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A PROBABILISTIC ANALYSIS OF RAPID BORON DILUTION SCENARIOS*

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ABSTRACT

A probabilistic and deterministic analysis of a rapid boron dilution scenario related to reactor restart was performed. The event is initiated by a loss of off-site power during the startup dilution process. The automatic restart of the charging pump in such cases may lead to the accumulation of a diluted slug of water in the lower plenum. The restart of the reactor coolant pumps may send the diluted slug through the core adding sufficient reactivity to overcome the shutdown margin and cause a power excursion. The concern is that the power excursion is sufficient in certain circumstances to cause fuel damage. The estimated core damage frequency based on the scoping analysis is 1.0-3.0E-05/yr for the plants analyzed. These are relatively significant values when compared to desirable goals. The analysis contained assumptions related to plant specific design characteristics which may lead to non-conservative estimates. The most important conservative assumptions were that mixing of the injected diluted water is insignificant and that fuel damage occurs when the slug passes through the core.

INTRODUCTION

The general objective of the present work was to improve the understanding of rapid boron dilution events in pressurized water reactors (PWRs). Boron dilution events have always been of concern in PWRs. A slow inadvertent dilution due to malfunction of the chemical and volume control system (CVCS) is a design-basis event satisfying stringent acceptance criteria. Beyond-design-basis dilution events may also be postulated[1] by considering failures in addition to a CVCS malfunction.

These beyond-design-basis dilution events may be separated into three types according to the resulting power rise in the reactor core. In the first group, the power excursion is caused by a relatively slow, uncontrolled dilution in which the boron concentration changes slowly throughout the core. This type of event requires a large volume of diluted water. It is relatively easy to analyze as the power increase is determined by a linear reactivity addition, mitigated by feedback effects, until stopped by operator action or fuel damage.

In the second type, the reactor coolant pumps (RCPs) are off and diluted water accumulates in the lower plenum and the bottom of the core becomes critical. As power rises, the natural circulation rate increases drawing diluted water into the core, further increasing power.

The third type of power excursion is caused by a slug of diluted water rapidly entering the core and that is the subject of this study. If the slug of water passed rapidly through the core, the potential exists for causing catastrophic fuel damage, i.e., rapid changes in the fuel geometry, rather than relatively slow fuel melting. Less diluted water is required than in the first type of dilution in which water mixes uniformly with the reactor coolant system (RCS).

A rapid boron dilution event is postulated to occur when two requirements are met. First, unborated or diluted water must enter into the reactor coolant system when there is little circulation and must collect in parts of the system. Second, a reactor coolant pump (RCP) must be started so that a slug of diluted water passes rapidly through the core with the

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potential to cause a power excursion and consequent fuel damage.

The rapid dilution event would occur when the RCPs are not running as would be the situation during a shutdown period. This period is also the time when the core might be more vulnerable to this type of event because control rods are already inserted and, therefore, reactor trip would not be possible to mitigate the power excursion.

In the following, some of the details of the specific probabilistic analysis will be discussed along with a brief summary of the concomitant deterministic analysis. The deterministic studies included the extent of mixing when a source of diluted water is introduced into the RCS. Additionally, a simplified neutronic analysis was carried out to understand the potential consequences of a diluted slug passing through the core. This included static calculations of reactivity for different slug geometries and dilutions and dynamic calculations of the power excursion due to the passage of the diluted slug through the core.

ANALYSIS

One particular scenario which could occur during reactor startup was recently studied in Europe and discussed in an NRC information notice[2]. The reactor is being brought back to a critical configuration by deboration with the RCS at hot, pressurized conditions and the shutdown banks withdrawn.

The initiating event is a postulated loss of off-site power (LOOP) with a subsequent reactor and RCP trip. Even though the charging pumps would stop, it is assumed that emergency power is brought quickly on line reconnecting the pumps to the emergency buses. The pumps will continue to take their suction from the volume control tank (VCT), injecting diluted water into the RCS. Assumptions are made that the operator takes no action to switch to a boration mode, and that the VCT contains a relatively large volume of water which is at a boron concentration that is much less than that originally in the RCS.

The diluted water may be colder than the RCS and after it is pumped into the cold-leg it may not mix very well so that the water can collect as a diluted slug at the bottom of the reactor vessel. The probability of minimal mixing is enhanced if the event takes place after a long refueling when the decay heat level is low and consequently the amount of natural circulation in the RCS is relatively low.

If off-site power is recovered, it is likely that the operator will start an RCP to continue the startup operations. This will send a slug of diluted water through the core, potentially leading to fuel damage. A probabilistic analysis has been done for this event for a European PWR. The estimated core damage frequency (CDF) was found to be high enough so that corrective actions were taken and a program of analysis and experimentation was initiated regarding the effect of mixing on the creation of the slug. The corrective action was a hardware change which would switch the suction of the charging pumps to the refueling water storage tank (RWST) when there was an RCP trip. Since the boron concentration in the RWST is very high this would eliminate the possibility of the dilution accident.

In order to analyze the potential contribution to the CDF, a probabilistic scoping assessment of this scenario was done for three PWRs representative of the three U.S. reactor vendors, B&W, CE and W. The analysis was done for the reactor start up scenario to understand not only important system and operator actions, but also to identify any major differences that might exist between plants designed by the each of the U.S. PWR vendors.

For each plant the systems through which unborated or diluted water might enter the RCS was analyzed together with the electrical supply system. A probabilistic analysis was developed including the actual timing, modeling and quantification of the relevant actions. The quantification was done separately for refueling and nonrefueling outages.

During startup of the reactor, the operator has to deborate the RCS from shutdown boration level to achieve criticality. The dilution requires adding a predetermined amount of demineralized water to the RCS through the letdown storage tank.

The rate of addition of deborated water may be as much as or less than the letdown flow. The volume of the batch size is generally larger than the VCT which requires the operator to divert some of the letdown flow into the purification system. Consequently, the boron concentration in the VCT may decrease as demineralized water is being added. If the transfer rate is slower than the makeup rate through the charging pumps then the VCT level is maintained by the combination of partial letdown and dilution flow into the tank.

As a result of this process the following system conditions may be obtained:

1 - The VCT volume is diluted to low boron concentrations by adding demineralized water.

2 - Depending on the demineralized water transfer rate or dilution rate, the boron concentration may be as low as 0-200 ppm or may range to a maximum of about 50% of the RCS boron concentration, i.e., 1000-1200 ppm.

3 - The water level in the VCT is maintained at an intermediate position during the deboration operation.

Therefore, there is a substantial amount of diluted water stored in the VCT, which is available for injection into the RCS following a restart of the RCP after a LOOP event.

In general, the important features of the electrical system may be summarized as follows:

1 - Loss of grid events usually lead to the trip of the RCPs and normally there is not sufficient backup power to restart the pumps. The RCPs may be restarted only if off-site power sources recover.

2 - The charging pumps and instrument air compressors are normally sequentially loaded to the emergency power sources and after a loss of off-site power event this equipment is restarted in about 0.5-1. minute.

The outcome in a boron dilution scenario is strongly dependent on the timing of events or the time evolution of the expected responses. The normal deboration process itself is rather time consuming due to the small makeup and letdown flow relative to the total RCS volume. The change in the RCS boron concentration (C) can be calculated using

$$\frac{dC}{dt} * V_{RCS} = W_M * C_M - W_L * C_L$$

where V_{RCS} is the volume of the RCS, C_M and C_L are the boron concentration of the makeup and letdown, respectively, and W_M and W_L the makeup and letdown flow rates, respectively. The initial boron concentration will exponentially be diluted to the final boron concentration as a function of time. The solution of this equation and the average length of deboration as estimated by station operators were consistent and in the range of 5-12 hours depending on the actual actions occurring during the start up process.

The available diluted water volume that can be injected into the RCS was estimated by simple balance calculations and assuming typical pumping rates. The probability for conditional core damage P(CCD) was defined in order to determine the time-dependent probability that there is core damage once injection starts into the RCS while there is no longer forced circulation. For the situation after refueling, it is assumed that P(CCD) varies linearly between zero and one depending on the amount of diluted water that enters the system. The value of zero is expected at the beginning of the time period when no diluted water has entered under the relatively stagnant flow conditions. The value of one is associated with the assumption that if the full diluted volume of the VCT is injected into the cold leg, a sufficiently diluted region will accumulate in the lower plenum so that fuel damage with the restart of an RCP is certain.

After the suction source of the charging pumps switches to the RWST (on low level in the VCT) the potential for core damage decreases since borated water is injected and presumably mixes with the diluted water. It is, therefore, further assumed that after a period of time the P(CCD) will decrease linearly to zero and there is no longer the possibility of a rapid dilution event occurring if an RCP is restarted.

The time dependence of P(CCD) is shown in Figure 1 for one of the three reactors modeled. The bottom curve is for startups other than after refueling where the decay heat is expected to be much larger increasing the natural circulation rate. If the natural circulation flow rate is sufficiently large then after injection of diluted water there may be sufficient mixing to reduce the probability that there will be core damage and this is taken into account by decreasing P(CCD) by a factor of 0.5 as indicated.

The RCP restart action was also modelled as a function of time. Once a power source is available, the operators are expected to start the RCPs, since the preferred method of operating at this stage of the startup is to keep forced circulation in the RCS. The actual time dependent behavior was established based on discussion with operators and plant startup

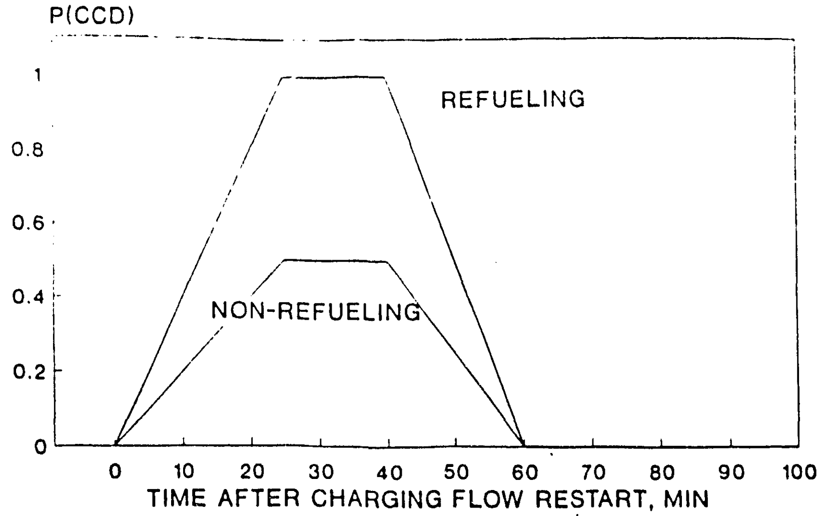


Figure 1 Conditional Core Damage Probability

procedures.

Plant specific event trees were developed as indicated in Figure 2, to evaluate the different accident sequences, in particular those leading to core damage due to rapid dilution. The top events question the availability of the electrical power supplies and the charging function as well as the potential for recovery. In addition, the conditional probability of core damage P(CCD) is included and the final top event questions the availability of the RCP.

The time dependence is modelled in the event tree by calculating the contribution of each sequence in each time period (t, $t+\Delta t$) and then summing for the total time in which there is core damage potential. The probability at a given time P(CCD) is obtained using the distributions shown in Figure 1 and the other distributions are similarly derived from the other time functions. In the case of cumulative distributions, like the RCP restart, the derivative of the time dependent distribution was used.

The evaluation of the time dependent CD sequences involve a convolution integral of the form

$$Seq.\text{-}CDF = \int_t dt\, P_1(t) \int_{t'} dt'\, [P_2(t')....]$$

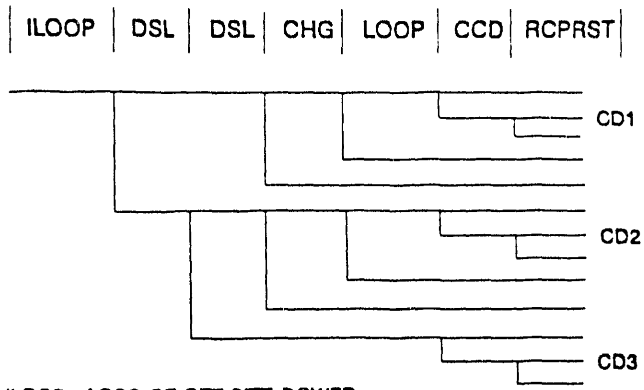
with the appropriate probabilities. For simplicity, the time dependence of the various probability terms were either assumed constant or at most linearly varying over the respective time periods.

The results of the scoping analysis for the three plants are given in Table 1 which indicates the expected CDF along with the initiating frequency used in the analysis. The CDF is similar for all three plants and in the range considered significant.

These results are dependent on plant design and various assumptions made during the study. The important ones are as follows:

1 - The dilution time during start-up is ~8 hrs. The consequences of the event are independent of when the loss of off-site power occurs during this period. In reality, an event occurring early in the period will have more shutdown margin to overcome and this is expected to have less of an effect than an event occuring near the end of the normal dilution procedure.

2 - For all three plants the dilution is done through the VCT. There are plants where the dilution flow is introduced directly to the charging pump suction and these have no potential for adding unborated water to the RCS.



ILOOP - LOSS OF OFF-SITE POWER
DSL - DIESEL GENERATOR FAIL TO START
NRAC DSL - NON-RECOVERY OF DIESELS
CHG - CHARGING PUMPS FAIL TO OPERATE
NRAC LOOP - NON-RECOVERY OF OFF-SITE POWER
CCD - CONDITIONAL CORE DAMAGE
RCPRST - RCP'S RESTARTED BY OPERATOR

FIGURE 2. BORON DILUTION EVENT TREE

3 - The potential for an accident is limited by the amount of diluted water in the VCT as the supply of primary grade water is stopped by a supply pump. There are plants where the primary grade water supply pump is connected to the emergency bus and the probability of the accident will be increased if primary grade water continues to be pumped into the VCT and RCS.

The analysis was augmented by mixing and neutronics calculations which seem to indicate that the probabilistic analysis may lead to relatively conservative results[3]. The main results of the mixing analysis were that the boron concentration in the lower plenum was not expected to be lower than 1080 or 900 ppm for the two plants analyzed, respectively, assuming (in both cases) that the boron concentration in the RCS at the time of the loss of off-site power event was 1500 ppm. This means that the reactivity addition would correspond to a change of only 400-600 ppm rather than the 1500 ppm that was theoretically possible.

The neutronic calculations indicate that the slug boron concentration would have to be less than 430 ppm for catastrophic fuel damage to occur if the shutdown margin was 4% and the Doppler feedback was relatively strong. If the shutdown margin is smaller or if the core has a smaller Doppler feedback, then a smaller dilution would cause a problem. These factors vary significantly during a fuel cycle and for different cycles so that it can have an important effect on the results.

SUMMARY

The analysis of a rapid boron dilution event has been carried out using probabilistic, mixing and neutronics calculations. The probabilistic analysis, discussed in this paper, was completed for three U.S. reactor vendors. The CDF varies from about 10^{-5} to $3x10^{-5}$ per reactor year which is in the range of other internal events considered significant.

The analysis shows the importance of the primary grade water pump. The potential for an accident is limited by the amount of diluted water in the VCT as the supply of primary grade water is stopped by the trip of the supply pump. The mixing and neutronic calculations indicate that the results of the probabilistic analysis may be too conservative. The results will be a function of plant design and of particular importance are the volume and boron concentration of the VCT, the pumping rate of the

TABLE 1
SUMMARY of Core Damage Frequencies

	B&W PLANT		CE PLANT		W PLANT	
	INIT FR /YR	CDF /YR	INIT FR /YR	CDF /YR	INIT FR /YR	CDF /YR
REFUELING	4.9E-05	1.1E-05	6.0E-05	7.5E-06	6.0E-05	3.7E-06
NON-REFUELING	1.6E-04	1.8E-05	2.0E-04	1.3E-05	2.0E-04	6.1E-06
TOTAL		2.8E-05		2.0E-05		9.7E-06

charging flow, the mixing in the cold leg and downcomer, and the shutdown reactivity margin.

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