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PROBABILISTIC TREATMENT OF ROD RUN-IN ACCIDENT INITIATORS AND THE REACTIVITY FEEDBACK RESPONSES IN EBR-II

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ABSTRACT

The idea of treating an accident initiator in a probabilistic manner is developed. Instead of using a bounding value, the rod reactivity insertion in an unprotected transient overpower accident is described realistically as a distribution of insertion magnitudes. The initiator analysis uses EBR-II Operating Instructions and data files of rod worths and position histories. The average insertion magnitude is found to be 16¢, which is only about half of the feedback reactivity from zero to full power. The probability of inserting 130¢ or more, the Technical Specification limit, is less than 10^{-6}. The initiator characteristics are then propagated through a probabilistic analysis of the reactivity feedback response to the initiator. This analysis shows that reactivity feedbacks reduce by four orders of magnitude the probability of a rod run-in event resulting in substantial core damage, in addition to the more than five order of magnitude margin afforded by the scram system.

I. INTRODUCTION

The Experimental Breeder Reactor II (EBR-II) is a small, sodium-cooled, fast-neutron-spectrum reactor with a steam power plant that produces about 20 MW of electricity. It has been operated primarily as an irradiation facility and for plant transient tests, since 1964. The current focus of EBR-II is as a prototype for the Integral Fast Reactor (IFR) concept.[1]

EBR-II has been the subject of numerous safety studies, both theoretical and experimental, over the years. Recently, a Level-1 probabilistic risk assessment (PRA) was performed for steady-state operation of EBR-II.[2] One objective was to develop a probabilistic approach for treating the passive safety characteristics of a IFR. At least two significant innovations were developed in this regard.

One innovation was to evaluate the effect of reactivity feedbacks in a probabilistic manner. Unlike reactors previously subjected to a PRA, EBR-II has passive safety characteristics that greatly reduce the likelihood of core damage in a wide range of unprotected accidents. Thus, for the first time in a PRA, it was desirable to quantify the effectiveness of reactivity feedbacks. The method for doing this was presented in Ref. 3. Results for five of the eight steps in the method were given there for all anticipated transients without scram, and the complete process was carried out for loss-of-normal-power events.

The other innovation was to treat an accident initiator in a *probabilistic manner*. Often the characteristics of an accident initiator are uncertain or there is a distribution of possible initiator conditions. The typical treatment of these situations is to use bounding values to describe the initiators. This can lead to distorted or even qualitatively incorrect damage frequencies.

The purpose of this paper is to demonstrate the utility of these two innovations by presenting an analysis of EBR-II rod run-in accidents without scram. The run-in initiator is characterized in a realistic manner and these characteristics are propagated through a probabilistic analysis of the reactor responses to the initiator.

II. ANALYSIS OF RUN-IN INITIATORS

The rod run-in event is the dominant initiator of transient overpower accidents in EBR-II. The run-in accident in EBR-II is the analog of the rod ejection accident in most other reactors. Insertion, rather than withdrawal, of control and safety rods causes positive reactivity to be introduced in EBR-II because these rods contain fuel.

A conventional approach to defining the initiator would be to use bounding values from the Technical Specifications. In this case, a control rod would be assumed to insert $1.30 at the rate of 0.01 $/s. Reactivity feedbacks are not strong enough to overcome such an insertion before damage occurs. Thus, in this approach, the conclusion is quickly reached that the core damage probability is essentially unity given a rod run-in accident without scram.

Use of these Technical Specification limiting values is unrealistic in at least two respects. First, the design of the core and control rods is such that control rods are always worth much less than the $1.30 limit. A typical control rod worth is $0.80 and the largest observed worth was $0.99. Second, and more important, the full rod worth is never available for a run-in during steady-power operation; all rods are normally more than half inserted, leaving less than half their total worth available for an accidental run-in to full insertion. Combining a typical control rod worth and a typical control rod insertion position yields less than a $0.20 run-in reactivity potential, at a rate of 0.004 $/s. Since it is likely that reactivity feedbacks can overcome this initiator, quite a different conclusion is reached about the outcome of unprotected rod run-in accidents.

Back-of-the-envelope initiator estimates, like those in the previous two paragraphs, are useful for screening purposes, but a more thorough description of the initiator is needed for an accurate failure analysis. A complete description includes the run-in frequencies, the magnitudes of the reactivity inserted and the rates of reactivity insertion. The initiator analysis used here to produce such a description has five interrelated steps.

The first step identifies patterns and frequencies of rod use. The Operating Instructions, administrative limits and operating history provided this information. Several operation categories of rods were identified, each with its own set of characteristics - range of possible axial insertion positions and frequency of up-motion demands.

The second analysis step determines the insertion rates in terms of rod drive speeds. The System Design Description yielded this information for each type of rod. Rod insertion speeds were converted to reactivity insertion rates using rod worth profiles found in the next step.

The third step finds the spectrum of rod insertion magnitudes, and associated insertion rates, for each category of rod that *may* run in. This information was obtained by processing data files of measured rod worths and position histories covering four years of operation. Run-in of one rod, two rods and many rods were considered. A discrete probability density function (pdf) was constructed from the data to describe each spectrum. In all, seven pdfs were generated.

To make feasible the processing of years worth of data, it was necessary to use rod positions archived in the form of 60-minute time averages. The problem with this is that short-duration departures from an average rod position are not apparent. However, it is known from operating procedures that significant rod movements at steady power are much less frequent than this, with only one important exception. The exception is a control rod operability test conducted once each day. Some rods are moved out about 9 cm during this test, creating a much larger than normal reactivity insertion potential for a very short time each day. This phenomenon was accounted for by reconstructing a typical daily operability test in the data processing program. This added a noticeable tail to the distributions for some rod categories but had little effect on total core damage probabilities.

The safety rod pdf could not be used directly as generated from position histories because of an uneven pattern of activity. About 58% of the time these rods are fully inserted and inactive. For Reactivity Control System failures that are proportional to exposure time, the as-generated pdf was adjusted to remove this time of full insertion. A completely different safety rod pdf was constructed, based on how these rods are used, for system failures that are proportional to the number of up-motion demands.

The fourth analysis step finds the Reactivity Control System's failure modes that can result in a rod run-in. The run-in frequency for each failure mode is also found. This was done using a fault tree analysis. Dependency among events (e.g., common cause) was treated. Because reactivity control is such a "hands-on" activity, the analysis included human error and human recovery actions, which can make conditions worse. No significant flaws in the system or its operation were found. The dominant sources of failure, switch and relay malfunction, are unavoidable and have reasonable failure rates. The total run-in frequency was found to be 0.0382/y, with an error factor of 4. Of this, 0.0007/y is due to the simultaneous run-in of more than one rod.

The fault tree analysis was conventional except that track was kept of the rod categories involved in each failure mode. This was necessary to know what mix of reactivity insertion magnitude pdfs applies to a rod run-in. For each basic event in the tree, the probability that a given type of rod is associated with the event was determined. The mix of pdfs at each gate was found by frequency weighting as the failure rates were propagated through the tree.

The final step consists of integrating all the information into a complete specification of the run-in initiator. A cumbersome but rigorous random sampling scheme was developed to select reactivity insertion magnitudes from the seven pdfs and use the appropriate insertion rates. However, an approximation was found to be valid that allowed use of a process that is simpler and allows the distribution of possible transient outcomes to be traced out with many fewer transient calculations.

The reason for keeping the seven rod categories distinct is that the reactivity insertion rate is different for each one. However, because the insertion rates are all slow compared to the reactivity feedback response, the transient outcome is insensitive to the exact insertion rate. Thus it was possible to produce a single, composite insertion magnitude pdf. The composite was produced by averaging the seven pdfs, using as weight factors the conditional probabilities that the various rod categories would contribute to a run-in.

Correspondingly, approximate insertion rates were specified based on weighted averages. An insertion rate of 0.34 ¢/s was used for insertions between 0¢ and 55¢, where the actual rate ranges from 0.26 ¢/s to 0.45¢/s. Between 55¢ and 90¢, the actual rate ranges between 0.89¢/s and 0.95¢/s; 0.90¢/s was used for all insertions above 55¢.

The composite pdf is shown in Fig. 1. The pdf gives the conditional probability that the strength of the initiator will be within a 5 cent interval, given that there is an accidental rod run-in. The pdf actually goes up to 250¢ but the plot stops at 60¢ because the large-reactivity tail is below the resolution of the plot.

The pdf reveals a dramatically smaller magnitude initiator than the Technical Specification limit of $1.30. The average reactivity insertion magnitude is only 16.1¢. This is only about half as large as the power reactivity decrement (PRD), the feedback reactivity from hot zero power to full power. Given a run-in event, the conditional probability that the insertion is $1.30 or more is extremely small, $9x10^{-7}$.

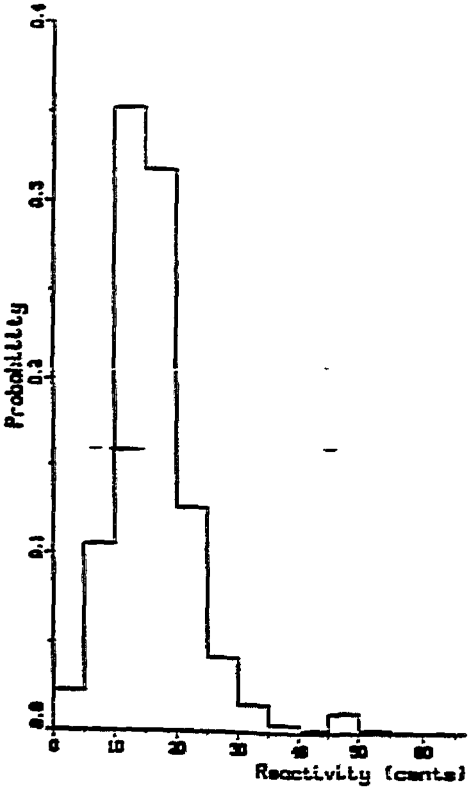

Fig. 1. Pdf For Composite Run-in Reactivity

II. FEEDBACK FAILURE ANALYSIS

Reactivity feedbacks tend to reestablish a balance between fission heat production and heat removal when the reactor is subjected to an upset condition, such as a rod run-in. Our inability to know with certainty whether the feedbacks are strong enough to reestablish the balance, without temperatures exceeding safe limits, is what makes the outcome a probabilistic issue. Accordingly, the failure analysis consists of evaluating the ability to predict what the reactor response to the accident initiator will be. Basically, the probability that reactivity feedbacks fail to prevent damage was computed by propagating data and modeling uncertainties through transient calculations.

The eight-step process used to do this is described in Ref. 3. The results from there that are relevant to the rod run-in analysis are summarized as follows. The accident initiators were screened in Step 1, where it was determined that a detailed analysis of run-in accidents was warranted. The second step consisted of calibrating the transient calculation models, used with the SASSYS code,[4] to give results in good agreement with key EBR-II passive safety demonstration experiments.[5] Input parameters were screened in the third step, identifying those sufficiently important that their uncertainties should be propagated. Eight parameters, associated with six reactivity feedback phenomena, were selected for uncertainty propagation in rod run-in calculations. Step 4 consisted of quantifying the parameter uncertainties in the form of a pdf for each one. The functional form selected was either a normal or a log-normal distribution and the mean, variance, etc. were chosen to reflect our state of knowledge about the feedback parameters. Strong correlations among parameters were account for. Reactivity feedback data measured in EBR-II are used to force the parameter uncertainty propagation to be consistent with the observed feedback characteristics. Descriptions of experimental constraints were developed in Step 5 for two measured quantities, the PRD and the prompt feedback obtained from a rod drop measurement (RDF). Steps six through eight are presented below in some detail because they are carried out separately for each accident initiator.

The spectrum of possible rod run-in accident initiators is accommodated in this process by treating the initiator as if it were an uncertain input parameter. The distribution of this parameter is the discrete pdf in Fig. 1.

A. Computation of Response Surfaces

Step 6 is the computation of response surfaces. A response surface is generated by calculating transient responses for various combinations of input parameters and then fitting the results to a lower order, multivariate polynomial. This surface provides an approximate description of the functional relationships between the input parameters and the transient outcome quantities of interest. The parameter uncertainties can be propagated through this function inexpensively once the function is known. The PROSA-2 code[6] provided the framework for this. A response surface was needed for each accident consequence quantity (peak temperature) being followed and for each of the experimental constraint transients (PRD and RDF), but the constraint surfaces were already available from the analysis of loss-of-normal-power accidents.[3]

The combinations of input parameters (knot points) for which transient responses are calculated must be selected judiciously. The optimum choice is the smallest set of knot points that yields a response surface with adequate accuracy. PROSA's "single-quadrant" selection and fitting scheme was used. This scheme employs quadratic polynomials. The knot point selection variable was set to yield parameter extremes that are about 2.6 standard deviations to each side of the mean parameter value. This scheme was extended for the rod run-in analysis to enhance accuracy in the region of the parameter space where core damage is likely to occur. The extension is to add one extra knot point per parameter, where the parameter is displaced from the mean about four standard deviations in the direction that tends to cause higher transient temperatures (4σ points). This increased from 55 to 64 the number of SASSYS transient calculations required to construct the rod run-in response surfaces. The extra computational effort is more than offset by enhanced accuracy for small failure rates.

Function transformations were used to improve the accuracy of the response surface approximation. It is known from quasi-static reactivity balance analyses of transient overpower accidents that the asymptotic coolant outlet temperature change is proportional to the inserted reactivity and inversely proportional to reactivity feedback parameters. This suggests that peak fuel temperatures, which are the transient outcome quantities of interest here, have similar functional relationships to run-in reactivity and feedback parameters. The inverse proportionality is a problem because it cannot be well represented over a wide range by a low order polynomial. However, by using PROSA's variable transformation capability, a linear relationship of transformed temperature to feedbacks and transformed rod reactivity was formulated. The PROSA edits indicated that these transformations were very effective.

The importance of each input parameter is computed by PROSA using the response surfaces. This importance measure is basically the product of the sensitivity coefficient and the parameter uncertainty. Insertion reactivity is by far the most important parameter. Of all the feedbacks, uncertainties in sodium density effects have the largest impact on peak temperatures. Bowing uncertainties and fuel conductivity uncertainties are also important.

B. Propagation of Uncertainties

In Step 7, the input parameter distributions were sampled at least 100,000 times and translated into transient outcomes using the response surfaces. This knot point sampling was done randomly, i.e. by Monte Carlo, and yielded the distributions of possible transient outcomes. The fraction of an outcome distribution lying beyond the damage threshold is the failure probability. The experimental constraints were imposed in this sampling process using a rejection technique.

Two damage states defined in the EBR-II PRA are used here. Fuel melting is the first damage trigger to be reached in rod run-in accidents. The threshold of minor core damage (MCD) is fuel melting in the hottest driver subassembly. The threshold of core damage (CD), the most severe category, is fuel melting in an average driver subassembly.

The distribution of peak temperatures for the hottest driver subassembly (MCD) is shown in Fig. 2. The damage threshold line is the fuel's solidus temperature. The conditional damage probability is the fraction of the distribution to the right of the threshold, which clearly is small. The error bars show the statistical uncertainty for each interval of the histogram.

Quantitative conditional failure probability results are given in Table I. The uncertainties in the table include only the Monte Carlo sampling statistics. (Total uncertainty is addressed in the next subsection.) The first line shows the most accurate values, which are based on the complete insertion magnitude pdf and both experimental constraints. Given a rod run-in without scram, the conditional probability is approximately 1 in 100 for MCD and 1 in 10,000 for CD. Thus, the reactivity feedbacks are very effective in mitigating this accident. Comparing results on the first three lines shows the impact of forcing the net feedback uncertainties to be consistent with feedback measurements. The RDF constraints have a negligible effect (lines 1 and 2) but use of the PRD data do make an important improvement (lines 1 and 3). The last line gives the conditional damage probabilities when just the average rod run-in reactivity, 16.1¢, is used. These damage probabilities are much smaller than when the inserted reactivity is allowed to vary; the high reactivity wing of the insertion distribution boosts the core damage probabilities by about two orders of magnitude.

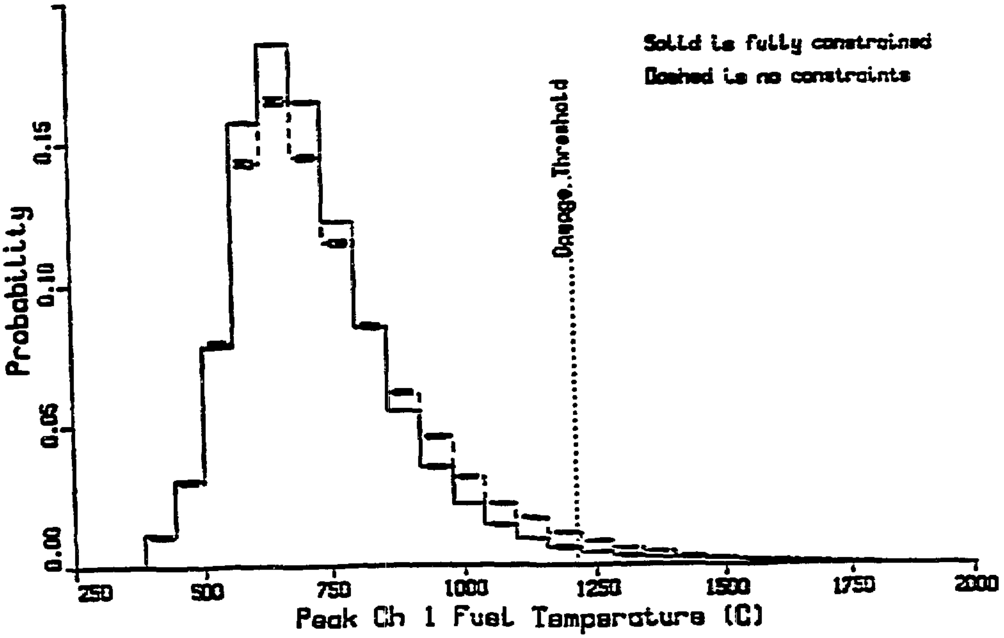

Fig. 2. Run-in Outcome Distribution For Minor Core Damage

Table I. Run-in Accident Conditional Damage Probabilities

	MCD	CD
Best Method	0.011 ±1.5%	1.2×10^{-4} ±15%
Only PRD Constraints	0.011 ±1.2%	1.3×10^{-4} ±11%
No Exp. Constraints	0.019 ±2.0%	1.8×10^{-3} ± 8%
Avg. Insertion Magnitude	1.7×10^{-4} ±1.5%	3×10^{-6} ±81%

C. Accuracy Assessment

Sensitivity calculations were done to assess the reliability of the damage probability predictions, which is Step 8. An extreme test of errors due to using approximate reactivity insertion rates was made by increasing the insertion rate by almost a factor of three. (The total insertion was 25¢). This changed peak temperatures by less than 2 degrees, which implies a negligible effect on failure rates. Omissions due to parameter screening also were shown to have a negligible impact; only one potentially significant parameter was screened out and the importance measure for it was virtually zero.

The accuracy of the response surface approximation was also evaluated. A model problem was constructed that has the approximate functional form of the true rod run-in problem. Compared to the analytic solution, the response surface solution, based on the standard single-quadrant scheme, was in error by 30% for damage probabilities of approximately 10^{-3}. The two main sources of error were the difficulty of fitting 1/x type behavior with a quadratic polynomial and the limited number of knot points from which to construct the surfaces. For the actual rod run-in analysis, the first source was addressed by using functional transformations and the second source was addressed by adding the 4σ knot points. Sensitivity calculations show that the combined effect of these enhancements is about 30%. Thus the residual error due to the response surface approximation should not be large compared to this.

Finally, the sensitivity of failure probabilities to assumptions about the input parameter distributions was investigated using tests similar to those described under Step 8 in Ref. 3. Unrealistically large changes in the feedback parameter distributions change the CD probability by only about a factor of 2 and change the MCD probability much less than that. There is a strong sensitivity to the insertion reactivity distribution but that distribution, and its uncertainty, are well known from the accident initiator analysis.

Combining all the sensitivity results, a conservative estimate of the error factor is 1.5 for MCD and 3 for CD. Most of this is from uncertainty in the insertion reactivity distribution. The error factor definition in the EBR-II PRA is the ratio of the 95th percentile value to the median value of the distribution, where the distribution is log-normal. It can be thought of as a measure of 2σ (95% confidence interval) for uncertainty distributions that are nearly normal.

IV. DISCUSSION

To get damage frequencies from the conditional damage probabilities, they must be multiplied by the frequency of rod run-in events and the probability of no scram occurring. The conditional damage probabilities obtained from the feedback failure analysis are 0.011 for MCD and 1.2×10^{-4} for CD, with error factors of 1.5 and 3, respectively. The total run-in frequency obtained from the initiator analysis is 0.0382/y, with an error factor of 4. Given a transient overpower event, such as a rod run-in, the EBR-II PRA gives the probability of failure to scram as 7.8×10^{-6}, with an error factor of 6.1. Combining these data yields a rod run-in accident without scram resulting in MCD with a frequency of 3×10^{-9}/y and one resulting in CD with a frequency of 4×10^{-11}/y. The error factors for these frequencies are 11 and 13, respectively. These numbers show there is very little risk from rod run-in accidents without scram. This conclusion applies to operation at power - startup accidents were not addressed.

Run-in accidents would have been considered a more serious threat if they had been treated in a conventional manner. Use of the probabilistic analysis method developed in Ref. 3 allowed credit to be taken for the mitigating power of reactivity feedbacks. The probabilistic treatment of the accident initiator, allowed use of realistic reactivity insertions, which the feedbacks are capable of overcoming. The conditional damage probability estimates would have been unity, not several orders of magnitude less, if either of these analyses had not been used.

There is another class of anticipated transients without scram that could be analyzed by these techniques for EBR-II - loss-of-flow accidents. The ability of reactivity feedbacks to prevent damage depends strongly on the time history of the flow coastdown. An initiator analysis should be able to quantify the measured coastdown characteristics in the form of a pdf for one or two parameters. A probabilistic failure analysis could then treat them as uncertain input parameters.

The idea of specifying an accident initiator in terms of distributions could be used even at the design stage. The well-established operating procedures and the long history of rod positions allowed the reactivity insertion potential to be characterized very accurately. But the existence of rod design characteristics and operating plans would be sufficient to construct an initiator distribution that would be much more realistic than projected total rod worths or proposed Technical Specification limits on rod worths. The notion is, of course, not limited to control rod accidents.

It would be even more fruitful to carry the idea a step further. Rod designs and operating procedures could be established with accidental rod insertion potential as one of the considerations. Making this accident a low risk could become part of the basis for setting rod worths and establishing operating procedures. The first part of this has, in fact, been done for the IFR concept; it has been proposed to render rod reactivity insertion accidents essentially benign by tailoring the breeding ratio to give a near-zero burnup reactivity swing,[7] eliminating the need for control rods with high worths. The EBR-II analysis shows that reactivity feedbacks are capable of making the rod reactivity insertion accident unimportant, even when total rod worths are large, if appropriate operating procedures and limits exist. Employing this aspect in the design process would allow some relaxation of the design restrictions imposed by consideration of this accident.

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