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Sequence Analysis after Core Damage to Determine Safety Level of the AP1000

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Abstract

In safety analysis, one of important parameters is core damage as this occasion can cause fission products to release. In that regard, all possible sequences afterward must be analyzed in order to ensure that all events have been considered, because each sequence has different consequence. The objective of this research is to determine the probability of event sequences after core damage so safety level of AP1000 could be known. The AP1000 reactor is chosen as the research object because currently many units are under construction. In this research the accident sequences were analyzed by using event tree, and the probability of top event was calculated by fault tree analysis. Meanwhile, the failure rates of component or operator action were collected from IAEA documents and also published documents of the AP1000 from Westinghouse Inc. The analysis results show that probability of event sequences which causes fission product release is ranging from 10^{-2} to 10^{-26} and the total probability is 3, 48 x 10^{-2}. Based on this analysis, it can be concluded that the AP1000 has high safety level because the probability of event sequences leading to fission product release is small. Moreover, if these results are joined with core damage probability then probability of fission product release would be less than 10^{-9}.

Keywords: safety analysis, core damage, event sequence, event tree, AP1000

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1. Introduction

Safety is the main priority in nuclear facilities, especially in power and research reactors. Therefore safety analysis to the nuclear facility design must be carried out rigorously as contained in the government regulation of Indonesia no. 54 year 2012 concerning safety and security for nuclear installation.

Based on fundamental safety principles [1], the general safety objective is to protect individuals, society, and environment from harm by establishing and maintaining in nuclear facilities effective defenses against radiological hazards. To achieve these objectives appropriate specific safety requirement is necessary and technically have three implementations. The first is to prevent accidents and to mitigate the consequences of any accidents that possibly will occur. The second is to ensure all possible accident is taken into account in the design with any risk would be minor. The third implementation is to ensure that probability of accidents with serious radiological consequences is extremely low.

There are three aspects of lessons that could be taken from the Fukushima accident [2-4]. First, it is important to develop each likely postulated initiating event in the nuclear

reactor. It would be easy to mitigate when a hypothetical event is occurred. Second, nuclear reactor which is used as energy source (Nuclear Power Plant, NPP) has complex characteristic, therefore safety design shall be provided since the beginning rather than after the accident happen. Third, all risk possibility and mitigation method shall be generally known in advance.

The fission product release to environment is a consequence of reactor existence that must get a careful attention. Fission product could be released to environment in two stages: (1) core damage and (2) containment system fail to function after the core damage happen. Therefore, these two parameters can be used as reference to find out the safety level of a light water reactor. The smaller occurrence probability means the higher level of reactor safety. There are three levels of the probabilistic safety assessment (PSA) where each has purpose in the safety analysis. Level 1 PSA is to determine core damage probability, so that it can be known the reliability level of safety system. Level 2 PSA is to establish the probability of fission product release, therefore it can find out reliability level of stage or system that issued to prevent the fission product release to the environment. Whereas level 3 PSA is to calculate risk that is accepted by public and other societal if accident happen.

The AP1000 (Advanced Passive Pressurized Water Reactor 1000) is a two-loop3400 MWt pressurized water reactor (PWR) which is included as generation III+ and use passive system as core cooling system to prevent core damage. This reactor type is being built in some countries currently.

Several research activities related with PSA have been carried out i.e. to determine failure probability of non-safety system to prevent severe accident [5], probabilistic analysis to modify the system [6], and analysis of system failure scenario to determine severe accident probability of AP1000 [7]. As continuation of the research to determine the failure probability of AP1000 safety system, the purpose of this paper is to analyze event sequences after core damage in AP1000 by using probabilistic method. Based on this analysis, it will be known safety level of the AP1000. The analysis is done by using event tree and each probability of top event is calculated by using fault tree analysis. Failure rate of component used in calculation is based on AP1000 data that is published by Westinghouse and data from IAEA Tecdoc [8-12].

2. Level 2 PSA and Description of AP1000

To ensure that nuclear power plant is designed and operated with safe and secure, therefore it is needed safety analysis before the reactor was built as mandated on Government Regulation of Indonesia no. 2 year 2014 regarding licensing for nuclear installation and nuclear material utilization.

Probabilistic safety assessment is one of the methods that was used to the safety analysis. Within the scope of this analysis includes determining fission product release to environment if design basis accident (DBA) was occurred. It caused core damage as well as potentially release fission product. This analysis is known as level 2 PSA. The analysis is assumed that systems are included level 3 DiD (Defence in Depth) which is to overcome DBA failed. In fact, design basis accident and core damage is very small possibility.

The important insight in the level 2 PSA is to identify path of the radioactive materials released form fuel to containment that might disperse into the environment [13, 14]. Important results that will be obtained in this analysis is to prevent the accident propagation, mitigation action that is required and physical barrier that is provided. Therefore, the purpose of an evaluation of power reactor after core damage is to identify adequacy and availability these aspects. The probability of release to environment is depending on the quantity of core melt and effort to mitigation action that is done in the containment also the integrity of containment.

In the level 2 PSA is used containment event tree (CET) that is to describe accident propagation or an occurrence. The aim of analysis is to identify accident sequence which is to lead against the loss of confinement function.

AP1000 is PWR generation III+ type which all core cooling systems use passive system (passive core cooling system, PXS). These system consist of the accumulator, the core makeup tank (CMT), the passive residual heat removal system (PRHR), the automatic depressurization system (ADS), the In-containment refueling water storage tank (IRWST) and the passive containment cooling system (PCS). These systems are category of level 3 DiD that is to prevent design basis accident. Except for PCS was still needed to mitigate after core damage that is to minimize consequence [15].

The accumulator is used to inject water to the reactor core when the core pressure is low, e.g. in the event of large loss of coolant accident (LLOCA) condition. The CMT is functioned to inject water if small loss of coolant accident (SLOCA) is occurred, also other events when the core pressure is still high. The PRHR is used to remove decay and residual heat in the reactor and is operated passively. The IRWST is provided as heat sink from the PRHR. The ADS is to control pressure of the level 3 DiD systems except for the accumulator and the PCS, so these systems is operating optimally. The PCS has a function as ultimate heat sink which is operated passively. These systems diagram are illustrated in Fig. 1.

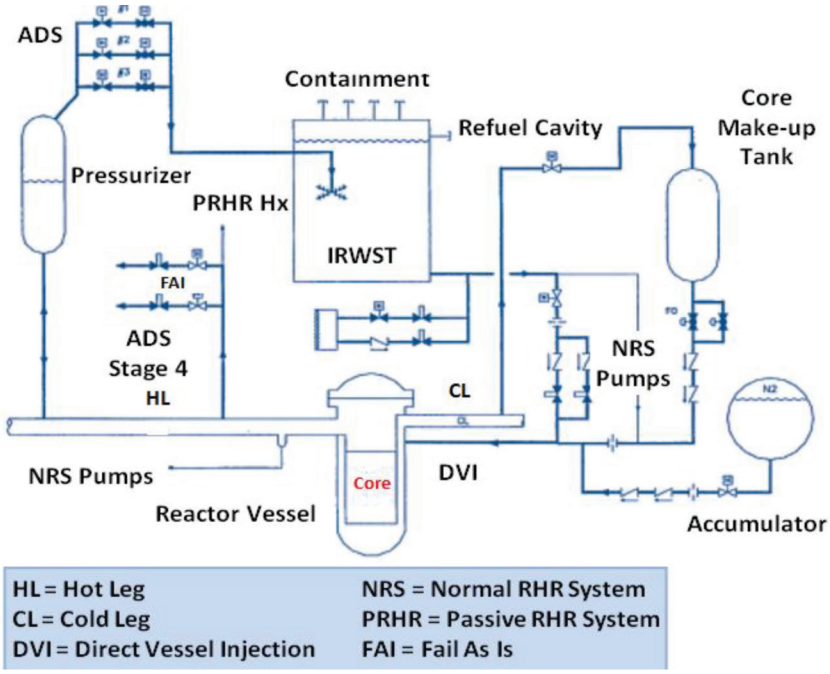

Figure 1: Diagram of AP1000 [15].

With the proper functioning of these systems, core damage is not happened caused design basis accident. However, AP1000 is strictly designed to mitigate core damage. Because core damage is significance parameter for safety level on the light water reactor. To mitigate after core damage, the operator can flood the reactor cavity as shown in Fig. 2. Water which is used for this process from IRWST. This condition will cause the lower portion of the reactor vessel become submerged. Based on an insulating structure that around the reactor vessel will configurate the water stream to reach the vessel. The water will flow around the bottom vessel head and up the vessel insulation wall annulus. In this event, to vent resulting steam from cooling the bottom

vessel from the reactor cavity, so that the reactor vessel become depressurization. This cooling process is sufficient to prevent molten core debris in the lower head caused of melting the steel vessel wall and spilling to containment. Retaining the debris in the reactor vessel provide protection the containment integrity. This process prevent severe accident phenomena, such as ex-vessel steam explosion and core-concrete interaction with molten core material.

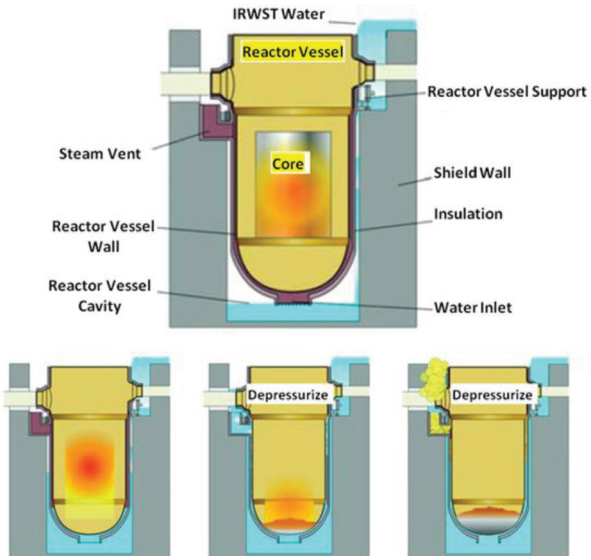

Figure 2: Cooling Phenomena on the Reactor Core Damage [16].

on the probabilistic safety assessment consider all event combination if all cooling event on the reactor vessel was failed. However based on the probabilistic theory, probability of this event is very small. Nevertheless, shall be done analysis because it have seriously consequence.

3. Methodology

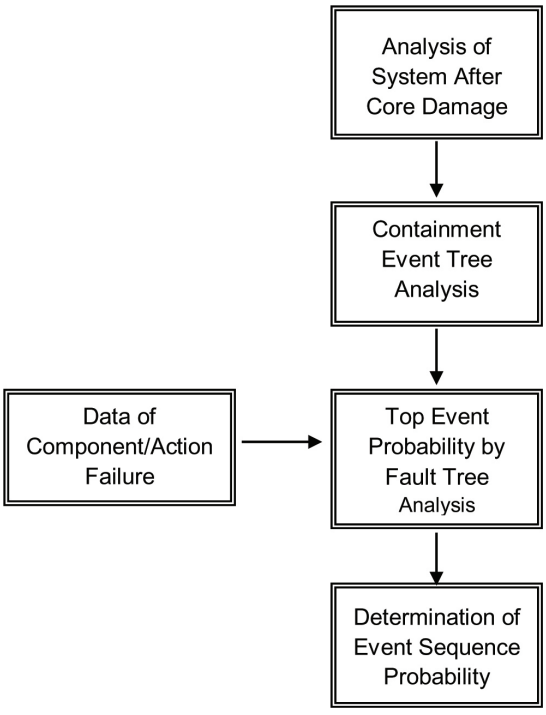

Figure 3: Analysis Stages for Calculation of Event Sequence Probability.

Analysis is carried out by constructing CET. The core melt event is assumed, several top events is selected as event sequence or event propagation by using analysis of system. The top events which is selected is to mitigate radioactive material release. Furthermore, each probability of top event is determined by using fault tree analysis. Data of component failure is adopted AP1000 data which was published and IAEA generic data [8-12]. Finally, the total probability of event sequences are calculated. Scope of event sequence analysis that is considered is based on standard mitigation system of PWR. Simply methodology diagram which is done shown in Fig. 3.

4. Result and Discussion

The analysis of system has been done and based on Fukushima accident learning, then mitigation stages which are to prevent radioactive materials release are constructed. There are ten stages that is depressurization after unflooding core (PT), Containment Isolation (IP), Reactor Cavity Flooding (PK), Core Flooding (PR), Debris drop to Cavity (DK), Containment Cooling by PCS (PC), Steam Release by Venting (PV), Containment Integrity (IS), Hydrogen Control (PH), and Fire/Explosion Control (PL). To use these top events, then it is constructed event tree as illustrated in Fig. 4. As shown in Fig. 4, there are 21 event sequences, The fission product release is not occurred in the event sequence no. 1 because all mitigations is success. The event sequence no.1 is event which is expected on the safety of power reactor. In this event, core damage is occurred but fission product is remain in the containment.

PCS is important system as shown in Fig. 4, if PCS is success, then is not needed venting and containment integrity, because cooling process is continuity, so the core damage process are not sustained. In this event would be more better if hydrogen control is success, so that it is not required fire/explosion control (event sequence no. 1, 6, 10, and 15). The PCS system is similar with containment spray (CS) on the PWR generation II that is to cool the containment and to deposition fission product. The difference is PCS including passive system so it can be operated without electric power supply, whereas CS is active system.

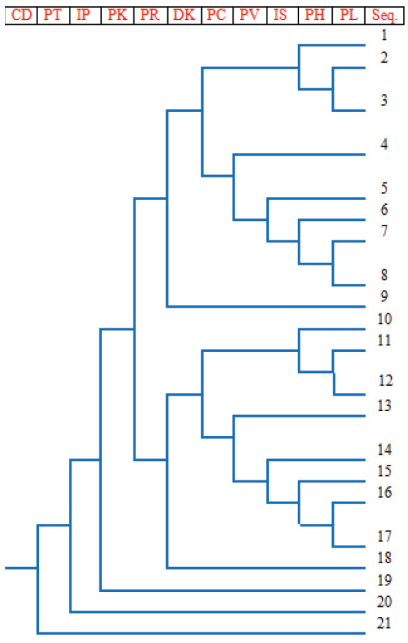

Figure 4: Containment Event Tree.

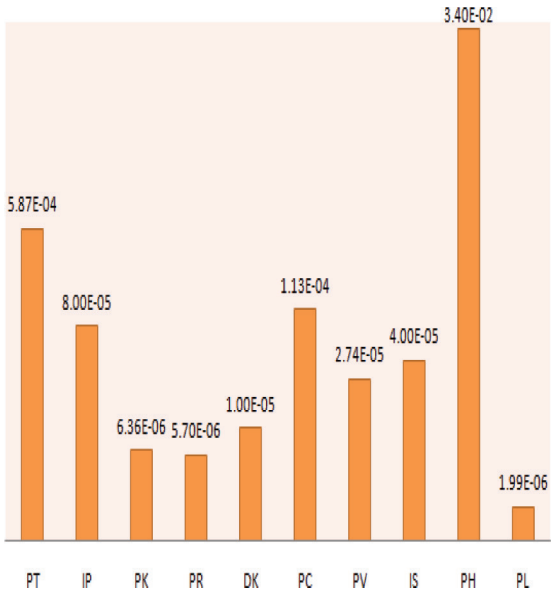

Figure 5: Probability of Top Events.

If PCS failed and then temperature will rise. In this event, pressure will increase or will be possibility produced hydrogen, then venting shall operate. If this mitigation is success, then it is not needed containment integrity, hydrogen control, and fire/explosion control (event sequence no. 4 and 13). If venting system is fail, then prevention of fission product release is depended on containment integrity, hydrogen control and explosion control (event sequence no. 5, 6, 7, 8, 14, 15, 16 and 17).

Result of event tree analysis also show if debris is not entered to reactor cavity, then PCS, hydrogen control and explosion control become not function (event sequence no 9 and 18), so it have possibility to be released fission product to environment.

Fig. 4 also show three probability of top events shall be very small that is depressurization, containment isolation, reactor cavity flooding (sequence no. 19, 20 and 21). In this case, there are not other event that can mitigate if these systems failed. If it be compared with PWR generation II, reactor cavity only seen at the PWR generation III+. This system is to contain debris or core melting.

By using fault tree analysis, probability of top event is shown in Figure 5. Failure probability of top events is enough small that is 10^{-2} to 10^{-6} because each probability of system will be multiplied with the other system or actions, so become the event sequence.

Calculation of event sequence probability is presented in Table 1. Table 1 show that the probability of event is generally small that is 10^{-2} to 10^{-26}. It means mitigation system of AP1000 could confine fission product after core damage occurred.

Probability of each sequence is not linear with quantity of fission product release or consequence. It means large probability of event sequence do not always release large quantity of fission product, so also on the contrary.

Probability of event sequence no. 2 is largest that is 3.40×10^{-2}, but quantity of the fission product released is small. In this case, all top events which assumed is success, only the hydrogen control fail. However the explosion/fire control is not occurred because fire control is success so that quantity of fission product release is small.

Probability of event sequence no. 17 is smallest that is 4.77×10^{-26}. Nevertheless if observed on this sequence, there are failure for six top events (PR, PC, PV, IS, PH and PL), then quantity of the fission product release is large. In this event, because of core unflooding so core damage is occurred. Hereafter, it is followed failure of PCS. It means core is not happened cooling process, so possibility core damage continued. Moreover, this condition is initiated with failure of venting system, then pressure and temperature increased and core damage become seriously. In this scenario, containment integrity also fail, and amount of hydrogen that is produced from core damage phenomena is increasing because hydrogen control also fail. In this event, it will initiate fire or explosion occurrence because fire or explosion control also fail. To determine quantity of each sequence is required comprehensively analysis especially deterministic analysis.

Table 1 and Fig. 4 show probability of three event sequences (no. 19, 20 and 21) that are 10^{-4} to 10^{-6}. These sequences require attention that are PT, IP and PK. If three top events is happened, then the other top events are not significantly function to prevent continually core damage and it might happen fission product release with large quantity.

Based on Table 1, quantitative of fission product release can be distinguished three levels that are minor, intermediate and major. For example, event sequence no. 2 as minor level, event sequence no. 4 as intermediate level and event sequence no. 17 as major level. To clasify all event sequences, it is required deterministic analysis with including physical phenomena for each sequence.