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Reactor Power Cutback Feasibility to a 12-Finger CEA Drop to Avoid Reactor Trips

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Abstract

EPRI URD requires that the reactor be capable of accommodating an unintended CEA drop without initiating a trip and operating at a reduced power with any single CEA fully inserted. YGN 3 and 4 reactors have 12-Finger CEAs, and the CPCS will trip the reactor due to their large reactivities when one of them is dropped at a high power. The ABB-CE reactor power cutback system has been proposed to be used against the 12-Finger CEA drop to avoid the reactor trips. The results of this study show that the reactor power cutback can prevent the reactor trips of the 12-Finger CEA drop when the CPCS has enough operating thermal margin (more than 9% for YGN 3&4 Cycle 1). It is noted, however, that the probability of a 12-Finger CEA drop is very low, less than one per 100 reactor years for YGN 3&4 and System 80^+ plants.

1. Introduction

This study addresses a feasibility evaluation for CPCS (Core Protection Calculator System) initiation of reactor power cutback (RPC) to avert unwanted reactor trips due to a 12-Finger CEA (Control Element Assembly) drop. The CPCS consists of four CPCs (Core Protection Calculators) and two CEACs (CEA Calculators). The primary function of the CPCS is to generate low DNBR (Departure from Nucleate Boiling Ratio) and high LPD (Local Power Density) trip signals to avoid DNB and fuel centerline melting during an AOO (Anticipated Operational Occurrence). Each CEAC monitors the position of all CEAs within the subgroups. Should a 12-Finger CEA deviate from its subgroup position by more than a specified amount, the CEACs calculate and transmit appropriate penalty factors to the CPCs that result in reductions in margin-to-trip for low DNBR and high LPD. The CEACs also evaluate changes in CEA positions indicative of a RPC event and inform each CPC if they detect it. For YGN 3&4 (Yong Gwang Nuclear 3 and 4), there is a good chance of reactor trips when a 12-Finger CEA is dropped above 75% power.

Paragraph 7.2.1.6 of EPRI (Electric Power Research Institute) Advanced LWR (Light Water Reactor) URD (Utility Requirements Document)[1] says :

"During power operation the reactor shall be designed to accommodate the following events associated with an unintended control rod drop.

- No scram upon dropping a control rod ;
- Operation at reduced power for four hours with any single control rod drive fully inserted ;

- Recover rod without initiating a scram or exceeding fuel design limits.

Providing the capability for continued operation, despite an unintended single rod drop, will improve the plant capacity factor and reduce the wear associated with a shutdown and startup."

The ABB-CE RPCS (RPC System)[2] and CPCS have been proposed to be used against a 12-Finger CEA drop to avoid the reactor trips[3]. The current RPCS is designed to enable continuous operation of the reactor without trips in the events of the loss of one of the two main feedwater pumps and loss of load to improve plant availability and capacity factors. Per Reference 3, the RPCS and CPCS designs are expanded to include new CPCS RPC demands which can avoid reactor trips due to an inward CEA deviation including a CEA drop or failures that look like such deviation. Among the inward deviations, 12-Finger drop is the most severe, and a solution for it will bound all the other inward deviations. Under the expanded function of the RPCS, it will provide a rapid power core power reduction on a CPCS RPC demand by releasing the preselected CEAs (Bank 5 or Banks 5+4 depending on core conditions) to drop into the core and reduce the turbine power.

Reference 2 demonstrated that the reactor trip could be avoided in the event of a 12-Finger CEA drop by the RPC initiation assuming that the secondary system followed the primary reactor power decrease. But the assumption should be relaxed and a conservative approach should be taken since higher secondary system power gives more adverse results. It calculated the DNBR based on the core power saying that the heat flux lags behind the power changes. But the DNBR depends on the heat flux instead of the core power. Most importantly, one can get a different conclusion from the numerical values and their trends of its Tables 2 to 7. Since their DNBR values are below 2.40 (the low DNBR limit of it) or will be below 2.40 when the values are extrapolated against time, one cannot conclude that the reactor trip can be avoided without DNB by the RPCS. One should also evaluate whether the DNB can be avoided if the RPCS succeeds partially(e.g., RPC with no turbine power reduction).

With different approaches from Reference 2 correcting the above difficulties, this study evaluates whether the CPCS initiated RPC can prevent the reactor trips in case of a 12-Finger CEA drop meeting the above EPRI URD requirements. It is discussed whether the reactor can be safely operated in case of unsuccessful RPC operations for a 12-Finger CEA drop. The estimated probability of a 12-Finger CEA drop is also presented along with a judgement whether the expanded RPC scope should be incorporated in the future ABB-CE plants of 12-Finger CEAs. YGN 3&4 Cycle 1 is the reference plant for numerical calculations.

2. 12-Finger CEA Drop Possibility

YGN 3&4 have 73 CEAs of 32 12-Finger CEAs and 41 4-Finger CEAs including 8 4-Finger PSR (Part Strength Rod) CEAs[4]. Since all the 4-Finger CEAs have relatively small reactivities, the reactor will not be tripped by a drop. For the 12-Finger CEAs, the CPCS will trip the reactor due to their large reactivities when one of them is dropped at a high power (approximately above 75% power for YGN 3&4 Cycle 1).

It is generally believed that control rods in the future plants will move more frequently than those in the present plants to support the daily load follow and frequency control operations, and they will be more susceptible to control rod drop. However, all 12-Finger CEAs cannot be inserted into the core when the core power level is above zero for YGN 3&4 since all of them are for shutdown Banks A and B, and Bank 1[4]. Even for future System 80$^+$ plants of CESSAR-DC, all the 12-Finger CEAs are for shutdown Banks A and B which cannot be inserted into the core above zero power, and Bank 1 which is not allowed in the core above 20% power[3]. Therefore, the use of 12-Finger CEAs for daily load follow and frequency control is not expected for the present and future plants.

Reference 5 says: "CE's recent experience is about 0.08 CEA drops per reactor year. This value is believed to exclude drops during power ascensions such as startups. The use of the ACTM (Automatic CEA Timing Module) controllers for CEA motion could decrease this to about 0.01 CEA drops per reactor year providing that the reactor operators are knowledgeable of the ACTM software performance." YGN 3&4 and System 80$^+$ plants have the ACTM. It should be noted that 0.01 CEA drop probability per reactor year includes both 4-Finger and 12-Finger CEAs, and 12-Finger CEAs are not usually expected to be used for the startup tests. Therefore, it can be said that the probability of the 12-Finger CEA drop is less than one per 100 reactor years for YGN 3&4 and System 80$^+$ plants.

3. Analysis Method

For the numerical calculations of YGN 3&4 Cycle 1, the following ABB-CE design computer codes are used: ROCS, CESEC, CETOP-D and CPCFORTRAN. The ROCS is the standard nuclear design code calculating the reactivity insertions and Fr's of the dropped CEAs. The CESEC is the non-LOCA system analysis code calculating the reactor power, core heat flux, steam generator pressure, RCS (Reactor Coolant System) temperatures and pressure based on the reactivity values of the ROCS. The CETOP-D is the thermal-hydraulics code for the non-LOCA safety analysis calculating the DNBR values based on the above CESEC outputs and ROCS calculated Fr's. The CPCFORTRAN simulates the CPCS behaviors based on the CPCS measurement parameters of CEA positions, RCS temperatures and pressure which are mostly given by the above CESEC outputs. The CPCFORTRAN outputs include the CPCS calculated DNBR values.

The following full power cases have to be considered to study the feasibility of CPC initiated RPC to avoid unwanted reactor trips due to a 12-Finger CEA drop.

Case A. Successful CPCS and RPCS Operations: A 12-Finger CEA drops and the CPCS detects it. The CPCS initiates RPC in 0.229 seconds [6], the RPCS makes the CEDMCS (CEA Drive Mechanism Control System) drop Bank 5 or Banks 5+4 CEAs depending on core conditions, and the CEAs reach the core bottom in 4 seconds. The reactor power rapidly decreases due to the reactivity insertions of the dropped CEAs, but will somewhat increase again after the decrease due to negative FTC (Fuel Temperature Coefficient) and MTC (Moderator Temperature Coefficient). Subsequent insertion of other Banks either automatically by the RRS (Reactor Regulating System) or manually by the operator occurs as necessary for a successful RPC. The actuation logic also temporarily changes plant control to a turbine follow mode by first initiating a rapid turbine power reduction to 60% power followed by a further reduction if necessary to balance turbine power with the reactor power. If the reactor power stays above 60% power due to failure or operator bypass of the RRS, the excess amount of power (up to 15%) above 60% is dumped to the condenser by the SBCS (Steam Bypass Control System). The CPCS will not apply the dropped CEA penalty factors and the dropped CEA Banks' (Bank 5 or Banks 5+4) radial peaking factors during the RPCS actions but apply them after a delay time. The CPCS will not trip the reactor without DNB due to the increased radial peaking factor and penalty factors, since the reactor power will be below 60% after the delay time.

Case B. Successful CPCS and Partially Successful RPCS Operations: A 12-Finger CEA drops and the RPCS detects it. The CPCS initiates RPC in 0.229 seconds and the RPCS makes the CEDMCS drop the preselected CEA Banks (Bank 5 or Banks 5+4) into the core. But the turbine produces full power or near full power due to a failure in the turbine control system. The reactor power decreases due to the reactivity insertions of the dropped CEAs but will eventually restore to the near original power due to the negative FTC and MTC. The CPCS will apply the radial peaking factors of the dropped CEA Banks (Bank 5 or Banks 5+4) in addition to the dropped 12-Finger CEA penalty factors after a delay time. If it is needed, the CPCS will trip the reactor without DNB due to the increased radial peaking factor and penalty factors after the delay time.

Case C. Successful CPCS Operation but No RPC Action : A 12-Finger CEA drops and the CPCS detects it. The CPCS initiates RPC but the RPCS takes no action due to failure or operator bypass of it. The turbine will produce full power or near full power. The reactor power decreases due to the reactivity insertion of the dropped CEA but will eventually restores to the near original power due to the negative FTC and MTC. The CPCS will apply the dropped CEA penalty factors within 7 seconds to compensate for the increased Fr (integral radial peaking factor) due to the dropped CEA. The CPCS will trip the reactor without DNB due to the penalty factors.

For conservatism, the dropped 12-Finger CEA is the one with the biggest Fr, and the most negative FTC and MTC values of the YGN 3&4 Cycle 1 are used. Fixed axial shapes are used throughout the transients for the CETOP-D and CPCFORTRAN DNBR calculations. The Fr's are linearly interpolated from ARO (All Rods Out) conditions to ARI (All Rods In) conditions against time for the CETOP-D DNBR calculations when the CEAs are dropping. The Fr will increase with time up to 3−4% in 15 minutes due to the Xenon redistribution effect when a 12-Finger is dropped into the core. If the CEA is recovered in 15 minutes, the Fr increases will have negligible effect on the DNBR values. Since it is highly recommendable to recover dropped CEAs as early as possible, the Fr values without the Xenon redistribution effect are used in the following simulations assuming that the dropped CEA will be recovered in 15 minutes. However, the operator can either recover the dropped CEA or reduce the plant power in an orderly mannner in 15 minutes to accommodate the Xenon redistribution effect. If the reactor is operated at an appropriately low power, it will not trip for more than 4 hours without DNB even with a dropped 12-Finger CEA. This meets the EPRI URD.

By adjusting the radial peaking factor, the initial reactor (CETOP-D) DNBR value at time zero is made as 1.69 which is 16% higher by power unit than the YGN 3&4 Cycle 1 limit DNBR value of 1.30. The 16% margin is called the ROPM (Required Over Power Margin) which always exists in the reactor during the plant operation for the DNB LCO (Limiting Condition for Operation). By adjusting the CPC uncertainty factor, the initial CPCS DNBR value is also made as 1.69, which means that the CPCS is at 16% operating thermal margin. It is noted that the initial reactor (CETOP-D) DNBR value will always be higher than the initial CPCS DNBR value due to the ROPM requirements. The reactor power, steam generator power, turbine power, RCS temperatures and pressure are assumed to be at nominal conditions at time zero. The CEA positions are assumed to be at the ARO condition at time zero.

Case A Simulation : The best estimate high turbine power behavior after RPC at the full power is constructed in Figure 1 based on the descriptions of

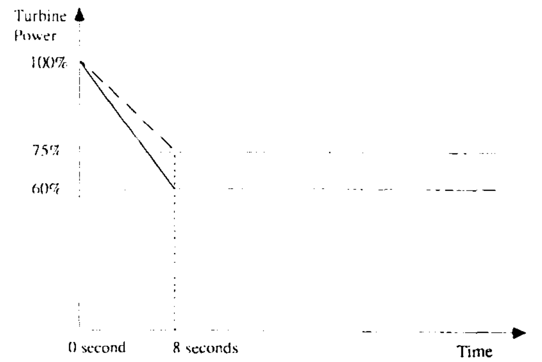

Fig. 1. Best Estimate High Turbine Power Behavior After RPC for Case A (Broken Line is for the Upper Uncertainty Limit)

Reference 7. The broken line of the figure is the upper uncertainty value to the best estimate high power behavior considering the existence of the SBCS. Since the reactor power will increase more due to the negative FTC and MTC after the RPC, the broken line of the figure is used to simulate the turbine power. Because the 12-Finger CEA and preselected RPC Banks drop with only 0.729 second time difference (0.229 seconds for RPC detection plus 0.5 seconds for RPC CEA drop magnetic decay time), they are assumed to drop at time zero for the simulations. The plant behaviors are simulated using the ROCS, CESEC and CETOP-D codes for both Bank 5 and Banks 5+4 RPC transients. The CPCS behaviors are simulated for the above transients using the CPCFORTRAN code for both 20 and 25 seconds of the penalty factor delay time (TCBP), whereas the YGN 3&4 Cycle 1 final design value of TCBP is 25 seconds.

Case B Simulation : Since the reactor power will increase more due to the negative FTC and MTC after the RPC, the full power is assumed to be the turbine power throughout the simulation. Because the 12-Finger CEA and preselected RPC Banks drop with only 0.729 second time difference (see Case A), they are assumed to drop at time zero for the simulations. The plant behaviors are simulated using the ROCS, CESEC and CETOP-D codes for both Bank 5 and Banks 5+4 RPC transients. The CPCS behaviors are simulated for the above transients using the CPCFORTRAN code for both 20 and 25 seconds of the penalty factor delay time (TCBP), whereas the YGN 3&4 Cycle 1 final design value of TCBP is 25 seconds.

Case C Simulation : Since Case C is exactly the same as the present 12-Finger CEA drop CPCS simulation, no further simulation is necessary to show the proper reactor trip without DNB.

4. Results and Discussions

The simulation results of Cases A and B for Bank 5 RPC are shown in Figures 2 to 6. The simulation results for Banks 5+4 RPC are not shown since its DNBR values are bounded by the Bank 5 RPC values. This is due to the fact that Banks 5+4 has more reactivity and Banks 5+4 RPC flattens the 12-Finger CEA drop radial peaking because Banks 5+4 has more CEAs than Bank 5.

As shown in Figure 4, the reactor has always higher DNBR values than the limit value of 1.30 during the Case A RPC transient since the reactor will have an initial DNBR value which is higher than 1.69 due to the minimun 16% ROPM requirement. As can be seen from Figures 5 and 6, the CPCS will not trip the reactor for Case A RPC transients when the CPCS operating thermal margin is larger than 9.0% (noted as I in Figure 5) for TCBP=20 seconds, and 8.1% (noted as I in Figure 6) for TCBP=25 seconds. As can be seen from the same figures, the CPCS will trip immediately after the TCBP for Case B transients when the CPCS operating thermal margin is less than 21.3% (noted as I+II+III in Figure 5) for TCBP=20 seconds, and 23.5% (noted as I+II+III in Figure 6) for TCBP=25 seconds. The reactor will not experience the DNB for all of the transients of Figures 5 and 6 except the Case B RPC transient of TCBP=25 seconds. It will experience the DNB because the CPCS initiates the reactor trip at the time point of 25 seconds (=TCBP), around the reactor DNB initiation time of Figure 4. By the way, the present YGN 3&4 Cycle 1 TCBP is 25 seconds which is determined from point a of the figure. Therefore if the TCBP is determined from point a of the figure, it should be reduced by about 5 seconds for a safe reactor operation of Case B. The 5 second reduction will have no effect for successful terminations of Case A transients except the required CPCS operating thermal margin incease of 0.9% from 8.1% to 9.0% as described above. Another Case B of theoretical interest exists when the CPCS has operating thermal margin greater than 21.3%. In this case, the CPCS will trip the reactor at least 5 seconds before the reactor (CETOP-D) experiences the DNBR, which is enough to prevent the DNB.

From the above simulation results, the followings can

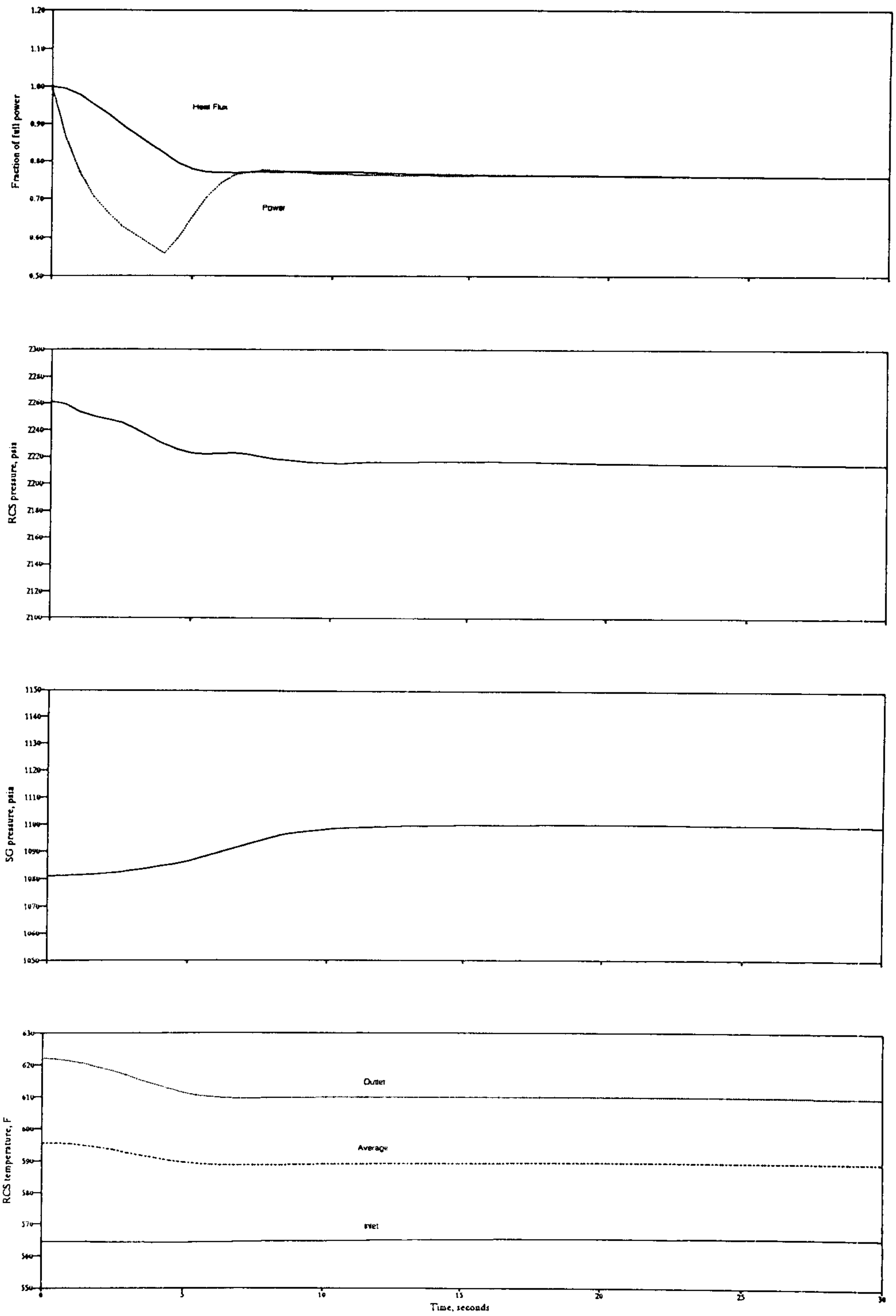

Fig. 2. Plant Response to Bank 5 Reactor Power Cutback of Case A

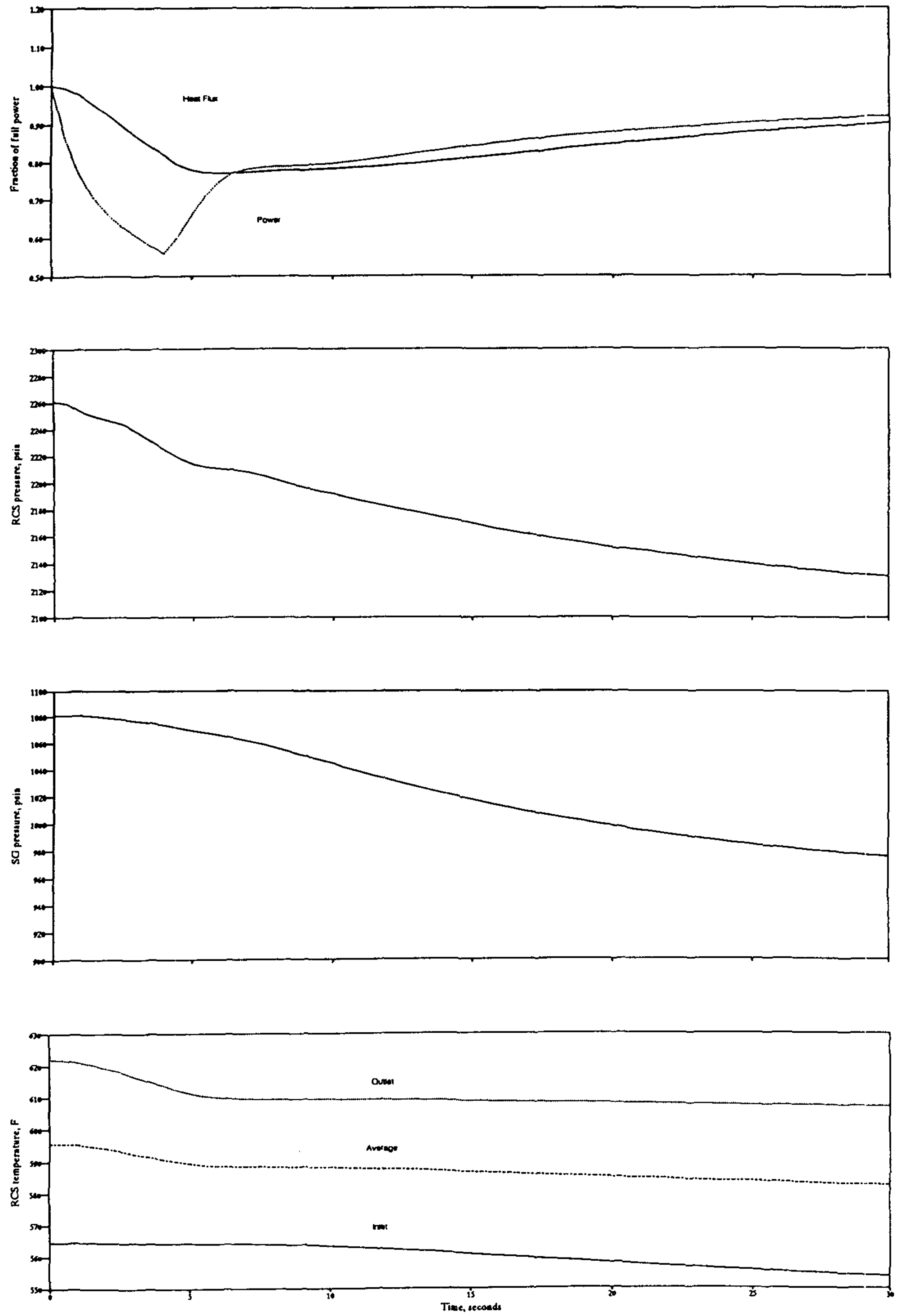

Fig. 3. Plant Response to Bank 5 Reactor Power Cutback of Case B

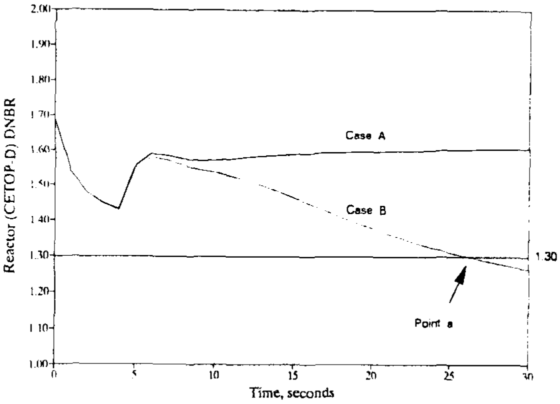

Fig. 4. Reactor (CETOP-D) DNBR Values of Bank 5 RPC for Cases A and B

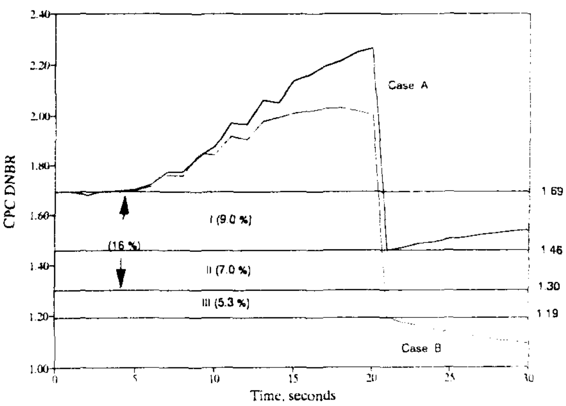

Fig. 5. CPC DNBR Values of Bank 5 RPC and TCBP=20 seconds for Cases A and B

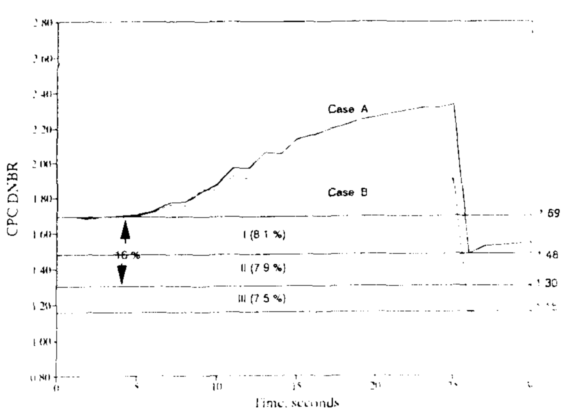

Fig. 6. CPC DNBR Values of Bank 5 RPC and TCBP=25 seconds for Cases A and B

be observed:

- The CPCS initiated RPC will not trip the reactor without DNB when the CPCS has more than 9% operating thermal margin.
- The CPCS penalty factor delay time (=TCBP) should be set 5 seconds ahead of the CETOP-D limit DNBR time of the partially successful RPCS operation.
- The CPCS may trip the reactor to prevent the DNB for partially successful and unsuccessful RPCS operations during the CPCS initiated RPC.
- In all the possible design cases, the reactor will not experience the DNB.

It should be noted that the dropped 12-Finger CEA be recovered or the reactor power be further reduced in 15 minutes to prevent the DNB due to the Xenon redistribution effect. Because the minimum required 9% CPCS operating thermal margin is smaller than the 15% EPRI thermal margin requirement[1], it will not be an extra bumden for the next generation reactors, such as, System 80$^+$ reactors. As discussed in Section 2, it should be noted that the probability of 12-Finger CEA drop is very rare, less than one per 100 reactor years. This is very important information in deciding whether the expanded RPC scope is incorporated or not in the future ABB-CE plants of 12-Finger CEAs. Another information one has to consider here is that the CPCS needs more than 9% operating thermal margin for the successful RPC without trip. Ultimately, the utility companies have to decide the CPCS initiated RPC for the 12-Finger CEA drop based on the above informations. The authors' personal judgement is, however, that it is not too late to wait until the ACTM type ABB-CE plants including YGN 3&4 show several reactor trips due to the 12-Finger CEA drop.

5. Conclusions

The feasibility is evaluated for CPCS initiation of reactor power cutback to avert unwanted reactor trips due to a 12-Finger CEA drop at ABB-CE plants. It is calculated whether the reactor can be safely operated in case of successful and unsuccessful RPC operations for a 12-Finger CEA drop.

The CPCS initiated reactor power cutback can prevent reactor trips of 12-Fings CEA drop without DNB when the CPCS has enough operating thermal margin (more than 9% for YGN 3&4 Cycle 1). The CPCS may trip the reactor to prevent the DNB for partially successful and unsuccessful RPCS operations during the CPCS initiated RPC. It has been shown that the reactor will not experience the DNB in all possible cases. It is noted, however, that the probability of a 12-Fings CEA drop is very low, less than one per 100 reactor years for YGN 3&4 and System 80$^+$ plants.

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