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Probability and Consequences of a Rapid Boron Dilution Sequence in a PWR[1]

D. J. Diamond
P. Kohut
H. Nourbakhsh
K. Valtonen[a]
P. Secker[b]
Brookhaven National Laboratory
Department of Advanced Technology
Upton, NY 11973-5000

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Background

The reactor restart scenario is one of several beyond-design-basis events in a pressurized water reactor (PWR) which can lead to rapid boron dilution in the core. This in turn can lead to a power excursion and the potential for fuel damage. The scenario occurs during the period when the reactor is being deborated according to normal procedures so that criticality can be achieved. A loss of offsite power (LOOP) is the initiating event. When this occurs, there is reactor trip (the shutdown banks would be withdrawn during deboration) and trip of the charging pumps and the reactor coolant pumps (RCPs). Emergency power is brought on-line quickly, and the charging pumps are energized from the emergency bus. The RCPs remain tripped. It is assumed that the volume control tank (VCT), which supplies the suction for the charging pumps, is filled with a large volume of highly diluted water. This water continues to be pumped into the reactor coolant system (RCS), if the operator takes no action to switch the suction to a borated source. Since the RCPs are not running, if the natural circulation flow rate is low (e.g., soon after a refueling), there is the potential for a slug of diluted water to accumulate locally in the RCS.

The next event in the scenario is the start of an RCP. This only happens after offsite power is restored. It is assumed that the operators will start the RCP in order to resume the restart procedure. When this occurs, it is assumed that the slug passing through the core adds sufficient reactivity to overcome the shutdown margin and cause a power excursion. Furthermore, the concern is that the power excursion is sufficient to cause fuel damage.

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[a]Finnish Centre for Radiation and Nuclear Safety, Helsinki, Finland

[b]Department of Nuclear & Energy Engineering, University of Arizona, Tucson, Arizona

A probabilistic analysis had been done for this event for a European PWR. The estimated core damage frequency was found to be high partially because of a high frequency for a LOOP and assumptions regarding operator actions. As a result, a program of analysis and experiment was initiated and corrective actions were taken. A system was installed so that the suction of the charging pumps would switch to the highly borated refueling water storage tank (RWST) when there was a trip of the RCPs. This was felt to reduce the estimated core damage frequency to an acceptable level. In the U.S., this original study prompted the Nuclear Regulatory Commission to issue an information notice[1] to follow work being done in this area and to initiate studies such as the work at BNL reported herein.

In order to see if the core damage frequency might be as high in U.S. plants, a probabilistic assessment of this scenario was done for three plants. Two important conservative assumptions in this analysis were that (1) the mixing of the injectant was insignificant and (2) fuel damage occurs when the slug passes through the core. In order to study the first assumption, analysis was carried out for two of the plants using a mixing model. The second assumption was studied by calculating the neutronic response of the core to a slug of deborated water for one of the plants. All three types of analyses are summarized below. More information is available in the original report.[2]

Probabilistic Analysis

The plants chosen--Oconee, Calvert Cliffs, and Surry--represent a sample from the three U. S. reactor vendors: Babcock & Wilcox, Combustion Engineering, and Westinghouse, respectively. An example of the event trees developed for each of these plants is the one shown in Figure 1 for Calvert Cliffs.

The first top event, ILOOP, is the loss of offsite power initiator and represents the loss of the electrical grid and/or the two 500 kV and the 69 kV transmission lines.

The next top event, DSL, questions the availability of the emergency diesel generators which would provide backup power for the safety systems but not for the RCPs. The diesel generators may fail to start but could recover after a certain period of time, and this is modelled in the top event NR-DSL or nonrecovery probability of the diesel generators. Note that the top branch (i.e., success) under this event represents recovery of the diesel generators.

The charging pump availability is examined at the top event CHG. The recovery of the offsite power is an important event, and P(NR-LOOP) expresses the probability of nonrecovery in a given time interval and is the lower branch (or failure path) on the tree.

The last two top events are related to the condition of the diluted slug and its potential effect on the reactor core. CCD is conditional core damage given that the diluted water has entered the RCS. The RCPRST top event reflects the probability of restarting the RCPs after the LOOP event recovered.

There are three sequences marked in Figure 1 involving core damage potential. The other sequences are unrelated scenarios that do not involve dilution accidents. The three sequences are summarized as follows:

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Sequence 1: After a LOOP event, the diesel generators start and the charging flow is automatically reestablished. As soon as offsite power is recovered, the operator restarts the RCPs in a time frame of about 30 minutes. The charging flow is reduced to 44 gpm to extend the time window for LOOP recovery before borating the RCS.

Sequence 2: After the LOOP event, the diesel generators fail to start but recover sooner than the offsite power, and charging flow is automatically restarted. After offsite power recovers, the RCPs may start and core damage may result.

Sequence 3: This is similar to Sequence 2 except the offsite power recovers earlier than the diesel generators. Both charging and the RCPs may be started leading to the dilution event.

These sequences were quantified using data for the initiating event and for the various probabilities that were taken from appropriate sources. Startup after both a nonrefueling and a refueling outage was considered. The difference between the two was primarily the different natural circulation rates expected and the resulting different conditional core damage probability.

The results of the analysis for the three plants are given in Table 1 which shows not only the expected core damage frequency (CDF) but also the initiating frequency. The latter was of particular interest because in the analysis done in Europe, the initiating frequency was quoted as being an order of magnitude higher. The CDF is similar for all three plants and in the range considered significant.

Table 1 Summary of Important Frequencies

	OCONEE		CALVERT CLIFFS		SURRY	
	INIT FR /YR	CDF /YR	INIT FR /YR	CDF /YR	INIT FR /YR	CDF /YR
Refueling	4.93E-5	1.05E-5	6.03E-5	7.54E-6	6.03E-5	3.66E-6
Non-Refueling	1.64E-4	1.75E-5	2.01E-4	1.25E-5	2.01E-4	6.08E-6
Total		2.80E-5		2.00E-5		9.74E-6

These results are dependent on plant design and various assumptions used in the analysis. The most important considerations are summarized below. Note that some of them result in overestimating the core damage frequency.

1. The dilution time during startup is eight hours, but in the analysis, the consequences of the event are independent of when during this period the loss of offsite power occurs. In reality, an event occurring early during this period will have more shutdown margin to overcome and is, therefore, expected to have less of an effect than an event occurring near the end of the normal dilution procedure.

2. No credit is given for the operator to take action and stop the charging flow from the VCT after the LOOP. Although dilution while the shutdown banks are inserted or the RCPs are stopped (as would be the case after a LOOP) is not a normal procedure, it is assumed that since the operator knows that the flow from the primary water makeup pump has ceased, that no other action is deemed warranted. An action that could be taken by the operator would be to switch the charging pump suction to the RWST.

3. For all three plants, the dilution is done with flow from the VCT. It should be noted that in some plants the suction for the charging flow comes directly from the primary grade (PG) makeup water source, and once the PG water pump is tripped, there is no longer the potential for adding unborated water to the RCS.

   Oconee: The dilution rate is about the same as the letdown, and the volume in the letdown storage tank is diluted to low boron levels (0-200 ppm). The available volume in the letdown storage tank is about 1900 gal.

   Calvert Cliffs: The dilution rate is matched by the letdown flow rate. The VCT is eventually diluted to a very low boron concentration. The available volume for injection into the RCS is about 2900 gal.

   Surry: The dilution rate is generally lower than the charging rate, and the VCT may get diluted to a very low boron concentration (0-100 ppm). The dilution flow is always directed to the VCT, and bypassing is allowed only during xenon transients. The available volume for injection into the RCS is about 1600 gal.

4. For all three plants, 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 PG makeup pump. However, there are plants where this pump is connected to the emergency bus, and the probability of an accident will be increased if primary grade water continues to be pumped into the VCT. This appears to be the case for some plants in France and Sweden. At the Ringhals plant in Sweden, of three units designed by Westinghouse, two have the PG water pump connected to the emergency bus. The question of whether the makeup pump trips or continues to run has to be evaluated on a unit by unit basis.

5. Refueling outage: The conditional core damage probability is linearly changing between zero and one, corresponding to the amount of diluted water injected into the RCS. Mixing and switchover to a borated source reduces the probability of core damage from one to zero over a short period of time.

   Non-refueling outage: The probability for conditional core damage varies between zero and one-half to account for the potentially higher natural circulation rate and mixing.

   For any outage, the probability of core damage used is expected to be conservative because it does not account for any mixing that may occur (discussed further below).

6. If offsite power, or another adequate power source, is available, the reactor coolant pumps will be started over a 30-minute interval.

Thermal-Hydraulic Analysis

In the probabilistic analysis, the conservative assumption was made that the charging flow, consisting of highly diluted water, does not mix sufficiently with the borated water in the RCS so that a diluted region accumulates in the lower plenum with the potential to cause a power excursion. It is known that there will be some mixing, and, hence, an attempt was made to quantify the extent of this mixing. The analysis assumes that the unborated charging flow is colder than the water in the RCS, and it is injected into the cold leg which is otherwise stagnant or at a low natural circulation flow rate.

The modelling approach is similar to that used in the regional mixing model developed by Nourbakhsh and Theofanous[3,4,5]. That work was in support of the NRC Pressurized Thermal Shock (PTS) study to predict the overcooling transients due to high pressure safety injection into a stagnant loop of a PWR. The analysis includes quantification of mixing (entrainment) at locations where the mixing is expected to be intense, such as at the connection of the charging line to the reactor coolant system and in the downcomer. These mixing models are then used to determine the dilution boundary as a function of time.

Qualitatively, the physical condition may be described with the help of Figure 2. In the absence of loop flow, the relevant parts of the system include the loop seal, pump, cold leg, downcomer, and the lower plenum. Initially, this portion of the primary system is filled with borated water with a boron concentration of ~1500 ppm and at a temperature near that of normal operation (~290°C or ~550°F). The dilution transient occurs with charging pump(s) injecting unborated water into the cold leg at a rate of ~45 to 96 gpm. Typical temperatures of the makeup (charging) flow are 200°C to 260°C (400°F to 500°F) although, depending on the plant and the stoppage of letdown flow during LOOP, lower temperatures, on the order of 70°C (160°F) are also possible.

The ensuing flow regime is schematically illustrated in Figure 2. A "cold diluted stream" originates with the charging buoyant jet at the point of injection, continues toward both ends of the cold leg, and decays away as the resulting buoyant jets fall into the downcomer and pump/loop-seal regions. A "hot stream" flows counter to this "cold diluted stream" supplying the flow necessary for mixing (entrainment) at each location. This mixing is most intensive in certain locations identified as mixing regions (MRs). MR1 indicates the mixing associated with the highly buoyant charging jet. MR3 and MR5 are regions where mixing occurs because of the transitions (jumps) from horizontal layers into falling jets. MR4 is the region where the downcomer (planar) buoyant jet finally decays. The cold streams have special significance since they induce a global recirculating flow pattern with flow rates significantly higher than the charging flow. The whole process may be viewed as the quasi-static decay of the cold diluted stream within a slowly varying "ambient" temperature and boron concentration.

The Regional Mixing Model, which has been developed to study the thermal mixing of interest to pressurized thermal shock, was utilized to assess the extent of boron mixing in the absence of loop flow during a reactor restart scenario. Illustrative reactor predictions for Surry and Calvert Cliffs indicate significant mixing during the boron dilution transients.

Indeed, for the cases considered, the boron concentration in the lower plenum does not fall below 900 ppm. However, these cases do not encompass all possible physical situations for these plants. It would also be desirable to assess the applicability of the model when the temperature of the charging flow is higher, to improve the understanding of mixing when the injectant enters at the side or bottom of the cold leg piping, and to study mixing under low natural circulation flow.

Analysis of Consequences

A synthesis method was used to study the core response. Static 3-dimensional core calculations are combined with point neutron kinetics calculations to determine the power excursion. The static calculations determine the slug reactivity which is input to the power calculation. In lieu of doing detailed boron transport calculations, different slug geometries and boron concentrations are assumed. The slug is assumed to enter the core uniformly across either the entire inlet area or across only a section of the inlet. The slug reactivity is calculated as a function of the position of the slug front, and a constant speed is assumed in order to translate the space dependence into a time dependence.

The neutron kinetics model is combined with a heat conduction model in order to improve the accuracy of the fuel temperature calculation relative to an adiabatic model. This model also calculates the core average fuel enthalpy. At the time at which the fuel enthalpy is at a maximum, the position of the slug front is noted, and the corresponding static calculation is used to determine the power peaking factor. The local peak fuel enthalpy is then calculated by adding to the initial core average fuel enthalpy the increase in core average fuel enthalpy multiplied by the power peaking factor. The local peak fuel enthalpy can then be compared to the criterion for catastrophic fuel damage. This is taken to be 280 cal/g (1.2 MJ/kg) which is the acceptance criterion for design-basis reactivity-initiated accidents calculated for licensing. The enthalpy criterion may change in the future because of concerns about high burnup fuel behavior. In that case, these results could be reinterpreted with the new criterion.

Note that if there is no catastrophic fuel damage, there is still the possibility of release of fission products due to cladding damage either because of stresses caused at lower enthalpies or because of dryout on the surface of the clad. There is also the possibility of a pressure increase that could be excessive under shutdown conditions.

Boron dilution reactivity as a function of time was taken from static calculations for a model representing Calvert Cliffs. The constant speed used for the slug front was 61 cm/s (2.0 ft/s) which corresponds to 13 percent of rated flow. This is an approximation to the flow which would increase from close to zero (assuming little natural circulation) to 20 percent of full flow in about 20 seconds.

A constant negative reactivity representing the initial shutdown margin was used. This is meant to account for the worth of the shutdown banks in the reactor startup scenario and, in general, for any other contribution to shutdown margin that might be present before the dilution begins. In the present calculation, 4 percent shutdown is assumed to be the base initial condition. In Calvert Cliffs, this is approximately equal to the shutdown bank worth, but in other plants, the shutdown worth might be smaller.

Fuel temperature reactivity was calculated during the dynamic simulation using the core average fuel temperature calculated by the model and a Doppler feedback coefficient expressed per unit change in square root of absolute temperature. The Doppler feedback is strongest in the region where the fuel temperature is highest and since the power, and hence the neutron importance, is also highest in this region, it is a gross inaccuracy to represent the Doppler feedback using a core-average fuel temperature. To improve upon the accuracy of the fuel temperature feedback, a Doppler weighting factor (DWF), obtained from static calculations, was applied to the reactivity calculated using the core average fuel temperature.

The power response for a typical event is shown in Figure 3. It consists of a sharp (prompt-critical) power rise after the slug has moved into the core. This is terminated by Doppler feedback. The power then rises again due to the fact that the slug is still passing through the core, and approximately two seconds later the power decreases as the slug leaves the core. There is also a decrease in fuel enthalpy primarily from the fact that there is heat transfer from the fuel into the coolant, and this becomes appreciable in the period after 6 seconds. Note that when there is a large amount of energy transferred into the coolant, the model is no longer applicable. Two-phase flow would be expected, and significant negative feedback from the coolant would affect the response of the fuel rods. Although this was not modeled in this calculation, the peak fuel enthalpy was calculated during the period of 5-6 seconds when the core average fuel enthalpy reaches a peak.

These results will be most sensitive to the initial shutdown margin, the Doppler feedback, and the properties of the slug. Other factors which will have a secondary impact are the delayed neutron fraction, the neutron lifetime, and the speed at which the slug moves through the core.

The initial shutdown margin represents what the condition of the core might be by virtue of the operating mode combined with the effect of any control rods that might insert prior to the slug passing through the core. In the reactor restart scenario, even if the core was initially at its final boron concentration, there would still be some negative reactivity as the reactor is usually brought to critical on the movement of the regulating banks. Assuming that the reactivity hold-down of the regulating banks is small, then the initial shutdown margin is just the worth of the shutdown banks which would scram when there was a loss of offsite power. Although this was assumed to be 4 percent in the base case, for some plants this might only be 2 percent. If there were no rods initially withdrawn, then the smallest shutdown margin that could be expected would be the 1 percent requirement when at hot shutdown conditions. Hence, the calculations were done with an initial shutdown margin down to 1 percent. At the other end of the scale is the fact that if the shutdown margin were equal to or greater than the amount of reactivity which could be inserted by the diluted slug, then no power excursion can take place. In the case being considered with a 750 ppm slug, this is 5.9 percent.

The results of these calculations are shown in Figure 4. Peak fuel enthalpy is plotted for the time corresponding to immediately after the initial power spike and for the time at which the core average enthalpy exhibits a broad maximum. The times at which these peaks occur become later with an increase in initial shutdown margin as it takes longer to overcome that barrier and become supercritical. As can be seen, when the initial shutdown margin is between 1 percent and 2 percent, the peak fuel enthalpy can exceed the 280 cal/g criterion for catastrophic fuel damage. This is not the result of the initial power burst but rather the fact that the power remains high due to the continued presence of the diluted slug.

Figure 4 also shows the effect of reducing the Doppler feedback by a factor of 0.5. The reduction in the Doppler coefficient from -1.4 pcm/°C to -0.7 pcm/°C is consistent with the range of coefficients expected during operation of this cycle of Calvert Cliffs and similar to how other PWRs operate.

An estimate of the boron dilution necessary to cause the fuel enthalpy to exceed 280 cal/g when the initial shutdown margin is 4 percent can be made by using the results shown in Figure 4. Since that figure shows that a reduction of the shutdown margin to approximately 1.5 percent would cause the peak fuel enthalpy to exceed 280 cal/g, it can be estimated that at an initial shutdown margin of 4 percent one would need additional reactivity worth 2.5 percent, or approximately an additional dilution of 320 ppm. Hence, if the boron concentration of the slug was approximately 430 ppm and the initial shutdown margin was 4 percent, catastrophic fuel damage might be likely. Note that with this boron concentration, the volume of the diluted slug would be 1.4 times the volume of the unborated water assumed to be available from the VCT or 10.6 m^3 (375 ft^3). The length of the slug would then be approximately 2.1 m (7 ft) rather than the 3.0 m (10 ft) for the nominal case. This is not expected to alter the behavior of the power excursion during the period where the fuel enthalpy reaches a maximum; however, if the slug was even smaller and more dilute, it is not clear that the situation would lead to a higher fuel enthalpy. The competition between a higher positive reactivity insertion and a shorter insertion time in the limit of zero volume leads to a smaller effect.

Summary

The analysis of a rapid boron dilution event has been carried out in three different ways: (1) a probabilistic analysis for the core damage frequency, (2) a mixing analysis to determine the extent of dilution before injection into the core, and (3) neutronics calculations to determine core behavior and the consequences in terms of fuel damage.

The probabilistic analysis was done for reactors from each of the three U.S. reactor vendors. The CDF varies from 9.7 to 2.8E-5/yr for the three plants which is what is calculated for other internal events that are considered important. The analysis shows the importance of the primary grade water pump. For all three plants, 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 PG makeup pump. However, there are plants where this pump is connected to the emergency bus, and the probability of an accident will be increased if primary grade water continues to be pumped into the VCT.

For all three plants, the dilution is done with flow from the VCT. In some plants, the suction for the charging flow comes directly from the primary grade makeup water source, and once the PG water pump is tripped, there is no longer the potential for adding unborated water to the RCS.

The results are dependent on assumptions used in the analysis three of which are summarized below. These assumptions result in overestimating the core damage frequency.

1. The dilution time during startup is 8 hrs. The consequences of the event are assumed independent of when during this period the loss of offsite power occurs. In reality, an event occurring early during this period will have more shutdown margin to overcome and is, therefore, expected to have less of an effect than event occurring near the end of the normal dilution procedure.

2. No credit is given for the operator to take action and stop the charging flow from the VCT after the LOOP. Although dilution while the shutdown banks are inserted or the RCPs are stopped (as would be the case after a LOOP) is not a normal procedure, it is assumed that since the operator knows that the flow from the primary water makeup pump has ceased, that no other action is deemed warranted. An action that could be taken by the operator would be to switch the charging pump suction to the RWST.

3. The analysis does not account for any mixing at the point of injection or mixing of the diluted water due to its flow into the downcomer and down to the lower plenum. It does, however, approximately account for the effect of natural circulation on mixing. Mixing analysis performed for this study shows that this may be very conservative under certain conditions.

Mixing analysis was done with the Regional Mixing Model developed to study the thermal mixing of interest to pressurized thermal shock. Illustrative predictions for reactor designs from two vendors show significant mixing during the event. For the cases considered, the boron concentration in the lower plenum does not fall below 900 ppm when the initial boron concentration in the vessel is 1500 ppm. However, these cases do not encompass all possible physical situations for these plants. It would be desirable to assess the applicability of the model when the temperature of the charging flow is higher, to improve the understanding of mixing when the injectant enters at the side or bottom of the cold leg piping, and to study mixing under low natural circulation flow.

The neutronic results show that there is the possibility of catastophic fuel damage depending on (1) the initial shutdown margin, (2) the Doppler feedback, and (3) the properties of the slug, especially the boron concentration. The intial shutdown margin depends on the reactor state at the time of initiation of the event and the reactivity worth of the shutdown bank which will scram before the slug enters the core. The Doppler feedback is responsible for initially terminating the power excursion. This number can vary by a factor of 2 during a fuel cycle, and ,therefore, results will be sensitive to where in the fuel cycle the event takes place. After the initial power excursion, the power remains high until the slug has passed sufficiently through the core so that power decreases. Since there may not be much shutdown margin to begin with, after the slug passes through the core, the decline in power may not be as rapid as occurs with reactor trip. This also impacts the consequences in terms of fuel damage.

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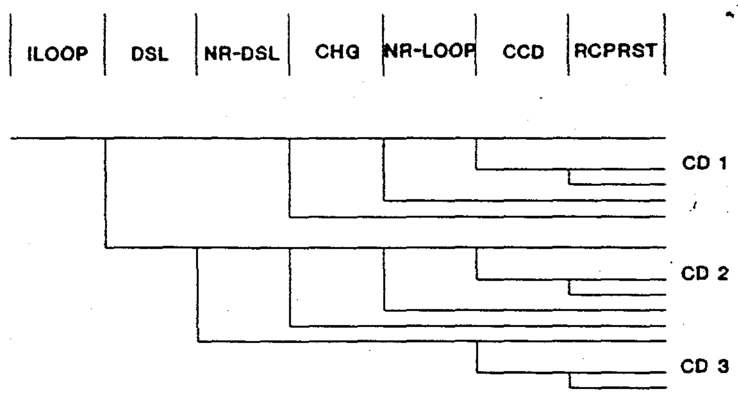

Figure 1 Boron Dilution Event Tree - Calvert Cliffs

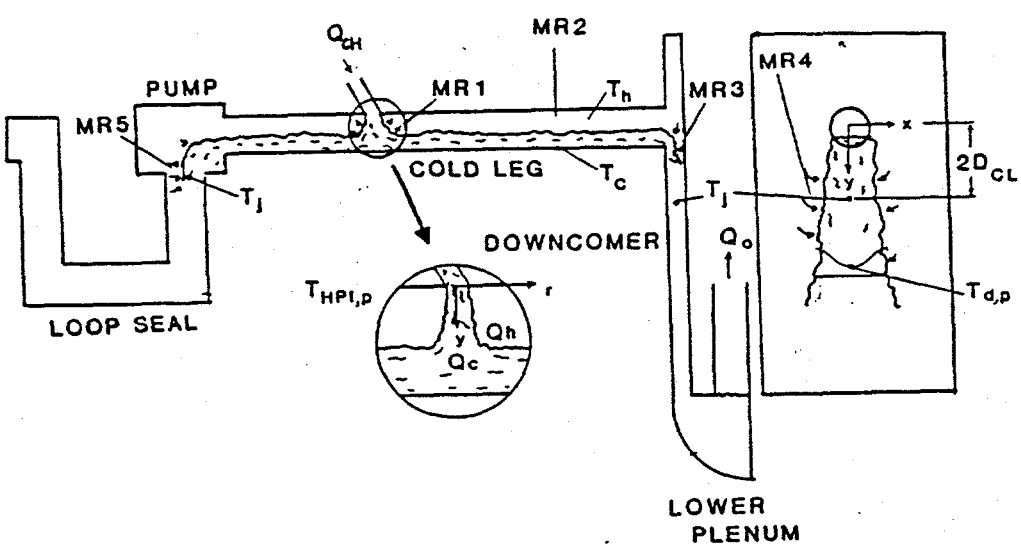

Figure 2 Schematic of the Flow Regime and Regional Mixing Model

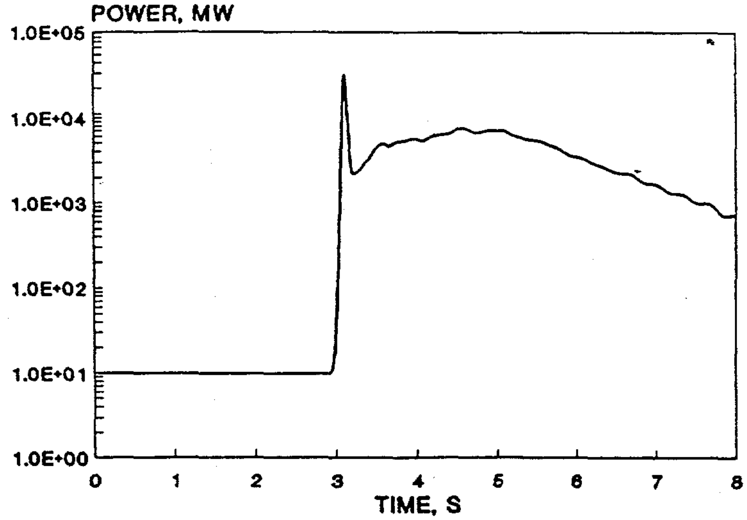

Figure 3 Core Power with Finite Slug

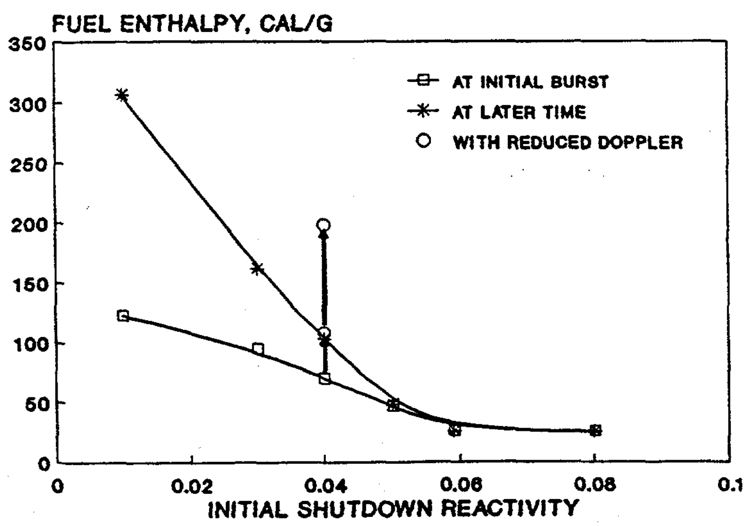

Figure 4 Peak Fuel Enthalpy vs. Shutdown Margin