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Improvement of Pressurizer PROV System through Micro-Computer and PRA

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마이크로 컴퓨터와 확률론적 리스크 평가를 통한 가압기 보호계통의 설계 개선

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Abstract

Small break LOCA caused by a stuck-open PORV is one of the important contributors to nuclear power plant risk. This paper deals with the design of a pressurizer surveillance system using micro-computer to prevent the malfunction of system and has assessed the effect of this improvement through Probabilistic Risk Assessment (PRA) method. Micro-computer diagnoses the malfunction of system by a process checking method and performs automatically backup action related to each malfunction. Owing to this improvement, we can correctly diagnose "Spurious Opening", "Fail to Reclose" and "Small break LOCA" which are difficult for operator to diagnose quickly and correctly and reduce the probability of a human error by an automatic backup action.

요　　약

TMI와 월성 사고 이후 PORV를 통한 Small LOCA는 원자력 발전소 리스크의 중요한 요소로 부각되었다. 본 논문에서는 이 계통을 통한 Pressurizer Surveillance System의 설계와 그에 따른 영향을 확률론적 리스크 평가(PRA) 방법으로 해석하였다.

마이크로 컴퓨터는 계통의 고장(Malfunction)을 공정 확인 방법(Process Checking Method)으로 진단하고 그 진단에 따른 후속 동작(Backup Action)을 자동으로 수행한다. 이러한 개선에 따라 운전원의 빠르고 정확한 판단이 어려웠던 "Spurious Opening", "Fail to Reclose" 및 "Small Break LOCA" 등의 진상(Symptom) 이 정확히 진단되고, 후속 동작의 자동화로 인하여 인간 실수 확률이 기계적 실수 확률로 감소 하게 되었다. 결국, 이러한 개선은 계통의 신뢰도 증가로 Small LOCA 확률의 감소를 가져다 준다.

I. Introduction

Considerable interest has been focused on the small break LOCA caused by a stuck-open Power-Operated Relief Valve (PORV) in recent years, since TMI accident and Wol Sung (WS) incident. The small break LOCA caused by a stuck-open

PORV accounts an important part in small break LOCA which is one of the important contributors in nuclear power plant risk.

Therefore, this small LOCA frequency must be decreased so that we can reduce the risk of nuclear power plant. To perform this purpose, at first, the related part from TMI accident and WS incident is briefly explained as follows.

TMI Accident

PORV is opened by the perssure build up of a primary system due to undercooling which is caused by a total loss of feedwater. The PORV, which should have closed as the primary system pressure dropped, failed to reclose. This event initiated a small break LOCA.

This situation was continued for 2 hours and 18 minutes after initiating event until the block valve upstream from the PORV was shut. This phenomenon can be regarded as "Fail to Reclose of PORV".

WS Incident

Pressure protection function of CANDU PWR heat transport system is performed by a Liquid pressure Relief Valve (LRV). The closure and opening of a LRV is actuated by pressurized air through three solenoid valve. LRV is actuated by a 2 out of 3 logic.

The plant personnel were carrying out a routine test of the heat transport system liquid relief valve. During the test a fuse blew and the electrical power supply to one of the three channels was lost. Coincident with this another channel had been failed and so the liquid relief valve opened.

This situation had been continued for 30 minutes until fuse was rechanged. This event caused heavy water of the heat transport system to spill into the containment building. The phenomenon can be represented as "Spurious Opening" of relief valve due to the malfunction of pressure protection system.

The importance of a small break LOCA through PORV can be sufficiently perceived by above experience and others. In this work, the concept of process checking method through micro-computer is introduced to diagnose the malfunction of pressurizer pressure protection system. And this paper deals with the design of pressurizer pressure surveillance system using process checking method and the assessment of the developed system.

As a result, the reliability of pressurizer PORV system is increased and the probability of a small LOCA through PORV is decreased. To evaluate this improvements through PRA methodology, data of Reference 1 were used.

II. Developed System Description

II. 1 Description of Present System

Subsequent to the incident at TMI, several modifications in plant design and operation have been implemented to reduce the number of challenges to the PORV. To evaluate the improvement of this work, the PWR plant implemented with TMI action items (post-TMI modification plant) is considered as a reference plant. Therefore, this section brief description of the post-TMI modification.[2]

First, the derivative time constant was removed in the PID controller for the pressurizer PORV. Removal of the derivative action will decrease the likelhiood of opening the PORV since the actuation signal for the valve is then no longer sensitive to the rate of change of pressurizer pressure.

Second, the setpoint on the PORV interlock bistable was changed from 2185 psig to 2335 psig, equivalent to PORV opening setpoint. This change makes the pressure control signal a redundant signal and makes the frequency of an inadevertant PORV opening much smaller, The spurious PORV opening frequency is expected to decrease due to the effect of coincident logic or random process measurement failures. This should eliminate the PORV actuation due to pressure transmitter or channel failures.

Third, the Westinghouse Reference Emergency Operating Instructions (EOI) have been updated to include notes and specific procedural steps to isolate PORVs. These EOIs have been incorporated into plant specific procedures, the stuck-open PORV during another transient, not common practice prior to TMI, was included on operator training program.

These changes virtually assure that the PORV is closed in any questionable situation, the additional familiarity with this transient makes the operator's diagnosis more reliable and exact in backup action according to the diagnosis.

An assessment of the effect of modifications on the PORV challenge rate and on the probability of small LOCA through PORV is discussed in reference 1.

II. 2 Description of Developed System

II. 2. 1 Diagnosis of Malfunction and a Backup Action

Each malfunction is diagnosed by the process checking method and the backup action to the diagnosis is automatically performed. This can be described in detail as follows.

Spurious Opening

Micro-computer continuously checks the signal of PORV position sensor until PORV is opened, at the node B in figure 1. If PORV is opened, micro-computer check the signal of pressure sensor whether RCS pressure is above PORV open setpoint or not. If RCS pressure is below PORV open setopoint, this situation implies "Spurious Opening". That means PORV is opened regardless of the status of RCS pressure.

Therefore, micro-computer diagnoses this malfunction as "Spurious Opening" and transmits the information on the CRT in the control room. Also, micro-computer performs the backup

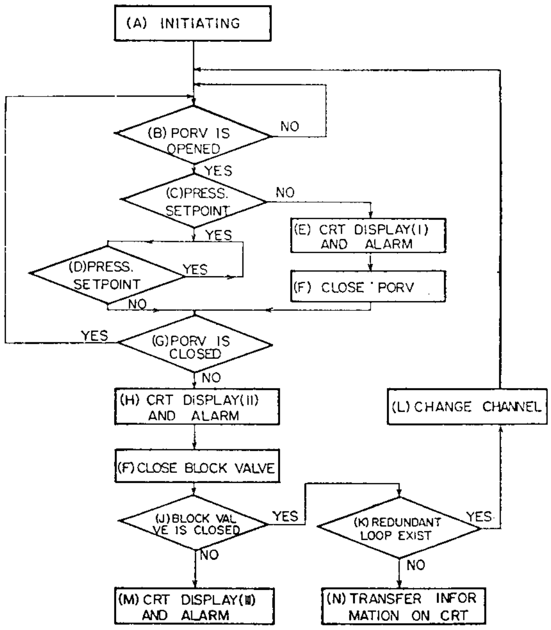


Fig. 1. Logic flow Block Diagram

action which tramsmits the generated PORV closure signal to an actuation device.

Fail to Reclose

At the D node, micro-computer checks the signal of a pressure sensor until pressure is below setpoint. If pressure is below setpoint, micro-computer checks PORV closed after delay time, valve actuation duration time. Also, after actuation of backup action for "Spurious Opening" at the F node, micro-computer ckecks that PORV is closed after delay time. As a result, if PORV is closed, micro-computer returns to the node B and prepares for checking of the next PORV opening. If PORV is still opened, this situation implies "Fail to Reclose". That means PORV which should have been closed is still open due to any causes.

Therefore, micro-computer diagnoses this malfunction as "Fail to Reclose" and transmits the information on the CRT in the control room. Also, micro-computer performs backup action which transmits the generated signal of block valve closure to control unit.

Small LOCA through PORV

After actuation of backup action for "Fail to Reclose", micro-computer checks whether block valve is closed or not. If a block valve is still open, this situation is called "Small LOCA through PORV". Therefore, micro-computer transmits a warning message, "Small LOCA through PORV", on the CRT. If block valve is closed, micro-computer transmits the information of a present state on the CRT.

II. 2. 2 Automation of PORV Block Valve

Actuation of PORV block valve is automatized. Block valve is automatically actuated when required by a process checking method. Of course, the system is allowed to place in manual or automatic to allow full manual control of the block valve when needed. A detail effect of this change is described in section III. 2.

III. Assessment of Developed System

To assess the developed system, Probabilistic Risk Assessment (PRA) technique is used and described in detail as follows.

III. 1 Top Event Definition

The following definition of a small break LOCA through PORV as the top event will be used to quantity the probability of such an event.

Steam release from the PORV will be considered a small break LOCA if the magnitude and duration is sufficient to automatically actuate safety injection on low pressurizer pressure.

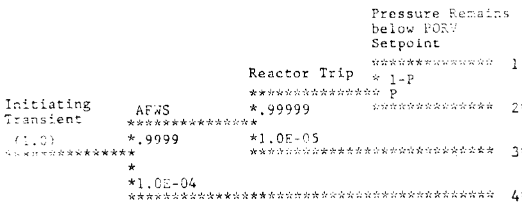
According to the above definition, a transient which results in a PORV opening and subsequent depressurization is not classified a small LOCA if the PORV is closed or blocked prior to satety injection actuation on low pressurizer pressure. Similarly, a PORV leak or incomplete closure would not constitute a small break LOCA unless the primary pressure and level control system failed to maintain pressure or inventory, resulting in an eventual actuation of safety injection.

For a loss of all feedwater transient, the time duration between the initial pressure decrease below the PORV closure setpoint and the initiation of safety injection is approximately 2 to 3 minutes.

III. 2 Post-TMI Event Tree

The transients chosen as initiating events for the PORV LOCA evaluation include those which have the potential of causing the PORV to open. The probabilities for the PORV opening, safety valves opening and the PORV being closed are incorporated into the branch nodes of the transient event trees. Initiating events are classified with 16 categories listed in Table 1. Blanch node in relation to failure of mitigating safety systems where lifting the PORV is a certainty is not considered. The reason of above consideration will be explained as examples. Figure 2 shows a sub-level event tree which depicts how the ATWS and loss of AFWS are considered in the event tree.

In this analysis, one of the most important questions which must be answered is, what probability will the PORV set pressure be exceeded assuming that AFWS and reactor trip function as designed with. This probability is designed "P" on the Figure 2. The Uncertainty in estimating the value of P either from transient



* Indicates paths where pressure exceeds the PORV setpoint

P	$P^* = P_2 + P_3 + P_4$
.2	.200088
.4	.400066
.6	.600044
.8	.800022

Fig. 2. Treatment of ATWS and Loss of AFWS

Table 1. Event Tree Initiating Events Condisered

Transinent Number	Transinent Name
T 1	Loss of Main Feedwater, Offsite Power Available
T 2	Loss of Main Feedwater due to and Co-ncident with loss of Offsite AC Power
T 3	Loss of Main Feedwater Concident with loss of all AC Power
T 4	Turbine Trip
T 5	Large Load Rejection without Turbine Trip
T 6	Misv Closure-all Loops
T 7	Inadverent Safety Injection *High Head Plant*
T 8	Main Feedline Rupture, *High Head Plant*
T10	CVCS Malfunction Resulting in Power Increase
T11	Complete Loss of Reacter Coolant Flow
T12	Partial Loss of Reacter Coolant Flow
T13	Locked (ORSheared) Reacter Coolant Pump Roter
T14	Uncontrolled Bank Withdrawal Resulting in Power Increase
T15	Suprious PORV Opening
T16	Excessive Steam Generator Tube Leakage or Tube Rupture

simulation or data analysis does not justify the explicit inclusion of safety systems fialures such as the Reactor Protection System (RPS) or AFWS. Therefore, they will be ignored.

The event tree used for transients T_1 through T_{14} and T_{16} is shown in Figure 3, while the simple and more specialized event tree for the spurious PORV opening is shown in Figure 4.

The description of a branch nodes which are utilized in the event tree is offered in reference 1. Each path endpoint is categorized by a

Table 2. Consequence Description

Design-ation	Description
NR	No PORV or safety valve relief occurs
RR	Relief occurs but valve recloses on demand
R 3	Relief occurs, valve fails open, reclosed within 3 minutes of close demand
R10	Relief occurs, valve fails open, reclosed within 10 mintues of close demand
RVO	Relief fails open and unisolated within 10 minutes or unisolatable
SVO	Safety valve fails open and remains open

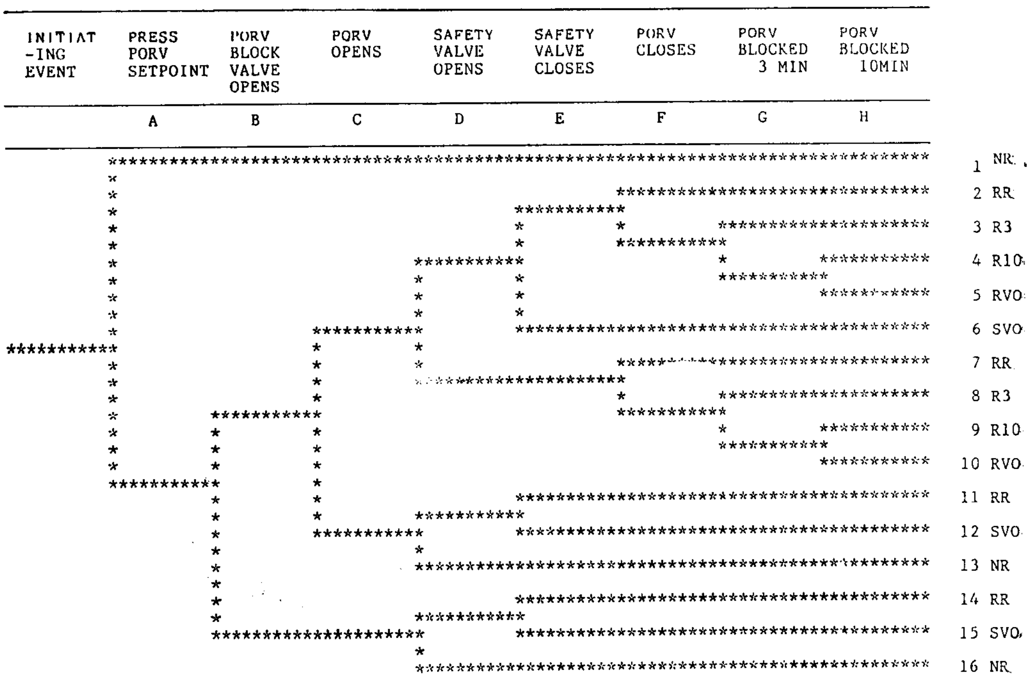


Fig. 3. Transient Event Tree for Transinents T1 through T14 and T16 in Post-TMI

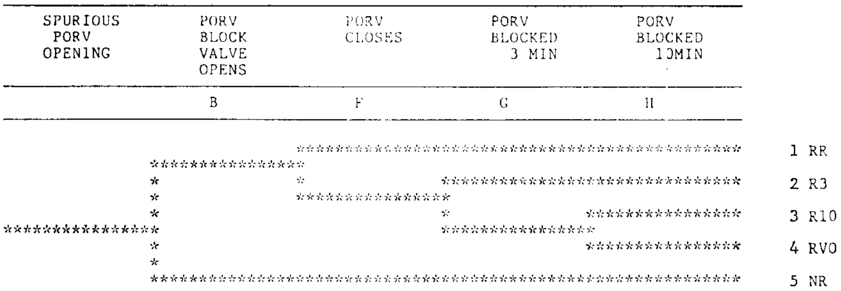


Fig. 4. Transient Event Tree for Spurious PORV Opening in Post-TMI

consequence description, as Table 2. Consequence categories R10 and RVO will be classified as small-break LOCA through PORV while SVO is a small-break LOCA through safety valve. The path endpoints on each of the transient event trees are labeled with one of the consequence categories.

III. 3 Event Tree with Developed System

III. 3. 1 Deletion of a PROV blocked node

The node B of post-TMI event tree represent whether one PORV block valve is open or not, when the challenge to the PORV occurs. Intentional PORV blocking due to valve leakage is incorporated into the probability for sucess and failure at this node. The probability that block valve has been closed when the demand to the PORV occurs, is 55 percent. But, this node is deleted for the following reason.

The number of a pressurizer relief loop changes from two to three in the present current PWR plant. The more the number of a pressurizer relief loop increases, the more the probability of a block valve opening loop existence increases.

If a plant has three pressurizer relief loops, since the probability of one blocked loop existence is 55 percent, the probability of more than one block valve opening loop existence is 83 percent. By the sensitivity study in Section III. 4. 3, the more the proabbility of a blocked loop existence increases, the more the probability of total small LOCA through this system increases. Total small LOCA through this system means the sum of a small LOCA through PORV and safety valve. Therefore, if the probability of a blocked loop existence is reduced by a aministrative change or other efforts, the probability of more than one block valve opening existence will be increased.

As a result, Deletion of B node is more reasonable than the existence of B node in the event tree.

III. 3. 2 Change According to Automatic Block Valve

Since PORV block valve becme automatic in this improvement, the judement of a operator is not needed when closing PORV valve. That is, the consideration of a time dependent operator reliability is not significant. Therefore, the G node and H node of a Post-TMI event tree can be alternated with the F node in Figure 6.

In this event tree analysis, blanch node in relation to the failure of a valve position sensor is not considered. Figure 5 shows a sub-level event tree which depicts how the failure of a

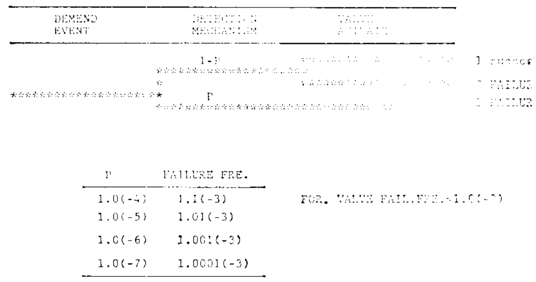


Fig. 5. Comparison of Valve Malfunction Versus Senser Failure

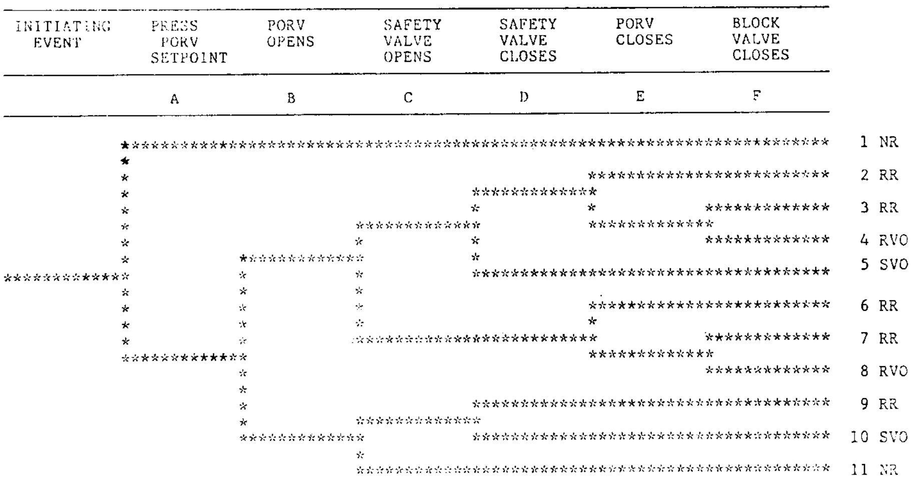


Figure 6. Event Tree with Developed System

valve position sensor is considered in the event tree.

The probability of a valve position sensor failure is designated "P" on the figure. And the probability of a block valve closure failure is assigned with 10^{-3} from a generic data. The malfunction frequency of a block valve closure system is the sum of endpoint 2 and endpoint 3. Due to the evaluation of a block valve closure system failure frequency according to several P value, this frequency is nearly independent with a P value, because a P value is and must be great less than a block value closure failure frequency. As a result, only node F can represent sufficiently the actuation state of a block valve closure system.

Event Tree with Developed System used for transients T_1 through T_{14} and T_{16} is shown Figure 6, while the simpler and more specialized

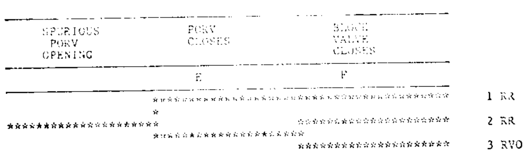


Fig. 7. Spurious Opening Event with Developed System

event tree for the spurious PORV opening is shown in Figure 7. And descridtions of event tree nodes is explained as follows.

Descriptions of Event Tree nodes

Node A Upward paths at this node indicate that a demand was not made on the PORV due to pressure increase above the PORV opening setpoint (2335 psia). Downward paths at this node indicate that the pressure was sufficiently high to cause the PORV to open.

Node B Upward paths represent PORV opening. Downward paths represent PORV staying closed.

Node C Upward paths represent the opening of safety valve. Downwards paths represent the safety valve staying closed The actual significance of this node is whether the safety valve set pressure is exceeded, i.e., the failure of a safety valve to open at pressure above its set pressure is not considered. The set pressure for safety valve is the RCS design pressure and is 2500 psia for Westinghouse plants. For the special cases where both the safety and relief valves are expected to open, the probability of the safety valve opening must reflect this.

Node D Upward paths represent the successful reclosing of a pressurizer safety valve when the pressurizer pressure falls below the set pressure. Downward paths represent the failure of a safety valve to reclose when the pressurizer pressure falls below the set pressure.

Node E Upward paths represent the successful reclosing of a pressurizer PORV when the pressurizer pressure falls below the PORV closure set pressure. Downward paths represent the failure of a PORV to reclose subsequent to an opening.

Node F Upward paths the successful reclosing of a pressurizer block valve when demand be required. Downward paths represent the failrue of a block valve to reclose subsequent to an opening.

III. 4. 1 Base Data

III. 4. 1 Base Data

In order to quantify the event tree paths, probability data for each path at each node is needed. The necessary data are three general types, including initiating event frequencies, system, component or human unreliabilities, and transient characteristic probabilities.

Initiating event frequencies allow the probabilities in each initiating event tree to be weighted. For transients which occur with high frequency, data from operating PWRs (based on 181 reactor years) is used. For estimation of an improbable transients frequencies, data are taken from WASH-1400 and generic data. The transient frequency data used are tabulated in Table 3. A more detailed description of the data can be found in Ref. 1, 3.

Specifically, it is necessary to know the probabilities of PORV and safety valves to close on demand, the failure probability of a PORV or block valve to operate on demand, and the reliability of operators to isolate stuck-open PORVs for variant transients. Also, according to the automation of block valve, the failure probability of a block valve to close on demand is needed. In this analysis, the failure probability of a block valve to close on demand is considered as the same as that of PORVs. Table 3 summarizes the data used for components system and operators.

Table 3. Frequency & Probability Data for Post-TMI

Transient	Frequency	P(A)	P(B)	P(C)	P(D : B or C)	P(D : B and C)	P(E)	P(F)	P(G)	P(H)
T 1	3.0	.01	.55	.01	.01	.001	.001	.001	.025	.005
T 2	0.27	.01	.55	.01	.01	.001	.001	.001	.025	.005
T 3	7.0E-6	.01	.55	.01	.01	.001	.001	.001	.025	.005
T 4	1.0	.0005	.55	.01	.01	.001	.001	.001	.025	.005
T 5	1.0	.05	.55	.01	.10	.01	.001	.001	.025	.005
T 6	0.07	.10	.55	.01	.20	.02	.001	.001	.025	.005
T 7	0.01	.13	.55	.01	.10	.001	.001	.001	.40	.05
T 8	1.0E-4	.005	.55	.01	.01	.001	.001	.001	.40	.005
T 9	1.0E-4	.13	.55	.01	.10	.001	.001	.001	.40	.005
T10	0.03	.001	.55	.01	.001	.001	.001	.001	.025	.005
T11	0.12	.005	.55	.01	.001	.001	.001	.001	.025	.005
T12	0.01	.025	.55	.01	.01	.001	.001	.001	.025	.005
T13	0.001	.25	.55	.01	.20	.001	.001	.001	.025	.005
T14	0.01	.01	.55	.01	.001	.001	.001	.001	.025	.005
T15	0.002	NA	.55	NA	NA	NA	NA	.001	.025	.005
T16	0.03	.50	.55	.01	.0	.0	NA	.001	.025	.005

Table 4. Post-TMI Frequency (Probability/Reactor-Year)

Transient	NR	RR	R3	R10	RVO	SVO	TOT
T 1	.30E+01	.43E−03	.34E−03	.34E−08	.17E−10	.30E−06	.30E+01
T 2	.20E+00	.90E−03	.87E−06	.22E−07	.11E−09	.12E−07	.20E+00
T 3	.70E−05	.32E−07	.30E−10	.78E−12	.39E−14	.70E−12	.70E−05
T 4	.10E+01	.22E−03	.22E−06	.55E−06	.28E−10	.50E−09	.10E−01
T 5	.97E+00	.25E−01	.22E−04	.55E−06	.28E−08	.30E−05	.10E+01
T 6	.94E+00	.25E−01	.43E−05	.11E−05	.56E−09	.12E−05	.10E+00
T 7	.47E−01	.33E−02	.17E−05	.11E−05	.58E−07	.36E−06	.50E−01
T 8	.20E−02	.45E−05	.27E−08	.17E−08	.89E−10	.60E−10	.20E−02
T 9	.19E−02	.13E−03	.69E−07	.44E−07	.23E−08	.15E−07	.20E−02
T10	.30E−01	.13E−04	.13E−07	.33E−09	.17E−11	.30E−10	.30E−01
T11	.12E+00	.27E−03	.26E−06	.66E−08	.33E−10	.60E−09	.12E+00
T12	.10E−01	.23E−04	.22E−07	.55E−09	.23E−11	.30E−09	.10E−01
T13	.86E−03	.14E−03	.11E−06	.28E−08	.14E−10	.29E−07	.10E−02
T14	.98E−02	.22E−03	.22E−06	.55E−08	.28E−10	.50E−09	.10E−01
T15	.11E−02	.90E−03	.88E−06	.22E−07	.11E−09	.00E+00	.20E−02
T16	.47E−01	.13E−01	.13E−04	.13E−04	.13E−08	.00—+00	.00E−01
Total	.55E+01	.50E−01	.44E−04	.20E−05	.65E−07	.49E−05	—

Table 5. Sensitivity Study-PORV Blocked 10%

Transient	NR	RR	R3	R10	RVO	SVO	TOT
T 1	.30E+01	.57E−03	.26E−06	.67E−08	.34E−10	.30E−06	.30E−06
T 2	.20E+00	.18E−02	.17E−02	.44E−05	.22E−07	.40E−08	.20E+00
T 3	.69E−05	.62E−07	.61E−10	.16E−11	.78E−14	.70E−12	.70E+05
T 4	.10E+01	.45E−03	.43E−06	.11E−07	.56E−10	.50E−09	.10E+01
T 5	.95E+00	.45E−01	.43E−04	.11E−05	.56E−08	.99E−06	.10E+01
T 6	.91E−01	.91E−02	.87E−05	.22E−06	.11E−08	.40E−06	.10E+00
T 7	.44E−01	.59E−02	.35E−05	.22E−05	.12E−06	.77E−07	.50E−01
T 8	.20E−02	.89E−05	.53E−08	.34E−08	.18E−09	.20E−10	.20E−02
T 9	.18E−02	.23E−03	.14E−06	.88E−07	.46E−08	.31E−08	.20E−02
T10	.30E−01	.27E−04	.26E−07	.66E−09	.33E−11	.30E−10	.30E−01
T11	.12E+00	.53E−03	.52E−06	.13E−07	.67E−10	.60E−09	.12E+00
T12	.10E−01	.45E−04	.43E−07	.11E−08	.56E−11	.99E−10	.10E−01
T13	.77E−03	.23E−03	.22E−06	.55E−08	.28E−10	.77E−08	.10E−02
T14	.96E−02	.45E−03	.43E−06	.11E−07	.56E−10	.50E−09	.10E−01
T15	.20E−03	.18E−02	.18E−05	.45E−07	.22E−09	.00E+00	.20E−02
T16	.33E−01	.27E−01	.26E−04	.26E−06	.27E−08	.00E+00	.60E−01
Total	.55E+01	.93E−01	.88E−04	.40E−05	.13E−06	.18E−05	—

Transient charactieristic data include the probabilities that the PORV setpoint will be exceeded for a giveninitiating event and the probabilities that the safety valve will open with and without the PORVs in service. These differ for each transient. The detail discussion of these parameters is included in reference 1.

Table 3 summarizes the frequency data, reliability data and the transient characteristic data used in the post-TMI baseline calculation. The symbols P(A), P(B), …represent the failrue probability at nodes A, B, …while P(D: B or C) means the probability of item D succeeding given a failure of B or C. This distinction must be made for the probability of a safety valve opening since the probability depends upon whether relief was achieved via the PORV.

A summary of the post-TMI baseline probabilities and frequencies is shown in Table 3. In the Table 7, the probabilities and frequencies for developed system is arranged. These are based on the data of post-TMI modification.

III. 4. 2 Result of Post-TMI

A post-TMI baseline calculation has been performed and is shown in Table 4. The plant simulated is a high head plant. Looking at the sum of RIO and RVO frequencies, the PORV LOCA frequency is found to be 0.21×10^{-5} for post-TMI assumptions. And SVO frequency is found to be 0.49×10^{-5} for post-TMI assumption.

Sensitivity studies have been performed relative to the post-TMI baseline to demonstrate the sensitivity of the friquencies to the probability of the PORV being blocked. This sensitivity studies have been performed to evaluate the effect of a redundant loop concept. A detailed description of this effect is shown in section III. 4. 3.

III. 4. 3. Evaluation of Developed System

A. Diagnosis of the malfunctions

Spurious PORV Opening

The Spurious PORV opening can be appeared when pressure transmitter or channel is failed, as well as pressuqe channels are tested due to failure to switch to a different control channel prior to the test.

If a Spurious PORV opening, though infrequent, is occurred, the mitigation of the transient is not easy, prior to improvement. This is because it is difficult for operator to perceive quickly this malfunction. In the post-TMI evaluation, the effect of this transient is so underestimated. In the post-TMI event tree, Figure 4, the node F is not appropriate for this tranisent Analysis. Since a pressure transmitter or channel has been already failed, PORV cannot be automatically closed.

Eventually, because PORV cannt be automati-

Table 6. Sensitivity Study-PORV Blocked 90%

Transient	NR	RR	R3	R10	RVO	SVO	TOT
T 1	.30E+01	.33E−03	.29E−07	.75E−09	.37E−11	.31E−06	.30E+01
T 2	.20E+00	.22E−03	.19E−06	.49E−08	.25E−10	.18E−07	.20E+00
T 3	.70E−05	.75E−08	.68E−11	.17E−12	.87E−15	.70E−12	.70E−05
T 4	.10E+01	.50E−04	.48E−07	.12E−08	.62E−11	.50E−09	.10E+01
T 5	.99E+00	.94E−02	.48E−05	.12E−06	.62E−09	.46E−05	.10E+01
T 6	.97E−01	.28E−02	.97E−06	.25E−07	.12E−09	.18E−05	.10E+00
T 7	.49E−01	.12E−02	.39E−06	.24E−06	.13E−07	.59E−06	.50E−01
T 8	.20E−02	.11E−05	.59E−09	.38E−09	.20E−10	.91E−10	.20E−02
T 9	.20E−02	.49E−04	.15E−07	.98E−08	.51E−09	.23E−07	.20E−02
T10	.30E−01	.30E−05	.29E−08	.74E−10	.37E−12	.30E−10	.30E−01
T11	.12E+00	.60E−04	.58E−07	.15E−08	.74E−11	.60E−09	.12E+00
T12	.10E−01	.54E−05	.48E−08	.12E−09	.62E−12	.46E−09	.10E−01
T13	.93E−03	.70E−04	.24E−07	.62E−09	.31E−11	.45E−07	.10E−02
T14	.99E−02	.50E−04	.48E−07	.12E−08	.62E−11	.50E−09	.10E−01
T15	.18E−02	.20E−03	.19E−06	.50E−08	.25E−10	.00E+00	.20E−02
T16	.57E−01	.30E−02	.29E−05	.29E−07	.30E−09	.00E+00	.60E−01
Total	.56E+01	.17E−01	.97E−05	.45E−06	.15E−07	.74E−05	—

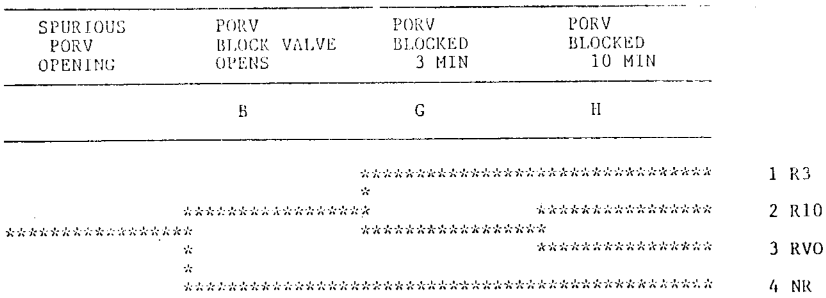


Fig. 8. Modification of Post-TMI Event Tree for Spurious PORV Opening

cally actuated, a PORV block valve must be used to mitigate the transient. Therefore, the operator reliability has to be considered as the G node and H node. According to the deletion of node F, reorganized event tree is presented as Figure 8. By this event tree, the frequency of a PORV small LOCA caused by a Spurious Opening is 2.24×10^{-5}. This value is very large, compared with the others. Of course, though the uncertainty of a data is existed and the malfunction due to this single transient does not nearly bring forth a severe result, this modal malfunction dominantly contribute to a PORV small LOCA can be perceived.

But, after this improvement, this malfunction is exactly diagnosesed by the process checking method and accompanied with an automatic babkup action, PORV closing. An automatic backup action is performed OR control gate or redundant closure control unit. Though PORV is not closed, the following malfunction symptom, fail to reclose, is diagnosed by the process checking method and a backup action is performed by the block valve closure. As the results, an exact symptom is offered and the unreliability of an operator is removed. The event tree with this improvement is shown in Figure 7.

Fail to Reclose

The diagnosis of this malfunction removes the unreliability of an operator when block valve is required to close. As a result, the node F in the developed system event tree substitutes for the node G and node H in figure 3. A PORV block valve is assumed to be a similar type with a PORV and the probability of a PORV failure to reclose is applied for block valve failure data. Therefore, a time dependent operator reliability, as shown Figure 9, is substituted by the probability of a PORV failure to reclose which is 10^{-3}.

B. Automation of a block valve

In order to evaluate the effect of an automatic PORV block valve closure system design, it is necessary to consider some characteristics.

First of all, an conceptual automatic PORV block valve control system, which the process checking method is not applied in, will be descried as follows.

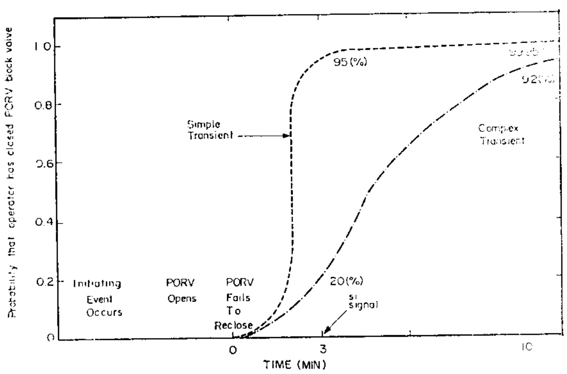


Fig. 9. Time Dependent Operator Rellabiitiy

Table 7. Developed System Frequency & Probability Data

Transient	Frequency	P(A)	P(B)	P(C/B)	P (C/B*)	P(D)	P(E)	P(F)
T 1	3.0	0.01	0.01	0.001	0.01	0.001	0.001	0.001
T 2	0.27	0.01	0.01	0.01	0.01	0.001	0.001	0.001
T 3	7.0E−06	0.01	0.01	0.01	0.01	0.001	0.001	0.001
T 4	1.0	0.0005	0.01	0.01	0.01	0.001	0.001	0.001
T 5	1.0	0.05	0.01	0.01	0.1	0.001	0.001	0.001
T 6	0.07	0.1	0.01	0.02	0.2	0.001	0.001	0.001
T 7	0.01	0.13	0.01	0.001	0.1	0.001	0.001	0.001
T 8	1.0E−04	0.005	0.01	0.001	0.01	0.001	0.001	0.001
T 9	1.0E−04	0.13	0.01	0.001	0.1	0.001	0.001	0.001
T10	0.03	0.001	0.01	0.001	0.001	0.001	0.001	0.001
T11	0.12	0.005	0.01	0.001	0.001	0.001	0.001	0.001
T12	0.01	0.025	0.01	0.001	0.01	0.001	0.001	0.001
T13	1.0E−03	0.25	0.01	0.001	0.2	0.001	0.001	0.001
T14	0.01	0.01	0.01	0.001	0.001	0.001	0.001	0.001
T16	0.03	0.5	0.01	0.0	0.0	0.001	0.001	0.001

In this conceptual automatic PORV block valve control system, the question as to whether the PORV and PORV block valve control signal receive from the same or different pressure channel is existed. The choice among these configurations depends upon wheher the failure to open the PORV when nteded is of greater significance than failure to isolate flow from the PORV or not. At any rate, whichever configuration is chosen, a PORV block valve must be coincidently open and closed together with a PORV. As a result, the following problems are considered.

First, due to coincident opening and closure, the challenge of PORV block valve actuation is increased than in the manual model. Consequently, the frequency of the system malfunction is increased. Second, in case that all of them fail to close due to common mode failure, small break LOCA through PORV is generated. For these reasons and others, this automatic PORV block valve closure system which is not applied the process checking method, has not been adopted.

But, if a process checking method is applied in the PORV block valve control system, a PORV block valve is not always coincidently opened and closed with PORV. It means that it is opened on normal condition and only closed when required. In other words, it is automatically closed when a transient is identified as fail to reclose. As a result, the challenge to PORV block valve opening and closure is more decreased and the frequency of a system malfunction is more decreased than that of formerly system. The quantitative effect due to this modification is the result of substitution the probability of value failure for the reliability of an operator.

C. Sensitivity study and redundant loop problem

Sensitivity study has been performed relative to the post-TMI plant to demonstrate the sensitivity of the frequencies to the probability of the PORV being blocked. This is reflected in the baseline cases which assumed that the PORVs were blocked 55% of the time. In this sensitivity study, the probability of node B was simply assigned at 10% and 90% to demonstrate the sensitivity of the frequencies. Tables 5 and 6

Table 8. Developed System Frequency (Probability/Reactor-Year)

Transient	NR	RR	RVO	SVO	Total
T 1	.30E+01	.30E−01	.30E−07	.33E−07	.30E+01
T 2	.27E+00	.27E−02	.27E−08	.27E−07	.27E+00
T 3	.69E−05	.69E−07	.69E−13	.70E−12	.70E−05
T 4	.10E+01	.50E−03	.49E−09	.50E−08	.10E+01
T 5	.95E+00	.50E−01	.49E−07	.50E−08	.10E+01
T 6	.63E−01	.69…−02	.69E−08	.15E−06	.70E−01
T 7	.87E−02	.13E−02	.13E−08	.26E−08	.10E−01
T 8	.10E−03	.50E−06	.49E−12	.54E−12	.10E−03
T 9	.87E−04	.13E−04	.13E−10	.26−−10	.10E−03
T10	.30E−01	.30E−04	.30E−10	.30E−01	.30E−01
T11	.12E+00	.59E−03	.59E−09	.60E−09	.12E+00
T12	.98E−02	.25E−03	.25E−09	.27E−09	.10F−01
T13	.75E−03	.25E−03	.25E−09	.75E−09	.10E−02
T14	.99E−02	.99E−04	.99E−10	.10E−09	.10E−01
T16	.15E−01	.15E−01	.15E−07	0.	.30E−01
Total	.55E+01	.11E+00	.11E−06	.77E−06	—

present the results of cases assuming PORV blocked 10% and 90% of the time respectively. There is nearly an order of magnitude difference in PORV LOCA frequency in going from 10% to 90% block rate. However, the total small LOCA frequency is increased by 130%.

According to this result, the probability of total small LOCA frequency is more increased as the PORV block rate is increased. Therefore, to decrease the PORV block rate is to decrease a total small LOCA frequency. By this reason, the the addition of a redundant loop is considered. But, this change accompanies with several effects.

First of all, because the number of a loop in creases, the probability of the PORV being blocked is decreased. But it makes the frequency of block valve actuation increase. As a result, it become a cause of the frequency of small LOCA increase.

To settle this problem, the sequential operational procedure using process checking method can be proposed. So to speak, as K node in Figure 1, in case that PORV of one loop is stuck opened and block valve is instantly isolated. Micro-computer checks whether a redundant loop which is not blocked is existed or not. If a unblocked redundant loop is existed, the loop become a now controlled loop. But, this sequential operational procedure accompanies with complexity of a system and the reliability problem of process checking. Therefore, the evaluation of the addition of a redundant loop and the sequential operational procedure is beyond the scope of this paper.

D. Results

Table 8 shows the result after the improvement in reference plant, and Table 9 presents the comparison before and after this improvement. The results shows that the probablity of a stuckopen PORV LOCA decreases from 2.1×10^{-6} per reactor year to 1.1×10^{-7} per reactor ʎear, and the probability of a safety valve LOCA from 4.9×10^{-6} per reactor year to 7.7×10^{-7} per reactor year. The probability of a spurious opening PORV LOCA has been reduced to 2.1×10^{-9} per reactor year, which is really negligible value.

Table 9. Comparision of Results

Case	PORV LOCA	Safety Valve LOCA	PORV LOCA Caused T15	Total Probability
Post-TMI				
High head Plants	0.21E−05	0.49E−05	0.23E−07	0.70E−05
PORV 10% Blocked	0.41E−05	0.18E−05	0.26E−06	0.59E−05
PORV 90% Blocked	0.47E−06	0.74E−05	0.50E−08	0.79E−05
Developed System	0.11E−06	0.77E−06	0.20E−08	0.88E−06
Post-TMI/Devel. SYS.	5.2%	16%	8.7%	12.6%

These represents approximately a reduction to 5% and 16%, in PORV LOCA frequency and safety valve LOCA frequency, respectively. The frequency of a spurious opening PORV LOCA reduced to approximately 0.01%.

IV. Conclusions and Recommendation

The developed pressurizer pressure surveillance system which uses a process checking method exactly diagnoses the malfunction of a system. The diagnosed malfunction categories are "Spurious Opening", "Fail to Reclose" and "Small LOCA through PORV".

After diagnosis, micro-computer transmits the information to the control room so that an operator can use it when needed, and automatically performs backup actions. These backup actions always act as the preventive direction of PORV small LOCA, which are the closure of a PORV and closure of a block valve. Therefore, although a backup action is actuated by the failure of a process checking system, the consequence never leads to PORV small LOCA. And the block valve has been modified to the automatic mode, to automatically perform the backup action. The automation of a block valve eliminates the term of a human reliability which is caused by an operator judgement error and delayed time.

The results of this improvement are that the frequency of a total PORV small LOCA is decreased by approximately one order and the frequency of PORV small LOCA caused by "Spurious Opening" is decreased by approximately four order of magnitude. That is, this developed surveillance system improves the reliability of a pressurizer pressure protection system, and leads to the decrease of the frequency of a small LOCA through this system.

In conclusion, the process checking method developed in this study can be applied any system and the applied system can improve reliability by the diagnosis of malfunction and a backup action. Besides these advantages, the technique for this improvement is simple and the cost of the system change for this improvement is quitely negligible.

Therefore, this develoded surveillance method can be recommended to be applied to the other important systems of a nuclear power plant.

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