ANL/IFR/CP--80827
Conf-940407--12

ADVANCES IN CRITICALITY PREDICTIONS FOR EBR-II

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Final paper for American Nuclear Society Topical Meeting on Advances in Reactor Physics, April 11-15, 1994, Knoxville, TN

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Work supported by the U.S. Department of Energy, Nuclear Energy Programs, under Contract W-31-109-Eng-38.

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KEYWORDS: Criticality, EBR-II, Source multiplication

ABSTRACT

Improvements to startup criticality predictions for the EBR-II reactor have been made. More exact calculational models, methods and data are now used, and better procedures for obtaining experimental data that enter into the prediction are in place. Accuracy improved by more than a factor of two and the largest ECP error observed since the changes is only 18¢. An experimental method using subcritical counts is also being implemented.

INTRODUCTION

Criticality predictions for startups of the Experimental Breeder Reactor II (EBR-II) reactor are required to be accurate even though a cautious procedure is followed in approaches to critical. The inverse of the neutron detector count rate is plotted against rod insertion as the fueled control rods are inserted one by one. When the reactor is close to critical, the plot is extrapolated to criticality and this projection is compared to a previously declared estimated critical position (ECP). "Adequate" agreement must be observed before the startup can proceed to criticality. In addition, if there is not adequate agreement between the ECP and actual criticality, the reactor is shut down until the discrepancy is resolved. In the fall of 1991, the Department of Energy made 33¢, until then just an internal administrative notification threshold, the required level of agreement. Recently the requirement was changed to 50¢. The purpose of this paper is to describe how criticality predictions have been improved to meet these stringent requirements.

Several factors contribute to making the required ECP accuracy a challenging goal for EBR-II. As an irradiation facility and a prototype for the Integral Fast Reactor concept,[1] the core loading often varies substantially from run to run; the average core radius changes as much as 7%, experimental subassemblies containing exotic materials or non-standard fuel types come and go, and the driver subassembly distribution is rearranged to tailor experimental environments. There is no symmetry, either axially or in the hex plane, making it important to use full, three-dimensional (3-D) models for predictions. Other factors are identified in subsequent sections.

The ECP determination starts from a measured zero-power critical configuration. Any burnup reactivity loss since that measurement and the worth of changing to the new core loading must be estimated. Then, estimated rod worths are used to find what change in control rod position is needed to compensate for the loading change worth. Errors that are not very small compared to the 33¢ accuracy compensate for the loading-change worth (LCW) (and for burnup if appropriate). Only once was there an attempt to apply a calculated adjustment for rod worth changes induced by the loading change; usually the worth changes are too small to warrant the considerable effort. The worth of partially inserting a rod is now determined more accurately; a generic rod worth shape was used in the past, but now a fourth-order polynomial fit is made each time a rod is calibrated.

CRITICALITY CALCULATIONS

A. WORTH TABLES

A worth table approach was the only method used to determine the loading change worth before the imposition of the new accuracy requirement. The worth tables in use then (traditional tables) were created many years ago and it is no longer clear what computer codes, cross section data and reactor model were used.

New tables were generated. Actually, two new sets of tables were created, one based on a loading with a small core radius and the other based on a loading with a more typical core radius. The radius of the core being considered dictates which new set is the appropriate one to use. ENDF/B Version 1 neutron cross section data were employed in a combination of R-Z and X-Y geometry diffusion theory calculations. These somewhat dated models and data were used because one goal was to understand the origin of the traditional tables. The new tables include almost all materials that may be loaded into the core, whereas the traditional tables accounted for only the ten most common isotopes in the core.

The new worth tables have proven to be much more accurate than the traditional ones. The LCW was computed for three loading changes using both the new and traditional tables, and the predictions were compared with the measured worths. The errors range from -54¢ to +17¢ with the traditional tables but only from -17¢ to -1¢ with the new tables.

The accuracy of the worth table approach is limited by two inherent assumptions. It is assumed that the flux distribution is unaltered by the loading change, i.e., first order perturbation theory (FOP) is used. Furthermore, the worths are assumed to apply to any reactor loading, not just the one on which the tables are based. The creation of different tables for two different core radii addresses the second condition but only to a modest degree.

Although a more accurate approach has replaced worth tables as the primary source of the LCW for the ECP, the worth tables still serve valuable functions. Technical Specifications require monitoring of shutdown reactivity at every step in the fuel handling. Since worth tables are quick and easy to use, they are well suited for shutdown reactivity monitoring during extensive fuel handling. Also, the tables are used to produce an independent estimate of the LCW, which has uncovered errors in the primary calculations. Finally, worth tables are very useful in designing new core loadings.

B. EXACT PERTURBATION APPROACH

The new primary approach is an eigenvalue-difference estimate based on models of the exact loadings. This is the adiabatic reactivity approximation,[2] which is valid under the static conditions here. Hexagonal-Z geometry is used with homogenized descriptions of the subassemblies. Burnup-dependent compositions are obtained with the REBUS code using a similar model and the same broad group cross sections.[3] The nine-group cross sections were generated from ENDF/B Version 5.2 cross section data and collapsed in the transport-corrected P_0 approximation for typical EBR-II compositions. The nodal diffusion option of the DIF3D code[4] is employed.

The most questionable aspect of this method is the use of diffusion theory. This approximation is used because 3-D transport methods are not computationally efficient enough for routine use. The small core radius ($\approx$32 cm) and pancake geometry (H/D $\approx$ .5) result in high leakage. This, in turn, leads to large diffusion errors for some quantities, e.g., a $\approx$4% eigenvalue error. Generally quantities in the reflectors and blanket have large errors when diffusion theory and the standard nine-group cross sections are used.[5]

Fortunately, the effects on the ECP are not large because it is dominated by core changes, where diffusion theory works surprisingly well. Transport corrections were estimated for three loading changes. They range from 1¢ to 11¢. For an extensive loading change, more than 50 core positions, that included a substantial change in core radius, (Run 159A loading) a continuous energy Monte Carlo calculation of the LCW was performed. The error in the nine-group diffusion theory result relative to the Monte Carlo result is only 5.4 ± 3.2¢. Thus, while transport errors in the diffusion theory ECP are significant, they are quite tolerable.

An unusual phenomenon affecting the ECP is irradiation-induced axial growth of the metal alloy driver fuel. The elongation is as much as 10% over the life of this fuel. This effect is currently included using a simple, binary model. A fresh driver replacing a highly burned one has the largest impact, as much as 5¢. The contribution to the total LCW has been as large as 13¢. This justifies efforts to improve the modeling of fuel growth.

Composition uncertainties make a contribution to the ECP errors. The sensitivity to core burnup uncertainties was estimated by using two different calculations of burnup, the REBUS predictions and predictions from a more approximate method that was used for many years. The contributions to the LCW from individual subassemblies differed by a few tenths of a cent and the total LCW changed by at most a few cents. Although fissile buildup in the blanket is much more uncertain than core burnup, it has very little effect on the LCW because exchanges in the blanket are unimportant.

Composition uncertainties unrelated to burnup may be more important. A systematic reassessment of all subassembly hardware has just been completed and a new neutronics model based on this information is nearly in place. This is part of the development of a physics database for EBR-II.[6] Preliminary indications are that some contributions from above and below the core change significantly while contributions from the core region are little changed. This is because large differences in the excore regions of some subassemblies were neglected in the old model. The effect may approach 10¢ for some loading changes.

The LCW is affected to a surprisingly large degree by the insertion pattern of the control and safety rods. Both calculations and measurements show that the LCW for one typical reload differed by as much as 15¢ depending on whether the control rods are in a particular 14-inch startup bank or all fully inserted. In a more practical test, the calculated LCW changed by 9.4¢ just by changing from one 14-inch startup bank to another that is not very different. For the massive reload case, Run 159A, even larger variations in LCW have been calculated. This sensitivity is a manifestation of flux redistribution effects; the loading change causes a flux redistribution that affects the rod worths and, conversely, rebanking the rods causes a flux redistribution that affects the LCW.

The practical question is what rod pattern, when used in the LCW calculations, will result in the most accurate ECP. The answer is a pattern as close as possible to the new startup pattern. The most accurate rod worths available for predicting what rod insertion changes are needed to compensate for the loading change (and possibly burnup) are the worths measured with the old loading. But the appropriateness of these rod worths diminishes as the core configuration (subassembly loading and rod insertion pattern) deviates from the configuration that existed during the rod calibrations. Thus, we want to use them to determine the reactivity effect, with the <u>old</u> loading, of moving the rods from the old shutdown 14-inch critical bank to the anticipated new startup 14-inch bank. Then we account for the balancing reactivity effect of the loading change as if it were made with the new startup rod pattern. In this way we do not need to assume that the old measured rod worths are appropriate to the new loading. In effect, we want the LCW calculation to include a prediction of the change in the worth of the rod pattern that will exist when criticality is achieved.

It might be argued that this is not possible to do, since the new critical rod configuration is what we are trying to find in the first place. But it is not necessary totally to eliminate estimates of the worth of rod adjustments made with the new core loading in place; the goal is just to minimize them. Here is how that is achieved. The worth tables are used to get a preliminary estimate of the LCW, and with that, a preliminary estimate of the ECP is produced. A 14-inch bank close to this preliminary ECP is then used in the eigenvalue calculations for both the old and new loadings. Only after that, when making the final reactivity balance, is it necessary to assume the rod worths measured with the old loading apply to the new loading.

FOP worth calculations have been done to supplement many of the eigenvalue-difference results. Not much extra computational effort is required, just an adjoint eigenvalue calculation for the reference (old loading) configuration and a perturbation calculation. An exact perturbation (EP) calculation is now also done routinely, simply by supplying the perturbed-state (new loading) forward flux, instead of the reference forward flux, in a second perturbation calculation. These calculations are done primarily to facilitate error checking. They yield the contributions to the LCW from each subassembly exchange, which are compared with the worth table results. Any large differences are investigated and this has helped uncover a number of input errors.

A typical example of the comparisons is shown in Table I. The exact perturbation total LCW is the same as the eigenvalue-difference result, of course, but the position dependent contributions are exact only if all the grid changes occur simultaneously, a practical impossibility. The close agreement between EP and FOP for the individual loading steps indicates that the flux redistribution does not have a large effect on any one subassembly exchange. The FOP and EP totals are not much different.

Table I. Run 163A LCW (¢)

Position	EP	FOP	Tables
2E1	14.1	12.4	14.1
2F1	3.0	2.1	-1.7
3F2	-15.8	-17.3	-13.1
4E3	-8.6	-9.4	-13.3
5A1	4.1	4.2	5.4
5A2	44.5	44.2	45.0
5A3	7.3	7.1	1.4
5D3	58.4	57.6	57.4
6C4	31.4	31.4	30.6
6F3	31.1	31.3	26.8
Total	169.5	163.5	152.9

The average FOP error relative to EP for nine LCW calculations that have been compared is only -3.4 ± 1.8¢. This excludes the massive Run 159A loading change, where FOP was found to be hopelessly inappropriate, predicting LCW values that differed by more than $3 depending on whether the initial state or the final state was used as the reference.

Generation of the 3-D models for the loadings by hand is both tedious and prone to human error. Consequently, important factors under development are creation of an EBR-II physics database[6] and automated generation of the models using the database. Partially automatic input generation for loading changes has in fact been in place for the last six loadings. These efforts are significantly increasing the reliability of the ECP predictions.

C. PREDICTION ERRORS

The improvements in the experimental input and the calculational approach have resulted in much more accurate criticality predictions. This can be seen graphically in Fig. 1, which displays five error distributions. Parameters that characterize these error distributions are shown in Table II. (Absolute is abbreviated as Abs. there.) The excess reactivity, ECP and LCW are closely related quantities. They differ only in what control rod worths must be predicted. The LCW derived from experimental data for each reload corresponds to the same control rod bank as was used in the eigenvalue calculations. Measurement uncertainties, which are estimated to be a few cents, have been ignored in this analysis.

A number of observations can be made about the accuracy.

- The old approach did not satisfy the new accuracy requirements. The data cover startups during 1983 through 1991. If they had been in place at that time, the 33¢ requirement would have been violated 9 times and the 50¢ requirement would have been violated 3 times.
- The new approach, 3-D eigenvalue difference, has been used enough times (15) to establish its accuracy reasonably well. Included is a loading change as drastic as any expected to occur (Run 159A). There is no important bias, as indicated by the mean errors being no larger than 1¢. More importantly, the error range easily satisfies the new accuracy requirements.
- The eigenvalue-difference error spread is significantly wider for the excess reactivity than it is for the ECP or the LCW. The larger errors occur because rod worths are altered by the loading change, and with the prescription for banking the rods in the model, neglect of these change is minimized for the ECP but remains a significant problem for prediction of the excess reactivity.
- It was observed earlier, from three test cases, that the new worth tables are much more accurate than the traditional ones. Fig. 1 and Table II indicate that the new worth tables, in combination with the improved experimental input, can satisfy the new accuracy requirements in most cases. One exception is the massive reload for Run 159A, which was excluded from this error distribution. Only one other data point does not satisfy the 33¢ accuracy requirement. The difficulty there was a large number of subassembly exchanges where the fuel length changed (fuel growth).

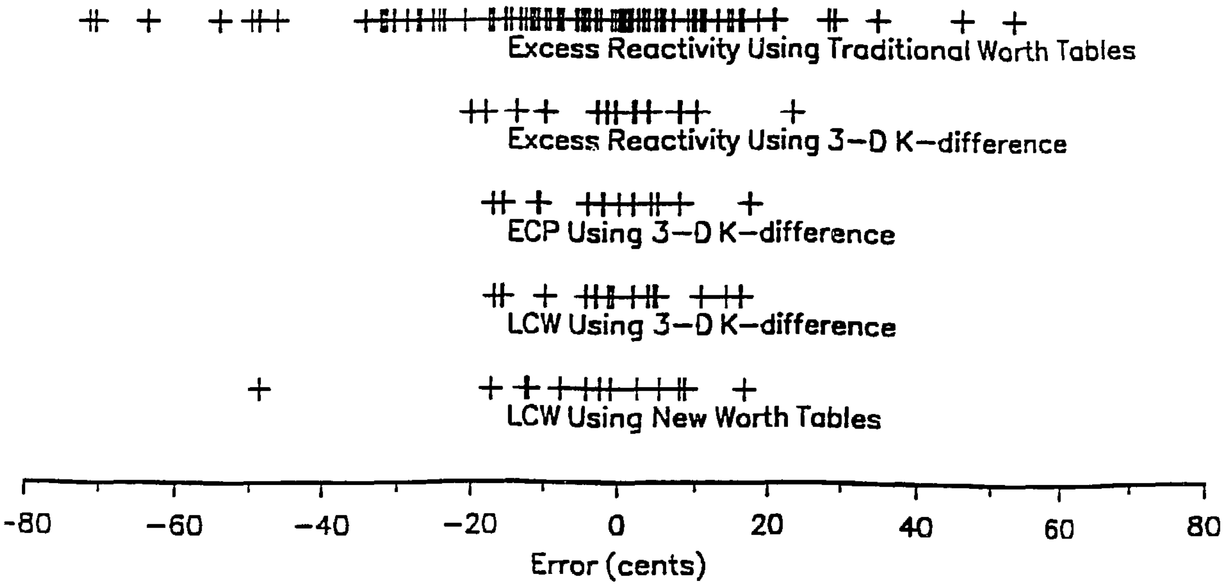

Fig. 1. Error Distributions Related to EBR-II Criticality Predictions

Table II. Error Distributions Related to EBR-II Criticality Predictions

	Characteristics of Error Distribution					
	No. of	Range (¢)		Mean	Sample Std.	Mean
Quantity Predicted, Method	Values	Min.	Max.	(¢)	Dev. (¢)	Abs. (¢)
Excess Reactivity using Traditional Worth Tables	88	-71	54	-5.8	22.7	16.5
Excess Reactivity using 3-D Eigenvalue Difference	15	-20	24	-0.4	11.4	8.4
ECP using 3-D Eigenvalue Difference	15	-17	18	-1.0	9.5	7.3
LCW using 3-D Eigenvalue Difference	15	-17	16	0.6	9.6	7.3
LCW using New Worth Tables	13	-49	17	-4.9	16.3	11.2

SUBCRITICAL SOURCE MULTIPLICATION

An experiment-based alternative for determining the EBR-II loading change worth is being developed. The method, modified source multiplication,[7] has been used extensively at the ZPPR critical experiment facility and is being implemented at EBR-II. It is intended to provide an independent check on the primary LCW calculation.

The fundamental notion is that subcriticality is inversely proportional to the neutron detector count rate. The exact relationship is developed in Ref. 7. Eq. 3 from there, when adapted to the EBR-II conditions, can be written as

$$\$_2 = \$_1 \cdot (R_1/R_2) \cdot D_{12} \cdot (\epsilon_2/\epsilon_1) \cdot (S_{e2}/S_{e1}) \; .$$

The subcriticality of reactor configuration 2, $\$_2$, is related to the known subcriticality, $\$_1$, of reactor configuration 1 through a combination of four factors. R_1/R_2 is the raw count rate ratio. D_{12} accounts for decay of the neutron source between the times when count rate measurements R_1 and R_2 are made. This factor was not included in Ref. 7 because there was no significant decay in the cases considered there. ϵ_2/ϵ_1 is the ratio of detector efficiencies for configurations 2 to 1. The detector efficiency is itself a ratio: detector count rate divided by total reactor fission rate. S_{e2}/S_{e1} is the ratio of source importance ratios for configurations 2 to 1. The source importance ratio for configuration i is the average importance of a source neutron divided by the average importance of a fission neutron, where the importance function is that of the fundamental mode in configuration i. The factor in Ref. 7 that accounts for the change in β_{eff} from configurations 1 to 2 is omitted here because that change is negligible for EBR-II.

The most basic requirement is acquisition of count rate data. There have always been three ex-core neutron detectors that respond when the reactor is subcritical. However, pulse count rate data were only recorded by hand and only for short counting intervals, before the new ECP requirements were imposed. This limitation was eliminated by the recent installation of a four channel scaler with an RS-232C interface. Three of the channels are connected to the pulse output of the fission chambers. The fourth channel serves as a timing channel. The data acquisition is configured such that synchronization of the three chamber signals is virtually guaranteed, thus allowing continuous recording of correlated count rate data.

Determination of an accurate reference subcriticality ($\$_1$) is an area needing more work. Inverse kinetics analysis of a rod drop typically was used at ZPPR. Both operational and mechanical problems have precluded that option so far at EBR-II. The current approach uses as $\$_1$ the subcriticality at the beginning of fuel handling, when all the control rods are out of the core. It is assumed that the net worth of all the control rods withdrawn from the zero-power critical configuration is the sum of the rod worths measured individually at critical. Calculations indicate that the rod worths are not additive, due to rod interaction effects, and that the error is on the order of 5-10%. In the worst case over the last 15 loadings, the resulting error in the inferred LCW could be as large as 15¢.

The source decay correction factor, D_{12}, is easy to obtain if the fuel handling occurs at least 24 hours after shutdown. Source neutrons are generated when gamma rays emitted from the decay of ^{124}Sb in an antimony rod produce photoneutrons in the surrounding beryllium annulus. In the first 24 hours, the source decay is complicated by the significant presence of other emitters of gamma rays sufficiently energetic to produce photoneutrons in the Be.

The ϵ_2/ϵ_1 and S_{e2}/S_{e1} are calculated using similar methods models and data as those used for the primary LCW calculations (3-D nodal diffusion theory with nine-group cross sections, but fixed-source as well as eigenvalue calculations are done). The source subassembly is in the radial reflector region. The detectors are in the outer shield, far from the core and see a thermalized flux. The evidence in Ref. 7 suggests that this approach should be adequate despite these difficulties, basically because the required factors are ratios of ratios, making them insensitive to calculational errors. The standard 3-D model was extended to encompass the detectors, making it more than four times larger. Preliminary tests suggest that nodes at the edge of the standard model on a line of sight to the detector give nearly the same efficiency ratio as nodes at the actual detector location.

Results of an analysis using subcritical count rate data from a recent loading are given in Table III. The three detectors are referred to as Channels A, B and C. The LCW is simply $\$_2$-$\$_1$. The experimental values bracket \$0.40, the LCW value calculated by the primary method with control rods modeled in the fuel handling position. The ratio of source importance ratios is very near unity. This is typical, but for the massive Run 159A reload it was a 16% correction.

Table III. Subcritical Source Multiplication Analysis for Run 166A.

Detector	$\$_1$	R_1/R_2	D_{12}	ϵ_2/ϵ_1	S_{e2}/S_{e1}	$\$_2$	LCW (\$)
Channel A	-6.28	0.902	0.987	1.067	0.998	-5.95	0.33
Channel B	-6.28	0.957	0.987	0.993	0.998	-5.88	0.40
Channel C	-6.28	0.952	0.987	0.995	0.998	-5.86	0.42

The detector efficiency ratios should bring all the channels into agreement. Channels B and C were in reasonable agreement before applying the efficiency correction (R_1/R_2) and they agree better after applying it ($\$_2$). Channel A had a smaller count rate ratio and the detector efficiency correction overcompensates. The ratio would have to be only a little smaller, 1.053, to achieve consistency, an indication of the sensitivity to this factor.

CONCLUSIONS

Although the traditional technique for determining an ECP at EBR-II is not accurate by modern standards, its use did not pose a direct threat to safety. A disciplined approach to critical, where the inverse count rate is monitored as the fueled control rods are inserted, has always been used routinely and it precludes a criticality accident at startup. The arguments for making criticality predictions as accurate as practical are less direct, having to do with "best practices" and quality assurance. Having the best possible ECP increases the probability of detecting a loading error or some unexpected material rearrangement.

Experimental input is one area where there have been improvements. The experimental test of the ECP during the approach to critical was made more accurate by coming closer to critical before making the extrapolation. Standardization of the control rod insertion sequence and measurement of a startup-type control bank at the shutdown of the old run have helped minimize errors associated with using old measured control rod worths.

The old calculational approach for determining the LCW has been replaced. It has been found, by generating new worth tables, that the old basic approach of using worth tables is reasonably accurate in most cases, but the traditional worth tables are not accurate for modern loadings and they neglect too many materials. Worth tables are now used to check results from the new primary method, eigenvalue-difference calculations using 3-D models of the exact loadings.

There has been a major improvement in the accuracy of the ECP and related quantities. There is now no significant bias, the mean absolute error has been reduced from 17¢ to 7¢, and the maximum absolute error has dropped from about 70¢ to about 20¢. Still, it is appropriate that the new accuracy requirement was relaxed from 33¢ to 50¢; several error sources at least as large as 5¢ have been identified and an unfortunate combination of errors totaling more than 33¢ could occur.

Sources of error in the new approach have been evaluated and additional improvements are being made. Errors from using diffusion theory were estimated to be ≈10%, which is surprisingly small considering the high leakage. Three-dimensional transport calculations will be done more as computationally more efficient tools become available. The simple model of axial fuel growth works adequately but improvements are planned. Composition uncertainties are being reduced by the development of a new 3-D model. The LCW was found to be sensitive to the control rod bank and a modeling strategy that minimizes the error associated with that is being used. Results are checked against worth table predictions to catch human errors and increased automation of model generation will further reduce this potential problem.

The subcritical source multiplication technique is being implemented to provide an experimental estimate of the LCW prior to startup. It appears unlikely to develop into a highly accurate approach. A fundamental limitation is that the LCW varies with the control rod insertion pattern; calculated estimates of the effect of the different rod positions during refueling and startup range from 5¢ to 25¢. Other problems are the difficulty in getting an accurate subcritical reference reactivity and the sensitivity to calculated detector efficiency ratios. The technique can provide another check of the primary calculation, however, as illustrated in the previous section.

ACKNOWLEDGEMENTS

K. N. Grimm created the new worth tables and computed transport corrections. R. D. McKnight provided the 9-group cross sections and the end-of-cycle atom densities. P. J. Finck ran the Monte Carlo calculations for Run 159A. P. L. Angelo streamlined the use of worth tables and D. M. Smith made most of the LCW predictions with them. D. C. Cutforth facilitated the improvements to experimental input to ECP predictions. S. G. Carpenter gave advice on implementing the subcritical source multiplication method.

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