Risk Assessment for Loss of Component Cooling Water Scenarios Based on WOG2000 Model and Considering the Effectiveness of RCP Passive Shutdown Seal

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Abstract: For pressurized water reactors (PWR), the biggest concern with losing component cooling water (CCW) is that the centrifugal charging pump (CCP) has to be manually tripped within 10 to 15 minutes of losing cooling, thus losing the reactor coolant pump (RCP) seal injection flow and thermal barrier cooling. In this situation, the RCP seal will be exposed to the high-temperature primary side cooling water and lead to RCP seal fail, resulting in loss of coolant accident (LOCA). To cope with this issue, many nuclear power plants have decided to replace the RCP seal by the new passive thermal shutdown seal (PSDS). The PSDS is a fail-safe protection device that will significantly reduce leakage from the RCP seal in case of loss of cooling. In Taiwan, the reference Nuclear Power Plant (MNPP) has accomplished the installation of RCP passive shutdown seal. Therefore, the purpose of this paper is to evaluate the benefits of RCP passive shutdown seal in the loss of component cooling water scenarios based on WOG2000 model proposed by the Westinghouse Owners Group (WOG) in WCAP-15603-NP, Rev.1. The assessment results show that the overall risk of loss of component cooling water scenarios can be reduced by about 53% to two orders of magnitude. The constructed probability risk assessment (PRA) model will be discussed in more detail in the paper and the difference between base and WOG2000 model will also be presented.

KEYWORDS: ***CCW, RCP Seal LOCA, PSDS, PRA***

1. INTRODUCTION

The biggest concern with losing all CCW systems is that the CCP has to be manually tripped within 10 to 15 minutes of losing cooling, thus losing the RCP seal injection. Since the coolant of the RCP thermal barrier is also lost, the RCP seal will also be exposed to the high-temperature primary side cooling water. This unfavorable environment will cause the RCP seal to fatigue or fail, and result in RCP seal LOCA. The PRA of most plants therefore assume that core meltdown occurs when all CCW systems are lost, but if the operator does the right thing (e.g. intermittently running the RHR pump to replenish reactor cooling water), there is still a chance that RCP seal LOCA can be avoided.
In addition to losing all CCW [represented as T(C1)], losing CCW A train[represented as T(CA)], losing all nuclear service cooling water [represented as T(C2)], and losing 4.16-kV vital bus A train [represented as TAPB] would result in similar scenarios. In this paper, the risk benefits of installing RCP passive shutdown seal is investigated using a PRA method and the above 4 types of scenarios are identified as initiating events (IEs).

2. METHODS

2.1. Basic model

The basic model does not take credit of the PSDS and a key assumption in the seal leakage model is the timing for RCP seal-LOCA. The model assumes that no RCP seal failure occurs within the first 30 min, and 5%, 95% failure probabilities within the first and tenth hours, respectively. According to the above assumptions, it can be described as a Weibull distribution[5-8], defined as

$$PDF_{weibull}[\alpha,\beta,\mu;t] = \frac{\alpha}{\beta}\cdot\left(\frac{t-\mu}{\beta}\right)^{\alpha-1} .\mathrm{Exp}\left[-\left(\frac{t-\mu}{\beta}\right)^{\alpha}\right]\ (for\ t>\mu), \quad (1)$$

where the seal failure probability is assumed to be zero if the random variable (seal failure timing t) is earlier than the delay time μ[9]. This leads to these parameters a shape parameter α of 1.38, a scale parameter β of 4.29, and a delay time parameter μ of 0.5 h, where we used the calculations t 0.95 = 10 – 0.5 = 9.5 and t 0.05 = 1 – 0.5 = 0.5.

In addition, if the operator is able to perform emergency cooldown (ECD) as directed in Emergency Operating Procedure (EOP) within the first 30 minutes, the probability of seal failure is assumed to be zero. Assuming that all three seals of the RCPs are suddenly opened simultaneously at a maximum seal leakage rate of 450 gpm/RCP, the total leakage rate is 1350 gpm, roughly equivalent to a small-LOCA event. In this case, the core uncovers in approximately 2 hours.

The basic models were modeled as event trees and are shown in Fig. 1. to Fig. 4., and the relevant PDS codes of the sequences are shown in Table I. The success criteria for each heading of the event tree are described below:

(1) K: Reactor Protection System Operation. After the reactor protection system is activated, the number of control rods not completely inserted into the core is not more than two bundles.
(2) Q: Reactor Coolant System Boundary Integrity. Any power operated relief valve (PORV) or safety valve (SV) of the pressurizer is stuck open, or the isolation of the PORV fails.
(3) L: Secondary Heat Removal. At least one train of auxiliary feed water system, main feed water system, condensate system, or starup feedwater pump successfully started.
(4) D(C): Maintenance of Seal Injection. When loss of all component cooling water systems , it is assumed that the RCP seal will not fail for at least the first 30 minutes. During this period, the operator must establish a backup cooling water source for component cooling pump (CCP) to maintain a CCP active and supply RCP seal coolant.
(5) X(C): Emergency Cooldown and Depressurization. The operator uses steam generator PORVs or blowdown system or steam dump valves in 30 mins to reduce temperature and pressure.
(6) J(C): Low-Head Safety Injection. After the reactor cooling water system was successfully depressurized, the residual heat removal (RHR) pump was used to replenish the reactor. Although the RHR pump cannot continue to run under the loss of cooling water, since its injection flow rate of 3000 gpm is much greater than the maximum RCP seal cooling water loss rate, the task of replenishing water can
(7) be achieved by starting and stopping the operation of the RHR pump alternately. The operator must arrange the backup cooling water source for the RHR pump within 1 hour after the RHR pump is running, so that the RHR pump will not be damaged due to high temperature.
(8) Z: Steam Generator Cooldown to Cold Shutdown. The operator removes the heat from the primary side by means of gravity drainage of the steam generator “bleed & feed” system, and cools the unit to a cold shutdown.

TABLE I. Plant Damage Status

PDS#	Legend
OK	Sequence is free from core damage.
CD	Core Damage
TPK	Sequence is transferred to ATWS event tree.

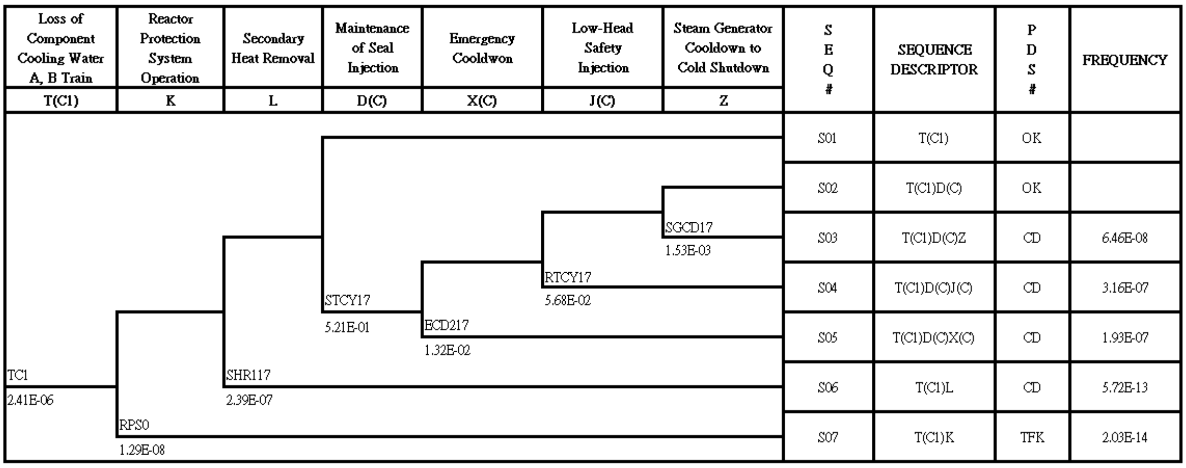

Fig.1. Basic model for T(C1) event.

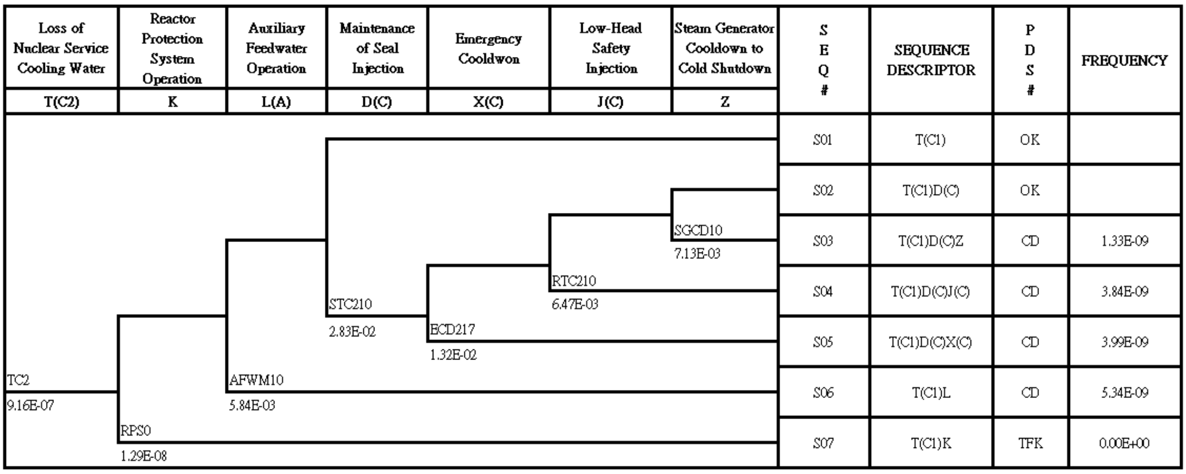

Fig.2. Basic model for T(C2) event.

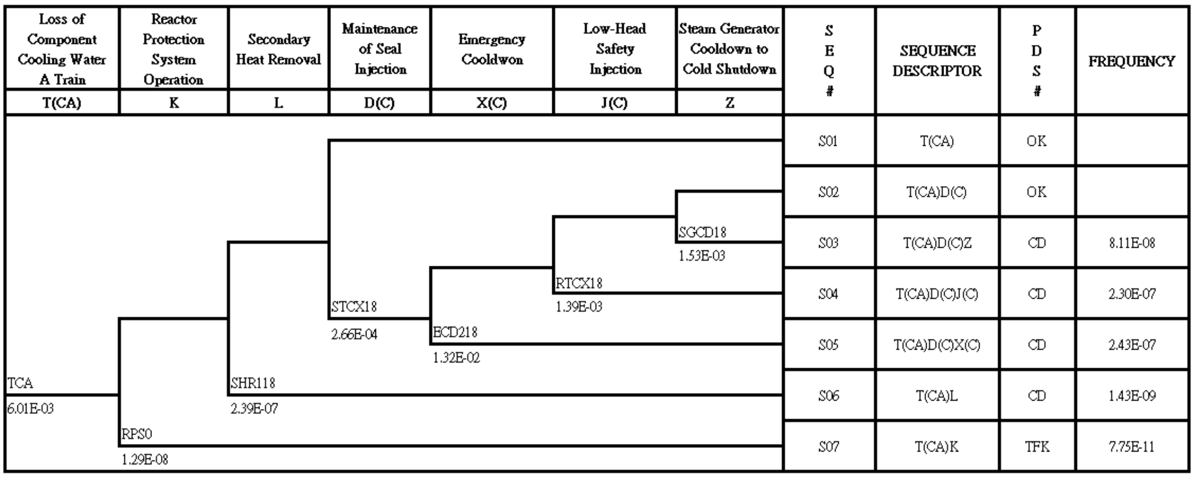

Fig.3. Basic model for T(CA) event.

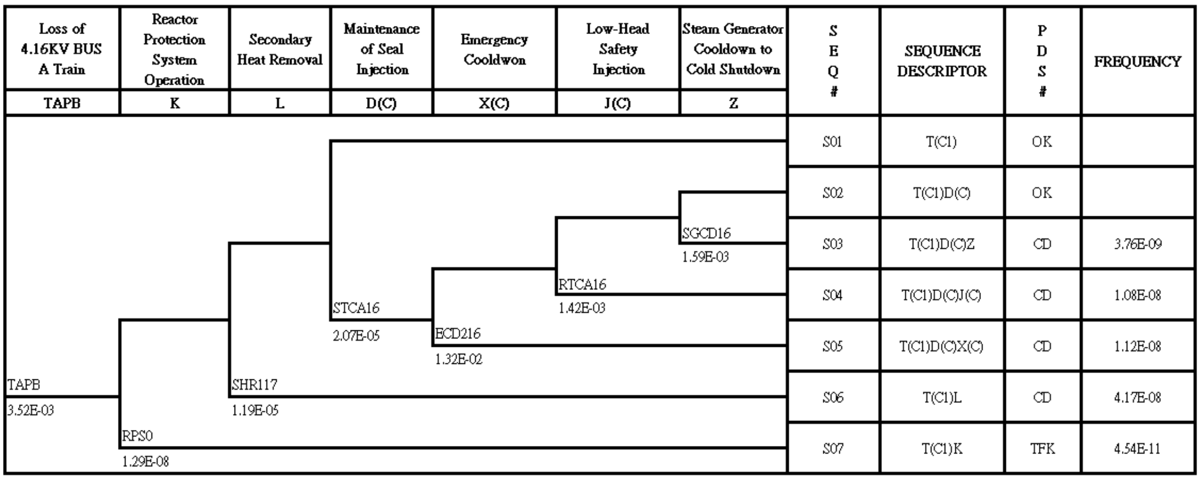

Fig.4. Basic model for TAPB event.

2.2. WOG2000 Model

In the WCAP-15603 (Rev.1), WOG (Westinghouse Owner Group) developed the WOG 2000 model to illustrate the leakage model of the RCP seal with high temperature O-ring after losing all seal cooling, and assumed that the RCP seal could be damaged after 13 minutes of losing all coolant. In that model, probability, leakage rates, and the timing of the situation occurrence were used to describe scenarios. In conjunction with the sequence of the event tree, the leakage rates ranged from 21 gpm/RCP to 480 gpm/RCP. The RCP seal has two failure modes, which are BP (Binding and Pop-open) failure mode and O-ring Extrusion failure mode. The former refers to opening of the rcp seal faces due to hydraulic instability caused by fluid, and binding failure of the seal ring against the housing inserts due to secondary seal extrusion. The latter is overheating of the secondary sealing elastomers and allowing excessive leakage. In the case of successful emergency cooling and depressurization on the secondary side, it can be further assumed that the O-ring Extrusion failure mode will not occur.

Based on the assumptions and analysis made in WCAP-15603, the basic model in Fig. 1 is modified as WOG2000 Model and shown in Fig. 5. The heading BP1/2 refers to the RCP#1/2 seal BP failure mode, and OR1/2 refers to the RCP#1/2 seal O-ring Extrusion failure mode. Because sequences S02 to S05 can be further combined, the event tree finally formed as Fig. 6. The T(C2), T(CA), TAPB WOG2000 models are shown in Fig.7 to Fig. 9 respectively.

2.3 PSDS Model

PSDS is a passive mechanical device, which can be installed in the existing RCP assembly. When the water temperature exceeds the working temperature of the PSDS, the PSDS starts to actuate, and can limit the RCP seal leak rate less than 1gpm/RCP. In the report "PRA Model for the Generation III Westinghouse Shutdown Seal, PWROG-14001-P", two headings were added to the WOG2000 model to simulate the effectiveness of PSDS on the PRA model. The first is "PSDS Actuated and Seals", which reflects whether the PSDS can actuate normally and maintain a good sealing capability after the event. The second is "RCP Trip to Prevent PSDS Damage", which reflects the experimental results of PSDS that if the shaft is rotating faster than 44 rpm at the time of PSDS actuation, it can cause loss of PSDS sealing capability. Use the labels "S" and "R" to represent these two headings and the WOG2000 model is modified to form the PDS model as shown in Fig. 10 to Fig. 13, where in the heading "R", it is assumed that the time available for the operator to trip the RCP after the event is 27 minutes.

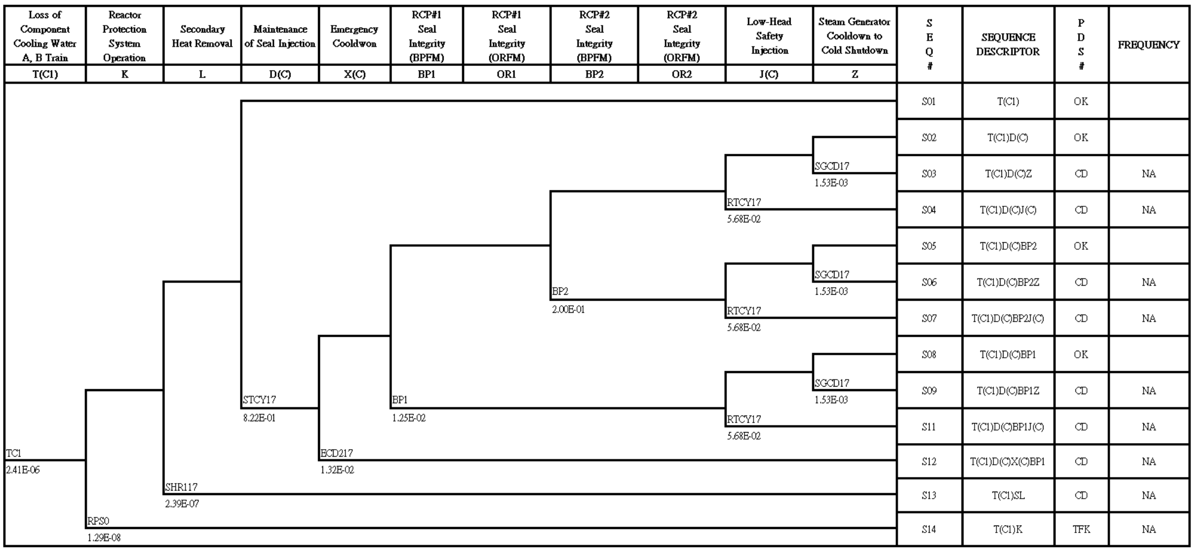

Fig. 5. WOG2000 model for T(C1) event (branch structure has not been merged)

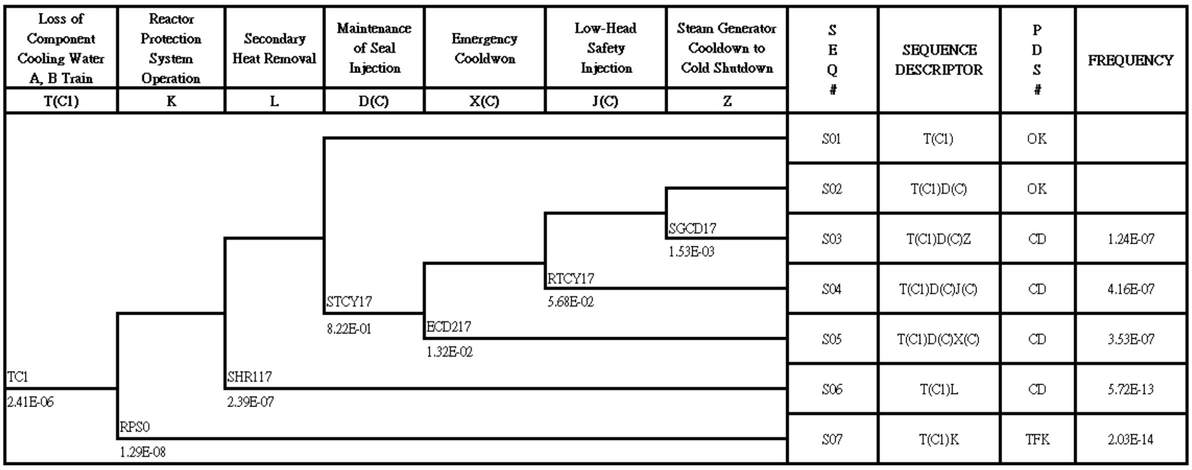

Fig. 6. WOG2000 model for T(C1) event

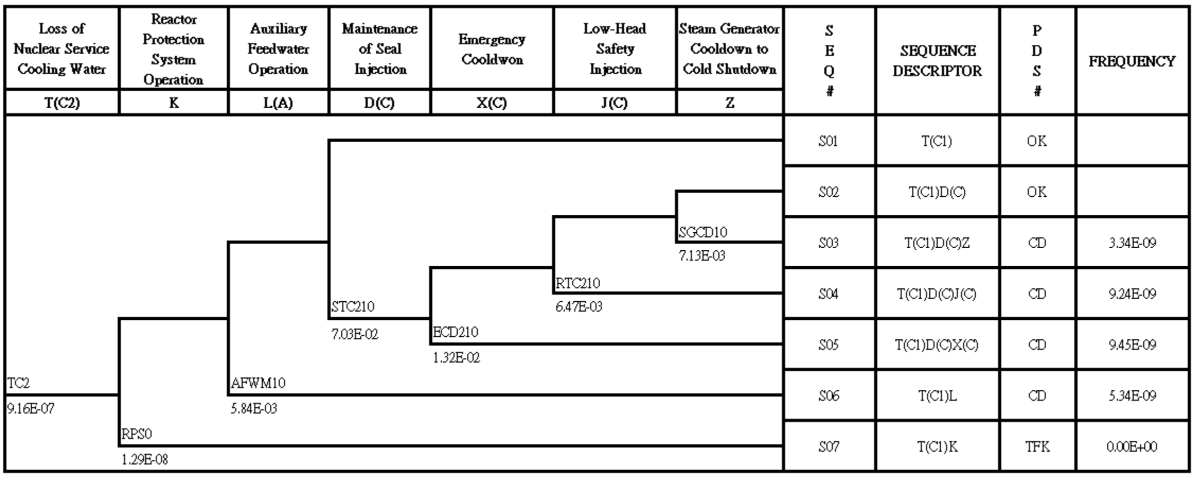

Fig. 7. WOG2000 model for T(C2) event

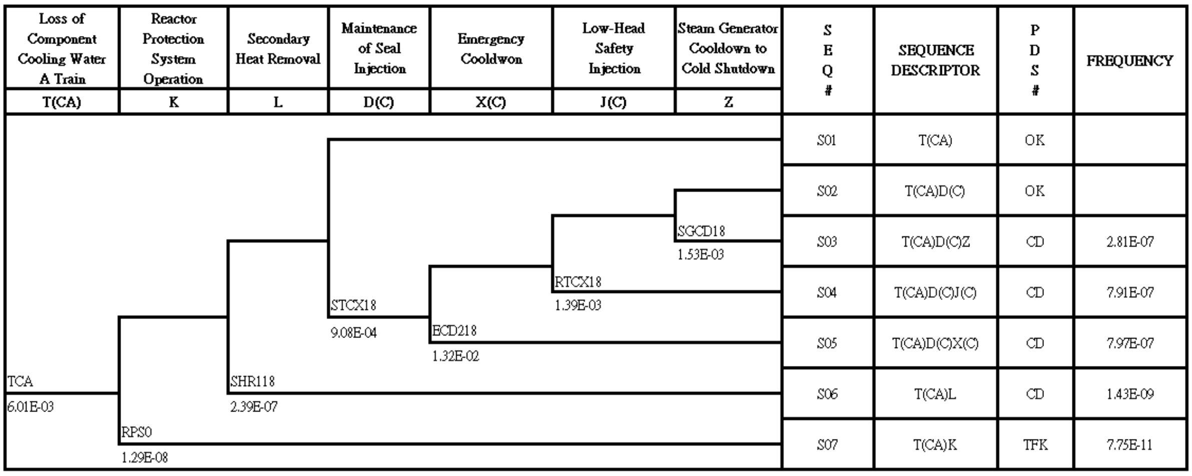

Fig. 8. WOG2000 model for T(CA) event

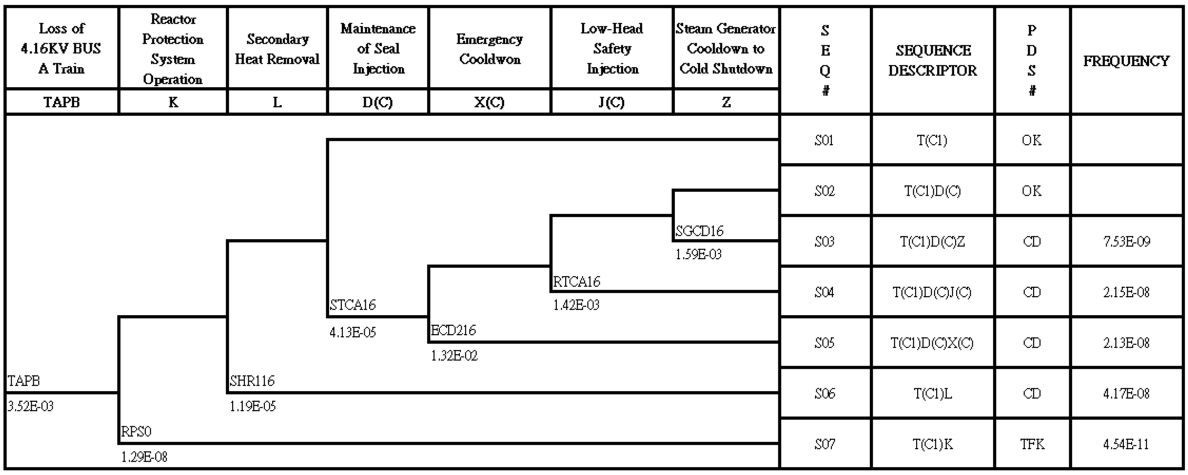

Fig. 9. WOG2000 model for TAPB event

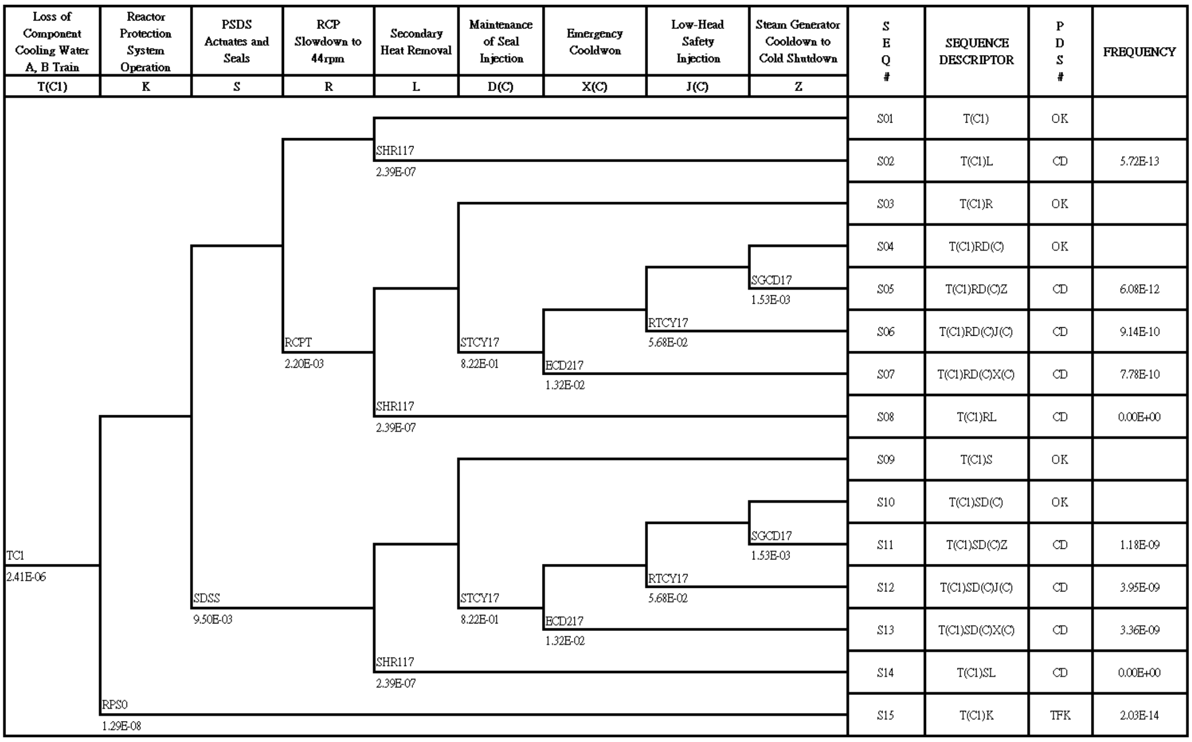

Fig. 10. PSDS model for T(C1) event

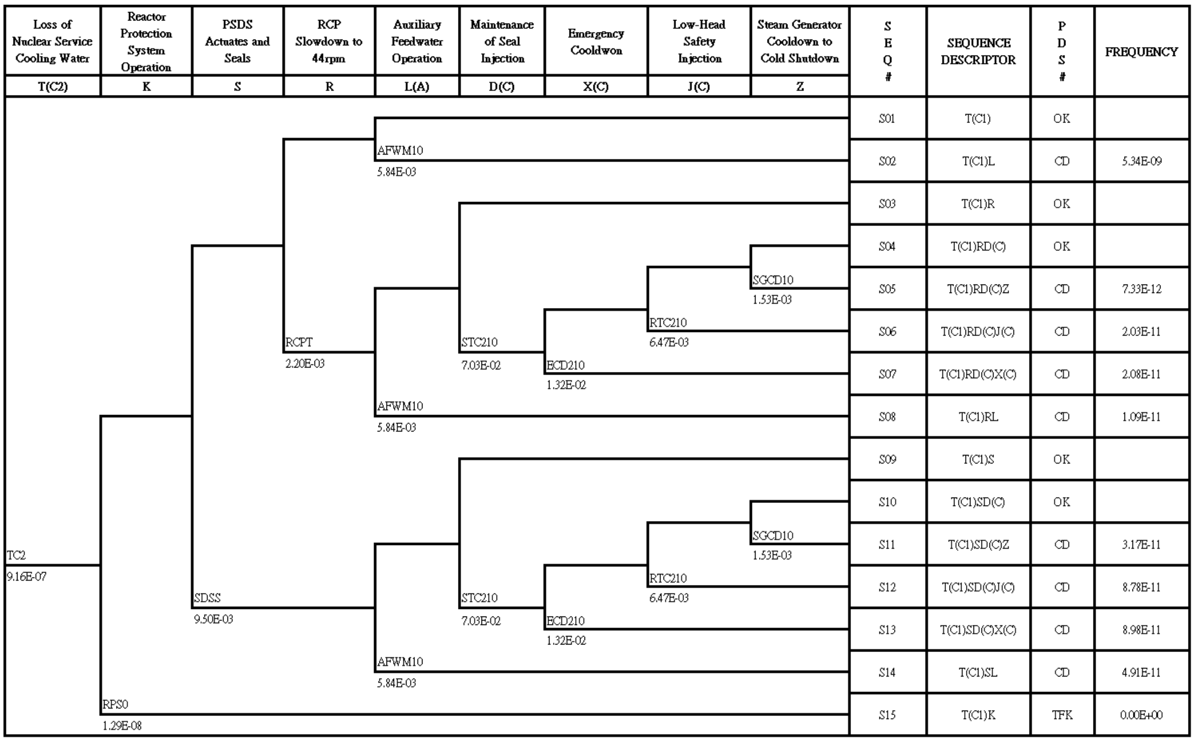

Fig. 11. PSDS model for T(C2) event

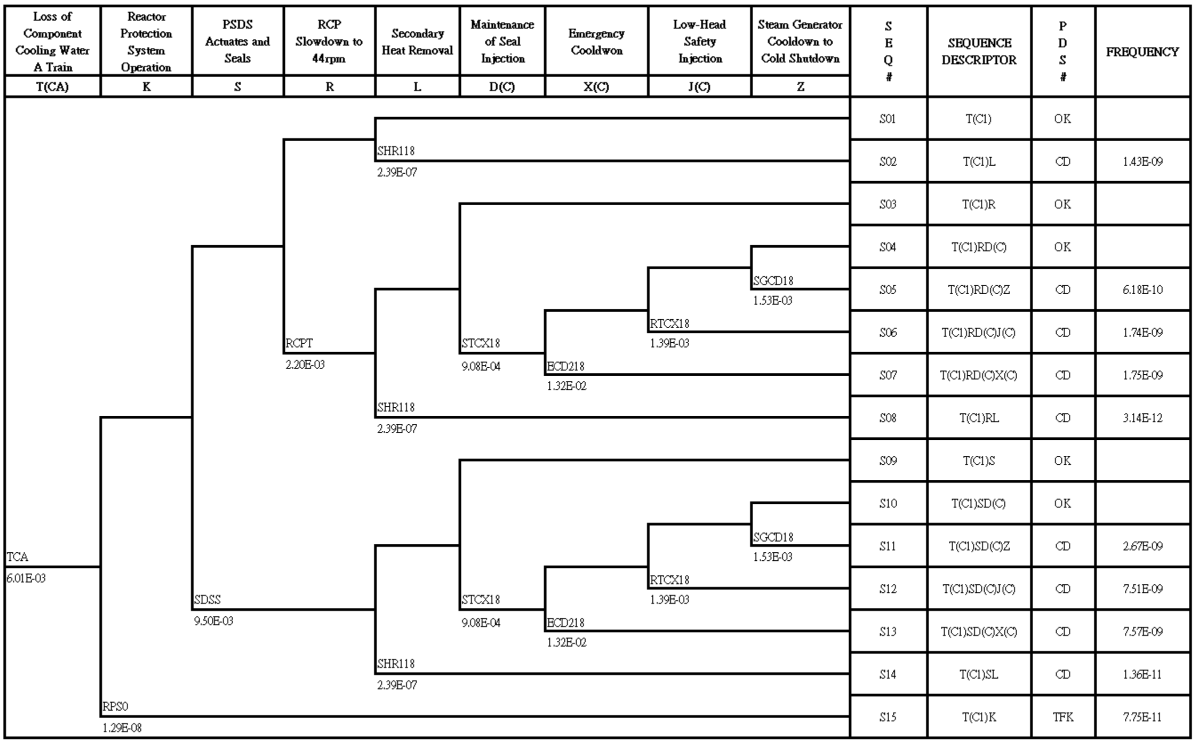

Fig. 11. PSDS model for T(CA) event

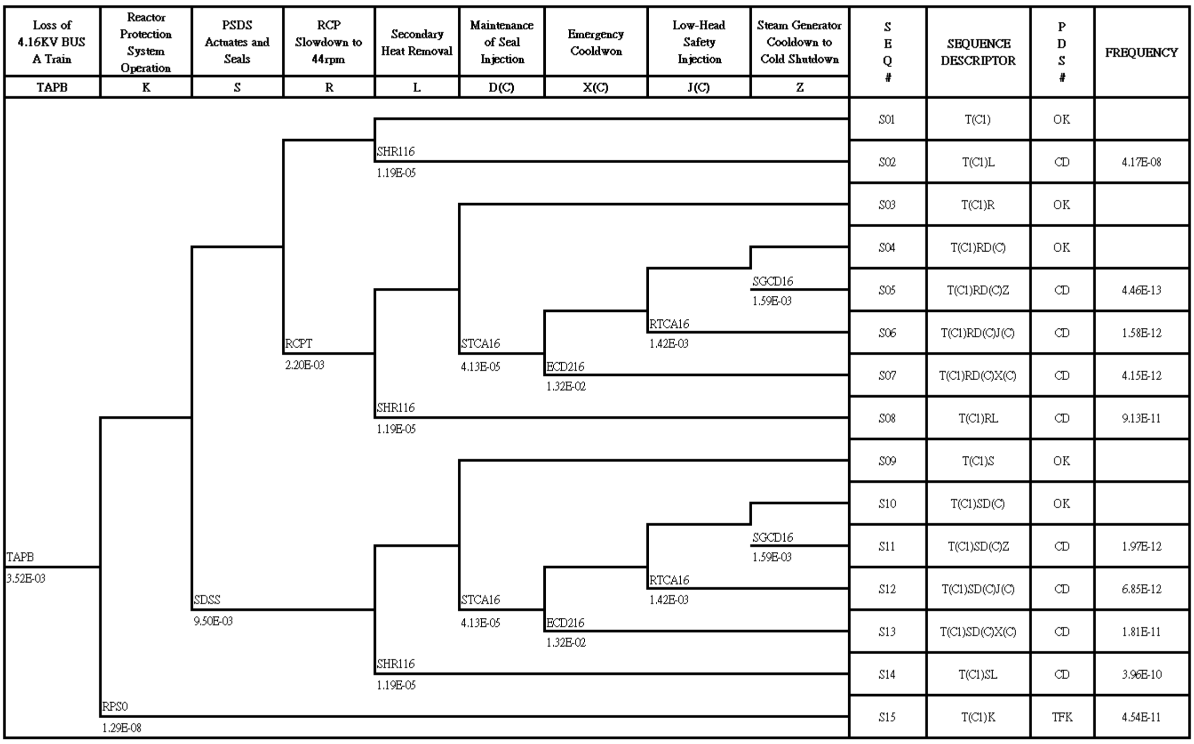

Fig. 11. PSDS model for T(APB) event

Table II. Quantification Results

Model\Event	T(C1)	CDF_i/ $CDF_{WOG2000}$	T(C2)	CDF_i/ $CDF_{WOG2000}$	T(CA)	CDF_i/ $CDF_{WOG2000}$	TAPB	CDF_i/ $CDF_{WOG2000}$
Basic	5.74E-07*	6.43E-01	1.45E-08	5.30E-01	5.55E-07	2.97E-01	6.75E-08	7.33E-01
WOG2000	8.93E-07	1.00E+00	2.74E-08	1.00E+00	1.87E-06	1.00E+00	9.20E-08	1.00E+00
PSDS	1.02E-08	1.14E-02	5.60E-09	2.05E-01	2.33E-08	1.25E-02	4.23E-08	4.59E-01

*****core damage frequency (1/ry)

3. QUANTIFICATION RESULTS AND DISCUSSIONS

The quantification results via the WinNUPRA software package[10] are shown in Table II. Taking the WOG2000 model as the benchmark, the results show that the CDF of the basic model is about 30% to 70% of that of the WOG2000 model, while the CDF of the PSDS model is about 1% to 46% of that of the WOG2000 model. The reason why the CDF of the basic mode is smaller than WOG2000 mode is that the basic mode assumes that the RCP seal will not fail in the first 30 mins after losing all RCP seal coolant, and the operator can try to maintain the RCP seal coolant during these 30 mins to avoid RCP seal LOCA. However, the WOG2000 model assumes that RCP seal LOCA may occur 13 minutes after the event and the operator has relatively little time to use. Therefore, the WOG2000 model has a higher value in the calculation of the relevant human error probability.

Comparing the PSDS model with the WOG2000 model, under different initiating events, the magnitude of CDF reduction due to the function of PSDS is different. Among them, T(C1) and T(CA) can reduce CDF by about two orders of magnitude, and T(CA) becomes 21% of the reference value, and TAPB becomes 46% of the reference value. The main reason for this difference is that the CDF composition of T(C2) and TAPB has a relatively high proportion in the scenario where the secondary heat removal cannot be successfully performed, and the frequency of this kind of scenario can't be reduced by installing PSDS. RCP passive shutdown seal can only reduce the CDF caused by RCP seal leakage.

4. CONCLUSIONS

Through this study, three PRA models are established. They are the basic model currently being used in the reference nuclear power plant, WOG2000 model considering high-temperature O-ring, and the PSDS model based on WOG2000 model and considering the generation III Westinghouse shutdown seal. Since the basic model assumes that the RCP seal will not fail in the first 30 mins after losing all seal coolant, the evaluation results of this model are somewhat optimistic.

In WOG2000 mode, scenarios were constructed based on the combination of RCP seal failure modes, and assumed that the RCP seal could be damaged after 13 minutes of losing all coolant. This model is currently widely used in the industry and is used as a benchmark for comparison with the other two models.

The PSDS model is based on the WOG2000 model and adds two event tree headings to reflect the utility of the PSDS. As long as the PSDS can actuate normally and maintain a good sealing function, and the operator was able to reduce the rotating speed of the RCP to below 44 rpm in time, the leakage rate of the RCP seal can be limited to less than 1gpm/RCP. Comparing with the WOG2000 model, the CDF can be reduced by about 53% to 2 orders under different initiating events. The more significant the effectiveness of PSDS is, the more the scenarios weights that lead to CDF are related to RCP seal leakage.

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