COLLECTION AND EVALUATION OF KINETICS DATA

FROM EBR-II RUN 46A

by

H. A. Larson and I. A. Engen

EBR-II Project
Argonne National Laboratory
Argonne, Illinois - Idaho Falls, Idaho

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ABSTRACT

This report is a summary and analysis of information from rod-drop experiments for run 46A of the EBR-II reactor. Experiments were performed at several power levels during the start-of-run approach to 62.5 MWt and during the end-of-run reduction in power.

By using an XDS Sigma-5 computer system, rod-drop data were collected on line and numerically reduced by an inverse-kinetics procedure to produce drop-rod calibration information, time-dependent reactivity feedback, and frequency-dependent reactivity feedback.

After the accuracy of the calculations performed with the XDS Sigma-5 computer system was verified, data and calculations were graphically summarized and comparisons were made with results of run 38A, the previous 62.5-MWt run. At the end of run 46A, data were recorded with both compensated and uncompensated ion chambers, thus allowing a comparison of information from the two types of chambers.

I. INTRODUCTION

Many rod-drop experiments were done on the EBR-II reactor during run 46A. This report is intended as both a collection of rod-drop data for reference purposes and an analysis of these data, including some comparisons with run 38A, the previous 62.5-MWt run.

The reactor was started up and brought to a power level of 50 MWt on Sept. 21, 1970. After a series of rod drops at 50 MWt, the power level was reduced to 500 kWt to calibrate the reactivity worth of the drop rod. Additional rod drops were made and the power level was again increased

to 50 MWt. Rod drops were repeated at 50 MWt and the resulting feedback data were used to predict the feedback at 56 MWt. Then, the power level was increased to 56 MWt, and additional rod-drop tests were conducted. The sequence was repeated and the power level was increased to the goal of 62.5 MWt on Sept. 25. Rod-drop measurements were repeated at this power level.

After a run length of 751 MWd, rod-drop experiments were performed again at 62.5 MWt. Then, by a procedure inverse to that of the startup procedure, the power level was reduced to 500 kWt, with rod-drop tests being taken at 56, 50, and 40 MWt. Calibration data were also collected at 500 kWt.

The contents of this report were generated by a collection of computer programs newly converted from the IBM systems 1620 and 360/75 to the Sigma-5 data-processing system, otherwise known as the digital data-acquisition system (DAS), supplied by Xerox Data Systems. The former system utilizes the method described in Ref. 1 to reduce and analyze data, whereas the latter system is an on-line computer system,² which connects the programs in contiguous fashion. The Sigma-5 computer system, which collects and processes data on line, significantly decreases both processing and manpower requirements below those of the former system of data collection. Comparison of data from both systems shows excellent agreement.

Feedback-reactivity data show, in general, the same characteristics as the results of rod-drop tests from previous EBR-II runs, but there were some differences in the behavior of the feedback-reactivity curves when compared with previous runs. These differences will become especially clear from an observation of the changes in the behavior of the parameters of the feedback-reactivity transfer-function model.¹

The feedback reactivity at 50 MWt was used to predict the feedback reactivity at higher power levels by linear extrapolation of the feedback data; coefficients of each feedback term of the model were multiplied by the ratio of the power increase. These studies show a limited amount of success, indicating that some nonlinearities may be affecting the reactor response in this power range.

II. ON-LINE DATA ACQUISITION

The XDS Sigma-5 computer system will be used as an operational aid

and in data reporting and analysis.² It allows direct interface with the reactor, and thus on-line, real-time analysis.

For reduction and analysis of data from rod-drop and rod-oscillation experiments, the on-line system will replace the data-gathering system now in use,^{1,3} which consists of analog-to-digital (A/D) conversion of raw data, then further magnetic tape-to-card reduction by an IBM-1620 computer, and subsequent inverse-kinetics analysis of these data by the IBM-360/75 computer system through an IBM-1130 remote input-output terminal. With the new computer system, raw data are loaded directly into core, where necessary computations can be immediately performed. In addition to core storage, the new system has rapid-access disk storage and magnetic-tape drives for further direct- and sequential-access storage facilities, respectively.

The computer programs necessary to calculate zero-power reactivity and feedback reactivity, and to model the feedback reactivity to fit an assumed polynomial form for the feedback transfer function, have been converted from the IBM-1620 and 360/75 systems to the Sigma-5 computer system. The zero-power reactivity is calculated by using an inverse-kinetics program;^{3,4} the feedback reactivity is determined by inverse kinetics and the zero-power reactivity. Finally, the modeling is performed as described by Hyndman and Nicholson,¹ i.e., the reactor feedback transfer function is empirically fitted to an assumed polynomial form characteristic of linear feedback systems.

Figure 1 compares rod-drop feedback reactivity processed by the two systems. The continuous curve for feedback was derived from the IBM-1620 and 360/75 systems in the conventional manner. The open-circle points define values derived from the Sigma-5 analysis. The agreement is excellent, as it was with all other rod-drop data processed by the two methods during run 46A. This excellent agreement indicates that the new system is operational for on-line processing of rod-drop data. Information presented in this report is that processed by the Sigma-5 system.

Experience indicates that the use of the new system results in a significant savings over the one formerly used. This savings is due primarily to the elimination of the requirement that data be physically handled from one stage of computations to the succeeding stage. Further advantages are realized because the new system is completely available on site. Other

Fig. 1. Comparison of Feedback Function as Measured by Conventional and Sigma-5 Methods

advantages are realized for data storage. Immediate storage of card output for the rod-drop tests is now unnecessary.

III. DATA TAKEN AT START OF RUN 46A

Data taken at the start of run 46A included those for calibration, feedback reactivity, and output from modeling calculations.

A. Zero-power Rod Drops and Calibration

The reactivity worth of the drop rod was established through calibration measurements conducted at a reactor power level of 500 kW (zero power) during the start of run 46A. The measured worth of the drop rod when steady-state reactivity was achieved was 0.019 dollar; this value is an increase of 12% over the worth noted during run 38A, the previous 62.5-MWt run but is approximately the same as the drop-rod worth of 0.0185 dollar of run 45A. The difference in rod worth between runs 38A and 46A may be attributed to a difference in loading for the two runs: run 46A contained almost twice as many experimental subassemblies. Figure 2 is the loading scheme for run 46A.

The rod-worth calibration curve for the start of run 46A (Fig. 3) shows the reactivity at 500 kW versus rod position as determined by the inverse-kinetics code. The curve is a point-by-point arithmetic average of four distinct rod-drop tests.

Figure 4 shows the zero-power reactivity for the first 20 sec after the rod drop. Feedback effects at this power level should be nonexistent; thus, change in reactivity with time should be a flat, straight line, with zero slope, whose intercept with the reactivity axis indicates the reactivity worth of the drop rod. A slight reactivity recovery is seen near the end of rod drop, but the line flattens after about 5 sec. An extrapolation shows a rod worth of approximately 0.019 dollar.

B. Feedback Reactivity

Feedback reactivity was calculated for several rod-drop tests; reactivity was calculated by inverse-kinetics calculations³ at reactor power and at

Fig. 3. Rod-drop Calibration Curve at 500 kW at Start of Run 46A

Fig. 4. Reactivity for Rod Drop at 500 kW at Start of Run 46A

500 kWt. The difference between them is the computed feedback reactivity. Several rod drops were made at each of the power levels of 50, 56, and 62.5 MWt. Then an average feedback reactivity is found by using an arithmetic mean for the rod drops at each power level.

Rod-drop data for start of run 46A are illustrated in Figs. 5, 6, and 7, which show the power and average computed feedback recovery at 50, 56, and 62.5 MWt, respectively. In these cases, the feedback is negative and, for 0-2 sec after the drop, is prompt.

These figures show that the feedback reactivity is a monotonically increasing function of the time except near time zero (near the end of rod motion), where a small decrease is seen. This decrease is consistent in all feedback-reactivity plots; hence random noise is ruled out as a cause. Evidently the decrease is a response of the system to the positive shift in the power trace at the end of rod drop, i.e., it reflects a relatively small positive reactivity insertion that is seen for a relatively short time.

The effect is seen more clearly in Fig. 8, in which the rod-drop information for run 46A at 50 MWt (Fig. 5) is shown with an expanded time scale. A position-versus-time curve for the drop rod shows that the major portion of the reactivity is removed between approximately 0.12 and 0.21 sec after rod drop. After 0.21 sec, there is only a slight decrease in rod worth, which corresponds to a slight increase in system reactivity. Note that this is approximately the point at which the power starts to increase. The net result of this positive reactivity is the compensation for any negative feedback between 0.2 and 0.3 sec.

The positive reactivity insertion near the end of the rod drop is believed to be a result of the segmented construction of the drop rod. The rod was constructed in alternating sections of stainless steel and sodium of different sizes to minimize the reactivity-insertion time.⁵

Figures 5 through 7 show characteristics in feedback reactivity that differ considerably from corresponding data of run 38A.⁶ In Fig. 9 selected points of feedback reactivity from the 62.5-MWt rod drop of run 46A have been superimposed upon the corresponding curve from run 38A. The prompt feedback is quite different from that of run 38A, with a much sharper roll-off immediately after rod drop for run 38A, but greater delayed feedback for run 46A.

Fig. 5. Power and Negative Feedback at 50 MWt at Start of Run 46A
(average from five rod drops)

Fig. 6. Power and Negative Feedback at 56 MWt at Start of Run 46A (average from five rod drops)

Fig. 7. Power and Negative Feedback at 62.5 MWt at Start of Run 46A (average from four rod drops)

Fig. 8. Expanded Plot for Power and Reactivity Feedback at 50 MWt at Start of Run 46A

Fig. 9. Comparison of Computed Feedback Reactivity for Runs 38A and 46A at 62.5 MWt
(run-46A data shown by dots and circles)

The slower rolloff indicates a longer time constant for fuel feedback effects in run 46A. The larger delayed feedback indicates that the rod worth is greater for run 46A; two fuel assemblies immediately adjacent to the drop rod in run 38A contain nonfuel material that contributes to a lower neutron density in that region.

C. Start-of-run Feedback Models

With the method outlined by Hyndman and Nicholson¹ a relatively simple mathematical model was used to attempt to interpret feedback effects from rod-drop data taken during run 46A. The procedure involved separation of the measured feedback reactivity into individual time-dependent components by fitting transfer-function data empirically to the measured data; a series of trial-and-error iterations forced the assumed frequency-dependent transfer function to fit the measured data.

The models were assumed to be linear; nonlinear effects associated with subassembly bowing were ignored.^{7,8} Consequently, the model for reactivity feedback cannot be considered as a unified model encompassing all causes such as frequency, power, temperature, and coolant flow rate. The two smallest time constants, e.g., were attributed by Hyndman and Nicholson¹ to fuel and coolant expansion, while the remainder of the terms were due, in part, to subassembly-bowing effects and expansion of control-rod shafts.⁹

The models, which incorporate the results of the curve-fitting procedure as applied to the 50-, 56-, and 62.5-MWt rod drops of run 46A, are:

<u>Power Level,</u> <u>MWt</u>	<u>Feedback Model</u>
50	$-H(s) = \frac{0.1}{1+0.2s} + \frac{0.048}{1+0.4s} - \frac{0.018}{1+2.0s}$
56	$-H(s) = \frac{0.08}{1+0.2s} + \frac{0.0312}{1+0.4s} + \frac{0.037}{1+2.0s} + \frac{0.031e^{-5.0s}}{1+5.4s}$
62.5	$-H(s) = \frac{0.095}{1+0.2s} + \frac{0.0335}{1+0.4s} + \frac{0.051}{1+2.0s} + \frac{0.020e^{-5.0s}}{1+5.4s}$

The amplitudes of the feedback transfer function are expressed in units of

dollars of reactivity and are defined as the product of the power level (in megawatts) and the differential power coefficient of reactivity (in dollars of reactivity per megawatt). Thus, the feedback, $-H$, is a complex quantity expressed in dollars of reactivity. For the reactor operating at steady-state conditions with $s = 0$, $-H$ represents the power-reactivity decrement (PRD), which is the amount of reactivity required to bring the system from hot critical to the power level at which the measurements were made.

In the above models, a positive amplitude indicates a negative feedback effect. Similarly, a negative amplitude indicates a positive feedback effect.

If feedback effects in the range of 50 - 62.5 MWt were strictly linear, a simple multiplication of the amplitude for the 50-MWt model by the ratio of the power levels, $62.5/50$, should give the amplitudes measured at 62.5 MWt. Examination of the values in the models, however, shows that the prompt-feedback terms decrease with increasing power and the delayed-feedback terms increase. Therefore, feedback is not strictly linear in this range; thus, no reasonable linear extrapolation of the feedback reactivity from 50 MWt may be made.

On the other hand, multiplication of the amplitudes for the 56-MWt model by the factor $62.5/56$ gives a reasonable prediction of the measured feedback reactivity for the 62.5-MWt rod drop. Figure 10 compares predicted with measured data. In this plot the amplitude for the 56-MWt model is multiplied by the factor $62.5/56$ and the result is superimposed on the measured feedback reactivity at 62.5 MWt.

The conclusions reached above are not strictly in accord with run 38A,⁵ for which the feedback was linear in the range 50-62.5 MWt and reasonable predictions could be made of higher measured power levels by using linear extrapolations. Significantly, the changes in the character of the measured reactivity-feedback curves in run 46A, although small, are reflected by significant differences in the magnitudes of the individual components of the mathematical model (assuming that the time constants are the same).

The feedback transfer function is found by an empirical curve-fitting procedure and is not intended as a unique representation of the feedback-reactivity function. Other models with different time constants can be used in similar fashion to produce an equation that adequately represents the

Fig. 10. Comparison of Measured 62.5-MWt Feedback with Feedback-reactivity Curve
Calculated from 56-MWt Data: Start of Run 46A

data. However, the time constants used in this report do reflect the results of an analysis based on a physical foundation.¹

IV. DATA TAKEN AT END OF RUN 46A

Data on calibration, feedback reactivity, and modeling were obtained from the rod-drop experiments performed at the end of run 46A. These data were taken at power levels of 62.5, 56, 50, and 40 MWt, with calibration data again taken at 500 kWt.

Two ion chambers were used for end-of-run rod-drop calibration data. One, the J3 chamber, was the uncompensated chamber used for previous rod-drop experiments. It was located at approximately mid-core level in the J3 thimble. The other, the J4 chamber, was a compensated ion chamber located just above core level in the J4 thimble.

The analysis of end-of-run feedback reactivity, performed with the inverse-kinetics procedure on the Sigma-5 computer system, was done with reactor-power information provided by the compensated J4 chamber. These data also provided the feedback reactivity to which the mathematical models were fitted.

A. Zero-power Rod Drops and Calibration

At the end of run 46A the reactivity worth of the drop rod was established by using reactor-power data at 500 kWt and using both the J3 and J4 chambers. For these two chambers, plots of normalized reactor power and reactivity covering the 2 sec after initiation of rod drop are shown in Figs. 11 and 12, respectively.

If the rod worth is defined as the asymptotic value of the system reactivity after a rod drop at zero power, the worth using the uncompensated ion chamber (Fig. 11) is approximately 0.016 dollar. But Fig. 12 indicates that the rod worth using the compensated ion chamber is about 0.0185 dollar, a difference of about 14%.

To resolve this difference in indicated rod worth, a computer investigation was made in which the power level indicated by the J3 chamber was reduced by 10% before application of the inverse-kinetics program. This

Fig. 11. Normalized Power and Reactivity for Rod Drop at 500 kWt: End of Run 46A
(with uncompensated J3 chamber)

Fig. 12. Normalized Power and Reactivity for Rod Drop at 500 kWt: End of Run 46A
(with compensated J4 chamber)

reduction was made to approximate the removal of a constant signal from the power such as would be accomplished by compensating the chamber in a constant gamma field. The subsequent calculated reactivity is seen in Fig. 13. The asymptotic value of the reactivity is lowered to nearly that value obtained with the compensated J4 chamber, indicating that this rod-worth difference may be caused by calibration.

Inspection of Figs. 11 and 12 also shows that the characters of the curves are not identical, especially later than about 0.3 sec. The compensated ion chamber indicates a rod worth much flatter than that for the uncompensated chamber. Figure 13 further shows that the gradual drift seen in Fig. 11 may not be explained by the assumption of a constant gamma source. Clearly, however, any transient gamma source present in the signal would also be eliminated from the information from a compensated ion chamber.

B. Feedback Reactivity

Rod-drop experiments were done at the end of run 46A for each of the power levels of 40, 50, 56, and 62.5 MWt. Data were recorded only from the compensated ion chamber during these tests. Consequently, to compute reactivity feedback for these tests, the zero-power reactivity as determined from the compensated J4 chamber was used in the reactivity-feedback computer program. The results of averaging feedback reactivity over several rod drops at each of the above power levels are shown in Figs. 14, 15, 16, and 17, respectively.

After completion of the rod drop, a constant value for the time-dependent zero-power reactivity is used in the feedback-reactivity computer program. Consequently, the zero-power reactivity obtained from the uncompensated and compensated chamber will, for all practical purposes, differ by a constant value. The feedback reactivity, therefore, as determined by the uncompensated ion chamber, should not differ significantly from that shown above. Unfortunately, this assumption may not be verified because only data from the compensated ion chamber were recorded.

Fig. 13. Normalized Power and Reactivity for Rod Drop at 500 kWt: End of Run 46A
(with uncompensated J3 chamber; power reduced by 10%)

Fig. 14. Power and Negative Feedback at 40 MWt: End of Run 46A (average from three rod drops)

Fig. 15. Power and Negative Feedback at 50 MWt: End of Run 46A (average from three rod drops)

Fig. 16. Power and Negative Feedback at 56 MWt: End of Run 46A (average from five rod drops)

Fig. 17. Power and Negative Feedback at 62.5 MWt: End of Run 46A (average from five rod drops)

C. End-of-run Feedback Models

The results obtained by applying the feedback curve-fitting procedure to end-of-run data are shown below:

<u>Power Level, MWt</u>	<u>Feedback Model</u>
40	$-H(s) = \frac{0.06}{1+0.2s} + \frac{0.03}{1+0.4s} + \frac{0.014}{1+2.0s} + \frac{0.025e^{-8.5s}}{1+2.0s}$
50	$-H(s) = \frac{0.08}{1+0.2s} + \frac{0.01}{1+0.4s} + \frac{0.035}{1+2.0s} + \frac{0.037e^{-5.0s}}{1+5.4s}$
56	$-H(s) = \frac{0.085}{1+0.2s} + \frac{0.0312}{1+0.4s} + \frac{0.037}{1+2.0s}$
62.5	$-H(s) = \frac{0.095}{1+0.2s} + \frac{0.0335}{1+0.4s} + \frac{0.048}{1+2.0s} + \frac{0.020e^{-5.0s}}{1+5.4s}$

As with start-of-run curve fits, the units for the feedback transfer function are dollars of reactivity expressed as the product of the power level and the differential power coefficient of reactivity.

During the prompt part of the feedback, the models for 56 and 62.5 MWt show generally the same character and magnitude as those for start of the run. Only limited importance may be given to the fourth, or delayed, term because only data recorded up to 15 sec were used for the determination of the equations.

The models for the 40- and 50-MWt rod drops will not extrapolate to higher power levels linearly; this was seen in start-of-run modeling calculations. However, in contrast to start-of-run data there is no change in sign in the third term of the equations. It would be expected that the time-dependent characteristics of the reactor at the lower power level would change because, after reactor operation at 62.5 MWt for several hundred MWd, the mechanical stresses in the core should not be the same as at the start of the run.

V. SUMMARY

Rod-drop tests were performed at both the beginning and end of run 46A, and some analysis of results was also performed.

The programs for reduction and analysis of rod-drop data were converted from the system previously used to a newly acquired XDS Sigma-5 computer system. This conversion resulted in significant time savings for processing the data. The new system is well integrated and provides convenient sequential operation of the various program segments. There are advantages in data storage; the information on reactor power obtained in the rod-drop tests is now stored on magnetic tape rather than cards.

Feedback-reactivity plots for reactor power levels of 50 MWt or less differ from those for reactor power levels greater than 50 MWt. The predominant difference is a "weakening" of the more prompt part of the feedback curve and a higher asymptotic value for the feedback. There is, at present, no firm explanation of this characteristic change except possibly the saturation of some feedback mechanism above 50 MWt.

The reactivity-feedback information was further analyzed by fitting it with a polynomial characteristic of linear feedback systems. This change allowed separation of the feedback reactivity into several time-dependent terms, each of which was previously postulated as characteristic of a feedback mechanism. A further attempt was made to predict feedback models for higher power levels by multiplying each term of the feedback curves of lower-power models by the ratio of the respective power levels. For those cases in which the characteristic shape of the feedback reactivity was unchanged with changing power level, this method was successful.

The feedback reactivity for the 62.5-MWt rod-drop experiment of run 46A differed in character and magnitude from that of run 38A. The change in total feedback-reactivity worth is due to the difference in worth of the drop rod; it was worth 12% less in run 38A, a 12% change in zero-power reactivity. This decrease is subsequently reflected in the feedback reactivity. The reason for this difference would be difficult to resolve because of the difference in loadings for the two runs.

End-of-run rod-drop tests were done with both a compensated and an uncompensated ion chamber. These two chambers indicate a different rod worth, or zero-power reactivity. Computer studies indicate that the difference is due to the constant gamma source sensed by the uncompensated chamber. A slight difference in the shapes of curves for zero-power reactivity after a rod drop is hypothesized to be due to a transient gamma source also sensed by the uncompensated chamber.

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