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Core Model Performance for Training Simulators

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ABSTRACT

Cycle specific core performance on a training simulator is a significant motivation for a simulator core model upgrade. The accuracy of the numerical method used in the core model is the primary consideration in the evaluation of the core model. The characteristics of an "engineering grade" core model and the benefits of using such a core model are described. A standard benchmark data set is then analyzed with the engineering grade core model SIMULATE-3R. Further, the effects of using more approximate models are quantified.

1. CORE MODEL PERFORMANCE

Prior generation simulator core models often made use of several simplifying assumptions including

- 1D Axial Diffusion Theory
- Single Energy Group
- Coarse Mesh Feedback
- Generic Nuclear Data

Many of these assumptions were required in order to achieve real-time performance on relatively slow, special purpose computer platforms.

Upgrades to engineering grade core models are made feasible by the availability of inexpensive, high performance CPUs. In the past six years, most simulator software has been "rehosted" to conventional platforms, commonly dual CPU Pentium machines running Windows. The rehost process has enabled significant upgrades in all classes of models, both because of raw power available and the fact that the simulator can be installed and maintained readily in standard Windows-based tools, including compilers, configuration control utilities, and database management tools.

Beyond the fact that CPUs make it possible, there are several industry factors which influence the desire for increased fidelity. Beyond an increase in numerical accuracy, there is desire to train on the core cycle that is actually loaded rather than generic cores. Although INPO had initiated movement in this direction as early as 1996, the USNRC has recently codified cycle specific requirements for simulators if licensees wish to take credit for reactivity manipulations performed on the simulator instead of the plant itself. The following is excerpted from 10CFR55.46:

> (2) Facility licensees that propose to use a plant-referenced simulator to meet the control manipulation requirements in Sec. 55.31(a)(5) must ensure that:
>
> (i) The plant-referenced simulator utilizes models relating to nuclear and thermal-hydraulic characteristics that replicate the most recent core load in the nuclear power reference plant for which a license is being sought; and
>
> (ii) Simulator fidelity has been demonstrated so that significant control manipulations are completed without procedural exceptions, simulator performance exceptions, or deviation from the approved training scenario sequence.
>
> (3) A simulation facility consisting solely of a plant-referenced simulator must meet the requirements of paragraph (c)(1) of this section and the criteria in paragraphs (d)(1) and (4) of this section for the Commission to accept the plant-referenced simulator for conducting operating tests as described in Sec. 55.45(a) of this part, requalification training as described in Sec. 55.59(c)(3) of this part, or for performing control manipulations that affect reactivity to establish eligibility for an operator's license as described in Sec. 55.31(a)(5).

2. CORE NUMERICAL METHODS AND FEATURES

Core design numerical methods, along with measured plant data, provide the basis for assessment of the simulator model. All modern core design software employs an advanced nodal method of some sort. Some simplifications to core design models and practices are usually required to allow real-time execution on the training simulator. The following premises guided the simplifications made, and not made, in the development of the engineering grade core model SIMULATE-3R.

- Explicit modeling of all radial assemblies is required to model radial tilts, asymmetric rod insertion, and instrumentation readings.
- Assembly power predictions are strongly influence by local fuel temperature and moderator density variations. Axial average feedback parameters cannot reproduce core design accuracy in general.
- One-group energy models can be shown to introduce significant errors in the local neutron flux.
- The more detailed the core model, the more automation is required for updating the core. Prior generation models were relatively easy to update because they required so little data and the expectations on cycle-specific fidelity were not so high. The data set required to drive a larger, more modern core model is much more extensive and the expectations on fidelity are higher.

3. THE SIMULATE-3R REAL-TIME CORE MODEL

The following section describes the modifications introduced in the creation of the simulator core model SIMULATE-3R from the core design transient analysis code

SIMULATE-3K. SIMULATE-3K itself is derived from the static core design code SIMULATE-3.

An important design consideration in SIMULATE-3R is that all the following modifications are easily removed by the end user. As they are removed, the SIMULATE-3R core model moves toward the exact SIMULATE-3 core design result. Therefore, the SIMULATE-3R model can be scaled up in rigor as CPU performance improves.

- Most SIMULATE-3R (S3R) implementations use between 25% and 50% of the nodes used in core design. PWRs normally are relaxed to one radial node per assembly, whereas BWRs use a reduced axial mesh. The analysis performed herein uses 24 axial nodes and one radial node per assembly in the real time mode.
- Most core design software can infer the power (or flux) in an individual fuel pin from assembly-average conditions. This calculation is often called de-homogenization or pin power reconstruction. Such methods are required to meet licensing requirements for core design thermal safety limits. However, they are CPU intensive and simultaneously not very useful for training, so they are omitted in the real-time application.
- Core design nuclear data libraries generally are formulated in terms of large multi-dimensional tables which contain combinations of instantaneous and historical feedback variables. Changes in all historical variables, including exposure, are negligible on the time scale of a training simulation. Therefore, the historical variable may be treated as frozen at initialization, while the instantaneous feedback variables (density, temperature, boron, and rods) are treated explicitly in three dimensions in each time step. However, the fission products xenon, iodine, promethium, and samarium must be included explicitly in the formulation via microscopic data and time dependent concentrations.
- Whereas most engineering grade core models require an update conversion tool, S3R does not if the utility customer maintains a CASMO/SIMULATE core follow model. S3R reads the restart file and library directly at a given exposure point, collapses to the real-time mesh, and builds the fast cross-section library. Therefore, both the numerical method and the data are inherently self-consistent between the core follow software and the training simulator core. Further, no intermediate codes or post-process capabilities are required to update the core.

Several prior works have expanded on the details of the SIMULATE-3R development process and its practical implementation. Smith[1] has previously discussed the underlying numerical methods of SIMULATE-3 and Borkowski[2] has discussed the application of those methods to transient analysis in SIMULATE-3K. Rhodes[3] has presented a detailed discussion of the acceleration methods applied to SIMULATE-3K which enable real-time performance in SIMULATE-3R. This work also describes the implementation of SIMULATE-3R in three compact training simulators (Tokai-1, Tokai-2, Tsuruga-1) in Japan on multi-CPU DEC Alpha platforms. Borkowski[4] has also presented a discussion of the implementation of SIMULATE-3R into the Oconee full-scope simulator. This implementation differs from the predecessor in that it made use of more conventional hardware in the form Pentium-based PCs running Windows NT. The Oconee simulator was also the first to perform routine core cycle updating directly from SIMULATE-3 cycle depletions restart files. The Oconee implementation is more typical of all subsequent SIMULATE-3R projects. Borkowski et al[5] has also presented a summary paper which discusses portions of all the above topics.

4. OECD NEA PWR BENCHMARK PROBLEMS

It is possible to assess the accuracy of the real-time options by the application of a benchmark problem. The OECD/NEA (www.nea.fr) has developed a PWR-based benchmark problem[6] which has been used to assess Reactivity Insertion Accident (RIA) models. Several reports have been issued which compare the performance of core design software to reference solutions. The important characteristics are summarized below. A complete specification is available on the web-site.

- The core is comprised of 157 assemblies and 6 unique control rod banks. The assembly and bank arrangement is typical of most commercial three-loop PWRs.
- There are seven unique assembly designs, incorporating a range of enrichments and burnable poison loadings. Reflector assemblies are included for use in the periphery.
- All cross-sections are purely linear functions of density, fuel temperature and boron concentrations.

5. APPLICATION TO THE SIMULATOR CORE

The purpose of this comparison is not to replicate the simulations in the original licensing benchmark problem. The rate of reactivity insertion in the benchmark problem is limiting and hypothetical, and as such cannot be attained on the training simulator. Rather, the purpose is to use this problem to assess the training simulator core model result in comparison to an engineering grade core design result.

To accomplish that, the static analyses will be performed using both the core design methods of SIMULATE-3 and the real-time methods of SIMULATE-3R. The figures of merit for this assessment will be

- Power distribution
- Reactivity coefficients
- Rod worth

Additionally, an asymmetric rod drop will be included as a dynamic test.

It is also useful to assess the effect of applying weaker models (models not used in production versions of SIMULATE-3R) to this problem in order to assess the consequences. Some of these weaker models include

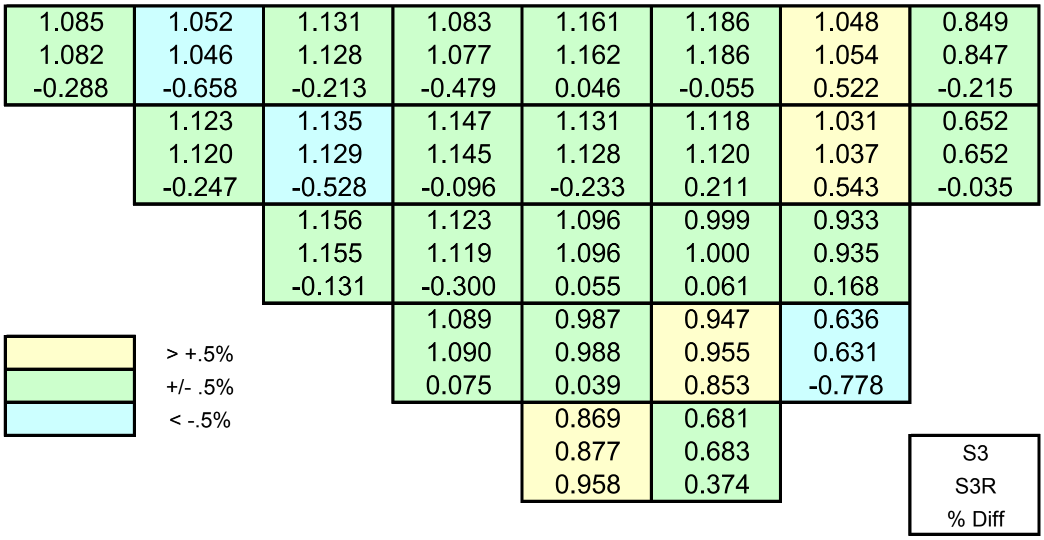
- One-group methods
- Low-order spatial methods

- Coarse thermal-hydraulic feedback

Finally, this problem can be used to assess the concept of "cancellation of error," which is described below.

5.1 Power Distribution

The Hot Full Power (HFP) two dimensional radial power distribution is provided in Figure 1. The comparison between SIMULATE-3 and SIMULATE-3R shows that 90% of the assemblies are with +/- 0.5% of the SIMULATE-3 solution and no assemblies are beyond 1%.



1.085 1.082 -0.288	1.052 1.046 -0.658	1.131 1.128 -0.213	1.083 1.077 -0.479	1.161 1.162 0.046	1.186 1.186 -0.055	1.048 1.054 0.522	0.849 0.847 -0.215
	1.123 1.120 -0.247	1.135 1.129 -0.528	1.147 1.145 -0.096	1.131 1.128 -0.233	1.118 1.120 0.211	1.031 1.037 0.543	0.652 0.652 -0.035
		1.156 1.155 -0.131	1.123 1.119 -0.300	1.096 1.096 0.055	0.999 1.000 0.061	0.933 0.935 0.168	
			1.089 1.090 0.075	0.987 0.988 0.039	0.947 0.955 0.853	0.636 0.631 -0.778	
				0.869 0.877 0.958	0.681 0.683 0.374		

🟨 > +.5%
🟩 +/- .5%
🟦 < -.5%

S3
S3R
% Diff

Fig. 1
Power Distribution Comparison Between SIMULATE-3R Real-Time Model and SIMULATE-3 Core Design Model

5.2 Reactivity Balance

Table 1 shows the HFP coefficient comparison for moderator temperature (MTC), isothermal temperature (ITC), uniform Doppler (UPD), Boron (BOR), and power (POW).

The results for all coefficients are nearly identical. However, it is important to make only a modest conclusion from that. Because all the feedback mechanisms in this data set are represented by purely linear functions, the above coefficients are merely the slopes of the lines used in the feedback function. Therefore it is *nearly impossible* to calculate the coefficients wrong for this problem, barring an actual coding error. The feedback functions are so simple, any reasonable cross-section methodology will do well.

The only exception to the above observation is POW. POW combines the effects of all feedbacks and also has a weak dependence on power distribution, so it is more sensitive to the real-time option of reduced mesh, although the absolute agreement is still excellent.

5.3 Rod Bank Worths

Table 2 shows that all bank worths agree with 50 pcm.

Table 1 Coefficient Comparison

```
SIMULATE-3
  Isothermal Temperature Coefficient    -31.20 pcm/Deg F
  Moderator  Temperature Coefficient    -29.71 pcm/Deg F
  Uniform    Doppler     Coefficient     -1.45 pcm/Deg F
  Boron                  Coefficient     -9.80 pcm/ppm
  Power                  Coefficient    -19.32 pcm/%
S3R
  Isothermal Temperature Coefficient    -31.28 pcm/Deg F
  Moderator  Temperature Coefficient    -29.78 pcm/Deg F
  Uniform    Doppler     Coefficient     -1.46 pcm/Deg F
  Boron                  Coefficient     -9.77 pcm/ppm
  Power                  Coefficient    -18.99 pcm/%
```

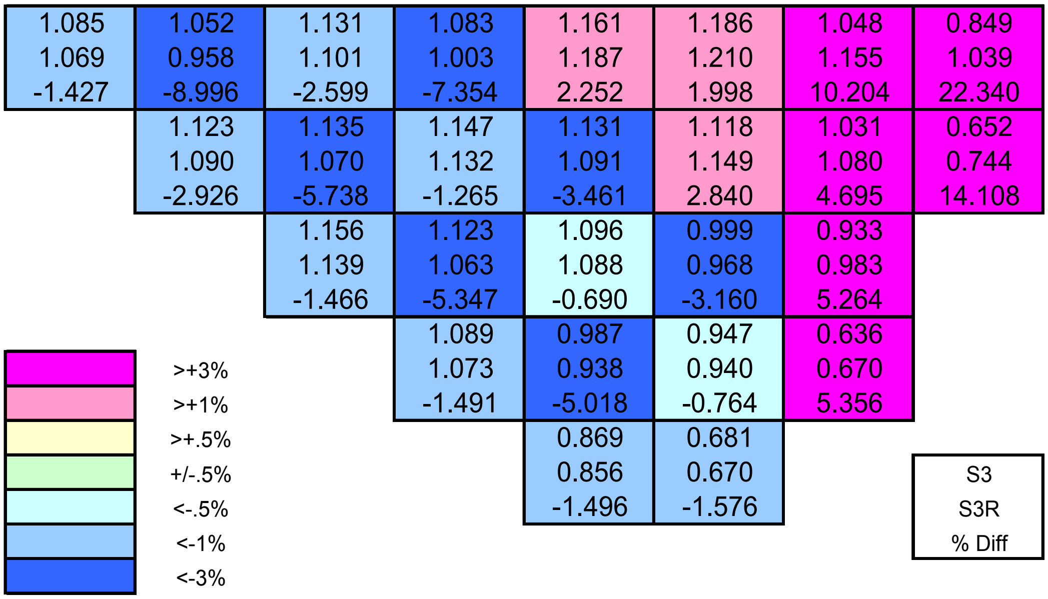
Table 2 Bank Worth Comparison

```
Bank 1  898.7  SIMULATE-3 Bank 4  646.7  SIMULATE-3
        864.0  S3R                688.5  S3R

Bank 2  963.0  SIMULATE-3 Bank 5 1047.6  SIMULATE-3
        936.5  S3R               1001.7  S3R

Bank 3 1347.9  SIMULATE-3 Bank 6 1209.1  SIMULATE-3
       1334.4  S3R               1229.4  S3R
```

5.4 Effect of One-Group Models

SIMULATE-3R can be invoked with a (non-default) one-group model. The effect of this approximation is shown in Figure 2. The comparison to SIMULATE-3 is very poor on two grounds. One, there are very large assembly errors throughout, and two, there is a pronounced “checkerboard” effect.

The checkerboard effect is due to the fact that the fast and thermal fluxes have very different shapes, and a one group model by definition cannot recreate two flux shapes. Fission neutrons are "born fast" and scatter about the core almost uniformly; the fast flux is therefore relatively flat. As neutrons slow into the thermal group, they are more likely to be absorbed, and the absorption cross-section of one assembly compared to its neighbors is significant. Therefore, there is considerable local shape to the thermal flux.



1.085 1.069 -1.427	1.052 0.958 -8.996	1.131 1.101 -2.599	1.083 1.003 -7.354	1.161 1.187 2.252	1.186 1.210 1.998	1.048 1.155 10.204	0.849 1.039 22.340
	1.123 1.090 -2.926	1.135 1.070 -5.738	1.147 1.132 -1.265	1.131 1.091 -3.461	1.118 1.149 2.840	1.031 1.080 4.695	0.652 0.744 14.108
		1.156 1.139 -1.466	1.123 1.063 -5.347	1.096 1.088 -0.690	0.999 0.968 -3.160	0.933 0.983 5.264	
			1.089 1.073 -1.491	0.987 0.938 -5.018	0.947 0.940 -0.764	0.636 0.670 5.356	
				0.869 0.856 -1.496	0.681 0.670 -1.576		

🟪	>+3%
🟥	>+1%
🟨	>+.5%
🟩	+/-.5%
⬜	<-.5%
🟦	<-1%
🟦	<-3%

S3
S3R
% Diff

Fig. 2
Adverse Effect of One-Group Nuclear Model On Power Distribution Prediction

5.5 Effect of Spatial Accuracy

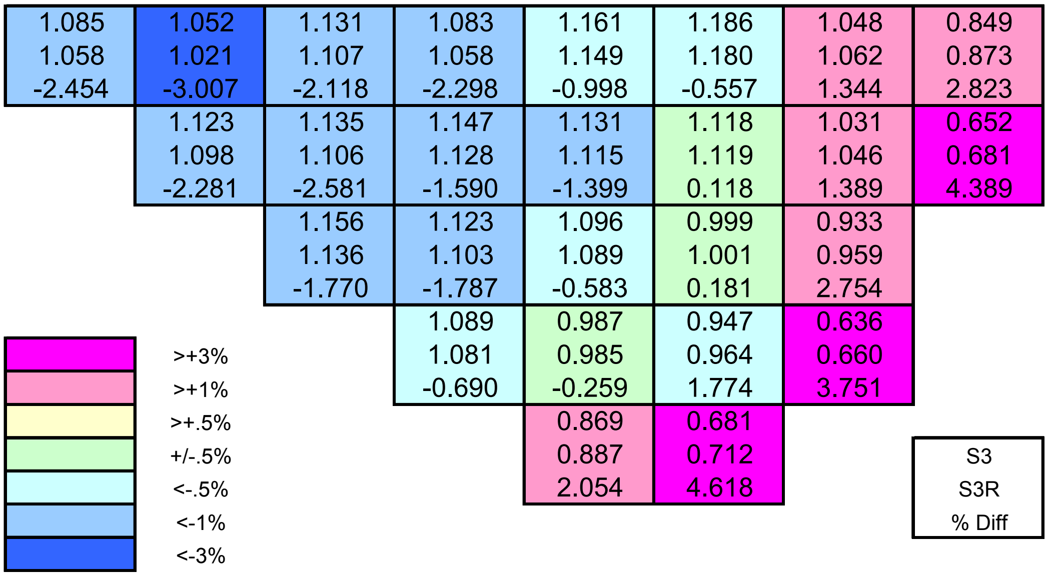
SIMULATE-3R can be invoked with a reduced order representation of the transverse leakage. The effect of this model is shown in Figure 3.

The error demonstrated with this approximation is about +/- 5%. Further, we also can see that there is a prominent "In/Out Tilt," where by reference solution is under-predicted in the center and over-predicted on the periphery. The tilt results from the fact that even a very poor model must, by definition, predict average flux right for a given power level because that is known by definition.

5.6 Effect of Coarse T/H Feedback

SIMULATE-3R by default uses one-for-one feedback between the nuclear and T/H mesh with no averaging. SIMULATE-3R can be invoked with a (non-default) homogenized feedback array. In this approximation, only a single average channel is modeled explicitly, and its feedback variables are applied plane-by-plane to entire core.

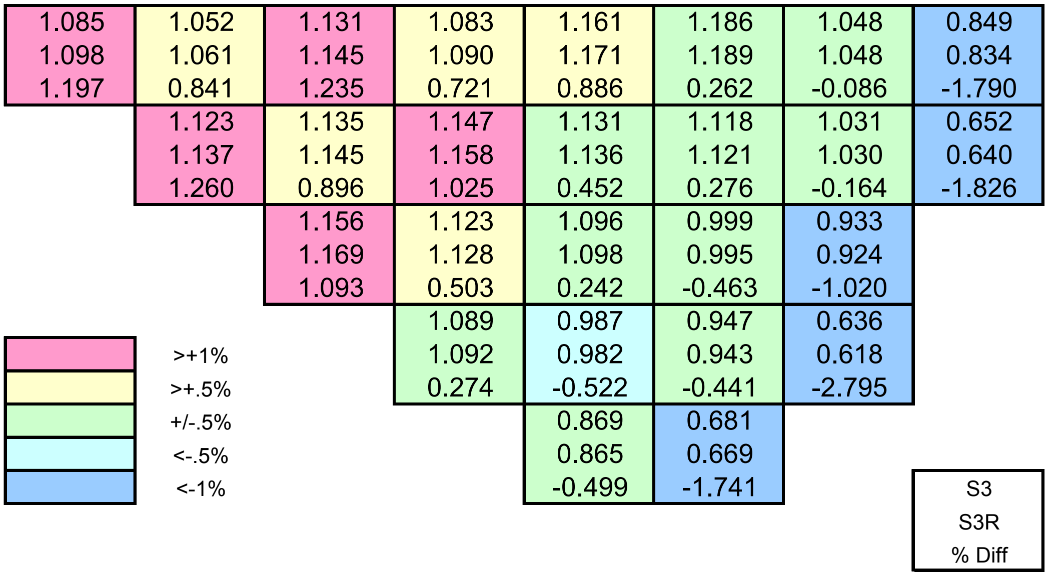
Figure 4 shows that this approximation introduces error on the order of 3%. While this is the least erroneous of any approximation introduced so far, it should be noted that this effect would probably be more significant with a more realistic cross-section feedback function, and would be much more significant in a BWR. Therefore, the error herein should be interpreted as a minimum error. Further, this assessment is a static assessment. In a truly dynamic event (like the rod drop discussed below), the error will be more significant.



1.085 1.058 -2.454	1.052 1.021 -3.007	1.131 1.107 -2.118	1.083 1.058 -2.298	1.161 1.149 -0.998	1.186 1.180 -0.557	1.048 1.062 1.344	0.849 0.873 2.823
	1.123 1.098 -2.281	1.135 1.106 -2.581	1.147 1.128 -1.590	1.131 1.115 -1.399	1.118 1.119 0.118	1.031 1.046 1.389	0.652 0.681 4.389
		1.156 1.136 -1.770	1.123 1.103 -1.787	1.096 1.089 -0.583	0.999 1.001 0.181	0.933 0.959 2.754	
			1.089 1.081 -0.690	0.987 0.985 -0.259	0.947 0.964 1.774	0.636 0.660 3.751	
				0.869 0.887 2.054	0.681 0.712 4.618		S3 S3R % Diff

▨	>+3%
▨	>+1%
▨	>+.5%
▨	+/-.5%
▨	<-.5%
▨	<-1%
▨	<-3%

Fig. 3
Adverse Effect of Spatial Truncation Error On Power Distribution Prediction



1.085 1.098 1.197	1.052 1.061 0.841	1.131 1.145 1.235	1.083 1.090 0.721	1.161 1.171 0.886	1.186 1.189 0.262	1.048 1.048 -0.086	0.849 0.834 -1.790
	1.123 1.137 1.260	1.135 1.145 0.896	1.147 1.158 1.025	1.131 1.136 0.452	1.118 1.121 0.276	1.031 1.030 -0.164	0.652 0.640 -1.826
		1.156 1.169 1.093	1.123 1.128 0.503	1.096 1.098 0.242	0.999 0.995 -0.463	0.933 0.924 -1.020	
			1.089 1.092 0.274	0.987 0.982 -0.522	0.947 0.943 -0.441	0.636 0.618 -2.795	
				0.869 0.865 -0.499	0.681 0.669 -1.741		S3 S3R % Diff

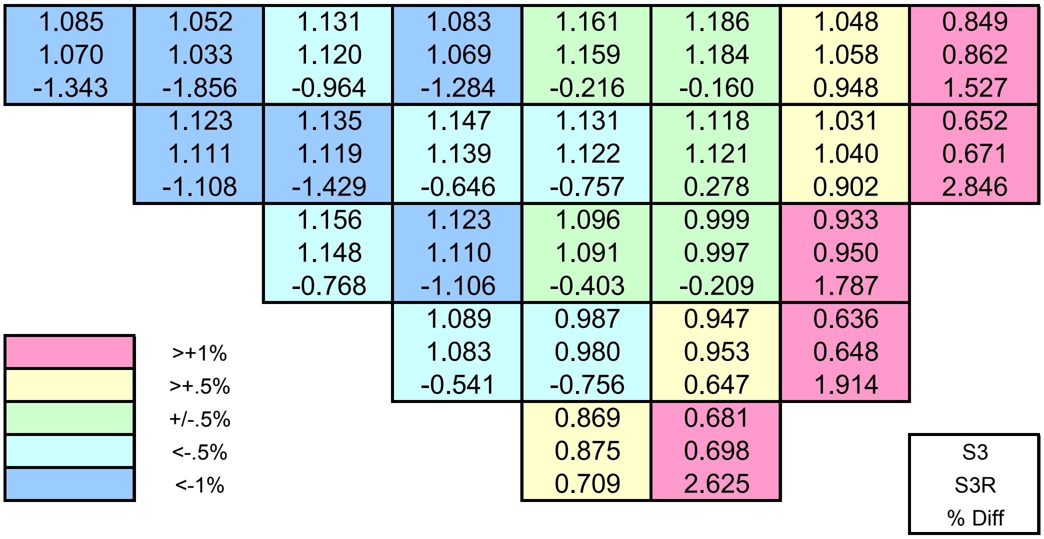
▨	>+1%
▨	>+.5%
▨	+/-.5%
▨	<-.5%
▨	<-1%

Fig. 4
Adverse Effect of Single Channel T/H Feedback On Power Distribution

5.7 Effect of Cancellation of Error

Cancellation of Error (COE) implies combining two approximations that introduce error in opposite directions, such the net numerical result is, at least superficially, in better agreement to the reference solution.

For example, Figure 3 and Figure 4 demonstrate errors in the opposite direction. By using both non-default models (low-accuracy spatial model and coarse T/H feedback) in the same case, it is shown in Figure 5 that the error of the error of the combination is lower than the error of the individual components.



1.085 1.070 -1.343	1.052 1.033 -1.856	1.131 1.120 -0.964	1.083 1.069 -1.284	1.161 1.159 -0.216	1.186 1.184 -0.160	1.048 1.058 0.948	0.849 0.862 1.527
	1.123 1.111 -1.108	1.135 1.119 -1.429	1.147 1.139 -0.646	1.131 1.122 -0.757	1.118 1.121 0.278	1.031 1.040 0.902	0.652 0.671 2.846
		1.156 1.148 -0.768	1.123 1.110 -1.106	1.096 1.091 -0.403	0.999 0.997 -0.209	0.933 0.950 1.787	
			1.089 1.083 -0.541	0.987 0.980 -0.756	0.947 0.953 0.647	0.636 0.648 1.914	
				0.869 0.875 0.709	0.681 0.698 2.625		

Fig. 5

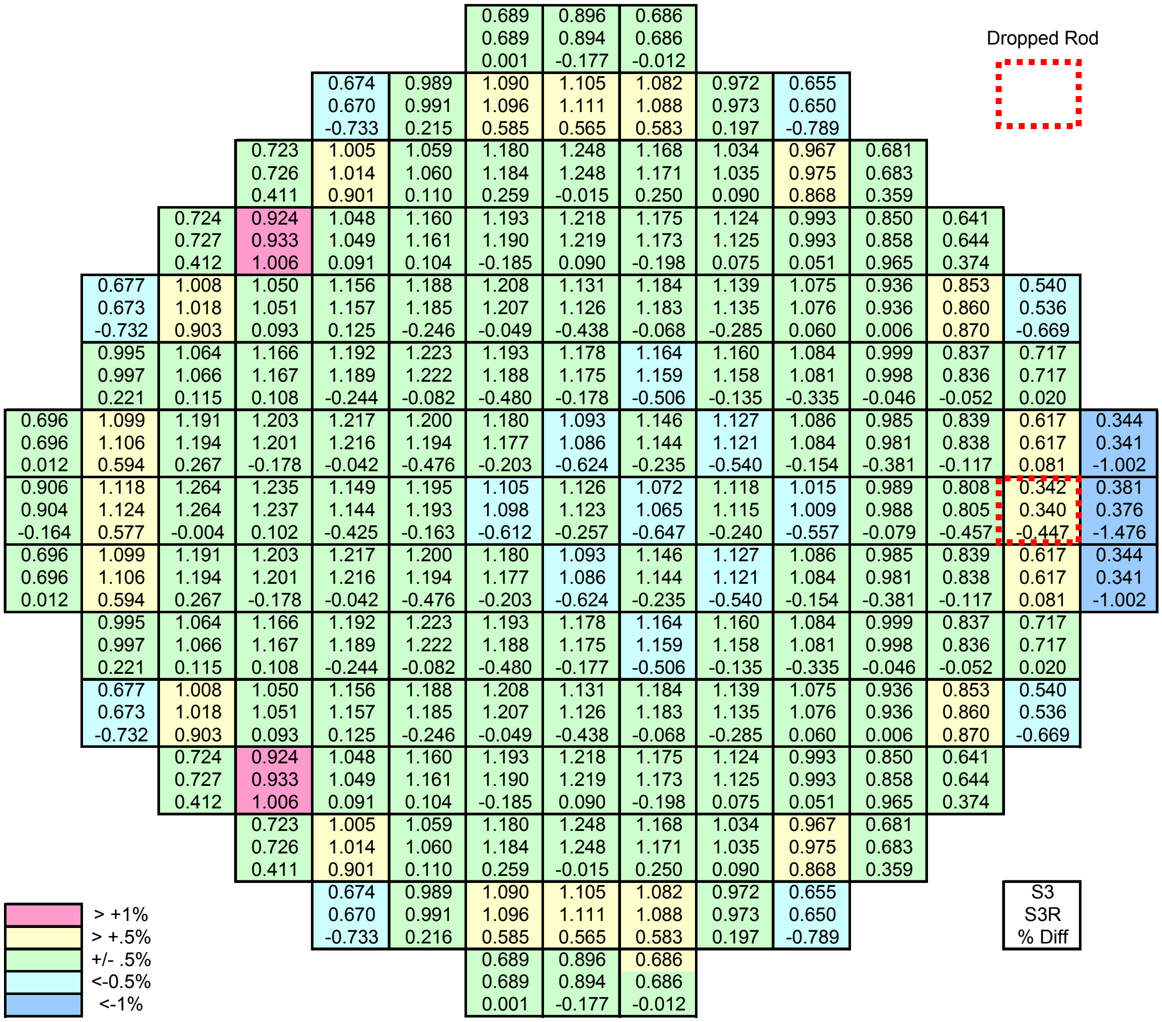
"Cancellation of Error:" Effect of Combining Spatial Truncation Error and Single Channel T/H Feedback Error To Reduce The Net Error On Power Distribution Prediction

However, it can be shown that the purported improvement in accuracy is not maintained for scenarios which differ from the reference case. To test the COE effect, an asymmetric rod is dropped from the HFP condition. A reference solution is generated with SIMULATE-3 in both power distribution and in the final stable power lever. Figure 6 shows the comparison of default SIMULATE-3R to the reference. The comparison to SIMULATE-3 in power distribution is almost as good as the reference (Figure 1).

Figure 7 shows that the COE technique, which was forced to agree well at one condition, agrees poorly away from that condition. The error of the power distribution in the dropped configuration is more than double that of the reference condition. Figure 8 shows the time series plots for all three cases. During the rod drop, all models perform about the same. However, the power recovery is severely overpredicted by the COE approach.

It stands to reason that combining two weak models should not lead to a stronger result. It can be concluded that theoretically weak models can be forced to give a “good” result at some reference condition. However, as the simulation moves away from the reference, it is reasonable to expect the error of the off-nominal cases will rise significantly compared to the error of the tuned reference solution.

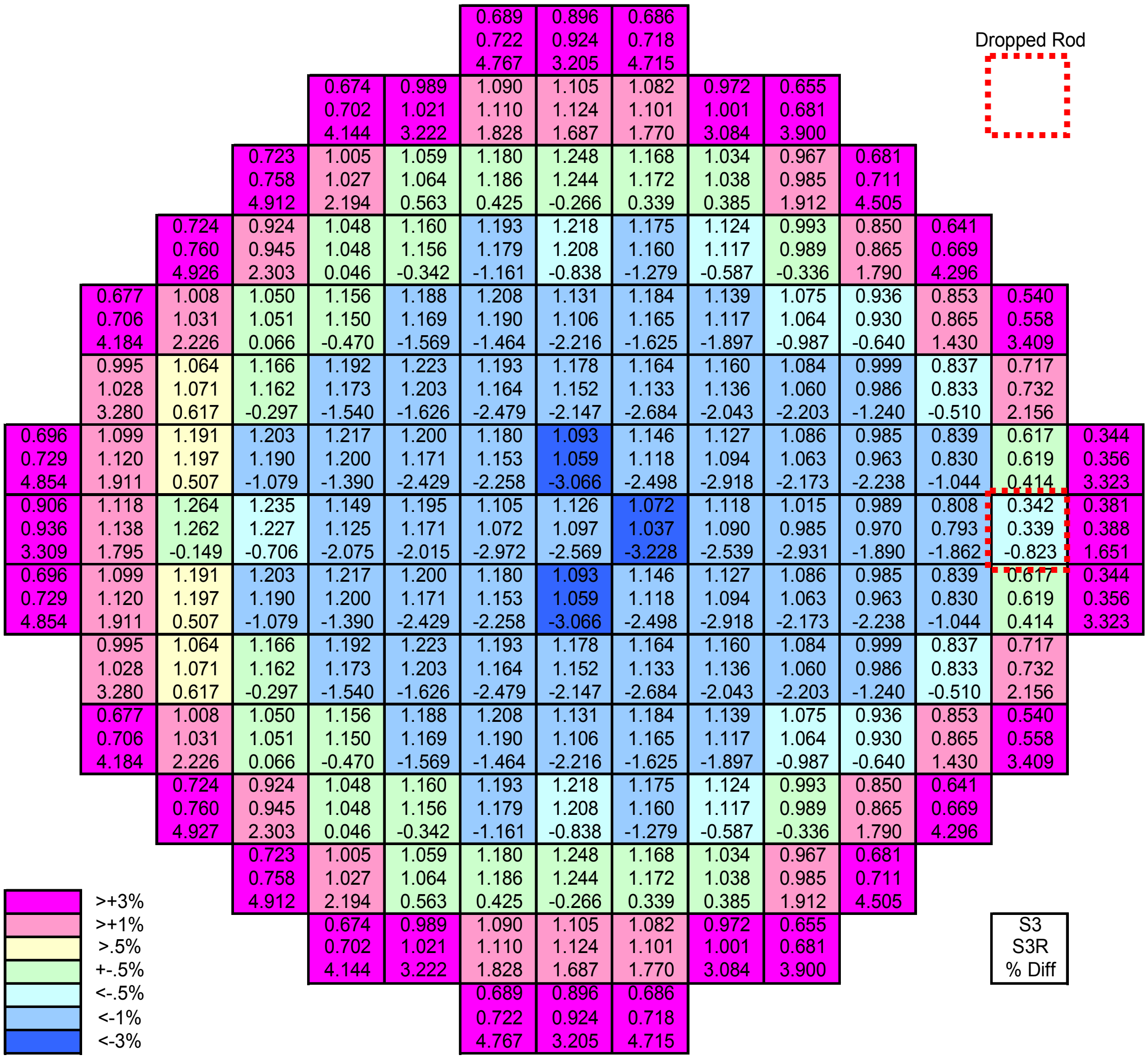
A secondary conclusion is that it is unreliable to force agreement, or tune, a theoretically weak core model to agree at a reference point and expect that same level of agreement as one moves away from the reference point.



						0.689 0.689 0.001	0.896 0.894 -0.177	0.686 0.686 -0.012						
				0.674 0.670 -0.733	0.989 0.991 0.215	1.090 1.096 0.585	1.105 1.111 0.565	1.082 1.088 0.583	0.972 0.973 0.197	0.655 0.650 -0.789				
			0.723 0.726 0.411	1.005 1.014 0.901	1.059 1.060 0.110	1.180 1.184 0.259	1.248 1.248 -0.015	1.168 1.171 0.250	1.034 1.035 0.090	0.967 0.975 0.868	0.681 0.683 0.359			
		0.724 0.727 0.412	0.924 0.933 1.006	1.048 1.049 0.091	1.160 1.161 0.104	1.193 1.190 -0.185	1.218 1.219 0.090	1.175 1.173 -0.198	1.124 1.125 0.075	0.993 0.993 0.051	0.850 0.858 0.965	0.641 0.644 0.374		
	0.677 0.673 -0.732	1.008 1.018 0.903	1.050 1.051 0.093	1.156 1.157 0.125	1.188 1.185 -0.246	1.208 1.207 -0.049	1.131 1.126 -0.438	1.184 1.183 -0.068	1.139 1.135 -0.285	1.075 1.076 0.060	0.936 0.936 0.006	0.853 0.860 0.870	0.540 0.536 -0.669	
	0.995 0.997 0.221	1.064 1.066 0.115	1.166 1.167 0.108	1.192 1.189 -0.244	1.223 1.222 -0.082	1.193 1.188 -0.480	1.178 1.175 -0.178	1.164 1.159 -0.506	1.160 1.158 -0.135	1.084 1.081 -0.335	0.999 0.998 -0.046	0.837 0.836 -0.052	0.717 0.717 0.020	
0.696 0.696 0.012	1.099 1.106 0.594	1.191 1.194 0.267	1.203 1.201 -0.178	1.217 1.216 -0.042	1.200 1.194 -0.476	1.180 1.177 -0.203	1.093 1.086 -0.624	1.146 1.144 -0.235	1.127 1.121 -0.540	1.086 1.084 -0.154	0.985 0.981 -0.381	0.839 0.838 -0.117	0.617 0.617 0.081	0.344 0.341 -1.002
0.906 0.904 -0.164	1.118 1.124 0.577	1.264 1.264 -0.004	1.235 1.237 0.102	1.149 1.144 -0.425	1.195 1.193 -0.163	1.105 1.098 -0.612	1.126 1.123 -0.257	1.072 1.065 -0.647	1.118 1.115 -0.240	1.015 1.009 -0.557	0.989 0.988 -0.079	0.808 0.805 -0.457	0.342 0.340 -0.447	0.381 0.376 -1.476
0.696 0.696 0.012	1.099 1.106 0.594	1.191 1.194 0.267	1.203 1.201 -0.178	1.217 1.216 -0.042	1.200 1.194 -0.476	1.180 1.177 -0.203	1.093 1.086 -0.624	1.146 1.144 -0.235	1.127 1.121 -0.540	1.086 1.084 -0.154	0.985 0.981 -0.381	0.839 0.838 -0.117	0.617 0.617 0.081	0.344 0.341 -1.002
	0.995 0.997 0.221	1.064 1.066 0.115	1.166 1.167 0.108	1.192 1.189 -0.244	1.223 1.222 -0.082	1.193 1.188 -0.480	1.178 1.175 -0.177	1.164 1.159 -0.506	1.160 1.158 -0.135	1.084 1.081 -0.335	0.999 0.998 -0.046	0.837 0.836 -0.052	0.717 0.717 0.020	
	0.677 0.673 -0.732	1.008 1.018 0.903	1.050 1.051 0.093	1.156 1.157 0.125	1.188 1.185 -0.246	1.208 1.207 -0.049	1.131 1.126 -0.438	1.184 1.183 -0.068	1.139 1.135 -0.285	1.075 1.076 0.060	0.936 0.936 0.006	0.853 0.860 0.870	0.540 0.536 -0.669	
		0.724 0.727 0.412	0.924 0.933 1.006	1.048 1.049 0.091	1.160 1.161 0.104	1.193 1.190 -0.185	1.218 1.219 0.090	1.175 1.173 -0.198	1.124 1.125 0.075	0.993 0.993 0.051	0.850 0.858 0.965	0.641 0.644 0.374		
			0.723 0.726 0.411	1.005 1.014 0.901	1.059 1.060 0.110	1.180 1.184 0.259	1.248 1.248 -0.015	1.168 1.171 0.250	1.034 1.035 0.090	0.967 0.975 0.868	0.681 0.683 0.359			
				0.674 0.670 -0.733	0.989 0.991 0.216	1.090 1.096 0.585	1.105 1.111 0.565	1.082 1.088 0.583	0.972 0.973 0.197	0.655 0.650 -0.789				
						0.689 0.689 0.001	0.896 0.894 -0.177	0.686 0.686 -0.012						

Figure 6

Comparison of SIMULATE-3 and SIMULATE-3R Prediction of Power Distribution in Response to a Rod Drop



						0.689 0.722 4.767	0.896 0.924 3.205	0.686 0.718 4.715						
				0.674 0.702 4.144	0.989 1.021 3.222	1.090 1.110 1.828	1.105 1.124 1.687	1.082 1.101 1.770	0.972 1.001 3.084	0.655 0.681 3.900				
			0.723 0.758 4.912	1.005 1.027 2.194	1.059 1.064 0.563	1.180 1.186 0.425	1.248 1.244 -0.266	1.168 1.172 0.339	1.034 1.038 0.385	0.967 0.985 1.912	0.681 0.711 4.505			
		0.724 0.760 4.926	0.924 0.945 2.303	1.048 1.048 0.046	1.160 1.156 -0.342	1.193 1.179 -1.161	1.218 1.208 -0.838	1.175 1.160 -1.279	1.124 1.117 -0.587	0.993 0.989 -0.336	0.850 0.865 1.790	0.641 0.669 4.296		
	0.677 0.706 4.184	1.008 1.031 2.226	1.050 1.051 0.066	1.156 1.150 -0.470	1.188 1.169 -1.569	1.208 1.190 -1.464	1.131 1.106 -2.216	1.184 1.165 -1.625	1.139 1.117 -1.897	1.075 1.064 -0.987	0.936 0.930 -0.640	0.853 0.865 1.430	0.540 0.558 3.409	
	0.995 1.028 3.280	1.064 1.071 0.617	1.166 1.162 -0.297	1.192 1.173 -1.540	1.223 1.203 -1.626	1.193 1.164 -2.479	1.178 1.152 -2.147	1.164 1.133 -2.684	1.160 1.136 -2.043	1.084 1.060 -2.203	0.999 0.986 -1.240	0.837 0.833 -0.510	0.717 0.732 2.156	
0.696 0.729 4.854	1.099 1.120 1.911	1.191 1.197 0.507	1.203 1.190 -1.079	1.217 1.200 -1.390	1.200 1.171 -2.429	1.180 1.153 -2.258	1.093 1.059 -3.066	1.146 1.118 -2.498	1.127 1.094 -2.918	1.086 1.063 -2.173	0.985 0.963 -2.238	0.839 0.830 -1.044	0.617 0.619 0.414	0.344 0.356 3.323
0.906 0.936 3.309	1.118 1.138 1.795	1.264 1.262 -0.149	1.235 1.227 -0.706	1.149 1.125 -2.075	1.195 1.171 -2.015	1.105 1.072 -2.972	1.126 1.097 -2.569	1.072 1.037 -3.228	1.118 1.090 -2.539	1.015 0.985 -2.931	0.989 0.970 -1.890	0.808 0.793 -1.862	0.342 0.339 -0.823	0.381 0.388 1.651
0.696 0.729 4.854	1.099 1.120 1.911	1.191 1.197 0.507	1.203 1.190 -1.079	1.217 1.200 -1.390	1.200 1.171 -2.429	1.180 1.153 -2.258	1.093 1.059 -3.066	1.146 1.118 -2.498	1.127 1.094 -2.918	1.086 1.063 -2.173	0.985 0.963 -2.238	0.839 0.830 -1.044	0.617 0.619 0.414	0.344 0.356 3.323
	0.995 1.028 3.280	1.064 1.071 0.617	1.166 1.162 -0.297	1.192 1.173 -1.540	1.223 1.203 -1.626	1.193 1.164 -2.479	1.178 1.152 -2.147	1.164 1.133 -2.684	1.160 1.136 -2.043	1.084 1.060 -2.203	0.999 0.986 -1.240	0.837 0.833 -0.510	0.717 0.732 2.156	
	0.677 0.706 4.184	1.008 1.031 2.226	1.050 1.051 0.066	1.156 1.150 -0.470	1.188 1.169 -1.569	1.208 1.190 -1.464	1.131 1.106 -2.216	1.184 1.165 -1.625	1.139 1.117 -1.897	1.075 1.064 -0.987	0.936 0.930 -0.640	0.853 0.865 1.430	0.540 0.558 3.409	
		0.724 0.760 4.927	0.924 0.945 2.303	1.048 1.048 0.046	1.160 1.156 -0.342	1.193 1.179 -1.161	1.218 1.208 -0.838	1.175 1.160 -1.279	1.124 1.117 -0.587	0.993 0.989 -0.336	0.850 0.865 1.790	0.641 0.669 4.296		
			0.723 0.758 4.912	1.005 1.027 2.194	1.059 1.064 0.563	1.180 1.186 0.425	1.248 1.244 -0.266	1.168 1.172 0.339	1.034 1.038 0.385	0.967 0.985 1.912	0.681 0.711 4.505			
				0.674 0.702 4.144	0.989 1.021 3.222	1.090 1.110 1.828	1.105 1.124 1.687	1.082 1.101 1.770	0.972 1.001 3.084	0.655 0.681 3.900				
						0.689 0.722 4.767	0.896 0.924 3.205	0.686 0.718 4.715						

Figure 7

Inferior Comparison of SIMULATE-3 and the “Cancellation of Error” Approach Applied to a Prediction of Power Distribution in Response to a Rod Drop

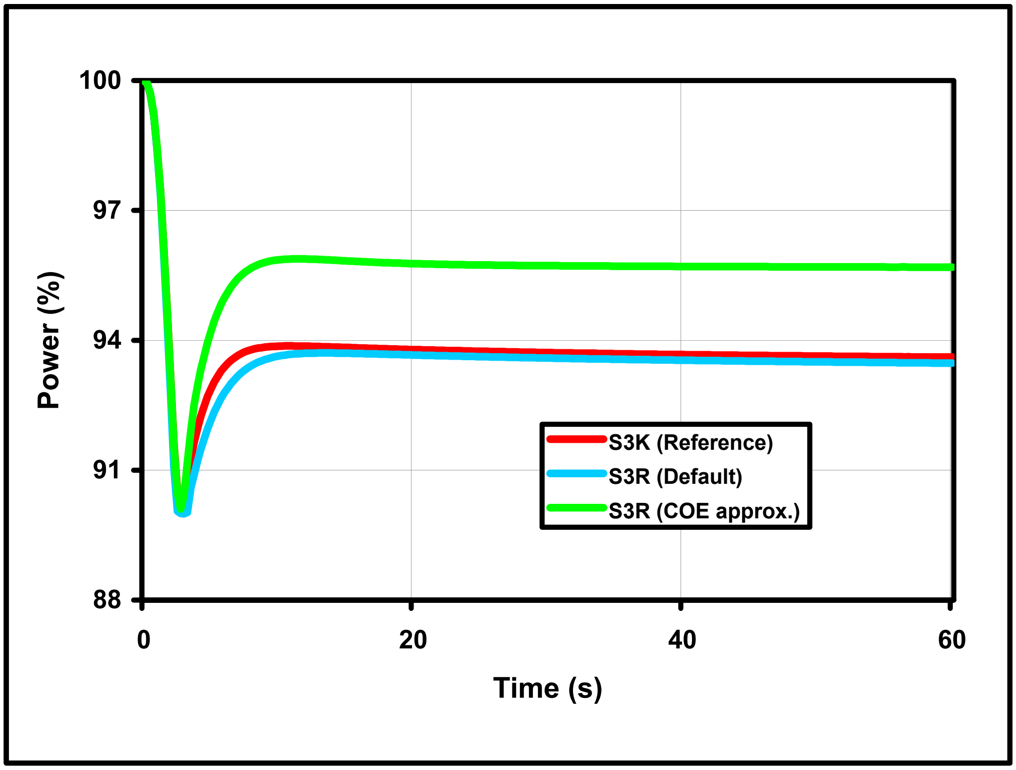


Figure 8

Time Response of Power After Rod Drop

6. SUMMARY

Advanced engineering grade core models are being applied to real-time training simulators. The motivation for such an upgrade is increased fidelity to core design methodology and measured plant data. A further expectation is that the core model use cycle specific nuclear data such that training is performed on the cycle actually loaded.

The capabilities of SIMULATE-3R are discussed in terms of how it complies with the expectations of a modern training core model. SIMULATE-3R is identified as a derivative of the design codes SIMULATE-3 and SIMULATE-3K.

The modifications which allow SIMULATE-3R to run in real-time as described. These modifications are assessed quantitatively by the application of a known benchmark problem data set. Additional, more approximate, methods are assessed as well. These methods can be shown to introduce significant errors.

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