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CONF-940774--1

BNL-NUREG-60231

SAFETY SIGNIFICANCE OF INADVERTENT OPERATION OF MOTOR OPERATED VALVES IN NUCLEAR POWER PLANTS[a]

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ABSTRACT

Concerns about the consequences of valve mispositioning were brought to the forefront following an event at Davis Besse in 1985 (NRC, 1985a). The concern related to the ability to reposition "position changeable" motor operated valves (MOVs) in the event of their inadvertent operation from the control room and was documented in Nuclear Regulatory Commission (NRC) Bulletin 85-03 (NRC, 1985b) and Generic Letter (GL) 89-10 (NRC, 1989). The mispositioned MOVs may not be able to be returned to their required position due to high differential pressure (dP) or high flow conditions across the valves. The inability to reposition such valves may have significant safety consequences as in the Davis Besse event. However, full consideration of such mispositioning in safety analyses and in MOV test programs can be labor intensive and expensive.

Industry raised concerns that consideration of position changeable valves under GL 89-10 would not decrease the probability of core damage to an extent which would justify licensee costs. As a response, Brookhaven National Laboratory (BNL) has conducted separate scoping studies for both Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs) using Probabilistic Risk Assessment (PRA) techniques to determine if such valve mispositioning by itself is significant to safety. The approach utilized internal events PRA models to survey the order of magnitude of the risk significance of valve mispositioning by considering the failure of selected position changeable MOVs. The change in core damage frequency[b] (CDF) was determined for each valve considered and the results were presented as a risk increase ratio for each of four assumed MOV failure rates. The risk increase ratios resulting from this failure rate sensitivity study can be used as a basis for a judgement determination of the risk significance of the MOV mispositioning issue for BWRs and PWRs.

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[a] Work done under the auspices of the U.S. Nuclear Regulatory Commission

[b] Some PRAs use core melt frequency instead of CDF. For consistency this paper uses the term CDF to represent risk.

INTRODUCTION

During the Davis Besse event in 1985, multiple MOVs were mispositioned by the control room operators and then were unable to be returned to their correct position due to incorrect torque switch settings that prevented them from operating under the existing high dP conditions. After the Davis Besse event, the NRC staff issued Bulletin 85-03 (NRC, 1985b), which recommended that licensees establish programs to ensure that MOV switch settings for several high-pressure safety-related systems were selected, set, and maintained correctly to accommodate the expected maximum differential pressures during both normal and abnormal events within the plant's design basis. The bulletin also indicated that inadvertent equipment operations (such as valve closures or openings) that are within the plant design basis should be assumed when determining maximum dPs. Supplement 1 (NRC, 1988) to Bulletin 85-03 clarified which valves were to be included when verifying the ability to recover from mispositioning and defined inadvertent equipment operations as discussed above.

After evaluating the responses to Bulletin 85-03 and performing a Regulatory Analysis, the NRC staff issued GL 89-10 (NRC, 1989), which extended the recommendations of Bulletin 85-03 and its supplement to "all safety-related MOVs as well as all position-changeable MOVs." Supplement 1 (NRC, 1990a) to GL 89-10 limited the scope to all MOVs which are both in safety-related piping systems and which can be mispositioned by operators from the control room.

The Regulatory Analysis for Generic Letter 89-10 included a value-impact analysis of the proposed expansion of the scope of Bulletin 85-03 to all safety-related systems as presented in NUREG/CR-5140 (Higgins, et al, 1988). Since Bulletin 85-03 already included the valve mispositioning issue, the value-impact analysis did not separately consider the value-impact justification of the inclusion of position changeable valves. Further, current PRAs rarely include errors of commission during an accident sequence, such as the inadvertent mispositioning of a valve. Therefore, a comprehensive quantitative evaluation of the effect on core damage frequency resulting from the inclusion of position changeable valves would require substantial remodeling of the PRA and was not performed in NUREG/CR-5140. However, it was qualitatively concluded that the inclusion of valve mispositioning in the analysis would enhance the benefit (value) obtained for the expansion of Bulletin 85-03 to all safety-related MOVs.

The Boiling Water Reactor Owner's Group (BWROG) agreed to address mispositioning of nine MOVs under Bulletin 85-03, but subsequently (Beck, 1990 and Beck, 1991) argued that valve mispositioning need not be considered in the licensees' responses to GL 89-10. The Westinghouse Owner's Group (WOG) has taken a position (Eliasz, 1992) concerning position changeable valves in PWRs consistent with that taken by the BWROG. Among the owners groups arguments is the statement that the PRA analysis in NUREG/CR-5140 does not clearly indicate that consideration of additional position changeable valves under GL 89-10 would decrease the probability of core damage to an extent which would justify the additional licensee costs. As discussed earlier, the analysis in NUREG/CR-5140 was performed to extend Bulletin 85-03, which already considered position changeable valves, to all safety-related systems. Therefore, that analysis did not separately justify the consideration of valve mispositioning.

As a result, BNL conducted two separate scoping studies (Ruger, et al, 1991 and Ruger, et al, 1993) using PRA techniques to determine if valve mispositioning (considered by itself) is significant to safety in BWRs and PWRs. Based on the sensitivity analysis in the BWR study, the NRC accepted (Murley, 1992) the BWROG argument that the licensees for BWRs need not include consideration of valve mispositioning from the control room in their programs for GL 89-10. The modified NRC staff position for BWRs is formally presented in Supplement 4 (NRC, 1992) to GL 89-10. The NRC staff is currently using the PWR study to determine a position concerning valve mispositioning in PWRs.

The remainder of this paper discusses the methodology used in the BNL studies and a summary of the results obtained.

ANALYSIS METHODOLOGY

Objective and Scope

The objective of these scoping studies was to use PRA techniques to determine if valve mispositioning is a safety significant issue. It was clear from the outset that a comprehensive evaluation of all mispositionable MOVs would not be possible using existing PRAs. Current PRAs rarely include errors of commission during an accident sequence, such as inadvertent mispositioning of valves. This is due to the difficulty in modeling such errors, which have an extremely large number of possibilities. However, within program constraints, the risk-significance of the more important, active and passive, position changeable, MOVs was estimated.

The "position changeable" valves under consideration include all MOVs in safety-related systems that are not prevented from inadvertent operation from the main control room (i.e., by keylock switch, breaker racked out, etc.). These MOVs may be considered as active or passive. Consistent with the ASME Code, Section XI definitions, active valves are considered to be valves which are required to change position in order to perform a specific function in shutting down the reactor to a cold shutdown condition or in mitigating the consequences of an accident. Passive valves are not required to change position to accomplish these specific functions. Passive valves are generally test or maintenance valves. In this work active valves include any MOVs which receive an automatic actuation signal or which may require remote manual operation during postulated scenarios. Mispositioning of valves with either active or passive safety functions is of concern. Mispositioning can occur prior to an event (e.g., test valve left open after completing a test) or during the course of an event.

Mispositioning of passive valves was clearly part of the original concern and these valves certainly warrant consideration. However, valves that perform an active safety function are also capable of being mispositioned. After an active valve performs its required function during an event, either by manual or automatic activation, the potential exists for a subsequent mispositioning (either inadvertently or intentionally due to misdiagnosis) by the operator, back to its original position. Also note that many mitigation systems are in a standby mode during normal operation, with relatively low dP and flow conditions. Sometime later during an event, after initial valve actuation, higher dP or flow conditions may develop that could prevent recovery from a subsequent mispositioning, even though the valve initially actuated from its standby condition. In analyzing their MOVs under Generic Letter 89-10, licensees may not have considered such mispositioning of active valves, and hence, may not have addressed the worst case dP and flow conditions.

Some utilities have used the practice of blocking a passive valve from inadvertent operation to prevent its mispositioning. This can be done by several means such as, keylock switches, physically locking the valve, and racking out the circuit breaker to the motor operator. However, since the location of blocked valves is very plant-specific and their identification is difficult, valves prevented from inadvertent operation from the control room, at some plants, were still included in the present analysis. Therefore, all active and passive MOVs which could be identified as capable of degrading safety systems by the process outlined above, were evaluated for their risk significance.

Valves that are considered "passive" are candidates for blocking, because they will not have to automatically change position on automatic system operation. A utility may choose to block a passive valve in order to avoid the need for a GL 89-10 analysis. However, the blocking of even passive MOVs can cause concerns, since it limits the flexibility that operators have in re-configuring the system in response to ongoing events and component/system level failures. Therefore, blocking should be approached with caution and each case should be carefully evaluated.

PRA Models

The approach utilizes an internal events PRA model to determine the change in CDF of selected position changeable MOVs. The first step identifies all active and passive position changeable valves in the PRA. They are then failed (failure rate increased to 1.0 failures per demand) one at a time. The resulting change in CDF is then calculated with the non-failed MOV failure rates remaining at their standard, base case, PRA values (usually 10^{-5} to 10^{-3} failures per demand). This initially assumes that the probability of both inadvertent operation and the inability to subsequently reposition (due to high dP or flow) is a certainty (probability = 1.0). Valves which are not risk significant can then be screened out. For those valves, where this first step results in a notable (>2X) change in CDF, a parametric sensitivity study is used to estimate the effects of the probabilities of both mispositioning (e.g., due to operator error) and the failure to correctly reposition due to differential pressure and flow conditions.

Two BWR and two PWR plant PRA models were selected for the studies in order to include as wide a range of dominant accident sequences and plant systems as practical. Two criteria affecting the selection process were; 1) the availability of PRA models on the Integrated Reliability and Risk Analysis System (IRRAS) (Russel, et al, 1991) and the System Analysis and Risk

Assessment System (SARA)[c] and, 2) the inclusion of different nuclear steam supply system (NSSS) vendors. IRRAS/SARA contains PRA data for the dominant accident sequences for the NUREG-1150 (NRC, 1990b) power plants. Three NUREG-1150 plants were used for these studies; Peach Bottom (BWR), Grand Gulf (BWR), and Surry 1 (Westinghouse PWR). Oconee 3 (B&W PWR) was selected as the fourth IRRAS/SARA model, even though it is not a NUREG-1150 model, because it was the only B&W plant available. Use of these four IRRAS/SARA models should provide a reasonable sampling of risk-significant MOVs in both BWRs and PWRs. This approach should therefore identify the most risk-significant valves. However, this position changeable valve identification process will not be exhaustive, as described below.

First, certain passive MOVs may not be modeled, even in the full PRA, because they were not perceived to have a risk significant safety function, (e.g., motor operated drain valves). Secondly, since the IRRAS/SARA model only contains the dominant accident sequences for each plant, both active and passive MOVs in the remaining non-dominant sequences will not appear. Before truncation, these non-dominant sequences were quantified using standard PRA MOV failure rates (approximately 10^{-5} to 10^{-3} failures per demand.) These sequences were not risk significant with these standard MOV failure rates, but could possibly be more significant if the higher valve failure rates appropriate to the mispositioning issue were used. For the same reason, certain MOVs in the dominant sequences are also not included. These are valves which are in cutsets that were truncated from the sequence, when using the standard failure rates. Again, use of larger failure rates would make these cutsets more significant. Finally, since the dominant accident sequences and system designs are plant specific, consideration of selected plants also limits the systems and valves considered.

There is some concern that the base case PRA MOV failure rates should actually be considerably above base case values to account for poor MOV operation under high dP or high flow conditions, as discovered during GL 89-10 testing. The current base case failure rates were derived from experience obtained from stroke testing and operation of MOVs generally, without high dP or flow across them. To be consistent with existing PRAs, standard MOV failure rates

[c] IRRAS 2.5 and SARA 4.0 were used for this analysis. Use of SARA is equivalent to the use of the sequence/cutset analysis portion of IRRAS.

were used as a base case in this analysis. It should be noted that the occurrence of scenarios resulting in the maximum design dP or flow at a particular valve, when it is called upon to operate, is somewhat unlikely. Further, the use of lower base case failure rates typically results in a larger risk increase upon failure. Thus, such an assumption should be conservative.

MOV Identification

Several steps were taken to include as many position changeable MOVs in these scoping studies beyond the limitations of the IRRAS/SARA models. Most of the truncated valves are identifiable from the PRA documentation or the system flow diagrams. Once identified, their relative risk-significance (at a failure rate of 1.0 failures per demand) can be estimated by failing the equivalent function modeled in the PRA, which is affected by the MOV failure. For example, if a normally open MOV in a pump suction line is to be evaluated in a failed closed position, but it does not specifically appear in the PRA, the change in CDF due to its failure can be approximated by the failure of the pump. This procedure can be used to evaluate valves in truncated cutsets, as well as valves which were not modeled, but only for plant systems which appear in the dominant accident sequences.

MOV failure rates are adjusted and, where necessary, functionally equivalent components are failed as well. The appropriate MOVs and components are determined through reviews of the PRAs and system flow diagrams. An additional analysis of each PRA was performed with IRRAS/SARA to identify any additional systems which did not have any MOVs in the dominant sequences but, when failed, result in noticeable increases in the CDF. These systems were then reviewed to determine if they contained MOVs that had been eliminated during the truncation process discussed previously. System flow diagrams were then used to determine if any functionally equivalent components to these MOVs could be identified. However, no equivalent components were found for valves determined in this manner, which could be used to determine their increase in CDF when failed. Since neither the MOVs or equivalent components are in the dominant cutsets it is likely (although not certain) that the risk significance of mispositioning these MOVs is low.

This process should identify most of the risk-significant position-changeable MOVs, and will provide a quantitative estimate of the risk importance of mispositioning the individual MOVs. However, it should be clear that the results are not intended to be a comprehensive list of all mispositionable valves that must be included under GL 89-10.

Multiple Valve Mispositionings

In identifying valves for evaluation at BWRs, only single valve mispositionings were considered. An investigation, which included a visit to the Shoreham (a BWR-4) Control Room Simulator, revealed that no single control could operate valves in different system trains. Therefore, it was not considered credible for BWRs that an operator would inadvertently misposition more than one valve. There is multiple control of some valves in series, i.e., in the same piping with the same function. However, these are usually isolation valves where the inadvertent closing of two valves would have the same effect as closing one. Also, valves which are aligned in series with another valve having the same function, but with separate controls, were not evaluated in cases where inadvertent operation of both was required for system degradation. Inadvertent opening of one of two MOVs in series would not change the dP across it.

For the PWR plants, several pairs of valves in each plant were evaluated for the potential for simultaneous mispositioning. These valves were identified from system diagrams as similar valves in multiple train systems, whose common-cause failure (CCF) could result in significant system consequences. This CCF evaluation also considered the location of the controls for these MOVs. As in the case of BWRs, operation of valves in series, (i.e., the same piping with the same function) were not considered as part of the CCF analysis.

SAFETY SIGNIFICANCE OF MOVS

Sensitivity Study

The methodology described in the previous section can be used to determine the increase in the plant CDF, assuming that any of the identified MOVs is mispositioned and a differential pressure or flow condition exists that prevents the valve from returning to its required position.

When calculating the risk importance of the position-changeable MOVs, the failure rate of these MOVs was increased to 1.0 failures per demand. This was a simplification and can more properly be expressed as follows.

First, one assumes that an initiating event for a particular PRA accident sequence (e.g., station blackout) has occurred. For the valve to fail through the mispositioning scenario considered in this analysis, the following must occur:

1. The MOV must be moved to an incorrect position.
   (Probability = $P_{misposition}$)

2. There must be a high dP or high flow condition at the valve.
   (Probability = $P_{Hi\ dP}$)

3. The valve must then fail to reposition when (and if) recovery is attempted.
   (Failure Rate, FR = $FR_{reposition}$)

Thus the correct expression to use for the failure rate of the MOVs in the PRA calculations would be

$$FR_{PRA} = P_{misposition} \times P_{Hi\ dP} \times FR_{reposition}$$

As stated above, the initial calculation, performed separately for each valve, assumed that both probabilities were 1.0 and that $FR_{reposition}$ was 1.0 failure per demand. One should note also, that even this more detailed expression is somewhat of a simplification. For example, other possibilities that could be considered are the failure of the operators to even attempt repositioning, or normal hardware failures of the MOV during an attempted repositioning.

The actual determination of probability values for $P_{misposition}$ and $P_{Hi\ dp}$ is quite difficult and beyond the scope of this study. Also $FR_{reposition}$ may not be as high as 1.0 failures per demand. Therefore a sensitivity study was performed to determine the effect on CDF as the value

$$FR_{PRA} = P_{misposition} \times P_{Hi\ dP} \times FR_{reposition}$$

is varied between the lower base case MOV failure rate values of the PRA and the high value of 1.0 failures per demand.

The PRA base case values for MOV failure rates are generally in the range of 1×10^{-5} to 3×10^{-3} failures per demand. The sensitivity study was done for three values of FR_{PRA} between 10^{-3} and 1.0 failures per demand. This sensitivity study only included valves having a CDF for a failure rate of 1.0 failures per demand greater than two times the base case PRA CDF (with standard valve failure rates). The change in CDF for these valves at failure rates less than 1.0 failures per demand would be less than twice the base case PRA CDF, and would not be considered significant.

A summary of the results are shown in Tables 1 and 2. More detailed results and explanations of some anomalies in the tables are presented in Ruger, et al (1991) and Ruger, et al (1993). The tabulated results are presented in the form of a risk increase ratio (RIR) which represents the ratio between the CDF with the indicated valve failure rate and the CDF of the base case PRA model with the standard valve failure rate. Note that none of the identified valves for Oconee 3, for which risk increase ratios could be obtained, had RIRs greater than 2.0. Therefore, no Oconee MOVs appear in Table 2.

The base case CDF of each PRA model is taken as the "point estimate" of the total CDF for internal events. Note that the point estimate of CDF is different from, and slightly lower than, the statistically derived mean value of CDF. The RIR is a measure of the relative risk-importance of each of the MOVs listed in the table. Valves which do not receive an automatic signal to change position, but which may be required to perform a function by remote manual (Rem. Man.) activation, are considered as active and are so indicated. Valves which are blocked (e.g., power removed) from inadvertent mispositioning are also indicated and are included in the analysis because similar valves at other plants may not be blocked.

It should be noted, that while the maximum risk increase ratios for unblocked MOVs are about the same order of magnitude for both PWRs and BWRs, the base case CDFs for the two PWRs considered here are significantly larger than the CDFs for the two BWRs. This difference in internal event CDF is typical for BWRs and PWRs in the U.S.(NRC, 1990b). This was also supported by a survey of the CDFs from twenty recent Individual Plant Examinations (IPEs), which included ten PWRs and ten BWRs. Therefore, even though the risk increase ratios may be comparable, the actual CDFs and changes in CDF will be larger for PWRs.

Calculations for Multiple Valve Mispositioning

In addition to the single MOV mispositionings considered in Tables 1 and 2, several pairs of valves were considered to have the potential for simultaneous mispositioning resulting in common-cause failures (CCF) at PWRs. These valves were identified from the flow diagrams for systems contained in the dominant accident sequences. The valves were selected when their CCF could result in significant system consequences, such as disabling of redundant trains. The identified MOVs are shown in Table 3, which also includes the results of a sensitivity study which considers both valves of each pair to have the indicated failure rate. As a check of the completeness of the CCF valve selection process, an earlier PC-based version of the Oconee 3 PRA (NSAC, 1984), which has the ability of evaluating pairwise failures of all MOVs in the dominant sequences, was run. All of the pairs of MOVs with significant risk increase ratios determined by this calculation were already included in Table 3, thus providing a confirmation of the valve selection process.

As expected, the risk increase ratio for multiple valve mispositionings is noticeably higher than for single valve mispositionings. However, the three probabilities contributing to the MOV failure rate discussed above are most likely lower for multiple valve events than for a single mispositioning event. This should be considered when evaluating the risk significance of multiple mispositionings.

To provide some basis for evaluating the potential for the occurrence of the multiple valve failures identified in Table 3, control room drawings for the respective plants were consulted to determine the relative locations of the controls for these pairs of MOVs. Information obtained from this study is provided in Table 3. Except for the Oconee 3 EFW valves, 3C-156 and -158, which have a relatively low paired risk increase ratio to start with, all other MOV pairs have controls which are in close proximity on the same control panel.

No analysis of the probability of simultaneously mispositioning these pairs of valves was performed, but this probability is expected to be small. However, the possibility of multiple valve mispositionings is worthy of consideration due to the high risk potential associated with such events.

In discussing multiple MOV mispositionings it is appropriate to consider the Davis-Besse event (NRC 1985a). The relevant portion of this event concerns the inadvertent pushing of the wrong two buttons, which closed two MOVs and isolated both steam generators from the emergency feedwater supply. The valves apparently were unable to be reopened because of high differential pressures that had developed, which then caused the torque switches in the valve operators to trip.

While this represents a significant common cause mispositioning event, the system involved is not typically found in PWRs. The MOVs involved were controlled by the Steam and Feedwater Rupture Control System (SFRCS). The SFRCS was designed as an engineered safety features actuation system for postulated transients or accident conditions initiated in the secondary side of the plant. The system senses loss of main feedwater (MFW) flow, rupture of an MFW line, and rupture of a main steamline. The safety function of the SFRCS is to provide safety actuation signals to equipment that will isolate the steam flow from the steam generators, isolate the MFW flow, and start and align the AFW system. Therefore, the inadvertent manual remote actuation of the wrong switches in the SFRCS signalled that both generators had experienced a steamline break or leak. The system responded, as designed, to isolate both steam generators. This defeated the safety function of the AFW system, which was needed for the event.

Neither Surry 1 or Oconee 3 have an SFRCS, nor is this system typical of other PWRs. Surry 1 has a large redundancy of MOVs isolating the AFW pumps from the steam generators. In fact, it would take six independent actions to cause such an isolation. For Oconee 3, four independent MOV mispositionings would be required to isolate the EFW pumps from the steam generators.

SUMMARY

MOVs are generally acknowledged to be important components in nuclear power plants when evaluated, either using conventional engineering judgement or using PRA type risk assessment techniques. The calculations performed as part of the value-impact assessment (Higgins, et al, 1988) for GL 89-10 showed that large risk increases occurred when groups of MOVs had their failure rates increased.

After the issuance of both Bulletin 85-03 and GL 89-10, subsequent testing and analysis identified significant engineering problems with MOVs, requiring extensive modifications and repairs to return the valves to a fully operable status. A significant amount, but not all, of the required work has already been completed.

One area not fully resolved is the consideration of valve mispositioning. Full consideration of this issue is difficult from an engineering analysis standpoint due to the many possible scenarios for mispositioning, some of which will have higher dPs and flows than the typical valve design basis. Questions naturally arose from industry as to the risk significance and the diminishing safety returns of fully analyzing and addressing this issue. Was the NRC requiring too much in this instance?

The studies described herein developed risk measures that allow a reasonable evaluation of the importance of individual and pairwise mispositioning events. Informed judgements can thus be made about the need for further actions in this area. As a result, it was determined in Supplement 4 to GL 89-10 (NRC, 1992) that BWRs need not further consider mispositioning. PWR plants had higher risk values and the final determination for PWRs was still under consideration a the time of the writing of this paper.

Care should be used in employing these results. The purpose of this study was to provide input to resolution of the industry's questioning of the risk-significance of the MOV mispositioning issue. The results provide a representative measure of the risk-significance of the issue derived from a sampling of PRAs. The study is limited in the number of valves by plant specific

considerations and the characteristics of the PRA models used. Different plants may employ different valve configurations than the two plants considered here. In addition, individual plants often have plant specific vulnerabilities which determine which sequences or cutsets are risk-significant. Also, PRA modeling assumptions and the PRA truncation process may have eliminated some risk-significant MOVs from the models used. For these reasons, the results should be used to obtain a representative measure of the risk significance attached to the mispositioning of MOVs in BWRs and PWRs and not to determine a restrictive list of position-changeable valves to be included under Generic Letter 89-10.

Given these constraints, the risk increase ratios resulting from these failure rate sensitivity studies can be used as a basis for a judgemental determination of the risk significance on the MOV mispositioning issue for BWRs and PWRs.

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Table 1. Failure Rate Sensitivity Analysis for Risk Significant MOVs (BWRs)

No.	System[a]	MOV	Active/Passive	Failure Rate (failures/demand) 10^{-2}	10^{-1}	0.5	1.0
GRAND GULF				Risk Increase Ratio[b]			
1.	SSW	MV11	Active	1.07	2.0	5.9	10.9
2.	SSW	MV1A, MV1B MV5A, MV5B MV18A, MV18B	Active	1.04	1.6	3.8	6.7
3.	RCIC	MV68	Active	1.01	1.2	2.2	3.7
4.	RCIC	MV10, MV13 MV19, MV23, MV31, MV45, MV46, MV63, MV64	Active	1.01	1.2	2.0	3.0
5.	HPCS	MV1, MV4, MV12, MV15	Active	1.01	1.2	1.8	2.6
6.	HPCS	MV23	Passive	1.01	1.2	1.8	2.6
PEACH BOTTOM				Risk Increase Ratio[b]			
7.	HPCI	MV14, MV15 MV16, MV19	Active	1.01	1.2	1.8	2.6
8.	HPCI	MV17, MV57, MV58	Active	1.01	1.1	1.7	2.4
9.	HPCI	MV20	Passive	1.01	1.1	1.7	2.4
10.	SLC	Pump Suction	Active	1.05	1.8	4.9	8.9

[a] System Acronyms
HPCI - High pressure Coolant Injection System, HPCS - High pressure Core Spray System, RCIC - Reactor Core Isolation Cooling System, SLC - Standby Liquid Control System, SSW - Standby Service Water System

[b] The risk increase ratio indicated in the table represents the ratio between the CDF with the failure rate of that valve set the indicated value and the CDF of the base case PRA model with the standard valve failure rate. The "point estimate" base case CDF is 2.06×10^{-6} events/Rx yr for Grand Gulf and 3.62×10^{-6} events/Rx yr for Peach Bottom.

Table 2. Failure Rate Sensitivity Analysis for Risk Significant MOVs (PWR)

	No.	System[a]	MOV	Active/Passive	Failure Rate (failures/demand) 10^{-2}	10^{-1}	0.5	1.0
SURRY 1					Risk Increase Ratio[b]			
	1	ACC	1865A	Active	1.1	2.6	8.8	16.6
	2	ACC	1865B	Active	1.1	2.6	8.8	16.6
	3	ACC	1865C	Active	1.1	2.6	8.8	16.6
	4	LPI	1890C	Passive[c]	1.5	5.6	24.4	47.9
	5	LPR	1860A	Active	1.03	1.5	3.3	5.7
	6	LPR	1862A	Active	1.02	1.5	3.3	5.7
	7	LPR	1890A	Passive[d]	1.03	1.4	3.1	5.2
	8	HPI	1350	Active-Rem. Man.	1.02	1.2	2.1	3.1

[a] System Acronyms
ACC - Accumulator System, HPI - High Pressure Injection System, LPI - Low Pressure Injection System, LPR - Low Pressure Recirculation System

[b] The risk increase ratio indicated in the table represents the ratio between the CDF with the failure rate of that valve set to the value at the top of the failure rate column and the CDF of the base case PRA model with the standard valve failure rate. The "point estimate" base case CDF is 3.20×10^{-5} events/Rx yr for Surry 1 and 1.78×10^{-5} events/Rx yr for Oconee 3.

[c] Open, Power Removed

[d] Closed, Power Removed

Table 3. Sensitivity Analysis for Potential Common-Cause Failure Risk Significant MOVs (PWRs)

				Failure Rate (failures/demand)				
No.	System[a]	MOVs	Active/Passive	10^{-2}	10^{-1}	0.5	1.0	Relative Control Locations
SURRY 1								
1	ACC	1865B&C	Active	1.3	3.9	12.7	16.6	Adjacent
2	HPI	1115B&D	Active	1.00	1.6	15.7	59.8	Adjacent
3	LPI	1864A&B	Active	1.01	1.6	13.3	48.4	In Close Proximity
4	LPR	1862A&B	Active	1.03	1.9	14.5	48.0	In Close Proximity
5	PPRS	1535 & 36	Active	0.99	1.02	1.2	1.4	Adjacent
OCONEE 3								
1	HPI	HP-24 & 25	Active	1.00	1.5	12.2	46.0	In Close Proximity
2	LPI	LP-19 & 20	Active	1.01	1.9	20.9	79.0	Adjacent
3	LPI	LP-12 & 14	Passive	1.00	1.4	11.0	41.0	Adjacent
4	LPI	LP-17 & 18	Active	1.00	1.5	11.1	41.0	Adjacent
5[b]	LPI	LP-5 & 8	Passive	1.4	4.9	20.6	50.0	Adjacent
6[b]	LPI	LP-21 & 22	Active	1.4	4.9	20.6	50.0	Adjacent
7[c]	EFW	3C-156 & 158	Active	0.97	1.02	1.6	4.0	On diff. vert. back panels.

[a] System Acronyms
ACC - Accumulator System, EFW - Emergency Feedwater System, HPI - High Pressure Injection System, LPI - Low Pressure Injection System, LPR - Low Pressure Recirculation System, PPRS - Primary Pressure Relief System

[b] Simulated by failure of pumps 3LP-P3A&B

[c] Simulated by the failure of all EFW pumps

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