INVESTIGATION OF ERROR SOURCES DURING CORE REACTIVITY MEASUREMENTS

Roger Blake
Utility Resource Associates
75 Holly Lane
Pilesgrove, NJ 08098

ABSTRACT

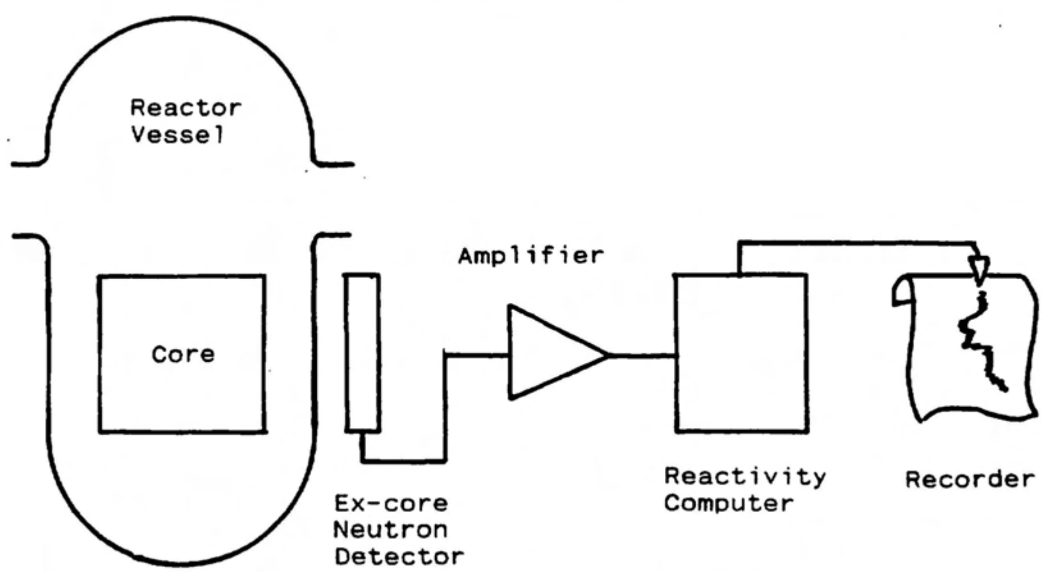
This paper describes an investigation of various sources of measurement errors potentially affecting zero power reactivity measurements. The purpose of the investigation was to determine the causes of observed measurement anomalies during several start up physics tests. The principle tool used in this investigation was a computer model which simulated the behavior of the core and instrumentation used during the tests. This simulator was designed to include several error sources which were turned on and off in an attempt to duplicate the observed anomalies.

INTRODUCTION

Startup physics tests are performed at PWR's following a refueling. These tests are made at zero power, and typically measure such core parameters as control rod worth and Isothermal Temperature Coefficient, ITC. These measurements are made with a reactivity computer using an input signal from one or more ex-core power range neutron detectors, which are uncompensated ion chambers. The computer interprets this input signal as core reactivity using the assumption that it is proportional to core average neutron flux. A typical test configuration is illustrated in Figure 1.

The core reactivity measurements are frequently characterized by anomalies in the recorded core reactivity behavior. The results reported in this paper trace the causes of at least some of these anomalies to distortions in the flux signal feeding the reactivity computer. These distortions can cause significant errors in the measurements. The potential consequence of such errors is the delay in power escalation.

FIGURE 1 TYPICAL STARTUP TEST CONFIGURATION



TYPICAL MEASUREMENTS - NO ANOMALIES

A typical test sequence is first to bring the reactor critical at zero power, with all rods out except for the controlling bank which is partially inserted. The next steps are to check-out the reactivity computer, measure the ITC, and then measure the worth of the controlling rod bank.

Figure 2 shows a typical strip chart recording made during a rod pull for the check-out of the reactivity computer. Time increases backward, from right to left. The core reactivity, ρ, is initially zero at mid scale. The control rod bank is then pulled out a few steps, introducing a constant, positive core reactivity of 40 pcm (1pcm=1% milli-ρ, or 10-5Δk). This causes the core neutron flux to increase from it's initial value of about 19% of full scale to ultimately 85%. At this point the rods are inserted to below their original position, creating a negative reactivity of -13 pcm which then causes the flux to begin to decrease. The data in Figure 1 are used to check the calibration of the reactivity computer. The rate of flux increase is measured directly from the strip chart and then compared to design values associated with a 40 pcm reactivity. In the absence of flux signal distortion, the reactivity trace should remain constant between the rod motions. This is observed to be the case in Figure 2.

The next step is to measure the ITC. A typical ITC measurement is shown in Figure 3. The x-axis is RCS temperature, and the y-axis is core reactivity. The test procedure is to vary the RCS temperature while holding other reactivity parameters constant. The core reactivity response is then plotted against temperature on an xy-plotter. Without distortion, the plot should be a straight line. The slope of the line, in pcm/°F, is the ITC, and is measured directly from the plot.

FIGURE 2
Typical Rod Pull for
Reactivity Computer Check-out
No Anomalies

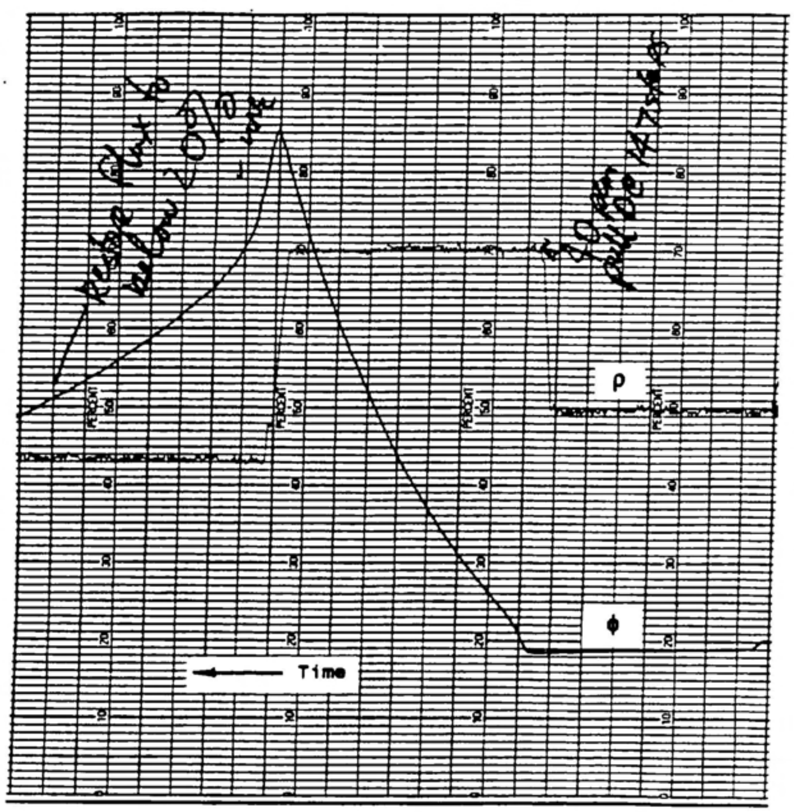


FIGURE 3
Typical ITC Measurement

No Anomalies

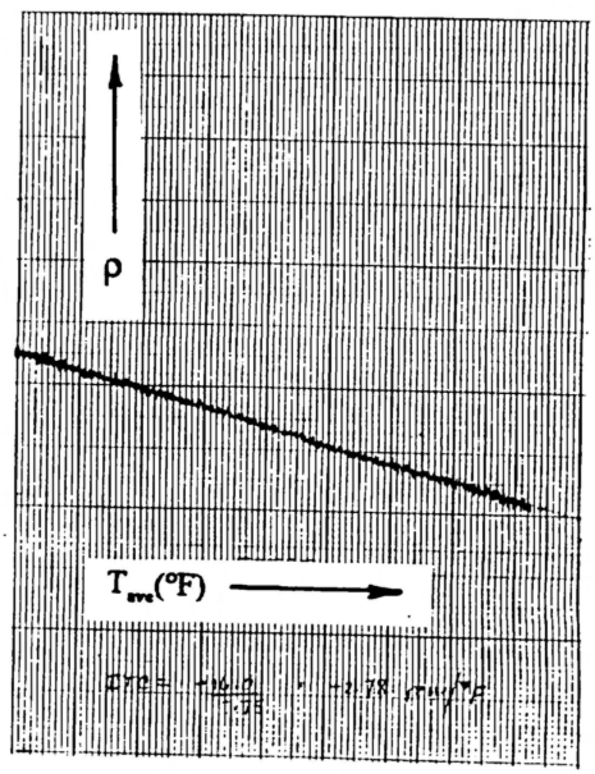
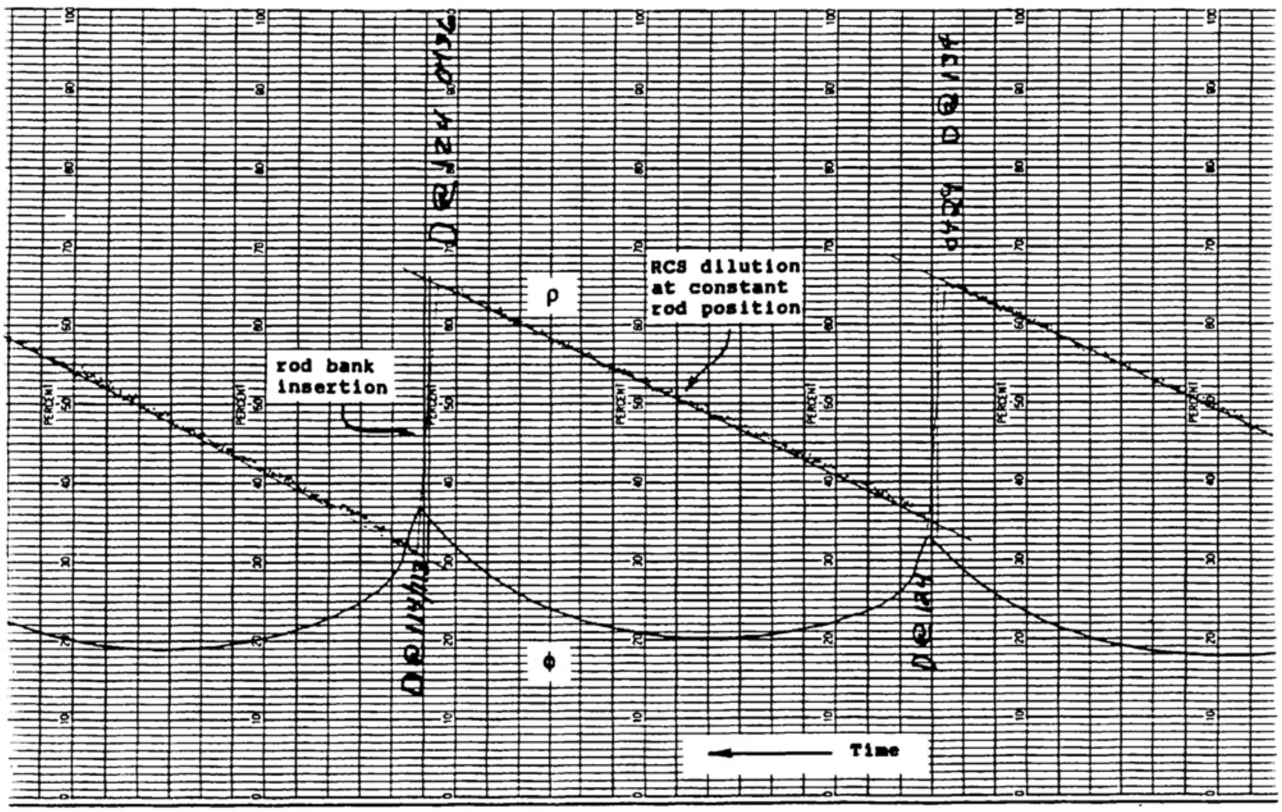


Figure 4 shows a typical strip chart recording made during a rod worth measurement. This has the same format as Figure 2. Time increases backward from right to left. Both core flux, the lower cusp-shaped trace, and core reactivity, the saw-toothed plot, are shown. During this test, the RCS boron concentration is slowly diluted with water. The decreasing boron causes a nearly constant, positive rate of change in the core reactivity. The reactivity zero point is at mid scale. When the reactivity is positive, the flux increases. At some point the flux increase is terminated by moving the control rod bank in a few steps. This creates a rapid negative step change in reactivity which then causes the flux to decrease. The flux continues to decrease until the continued dilution causes the reactivity to again become positive. The flux then increases until the rod bank is again inserted. This process is repeated until the rod bank has been fully inserted.

In the absence of anomalies, the reactivity trace should be a series of straight lines of positive slope between the rod motions as is shown in Figure 4. The reader should keep in mind that in Figure 4, the time or x-axis is reversed, and the RCS dilution portions of the trace have a positive slope.

Lines of best fit have been drawn on the reactivity traces by the test engineer using a straight edge. The vertical displacement of these lines is assumed to represent the incremental worth of the rod bank insertion. The sum of these displacements over the entire rod bank travel is the worth of the entire rod bank.

FIGURE 4 Typical Rod Worth Dilution Measurement - No Anomalies



OBSERVED MEASUREMENT ANOMALIES

Figures 5 and 6 are examples of measurement anomalies observed during a rod pull. Compare these to Figure 2. In both Figures 5 and 6, the reactivity trace during the period of positive reactivity when the rod has been pulled out, is not a horizontal line of constant reactivity as is shown in Figure 2. In Figure 5 it continues to increase (positive anomaly) after the rod motion has stopped. In Figure 6 the reactivity decreases (negative anomaly) after the rod motion has stopped.

Figure 7 is an example of an ITC measurement anomaly. Compare this to Figure 3. Two measurements are shown in Figure 7. The upper xy-plot was measured during an RCS heatup, the lower during a cool down. Both should be straight lines parallel to each other. The displacement between them is an arbitrary convenience achieved by adjusting the zero on the xy-plotter. The zero point is unimportant since only the slope of the lines are to be determined.

Figure 8 is an example of a measurement anomaly observed during a dilution rod worth measurement. Compare it to Figure 4. The reactivity trace between rod motions should be a straight line. The trace in Figure 8 has a definite bend or change in slope. This especially evident when viewed from the edge of the paper, along the trace line.

The anomalies illustrated in Figures 5 through 8 are not rare. They don't occur all the time, but they have been experienced during the startup of several reactor-cycles.

FIGURE 5
Positive Anomaly
During a Rod Pull

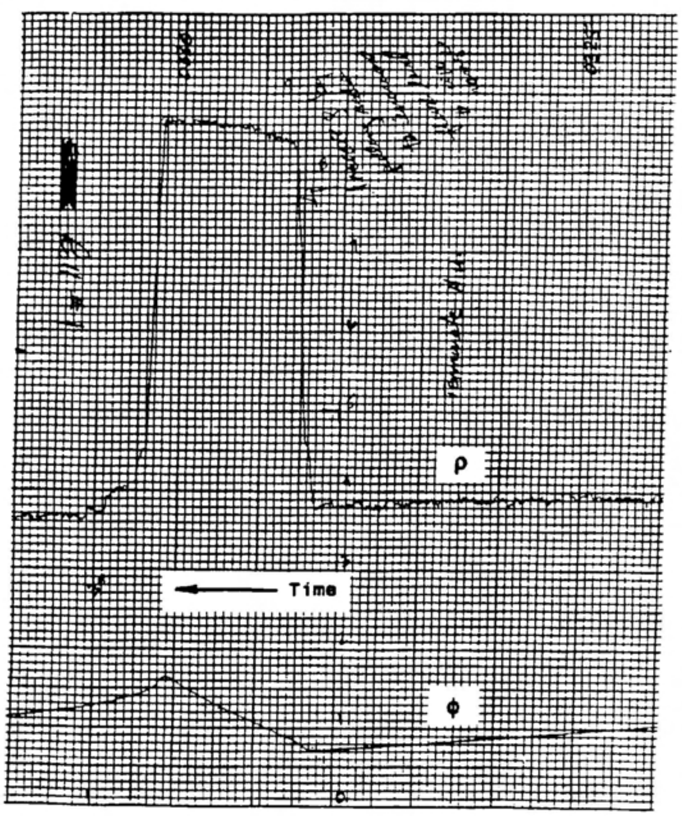


FIGURE 6
Negative Anomaly
During a Rod Pull

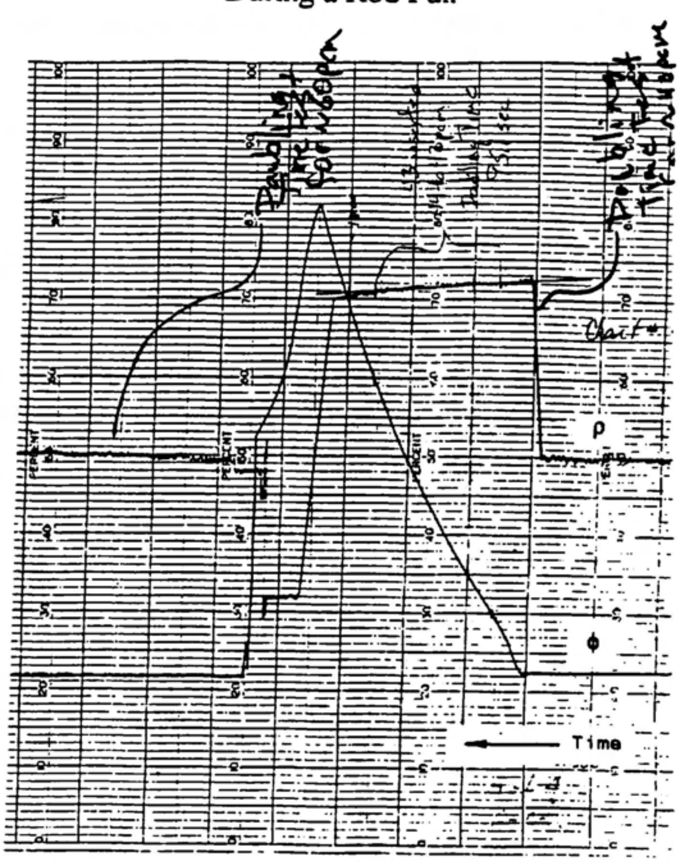


FIGURE 7 Anomalies During ITC Measurements

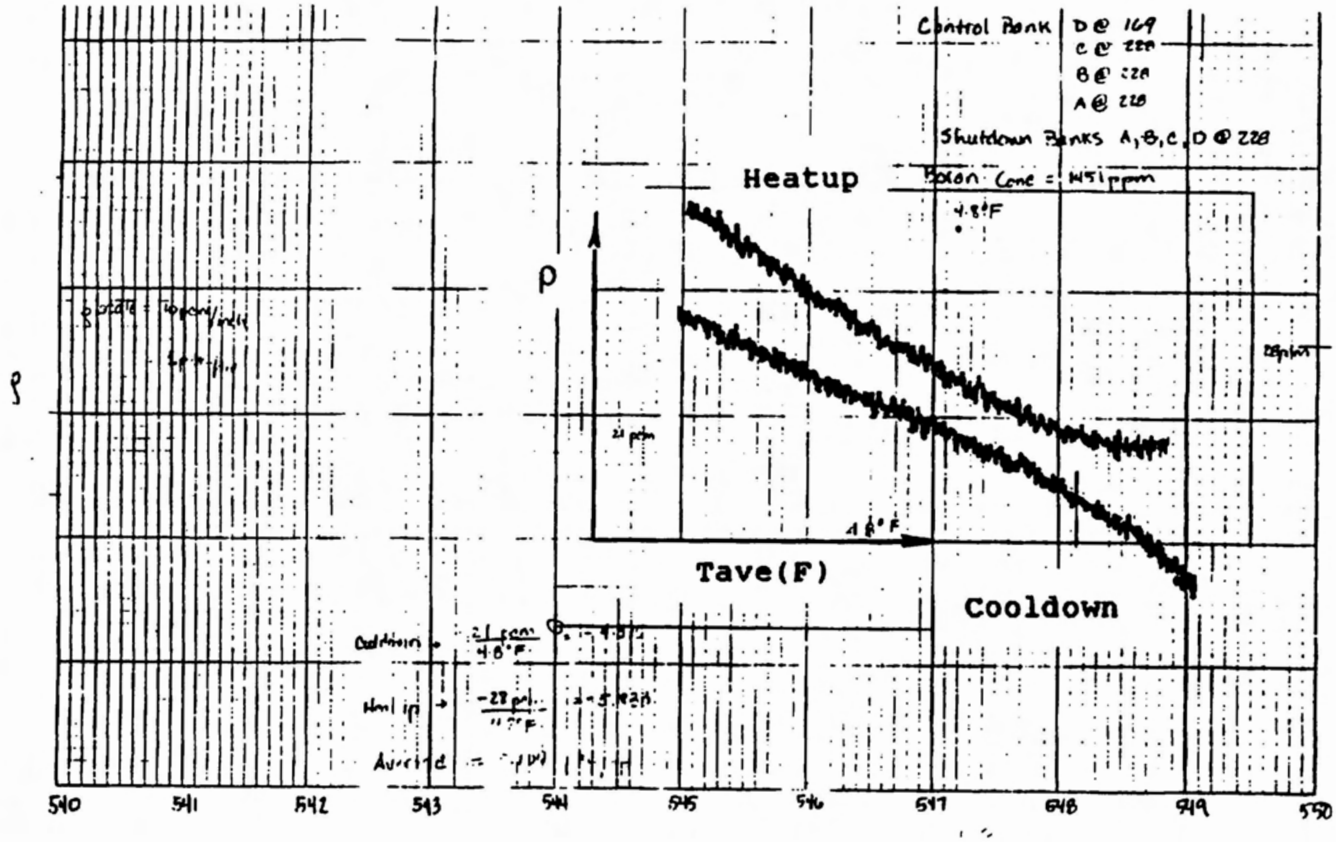
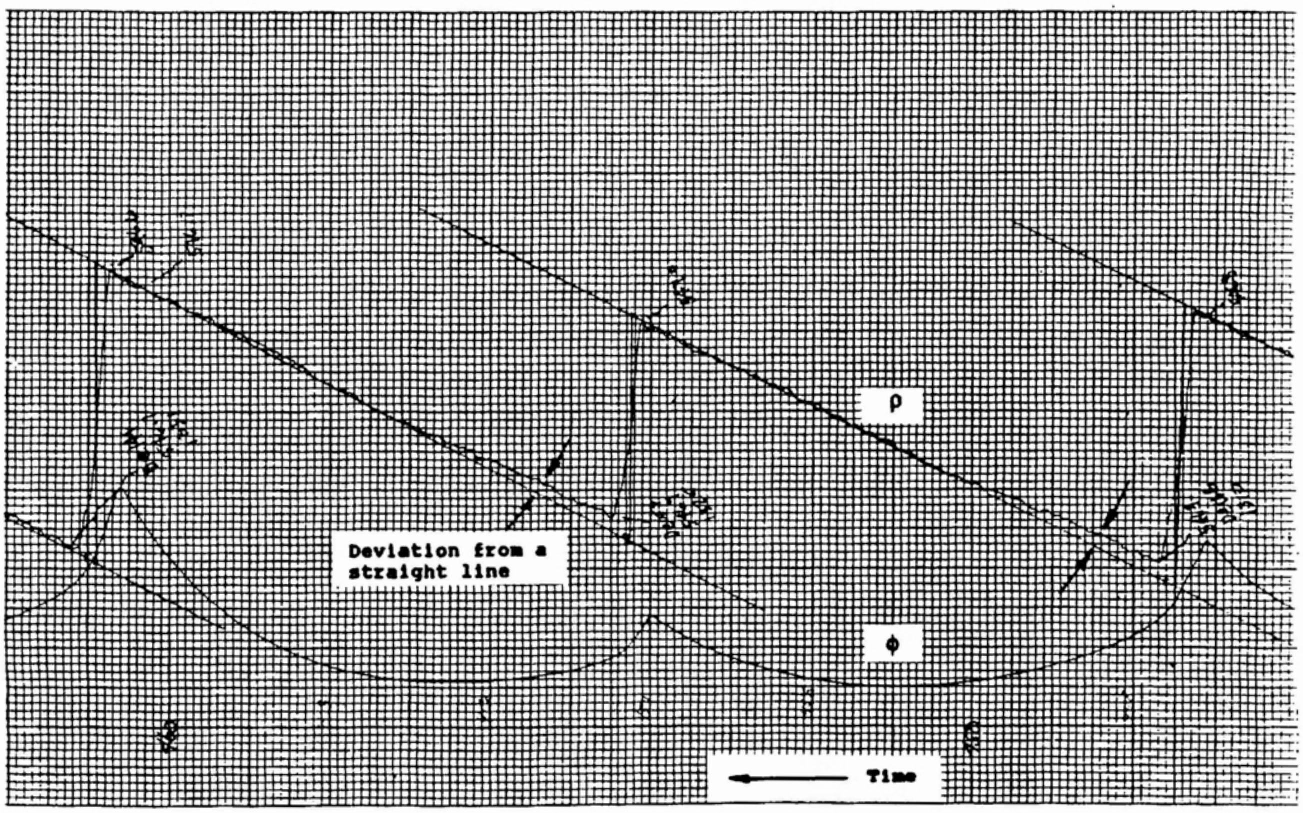


FIGURE 8 Anomalies During Rod Worth Measurements



ANALYSIS METHODOLOGY

The following is a list of suspected potential causes of the anomalies illustrated in Figures 5-8.

- Miscalibration of the reactivity computer
- RCS boron or temperature drift during measurements
- Spatial flux effects
- Gamma background signal
- Reactivity computer input filter
- Nuclear Heating
- Thermal lag of fuel temperature relative to RCS
- Other hardware signal distortion effects

The objective of the analysis was to find a cause that could explain the observed anomalies. If so, calculate the magnitude of the cause needed, and if possible, the corrected core parameter, ITC or rod worth, that would have been measured in the absence of the cause. It was decided that the best approach was to build a flexible computer simulator to test the effects of postulated causes under simulated test conditions.

The reader should note carefully the distinction between similar terms used in the descriptions given below. During the real tests at the actual reactor site, their is a real reactor core and a real reactivity computer. In this paper a computer simulator is described which models these two components. For clarity, an attempt has been made to use the words "core" and "reactivity computer" for the real hardware, and the words "simulator" and "simulated" to refer to the post test analysis described in this paper.

A simulator has been developed on a PC computer. It consists of two separate point kinetics models. One represents the core, and the other represents the reactivity computer used during the tests. The two models were linked by including a representation of the ex-core detectors and signal processing components. The simulator was designed to allow the user to simulate the execution of actual core measurements in the presence of one or more of the suspected causes of the observed anomalies. The simulated output from the reactivity computer can then be compared to the actual output to determine if the postulated cause can yield the observed results.

The user can control the independent test variables. The simulator then calculates the core neutron flux in response to these variables, determines the ex-core signal, applies user defined distortions, and uses the resultant signal to simulate the action of the reactivity computer. The input and output variables are described below.

User Defined Simulator Input Variables:

1. Delayed neutron constants for the core.
2. Delayed neutron constants for the computer
3. Gamma flux component
4. Core reactivity due to rod motion & boron as a function of time
5. RCS temperature as a function of time
6. Time constant for thermal lag of fuel relative to RCS temperature.
7. RCS Moderator Temperature Coefficient (MTC)
8. Fuel Temperature Coefficient (FTC)
9. Proportionality between core flux level and excore signal as a function of control rod motion and RCS temperature
10. Arbitrary distortion of signal between ex-core detector and computer
11. Time constant for the computer input filter.

Variables calculated by the Simulator

12. Fuel temperature based on the dynamic behavior of the RCS temperature (5) and the thermal lag of the fuel (6).
13. Core reactivity as the sum of the components: rods/boron(4), MTC(5&7), and FTC(8&12).
14. Core average neutron flux vs. time using 1, 3, and 13.
15. Relative ex-core signal using 3, 5, 9 and 14.
16. Input signal reaching the reactivity computer input filter using 10 and 15.
17. Output signal from filter to reactivity computer using 11 and 16. This is the signal used by the computer as the input to the calculation of reactivity.
18. The simulated value of the "indicated" core reactivity as it would have been be calculated by the reactivity computer based on 17..
19. Delayed neutron precursor concentrations for both the core and reactivity computer

Each of the point kinetics models computes the dynamic numerical solution to the coupled point kinetics equations.

$$\frac{dn}{dt} = \frac{\rho - \beta}{l*}n + \sum_{i=1}^{6} \lambda_i C_i$$

$$\frac{dCi}{dt} = \frac{\beta i}{l*}n - \lambda_i C_i$$

n = total neutron population in the reactor
C_i = total population of delayed neutron precursors of type i
β_i = effective fraction of delayed neutron precursors of type i
λ_i = decay constant of delayed neutron precursors of type i
l^* = effective neutron life time in the reactor

The core model calculates the flux level given the core reactivity (13), gamma level(3), and delayed neutron data(1). The reactivity computer model calculates the inferred reactivity(18), given the flux behavior(17), and computer calibration(2).

The model was checked by simulating the reactivity computer checkout test. The simulated flux periods in response to several in reactivity steps agreed with core design values to within a fraction of a second.

ANALYSIS RESULTS

Each of the suspected potential causes identified above were investigated. The results are discussed below. Several were eliminated based only on the test data, without the need to perform simulations. These include RCS boron or temperature drift, nuclear heating, and the thermal lag of the fuel temperature. These are discussed first.

RCS Boron or Temperature Drift

These were eliminated as possible causes based on the test data without the need for simulations. In Figure 5, the reactivity trace prior to the rod pull clearly shows a negative reactivity drift in progress. This drift continues after the rod is re-inserted to its original position. This drift could have been caused by a drift in either the RCS boron concentration or the moderator temperature. In either case it is clear from the figure that this negative drift can not be the cause of the positive reactivity anomaly during the rod pull. Aside from the drift being in the opposite direction, neither a boron or temperature drift would be expected to turn on and off in concert with the rod motion. A similar situation exists for Figure 6 in which there is no reactivity drift before or after the rod pull.

Based on the above considerations, a drift in the boron concentration of moderator temperature is not considered to be the cause of the observed anomalies.

Nuclear Heating

The anomaly in Figure 6 looks like that expected from the effects of nuclear heating. The physics tests are designed to be performed at a sufficiently low flux level to assure that the power produced by the fissions remains below the threshold of detectability. If the flux was allowed to increase above this threshold, then the fuel temperature would begin to increase above the moderator temperature. This is called nuclear heating. An increase in fuel temperature would cause a negative Doppler reactivity effect. The higher the flux, the more negative the reactivity. This is the general appearance of the reactivity trace in Figure 6.

To avoid the occurrence of nuclear heating, the test engineers increase the flux to a level higher than the planned test range. For the test associated with Figure 6, the flux was increased a full decade above that used for the test. No effects of nuclear heating were observed. Based on this, nuclear heating is not now considered to be a possible cause for the observed anomalies.

Thermal Lag of Fuel Temperature

The ITC test measures the combined reactivity effects of changes in the moderator (MTC) and fuel temperature (FTC). The test controls the change in moderator temperature. The fuel temperature is assumed to track the moderator. The test is executed slowly to allow the fuel temperature to remain in equilibrium with the changing moderator temperature. If the moderator change was too rapid, the fuel would lag. This might cause the plot of reactivity versus moderator temperature to appear as a curved line instead of a straight line as shown in Figure 3.

The signature of the ITC anomaly shown in Figure 7 are the curved lines. However, the curvature is in the opposite direction than would be expected due to fuel temperature lag. For this reason it is not considered to be the cause of the anomaly.

Reactivity Computer Input Filter

Simulations were performed with input filter constants as high as several seconds, which is larger than that used on the reactivity computer. None of these results produced the observed anomalies. The filter setting is not now considered the cause of the observed anomalies.

Core to Ex-core Coupling Effects

The term "coupling" as used here refers to the proportionality between the core average neutron flux level and that seen by the ex-core detectors used to provide the input to the reactivity computer. It is assumed that this proportionality remains constant during any reactivity measurement.

There are two general mechanisms that can change the proportionality. One is called spatial effects, and the other attenuation effects. Attenuation effects are caused by changes in the attenuation of neutrons between the core and excore detectors. This could conceivably be caused by changes in RCS boron concentration and/or changes in the moderator temperature. Attenuation was not considered in this analysis because there was sufficient test data to eliminate it.

Spatial effects are caused by a spatial redistribution of the flux in the core. Since the ex-core detectors only "see" the peripheral fuel assemblies, any redistribution that causes the flux in these assemblies to decrease will register on the reactivity computer as a negative change in reactivity even though the core average flux level may remain constant, and the core reactivity remains zero. This can typically occur as a result of a rod bank insertion in the fuel assemblies near the core periphery in the vicinity of the ex-core detector. The insertion can have two effects. First it causes a real negative core reactivity. Second, it can depress the local flux which could change the proportionality. The signal to reactivity computer would appear to have a larger relative negative change than the actual core average flux. The computer therefore overestimates the negative reactivity insertion. This is called "overshoot". When the same rod is withdrawn, the process is reversed and the computer overestimated the positive reactivity. Again this is overshoot.

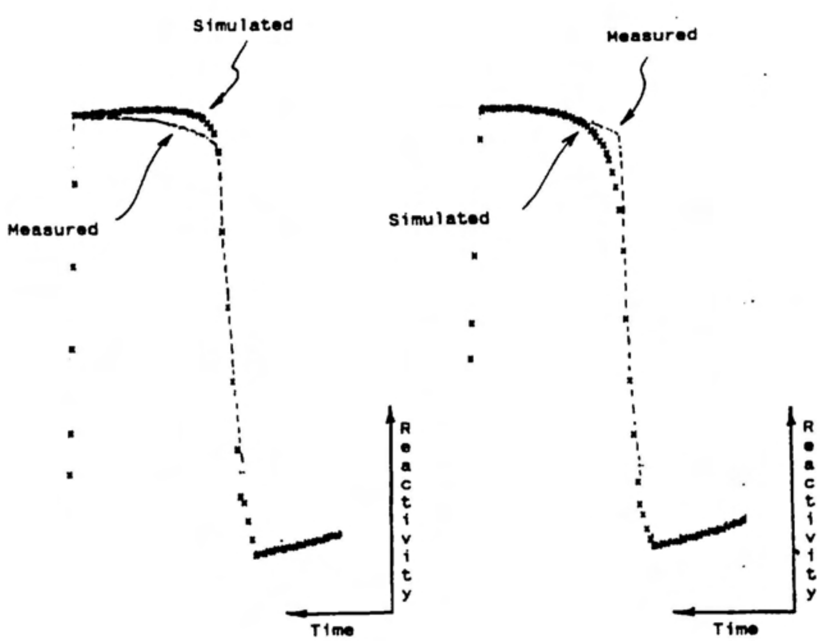
Although overshoot due to rod motion can be explained based on intuition, it is difficult to postulate an "undershoot" effect. This would be when reactivity is underestimated. It terms of redistribution, this would require the peripheral flux increase during a rod insertion, and decrease during a rod withdrawal. The rod pull anomaly shown in Figure 5 has the shape expected from an undershoot effect. The shape in Figure 6 is neither over or undershoot. Although it is not obvious what could cause undershoot, it was considered as a possible cause.

The effects of spatial redistribution were simulated by causing a change in the proportionally of the core/ex-core coupling during rod pulls. Traces with an initial reactivity undershoot somewhat like that shown in Figure 5 were created. Two of the simulated traces are shown in Figure 9. On the left, a simulated trace with a weaker undershoot is compared to the measured trace from Figure 5. The simulation has a greater initial curvature and the wrong slope at the end of the rod pull. A simulation with a stronger undershoot is shown on the right. It matches the final slope but is too low initially. These were the best matches that could be achieved. Based on these results it was concluded that spatial undershoot effects were not the cause of the observed anomalies.

Figure 9

Reactivity
Undershoot
Simulations

(Measured is
From Fig 5)



Miscalibration of the Reactivity Computer

This potential cause was investigated by mismatching the delayed neutron constants used to simulate the core and reactivity computer. Because the reactivity computer checkout results during the actual tests were within the acceptance criterion, the degree of mismatch was constrained to this limit. The criterion was that the observed flux period as measured from the strip chart agree with the design prediction associated with "indicated" reactivity on the strip chart to within 4% (relative). The simulation objective was therefore to try to find a mismatch that would create the observed anomalies shown in Figures 5 and 6, without causing the total reactivity error to exceed the 4% criterion.

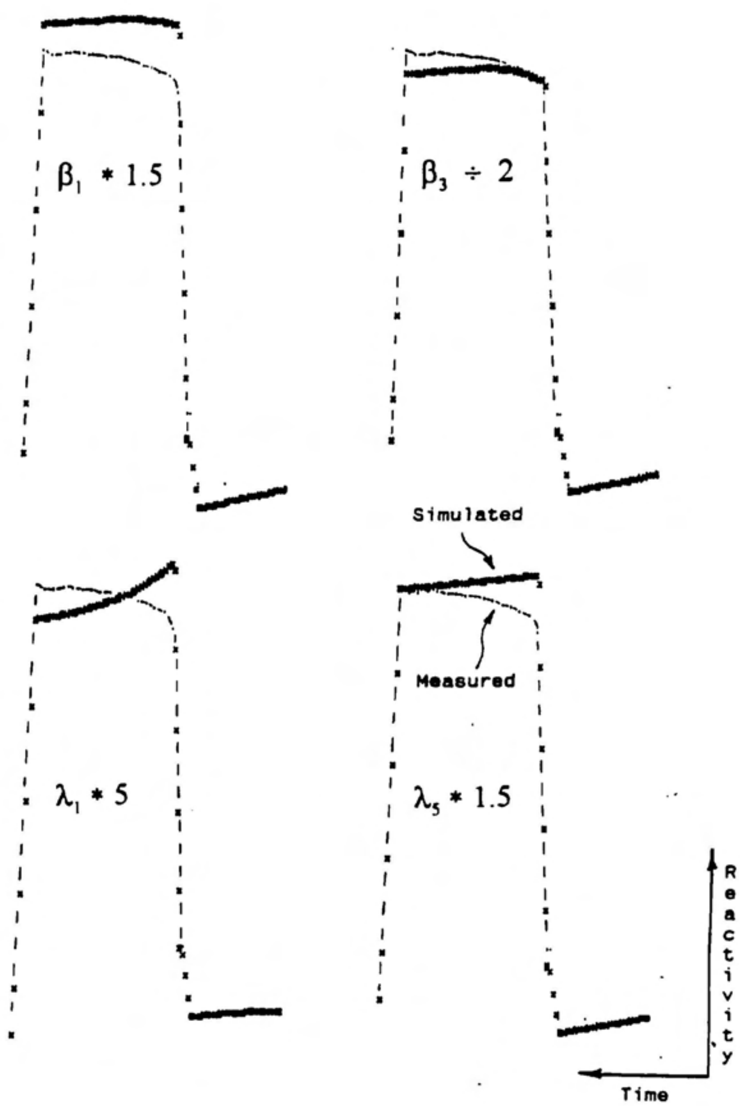
The simulations were based on the rod pull reactivity measurement shown in Figure 5. Various Beta(i) and Lambda(i) values were changed one at a time in each of several simulations. Typical simulation results and their comparisons to the Figure 5 measurements are shown in Figure 10.

The result was that although anomalies of similar general shapes could be generated, none was found that both matched the shape and maintained the 4% agreement on total error.

Figure 10

Reactivity Computer Miscalibration Simulations.

(Meas. from Fig.5)



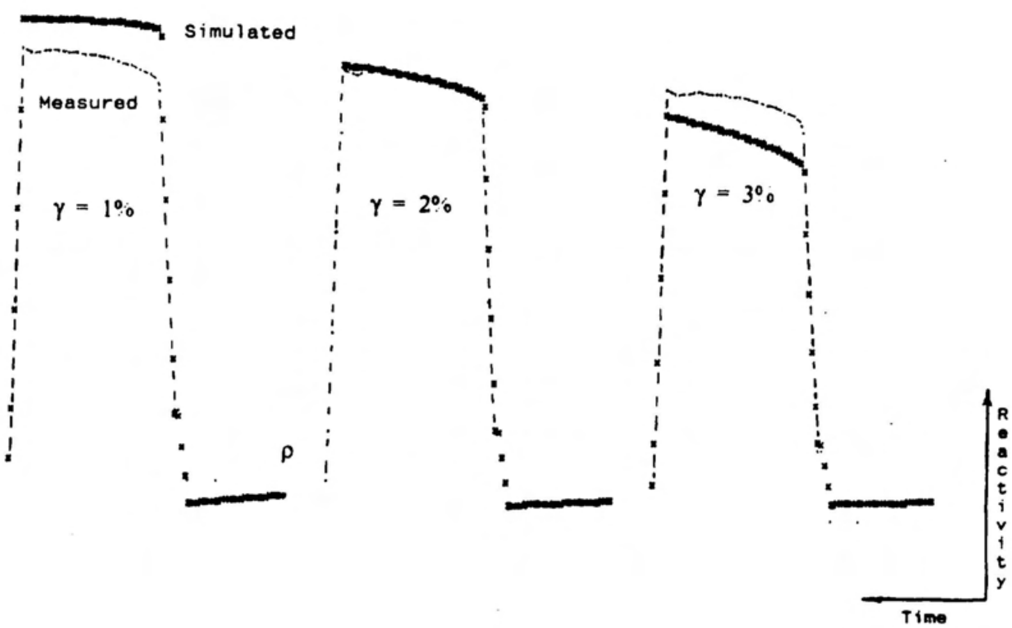
Gamma Background Signal

The radioactive decay of the fuel results in the emission of gamma rays (γ) which can cause a false signal in the ex-core detectors. During any given startup test, the level of the gamma signal component is constant. The effects of gamma on the physics measurements were simulated by adding a constant component to the signal reaching the ex-core detectors. It was found that the presence of the gamma signal could explain most, but not all of the observed anomalies.

Figure 11 illustrates the effect of various gamma signal levels on the simulation of the measured rod pull from Figure 5. Three gamma levels are shown. Each is expressed as a percentage of the full scale flux signal. The 1% level causes too little curvature. The 3% level causes too much. The 2% level provides an almost exact match to the observed anomaly shown in Figure 5. A significant feature which is illustrated in Figure 11 is the sensitivity of using a rod pull to detect and determine the level of gamma present during a test. In this case it clearly demonstrates that the level of gamma during the test was very nearly 2% of the full scale flux signal.

Figure 11

Simulated Effects of Gamma During the Rod Pull from Fig 5.



Once the gamma level was determined to be 2% from Figure 11, the ITC measurement from Figure 7 and the rod worth measurement from Figure 8 were simulated using this value.

The simulated ITC measurements are shown in Figure 12 which should be compared to the observed anomaly shown in Figure 7. The agreement is striking. The input MTC value was adjusted until the simulated flux behavior matched the measured flux. The curvature in the simulated reactivity trace was entirely a result of the gamma as calculated by the simulator.

The simulated rod worth measurements are shown in Figure 13 which should be compared to the observed anomaly shown in Figure 8. Again the agreement is striking. Like the ITC test,.the input reactivity was adjusted until the simulated flux behavior matched the measured flux. The curvature in the simulated reactivity trace was entirely a result of the gamma as calculated by the simulator.

FIGURE 12

Simulated
ITC Meas
from Fig 7
Using 2%
Gamma

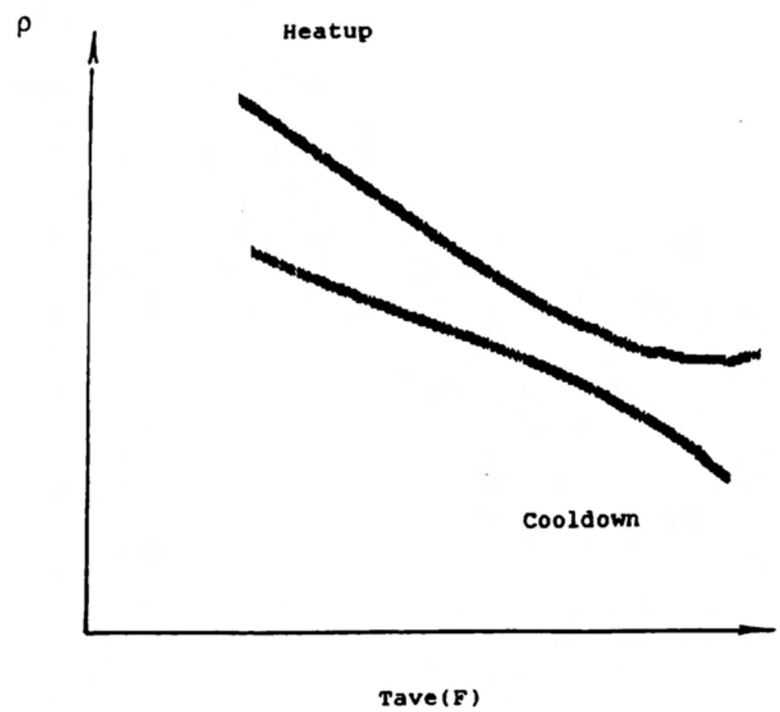


FIGURE 13 Simulated Rod Worth Measurement from Figure 8 Using 2% Gamma

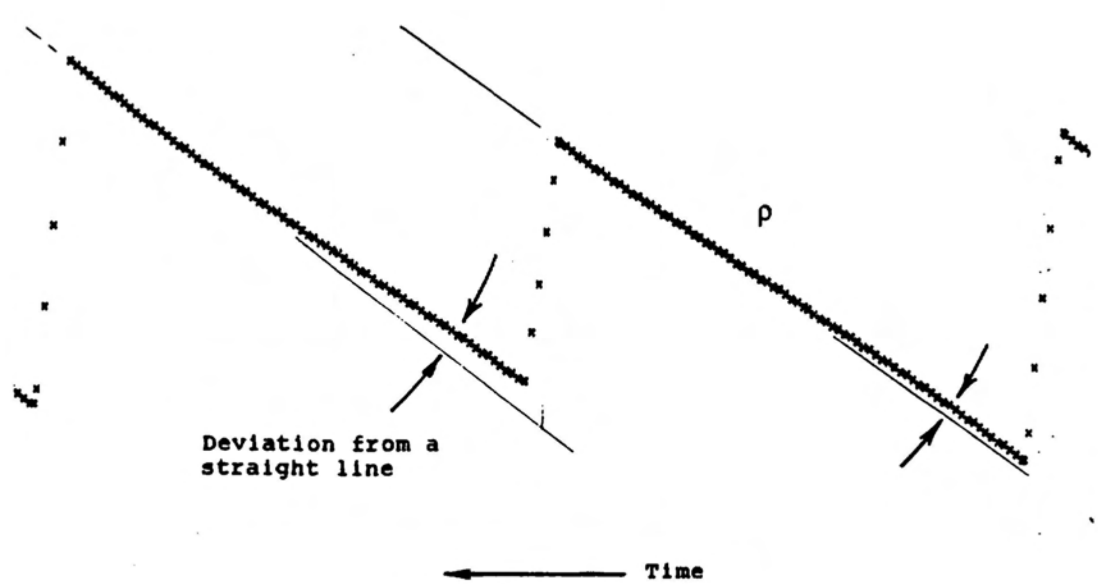


FIGURE 14

Simulated ITC

Using 2% Gamma

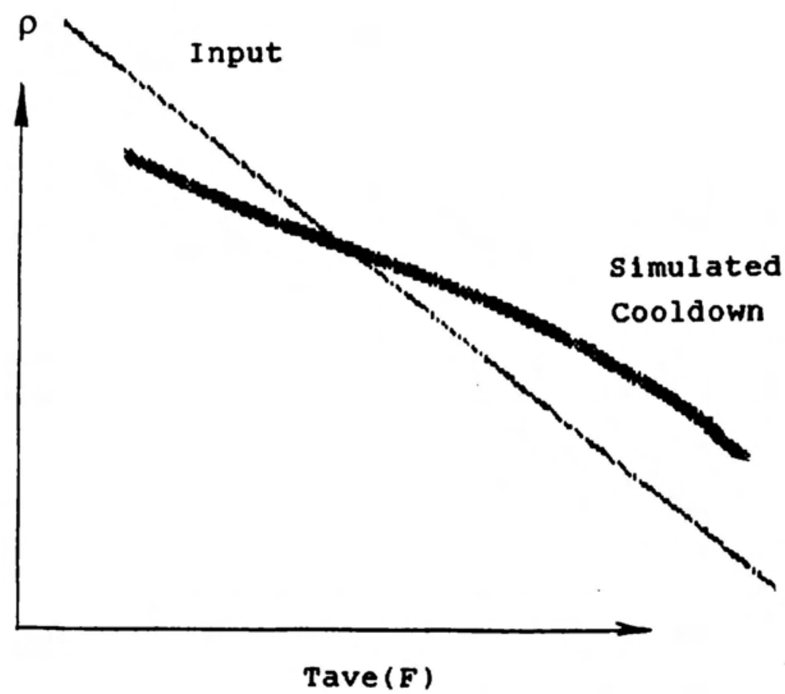
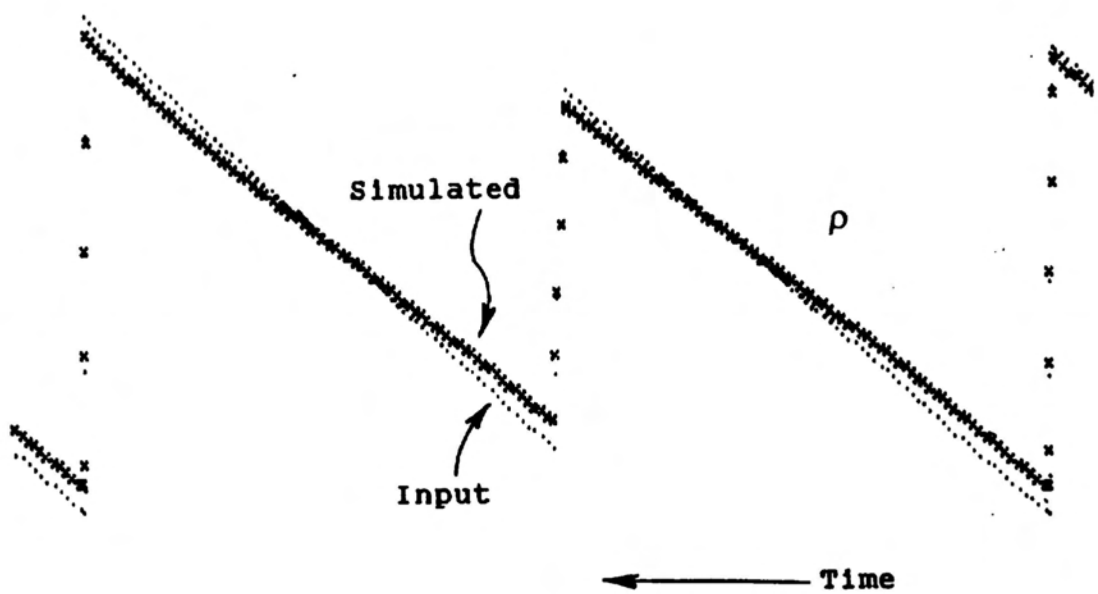


FIGURE 15 Simulated Rod Worth Measurement Using 2% Gamma



The last step in the analysis is to estimate the reactivity values that would have been measured if the gamma signal had not been present. These are simply the input reactivity values used in the simulation to match the observed flux behavior.

For the ITC simulation, the input values were MTC=-5pcm/F and FTC=-2pcm/F. This represents an ITC of -7pcm/F. An xy-plot of the ITC reactivity versus RCS temperature with and without the effects of gamma are shown in Figure 14. The straight line represents the input -7pcm/F. The curved line is the cooldown simulation from Figure 12. The slope of the curved line at the point that it intersects the straight line is about -3 pcm/F. Therefore the effect of the gamma was to cause an error in the measured ITC of about 4 pcm/F, from the input of -7 to the simulation slope of -3. This is a very significant error.

For the rodworth simulation, the input reactivity is compared to the simulation in Figure 15. For this measurement, the effect of the gamma was to cause an error in the measured reactivity swing during the rod motion by about -13%. This is also a significant error.

The above simulations demonstrate that effects of a small constant gamma signal 2% of full scale during the tests can explain all of the observed anomalies except that shown in Figure 6. The cause of this anomaly has not yet been identified, but is currently suspected to be due a hardware distortion occurring between the core and the reactivity computer. This is still under investigation.

CONCLUSIONS

The experience gained in this analysis has demonstrated that a small gamma background signal can have a dramatic effect on the reactivity measurements. Furthermore, these effects are not constant, they depend on the way the test is performed. Specifically, the magnitude of the errors introduced depend strongly on the flux behavior during the test and the procedures used to interpret the strip chart and xy-plots.

The only reliable way to determine the actual error in any measurements made in the presence of a gamma signal is to simulate the tests and match the observed flux behavior.

REFERENCES

Glasstone & Sesonske, "Nuclear Reactor Engineering", Van Nostrand, 1967
Scarborough, "Numerical Mathematical Analysis", Johns Hopkins Press, 1966