ASSESSMENT OF STATION BLACKOUT MITIGATION STRATEGY APPLYING THE ULTIMATE RESPONSE GUIDELINE TO MAANSHAN PWR

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ABSTRACT

The ultimate response guideline (URG) is developed by Taiwan Power Company to cope with the station blackout which loss of designed AC power and water supply. The URG is operated by the DIVing plan, (1) depressurize the reactor, (2) inject any available water into reactor by any available power supply if this critical status cannot be restored in time, (3) vent the containment if necessary to maintain containment integrity. URG relies on the use and operation of auxiliary feedwater system, depressurization of steam generators, and line-up the alternate water sources such as sea water when regular systems are not available.

The simulations start from normal operation at 100% power then an earthquake is assumed to happen, then tsunami strike the site 20 minutes later. The turbine-driven auxiliary feedwater system is assumed to be unavailable as conservative condition, and a seal leakage of 21 gpm (0.079 m^3/min) on each reactor coolant pump (RCP) is also modeled. Simulation results show that the case of SBO without URG strategy, the core water level drops to top of active fuel (TAF) in 4 hours as a SBO happens. But the case of that with URG strategy, the fuels could be fully covered by coolant for 70 hours.

The applying of URG strategy during SBO is to secure reactor core water coverage and fuel integrity as long as possible, and the results show that it can extend the time for core fuels to be uncovered for various hours in different situations. Furthermore, the duration gained by URG is possibly for building up AC power sources and long-term cooling system.

KEYWORDS
SBO, URG, TRACE, Maanshan PWR, seal leakage

1. INTRODUCTION

From the Fukushima accident, a natural disaster led to great damage to a nuclear power plant (NPP) in no time was realized. To build up the abilities to cope with crisis in NPP has become an important task. For compound events beyond design basis in Taiwan, such as SBO accident, the mitigation strategy named ultimate response guideline (URG) has been proposed by Taipower Company. The idea is to cool down the reactor core as soon as possible, to keep the fuel from uncovering and PCT exceeding 1088K (1500°F). It is achieved by three steps process [1], abbreviated as DIVing procedure, as shown in Figure 1. The brief descriptions are as below:

(1) Reactor depressurization: to perform first step controlled depressurization by regulating system safety/relief valve (SRV) and reduce the reactor pressure vessel (RPV) pressure.
(2) Water injection: to accomplish lineup of emergency power supply and any alternative water including raw water, firewater, or sea water within one hour. And if it is expected that reactor water level would be lower than top of active fuel (TAF), one performs second step emergency depressurization for water injection.
(3) Containment venting: to perform containment venting if containment pressure reaches its design limit.

Maanshan Nuclear Power Station is a two-unit Westinghouse three-loop PWR power station operated by Taiwan Power Company since 1984. If an intense earthquake and tsunami hit the plant, the sea water pumps, switch yard, onsite electric systems, emergency diesel generator or its fuel supply may be damaged and hard to recover. Since no AC power available, only turbine driven auxiliary feedwater system (TDAFW) can deliver cold water to steam generators (SG) to maintain the water level inside SG. If TDAFW trip due to some reason, water in the SG will boil off eventually, losing the heat sink of primary side. In the primary side, ECCS cannot operate without AC power, so there is no cooling water injection capability in the reactor coolant system (RCS) except passive accumulators (ACC) that are available when RCS pressure is lower than ACC nitrogen gas pressure. Under such circumstance without using any mitigation equipment or strategies, core damage will happen within a few hours. Taiwan Power Company has enhanced the capability of coping with extended station blackout situation by using mitigation strategies and alternate injection systems. The mitigation strategies for PWR plant that suggested by Taiwan Power Company put emphasis on removing the decay heat rapidly by controlling the steam generator pressure at a lower level while maintaining the steam generator water level at the same time by using any kind of injection method. The purpose of mitigation strategies is to bring the plant to safe condition as soon as possible and to keep the fuel covered with water.

This research first analyzes the SBO accident happened on 18 March, 2001 by using TRACE code and compares the results with plant data. The results show good agreement with plant data, and then this input model is used to analyze the mitigation strategies (URG). Two basic strategies are simulated in this study, main different between them is the steam generator depressurization strategy.

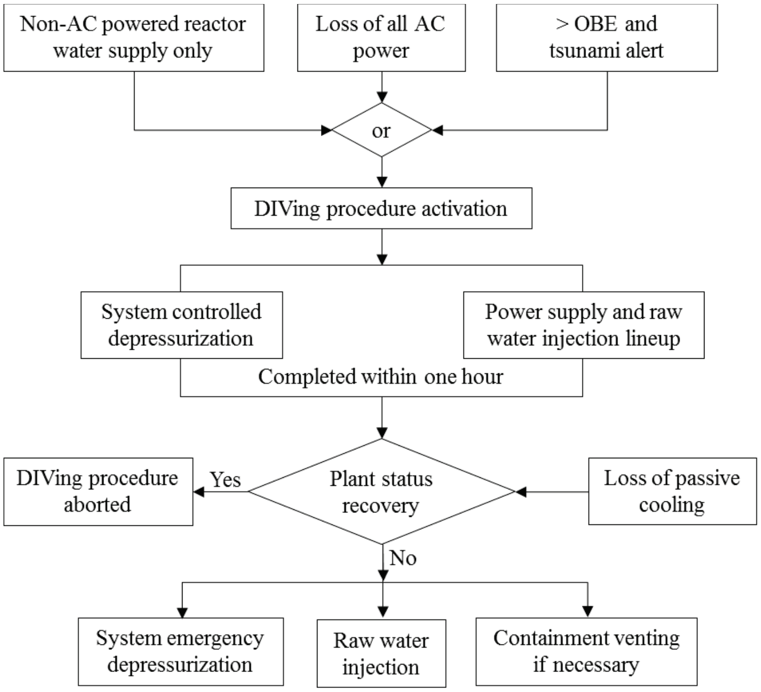


Figure 1. Illustrations of DIVing procedures.

2. VERIFICATION OF MAANSHAN SBO ACCIDENT WITH TRACE CODE

2.1. Introduction to Maanshan SBO Accident

During spring season in Taiwan, salty wind from the ocean can degrade the insulation of power transmission line and causing the instability of off-site power in nearby nuclear power station. On March 17th, 2001, 3:23 am, 345 kV off-site power line was lost due to seasonal salty wind and 161 kV off-site power was remained available. Unit 1 reactor tripped and was maintained at hot standby condition by operators.

At 0:46 am, March 18th, a malfunctioned breaker in on-site AC power electric system accidentally grounded, which produced electric arc that damaging other electric systems. Emergency 4.16 kV bus train A and B were both loss of power supply which is a station blackout situation. At 0:57 am, turbine driven auxiliary feedwater system (TDAFW) started automatically to provide cold water into steam generators.

At 0:58 am, reactor operators started to initiate the emergency operating procedure (EOP) to depressurize the steam generator. Auxiliary feedwater flow rate, steam generator pressure and steam generator water level ware controlled and maintained manually by the operators. At 2:54 am, the emergency diesel generator successfully supplied AC power to emergency 4.16 kV bus B, SBO situation was terminated [2].

Duration of SBO is about 2 hours, starts from 0:46 am to 2:54 am, March 18th, and the temperature and pressure of reactor decreased from 564 K, 15.3 MPa to 472 K, 4.2 MPa respectively. Fuels were covered with water and no radioactive materials were released during the whole accident. A brief accident scenario is shown in Table I. The verification of SBO accident is done by TRACE code with Maanshan input model, and the simulation starts from 0:30 am to 3:30 am, March 18th. TRACE input model and simulation results are introduced in the following sections. The simulation results are compared against measured data in Maanshan unit 1, and further studies on Maanshan SBO mitigation strategy are done by this input model.

Table I. Maanshan SBO accident scenario

Time (hr)	Simulation Time (hr)	Event
0	--	345 kV off-site power lost Reactor trip
21.12	0	Simulation start with hot standby condition
21.38	0.26	Breaker failure (SBO)
21.57	0.45	Turbine driven auxiliary feedwater (TDAFW) start
21.58	0.46	Initiate EOP 570.20 (SG & RCS cooling)
23.52	2.4	SBO terminated
24.12	3	End of simulation

2.2. Description of Maanshan TRACE Model

The computer code used in this research is TRACE (TRAC/RELAP Advanced Computational Engine) which is a best-estimate thermal-hydraulic system code developed by US NRC, and the input model is edited by using SNAP (Symbolic Nuclear Analysis Package). Maanshan TRACE base model contains 69 hydraulic components, 380 control blocks, 34 heat structures and 2 power components. Main components including one 3-D vessel, three RCS loops, one pressurizer, three steam generators and basic plant control systems such as 3-element feedwater control, pressurizer spray, pressurizer level and heater control, and steam dump control.

The 3-D vessel component contains 2 radial rings, 6 azimuthal sectors and 12 axial levels. The outer radial ring represents downcomer region and the reactor core is placed in the inner radial ring from axial level 3 to axial level 6. Six control rod guide tubes are connected above the core region. Nuclear fuels are modeled by 6 heat structures each represents 6908 average fuel rods that uniformly placed in 6 azimuthal sectors. Each RCS loop contains hot leg piping, steam generator U-tube, crossover piping, reactor coolant pump, cold leg piping, accumulator tank and accumulator check valve. Pressurizer and pressurizer surge line are connected on RCS loop number 2. This base model has been verified with Maanshan Nuclear Power Station startup test data [3]. Figure 2 shows the whole plant scheme of Maanshan TRACE input model. Figure 3 is the detail description of major components in the input model. Plant initial condition data calculated by TRACE steady-state calculation are listed in Table II.

2.3. Simulation Results of Maanshan SBO Accident

SBO happens at 16 minutes after the simulation starts. 11 minutes after SBO, TDAFW automatically start. Operators control the auxiliary feedwater flow rate via regulating the throttling valve in order to maintain steam generator water level. Due to TDAFW system, all three steam generators narrow range water level simulation results are above 50% most of the time and show similar trend with plant data. Steam generator narrow range water level results are shown in Figure 4, Figure 5, and Figure 6.

Table II. Maanshan NPS steady-state initial condition

	Plant Data	*TRACE*	*Error (%)*
Core thermal power (MW)	2822	2822	0
RCS pressure (MPa)	15.513	15.518	0.03
Total RCS flow (Mkg/hr)	49.59	49.57	0.04
Pressurizer liquid volume (m^3)	23.79	23.786	0.017
Hot-leg Temperature (K)	599.75	601.7	0.33
Cold-leg Temperature (K)	565.35	566.57	0.22
Steam generator pressure (MPa)	6.74	6.91	2.5
Steam temperature (K)	555.45	558.09	0.48
Steam generator narrow range water level (%)	50	50	0

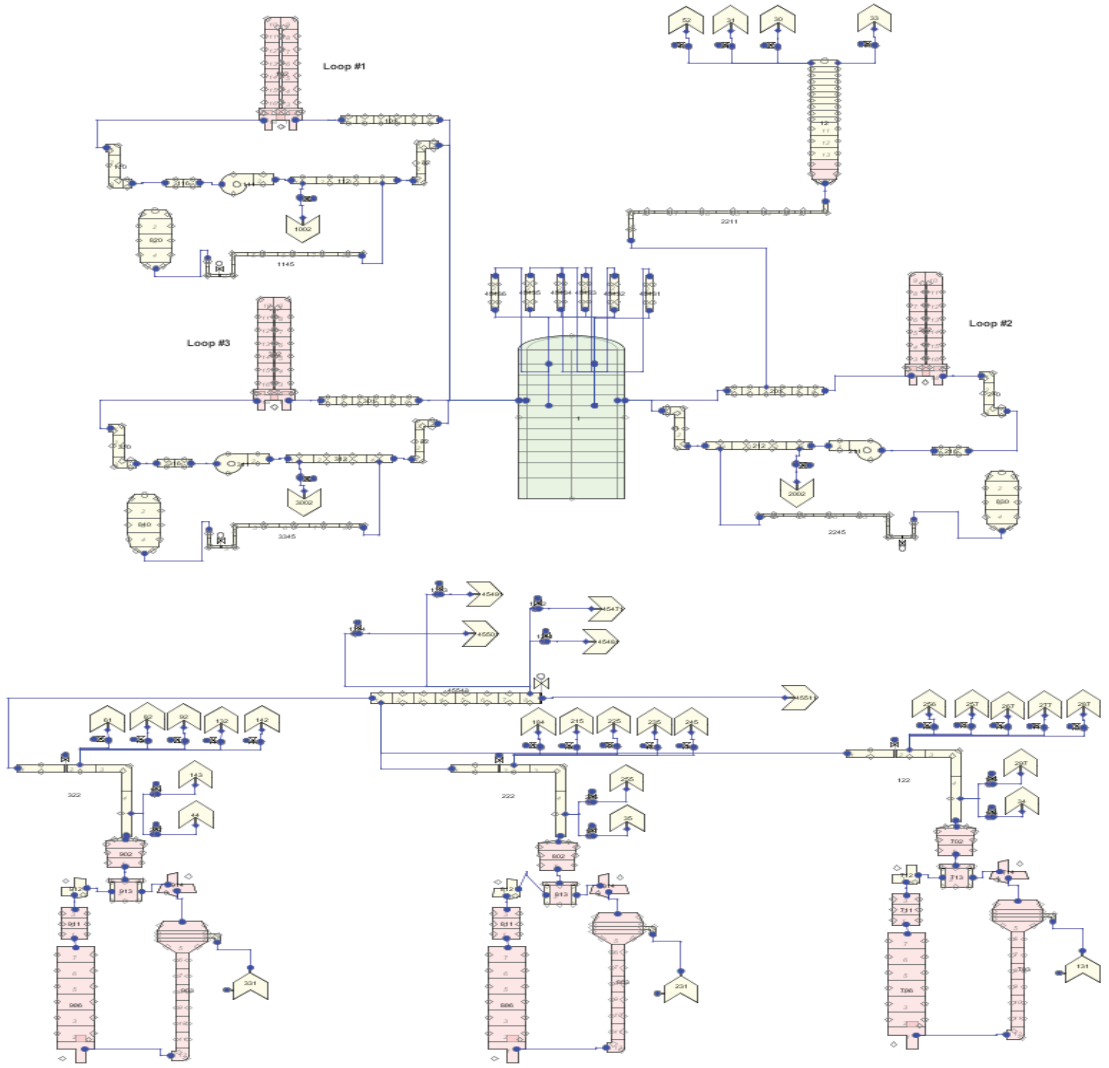


Figure 2. Schematic diagram of Maanshan TRACE input model.

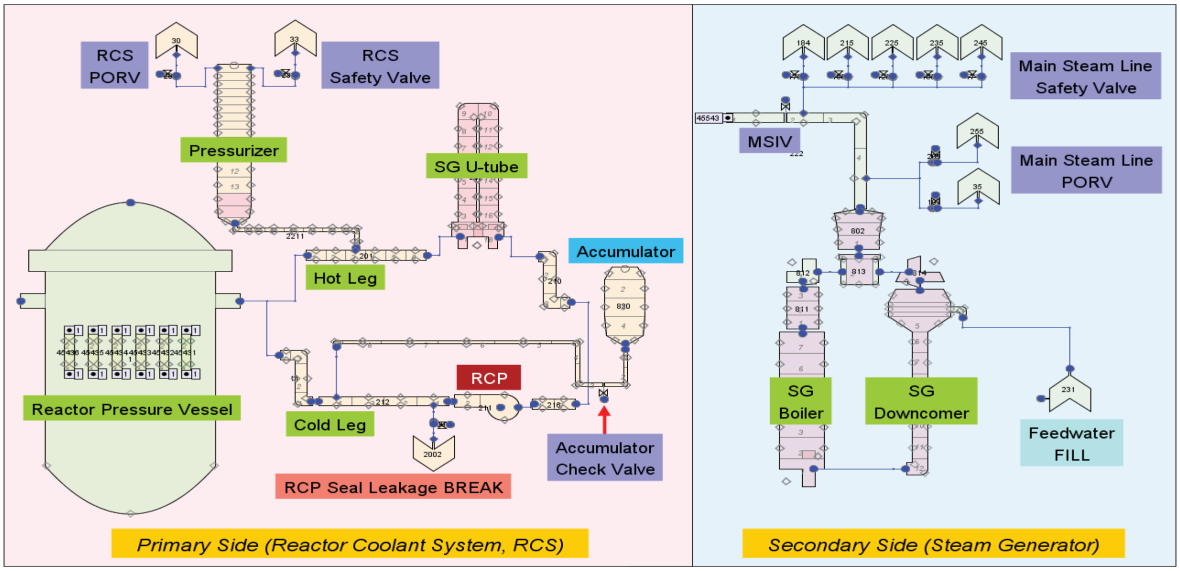


Figure 3. Detail description of major components in loop number 2.

12 minutes after SBO, the operators start to initiate EOP to lower the steam generator pressure by opening steam line PORV. In TRACE, PORVs are controlled base on steam pressure plant data, steam generators pressure simulation results are shown in Figure 7, Figure 8, and Figure 9. Steam generator depressurization can effectively remove residual heat from reactor coolant system, therefore coolant temperature and pressure decrease as steam generator pressure become lower. Figure 10, Figure 11, and Figure 12 show the cold leg liquid temperature for three RCS loops respectively. Figure 13 shows the reactor coolant system pressure variation. As the RCS coolant temperature decrease, coolant density also becomes smaller which lead to shrinkage of RCS coolant, therefore pressurizer water level decrease. Figure 14 shows the pressurizer water level during the transient. When reactor coolant system pressure become lower than accumulator nitrogen gas pressure which is about 4.2 MPa, water inside accumulator automatically injected into RCS via two check valves.

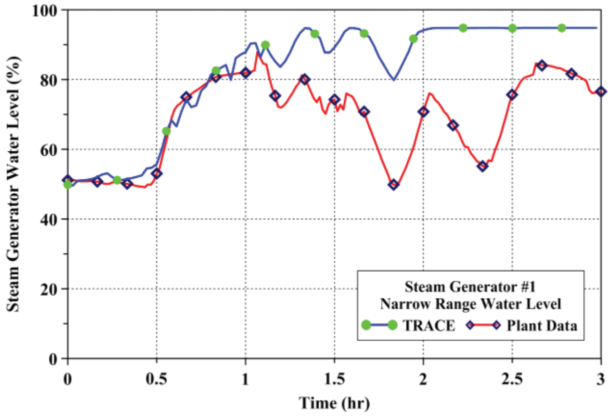


Figure 4. Steam generator #1 narrow range water level.

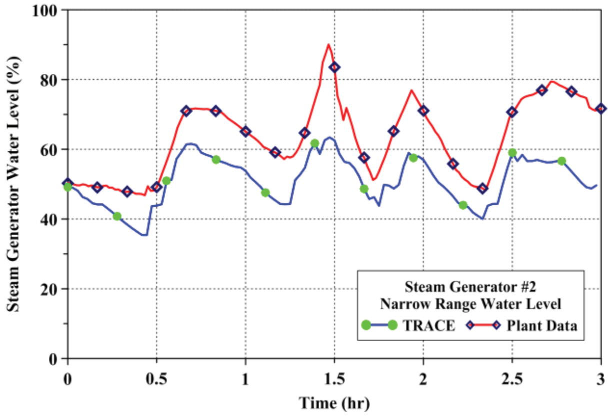


Figure 5. Steam generator #2 narrow range water level.

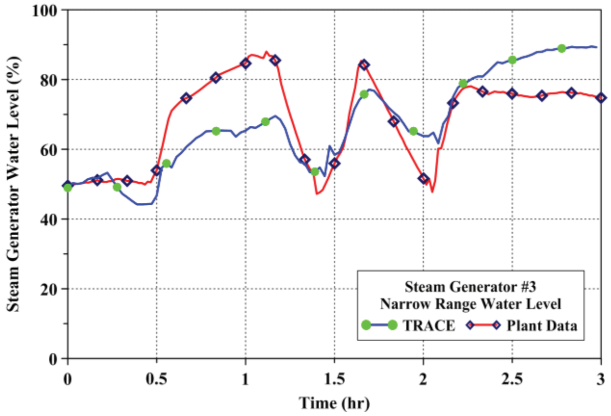


Figure 6. Steam generator #3 narrow range water level.

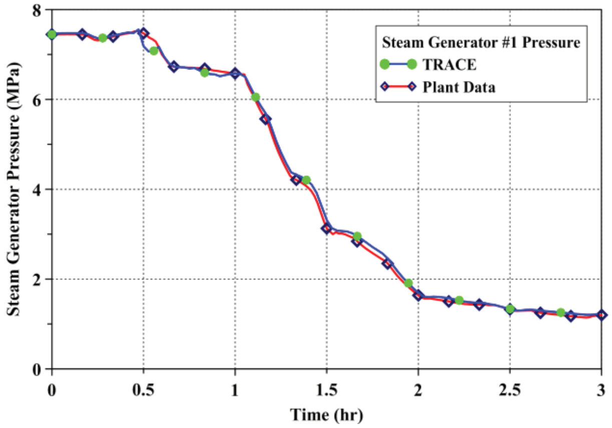


Figure 7. Steam generator #1 pressure.

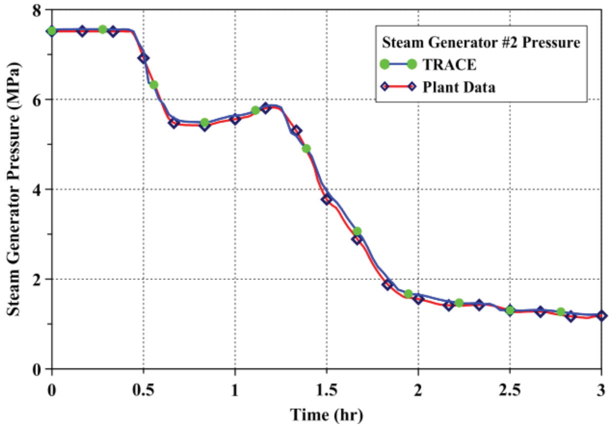


Figure 8. Steam generator #2 pressure.

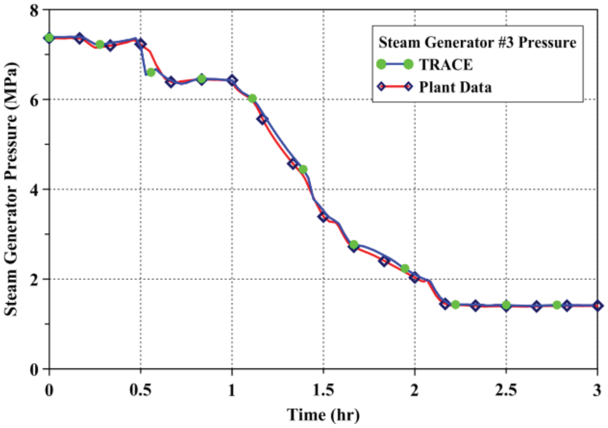


Figure 9. Steam generator #3 pressure.

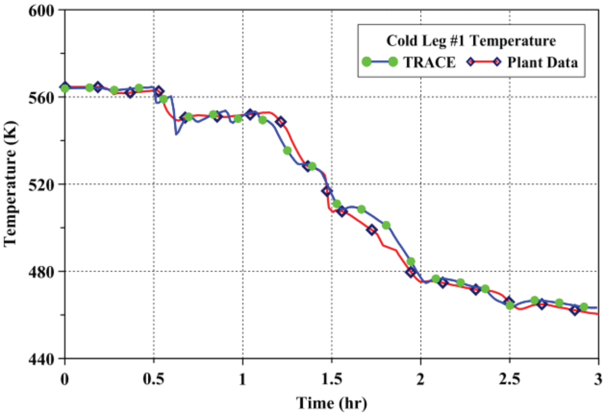


Figure 10. Cold leg #1 liquid temperature.

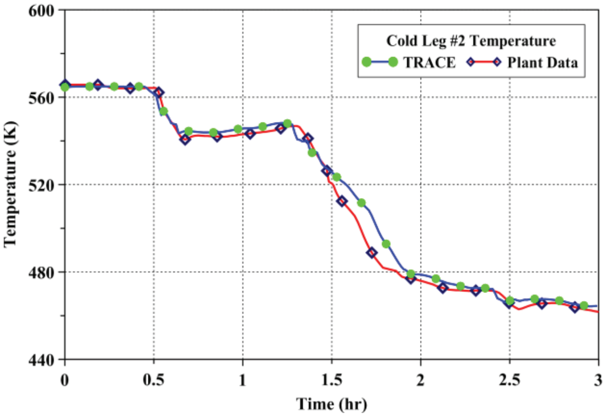


Figure 11. Cold leg #2 liquid temperature.

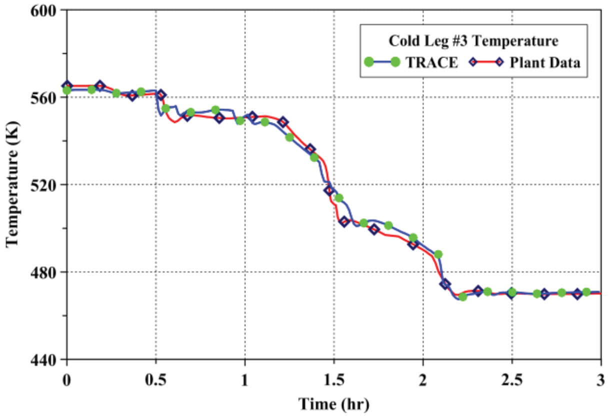


Figure 12. Cold leg #3 liquid temperature.

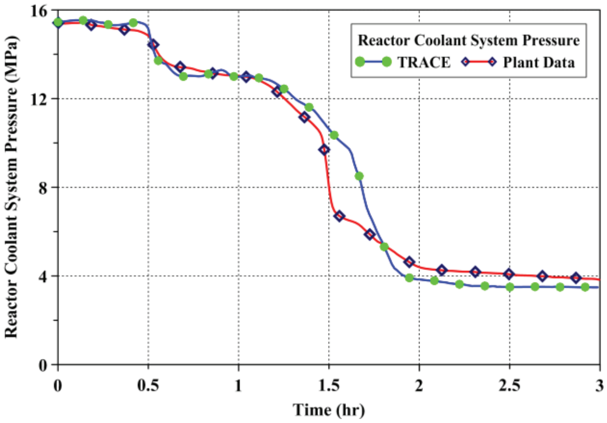


Figure 13. Reactor coolant system pressure.

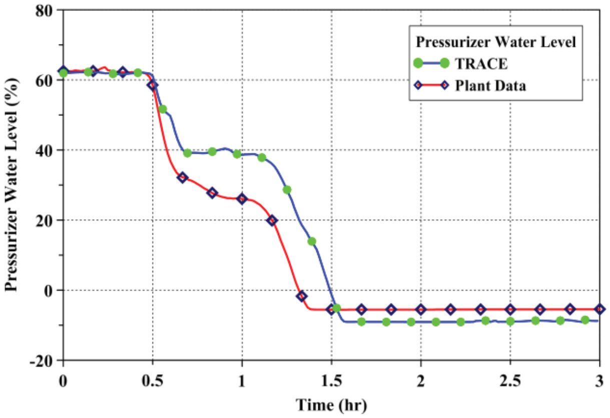


Figure 14. Pressurizer water level.

2.4. Discussion

During 2 hours SBO duration, the operators successfully execute RCS cooling by controlled-depressurization of steam generators. Since no emergency power available during SBO, the turbine driven auxiliary feedwater system become the most important coolant injection system. Reactor temperature and pressure decreased from 564 K, 15.3 MPa to 472 K, 4.2 MPa respectively, and no radioactive material was released during SBO. After emergency power was recovered, residual heat removal system took place to remove the decay heat continuously. From the above results, TRACE simulation of the Maanshan SBO accident shows good agreement with the plant data. In the next chapter, several SBO mitigation strategies will be simulated by using this input model to determine the best strategy.

3. SBO MITIGATION STRATEGY SIMULATION AND RESULTS

3.1. Description of SBO Mitigation Strategy

Taiwan Power Company has enhanced the capability of coping with extended station blackout situation by using mitigation strategies and alternate injection systems. In addition to regular ECCS and auxiliary feedwater system, some alternate injection systems such as diesel engine auxiliary feed pump and fire engine pump can also inject water into SG or RCS, but the operating pressure of the alternate systems is low compare to the regular systems, and onsite operators have to line-up the injection piping manually.

The water sources of alternate injection systems can be either CST, raw water reservoir, or sea water. The mitigation strategies for PWR plant that suggested by Taiwan Power Company put emphasis on removing the decay heat rapidly by controlling the steam generator pressure at a lower level while maintaining the steam generator water level at the same time by using any kind of injection method. If decay heat can be removed successfully via steam generators, RCS pressure will not build up to the opening set point of power operated relieve valves (PORV) that installed on the pressurizer so that no loss of inventory inside RCS. The purpose of using this kind of mitigation strategies is to bring the plant to safe condition as soon as possible and to keep the fuel covered with water.

There are three base cases in this study, one without any operators' action, and the other two with different mitigation strategies during SBO. For all three cases, the plant lose the offsite power due to a large earthquake happens at 60 second, then reactor, RCP, turbine and main feedwater trip immediately. Emergency diesel generator start up automatically after losing the offsite power, the motor driven auxiliary feedwater pumps (MDAFW) then start to deliver cold feedwater into three steam generators. 20 minutes after earthquake, SBO happens and is caused by an intense tsunami that wipes out electric devices related to emergency AC power. After losing the emergency AC power, MDAFW and ECCS are not available, and turbine driven auxiliary feedwater system (TDAFW) is assumed to fail. For conservative, RCP seal leakage is assumed to happen in all cases. The leakage rate corresponds to full system pressure is 21 gpm (0.98 kg/s) per pump [4-5].

3.1.1. Case A: no mitigation strategy

Case A has no operators' actions and is a comparison with case B and C to show the worst situation. The system response follows its default settings and logics. Calculation ends when cladding temperature reaches melting point of zirconium alloy.

3.1.2. Case B: mitigation strategy 1

Case B contains two main actions, including steam generators depressurization and alternate injection. After SBO happens at 20 minute with TDAFW is assumed to fail, the plant completely loss its regular coolant injection capability. Under this situation, onsite operators have to prepare any available kind of alternate injection method whatever is driven by fire truck, mobile engine driven pump, or gravity and connect these alternate equipment with the piping line in order to maintain water level in steam generators. The alternate injection preparation process is totally done by onsite operators, a minimum requirement of one hour preparation time start from tsunami wave backed away is requested by Taiwan Power Company. One hour after tsunami hit the plant, steam generator alternate injection is ready to use. Injection using alternate equipment requires lower steam generator pressure, therefore preforming steam generator depressurization at 1 hour by opening steam line power operate relieve valve (PORV) to depressurize steam generator to atmospheric pressure. 0.69 MPa (6 kg/cm^2) alternate injection operate pressure limit is used in this study, and injection flow rate and temperature are 200 gpm (12.6 kg/s) per steam generator and 20°C (293 K) respectively.

3.1.3. Case C: mitigation strategy 2

Case C contains three main actions, including steam generators controlled-depressurization, second stage depressurization and alternate injection. When SBO happens at 20 minute, reactor operators perform steam generator controlled-depressurization by manually adjusting the steam line PORV open fraction to maintain steam pressure at 1.57 MPa (15 kg/cm^2). TDAFW which is driven by steam can still operate at 1.57 MPa steam pressure, but it is assumed to fail in all cases. When alternate injection is ready at 1 hour after SBO, operators then perform second stage depressurization to depressurize steam generator to atmospheric pressure so that alternate injection system can deliver water into steam generator. Alternate injection system limitation, flow rate and temperature are the same as in case B.

3.2. Simulation Results of SBO Mitigation Strategy

Accident starts from 60 second. Reactor trip due to large earthquake, control rods drop into reactor core therefore only decay heat remains. Decay power used in this calculation is ANS 1973 decay heat curve. RCP motor rotation speed starts to decrease and fully stopped in 200 seconds, and then natural circulation flow is established in RCS loop. After main feedwater trip at 60 second, MDAFW continue to maintain steam generator water level. 20 minutes later, MDAFW trip due to SBO. Condenser and steam dump system cannot operate under SBO.

3.2.1. Results of case A

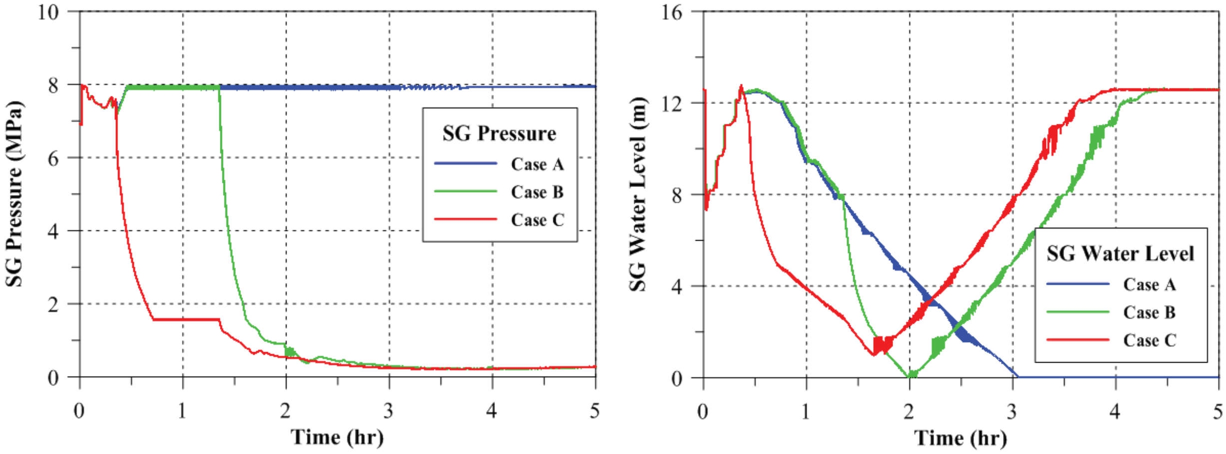
After MDAFW trip at SBO, there is no cooling water supply to steam generators. Heat from RCS continuously transfer to steam generator secondary side, steam pressure starts to rise and hold at PORV open set point of 7.96 MPa as shown in Figure 15(a). Steam is directly dumped into atmosphere via PORV, steam generator water level decreases slowly and dryout at about 3 hour as shown in Figure 15(b). RCS natural circulation flow slowly remove the decay heat to steam generator, so that RCS pressure also decrease slowly. When steam generators are all dryout, heat sink of RCS is lost. RCS natural circulation stop and pressure starts to build up. At around 3.5 hour, RCS pressure reaches and holds at pressurizer PORV open set point of 16.2 MPa, and then reactor water level starts to decrease very fast due to steam inside RCS is dumped into containment. Accumulator cannot inject cold water into RCS since RCS pressure is high, reactor water level drops to top TAF at about 4.1 hour. RCS pressure and reactor water level are shown in Figure 16(a) and Figure 16(b) respectively. Without water covering fuels, peak cladding temperature (PCT) increase sharply and beyond 1088 K (1500 °F) at about 4.6 hour as shown in Figure 17.

3.2.2. Results of case B

1 hour after SBO, that is, at 1.35 hour, steam generator alternate injection is ready, operators then open the steam line PORV to depressurize steam generator to atmospheric pressure. Steam generator water level decrease and become dryout at about 2 hour due to rapid depressurization. When steam generator pressure is lower than 0.69 MPa (6 kg/cm^2) at around 2.1 hour, alternate injection starts to inject cold water and steam generator water level starts increasing. RCS pressure also decrease sharply at 1.35 hour, it's because rapid steam generator depressurization can remove massive heat via heat transfer between RCS and SG secondary side. Reactor water level decrease at 1.35 hour is mainly because RCS water density become smaller caused by decreasing of RCS temperature, so that RCS water volume shrink and cause the water level to decrease. Accumulator can inject cold water to RCS when RCS pressure is lower than 4.2 MPa but isolated when steam generator pressure is lower than 0.93 MPa (8.5 kg/cm^2). Steam generator water level is recovered to normal position at about 4.3 hour. Reactor water level is finally stabilized at 1.54 m above TAF, and PCT is well below 1088 K (1500 °F).

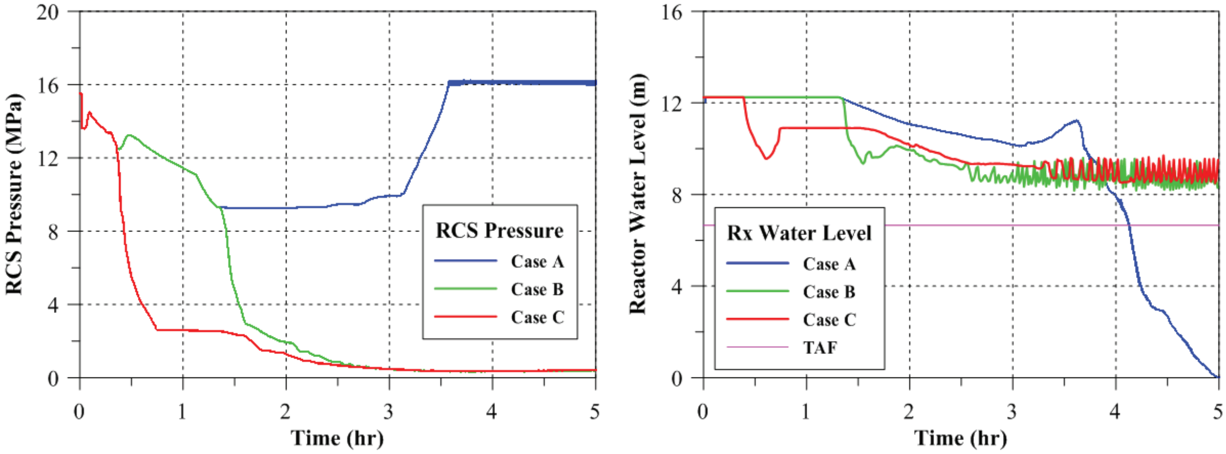
3.2.2. Results of case C

At 20 minute when SBO happen, operators perform steam generator controlled-depressurization by opening steam line PORV and hold the steam pressure at 1.57 MPa (15 kg/cm^2) as shown in Figure 16(a) until alternate injection is ready. Since steam pressure is under controlled, less steam is dumped into atmosphere so that steam generator water level decrease slower in controlled stage and doesn't become dryout. At 1.35 hour, operators perform second stage depressurization to depressurize steam generator to atmospheric pressure so that alternate injection can come into steam generator. RCS pressure decrease rapidly and stay at around 2.5 MPa is due to controlled-depressurization of steam generator. Steam generator water level is recovered to normal position at about 4 hour. Injection flow rate needed to maintain steam generator water level at normal position after 4 hour is about 8 kg/s for three SGs. Reactor water level is finally stabilized at 1.84 m above TAF, and PCT is well below 1088 K (1500 °F).



(a) (b)

Figure 15. Steam generator pressure and water level for case A, B, and C.



(a) (b)

Figure 16. RCS pressure and reactor water level for case A, B, and C.

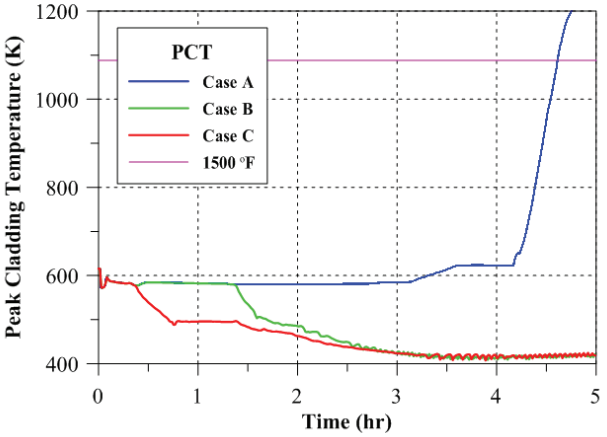


Figure 17. Peak cladding temperature for case A, B, and C.

The result from case A shows that core damage will occur within 5 hours after the earthquake if nothing has been done. Recall that the mitigation strategy is used in this kind of accident to prevent PCT from exceeding 1088 K (1500 °F) which is the temperature that metal-water reaction can self-sustain. If a large amount of hydrogen is generated by metal-water reaction, hydrogen explosion may occur and further compromise the integrity of reactor or containment. Results of case B and C show that both two strategies successfully keep the fuels covered with water and PCT is not higher than 1088 K. The benefit of depressurizing steam generator is indirectly remove the decay heat from RCS vie steam generator without losing RCS inventory, but the steam generator water level decrease. From Figure 16(b), it's obvious that steam generator water level decrease rapidly during depressurization, water level decreasing rate is even faster in case B and become dryout before alternate injection flow can come into steam generator. Controlled-depressurization in case C shows that not only RCS temperature and pressure can be reduced in the early stage of accident but also keep the steam generator from being dryout. In addition, RCP seal leakage flow decrease with decreasing RCS pressure, reducing the inventory loss in RCS. Therefore, strategy in case C is recommended for coping with SBO. Several studies of this strategy have also been done, the assumptions may be different but system responses are very similar [1].

4. CONCLUSIONS

When facing beyond design basis accidents, great uncertainties are associated with regular plant systems and components. Therefore, the (URG) strategy that can bring the plant to safety condition as soon as possible should be considered. The simulation results in this research show that performing steam generator controlled-depressurization at the early stage of accident and, if no regular coolant injection system available, line up the alternate injection system in 3.5 hours after SBO can keep the fuels covered with water therefore maintain the plant in safety condition. In addition, after plant is under controlled at the early stage of accident, onsite operators should recover AC power as quickly as possible so that ECCS can make up RCS inventory loss through RCP seal, and residual heat removal system can remove the decay heat in RCS continuously until reactor is at cold shut down.

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