Conf-910414--6

[illegible]

FEB 11 1991

A PROBABILISTIC METHOD FOR EVALUATING REACTIVITY FEEDBACKS AND ITS APPLICATION TO EBR-II

CONF-910414--6

DE91 007211

R. W. Schaefer

Argonne National Laboratory
P. O. Box 2528
Idaho Falls, ID 83403-2528

Paper for the Advances in Mathematics, Computations, and Reactor Physics
April 28 - May 1, 1991
Greentree Marriott
Pittsburgh, PA

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

tb

A PROBABILISTIC METHOD FOR EVALUATING REACTIVITY FEEDBACKS AND ITS APPLICATION TO EBR-II

R. W. Schaefer
Engineering Physics Division
Argonne National Laboratory
P.O. Box 2528
Idaho Falls, ID 83403-2528

ABSTRACT

The probability that reactivity feedbacks fail to prevent damage is computed by propagating data and modeling uncertainties through transient calculations, with these uncertainties being constrained by experimental evidence. Screening processes are used to identify the most important parameters and accident initiators. The response surface method is used to facilitate the error propagation and a Monte Carlo rejection technique is used to force the parameter variations to be consistent with the observed distribution of experimental quantities. The reliability of the failure probability estimates is evaluated.

This process is applied to ATWS events in the PRA for the EBR-II reactor. The loss-of-normal-power (LONP), loss-of-flow and transient overpower accidents without scram were found to warrant detailed analysis and a complete analysis has been made for the first of these. Six parameters are primarily responsible for the LONP outcome variations. The conditional probability of minor core damage from LONP without scram is 1.2×10^{-2}. The uncertainty in this estimate is a factor of 2. This damage estimate would be an order of magnitude higher if experimental information about feedbacks in EBR-II was not used. The conditional probability of major core damage from LONP without scram is $<10^{-4}$.

INTRODUCTION

Suppose an operating reactor is subjected to an accident initiator and there is no mitigating response from any active system, e.g., no scram. The tendency of the reactor to reestablish a stable state without sustaining core damage under these circumstances is referred to as passive safety. This is an important feature of both the current US LMR designs[1] and the 26 year old Experimental Breeder Reactor II (EBR-II). Although passive safety had never before been included explicitly in a probabilistic risk assessment (PRA), its importance made it desirable to do so in the EBR-II PRA[2].

The passive safety of EBR-II results from a number of features[3]. Natural circulation that cannot be stopped by value closure or pipe blockage assures coolant flow. Reactivity feedbacks bring heat production from fissions into balance with heat removal. Diverse passive decay heat removal mechanisms make long-term heat-up very unlikely and the large heat capacity of the sodium in the tank makes it extremely slow if it occurs.

The subject of this paper is the effectiveness of one of these features, the reactivity feedbacks. A probabilistic method for evaluating the effectiveness and some of the results are presented. The focus is on what are referred to as anticipated transients without scram (ATWS events), such accidents as unprotected loss of flow and transient overpower. The issue is whether the feedbacks can reestablish a balance between fission heat production and heat removal without temperatures exceeding safe limits.

Since the reactivity feedbacks result from the reactor constituents simply following the laws of physics (primarily thermal expansion), there are only two ways that they can fail. One is if the feedbacks inherently are not strong enough to overcome the accident initiator, and the other is if the initiator is so violent that it changes the reactor configuration, degrading or destroying the feedback properties. Since the second situation is so unlikely and difficult to predict, it is reasonable to make the conservative assumption that the conditional failure probability is unity. (Conditional refers to the fact that the probability of failure to scram is not included.)

Considering the other possibility, there is only one reality - passive safety either precludes core damage or it does not, for a given accident initiator. The notion of a probability of failure arises from our inability to know with certainty what the reality is. Accordingly, the analysis consists of evaluating the ability to predict what the reactor behavior will be for each accident initiator.

ANALYSIS METHOD

The main reason that calculated transient outcomes are uncertain is that the input data are uncertain. The uncertainty in each input parameter can be expressed by constructing a distribution of possible values called a probability density function (pdf). The pdf for the transient outcome quantity of interest, e.g. peak temperature, can be found by sampling from the input parameter pdfs and running transient calculations with these parameter values. The fraction of the peak temperature pdf that lies beyond a safe temperature limit is the passive safety failure probability. This is basically the method used by Mueller and Wade[3].

This error propagation process would be prohibitively expensive to carry out without taking measures to make it computationally efficient. There are several accident initiators to consider, many uncertain parameters on which a transient calculation depends, and many transient calculations (each with a different, randomly selected parameter value) required to propagate each parameter's uncertainty accurately. Two techniques were used to make the process efficient.

One technique is screening. The idea is to sort through all possibilities, discarding those that are unimportant. A screening process was used to identify the accident initiators for which the effectiveness of passive safety is so well known that no detailed error propagation process is needed for them. A screening process was also used to identify the important input parameters. The unimportant parameters were held constant at their best estimate values and only the important ones were treated as uncertain.

The other efficiency measure was to use the response surface method[4]. The idea is to find a simple function that approximates the analytically unknown functional relationship between the outcome quantity and the input parameters. The function, a multivariate low order polynomial, is called a response surface. The parameter uncertainties can be propagated through this function inexpensively by Monte Carlo sampling, once the function is known. Transient calculations must be run to compute the response surface, but many fewer of them are needed than if the uncertainty propagation were to be done directly. Unlike Latin hypercube sampling[5], an alternative technique, interactions between input parameters are accounted for explicitly.

The response surface method is impractical if the number of uncertain parameters is large. This number could be kept small primarily because it was unnecessary to model either the balance of plant or core disruptive processes. The dominance of only a few feedback phenomena was another helpful factor.

The reliability of accident outcome predictions for EBR-II can be enhanced markedly by using the large database of plant transient experiments on EBR-II[6-8]. These experiments have been conducted to examine the passive safety characteristics of EBR-II and to demonstrate that a number of ATWS events have a benign outcome. The analysis method has been tailored to make maximum use of these data.

These and other considerations are incorporated into eight steps, which comprise the analysis procedure. Steps are included that proved to be useful in other recent efforts to evaluate uncertainties in the outcome of reactor transients using probabilistic methods[9,10]. Each step is introduced in the following paragraphs and then is covered in more detail in the subsequent section.

Step 1. Screen Initiators

A screening analysis is done for each accident initiator. For initiators where this gives an unambiguous result, no further analysis is needed. The remaining accidents require a detailed analysis. The initiator screening was done principally using a quasi-static reactivity balance[11,1]. EBR-II plant experiments and past safety analyses supplemented the quasi-static evaluation.

Step 2. Calibrate Models

Some of the models used in the transient calculations are semiempirical, since it is not feasible to model all the processes from first principles. These models are adjusted to yield good agreement with key EBR-II passive safety demonstration experiments[6].

Step 3. Screen Parameters

The number of uncertain parameters is reduced initially by combining uncertainties from two sources - material displacements and the corresponding reactivity feedback coefficients. Then importance ranking is used to identify the important feedback parameters.

Step 4. Quantify Parameter Uncertainties

A pdf must be specified for each important parameter. There are not enough data to trace out a distribution for any of the parameters. Rather, a physically reasonable statistical distribution form is assumed and the available evidence is used to determine the distribution parameters (e.g., mean and variance).

Step 5. Develop Experimental Constraints

Since the uncertain feedback parameters cannot be measured in EBR-II individually, the uncertainty distributions developed in Step 4 are not based on much experimental data specific to EBR-II. The net reactivity from all the feedbacks is measurable, however, and in fact has been monitored routinely over the life of the reactor. These data can be used to force the parameter uncertainty propagation to be consistent with the observed feedback characteristics. In this step the data are used to construct a pdf or a range for the net feedback under the various experiment conditions. These are used as constraints in Step 7.

Step 6. Compute Response Surfaces

A response surface is needed for each transient type retained after the initiator screening. A surface is also needed for each type of feedback experiment that is used to constrain the uncertainty propagation. An appropriate polynomial form is chosen for each surface and the polynomial coefficients are determined from transient solutions corresponding to judiciously selected values of the input parameters.

Step 7. Propagate Uncertainties

Once the polynomial coefficients are known, determining the transient outcome corresponding to any set of input parameters is simply a matter of evaluating the polynomial with that set of parameters. The sets of input parameters, which we call knot points, are selected randomly from the parameter pdfs. Rejection criteria are imposed in this Monte Carlo sampling so that the knot points retained reproduce the experimentally observed distributions of feedback characteristics. The retained knot points, when used with the transient outcome surfaces, yield well defined outcome pdfs.

Step 8. Assess Accuracy of Failure Probabilities

Sensitivity calculations are done to assess the reliability of the failure probability predictions. These calculations evaluate the error due to parameter screening, the sensitivity to input parameter pdfs and the accuracy of the response surfaces.

APPLICATION OF THE METHOD

The PROSA-2 code[12] provided the framework for the response surface analysis. In Step 6 it was used to identify appropriate knot points to use in the explicit transient calculations. These transient calculations were made with the SASSYS code[13]. Once the transient solutions were available, the response surface coefficients were computed with PROSA-2. Then it was used to carry out the uncertainty propagation and failure probability calculation of Step 7. The code was modified to implement the experimental constraints in this step.

STEP 1 SCREEN INITIATORS

The uncertainties in the three quasi-static parameters, which reflect the passive feedbacks, were propagated through the quasi-static reactivity balance equation[1]. Experimental information about these parameters was combined with calculated values in the literature (e.g., Ref. 14) to construct pdfs for the parameters. The Monte Carlo uncertainty propagation capability of PROSA-2 was used to propagate the parameter pdfs.

The list of ATWS events to consider was defined in the EBR-II PRA. The screening results for these events are as follows:

* Loss Of Heat Sink - The failure probability is totally negligible. This quasi-static result is consistent with the actual demonstration of the EBR-II plant response to a LOHS initiator[6], which had a completely benign outcome.
* Pump Overspeed - The failure probability again is totally negligible. The asymptotic power-to-flow ratio is always less than unity so the temperatures do not increase. The pump run-up tests in EBR-II confirm this prediction[8].
* Loss Of Flow - A detailed passive safety analysis is needed. The quasi-static analysis shows that the asymptotic temperatures are benign with a very high probability. However, the real danger in a LOF accident occurs during a transient peak, which is not addressed in that analysis. Past safety analyses suggest that the failure probability should be low for long pump coastdowns and high with

short coastdowns. The plant experiments demonstrated that there is no damage if the coastdown time is sufficiently long[6].

- Loss Of Normal Power - A detailed passive safety analysis is needed. This accident is a long coastdown LOF followed by a LOHS. The latter phase is definitely benign. There was no damage in the SHRT 45 experiment[6], which simulated this accident, but less favorable conditions are possible.
- Transient Overpower - A detailed passive safety analysis is needed. The probability of fuel-clad eutectic formation appears to be high but extensive fuel melting may not occur.

All the remaining steps of the analysis have been carried out for LONP but Steps 6 and 7 need to be completed for LOF and transient overpower initiators.

STEP 2 CALIBRATE MODELS

Established, previously validated SASSYS models of EBR-II[15] were reevaluated based on data in the literature and additional experiments. Only the core and primary loop models are important on the time scale of interest here. Fuel conductivities and nominal feedback reactivity coefficients were revised based on an evaluation of values reported in the literature.

The bowing reactivity feedback model was also revised based on a large number of power reactivity decrement (PRD) experiments. This is an important feedback because it is the only one that can be positive and it can be more than 40% of net feedback (although it is typically ~15%). Since EBR-II's design is such that bowing is difficult to calculate from first principles, an empirical approach is usually taken, as was done here. Physical reasoning and evidence from 50 PRD measurements indicate that the bowing feedback slope is initially negative, changes to a positive value around 20 MWt and maintains that value until the vicinity of full power (62.5 MWt). In this vicinity the slope often starts to decrease and eventually it must become negative again. The new model incorporates the first two features but continues the second slope indefinitely beyond full power. This is a conservatism prompted by a lack of unambiguous evidence for the location of the second slope change. Nominal values for the new bowing model input parameters were derived from the difference between the nominal calculated nonbowing PRD versus power and the average of the 50 PRD measurements.

The modified EBR-II model in SASSYS yields improved agreement with PRD, rod drop and passive safety demonstration experiments. Results for SHRT 45[6], a LONP demonstration experiment, illustrate this. For this experiment, the prediction of peak feedback reactivity using the consequence analysis model is low by 10% and the model improvements reduced this error to less than 3%.

STEP 3 SCREEN PARAMETERS

There are three classes of candidate parameters. One is modeling parameters, such as the number of channels and time step size. Selected values are such that parameters in this class are relatively unimportant. Modeling assumptions also should be considered here. The calibration step greatly reduced this uncertainty and no residual effect was identified as being likely to cause a substantially optimistic failure probability estimate. The second class is parameters that affect the predicted material expansions - such things as thermal conductivity and expansion coefficients. The third class is reactivity coefficients of expansion and bowing. Only the third class was treated as uncertain and the uncertainty estimates were increased to cover uncertainties that properly belong to the second class.

The screening of these uncertain parameters was done by importance ranking. The importance of a parameter is the product of the parameter's uncertainty and the sensitivity of the transient outcome to a given change in the parameter. Screening uncertainty estimates for the feedback components were obtained from Ref. 3. Sensitivities were deduced from edits of component contributions to feedback reactivity histories in SASSYS calculations of each transient type. Of the 10 feedbacks in the SASSYS EBR-II model, four of these were found to be unimportant to all transients relevant to the detailed failure analysis. The feedbacks that are important to a transient or constraining quantity are identified by an "x" in Table 1. RDF in the table refers to constraining experimental quantities described under Step 5.

STEP 4 QUANTIFY PARAMETER UNCERTAINTIES

A normal distribution was selected for all of the retained parameters except fuel expansion. The parameters for all the feedbacks except bowing physically cannot change sign. This creates an asymmetry or skewness in the true distribution. However, except for fuel expansion, neglect of this effect introduces only a minor conservatism because this physical limit is more than four standard deviations from the mean. A log-normal distribution was used for the fuel expansion parameter, whose mean is 3.0 standard deviations from zero. Specification of the mean and standard deviation for each parameter is sufficient to complete the uncertainty quantification. Mean values are those developed in the evaluation of feedback parameters in Step 2.

The standard deviation estimates for the feedback components are based on an evaluation of the following sources: uncertainty estimates in the literature[3,16,17], the range of feedback values in the literature[16,18] and evidence from critical experiments[19,20]. Reference 16 values are smaller than the others, apparently because of an attempt to be consistent with the range of EBR-II PRD values. The spread in reported EBR-II feedback values primarily reflects the effect of core loading variations and some evolution in analysis methods, which make up only part of the total uncertainty. C/Es (ratios of calculated to experimental values) from Ref. 19 are based on more sophisticated neutronics analysis than that used to obtain EBR-II feedbacks and they do not include thermo-mechanical uncertainties. Table 2 shows the standard deviation values used here as well as related quantities from the literature.

Only a limited accounting for correlations among the uncertain parameters was made. The strongest correlation is among core Na, upper reflector and radial reflector feedbacks because they all are sodium density effects. This correlation was treated by expressing each of these as a product of two factors, one of which is common to all three feedbacks. Other correlations are less clear and were neglected.

STEP 5 DEVELOP EXPERIMENTAL CONSTRAINTS

The experimental constraints should allow the full distribution of feedback reactivities that EBR-II can exhibit but exclude feedback values that are unrealistic. Two types of experiments that reveal feedback properties have been performed often enough over the years to meet these criteria.

One is the PRD measurement, which yields the total feedback reactivity from hot zero power to full power. The PRD includes both prompt and slow feedbacks and has been measured at every subrun (a Technical Specification requirement). Fifty measurements made over the last ten years were selected to construct a pdf for the full-power PRD. The selection spans a wider range of core loadings than is anticipated for the future and includes the most extreme PRD values ever observed.

The other type of experiment used is the rod drop measurement of prompt feedback reactivity. This reactivity grows rapidly with time for a little more than a second, then the slope decreases and eventually an asymptotic value is approached. The feedback reactivities at 1.5 s and 8.0 s divided by the magnitude of the rod drop reactivity, called RDF(1.5) and RDF(8.0), respectively, were selected as constraining quantities. These two quantities and the PRD each emphasize feedbacks with different time constants. Not enough rod drop data were readily available to construct pdfs but limits on acceptable values of RDF(1.5) and RDF(8.0) were set.

STEP 6 COMPUTE RESPONSE SURFACES

Scoping calculations indicated that the "single-quadrant" response surface scheme[12] in PROSA-2 gives solutions of adequate accuracy for the least computational effort and it was selected on that basis. In this scheme one multivariate quadratic polynomial is used over the entire space. A minimum number of knot points is used with a multivariate extension of Lagrange interpolation to determine the polynomial coefficients. For LONP there are 6 uncertain parameters associated with the five important feedbacks, which implies 28 knot points. LONP, PRD and RDF transient calculations with SASSYS were needed for each knot point.

The single-quadrant scheme systematically selects knot points in a way that emphasizes the wings of the parameter distributions. This tends to make the response surface approximation most accurate in the domain that is of greatest importance to the passive safety failure probability. Knot points representing the parameter extremes were chosen such that 0.5% of the area under the pdf lay beyond the point (2.6 standard deviations from the mean for normal distribution).

The restriction that output quantities must behave smoothly enough to be well represented by a quadratic is easily satisfied by the PRD and RDF constraint quantities. This restriction did preclude using clad failure life fraction to monitor failure but top-of-core sodium or cladding temperatures proved to be good choices.

STEP 7 PROPAGATE UNCERTAINTIES

The scheme to impose the experimental constraints from Step 5 involves two parts. The first part begins with random selection of knot points from the parameter pdfs. For each random knot point RDF(1.5), RDF(8.0) and PRD are computed from their response surfaces. If any of these is outside the experimental range, the point is rejected. Otherwise the knot point is stored, according to the PRD value, in one of five files (bins). Each bin corresponds to an interval of the five-interval histogram that is the experimental PRD pdf. The five PRD bins are filled with knot points in this manner. 23% of the knot points were rejected for being outside the experimental ranges.

In the second part, the response surface equations for the transient outcome quantities are evaluated at knot points drawn from the PRD bins. The bin from which a knot point is drawn is selected by randomly sampling from the PRD cumulative distribution function (the integral of the PRD pdf).

An importance sampling scheme was included in the second part in order to define better the tail of the outcome distributions corresponding to failure. Failures come mostly from the PRD bin corresponding to the lowest PRD values since this implies the weakest net negative feedback. The number of points to draw from a bin each time it is selected can be specified; the weight associated with the point is the inverse of that number. This reduced the statistical variance of the minor core damage (defined below) probability by a factor of 4.6, for a given amount of computation time.

Two damage states defined in the EBR-II PRA are used here. Minor Core Damage (MCD) is defined as fuel melting, cladding failure or sodium boiling in the hottest, highest burnup driver subassemblies. Core Damage (CD), the most severe category, is indicated by fuel melting, cladding failure or boiling in an <u>average</u> driver subassembly.

Failure probabilities for LONP were computed three ways to see the effect of the experimental constraints. First no constraints were imposed, then only the PRD constraints were used and finally PRD and rod drop constraints were used. The resulting failure probabilities are shown in Table 3 and the outcome distributions for MCD are shown in Figure 1. The nominal SASSYS calculation of this accident yielded peak sodium temperature below, but close to boiling. Thus it is not surprising that the passive safety failure probability for MCD is as large as 0.14 without experimental constraints. The imposition of the experimental constraints reduces the MCD probability by more than an order of magnitude. The rod drop constraints add very little to the PRD effect for this accident, perhaps because of the long time scale of the accident. Very few samples yielded CD outcomes when there were no experimental constraints and none did with the constraints. Consequently, the non-constraint estimate of $2x10^{-4}$ has a large statistical uncertainty and the estimates with constraints are really just upper bounds.

STEP 8 ASSESS ACCURACY

A conservative upper bound was found for the error due to screening out parameters from the uncertainty propagation (Step 3). This was done by recomputing the LONP failure probabilities with only the two most important parameters treated as uncertain and comparing these with the reference results (6 uncertain parameters). The bound for each damage category is 19% for MCD and one order of magnitude for core damage. (It is generally true that errors and uncertainties become a larger percentage of the failure probability as the failure probability gets smaller.) The actual error from the parameter screening is small compared to these bounds, since the four parameters dropped for this test are much more important than the ones screened out in Step 3.

The accuracy of the single-quadrant response surface approximation was investigated by comparing it to more accurate approximations on a simplified version of the LONP problem. The simplification was to treat only the two most important parameters as uncertain, as in the test above. This made it feasible to trace out the true functional relationship with many more knot points and use higher order and more flexible polynomials.

The following conclusions were drawn from the response surface investigation. The uncertainty for the experimentally constrained MCD probability is less than a factor of 2. No CD failures were found in the experimentally constrained Monte Carlo sampling. Any reasonable extrapolation of that distribution would yield a CD probability many orders of magnitude less than the $2x10^{-4}$ value obtained with unconstrained sampling. Thus, although the investigation showed that single-quadrant probability estimates in the 10^{-4} to 10^{-7} range are two orders of magnitude too small, it still is very likely that the true, experimentally constrained CD probability is less than 10^{-4}.

The sensitivity to assumptions about the parameter pdfs was computed with the aim of finding plausible upper bounds on failure probabilities. Assumptions as pessimistic as experimental evidence and common sense would allow were made. First, different statistical distribution functions (log-normal and beta) were tried, without changing the mean and standard deviation. The distributions were skewed to the pessimistic side by postulating a bound (for which there is no evidence) as close as three standard deviations from the mean.

Next, three cases were run where the mean or standard deviation was allowed to change. In one, the standard deviation of the most important parameter was increased by 30% of its original value. In another, all standard deviations were increased by 25% of their original values. Finally, all means were moved one standard deviation in the pessimistic direction. This last case was exposed by the experimental constraining process as being hopelessly in conflict with the PRD and rod drop data.

The pdf sensitivity results are similar to those from the response surface tests. The MCD probability could increase by no more than a factor of two. The experimentally constrained CD probability remains below 10^{-6} for all assumptions.

DISCUSSION

This is the first explicit treatment of reactivity feedback effectiveness in a PRA. There had been no strong need for such a capability, since reactivity feedbacks generally are not able to prevent core damage in the reactors previously subjected to a PRA. In contrast, EBR-II and the Integral Fast Reactor designs[1] have passive safety characteristics that greatly reduce the likelihood of core damage in a wide range of unprotected accidents. Thus a probabilistic approach had to be developed to incorporate this feature into the EBR-II PRA.

The method incorporates established probabilistic techniques. Screening, response surfaces and Monte Carlo sampling are used. The overall approach is similar to those used in recent probabilistic treatments of transients[9,10]. The selected combination of available techniques is both effective and computationally efficient.

Two factors greatly simplified the task of computing failure probabilities. One is that the balance of plant is unimportant[2], making necessary only the modeling of the core and primary sodium loop. The other factor is that the damage category definitions in the PRA made it unnecessary to model the progression of core disruption. This eliminated concerns about the complex models and highly uncertain data associated with these processes. It also eliminated the more complex behavior of transient outcome quantities that occurs during core disruption, making the response surface approximation more suitable.

The EBR-II feedbacks are well understood and, with one exception, they are relatively easy to predict. There is no close competition between opposing feedbacks and even the sodium density effect, which is by far the strongest feedback, does not suffer from a close balance between opposing spectral and leakage effects. As a result, the best estimate values and the uncertainty estimates developed in Step 4 should be reliable. A conservative model was used to deal with bowing, the one feedback that is quite difficult to predict accurately.

The failure probabilities were reduced substantially by integrating the extensive EBR-II experimental database into the method. The computed failure probability reflects both the range of possible reactor conditions and the limits of our ability to predict the transient outcome. By using the experimental data, a powerful source of knowledge is brought to bear, which markedly increases our ability to predict the transient outcomes. The inherent safety demonstration experiments were used in the initiator screening and they provided benchmarks for calibrating the methods and models used to predict responses. The calibration process minimized what would have been a major source of uncertainty, one that is difficult to quantify and propagate. Experiments that measured feedbacks were used to constrain the feedback parameter uncertainties being propagated to be consistent with the observed feedbacks. The effectiveness of this last feature was illustrated by the drop in the LONP minor core damage probability from 0.143 to 0.012 when the constraints were applied.

The LONP results demonstrate that reactivity feedbacks provide a large safety margin. The conditional damage probability is 10^2 for the hottest driver element and is less than 10^4 for widespread fuel damage. These probabilities would be unity for all the initiators retained in the screening if there were no feedbacks. A large margin is also anticipated for LOF and transient overpower. This margin is in addition to the large safety margin, $\approx 10^4$, afforded by the scram system.

There are three areas of future work. One is completion of the analysis for LOF and transient overpower initiators. Another is development of an approach to estimate better very small failure probabilities, such as the LONP core damage probability. Finally, the method needs to be adapted for assessing Integral Fast Reactor designs, where there are only indirect experimental data on the passive response.

REFERENCES

1. D. C. Wade and Y. I. Chang, "The Integral Fast Reactor (IFR) Concept: Physics of Operation and Safety," Proc. Int. Topl. Mtg. on Advances in Reactor Physics, Mathematics and Computation, Paris, France, April 27-30, 1987.

2. D. J. Hill et al., "An Overview of the EBR-II PRA," Proc. 1990 Int. Fast Reactor Safety Meeting, Snowbird, UT, August 12-16, 1990, Vol. IV, p. 33, American Nuclear Society (1990).

3. C. J. Mueller and D. C. Wade, "Probabilities of Successful Inherent Shutdown of Unprotected Accidents in Innovative Liquid Metal Reactors," Proc. Int. Topl. Mtg. Safety of Next Generation Power Reactors, Seattle, WA, May 1-5, 1988, p. 704, American Nuclear Society (1988).

4. R. H. Meyers, Response Surface Methodology, Allyn and Bacon, Inc., Boston (1971).

5. R. L. Iman and J. C. Helton, "A Comparison of Uncertainty and Sensitivity Analysis Techniques for Computer Models," NUREG/CR-3904, SAND84-1461, Sandia National Laboratories (1985).

6. H. P. Planchon et al., "Implications of the EBR-II Inherent Safety Demonstration Test," Nucl. Engrg. Des., 101, p. 75 (1987).

7. G. H. Golden, Evolution of Thermal-Hydraulic Testing in EBR-II," Nucl. Engrg. Des., 101, p. 3 (1987).

8. W. K. Lehto et al., "Reactor Safety Implications of Pump Run-Up Tests in EBR-II," Nucl. Engrg. Des., 110, p. 47 (1988).

9. M. Khatib-Rahbar et al., "A Probabilistic Approach to Quantifying Uncertainties in the Progression

of Severe Accidents," Nucl. Sci. Eng., 102, p. 219 (1989).

10. R. S. May et al., "Probabilistic Methods for Evaluating Operational Transient Margins and Uncertainties, Nucl. Sci. Eng., 103, p. 81 (1989).

11. R. H. Sevy, private communication, Argonne National Laboratory, October 1985.

12. J. K. Vaurio, "PROSA-2: A Probabilistic Response-Surface Analysis and Simulation Code," ANL-81-33, Argonne National Laboratory (1981).

13. F. E. Dunn et al., "The SASSYS-1 LMFBR System Analysis Code," Proc. Int. Topl. Mtg. on Fast Reactor Safety, CONF-850410, Knoxville, TN, p. 999, April 1985.

14. D. Meneghetti and D. A. Kucera, "Delineations of Power, Power-to-Flow and Inlet-Temperature Feedbacks of EBR-II," Ann. Nucl. Energy, Vol. 17, No. 1, p. 19, (1990).

15. J. P. Herzog, "SASSYS Validation with the Shutdown Heat Removal Tests, Fifth Proc. Nuclear Thermal-Hydraulics, San Francisco, CA, Nov. 26-30, 1989.

16. L. K. Chang and D. Mohr, "The Effect of Primary Pump Coastdown Characteristics on Loss-of-Flow Transients Without Scram in EBR-II," Nucl. Engrg. Des., 97, p. 49 (1986).

17. Ph. Bergeonneau et al., "Uncertainty Analysis on the Measurements and Calculation of Feedback Reactivity Effects in LMFBR. Application of Super-Phenix-1 Startup Experiments," 30th NEACRP Meeting, Helsinki, Finland, September 1987, NEACRP-A-833 (1987).

18. D. Meneghetti and D. A. Kucera, "Comparisons of PRD Components For Various EBR-II Configurations," Ann. Nucl. Energy, 14, No. 9, p. 473 (1987).

19. R. W. Schaefer, "Critical Experiment Tests of Bowing and Expansion Reactivity Calculations for Liquid-Metal-Cooled Fast Reactors," Nucl. Sci. Eng., 103, p. 196 (1989).

20. C. L. Beck et al., "Sodium Void Reactivity in LMFBRs: A Physics Assessment," Proc. Topl. Mtg. Advances in Reactor Physics and Core Thermal Hydraulics, Kiamesha Lake, NY, September 22-24, 1982, NUREG/CP-0034, Vol. 1, p. 78 (1982).

Table 1. Important Feedbacks for Transients and Constraints

	Core Na	Fuel	Up. Refl.	Rad. Refl.	Control	Bowing
LOF, LONP	x		x	x	x	x
TOP	x	x	x	x	x	x
PRD	x	x	x	x	x	x
RDF(1.5)	x	x	x			
RDF(8.0)	x	x	x		x	x

Table 2. Feedback Uncertainties and Related Quantities

Feedback	Standard Deviation				C/E
	this work	Ref. 5	Ref. 9	Ref. 11	Ref. 12
Core Na	20%	6%	20%	30%	10%
Fuel	33%	11%	30%	47%→58%	1%→16%
Up. Refl.	30%	7%	20%	30%	
Rad. Refl.	25%		20%	30%	
Control	23%	5%	20%		10%
Bowing	70%	25%	15%→60%		1%→42%

Table 3. Passive Safety Failure Probabilities for LONP Accidents[a]

	Minor Core Damage	Core Damage
No Constraints	0.143 ±0.2%	2.0×10^{-6} ±70%
Only PRD Constraints	0.013 ±1.7%	$< 10^{-6}$
PRD and RDF Constraints	0.012 ±1.1%	$< 10^{-6}$

---

[a] The uncertainties shown reflect only Monte Carlo statistics.

Fig. 1. LONP Outcome Distribution For Minor Core Damage