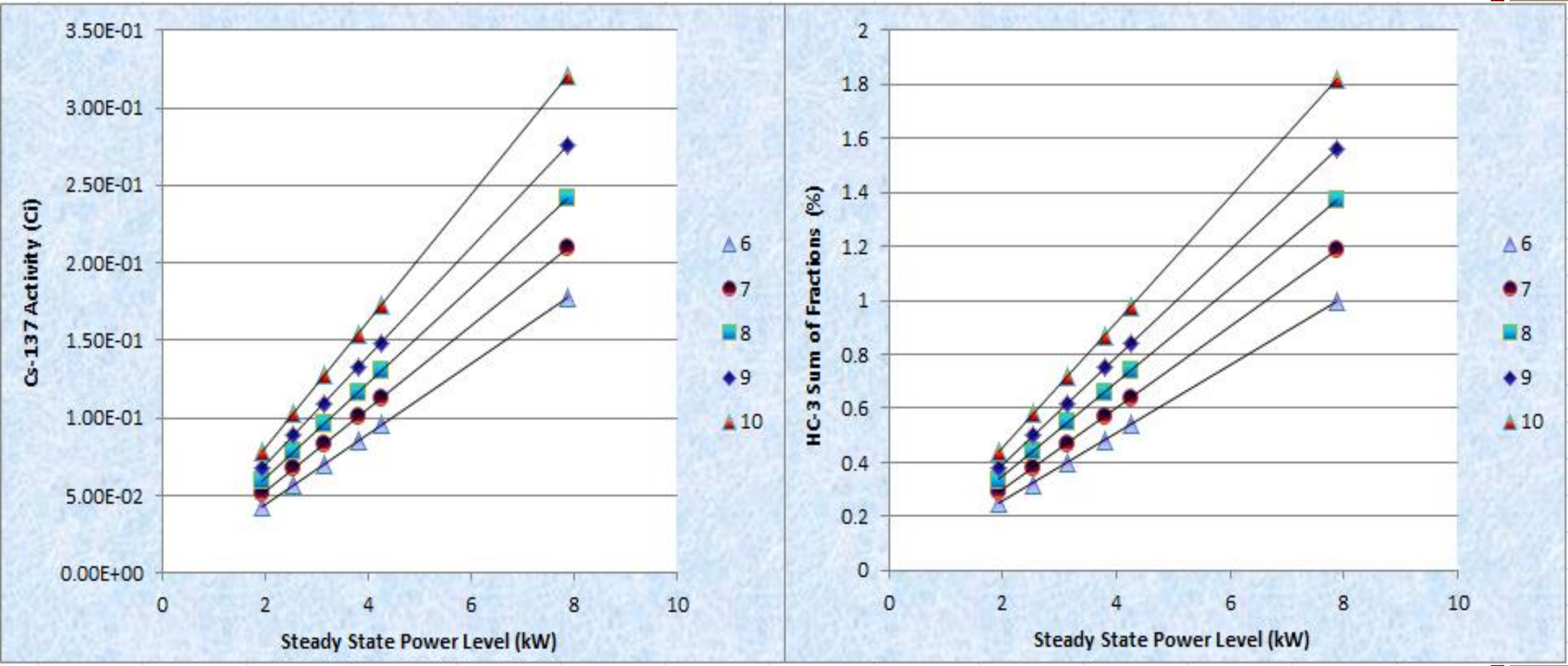


Figure 8. Activity of Cs-137 activity (left) and HC-3 sum of fractions (right) at present day for each of the six power levels considered for variable irradiation times.

Serpent ACRR Model

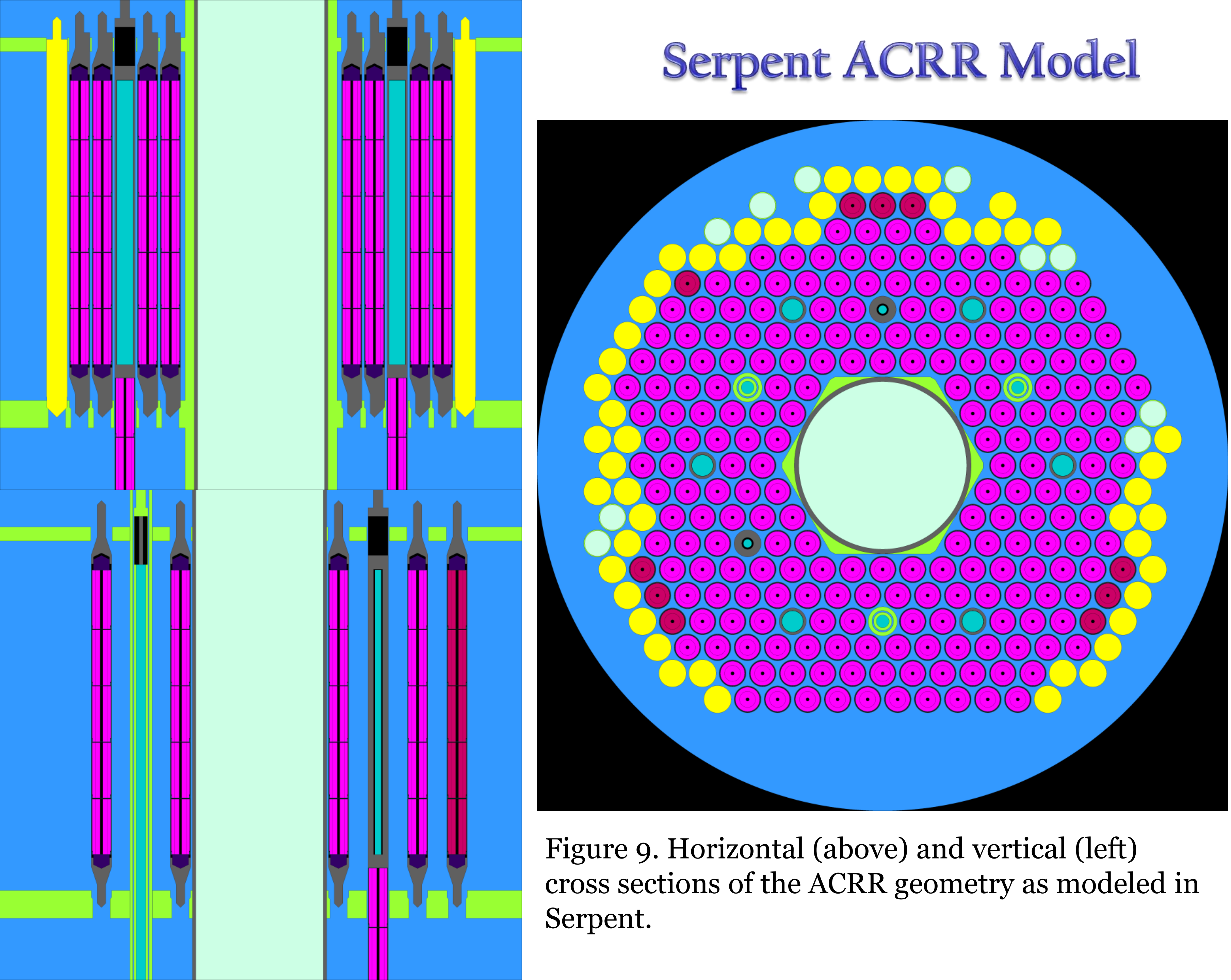
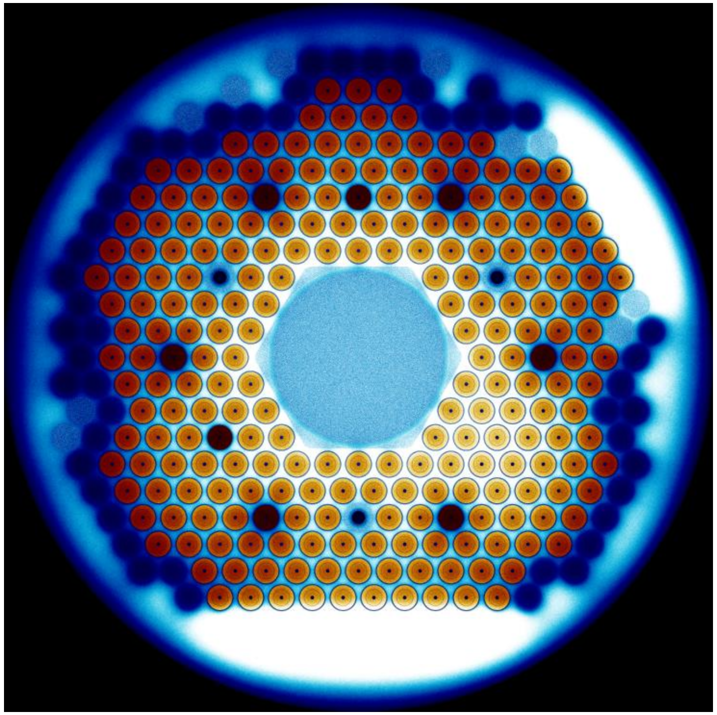


Figure 9. Horizontal (above) and vertical (left) cross sections of the ACRR geometry as modeled in Serpent.

Pretty Pictures



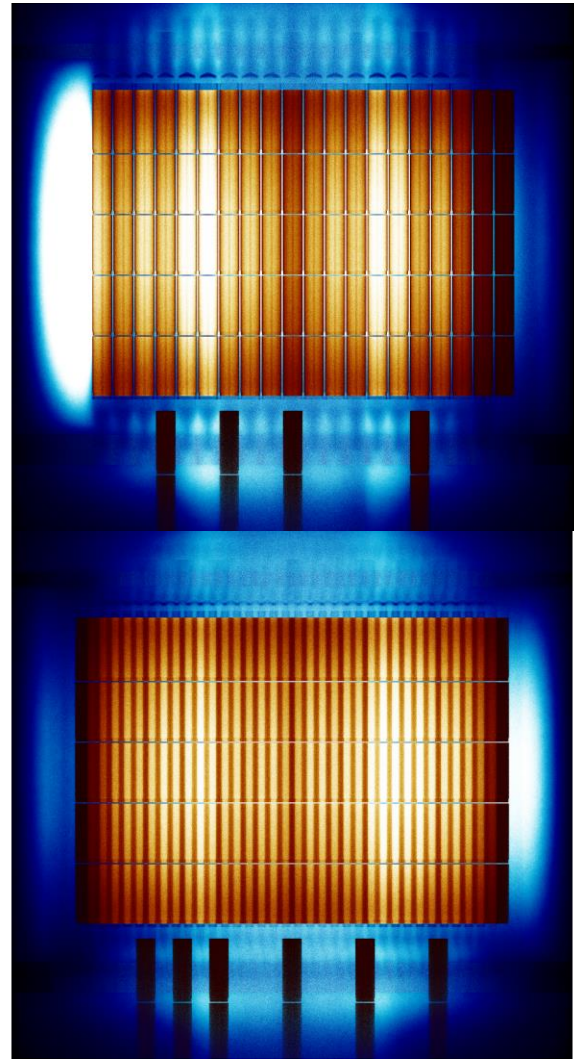


Figure 10. Horizontal (above) and vertical (right) cross sections of the ACRR thermal flux/fission rate density profile as calculated by Serpent.

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Future Work

- Further study of the errors inherent in the steady state power approximation to pulsing reactors.
- Use the Serpent ACRR model to predict detector response at various power levels.
- Use the Serpent ACRR model to predict flux and energy spectrum in the neutron radiography tube.

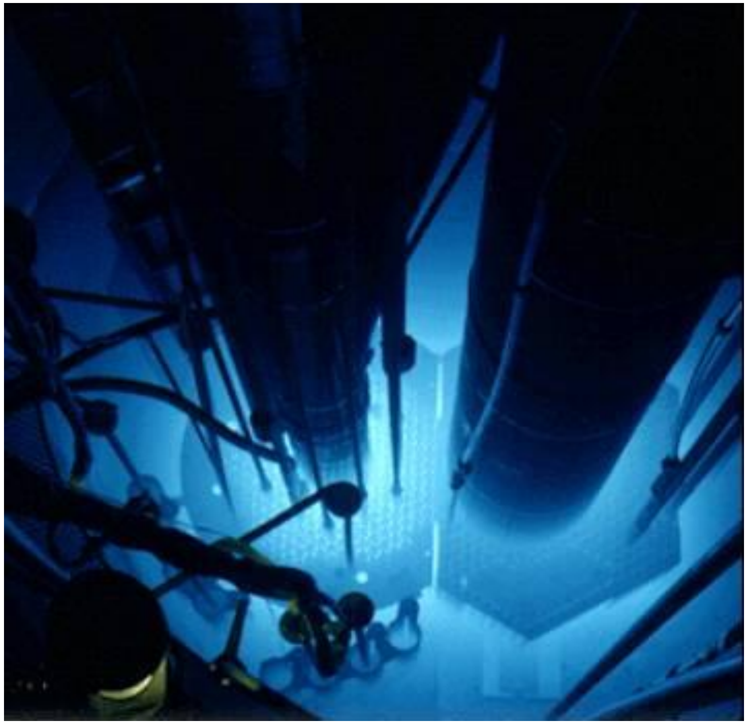

Figure 11. ACRR during operation.

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- Jaakko Leppänen
- Ed Parma
- Peter Subaiya
- Billy Martin
- Jesse Johns
- Dave Wheeler
- Kirk Mason
- Jamie Cash

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