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ABSTRACT

The technique for monitoring core reactivity during power operation used at the Fast Flux Test Facility (FFTF) is described. This technique relies on comparing predicted to measured rod positions to detect any anomalous (or unpredicted) core reactivity changes. It is implemented on the Plant Data System (PDS) computer and thus provides rapid indication of any abnormal core conditions. The prediction algorithms use thermal-hydraulic, control rod position and neutron flux sensor information to predict the core reactivity state. Initial results of using this technique based mainly on theoretical formulations is presented. The results show that the reactivity changes due to increasing reactor power (power defect) and burnup of the fuel were within ~16% of predicted values. To increase the sensitivity and accuracy of this technique, the prediction algorithms were calibrated to actual operating data. The work of calibrating this technique and the results of using the calibrated technique up through the third full operating cycle are summarized.

INTRODUCTION

Reactivity monitoring is generally recognized as desirable, if not mandatory by both the national and international LMFBR communities for trend assessments of any abnormal reactivity conditions. All existing and planned reactors have included some method for comparing predicted and measured rod positions during power operation. The primary motivation for these efforts is that the core reactivity state depends on the mechanical and temperature conditions existing in the reactor core. A relatively small change in these conditions will change the reactivity state and can be detected by the control rod movement required to keep the reactor critical at the desired power level. Thus, in effect, core reactivity state monitoring provides a look into the core internals. This is especially important in fast reactors because it is not possible to provide instrumentation access into the core region without suffering a severe economic penalty. Also, small core component movements in a fast reactor have a substantial reactivity effect and thus can be readily detected.

The Fast Flux Test Facility (FFTF) is a mixed oxide fueled, liquid metal fast reactor located near Richland, Washington and operated by Westinghouse Hanford Company for the Department of Energy. This reactor has a continuous on-line computer reactivity monitoring program called Reactivity Surveillance Procedures for Anomaly Detection (RSP-AD). This program provides a continuous comparison of predicted and observed control rod positions during normal plant operation, including startup and steady power operation. Reactivity predictions of both the worth of changes in the core state (e.g., temperature and irradiation changes) and the worth of the compensating control rod movements are required for the comparison. One advantage of this system is that it relieves the reactor operator from collecting data and making small corrections for

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real observable core changes. Another advantage is that due to the continuous monitoring, the technique can detect small, rapidly developing anomalous conditions. By responding appropriately to an alert, the reactor operator can take actions to avert or at least mitigate the consequences of such conditions in a timely manner.

An example of such conditions is the partial melting of several FERMI fuel elements. A post-analysis of the incident showed that a properly installed and maintained reactivity monitoring system could have detected the flow blockage and allowed the operator to terminate power operations prior to fuel melting. This experience provided the impetus to develop the RSP-AD reactivity monitoring technique for the FFTF. The advantages of this on-line capability prompted EBR-II and JOYO to install such systems. A similar system was under development at RHAPSODIE prior to its termination.

Many reactivity effects which aided in understanding changes in LMFBR cores were detected by such rod position (reactivity) monitoring. The foreign community (British, French and German) accurately detected and characterized the dramatic changes in the structural integrity of oxide fuels. They correlated their results with physical examinations of the fuel to show that fuel pellets expand freely in the axial direction, then adhere to the cladding and finally expand into axial voids as expansion on these fuels increase. At EBR-II forces exerted by stainless steel reflectors on core assemblies were also detected. The redistribution of fuel into cooler gaps near the cladding surface in JOYO fuel pins was also verified by reactivity monitoring.

This paper will first give a general description of the RSP-AD technique and then discuss the initial results of using RSP-AD based mainly on theoretical formulations. Then the work of calibrating the technique to actual operating data is discussed and results of using the calibrated technique up through the third full operating cycle are summarized.

GENERAL DESCRIPTION OF THE RSP-AD TECHNIQUE

The theoretical bases behind the RSP-AD technique is that the neutronic characteristics of the reactor core are determined by the isotopic composition, temperature and location of the core components. Thus, a change in the condition of a component will alter the neutron balance (net reactivity), changing the neutron population and hence the reactor power. Such component changes occur continually in the FFTF as the power level is changed and as the core components are irradiated. Normally the control rods will be repositioned either manually or automatically to restore the neutron balance to maintain the desired power level.

The RSP-AD technique functions to detect abnormal conditions (i.e., reactivity anomalies) by inferring the condition of the core components using a limited set of sensors (e.g., core power level, core coolant flow rate, core coolant temperature and control rod positions) and thus predicting the net core reactivity. By comparing predicted to actual net reactivity, reactivity anomalies can be detected.

Such a comparison requires reactivity predictions of both the worth of changes in the core state (e.g., temperature and irradiation changes) and the worth of the compensating control rod movements. The former changes are quite complicated and may not be accurately known. For example, temperature gradients across core assemblies can have a reactivity effect, but are difficult to calculate at every core position at any given reactor state. Also, there is no reasonable measurement technique to completely map the core temperatures.

Therefore, to represent these complex core processes with a tractable algorithm it was necessary to infer the detailed local core conditions from relatively global sensors, each having its own uncertainties. Relatively simple algorithms predicting the reactivity effects associated with these core-averaged temperature changes were developed from equations governing heat transfer in the reactor assuming all distribution functions (e.g., power density) and thermal-dynamic parameters are constant.

The predicted worth of reactor state changes was originally based on two- and three-dimensional calculations of the Doppler, axial and radial fuel expansion, sodium density, and assembly bowing effects. Predicted vessel and structural temperatures were used to predict the control rod positioning effect due to differential expansion (i.e., the movement of the control rods relative to the fuel due to the difference in thermal expansion of the core support structure, reactor vessel, control rod drivelines, control rod assemblies and fuel assemblies).

The irradiation-induced core reactivity changes were inferred from a calculation of the neutron fluence based on a nominal core power history. The burnup reactivity loss algorithms were based upon two-dimensional diffusion theory calculations of core burnup.

The predicted reactivity worth of rod movements was originally based on a worth shape (profile) measured during the rod pulls to initial critical with a partially loaded core. This shape was normalized to subsequent core loadings using individual control rod worths, predicted using two-dimensional diffusion theory calculations. Thus, for a particular control rod bank position change the corresponding reactivity change is calculated by multiplying the relative worth change between the two positions, based upon the worth shape, by the total bank worth.

The actual task of RSP-AD is to compute the net reactivity using these predictions of the reactivity worth of reactor state changes and rod movements based on current and previous reactor states and compare with observed net reactivity. Any differences are labeled as anomalous reactivity (or anomalies). This evaluation involves calculating the terms in the following balance equation:

$$\Delta\text{K-AR} = (\Delta\text{K-NET}) - (\Delta\text{K-EXTERNAL}) - (\Delta\text{K-INTERNAL}) - (\Delta\text{K-RESIDUAL}).$$

The term, ΔK-EXTERNAL, represents the reactivity added to the core by control rod withdrawal while ΔK-INTERNAL represents the reactivity subtracted from the core by changes in the temperature, location and isotopic composition of the core components. Their sum [(ΔK-EXTERNAL) + (ΔK-INTERNAL)] is the predicted net reactivity of the reactor. The calculational algorithms for these two terms actually yield the reactivity changes from an absolute condition (rods fully inserted for ΔK-EXTERNAL and isothermal, zero power refueling conditions for ΔK-INTERNAL). Additional adjustable parameters ΔK-E0 and ΔK-I0 are included to normalize the ΔK-EXTERNAL and ΔK-INTERNAL terms, respectively, to an initial reactor state. This normalization state is usually the zero power initial critical state at the beginning of each cycle. Therefore, the terms yield the reactivity changes from this initial state and will not be influenced by errors in predicting the rod positions at criticality.

The current net reactivity of the reactor (ΔK-NET) is inferred from the time behavior of the neutron population and the delayed neutron parameters using an inverse kinetics technique. The difference between this value and the predicted value [(ΔK-NET) - (ΔK-EXTERNAL) - (ΔK-INTERNAL)] is thus a measure of a possible anomalous condition. In practice, the ΔK-NET term remains close to zero for steady state conditions and usually ≤10¢ during normal reactor state changes. Thus the ΔK-NET term is not crucial to RSP-AD.

The total anomalous reactivity (difference between observed and predicted) is represented by the sum of the ΔK-AR and ΔK-RESIDUAL terms. The reason for this choice is that slowly developing anomalies due to isotope transmutation and rod bank worth prediction inaccuracies are anticipated. These anomalies are acceptable, but if not removed they would require that alarm settings for anomalous conditions be set quite high (equal to the total allowable anomaly over an operating cycle). Instead, the residual anomaly term (ΔK-RESIDUAL) is periodically modified to remove slowly developing, acceptable anomalies. Thus, the ΔK-AR term will remain close to zero and the RSP-AD technique will have full sensitivity to detect small but rapidly developing anomalies.

Currently, the ΔK-AR equation is evaluated every [illegible]0 seconds. In addition to the ΔK-AR calculation, a weighted rate of change of ΔK-AR and weighted average of ΔK-AR are calculated to help characterize the nature of an observed anomaly (e.g., rapidly or slowly occurring). These terms are weighted to reduce the effect of statistical uncertainties in the ΔK-AR values.

As mentioned previously, the instrumentation signals required for RSP-AD include the control rod position indications. These, when combined with the worth shape curve, allow computation of the ΔK-EXTERNAL term. The thermal-hydraulic state of the reactor (and thus ΔK-INTERNAL) is inferred from the core power level and the primary coolant loop core inlet temperature and mass flow rate. The latter two quantities are available directly from instrumentation signals. Power level is determined from neutron flux signals which are also available directly. Future plans will allow the use of the thermal power value calculated by the computer using secondary coolant loop parameters. The thermal power value has the disadvantage of not responding quickly to changes in the reactor core and is accurate only during steady-state operation. The proportionality between the thermal power and neutron flux signals will vary somewhat over the operating cycle. However, the flux instruments are calibrated to thermal power routinely during startup and during power operation. Since these adjustments are made in a similar manner each cycle, calibration of RSP-AD to actual operating data automatically incorporates these instrument calibration effects into the RSP-AD prediction algorithms.

INITIAL USE OF RSP-AD

During startup of the reactor to full power conditions, temperature and material density changes occur in the core resulting in an overall loss of reactivity. This reactivity loss from zero power isothermal conditions (~400°F) to full power conditions (core inlet temperature of ~680°F) is termed the power reactivity defect. Some of the reactivity feedback effects which are responsible for the power reactivity defect are highly reliable and reproducible (e.g., the Doppler effect), but others are subject to change based on local power conditions or the behavior of the fuel material (e.g., assembly radial movement and axial fuel expansion). One function of RSP-AD is to monitor this power reactivity defect change and alert the reactor operators of a change in core behavior.

The first measurement of the power defect using the RSP-AD technique was made during the FFTF's initial power ascent. The results are shown in the first row of Table I. The original purely theoretical prediction of the power defect was ~380±50¢ from refueling to full power conditions. The uncertainty in the predicted reactivity effect of moving the secondary control rod bank was ~±37¢. Combining these effects quadratically yields a total power defect prediction uncertainty of ~±61¢ (1σ), or ~16%. The observed reactivity anomaly (difference between observed and predicted rod positions) at full power was ~-60¢ (i.e., the rods were withdrawn ~0.7 inches further than predicted). This value was within one standard deviation of the prediction and represented a measured power defect of ~440¢. This agreement between measurement and purely theoretical predictions was considered to show an acceptable understanding of the reactivity feedback mechanisms. The observed deviation was anticipated due to, among other things:

- instrument calibration errors;
- the uncertainty in β_{eff} used to convert calculated reactivities (K_{eff}) to measured reactivities ($'s);

- the difficulties in predicting assembly radial movements (bowing);
- the uncertainties in the predicted reactivity effects associated with the remaining feedback mechanisms;
- the uncertainty in the predicted reactivity effect of withdrawing the secondary control rod bank.

TABLE I. FFTF POWER DEFECT DATA

	OPERATING PERIOD	DATE(1)	EFPD(2)	POWER DEFECT (¢) ± 15¢ (1σ)(3)		
	INIT. PWR.	11/14/80	7.9	STARTUP	431.0	
	ASCENT	-12/23/80	9.0	SHUTDOWN	440.0	440.0(4)
	NAT. CIRC.	3/4/81	11.5		430.0	447.0
	TESTING	-3/16/81	13.6		*	
	HIGH PWR.	8/21/81	20.0		448.0	*
ATP	PHYS. TESTING	-9/19/81	23.4		436.0	
	EXTENDED PWR.	11/13/81	24.3		432.0	413.0
	RUN	-11/23/81	32.0		425.0	
	DEA-2 RUN	12/16/81	32.4		427.0	*
		-12/18/81	32.4		429.0	
	CYCLE 1A	4/13/82	33.0		394.0	405.0
		-5/24/82	66.5		394.0	
	CYCLE 1B	8/26/82	77.8		386.0	402.0
		-11/11/82	134.4		383.0	
	CYCLE 2A	1/18/83	141.9		420.0	396.0
		-2/19/83	161.2		406.0	
	CYCLE 2B	2/28/83	161.0		404.0	395.0
		-5/22/83	234.8		400.0	
	CYCLE 3	7/19/83	244.4		402.0	402.0
		-10/23/83	336.3		401.0	

(1) DATES CORRESPOND TO ZERO POWER CRITICAL BANK POSITIONS.

(2) EQUIVALENT FULL POWER DAYS AT END OF EACH POWER DEFECT MEASUREMENT.

(3) TOTAL REACTIVITY FEEDBACK FROM 400°F ISOTHERMAL TO FULL POWER (680°F).

(4) CORRECTED FOR MEASURED BANK WORTH.

* DATA NOT AVAILABLE

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In general, the above sources of error were incorporated into the power defect uncertainty. The most notable exception was that due to assembly bowing. Uncertainties in the total reactivity effect due to this mechanism were possible. However, the rate of change of this effect with power (power coefficient) had such a wide range of possibilities that only the uncertainties due to fitting the calculated effect were properly included.

To accurately track subsequent power defect changes and increase the sensitivity of the RSP-AD reactivity monitoring technique, the initial data were used to revise the prediction algorithm. The technique used to revise the algorithm to match the measurement values was the well-known linear least squares method. No provisions were available to constrain individual feedback mechanisms to lie within physical limits in the computer model. Therefore, the terms in the algorithm attributed to Doppler and differential control rod expansion effects were assumed to remain constant (e.g., unchanged from theoretical model). Also, the secondary rod bank worth predictions (against which power defect predictions were compared) were assumed to be known. These worths were based on detailed measurements of reactivity near critical. Any systematic error was necessarily incorporated into the revised reactivity feedback algorithm. Finally, no attempt was made to revise the predicted reactivity effects of burnup since only limited data on these effects were available.

Using the revised RSP-AD prediction algorithm, the initial data were reanalyzed. The results showed that the fit gave anomalies ranging between ~±8¢, which was only ~2% of the total power defect. However, using the revised algorithm on power defect data taken during earlier operation showed that the fit was only good to ~±20¢. From these results it was apparent that some core changes occurred during early operation which resulted in the ~±20¢ anomalies. The actual physical mechanisms responsible for these changes were not identified.

Another possible source of uncertainty in the reactivity anomalies calculated with the revised algorithm is the predicted reactivity worth of secondary control rod bank movements. Errors in the original rod worth predictions were necessarily incorporated into the revised reactivity feedback algorithm.

USE OF REVISED RSP-AD TECHNIQUE DURING FFTF ACCEPTANCE TESTING

Following the initial power ascent the FFTF had several short operating periods in which core characterization measurements were made. These operating periods were collectively called the Acceptance Test Period (ATP). The revised power defect prediction algorithm was used in all of these operating periods and yielded the measurement results shown in Table I. Note that the power defect remained within ~5% (~23¢) for all of these operating periods. However, once the predicted rod bank worth for each operating period was corrected to measurement results, an apparent overall reduction in the power defect of ~6% (~27¢) was seen. This decrease could easily result from changes in the various modes of assembly bowing and/or fuel axial expansion. But no detailed analysis was made to attempt to identify the responsible nechanism(s) since there were no safety concerns. In spite of the apparent ~6% power defect reduction, the power defect prediction algorithm was not changed (i.e., refit to match measurement results) until data through an entire operating cycle were collected.

Aside from the power defect prediction, the ATP data also allowed an evaluation of the burnup reactivity algorithm. Specifically, during one testing period the reactor was held at full power conditions for eight days (Extended Power Run). The measured burnup loss rate during the hold period was ~15% higher than predicted (11.0 vs 9.6¢/day, assuming neptunium had reached equilibrium; the neptunium component of burnup is the apparent reactivity loss due to the delay in conversion of U-238 to Pu-239 caused by the 2.35 day half-life for the decay of Np-239 to Pu-239).

The comparison of observed and predicted burnup reactivity effects involves two basic predicted quantities. The first consists of the predicted real reactivity changes associated with the transmutation of isotopes due to neutron fluence and mechanical and structural changes due to both neutron fluence and thermal stresses. The second is the predicted reactivity change accompanying observed rod movements. These latter predictions are used to quantify the observed burnup effects.

The predicted reactivity worth of rod movements was based on secondary rod bank profile data obtained at refueling temperatures with a partially loaded core, prior to the first power ascent. The data, up to ~14 inches withdrawn (full out = 36 inches) on the bank, were substantiated by subsequent measurements in fully loaded cores, but data at higher bank positions were not possible at refueling temperatures because the cores were too reactive. The overall bank worth prediction technique, however, was shown to be accurate to within ~5% from run to run. This accuracy will result in only small anomalies. Therefore, the rod worth prediction technique was considered adequate.

The predicted burnup reactivity effects are subject to considerable error and are the source of most of the 40% allowable Technical Specification limit. The mechanical and structural effects are especially uncertain since predictions for the initial power ascent, using the best computer tools available, were not borne out by measurements.

The preceding paragraphs indicate possible sources of the discrepancy between predicted and observed burnup reactivity effects. However, insufficient data were available to allow attributing the error to a specific source. Therefore, for the first operating cycle, the predicted burnup reactivity loss was adjusted to agree with the Extended Power Run measurement data. The predicted reactivity change accompanying rod movement (i.e., rod worth profile) remained unchanged.

USE OF RSP-AD IN CYCLE 1

The RSP-AD algorithm used in Cycle 1 was previously calibrated to match the initially observed ATP power defect and burnup reactivity loss data. The rod worth prediction technique remained unchanged. The Cycle 1 power defect measurement results are shown in Table I. Note that the Cycle 1 data supported the ATP results which show that the power defect had decreased. Cycle 1 data suggested a decrease of ~9% or ~38¢ after correcting the anomaly data for measured rod bank worth results. Note also that the power defect remained relatively constant over the entire Cycle 1 operating period. This indicated that the reactivity feedback mechanisms did not change significantly during Cycle 1 irradiation.

The observed decreases in the reactivity feedbacks since initial power operation could easily be the result of changes in the assembly radial bowing characteristics since studies of this phenomenon, while uncertain, indicate that changes can be expected. Assembly bowing changes would be expected to be a function of power and should develop mainly during power operation. As seen in Table I there were no significant changes in the power defect between the ascent and descent of both parts of Cycle 1. Therefore, bowing changes during Cycle 1, if any, must have affected reactivity feedbacks over a limit range of power. Also, the many reactor startups and shutdowns which have occurred since the Cycle 1 feedback prediction algorithm was developed could have reduced the magnitude of the axial fuel expansion effects by the creation of lateral voids in the cold fuel.

In all instances, however, the total reactivity feedback magnitudes were demonstrated to be significantly larger than those required to mitigate possible accident power excursions. It is currently not possible to specifically identify the changes in the core characteristics which may have caused the observed reduction. Thus, to accurately track subsequent changes and increase the sensitivity of the established monitoring technique, a revised power defect prediction algorithm was developed for use in Cycle 2. This algorithm incorporates the changes seen in Cycle 1B and provided the best estimate of what could be expected during Cycle 2.

The same least squares fitting technique used to calibrate the RSP-AD power defect algorithm to the initial startup data was again used to calibrate the RSP-AD to the Cycle 1B results. Using this revised algorithm the Cycle 1B reactivity anomaly ranged from ~±6¢ which was only ~1% of the total power defect. Using Cycle 1A data, the revised algorithm showed that the fit was only good to ~±18¢ at power levels below 60%

but accurate to ~±7¢ at higher power levels. From these results it is apparent that some core changes occurred during early operation which gave anomalies of ~±18¢. The actual physical mechanisms responsible for these changes were not identified.

Aside from the power defect prediction, Cycle 1 burnup anomaly (anomaly accumulated only during full power operation) data allowed an evaluation of the burnup reactivity loss algorithm. Recall that the original predicted reactivity loss rate due to burnup was ~9.6¢ per day once the neptunium had reached its equilibrium concentration. Preliminary, short irradiation results suggested this loss rate should be increased by ~15%. Using the normalized prediction the reactivity loss was predicted within ~23¢ over the entire full power operation period of the first irradiation cycle (~11$ total loss). The 23¢ value is found by combining the final burnup anomaly for both Cycle 1A and Cycle 1B. This result is shown in Figure 1 by the plot of the Cycle 1 burnup anomaly as a function of full power days. However, if the same measured rod bank worth corrections applied to the Cycle 1A and 1B power defect measurements were applied to the burnup anomaly, the total Cycle 1 burnup anomaly would only be ~6¢. Therefore, the revised reactivity loss rate algorithm appeared in good agreement with observation.

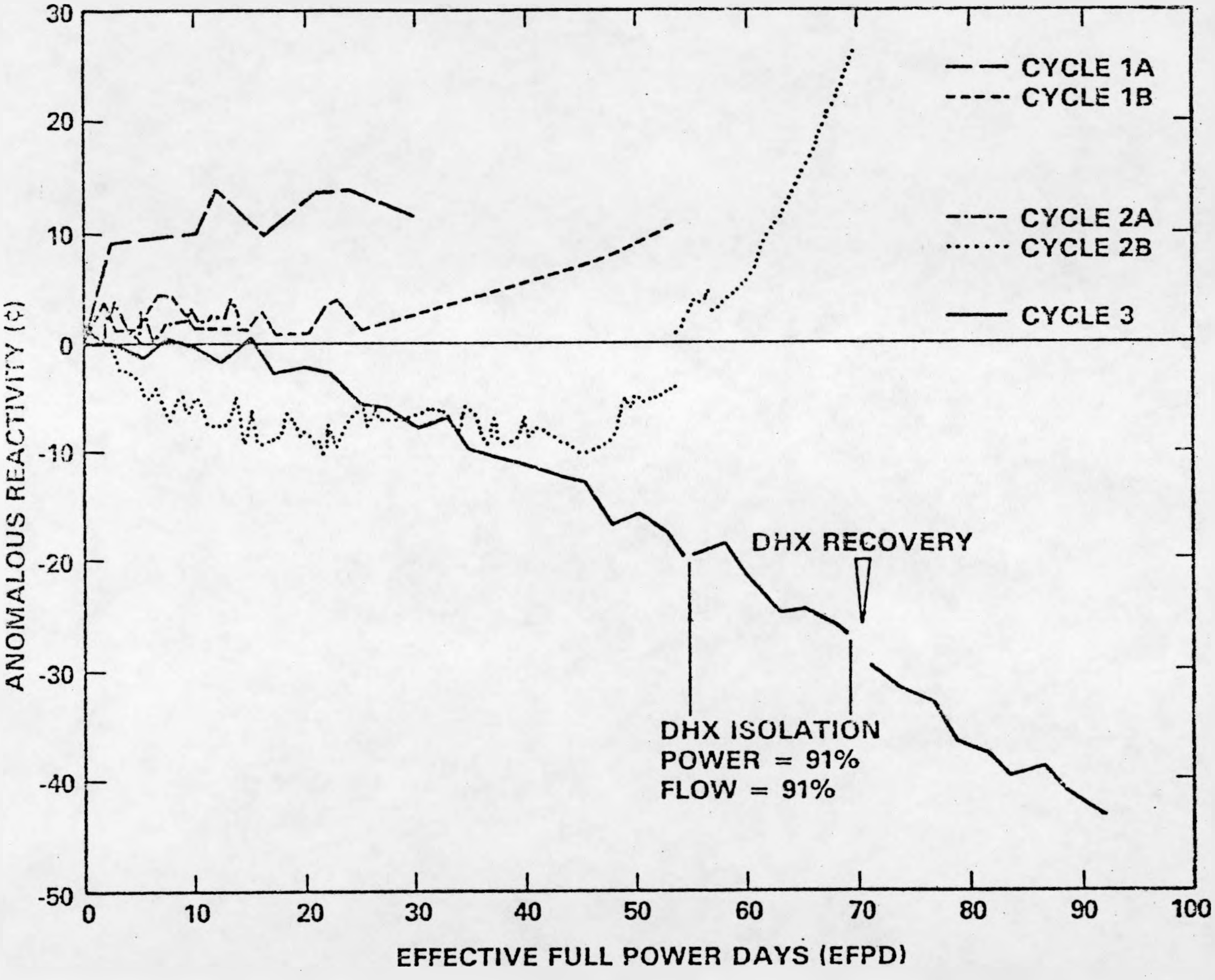

FIGURE 1. Anomalous Reactivity During Cycles 1, 2 and 3 Full Power Operation.

From Figure 1 note that Cycle 1A showed an initial ~10¢ burnup anomaly change within the first few days of full power operation. This change was similar to that seen during the Extended Power Run data. Since the anomaly change is much more rapid than the predicted burnup reactivity loss rate, it was attributed to core structural changes as the core components adjusted to full power temperatures. Cycle 1B showed this same initial behavior to a smaller degree.

USE OF RSP-AD IN CYCLE 2

Based on the Cycle 1 power defect measurement results the RSP-AD algorithm was recalibrated for use in Cycle 2. The total power defect was predicted to be ~402¢. The Cycle 2 power defect measurement results are given in Table I and show relatively good agreement with prediction. The power defect measurement values ranged from ~395¢ to ~395¢ after correcting for measured rod bank worth results. These values were within the prediction uncertainty. Note also that the power defect again remained relatively constant over the entire Cycle 2 operating period. This indicates that the reactivity feedback mechanisms did not change significantly through two full operating cycles. Therefore, the power defect model was considered adequate for use in the following Cycle 3.

The Cycle 2 burnup anomaly data however showed some interesting results. In Figure 1 the burnup anomaly change during Cycle 2A full power operation was consistent with that observed during Cycle 1. The preliminary, ~2.5 day, full power operation during Cycle 2A showed the same type of nonlinear reactivity change as observed in previous Cycle 1 operation. Again this phenomenon is probably due to fuel and structural material changes and relocations. Subsequent full power operation did not show any unusual behavior. The observed anomaly change was still within the rod positioning uncertainties (~±6¢). However, allowing for the rod positioning uncertainties and statistical variations in the data, it appeared that the observed rod reactivity changes were in agreement with the actual core burnup (i.e., no change in anomaly). This agreement suggested that the predicted rod bank worth used to quantify the reactivity changes associated with rod movements was apparently correct.

The anomaly change during Cycle 2B full power operation, however, showed an early downward trend which was attributed to an overprediction of the secondary bank worth. This overprediction assessment was based on additional data from individual rod worth measurements, differential rod worth measurements, stability measurements and count rate data obtained during the approach to the zero power critical state. However, during the middle of Cycle 2B full power operation, the burnup anomaly became relatively constant. This was obviously not consistent with an overprediction of rod worths shown.

Reflecting back on the early Cycle 2B downward anomaly trend it appeared that there were other reasons for the downward trend in addition to a rod worth overprediction. Since the anomaly decrease developed slowly and linearly, it did not show the characteristic nonlinear burnup rate which was seen in previous cycles over the first few days of full power operation. Thus, a change in the burnup reactivity feedback mechanisms was not indicated. Another possible reason could be a deviation from the rod worth profile prediction. This deviation was in fact evidenced from differential rod worth measurements made at zero power and would be expected based on the loading characteristics of the Cycle 2 core. But the important aspect of this anomaly trend was that it remained very small compared with the expected uncertainties in the burnup rate predictions.

At ~53 full power days in Cycle 2B, the reactor power was reduced during reactor scrams. This required relatching the control rods and rezeroing the position indicators with the control rod drive lines hot (~591°F). When the reactor was returned to full power, little additional expansion occurred and, thus, the indicated positions were closer to the true positions than had the rod indicators been zeroed at ~440°F, the normal zero power initial critical state isothermal temperature. This resulted in an additional prediction/observation deviation. This deviation increased as the rods were pulled to the nearly full out position (~36 inches withdrawn), indicating that the reactivity worth of control rod movements was higher than predicted in this region.

This underprediction was attributed to a deviation in the predicted rod worth profile at these higher rod positions. This conclusion was based on two results. First, the reactivity feedback prediction model was revised for Cycle 2 operation based on the Cycle 1B anomaly data and showed good agreement with prediction over both Cycle 2 operating periods. And second, the burnup algorithm was revised for Cycle 1 operation and has continued to show good agreement with observation (note the small and relatively constant burnup anomaly in Figure 1 for each initial period of full power operation). Therefore, the upward trend of the burnup anomaly over the higher bank positions was attributed to the rod worth profile prediction. This deviation was expected since the initial profile fit did not have data over the higher bank positions.

For future cycle operation, the rod worth profile prediction was revised to account for the observed deviation over the higher rod bank positions. This new profile maintained the same shape over the lower bank positions since the anomaly data indicate good agreement over these positions. To obtain a new profile prediction using the Cycle 2B burnup anomaly data, it was assumed that the old profile prediction was acceptable up to a position of ~29.0 inches withdrawn. This was the bank position at which the burnup anomaly started a definite upward trend.

USE OF RSP-AD IN CYCLE 3

Because of the agreement between the measured and predicted power defect seen in Cycle 2, the same RSP-AD power defect algorithm was again used in Cycle 3. The only change made was to the rod bank profile prediction over the higher (⩾29 inches) bank positions. The Cycle 3 power defect results are given in Table I and show good agreement with prediction. Note also that the power defect again remained relatively constant over the entire Cycle 3 operating period. This indicated that the reactivity feedback mechanisms did not change significantly over three full operating cycles. Therefore, the power defect prediction algorithm was considered adequate for use in future cycles.

The Cycle 3 burnup anomaly data are shown in Figure 1. During the very early part of Cycle 3, the rod positions agreed quite well with predictions. Deviations were consistent with the anticipated uncertainties in the reactivity required to raise the reactor temperatures to those characteristic of full power operation and the small nonlinearities in the initial reactivity burnout rate.

During the remainder of the Cycle, the observed rod positions deviated from prediction in a generally linear fashion. The small discontinuities in the data resulted from DHX (dump heat exchanger) isolation and subsequent power decrease for DHX recovery. At the end of Cycle 3 full power operation, the burnup anomaly achieved a maximum value of ~-43¢. Assuming the burnup rate prediction was correct, this corresponded to an overprediction of the secondary bank worth of 2-3%. This was consistent with the observed change in the calculational/experimental agreement in the individual rod worth measurements between Cycle 3 and Cycle 2B (~2.5%). The power defect value was corrected based on these results.

Reference to Cycle 2B is made for two reasons. The first is that Cycle 2B was the only cycle which was run to reactivity end of life. Therefore, accurate characterization of the full worth of the secondary rod bank was made. Also, for Cycle 3, the rod worth profile prediction was normalized to the Cycle 2B data over the higher bank positions (⩾29 inches). This was done to remove the underprediction of bank worth over the upper bank positions. Cycle 3 data to verify the rod worth profile characteristics seen above 29 inches for Cycle 2 was not available since full power operation ended with the secondary bank at ~29.6 inches. Until data results show otherwise, the same profile prediction will be used in future cycles.

SUMMARY

Experience at FFTF has shown good correlation with reactivity predictions. The initially observed reactivity changes due to increasing reactor power (power defect) and burnup of the fuel were within 16% of the predicted values. This agreement was within one standard deviation of the predictions. Since that time the power defect apparently decreased ~9% during the ATP but has remained stable and reproducible through the subsequent three full operating cycles. This power defect stability is not surprising in one sense because the experience at other facilities was factored into the design of FFTF. For example, the FFTF fuel pellets were dished to reduce the changes in axial fuel expansion which created difficulties overseas. Also, the FFTF radial reflectors were segmented to prevent them from exerting forces on the core like those at EBR-II. The FFTF core is somewhat unique when compared to these previous cores, however, because of the large number of heterogeneities required for testing. These same tests, when run to extreme conditions, could generate new and unplanned changes.

The current predictability of the FFTF core reactivity has allowed "inverse" uses of the data generated. For example, suspected spurious changes in the Relative Rod Position Indicator (RRPI) system have been verified by a change in anomalous reactivity. Also, a change in the observed power defect when correlated with a similar change in the burnup anomaly has been used to revise the assumed reactivity worth of the control rod bank. This latter worth is normally used to "measure" the reactivity changes. This same worth data is also used to predict the core excess reactivity for each cycle. This prediction is very important in accurately planning the cycle length and assuring sufficient reactivity exists to achieve the specific irradiation goals set for each irradiation period.

The RSP-AD technique is the first fully automated rod position monitoring system developed and implemented on a reactor before any operation. The accuracy and usefulness of this technique was demonstrated early in the operating history of the plant. The fact that no significant anomalies have been detected does not diminish the FFTF commitment to this kind of monitoring.