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AXIAL POWER MONITORING UNCERTAINTY IN THE SAVANNAH RIVER REACTORS (U)

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D. C. Losey and S. M. Revolinski

Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

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ABSTRACT

The results of this analysis quantified the uncertainty associated with monitoring the Axial Power Shape (APS) in the Savannah River Reactors. Thermocouples at each assembly flow exit map the radial power distribution and are the primary means of monitoring power in these reactors. The remaining uncertainty in power monitoring is associated with the relative axial power distribution. The APS is monitored by seven sensors that respond to power on each of nine vertical Axial Power Monitor (APM) rods.

Computation of the APS uncertainty, for the reactor power limits analysis, started with a large database of APM rod measurements spanning several years of reactor operation. A computer algorithm was used to randomly select a sample of APSs which were input to a code. This code modeled the thermal-hydraulic performance of a single fuel assembly during a design basis Loss-of-Coolant Accident. The assembly power limit at Onset of Significant Voiding was computed for each APS. The output was a distribution of expected assembly power limits that was adjusted to account for the biases caused by instrumentation error and by measuring 7 points rather than a continuous APS.

Statistical analysis of the final assembly power limit distribution showed that reducing reactor power by approximately 3% was sufficient to account for APS variation. This data confirmed expectations that the assembly exit thermocouples provide nearly all information needed for monitoring core power. The computational analysis results also quantified the contributions to power limits of the various uncertainties such as instrumentation error.

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INTRODUCTION

Reactor power limits are being reevaluated in a program to confirm reactor safety at the Savannah River Site. This analysis supported the reevaluation by assessing the reactor power limit reductions to account for uncertainties in monitoring the core Axial Power Shape (APS).

The analysis relied upon a somewhat different approach than had typically been used to solve reactor physics problems. The typical approach relied on core power distribution predicted using 3-dimensional diffusion theory. However, difficulties would arise in initializing the diffusion theory model to predict realistic power distributions that properly accounted for the limitless possibilities of control rod mispositioning, fuel fabrication deviations, fuel depletion, xenon and other factors affecting power distribution. Simplifying and worst case assumptions would have been required and would have produced overly conservative results. The economic penalty from this conservatism was unacceptable.

Instead of predicting core power distributions, this analysis used measurements from reactor operation and fuel fabrication processes. Several large databases of power distribution measurements were available which had not been utilized extensively for such analyses. Analysis utilizing unbiased samples from these databases gave results that are not overly conservative as with a worst case, predictive approach.

POWER DISTRIBUTION MONITORING

APS measurements have a secondary role in power distribution monitoring in the SRS reactors. More than 1600 thermocouples, four located at each assembly flow exit, measure absolute assembly power and are the primary means of monitoring power distribution. These thermocouples provide most, but not all, of the information needed to assess core power distribution. In addition to the thermocouples, nine vertical APM rods distributed throughout the core measure the axial flux from which the power distribution can be derived. Each APM rod has seven sensors in the axial direction that are located 0, ± 76, ± 107, and ± 152 cm from the core mid-plane. APMs need measure only a relative axial distribution because the thermocouples monitor absolute assembly power.

At each of the nine APM rod locations there is also a Traveling Wire Flux Monitor (TWFM) which measures a continuous axial flux shape be iron wire neutron activation. The TWFMs are more accurate than the APMs because they are a continuous iron wire giving a uniform axial response. The signals from the APM rods are monitored continuously by the Control Computers, but the TWFM measurements are taken manually about once a week. The APM rods are calibrated directly to the TWFMs thus measure axial flux which can be converted to power.

To assure reactor safety the core power distribution is controlled by limits placed on the allowed readings from the assembly thermocouples, APMs and TWFMs. These power limits are developed in safety analyses which consider a broad range of operating and accident conditions. The most restrictive condition for the Savannah River reactors is during a Loss of Coolant Accident (LOCA) from a double-ended guillotine process water pipe break. Reactor power limits are established to prevent Onset of Significant Voiding in the assembly coolant flow channels during this accident.

The FLOWTRAN code is a primary computational tool used to calculate the power limits for the SRS cores. The code is a thermal hydraulic model of a single assembly under LOCA conditions. Only a single limiting assembly need be modeled because the assembly flow channels are closed. APSs are one of the inputs to the FLOWTRAN code.

As part of producing reactor power limits the objective of the APS uncertainty analysis was to produce bounding APSs for the FLOWTRAN calculation. In this analysis the FLOWTRAN code was used to predict assembly power limits using APSs measured by either APMs or TWFMs.

METHODOLOGY

This analysis relied on measured APSs taken from several databases of reactor operational data. Determining reactor power limits required an unbiased sample of measured APSs. In addition only a limited number of APSs could be analyzed because the FLOWTRAN calculation for each assembly power limit required about six CPU minutes. To properly account for the expected distribution in APSs and to limit the number of APSs analysed, about 1000 were randomly selected for analysis. In addition to the random selection, the APSs were screened to eliminate those cases where the APM rods were miscalibrated. The shapes were also converted from neutron flux to power.

The APSs were then input to the FLOWTRAN code to calculate the basis set of power limits. Additional sources of uncertainty in the resulting APS power limits distribution were quantified. APM rod miscalibration was simulated by adjusting the power limit distribution based on actual deviation between APM and TWFM measurements. The variation in APS caused by axial fuel loading variation was also modeled. A final power limit distribution was produced from which a bounding power limit was taken.

An important assumption in the analysis was that the APM rod measurements were representative of APSs throughout the core and not biased by reactor operator control. This assumption would not be justifiable for single core map, but by analyzing enough measurements the assumption was valid because no significantly different influences affected APS at the APM rod locations compared to other locations. Reactor operators observed measurements from the APM locations and moved the control rods generally as a gang to adjust only the ratio of the readings from APM sensors two to six averaged over the three APM rods assigned to a gang.

APS VARIATION

This part of the analysis assessed the power limit reduction needed to account for expected APS variations caused by control rod positions and fuel depletion. The analysis used APM rod data input to FLOWTRAN calculations to predict a basic power limit distribution modeling the variation in APS. APM rather than TWFM data was used because the largest and most complete set of APSs were available from these databases. One database contained about 45,000 APS measurements. These APSs had been logged hourly from reactor measurements but were only kept for the last six months of reactor operation, so an entire fuel cycle was not spanned. Another smaller database more completely spanned several fuel cycles but logged APSs only twice a week and had about 1000 APSs. Together the two databases provided APSs completely spanning one fuel cycle and partially spanning two other fuel cycles.

To obtain an unbiased sample of APSs, a weighted random selection was used to take APM measurements from the databases. Data from the smaller database was given a higher weight because of its' relative importance in spanning the fuel cycles. Neither database stored the raw instrument signals. Instead the seven sensor readings had been converted to a more continuous curve by polynomial fitting. Utility routines were developed to recover the raw data.

The signals also had to be converted from neutron flux to power. This conversion used a simple depletion algorithm relating flux and power as a function of fuel exposure. The implementation required other information from the reactor databases. The fuel exposure was obtained by integrating assembly thermocouple data and flux measurements provided the axial exposure shape.

Some data was corrupted because the APM rods were miscalibrated. To eliminate the corrupted data, a screening process was developed. This process had to assure that as much corrupted data as possible was discarded but none of the outlying APSs that would produce the bounding power limits would be affected. The screen used the mean (μ) plus and minus four standard deviations (σ) at each of the seven sensor levels. Figure 1 shows the upper and lower screening criteria along with the mean APS from all of the stored APM measurements.

Once the 1000 APM measurements had been randomly selected, converted from the polynomial fit, and from flux to power and also screened, the APSs were input to FLOWTRAN and assembly power limits calculated. The output formed the basic distribution of 1000 power limits. Statistical analysis of this distribution resulted in a mean power limit of 5.81 $\pm$ 0.035 Megawatts (MW) and the lowest or bounding power limit was 5.67 MW. Thus, as shown in Table 1, a reactor power reduction of 2.4% would allow operation with the lowest rather than the mean of the 1000 APSs.

Normality of the basic distribution was investigated by making a probability plot and by using the Anderson-Darling goodness-of-fit test[1]. This test gave a modified statistic of

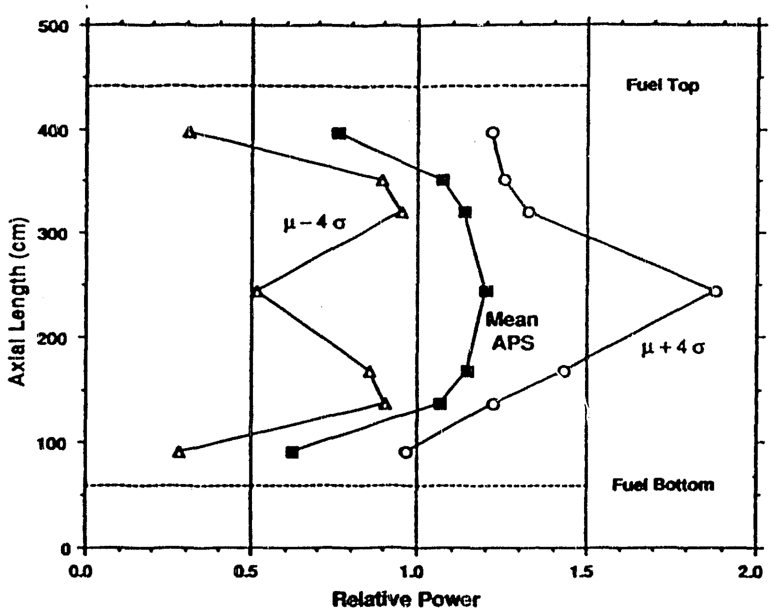

Figure 1. APM Data Screening Criteria

9.0 which, for comparison, should not exceed 0.752 and 1.159 at levels of significance of 0.05 and 0.005, respectively. The plot and test indicated that the power limits were not normally distributed and that attempts to extrapolate the data to lower probability cases assuming normality would have no meaning.

INSTRUMENT RESPONSE UNCERTAINTY

The basic distribution of 1000 power limits accounted for deviation in APSs as measured by the APM rods, but the additional uncertainty due to difference between APM and TWFM response was also accounted for. This difference in response is caused by APM rod miscalibration and also because the APMs measure only seven points rather than a continuous axial profile.

This analysis used a database of 328 TWFM and APM profiles for which power limits were calculated by the FLOWTRAN code. The data did not span even one complete fuel cycle, hence was not appropriate as the basic distribution. Figure 2 shows the power limits

Table 1. APS Monitoring Uncertainties

	Contribution to Power Limit (MW)	Contribution to Power Limit (%)
Mean Power Limit from 1000 APSs	5.81	100.0%
APS Variation lowest minus mean power limit	-0.14	-2.4%
Instrument Response	-0.06	-1.0%
Axial Fuel Loading	-0.01	-0.1%
Final Power Limit	**5.60**	**96.4%**

where the APM power limits on the Y axis are plotted against the more accurate TWFM data on the X axis. If the APM rods were as accurate as the TWFMs, all points would be on the diagonal line.

The mean and standard deviation in the TWFM power limits were 5.78 ± 0.038 MW while the corresponding mean and standard deviation for the APM power limits were 5.80 ± 0.034 MW. This indicates that on average the APM power limits are about 0.02 MW or 0.4% too high. This bias is nonconservative, hence it is important that it be accounted for in establishing the power limits.

One datum in Figure 2 is a noticeable outlier, having an APM profile power limit of 5.96 MW while the TWFM profile power limit is only 5.79 MW. This discrepancy was caused by a miscalibrated APM rod which caused a large difference in power limit because of sensitivity to APS in certain regions along the axial length. Power limits are most sensitive to the shape at about 80% down from the top of the assembly where voiding occurs.

The uncertainties associated with differences in APM and TWFM response were combined by a simulation process which modified each of the 1000 power limits in the basic distribution by randomly selecting ten power limit differences sampled from the 328 TWFM and APM residuals. The ten randomly selected residuals were added to each of the 1000 power limits, producing a distribution of 10,000 power limits with the differences in APM and TWFM response modeled. The contributions to the power limit presented in Table 1 were calculated based upon a 99.9 percentile ranking in the power limit distribution with the APM and TWFM response differences simulated.

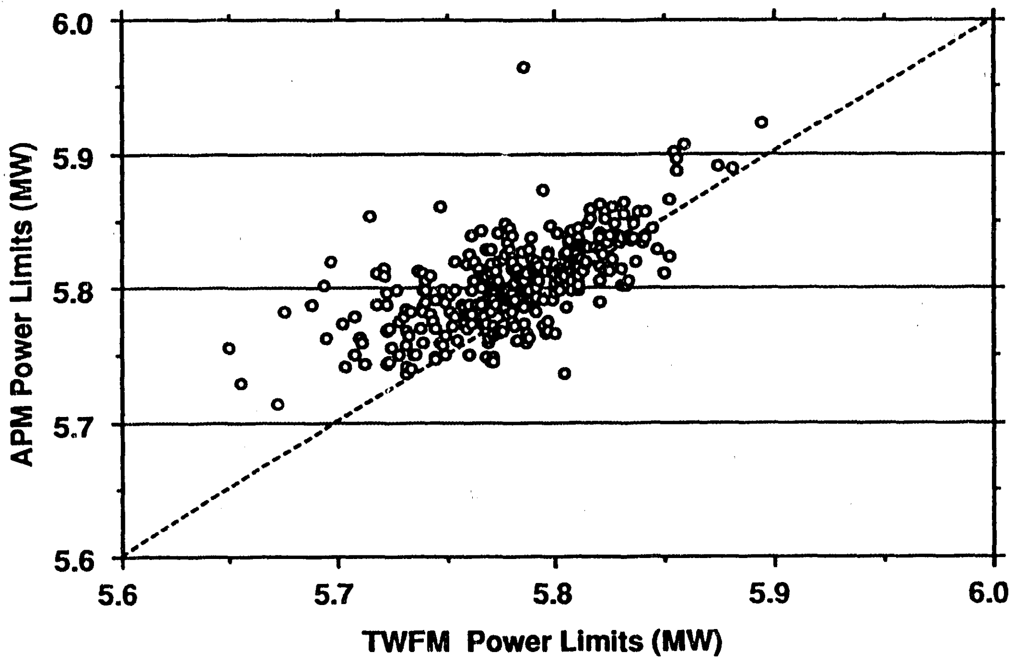

Figure 2. APM and TWFM Power Limits

AXIAL FUEL LOADING UNCERTAINTY

The uncertainty in axial power monitoring caused by variation in axial fuel loading was also accounted for in this analysis. APS and axial fuel loading are related by

$$P(z) = \Sigma_f(z)\,\phi(z)$$

where P(z) is the axial power, $\phi(z)$ is the axial flux and $\Sigma_f(z)$ is the fission cross section or axial fuel loading. In this equation only relative not absolute profiles are important for the reasons described earlier. The equation shows that variation in the fission cross section or axial fuel loading will have a direct effect on the axial power shape that will not be observable in the axial flux shape.

The basic distribution of power limits came from flux measurements taken with the APM rods that had been calibrated to the TWFMs. These flux measurements were converted to power using an algorithm that assumed the initial axial fuel loading was uniform. The axial fuel loading uncertainty analysis assesses the effect of this simplifying assumption by using a sample of 68 axial fuel loading measurements. These samples each contained ten relative fuel loading measurements along the axial length. The maximum relative axial fuel loading from any of the ten segments in the 68 measurements was 1.031 and the minimum was 0.954 compared to an average value of 1.0.

The effect of the 8% variation in the axial fuel loading was assessed by the same methods as for APM and TWFM response analysis. The first step was to randomly sample from the 68 fuel loading shapes to initialize the depletion algorithm at the start of the cycle. An axial fuel loading was randomly selected for each APM rod and the fuel loading was depleted over the cycle. At a randomly selected exposure during the cycle, the APS was written to the FLOWTRAN input file. To provide complete sampling of the axial fuel loadings, only one APS was taken for each APM rod during the cycle depletion. Thus the algorithm generating the APSs randomly and independently selected the initial axial fuel loading, the APM rod, and the exposure.

Seven cycle depletions were calculated giving 50 APSs with the axial fuel loading variation accounted for. For comparison the same 50 APSs were developed by initializing the depletion algorithm with a uniform axial fuel loading. The assembly power limits for two sets of 50 APSs are plotted in Figure 3. In this case the data fall very close to the diagonal line which shows that the effect of the axial fuel loading variation is small.

The simulation process again modeled the affects of axial fuel loading variation in the basic distribution of power limits. This process modified each of the 10,000 power limits from

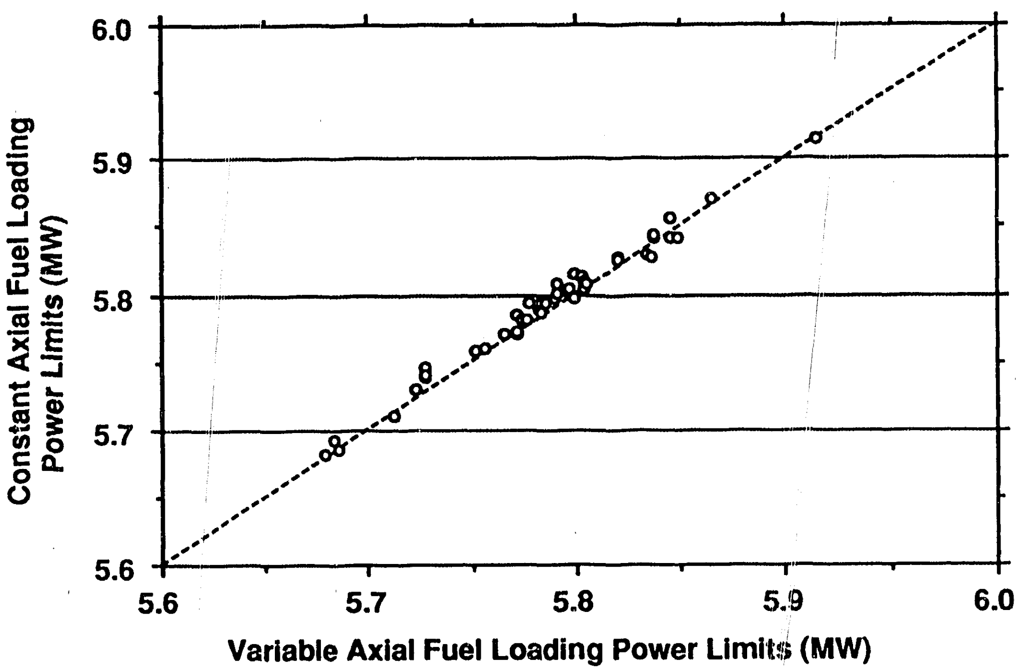

Figure 3. Axial Fuel Loading Effects on Power Limits

the APM TWFM response analysis by randomly selecting one of the 50 power limit residuals, producing another distribution with 10,000 power limits. The contribution to the power limit was calculated as the 99.9 percentile in this final distribution. As shown in Table 1, a power limit reduction of 0.01 MW or 0.1% was sufficient to account for the axial fuel loading variation.

CONCLUSIONS

This analysis assumed specific reactor accident conditions and has used the FLOWTRAN code as the model for predicting dependence of assembly power limits on APS.

This analysis has shown that a 3.6% power reduction will account for the expected variation in APS from the mean with the effects of instrument response and axial fuel loading uncertainty included. This 3.6% power reduction is considerably less than that which would have resulted with the more conventional predictive, worst case approach. The analysis demonstrated the economic benefit of collecting and storing reactor operational data. Had the APM rod measurements not been available, the economic penalty of using a more conservative analysis would have been severe.

Based upon this analysis, other uses for the databases of reactor operational data have been identified.

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