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An Expanded Use of Reactor Power Cutback System to Avoid Reactor Trips in the Event of an Inward Control Element Assembly Deviation

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제어봉 인입편차시의 원자로 비상정지 방지를 위한 출력 급감발 계통의 확대 적용

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Abstract

The ABB–CE System–80 reactor power cutback system(RPCS) is designed to enable continuous operation of the reactor without trip in the events of the loss of one of the two main feedwater pumps and loss of load, and thus improves plant availability in a cost effective manner. In this study expansion of RPCS has been investigated for continuous reactor operation without trip in the event of an inward control element assembly(CEA) deviation including a single rod drop. Under the expanded function of RPCS the control system will provide a rapid core power reduction on demand by releasing CEAs to drop into the core and reduce the turbine power, if necessary, to follow the reactor power variation. This design feature which is included as the new design features to be incorporated in the ABB–CE System–80+ meets the EPRI advanced light water reactor(ALWR) requirements. For this study core analysis models of System–80+ have been developed to simulate the nuclear steam supply system(NSSS) response as well as the RPCS initiation of rapid CEA insertion. The results of this study demonstrate that the reactor trip can be avoided in the event of inward CEA deviation including a single rod drop by the RPCS initiation and thus the plant availability and capacity factor would be increased.

요 약

ABB-CE사의 System-80 설계 특성 중 원자로 출력 급감발 제어계통(RPCS : Reactor Power Cutback System)은 2개의 주급수 펌프 중 1대가 정지하거나 전출력 부하 상실사고인 경우에도 원자로 정지없이 운전하게 함으로써 원전의 경제성 향상에 도움을 주고 있다. 이러한 RPCS의 적용

범위를 확대하여 단일제어봉 낙하를 포함한 제어봉 인입편차(inward deviation)가 발생하는 경우에도 RPCS를 작동시키면 원자로를 정지시키지 않고 운전을 계속할 수 있는지를 분석하였다. 즉 제어봉 인입편차가 발생시 제어봉을 순간적으로 낙하시켜 1차계통의 출력을 낮추면서 원자로를 정지시키지 않고도 과도현상을 수습할 수 있는지 분석하였다. 이렇게 확대된 RPCS는 미국 EPRI의 개량형 경수로 요건사항을 만족하는 것이며 제어봉 인입편차의 과도상태를 수용할 수 있도록 하는 ABB-CE사의 System-80+ 설계항목에도 포함되어 있다. 본 연구에서는 System-80+에 대하여 RPCS의 작동에 의한 제어봉의 삽입과 그에 따른 핵증기 공급계통의 변화를 모사할 수 있는 노심해석 모델을 개발하였다. 연구 결과 단일 제어봉 낙하를 포함한 제어봉 인입편차가 발생되어도 원자로 출력 급감발 제어를 확대 적용하는 경우 원자로 정지를 방지할 수 있게 되어 원전의 이용율을 향상시킬 수 있을 것으로 검토되었다.

1. Introduction

The System–80 NSSS design incorporates a number of design features aiming at improving overall plant availability and operational flexibility. One of the improved design features of the System–80 design is the reactor power cutback system(RPCS). The current RPCS was designed to avoid the reactor trips caused by two common initiation events : the loss of load/turbine and the loss of one of two on–line main feedwater pumps. During these events, the RPCS is designed to rapidly reduce reactor power by dropping preselected CEAs while the process parameters are maintained within the acceptable transient values by other NSSS control systems. The value of this system has been proven by preventing unnecessary reactor trips at ABB–CE nuclear plants. Over several generations of reactor designs, ABB–CE has made continuous performance improvements in the field of CEA drive mechanisms (CEDM) and control system. YGN 3&4 includes double–step magjacks and automatic CEDM timing modules which provide the closed loop control based on the micro–processor. Although these features are capable of reducing the frequency of CEA deviations, the demanding availability goals of the EPRI ALWR utility requirements document (URD) require better ability to cope with CEA related events, should they occur. The EPRI ALWR URD states "During power operation the reactor shall be capable of accommodating an unintended control rod drop without initiating a scram". Also it is anticipated that load following and frequency control operations will require more frequent movement of control rods and therefore control rod deviation will be more susceptible. One approach to avoid trips due to inward deviations of CEA is to accommodate the inward deviation through control actions.

In this study, the function of RPCS is expanded to avoid reactor trips due to CEA deviations of 12–finger CEAs (smaller CEAs do not cause a reactor trip problem). A feasibility analysis was conducted to determine the potential success of the expanding RPCS approach. This paper provides the results of the core physics scoping analysis and NSSS response for the System–80+ inward deviations of 12–finger CEAs and for the prevention of the trip event through reactor power cutback control actions. In this analysis, it was assumed that the secondary turbine system could follow the primary reactor power decrease.

2. Functional Description of current RPCS

The NSSS is normally operated with minor perturbations in power and flow. Certain large amount of plant imbalances can occur, however, such as a large turbine load rejection, turbine trip or loss of one of two on–line main feedwater pumps. Under these conditions, the NSSS can be maintained within the control band ranges by rapid reduction of NSSS power at a rate which is greater than that provided by the normal high speed CEA insertion.

The RPCS is a control system designed to accommodate certain types of imbalances by providing a "step" reduction in reactor power. The step reduction in reactor power is accomplished by the simultaneous dropping of one or more preselected groups of full strength regulating CEAs into the core. The CEA groups are dropped in the normal sequence of insertion. The RPCS also provides control signals to the turbine to rebalance the turbine and reactor power following the initial reduction in reactor power as well as to restore the steam generator water level and pressure to their normal controlled values. The system was designed to accommodate large load rejections and the loss of one feedwater pump.

The RPCS receives following two signals ; loss of any operating feedwater pump and two cutback demand signals from the steam bypass control system(SBCS). A two–out–of–two logic is required to actuate the system for load rejections or loss of a feedwater pump. The operator can also actuate the system manually.

The RPCS is actuated by receiving coincident two–out–of–two sensor logic signals indicating either large load rejection or loss of one main feedwater pump. The actuation initiates the dropping of the preselected pattern of CEAs. Subsequent insertion of other groups either automatically by the reactor regulating system(RRS) or manually by the operator occurs whenever necessary. The actuation logic also temporarily changes the 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 reactor power.

3. Motivation for RPCS Expansion

As mentioned earlier, the present EPRI ALWR design policy requires that plants sustain the rod deviation events without trips. It has been demonstrated in the previous analysis (Ref.1) that sufficient required overpower margin(ROPM) exists in case of insertion deviations of all 4–finger CEAs. This is not same as 12–finger CEAs, where an inward deviation results in a DNBR and/or linear power density(LPD) reactor trip. Since it is expected that control rods in the future plants will move more frequent than that in the present plants to support the load following and frequency control operations, those of the future plants will be more susceptible to control rod deviations.

One approach to avoid reactor trips in the events of inward deviations of 12–finger CEAs is to accommodate the event through control actions. A trip in case of such event can be avoided if the reactor power can be reduced rapidly. The core protection calculator(CPC) trip can be delayed long enough to allow the RPCS to reduce the reactor power and runback the turbine generator. Protection would still be provided even if the RPCS was not successfully functioned. This approach would require an interface from the CPCs to the RPCS to initiate the cutback. It would also require a determination of realistic deviation penalty factors since the present penalty factors would result in reactor trips even though power is reduced significantly.

In summary, the expanded function of RPCS could prevent reactor trips in the event of an inward CEA deviation including a single rod drop.

4. Analysis Method

4.1. Assumptions

Prior to initiating the core physics scoping analysis, several assumptions and analysis guidelines were identified as follows :

○ The use of the FLAIR computer code and the associated full-core neutronics model (Palo Verde Nuclear Generating Station Unit 2 cycle 2 full-core FLAIR model) are sufficient for this scoping analysis.

○ The use of the CESEC computer code and the associated data bases (System-80+) are enough for this scoping analysis.

○ Uncertainties normally associated with the use of FLAIR calculations and adjustments made for the best estimate calculations normally associated with single and subgroup CEA drop analysis are acceptable for use in this scoping analysis.

○ All initial, pre-drop operating conditions are from the nominal only (i.e., steady state, ARO, equilibrium xenon).

○ Octant-core symmetry.

4.2. Single 12-Finger CEA Drop Analysis

The core physics scoping analysis and the NSSS response for single 12-finger CEA drop were performed. Using the results of Reference 3, the assembly of number 204 was chosen as the most limiting case among seven possible 12-finger CEAs for the single 12-finger CEA drop. Time-dependent power distributions and maximum Fr at the beginning of cycle (BOC) were simulated using FLAIR code by changing rod positions of CEA. The FLAIR code rapidly calculates the realistic reactor core power distributions for a wide variety of reactor core simulations. The calculated maximum Fr was adjusted using the ROCS model benchmarking results and physical uncertainty correction factors (Ref.10).

The NSSS response after 40 seconds of a single 12-finger CEA drop was simulated using the CESEC computer program. The CESEC code is used to model the power production, heat removal, and coolant system temperatures, pressures, and flow rates based on the input driving functions such as feed flow, turbine steam demand, reactivity change.

From Reference 12, the values of space-time absolute reactivity insertion versus scram bank position at the axial shape index(ASI) of 0.0 were chosen for the reactivity versus time table needed in CESEC code since all cases of FLAIR results show that ASI values were very close to 0.0.

The reactivity worth of CEA 204 was 0.1073% $\Delta\rho$ based on Reference 11. The minimum DNBR(MDNBR) was calculated by CETOP-D computer program based on the adjusted maximum Fr and CESEC outputs. The CETOP-D code rapidly calculates the MDNBR which serves as a measure for the core thermal margin for ABB-CE reactors. Since the heat flux lags behind the power changes, the change in MDNBR was calculated based on the power change directly.

4.3. CEAs Drop Scenarios for RPCS Initiation Analysis

For this analysis only the lead bank and the first follow bank (called legal banks) were considered usable for a reactor power cutback. As shown in Figure 1, assembly numbers of 25, 115, 127, 217 belong to full-strength regulating group 3 (lead bank) and assembly numbers of 4, 113, 129, 238 and 67, 73, 169, 175 belong to full-strength regulating group 2.

In order to simulate the RPCS initiation to prevent CPC low DNBR trip, an RPCS initiation timing should be determined. Since the determination of the RPCS initiation timing is very important and could be a hard task, three different initiation times were simulated as follows :

○ Case 1 : RPCS initiation as soon as CPCs acknowledge the single 12-finger CEA drop

○ Case 2 : RPCS initiation after 2.0 seconds of the single 12-finger CEA drop (about 50% rod insertion in the core)

○ Case 3 : RPCS initiation when the single 12–finger CEA reaches the core bottom (full rod insertion in the core)

For each case, the lead full–strength regulating bank (group 3) insertion and the lead and the first follow full–strength regulating banks (groups 3 and 2) insertion were analyzed. FLAIR, CESEC and CETOP–D codes were used based on the same analysis procedures for the single 12–finger CEA drop analysis. Also the tables of the reactivity versus time for CESEC code were calculated based on the ASI of 0.0.

The reactivity worth of the lead bank (group 3) was 0.22% $\Delta\rho$ and the first follow bank (group 2) was 0.48% $\Delta\rho$ (Ref.7).

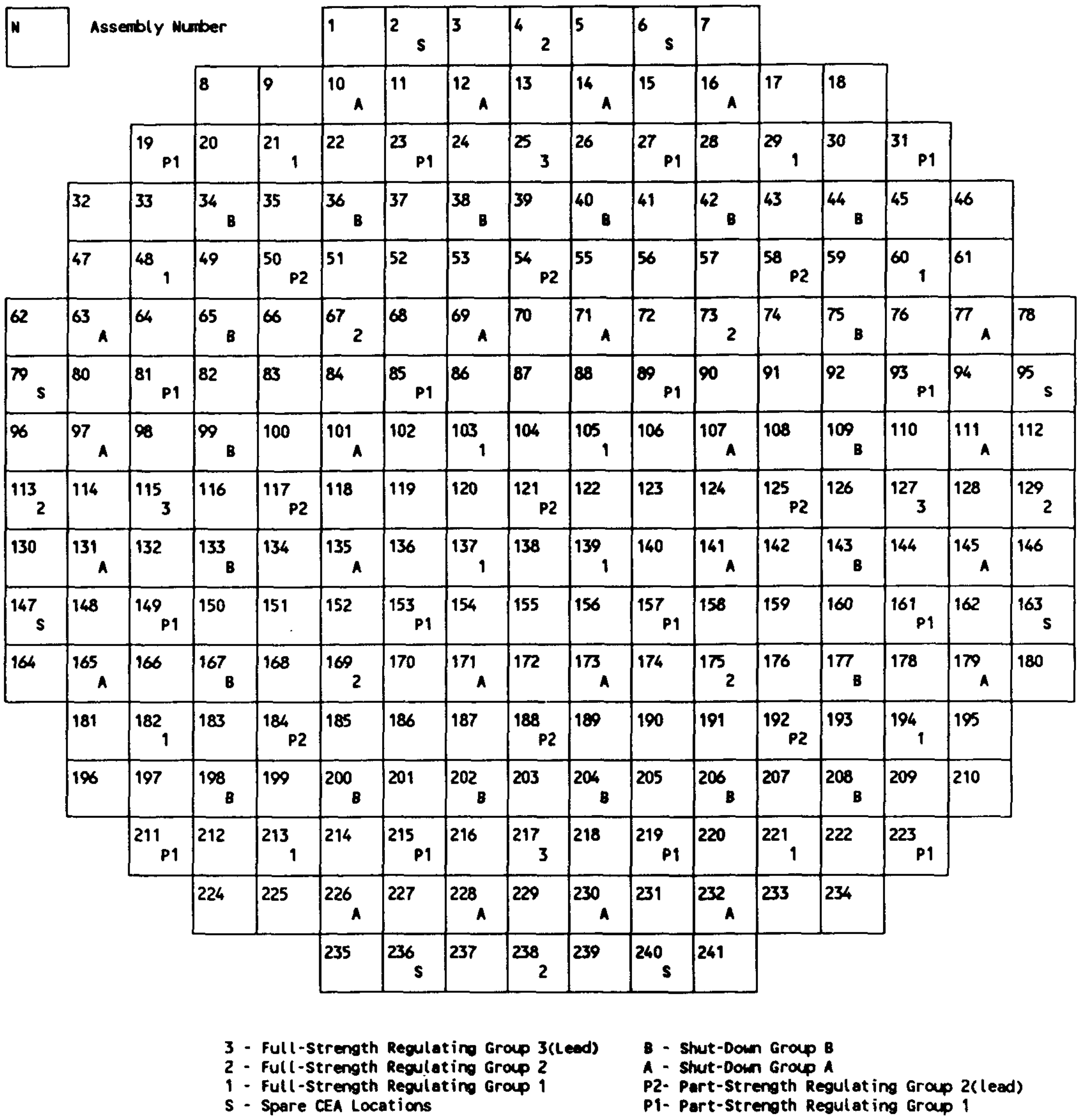

Fig. 1. System 80+ CEA Group Identification

5. Results and Conclusion

Table 1 shows the time-dependent FLAIR Fr, adjusted Fr and MDNBR in the event of drop of the single 12-finger CEA 204. This table shows, the low DNBR limit (2.40 from Ref.12) was violated after 7.5 seconds of the CEA 204 drop.

To simulate the RPCS initiation of rapid CEAs insertion, three different RPCS initiation times were simulated as mentioned in the section 4.3.

When CPCs acknowledge the CEA drop in 0.229 second (Ref.13) the rod was inserted only about 5% of the core. So for the case 1, single 12-finger CEA and lead bank (and possibly first follow bank) were considered to be dropped simultaneously. Figure 2 illustrates the NSSS response of the lead bank insertion, and Tables 2 and 3 show the time-dependent FLAIR Fr, adjusted Fr and MDNBR of the lead bank and legal banks insertion, respectively. As shown in Table 2, after the lead bank insertion the low DNBR limit violation was prevented and the MDNBR reached the highest value of 3.47 after 4.5 seconds of the rod insertion. Table 3 shows the same results for the legal banks insertion and the highest MDNBR value was calculated as 4.85.

Table 1. Drop Rod 204 at BOC ARO Full Power

Rod Position	Time (sec)	FLAIR Fr	Adjusted Fr	MDNBR
20[1]	10.00[3]	1.4519	1.5147	2.73
18	10.67	1.4667	1.5301	2.71
16	11.05	1.4899	1.5543	2.66
14	11.36	1.5140	1.5795	2.60
12	11.68	1.5380	1.6045	2.56
10	12.00	1.5621	1.6297	2.52
8	12.32	1.5867	1.6553	2.48
6	12.66	1.6116	1.6813	2.45
4	13.06	1.6358	1.7066	2.44
2	13.66	1.6537	1.7252	2.49
0[2]	14.40	1.6589	1.7307	2.65
0	15.00		1.7545[4]	2.58
0	16.30		1.7545	2.46
0	17.10		1.7545	2.41
0	17.50		1.7545	2.40
0	20.00		1.7545	2.34
0	40.00		1.7545	2.28

1) Rod Position 20 : fully withdrawn

2) Rod Position 0 : fully inserted

3) At time = 10.00 sec, rod begins drop

4) 15 min. xenon redistribution factor is included

For the case 2, the lead bank (and possibly first follow bank) was considered to be dropped after 2.0 seconds of the single 12-finger CEA drop. That is, lead bank (or legal banks) started to drop when single 12-finger CEA was inserted 50% in the core. Figure 3 illustrates the NSSS response of the lead bank insertion, and Tables 4 and 5 show

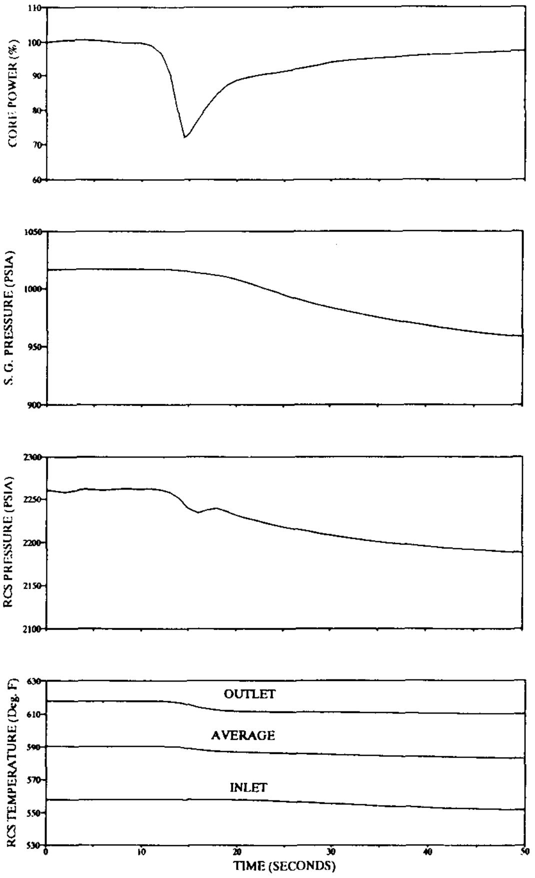

Fig. 2. NSSS Response to Rod 204 and Group 3 Drop Simultaneously

Table 2. Drop Rod 204 and Group 3 Simultaneously at BOC ARO Full Power

Rod Position	Time (sec)	FLAIR ASI	FLAIR Fr	Adjusted Fr	MDNBR
20	10.00	−.0194	1.4519	1.5155	2.74
18	10.67	.0008	1.4550	1.5187	2.74
16	11.05	.0414	1.4538	1.5174	2.76
14	11.36	.0273	1.4590	1.5229	2.76
12	11.68	.0419	1.4885	1.5537	2.71
10	12.00	.0476	1.5198	1.5863	2.68
8	12.32	.0441	1.5534	1.6214	2.64
6	12.66	.0320	1.5892	1.6588	2.63
4	13.06	.0145	1.6259	1.6971	2.71
2	13.66	−.0017	1.6545	1.7269	2.89
0	14.40	−.0080	1.6635	1.7363	3.44
0	14.50			1.7363	3.47*
0	15.10			1.7363	3.36
0	19.90			1.7363	2.66
0	30.10			1.7363	2.49
0	40.00			1.7363	2.43

*At time=14.5 sec, the lowest power level of 71.87% was reached

Table 3. Drop Rod 204 and Group 2 and 3 Simultaneously at BOC ARO Full Power

Rod Position	Time (sec)	FLAIR ASI	FLAIR Fr	Adjusted Fr	MDNBR
20	10.00	−.0194	1.4519	1.5200	2.73
18	10.67	.0193	1.4573	1.5256	2.74
16	11.05	.0926	1.4590	1.5274	2.77
14	11.36	.1026	1.4750	1.5442	2.77
12	11.68	.1417	1.5122	1.5831	2.74
10	12.00	.1608	1.5558	1.6287	2.73
8	12.32	.1536	1.6080	1.6834	2.72
6	12.66	.1215	1.6696	1.7479	2.76
4	13.06	.0724	1.7386	1.8201	2.97
2	13.66	.0237	1.7965	1.8807	3.43
0	14.40	.0045	1.8152	1.9003	4.76
0	14.50			1.9003	4.85*
0	15.10			1.9003	4.76
0	19.90			1.9003	3.30
0	30.10			1.9003	2.56
0	40.00			1.9003	2.40

*At time=14.5 sec, the lowest power level of 49.37% was reached

Table. 4. Drop Group 3 after 2 sec of Rod 204 Drop

Rod Position		Time	FLAIR	FLAIR	Adjusted	MDNBR
#204	Gr3	(sec)	ASI	Fr	Fr	
20	20	10.00	−.0194	1.4519	1.5154	2.74
10	20	12.00	−.0088	1.5621	1.6304	2.51
8	18	12.32	.0098	1.5738	1.6427	2.51
6	16	12.66	.0467	1.5741	1.6430	2.54
4	14	13.06	.0288	1.5812	1.6504	2.58
2	12	13.66	.0403	1.6079	1.6782	2.62
0	10	14.00	.0448	1.6224	1.6934	2.72
0	8	14.32	.0411	1.6317	1.7031	2.80
0	6	14.66	.0299	1.6418	1.7136	2.83
0	4	15.06	.0136	1.6519	1.7242	2.87
0	2	15.66	−.0019	1.6601	1.7327	2.98
0	0	16.40	−.0081	1.6633	1.7361	3.31
0	0	16.50			1.7361	3.33
0	0	19.90			1.7361	2.76
0	0	30.20			1.7361	2.50
0	0	40.10			1.7361	2.44

the time-dependent FLAIR Fr, adjusted Fr and MDNBR of the lead bank and legal banks insertion, respectively. As shown in Table 4, after the lead bank insertion the low DNBR limit violation was prevented and the MDNBR reached the highest value of 3.33 after 4.5 seconds of the rod insertion. Table 5 shows the same trend for the legal banks insertion and the highest MDNBR value was calculated as 4.77.

For the case 3, lead bank (and possibly first follow bank) was considered to be dropped when single 12-finger CEA was fully inserted in the core. Figure 4 illustrates the NSSS response of the lead bank insertion, and Tables 6 and 7 show the time-dependent adjusted Fr and MDNBR of the lead bank and legal banks insertion, respectively. For this case all the results before the lead bank (or legal banks) insertion were the same as those of single 12-finger CEA 204 drop (Table 1). As shown in Table 6, after the lead bank insertion the low DNBR limit violation was prevented and the MDNBR reached the highest value of 3.17 after

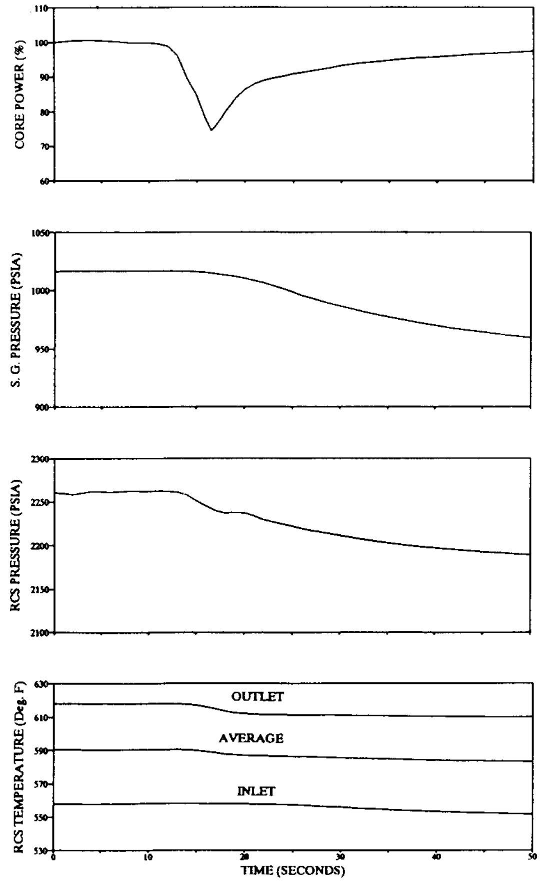

Fig. 3. NSSS Response to Group 3 Drop after 2 sec of Rod 204 Drop

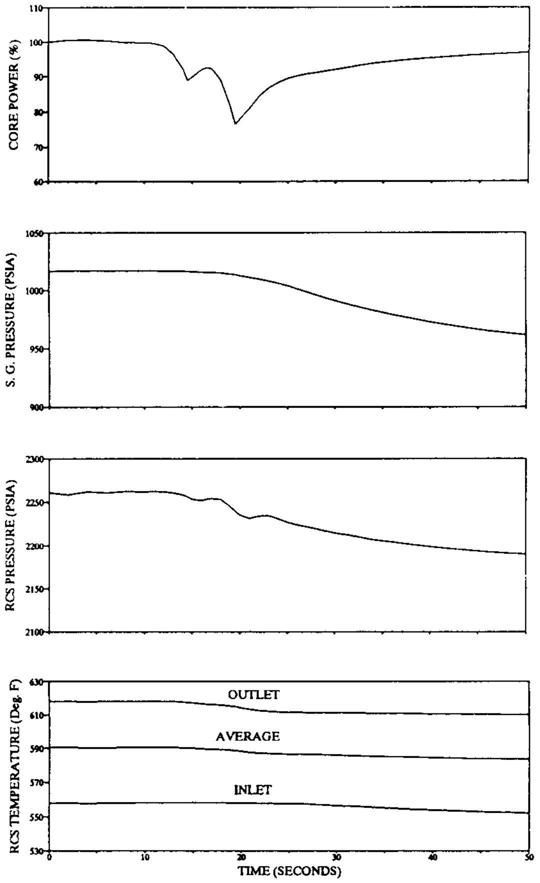

Fig. 4. NSSS Response to Group 3 Drop When Rod 204 at Core Bottom

4.5 seconds of the rod insertion. But the low DNBR limit could be violated about 35.0 seconds after the rod insertion. Table 7 shows the same trend for the NSSS response of the legal banks insertion and the highest MDNBR value was calculated as 4.66.

From above results it could be concluded that the lead bank (or legal banks) insertion could avoid the reactor trip in the event of single 12–finger CEA drop. The advantages of the expanded RPCS are to increase the plant availability and capacity factors and to minimize the potential for challenging plant safety systems.

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Table 5. Drop Group 3 and 2 after 2 sec of Rod 204 Drop

Rod Position		Time	FLAIR	FLAIR	Adjusted	MDNBR
#204	Gr3,2	(sec)	ASI	Fr	Fr	
20	20	10.00	−.0194	1.4519	1.5200	2.73
10	20	12.00	−.0088	1.5621	1.6354	2.50
8	18	12.32	.0280	1.5757	1.6496	2.50
6	16	12.66	.0968	1.5812	1.6554	2.52
4	14	13.06	.1018	1.6043	1.6796	2.55
2	12	13.66	.1367	1.6443	1.7214	2.64
0	10	14.00	.1538	1.6747	1.7533	2.73
0	8	14.32	.1470	1.7030	1.7829	2.83
0	6	14.66	.1172	1.7361	1.8175	2.92
0	4	15.06	.0708	1.7724	1.8555	3.12
0	2	15.66	.0235	1.8036	1.8882	3.54
0	0	16.40	.0044	1.8151	1.9002	4.69
0	0	16.50			1.9002	4.77
0	0	19.90			1.9002	3.74
0	0	30.20			1.9002	2.62
0	0	40.10			1.9002	2.42

Table 6. Drop Group 3 When Rod 204 at Core Bottom

Time (sec)	Adjusted Fr	MDNBR
14.4	1.7545	2.59
15.0	1.7545	2.58
16.3	1.7545	2.48
16.5	1.7545	2.48
17.1	1.7545	2.49
17.5	1.7545	2.52
18.7	1.7545	2.79
19.5	1.7545	3.17*
20.0	1.7545	3.08
30.1	1.7545	2.50
40.0	1.7545	2.41
50.0	1.7545	2.38

*At time=19.5 sec, the lowest power level of 76.41% was reached

Table 7. Drop Group 3 and 2 When Rod 204 at Core Bottom

Time (sec)	Adjusted Fr	MDNBR
14.4	1.7545	2.59
15.0	1.7545	2.58
15.9	1.7545	2.53
16.3	1.7545	2.55
17.1	1.7545	2.64
17.5	1.8376	2.62
18.7	1.8888	3.43
19.5	1.9002	4.66*
20.0	1.9002	4.53
30.1	1.9002	2.73
40.0	1.9002	2.45
50.0	1.9002	2.37

*At time=19.5 sec, the lowest power level of 51.10% was reached

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