Research Article

Assessment of Cesium Compound Behavior during Simultaneous Failure of Reactor Pressure Vessels and Spent Fuel Pools Using Modified ART Mod 2: Fukushima Daiichi Accident Simulation

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To support the regional strategy development of ASEAN NPSR using scientific research, Modified ART Mod 2 has been used to assess the fission product release from RPVs and SFPs independently. However, the Fukushima Accident suggested the possibility of simultaneous release from RPV and SFP which indicated the necessity of re-evaluation of the maximum source term. The objective was to assess the fission product behavior during a simultaneous failure in RPVs and SFPs of BWR type with Mark I containment design in multiple units using Modified ART Mod 2 in order to evaluate the maximum source term. The releases of cesium compounds in gas and aerosol forms from RPVs and SFPs of Units 1–3 of the Fukushima Daiichi NPP were selected as the case studies. It was found that the behavior of cesium compounds was mainly governed by the aerosols and atmospheric temperatures, which resulted in different characteristics in adsorption and thermophoresis. It also turned out that the simulation of a simultaneous release led to a smaller release than the summation of independent simulations of releases from RPV and SFP by 25%. This study helped estimate the maximum consequences in order to be able to effectively design the EPR for NPP accidents inside or outside the ASEAN region.

1. Introduction

It is well known that a severe accident in Nuclear Power Plants (NPPs) is one of the technological disasters affecting people and the environment worldwide [1]. This essentially means whether or not the country uses nuclear energy; it has the potential to be influenced by NPP incidents. The Association of Southeast Asian Nations (ASEAN) is one of the regional entities that concern about the radioactive effects from possible severe accidents in NPPs [2]. Although NPPs have never been operated in ASEAN countries, knowledge of nuclear safety analysis and assessments of nuclear severe accident consequences are still needed to design a regional plan for preventing, mitigating, and managing potential severe accidents in NPPs located around the region. These concerns of nuclear accident consequences lead to the establishment of the ASEAN Network on Nuclear Power Safety Research (ASEAN NPSR) whereby researchers and engineers in the field of nuclear power safety can jointly conduct research and derive findings from a regional standpoint. The goal of ASEAN NPSR is to strengthen Research and Development (R&D), Human Resource Development (HRD), and regional cooperation in the field of nuclear power safety in ASEAN in order to support the formulation of the regional strategy for accident management [2]. Therefore, ASEAN NPSR continuously promotes collaborative studies that contribute to the planning of Emergency Preparedness and Response (EPR) against NPP
accidents, starting from probable accidents in NPPs located around the region, in order to effectively protect people and the environment from nuclear severe accident consequences.

The first project of the ASEAN NPSR on transboundary atmospheric dispersion assessment of fission product release has continued with active participation from the ASEAN Member States over past years to together support the formulation of ASEAN EPR using scientific research data. In this project, the information on the amount and timeline of the radioactive release from NPPs, the so-called source term, is the main input data for the transboundary atmospheric dispersion assessment. Source term data has been obtained from a publicly available domain such as State-of-the-Art Reactor Consequence Analyses (SOARCA) [3]. SOARCA studied the radioactive effects of severe accidents in a representative Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR). Adopting source term data from SOARCA has two important drawbacks. The first one is that the core inventory is not that of the NPPs of interest, and the other is that only accidents caused by Reactor Pressure Vessel (RPV) failure in a single unit are taken into account. However, after the accident at the Fukushima Daiichi Nuclear Power Plant (1FNPP) in Japan happened, a concern on a multiunit accident of NPPs has become larger than that of a single-unit accident [4]. Consideration of the multiunit accident leads to a more comprehensive accident management strategy that covers the management of severer cases [5]. Looking back to ASEAN, NPPs around the region were built in the form of multiple units such as the Fangchenggang Nuclear Power Plant in China [6]. Thus, the use of source term data from SOARCA as the input data for the atmospheric dispersion calculation may be irrelevant. It is important that ASEAN has a regional capability to assess the source term data by itself in order to evaluate fission product release from a multiple-unit accident in an external location, which will be an important input for the transboundary atmospheric dispersion assessment.

After the accident in the 1FNPP, Tokyo Electric Power Company (TEPCO) put a large effort into the study of the behavior of the reactor core and the RPV and other essential components and examined unsolved issues from accident progression of Units 1–3 of 1FNPP [7]. Units 1–3 of 1FNPP are BWR technology with Mark I containment design in which Unit 1 is an earlier BWR/3 design while Units 2 and 3 are BWR/4 designs [8]. TEPCO aimed to disclose the complete picture of this severe accident and contribute to the improvement of the safety systems of the 1FNPP. Modular Accident Analysis Program 5 (MAAP5) [9] was the main accident analysis code that TEPCO used to analyze accident progression. An accident in Spent Fuel Pools (SFPs) was another major concern for 1FNPP because there were a lot of spent fuels in it which could damage and resulted in fission product release to the environment. Although severe damage of fuel assemblies in the SFP of all units of 1FNPP was not the main concern, the possibility of such accidents was recognized and thus studies on potential radioactive release from SFPs of 1FNPP were widely conducted. Oak Ridge National Laboratory (ORNL) performed the simulation of the SFP of Unit 4 which is the largest source of the spent fuels in the 1FNPP using the Oak Ridge Isotope GENERation (ORIGEN) code [10] whereby the deviation of thermal-hydraulic conditions was studied [11]. In 2018, the simulation of the inherent response of the SFPs of 1FNPP was conducted to analyze the influence of loss of cooling accident in the SFPs using MAAP 5.02 [12] in order to enhance the safety systems of the SFPs [13]. In the aspect of Probabilistic Risk Assessment (PRA) research, level 1 and level 2 PRAs of Mark I BWR which is the reactor type of 1FNPP were redone to calculate core damage frequency (CDF) and large release frequency (LRF) during the decommissioning state using accidents occurring in both RPVs and SFPs [14]. As for level 3 PRA, multiunit level 3 PRA was conducted based on conservative assumptions to estimate multiunit risk and to understand the risk characteristics in a multiunit context [4]. Therefore, in order to be able to consider consequences from the maximum radiological release from an NPP accident, it is necessary to consider the risks associated with both RPVs and SFPs in a multiunit accident [15]. It is obvious from these previous studies that there is a chance of a multiunit accident with simultaneous failure of RPVs and SFPs in NPP accidents. However, currently, studies on such accidents are limited. This implies the necessity of a study of a simultaneous failure in a multiunit accident in order to reinforce the awareness of stakeholders and strengthen the EPR planning.

Thailand has been using the code of Analysis of Radiactive nuclide Transport and deposition/Modification 2 (ART Mod 2) [16] of the Japan Atomic Energy Agency (JAEA) to conduct the source term analysis since 2015. ART Mod 2 code was modified and validated for the evaluation of fission product behavior of cesium compounds from RPVs into Primary Containment Vessels (PCVs) [17]. Four models of aerosol deposition phenomena were validated in order to increase the accuracy of the calculation, namely, gravitational settling, Brownian diffusion, diffusiophoresis, and thermophoresis. Next, Modified ART Mod 2 was applied to a study of cesium compound behavior in the SFP of the Robert Emmett Ginna Nuclear Power Plant in the USA, in the case of complete loss of cooling water [18]. Then, Modified ART Mod 2 was verified for the evaluation of fission product release of cesium compounds from SFP into PCV of Unit 3 of 1FNPP [19]. However, Modified ART Mod 2 has never been used to assess the fission product behavior in a complete accident system which includes the failures of RPVs and SFPs in multiple units.

The objective of this paper is to evaluate the fission product behavior of the cesium compounds in gas and aerosol forms during a simultaneous failure of RPVs and SFPs of BWR type with Mark I containment design in multiple units using Modified ART Mod 2 code. Also, this study is used to confirm the ability of Modified ART Mod 2 to provide the source term data of a release from the PCV to the environment for the transboundary atmospheric dispersion assessment under ASEAN NPSR. Cesium compounds are selected as representative radioactive materials for this study because they are the major radioactive compounds that have long-term effects on people and the environment due to the thirty-year half-life of
2. Gas and Aerosol Deposition Models in Modified ART Mod 2

Modified ART Mod 2 is a tool for calculating the transportation and deposition of the fission product release. In Modified ART Mod 2, fission product types are characterized into two forms including gas and aerosol forms. Figure 1 shows the characteristic of deposition phenomena of gas and aerosol in Modified ART Mod 2.

As for the gaseous fission products, models for condensation and adsorption are considered to evaluate fission product behavior only at the wall surface [16], while the aerosol fission products consider deposition on both the wall and the floor [17]. Phenomena of Brownian diffusion, diffusiphoresis, and thermophoresis are used to illustrate the aerosol deposition on the wall. Only gravitational settling is considered for the aerosol deposition on the floor in Modified ART Mod 2.

2.1. Gas Deposition Models

2.1.1. Condensation. Condensation of the fission product in gas form occurs from differences between partial pressure and saturated vapor pressure in the system. Model of condensation velocity \(v_{\text{cond}}\) (cm/s) is used to represent the gas deposition on the wall as follows:

\[
v_{\text{cond}} = \frac{D^k_g}{(1 - y_g)^{\delta_p}} \left( 1 - \frac{y^k(s)}{y^k_g} \right),
\]

where \(D^k_g\) is the diffusion coefficient of the radionuclides (cm²/s), \(\delta_p\) is the thickness of the boundary layer (cm), \(y_g\) is the ratio of partial pressure without the radionuclides (-), \(y^k_g\) is the ratio of partial pressure without the radionuclides of the total pressure (-), and \(y^k(s)\) is the ratio of saturated pressure without the radionuclides of the total pressure (-).

2.1.2. Adsorption. Adsorption depends on a physical reaction between radionuclides and the material surface under high-temperature conditions. In the code, the only physical adsorption without chemical interactions will be considered in the deposition on the wall. Gas deposition on the wall due to adsorption velocity \(v_{\text{ads}}\) (cm/s) is calculated using the model as follows:

\[
v_{\text{ads}} = A_0 \exp\left( -\frac{\xi_a^k}{k_B T_{\text{surf}}} \right),
\]

where \(A_0\) is the velocity constant of the radionuclides (cm/s), \(\xi_a^k\) is the activation energy of reaction of the radionuclide (erg), \(k_B\) is the Boltzmann constant (erg/(K.g)), and \(T_{\text{surf}}\) is the temperature of the surface (K).

2.2. Aerosol Deposition Models

2.2.1. Gravitational Settling. Aerosol deposition velocity due to gravitational settling \(v_{\text{gra}}(r_p)\) (cm/s) is derived from the drag force of the aerosol surface. In the code, the only aerosol form of fission product release will be considered as the deposition on the ground or liquid surface in the water environment. The deposition velocity of gravitational settling is a function that depends on the Reynolds number (Re). In the case of Re smaller than one, the aerosol deposition velocity is determined by the Stokes approximation. As for the case of Re larger than one, the aerosol deposition velocity is determined by Newton’s approximation as follows:

\[
v_{\text{gra}}(r_p) = \begin{cases} \frac{2r_p^2 (\rho_p - \rho_a)}{9 \mu_g} Cu(r_p), & \text{Re} < 1, \\ \frac{\mu_g \text{Re}}{2 r_p \rho_p}, & \text{Re} > 1, \end{cases}
\]

where \(r_p\) is the radius of aerosol (cm), \(g\) is the gravitational acceleration (cm/s²), \(\rho_p\) is the density of aerosol (g/cm³), \(\rho_a\) is the density of the gas (g/cm³), Cu \(r_p\) is the Cunningham factor (-), and \(\mu_g\) is the viscosity of gas (dyn.s/cm²).

2.2.2. Brownian Diffusion. Aerosol deposition velocity due to Brownian diffusion \(v_{\text{diff}}(r_p)\) (cm/s) can be modeled from an empirical model considering the turbulent damping process under the condition of upward flow direction in a vertical duct as follows:

\[
v_{\text{diff}}(r_p) = \begin{cases} 0.0899 \text{Sc}^{0.704} u_t, & \tau^* < 0.2, \\ 3.25 \times 10^{-4} \tau^{2.2} u_t, & 0.2 < \tau^* < 22.9, \\ 0.17 u_t, & \tau^* > 22.9, \end{cases}
\]

where \(\tau^*\) is the dimensionless particle relaxation time (-), \(\text{Sc}\) is the Schmidt number (-), and \(u_t\) is the friction velocity (cm/s).
2.2.3. **Diffusiophoresis.** Diffusiophoresis is affected by the flow of the condensing steam and partial pressures of noncondensable gas near the structure surface. Thus, the aerosol deposition velocity of diffusiophoresis \(v_{\text{diff}}(r_p)\) (cm/s) consists of both velocity of Stephan flow and gas momentum transfer as follows:

\[
v_{\text{diff}}(r_p) = U_c + \frac{C_u(r_p)}{\chi} \frac{\sqrt{m_p}}{\gamma_3 \sqrt{m_p} + \gamma_a \sqrt{m_a}} \gamma_p U_c,
\]

where \(m_p\) is the molecule weight of steam (g), \(m_a\) is the molecule weight of noncondensible gas (g), \(\gamma_p\) is the mole fraction of steam (-), \(\gamma_a\) is the mole fraction of noncondensible gas (-), \(U_c\) is the velocity of condensing steam (cm/s), and \(\chi\) is the shape factor (-).

2.2.4. **Thermophoresis.** Aerosol deposition velocity due to thermophoresis \(v_{\text{therm}}(r_p)\) (cm/s) is controlled by the difference of temperature gradients. The model of thermophoresis is generated by Monte-Carlo type numerical modeling as follows:

\[
v_{\text{therm}}(r_p) = \frac{2 \nu_g C_u(r_p) \left( \lambda_g + C_i Kn \lambda_p \right) (1 + (9 Kn/(4 + (\pi/2))))}{T_g (1 + 3C_m Kn) (2\lambda_g + \lambda_p + 2C_i Kn \lambda_p)} \nabla T_g,
\]

where \(\nu_g\) is the dynamic viscosity of gas (cm²/s), \(\lambda_g\) is the conductivity of mixed gas (erg/(K.cm.s)), \(\lambda_p\) is the conductivity of aerosol (erg/(K.cm.s)), \(C_i\) is the coefficient of the energy exchanges between the aerosol and gas (-), \(C_m\) is the coefficient of the momentum exchanges between the aerosol and gas (-), \(Kn\) is the Knudsen number (-), and \(\nabla T_g\) is the gradient of the temperature of the gas (K).

3. **Methodology**

In this paper, the release of CsI in gas form and CsOH in aerosol form from both the RPVs and the SFPs into the environment was assessed using hypothetical failure events of RPVs and SFPs of Units 1–3 of 1FNPP. Modified ART Mod 2 was used to simulate the accidents to study the fission product behavior in three cases including (1) a failure of RPVs (reference case), (2) independent failures of RPVs and SFPs, and (3) a simultaneous failure of RPVs and SFPs.

3.1. **Case 1: Failure of RPVs (Reference Case).** The first case was the simulation of the release of CsI gases and CsOH aerosols from RPVs of Units 1–3 of 1FNPP to PCVs, the fifth floor of Reactor Buildings (RBs), and the environment, respectively. This case was set to be a reference case for the comparisons in the following cases. Figure 2 shows the nodalization and flow directions of the first case. 13 volumes were used to represent the RPVs, the PCVs, the SFPs, and the RBs of Units 1–3 as well as the environment around the units. In this case, the fission product release of cesium compounds in each unit was transferred from the RPV to the PCV, the RB, and the environment, respectively. There is no consideration of the release from the SFPs. The geometry of each volume in Modified ART Mod 2 was determined based on the design of Units 1–3 [25–27], though all volumes were assumed to be in a cylindrical shape. Table 1 shows the geometry parameters for Modified ART Mod 2.

Regarding the source term from the RPVs, the amounts of CsI gas and CsOH aerosols were defined by multiplying the amount of cesium-137 (Cs-137) inventory in the core of Units 1–3 of 1FNPP [28] to the release fraction of CsI gas and CsOH aerosols calculated by TEPCO [29]. The radioactive cesium compounds release from the center of the RPVs of Units 1–3 which are represented by Volume 1, Volume 5, and Volume 9, respectively. Table 2 shows the cesium source term in the RPVs used as the inputs for Modified ART Mod 2. In this study, the aerosol size for all simulations was designed to match the aerosol distribution at the beginning of the aerosol phase, where aerodynamic mass median diameter (AMMD) and geometric standard deviation (GSD) are set to 3.35 and 1.5, respectively [30]. Aerosol mass distribution is assumed to follow log-normal approximation. As Modified ART Mod 2 requires ten representative values for aerosol diameters [16], ten different percentile values were selected to represent the CsOH aerosol sizes as shown in Table 3.

Thermal-hydraulic conditions during the accident in Units 1–3 of 1FNPP which affect the transportation and deposition of cesium compounds, including temperatures,
pressures, and hydrogen ($\text{H}_2$) gas flows, refer to the TEPCO reactor core condition report of Units 1–3 of 1FNPP [29]. Only the wall temperature of the RPV within Unit 3 came from the study of Paul Scherrer Institute (PSI) [31]. Figures 3(a)–3(c) show the temperatures of gas and aerosols of cesium compounds, the RPV walls, and the PCV walls of Units 1–3 used in the calculation. Figures 4(a) and 4(b) show the pressures in the RPVs and the PCVs of Units 1–3. Figure 5 shows the volumetric flow rates of $\text{H}_2$ gas from the RPVs of Units 1–3. Temperatures and pressures of the RBs and the environment were set at 298K and 0.1MPa to represent surrounding conditions.

Regarding the simulation timeline, the total time of simulation is 87 hours from 12.00 a.m. of March 11, 2011, to 03.00 p.m. of March 15, 2011, to cover the early phase of the release from Units 1–3. Unit 1 started to leak from a Safety Relieve Valve (SRV) 15 hours after the initiation of the accident. Then, the fission products started to leak from the PCV into the RB and the environment until the $\text{H}_2$ explosion happened at the 25th hour. Unit 2 started to leak from the SRV at the 77th hour. Unit 3 started to leak from the SRV at...
the 42nd hour into the RB and the environment until the H2 explosion happened at the 68th hour.

3.2. Case 2: Independent Failures of RPVs and SFPs. In the second case, independent releases of cesium compounds from the SFPs were considered in addition to the first case. Figure 6 shows the timeline and release pathways of the second case. The release of radioactive materials from the SFPs was assumed to occur independently from the release from RPVs. The release of cesium compounds from the SFPs of Unit 1 and Unit 3 was assumed to start after the H2 explosion which was the cause of the collapse of the fifth floor of RBs [32] and the rapid loss of coolant in the SFPs [11]. Only the SFPs of Unit 1 and Unit 3 where H2 explosions occurred during the accident were assumed as the sources of release. Nodalization of this case was set using 13 volumes like the first case. But in this case, there were two release pathways. From Figure 6, the first pathway was from the RPV as in the first case. The second release was from the SFP into the RB and the environment, respectively. Figure 7 shows the nodalization and flow directions of the second case. The amounts of CsI gas and CsOH aerosols being released from the SFPs of Unit 1 and Unit 3 were defined by multiplying the cesium-137 inventory in SFPs of 1FNP [32] to the same fractions of the release from the RPVs. Table 4 shows the cesium source term in the SFPs used for calculation in Modified ART Mod 2.

Thermal-hydraulic conditions for Modified ART Mod 2 code were set based on the simulation data during the complete loss of water from the study of inherent nuclear spent fuel pool response to a loss of pool cooling accident [13] since it was modeled based on the behavior of spent fuels within the SFPs of 1FNP. Figures 8(a) and 8(b) show the temperatures of the gas and aerosols of cesium compounds and the SFP walls used in the calculation. Figure 9 shows the volumetric flow rates of H2 gas from the SFPs of Unit 1 and Unit 3 to the RBs. The pressures within the SFPs of the two units were set 0.1 MPa like the RBs and the environment because they were linked to each other.

3.3. Case 3: Simultaneous Failure of RPVs and SFPs. The third case aims to model the possible conditions of a simultaneous failure of RPVs and SFPs in multiple units to investigate the consequences [32]. It resembled the second case, except that it considered the transportation of cesium compounds between the RPV and the SFP of each unit. The PCVs nearby the SFPs are an important part to link the transportation of cesium compounds between the RPVs and the SFPs. The volumetric flow rates and thermal-hydraulic conditions of this case were set to be the same as the second case, except that the interactions between Volumes 2 and 3, Volumes 6 and 7, and Volumes 10 and 11 were considered. Figure 10 shows the nodalization and flow directions of the third case.

4. Results and Discussion

4.1. Case 1: Failure of RPVs (Reference Case). Figure 11 shows the accumulative release of Cs-137 from the RPVs of Units 1–3 into the environment illustrated by Modified ART Mod 2 for the first case. It was found that the total of cesium-137 released at 87 hours after the initiation of the accident was 2.03E + 14 Bq. This was compared to the simulated total Cs-137 release based on the Fukushima monitoring data in Figure 11 [33, 34]. It was found that the summation of the accumulative releases of cesium-137 of Units 1–3 simulated by Modified ART Mod 2 was slightly lower than the monitoring data.

The main reason for the underestimation could be the assumption of single point source release in Modified ART Mod 2 [16], which essentially means multiple release points from a single volume cannot be modeled. However, in the real situation, it is highly likely that the radioactive materials release from multiple points due to multiple locations of cracked and molten fuels [35]. The results of Modified ART Mod 2 were considered acceptable as the reference case because the major part of the results was in the same order of magnitude as Terada et al. [33] and was smaller than Katata et al. [34] by only one order of magnitude.

Next, Figure 12 shows the accumulative release of CsI gas and CsOH aerosols from Units 1–3 in the first case. It was found that the CsI gas was the major part of the release to the environment, while the released CsOH aerosols were only in the order of 10^-8 of the total initial CsOH aerosols of Units 1–3. The majority of the CsOH aerosols tended to deposit in the units. The results are consistent with the studies of thermodynamic and kinetic studies of iodine and cesium transport in a nuclear severe accident at high temperatures [36]. This study showed that iodine and cesium had the potential to react with vapor and other iodine compounds to form CsI and CsOH in which more CsI tended to release into the ambiance than CsOH at high temperature due to different molecule structures. The results of Modified ART Mod 2 were also consistent with the studies by MAAP [29] and MELCOR 2.1 [31] where the majority of the CsOH aerosols deposited in the plants. However, the releases into the environment in MAAP and MELCOR 2.1 were around 1–2 percent which is much larger than the estimation of Modified ART Mod 2. This is again attributed to the assumption of single point source release in the code that affected the deposition rate and consequently the release of CsOH aerosols. On the other hand, in MAAP and MELCOR 2.1, fuels can be divided into multiple cells. This enables the
simulation of multiple point source releases which is closer to the actual condition [13, 37]. It remained as a future task for Modified ART Mod 2 development to enable handling of multiple point source releases which would increase the accuracy of environmental source term prediction.

Since the deposition of cesium compounds directly affected the amount of release into the environment directly, contributions of different deposition phenomena to the deposition of CsI gas and CsOH aerosols in each volume were summarized in Tables 5 and 6, respectively. It was found that the CsOH aerosol deposition was attributed to only three phenomena, namely, gravitational settling on floors, Brownian diffusion on walls, and thermophoresis on walls. As for the CsI gas, only the adsorption phenomenon affected its deposition on walls. In this study, the releases of gas and aerosols from the molten core were assumed not to deposit on the floor of the RPVs especially volatile fission products [38] in order to maintain conservatism [39]. Thus, gravitational settling was considered only in volumes other than the RPVs. Diffusophoresis of CsOH aerosols and condensation of CsI gas did not contribute to depositions on walls because the high temperature resulted in the decrease in factors driving the two phenomena such as the diffusion coefficient and the fractions of steam and air [16]. For CsOH aerosols deposition on walls, thermophoresis was more dominant than Brownian diffusion since high temperature contributed to large temperature gradients which induced the particle deposition on the wall from thermophoresis [40, 41], especially in the RPVs. A small contribution of Brownian diffusion indicated that the influence of the turbulent damping process could be significantly decreased if a large temperature gradient existed in the system [42]. Likewise, the CsI gas deposition on walls from physical adsorption was also driven by the increase in adsorption velocity at high temperatures [16]. Moreover, the difference in fractions of CsI gas release into the environment among the three units in Table 5 showed that the amount of adsorption was dependent on the starting time of the leakage described in Section 3.1. Figure 13 shows the percentages of accumulative CsI gas deposition due to adsorption in Units 1–3 estimated by Modified ART Mod 2. It was found that adsorption could rapidly increase in the RPVs at high temperatures before the leakage into the environment started when the ambient temperature significantly

Figure 3: Conditions of the temperatures of Units 1–3 for Modified ART Mod 2 code: (a) gas and aerosols, (b) the RPV walls, and (c) the PCV walls.
decreased. Thus, the amount of adsorption within the RPVs in Table 5 varied significantly.

4.2. Case 2: Independent Failures of RPVs and SFPs. Figure 14 shows the comparison of the total accumulative release of cesium compounds into the environment from Units 1–3 estimated by Modified ART Mod 2 of the second case and the first case. It was found that the total cesium compound releases at 87 hours were $2.98E+15$ Bq. When compared to the first case, it was found that the cesium compound releases of the second case were more than the first case by 14 times. This is because the total initial cesium-137 of Units 1–3 in the SFPs was larger than the RPVs and the release from SFPs could directly go to the RBs and the environment without the protection of the PCVs.

Next, contributions of different deposition phenomena to the deposition of CsI gas and CsOH aerosols in the SFP and the RB of Units 1 and 3 and the release into the environment were summarized in Tables 7 and 8. The values for the remaining volumes were identical to Tables 5 and 6. It was found that although the fractions of release from the SFPs into the environment were smaller than those from the RPVs, the SFPs gave larger release into the environment simply due to larger initial sources. In addition, the SFPs were not protected by the PCVs. Same deposition phenomena as the reference case could be observed, but there were significant differences in contributions of adsorption, thermophoresis, and gravitational settling. Adsorption and thermophoresis within the SFPs were by far less than the RPVs. Although the temperatures in the SFPs were high, the surroundings were different from the RPVs. The SFPs were always open and closer to the environment which made the surrounding temperature much lower than that of the RPVs [43]. Lower temperature decreases adsorption [16] and thermophoresis [40, 41] in the SFPs. Gravitational settling also occurred on the floor of SFPs which was not assumed to exist in RPVs. It became the dominant phenomenon for aerosol deposition in the SFPs.

There is one additional finding from Case 2 which could contribute to the planning of decommissioning. The results showed that the majority of the deposition in RPVs was on walls, while most of the deposition was on the floor in SFPs. Therefore, in the decommissioning after the accident, these highly contaminated areas should be cleaned or eliminated before other parts to help reduce the spread of contamination and radiation effect to workers in the field [44].

4.3. Case 3: Simultaneous Failure of RPVs and SFPs. Figure 15 shows the total accumulative release of cesium compounds into the environment from Units 1–3 using Modified ART Mod 2 code of the third case comparing to the second case. It was found that the total of cesium compound releases at 87 hours was $2.22E+15$ Bq which was less than the second case by around 25 percent. From Figure 16 which shows the comparison of the ratios of deposition on the wall to deposition on the floor within Units 1–3 of the second case and the third case, it was found that the deposition characteristics of the two cases are similar. Hence, the reason for the difference in the
Release into the environment could not be described by the deposition characteristics. The simple explanation could be that the transportation of the cesium compounds between the RPVs and the SFPs increased the total flow of cesium compounds among the volumes in the system. Hence, the cesium compounds had more chance to deposit in on the PCV walls due to gas adsorption.
This study showcased the integrated release from RPVs and SFPs in a multiunit accident with the most probable conditions. The release of cesium compounds from the SFPs still was the major contribution and was larger than the release from the RPVs by approximately one order of magnitude. These results were not surprising considering the designs of the two components. The RPVs of 1FNPP were located at the center of units and equipped with safety systems such as suppression pools directly connected to the RPVs to retain the fission product, while these safety features are not designed for the SFPs [8]. Although the amount of radioactive materials being released into the environment indicated that SFP failure would lead to larger effects to people and the environment when compared to RPV failure, the occurrence probability of SFP failure is smaller than that of the RPVs by several orders due to lower normal temperature and pressure during reactor operation [8, 10]. However, considering the size of the consequences when the event occurs, the conclusion that the SFP failure during an NPP severe accident requires attention remains true.

Finally, this study showed that Modified ART Mod 2 could evaluate the behavior of cesium compounds in gas and aerosol forms and the amount and timing of their releases into the environment during a multiunit accident with different conditions. Modified ART Mod 2 could contribute to the prediction of consequences of a hypothetical simultaneous failure in the RPVs and the SFPs. Finding from the three cases of the study helped indicate the weakness of the entire system of an NPP with multiple units and the limitation of the coverage of current safety systems which do not normally include the assurance of the safety of SFPs. As mentioned in the introduction section, an NPP accident can affect regions with no active NPPs which implies that ASEAN NPSR has to also put more effort into studying the SFP failure, especially when it occurs at the same time as the RPV failure. Although the magnitude of the earthquake can now be detected in a real-time manner [45], it is still far from the exact prediction [46]. We could never be certain that accidents like or severer than the one that happened at 1FNPP in 2011 will not happen again. Therefore, a holistic study of an NPP severe accident considering the releases from the RPVs and the SFPs should be conducted by ASEAN NPSR in order to help develop the regional strategy on EPR toward future NPP accidents. The EPR should be planned to cover failures in different locations within the reactor unit and also simultaneous accidents in multiple units.
Volume 13 is the environment.

Volume 1 is the RPV of the Unit 1.
Volume 2 is the PCV of the Unit 1.
Volume 3 is the SFP of the Unit 1.
Volume 4 is the RB of the Unit 1.

Volume 5 is the RPV of the Unit 2.
Volume 6 is the PCV of the Unit 2.
Volume 7 is the SFP of the Unit 2.
Volume 8 is the RB of the Unit 2.

Volume 9 is the RPV of the Unit 3.
Volume 10 is the PCV of the Unit 3.
Volume 11 is the SFP of the Unit 3.
Volume 12 is the RB of the Unit 3.

| Volume 13 | Volume 1 | Volume 2 | Volume 3 | Volume 4 |
|-----------|----------|----------|----------|----------|
| Volume 13 | Volume 1 | Volume 2 | Volume 3 | Volume 4 |

**Figure 10:** Nodalization and flow directions of case 3.

**Figure 11:** Total accumulative release of Cs-137 into the environment from Units 1–3 of the first case.

**Figure 12:** Total accumulative release of CsI gas and CsOH aerosols from Units 1–3 of the first case simulated by Modified ART Mod 2.
On the other hand, this work indicated the importance of possibly new NPP technologies especially Small Modular Reactors (SMRs) which are the potential to reduce risk of the SFP accidents [47]. SMRs’ technologies were considered as the one of main points in ASEAN NPSR to contribute to new nuclear safety research which concerns about new consequences’ forms of SMRs. This new nuclear safety research helped support the strength of the EPR in ASEAN through the collaborative work of ASEAN NPSR in the future.

| Unit | Type  | Volume no. | CsI gas deposition (% of initial CsI gas from the RPVs of each unit) | Adorption | Remaining | Total release into the environment of each unit |
|------|-------|------------|-----------------------------------------------------------------|-----------|-----------|------------------------------------------------|
| 1    | RPV   | 1          | 1.30E+01                                                       | 1.77E-01  |           | 8.61E+00                                       |
|      | PCV   | 2          | 2.55E-03                                                       | 6.32E+01  |           |                                                |
|      | RB    | 4          | 1.80E-04                                                       | 1.50E+01  |           |                                                |
| 2    | RPV   | 5          | 8.47E+01                                                       | 1.35E+01  |           | 5.44E-06                                       |
|      | PCV   | 6          | 3.45E-02                                                       | 1.81E+00  |           |                                                |
|      | RB    | 8          | 1.02E-05                                                       | 5.08E-03  |           |                                                |
| 3    | PCV   | 10         | 6.88E-02                                                       | 2.18E+01  |           | 7.97E+00                                       |
|      | RB    | 12         | 3.39E-06                                                       | 1.19E+00  |           |                                                |

Table 5: Deposition phenomena of CsI gas in Units 1–3 of the first case simulated by Modified ART Mod 2.

| Unit | Type  | Volume no. | CsOH aerosols deposition (% of initial CsOH aerosols from the RPVs of each unit) | GS(a) | BD(b) | TP(c) | Total release into the environment of each unit |
|------|-------|------------|--------------------------------------------------------------------------------|------|------|------|------------------------------------------------|
| 1    | RPV   | 1          | 0.00E+00                                                        | 5.77E-01  | 9.72E+01  |                                            |
|      | PCV   | 2          | 8.61E-04                                                        | 1.30E-02  | 2.11E+00  | 2.63E-07                                      |
|      | RB    | 4          | 1.59E-04                                                        | 8.59E-04  | 1.31E-01  |                                            |
| 2    | RPV   | 5          | 0.00E+00                                                        | 7.97E-01  | 9.56E+01  |                                            |
|      | PCV   | 6          | 3.44E-01                                                        | 5.50E-03  | 3.28E+00  | 3.76E-06                                      |
|      | RB    | 8          | 6.95E-04                                                        | 9.57E-06  | 7.30E-04  |                                            |
| 3    | PCV   | 10         | 2.17E-02                                                        | 1.46E-02  | 9.71E+00  | 4.22E-06                                      |
|      | RB    | 12         | 1.95E-04                                                        | 5.92E-04  | 8.50E-02  |                                            |

(a)Gravitational settling on floor. (b)Brownian diffusion on wall. (c)Thermophoresis on wall.

On the other hand, this work indicated the importance of possibly new NPP technologies especially Small Modular Reactors (SMRs) which are the potential to reduce risk of the SFP accidents [47]. SMRs’ technologies were considered as the one of main points in ASEAN NPSR to contribute to new nuclear safety research which concerns about new consequences’ forms of SMRs. This new nuclear safety research helped support the strength of the EPR in ASEAN through the collaborative work of ASEAN NPSR in the future.
Figure 14: Total accumulative release of cesium compounds into the environment from Units 1–3 estimated by Modified ART Mod 2 of case 2 comparing to the reference case.

Table 7: Deposition phenomena of CsI gas in the SFP and the RB of Units 1 and 3 of the second case simulated by Modified ART Mod 2.

| Unit | Type | Volume no. | CsI gas deposition (% of initial CsI gas from the SFPs of each unit) | Adsorption | Remaining | Total release into the environment of each unit |
|------|------|------------|---------------------------------------------------------------|--------|----------|-----------------------------------------------|
| 1    | SFP  | 3          | 1.24E−03, 5.37E−04, 1.82E−03, 4.88E+01                        |        |          | 5.12E+01                                      |
|      | RB   | 4          | 1.56E−03, 5.37E−04, 3.13E−03, 4.72E+01                        |        |          | 4.96E+01                                      |
| 3    | SFP  | 11         | 1.29E−07, 3.35E−26                                           |        |          | 3.35E−26                                      |
|      | RB   | 12         | 1.09E−07, 5.00E−08                                           |        |          | 5.00E−08                                      |

Table 8: Deposition phenomena of CsOH aerosols in the SFP and the RB of Units 1 and 3 of the second case simulated by Modified ART Mod 2.

| Unit | Type | Volume no. | CsOH aerosols deposition (% of initial CsOH aerosols from the SFPs of each unit) | GS(a) | BD(b) | TP(c) | Total release into the environment of each unit |
|------|------|------------|-----------------------------------------------------------------------------|-------|-------|-------|-----------------------------------------------|
| 1    | SFP  | 3          | 9.93E+01, 6.73E−01, 1.09E−07                                               |       |       |       | 2.86E−10                                      |
|      | RB   | 4          | 6.07E−11, 3.28E−10, 5.00E−08                                               |       |       |       |                                               |
| 3    | SFP  | 11         | 9.93E+01, 6.73E−01, 1.29E−26                                               |       |       |       | 3.35E−29                                      |
|      | RB   | 12         | 8.33E−30, 3.72E−29, 5.66E−27                                               |       |       |       |                                               |

(a) Gravitational settling on the floor. (b) Brownian diffusion on the wall. (c) Thermophoresis on the wall.

Figure 15: Total accumulative release of cesium compounds into the environment from Units 1–3 using Modified ART Mod 2 of case 3 comparing to case 2.
5. Conclusions

This paper assessed the fission product behavior of the cesium compounds in gas and aerosol forms during a simultaneous failure of RPVs and SFPs of BWR type with Mark I containment design in multiple units using Modified ART Mod 2 to demonstrate the ability of Modified ART Mod 2 to provide the source term data of a radioactive release from an NPP to the environment for the transboundary atmospheric dispersion assessment under ASEAN NPSR through the three case studies.

In the first case, Modified ART Mod 2 was used to simulate the cesium compound releases from the RPVs based on the past accident at 1FNPP. The behavior of the cesium compounds basically depended on the effect of high temperature which impacted adsorption and thermophoresis of the compounds. The second case considered independent releases from the SFPs and the RPVs to evaluate the maximum release in the environment. It was found that the release of cesium compounds of the second case was more than the first case by 14 times. This was simply due to larger initial sources and the inexistence of a multilayered protection system for SFPs. The third case considered the radioactive material flow between the SFPs and the RPVs. It was found that the release into the environment decreased by 25% since the increase in the total flow in PCVs heightens the chance for the cesium compounds to deposit on the PCVs walls due to gas adsorption.

This study helped understand the physical characteristics of a simultaneous failure of RPVs and SFPs, which could support NPP safety assurance and safe decommissioning. From the viewpoint of ASEAN NPSR, the study enabled an evaluation of different types of radioactive releases from an NPP, including a combined release from different sources. This ability when combined with the ability to assess transboundary atmospheric dispersion [48] will support the development of the ASEAN EPR guidelines which will be useful for the planning of regional response during an accident in an external NPP. Moreover, this work indicated the importance of new NPP technologies to avoid the SFP accidents in ASEAN such as SMRs which were considered the future nuclear safety research to help support the of the EPR in ASEAN in the future.

Data Availability

All research papers and documents are cited at relevant places within the text as references.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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