Experience with Scale Depletion for Spent Fuel

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Background

- Historical criticality analysis of PWR Spent Fuel Pools were done with many simplifications relying on the large margin to criticality provided by the uncredited soluble boron.
  - Used average assembly temperatures rather than the limiting assembly temperatures,
  - Used a typical axial burnup profile rather than the limiting profile,
  - Assumed uncertainties such as the depletion uncertainty could be covered by the uncredited soluble boron.
- These simplifications (which preceded 10CFR50.68) utilized the soluble boron in a way prohibited by 10CFR50.68 and have now been corrected.

Background – Accuracy Target

- With the new requirements and the loss of Boraflex, the criticality analysis for many spent fuel pools is very tight, meeting the requirements (after new NRC margin of 1%) by sometimes less than 0.1% in k.
- This sets the desired methods accuracy to 0.001 in k.

Background – Speed Requirement

- Analysis of Spent Nuclear Fuel requires multiple axial zones (we use 9, others use 18) to account for the end effect.
- A loading requirement needs analysis of multiple burnup/enrichment/cooling time combinations. (typically 8 burnup/enrichments and 4 cooling times= 32 state points)
- Ignoring the design determination of the loading requirements, the final verification analysis would require about 32*9 or about 300 depletion runs.

Background – Speed Requirements

- A SCALE 6.1 depletion takes about 5 hours.
- The total depletion time could take 1500 hours (ignoring design iterations and errors).
- Using multiple CPUs can make this manageable so this direct approach has been used.

Use of External Fortran Code

- The 9 axial nodes (if at a limiting set of temperatures) all can be derived from a single depletion by interpolating the atom densities between burnup steps.
  - Burnup steps must be 2 GWd/T or less
  - Use of linear interpolation has been demonstrated to provide the final k within the Monte Carlo uncertainty (0.00005).
  - Test to confirm individual isotopes was not needed for this application.

Use of External Fortran Code

- The Cooling Time dependency can be done external to SCALE (factor of 4 savings)
  - For cooling times of interest, 48 hours or more, the number of isotopes of concern to criticality who's concentration is changing is limited.
  - The branching at these cooling times is simple.
  - The same FORTRAN code used for interpolating to the desired burnup also decays to the desired cooling time.
  - Only 78 isotopes are decayed. Could have ignored decay in isotopes with half lives over 1000 years and this number becomes only 59 isotopes.
  - Verified by comparison with SCALE cases with same cooling time.

Use of External Fortran Code

- Some isotopes need to be corrected.
  - Fission gases due to transport to the fission gas plenum
  - Pm-149/Sm-149 due to low power operation at end of cycle.
- The Fortran code allows a multiplier for any isotope.

Atom Densities as a Function of Burnup

- The FORTRAN code reads atom densities output as plt files by OPUS.
- Use 186 isotopes (Use parm=(addnux=4))
- Others have used StdCmpMixNNNNN output.

SCALE changes that could eliminate the external program

- Branching exists now but to make it easier:
  - Allow the user to set a burnup/cooling time where the atom density file is produced and allow the user to define the file id.
  - Less important – allow the user to specify an atom density multiplier for any isotope (by name) that can be used with any of the above burnup/cooling time output files.
- Problems that would remain:
  - Since the final burnup requirement is not known at the design stage the burnups for the branch cases would not be known. The external interpolation program allows the depletion for a given enrichment to be done only once. Still it would be nice to be able to do a final case without the interpolation.
  - If different temperatures are used for each axial node this approach is less valuable.

SCALE Module Selection and Accuracy

- In SCALE 6.1 the only groupwise ENDF/B-VII cross section set was 238 groups. (One could have created their own broad group library and then defend it.)
- Transport calculation time is proportional to the number of energy groups.
- At 238 groups NEWT was slower than KENO.
- Convergence of KENO is confirmed by increasing the neutrons per generation and number of generations until calculated k's in final arrangement are within the uncertainty of the calculated k.
- 1000 generations with 4000 neutrons per generation was enough for convergence.

SCALE Module Selection and Accuracy

- SCALE 6.2.2 time tests

	56 Group	252 Group
Module	Run Time	Run Time
Polaris	263 minutes	-
Newt	38 minutes	136 minutes
KENO Va	312 minutes	332 minutes

- Used Polaris default parameters. Expect that I am missing some optimization feature.

Accuracy

- Newt is much faster than KENO Va so is it as accurate?
- To test this the EPRI burnup benchmarks were run. For this presentation only results for case 2 at 100 hours cooling are presented

ENDF/B-VII.0 SCALE 6.1.2 KENO 238 Groups

Burnup		sigma	delta k	meas delta	calc-meas
0	1.50022	0.00014			
10	1.38574	0.00019	0.11448	0.1146	-0.0001
20	1.29842	0.00019	0.2018	0.2021	-0.0003
30	1.22016	0.00013	0.28006	0.2806	-0.0005
40	1.14696	0.00013	0.35326	0.3545	-0.0012
50	1.07778	0.00013	0.42244	0.4238	-0.0014
60	1.01533	0.00012	0.48489	0.4867	-0.0018

ENDF/B-VII.0 SCALE 6.2.2 KENO 238 Groups

Burnup		sigma	delta k	meas delta	calc-meas
0	1.50161	0.00005			
10	1.388167	0.00005	0.113443	0.1146	-0.0012
20	1.300782	0.00005	0.200828	0.2021	-0.0013
30	1.222529	0.00005	0.279081	0.2806	-0.0015
40	1.148859	0.00005	0.352751	0.3545	-0.0017
50	1.079577	0.00005	0.422033	0.4238	-0.0018
60	1.017076	0.00004	0.484534	0.4867	-0.0022

ENDF/B-VII.1 SCALE 6.2.2 KENO 252 Groups

Burnup		sigma	delta k	meas delta	calc-meas
0	1.502908	0.00005			
10	1.388037	0.00005	0.114871	0.1146	0.0003
20	1.300357	0.00005	0.202551	0.2021	0.0005
30	1.221535	0.00005	0.281373	0.2806	0.0008
40	1.147167	0.00005	0.355741	0.3545	0.0012
50	1.076891	0.00005	0.426017	0.4238	0.0022
60	1.013026	0.00004	0.489882	0.4867	0.0032

ENDF/B-VII.1 SCALE 6.2.2 Newt 56 Groups 4x4 Mesh per fuel pin

Burnup		sigma	delta k	meas delta	calc-meas
0	1.502908	0.00005			
10	1.387957	0.00005	0.114951	0.1146	0.0004
20	1.300068	0.00005	0.202840	0.2021	0.0007
30	1.221176	0.00005	0.281732	0.2806	0.0011
40	1.146478	0.00005	0.356430	0.3545	0.0019
50	1.076017	0.00005	0.426891	0.4238	0.0031
60	1.01161	0.00004	0.491298	0.4867	0.0046

ENDF/B-VII.1 SCALE 6.2.2 Newt 252 Groups 4x4 Mesh per fuel pin

Burnup		sigma	delta k	meas delta	calc-meas
0	1.502908	0.00005			
10	1.388099	0.00005	0.114809	0.1146	0.0002
20	1.300184	0.00005	0.202724	0.2021	0.0006
30	1.221107	0.00005	0.281801	0.2806	0.0012
40	1.146396	0.00005	0.356512	0.3545	0.0020
50	1.075877	0.00005	0.427031	0.4238	0.0032
60	1.011736	0.00004	0.491172	0.4867	0.0045

ENDF/B-VII.1 SCALE 6.2.2 Newt 56 Groups 8x8 Mesh per fuel pin

Burnup		sigma	delta k	meas delta	calc-meas
0	1.502908	0.00005			
10	1.387906	0.00005	0.115002	0.1146	0.0004
20	1.300179	0.00005	0.202729	0.2021	0.0006
30	1.221454	0.00005	0.281454	0.2806	0.0009
40	1.147059	0.00005	0.355849	0.3545	0.0013
50	1.076984	0.00005	0.425924	0.4238	0.0021
60	1.012944	0.00004	0.489964	0.4867	0.0033

Observations

- The EPRI burnup benchmarks are ~~an~~ infinite arrays of 17x17 PWR (2D) assemblies in the core geometry.
- The case used here was 5 wt% U-235 but other cases had similar results.
- SCALE changes from 6.1.2 to 6.2.2 was 140 pcm (0.14% Δk)
- ENDF/B-VII.0 to ENDF/B-VII.1 change was 130 pcm (0.13 Δk)
- ENDF/B-VII.0 under predicts the change in k with burnup (conservative)
- ENDF/B-VII.1 over predicts the change in k with burnup (non-conservative) a factor of two more than VII.0
- Error for both cases is less than 1% of the Δk of depletion and use 5% of the Δk of depletion as an uncertainty.

Conclusions

- Need to use 8x8 mesh per fuel pin in Newt.
- SCALE 6.2.2 and Newt provides a greater than 5 fold speed increase from current depletion method.
- Will continue to use the external FORTRAN program and OPUS to generate the atom densities.
- Will convert to SCALE 6.2.2 and Newt (56 groups) for next analysis.

Conclusions

- ENDF/B-VII.1 is an improvement for fresh fuel but does less well than VII.0 for depletion.
- Error in Delta k of depletion is still small so the use of 5% of the delta k of depletion will be continued.