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Review Article

Development of a Korean roadmap for technical issue resolution for fission product behavior during severe accidents

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ABSTRACT

In order to develop a domestic research roadmap for severe accidents, a special committee was established by the Korean Nuclear Society. One of the subcommittees discussed the characteristics and the relevant technical issues in the stages of fission product release and physical forms of radionuclide release and transport. The group members developed a tree to identify fission product release phenomena by tracing failures of individual defense-in-depth barriers and added possible countermeasures against failure. For each elemental issue, they searched for technical problems by examining the phenomena, accident management actions, and regulatory aspects relevant to the mitigation features for containment, including mitigation strategies against containment bypass accidents. Regulatory concerns, including the source term and the acceptance criteria for radionuclide release, were also considered. They identified further research needs regarding important technical issues based on the degree of the current knowledge level in Korea and in foreign countries, looking at the significance and urgency of issues and the expected research period required to reach an advanced level of knowledge. As a result, the group identified the 12 most important and urgent issues, most of which were expected to require mid-term and long-term research periods.

1. Introduction

Since the Fukushima accident, many countries have been carrying out tasks to secure countermeasure systems against severe accidents so that protection of public health and environment from radiation hazards can be assured [1]. In Korea, a special safety inspection was conducted in March of 2011 by experts from regulatory organizations, industry, university, and research institutes. Based on the results, 56 items, including six measures taken by the operator itself, were identified as countermeasures against postulated severe accidents triggered by natural disasters. Many of these countermeasures, including installation of passive autocatalytic recombiners in the operating plants, have already been implemented for all domestic nuclear power plants (NPPs) [2,3].

Meanwhile, international efforts are underway to limit the release of radioactive material from severe accidents at NPPs by strengthening international convention. The International Atomic Energy Agency (IAEA) issued the Vienna Declaration on Nuclear Safety in February 2015, calling for dedicated efforts to limit off-site releases that could result in long-term contamination, as well as early or large releases. In addition, the IAEA conducted an Integrated Regulatory Review Service mission for the Korean regulatory body in July 2011 and provided follow-up actions in December of 2014. As a result, it was recommended that off-site dose criteria for severe accidents be established. Subsequently, rulemaking for severe accident requirements was finalized in June 2016. Severe

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accident management guidelines (SAMGs) must be submitted as an operating licensing requirement for new plants, while they must be submitted within 3 years for all operating NPPs. Therefore, the Nuclear Safety Act was revised to require the submission of an accident management program that covers not only the scope of design basis accidents, but also that of severe accidents when applying for an operating license. In order to implement the additional requirements, several subordinate decrees and laws have been established, including new design criteria for acceptable quantity and frequency of a large release and acceptable off-site dose due to a severe accident.

Under such circumstances, examination of the phenomena related to radioactive material release during a severe accident and development of mitigation measures were considered urgent tasks for the Korean nuclear community. Following discussions among domestic researchers in October 2014, a special committee on “Development of a Research Roadmap for Examination of Severe Accident Phenomena and Establishment of Countermeasure System” was set up in early 2015 by the Korean Nuclear Society (KNS). Accordingly, three subcommittees were organized to develop a comprehensive roadmap for the following areas: in-vessel phenomena, ex-vessel phenomena, and fission product (FP) behavior. In particular, the subcommittee on FP behavior operated effectively, holding nine meetings during the designated term between the kickoff meeting on January 22, 2015 and August 31, 2016.

In the meantime, similar activities had already been done in Europe [4,5] and Japan [6]. In Europe, “European expert network for the reduction of uncertainties in severe accident safety issues” established phenomena identification and ranking tables (PIRTs) for all aspects of severe accidents [4]. Then, its priority ranking was reassessed within the domain of the severe accident research network of excellence work program “Severe Accident Research Priorities” to harmonize and reorient research programs, to define new ones, and to close resolved issues on a common basis [5]. Meanwhile, based on findings from the Fukushima Daiichi NPP accident, Japanese experts developed PIRTs for thermal hydraulics and source term (ST) and summarized the highly ranked phenomena [6]. These previous studies have provided good examples for our subcommittees in developing domestic roadmaps. This paper describes the dedicated activities of the FP behavior group and elucidates recommendations for future research in Korea. It solely covers the FP release from an NPP, mainly focusing on pressurized water reactors.

2. Approaches to developing the roadmap

During a severe accident involving reactor core degradation, radioactive materials can be released to the environment if the reactor containment fails, is vented or is bypassed. The ST is normally defined as the magnitude and composition at the time of release, as well as the chemical and physical forms of released material [1,7,8]. Among radioactive materials, such as fission and activated products and actinides, FPs are the source of activation and may comprise the major portion of radioactivity during an accident. The magnitude of their release depends on the accident sequence, which includes the initiating event, subsequent plant response, and mitigating actions taken by the plant personnel. The accident progression paths can be characterized by three release stages: the release of radionuclides from the degraded fuel, their behavior during transport in the reactor coolant system (RCS), and their behavior in the containment. Furthermore, the amount of release is largely affected by the volatility of radionuclides, which governs the physical forms of their release and transport, i.e., gas/vapor or condensed material, namely, aerosol. Since they rely on chemical speciation, FP chemistry over a wide range of temperatures is very important in determining an accurate ST. For example, chemical reactions of FPs with the structural materials released from the damaged core or coolant material in the RCS play important roles in determining their airborne concentration in the containment atmosphere [9]. Aerosol physics also governs the radionuclide behavior in the RCS and in the containment because these materials are condensed during transfer from the damaged core to the containment, except for noble gases and gaseous iodine and ruthenium [1].

The subcommittee members discussed the release characteristics and agreed to examine the technical issues relevant to the three release stages and physical forms of radionuclides released and transported as described above. Thus, through internal brainstorming and an overview of the EU PIRT, they developed a tree for FP release phenomena by tracing failures of the defense-in-depth barriers. Fig. 1 shows a tree that describes the major elements in this task. In addition, elements for the establishment of countermeasures were added to the tree. In order to examine technical issues, they took into account the phenomena, accident management actions, and regulatory aspects relevant to mitigation features for containment and mitigation strategies against containment bypass accidents. Regulatory requirements for STs including the reference accident ST [7,10,11] and the acceptance criteria [12] were also included in the tree. Then, the group identified further research needs for important technical issues based on the degree of the current knowledge level in Korea and in foreign countries, the significance and urgency of those issues, and the expected research period required to reach the international level of knowledge. While the activities of each subcommittee were ongoing, the steering committee convened regularly to review the activities and to give feedback to the subcommittees. A report prepared by the subcommittee on FP behavior was reviewed by independent external experts who provided feedback. After collecting the relevant feedback, the report was finalized [13].

3. Identification of technical issues on FP release phenomena and the countermeasure system

With regard to the elements of the three release stages, the physical forms of radionuclides, and the countermeasure system described in section 2, the following aspects were examined: the relevant phenomena, experimental programs, computer modeling, the current knowledge level in Korea and in foreign countries, the significance and urgency of issues, and the expected research period required to reach the international level of knowledge. A summary of each element and the identified technical issues relevant to FP release and countermeasures is provided in the following sections.

3.1. FP release phenomena

Fig. 2 shows the general behavior of FPs from severe accidents in an NPP. Various kinds of elements, such as Xe, Kr, Cs, I, Ba, Sr, Te, Sb, Mo, Ru, Zr, Sn, and La are generated by fissioning uranium in fuel rods. The inventories of the FPs depend on thermal power, uranium enrichment, refueling cycle, and burn-up of uranium. Some volatile and semivolatile FPs diffuse to the grain boundaries and move to the open fuel porosities by vaporization and mass transfer processes, and then accumulate in the gap between the fuel rod and cladding during normal operation. If the fuel cladding fails, the FPs in the gap are released to the RCS. As fuel heat-up occurs during a severe accident, FPs including low-volatile FPs can be released outside of the fuel matrix, and the release of low-volatiles is considered to be governed by the volatilization of UO_2 [14]. In addition to this, a large amount of species other than the FPs might

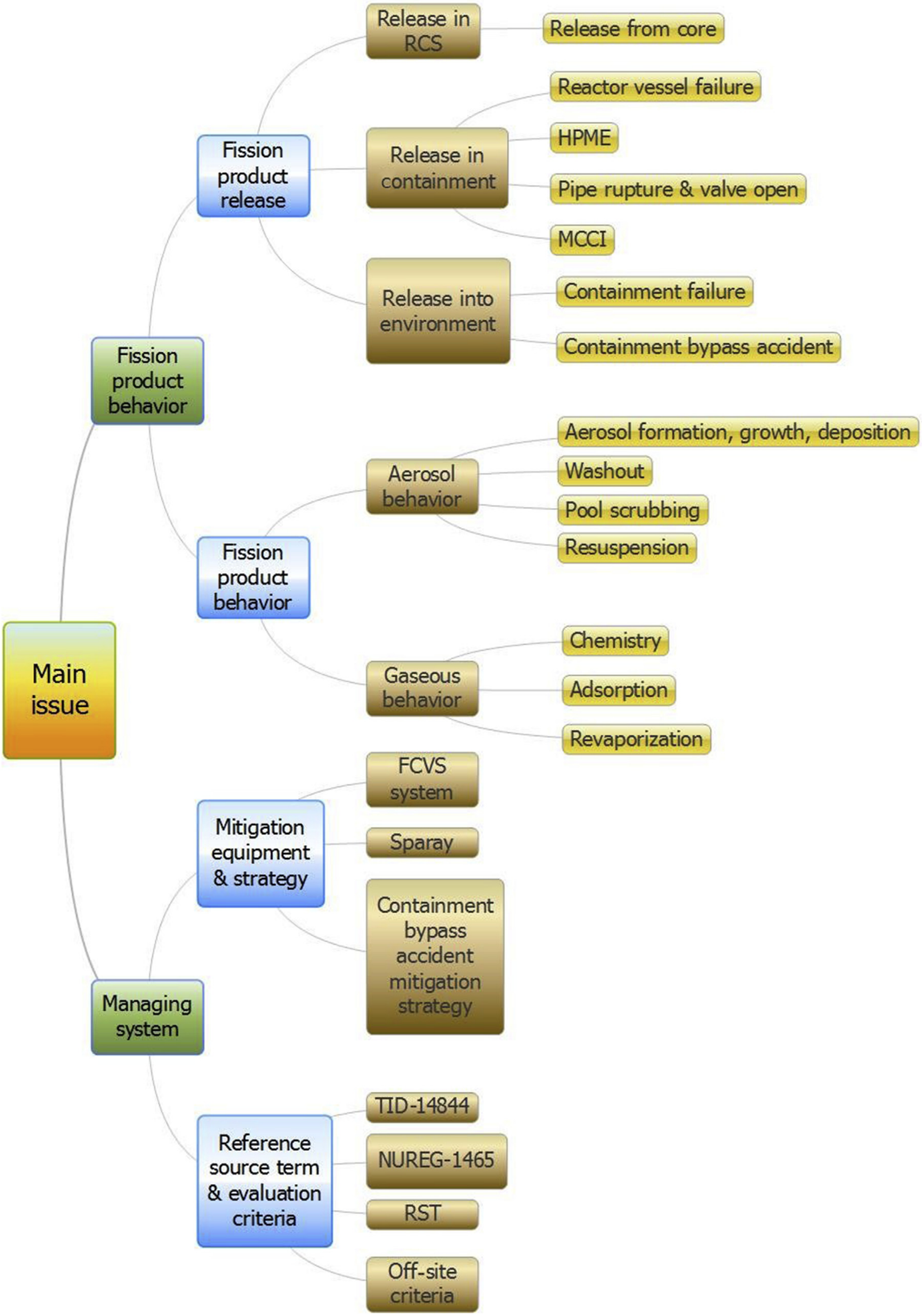

Fig. 1. Elements of the roadmap for examination of fission product release phenomena and establishment of countermeasures. FCVS, filtered containment venting system; MCCI, molten core concrete interaction; RCS, reactor coolant system; HPME, High pressure met ejection; RST, Reference source term.

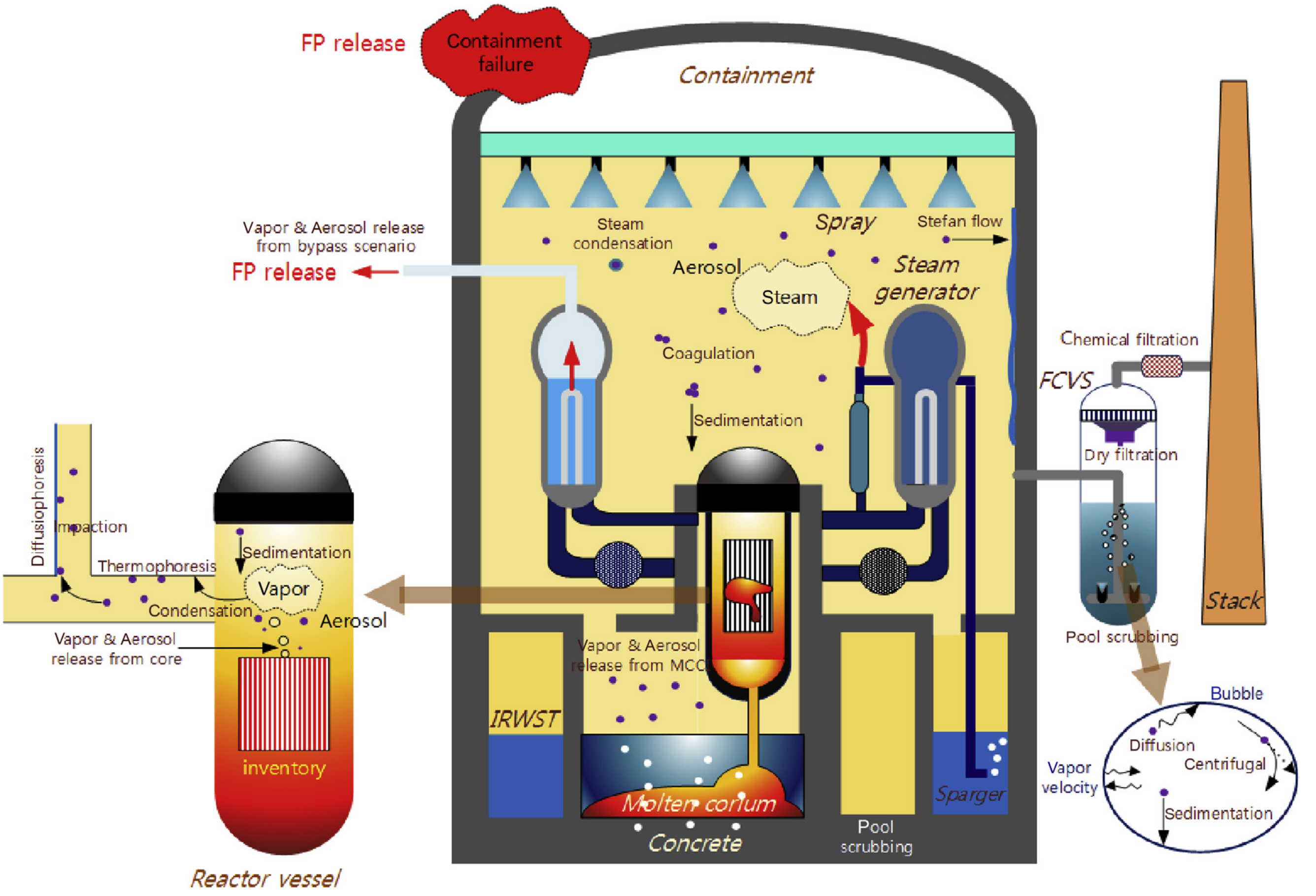

Fig. 2. Fission product behavior during a severe accident in a nuclear power plant. FCVS, filtered containment venting system; FP, fission product; MCCI, molten core concrete interaction; IRWST, In-containment refueling water storage tank.

also be released from the heated cladding and structural materials, such as stainless steel and Inconel alloys.

Such species are released into the RCS in the form of gases or vapors and are then swept by a steam-hydrogen gas mixture toward the break point in the RCS, experiencing a number of physicochemical processes. As the vapors cool down in the RCS, they take the form of aerosol particles when released into the containment, with the exception of the noble gases, iodine, and ruthenium, which can remain in partly gaseous form in certain circumstances [8]. The amount of gaseous iodine released into the containment depends on the reaction kinetics of the I-O-H system for the RCS, which is under the influence of FPs (Cs, Mo), boron (B) and control rod material (Ag, In, Cd, or B_4C) [15].

FPs experience a significant retention in the containment according to various mechanisms, including natural removal processes or plant features. Major natural removal mechanisms are aerosol deposition, adsorption of vapors on structural surfaces, and scrubbing through water, for instance, that overlying the core debris. Major engineered safety features for FP removal are the containment spray system and the filtration systems. The airborne FPs remaining in the containment atmosphere can escape to the environment via damaged areas or penetration leakage from the containment. Studies of the Fukushima Daiichi accident show that most of the airborne dose was caused by Cs, I, and Te species, and that the releases into the environment were driven mainly by chemical volatility at a given temperature and reduction potential within the containment [16]. In addition, FPs can also leach from the fuel and release to the environment through water pathways, which appeared to be the case for the Fukushima Daiichi accident.

3.1.1. Aerosol behavior

3.1.1.1. Aerosol formation and growth. Aerosols are solid particles suspended in the gas phase or in liquid droplets, ranging in size from 0.01 μm to 20 μm. Behavior of most aerosols that appear during severe accidents show very complicated aspects ranging from continuum mechanics to free molecular physics. The physical aspects affecting the characteristics of the aerosols can be enumerated according to the formation, growth, and shape of the aerosol particles. In addition, deposition of particles on the surfaces and resuspension of aerosol particles are also deemed important aspects.

Formation of aerosol: aerosol particles can be formed during various interactions between materials and by steam condensation. The major processes that form aerosol particles during an accident include the following: entrainment of solids or liquid droplets in a high velocity gas flow, expulsion of droplets by gases bubbling through liquids, shock waves produced in energetic interactions of molten materials with coolants, and high pressure melt ejection from the RCS [17]. The sizes of aerosols formed by mechanical processes and suspended in the gas phase are not relatively large and typically do not exceed 1–2 μm. Thus, these types of aerosol tend to be ignored during the accident analysis. However, the formation of aerosol particles from supersaturated steam is deemed the most important source and is treated very critically in the accident analysis.

Growth of aerosol: the major mechanisms that explain the growth of aerosols are growth by coagulation, by condensation, and by hygroscopicity. Aerosols can grow through continuous steam condensation or coagulation of particles. Of these processes, coagulation is considered the dominant mechanism responsible for the growth of aerosols following nucleation. Coagulation of aerosols affects the size and mobility of aerosols. In addition to the condensation and coagulation, hygroscopicity of aerosols is considered an important growth mechanism. For example, CsI and CsOH, which show strong solubility, can grow by hygroscopicity until equilibrium pressure in the solution is achieved.

3.1.1.2. Aerosol deposition and resuspension. Deposition of aerosol: The major processes that result in the deposition of aerosols include gravitational settling, diffusion to surfaces, turbulent deposition, inertial deposition, and phoretic processes, but this is not a complete list. Gravitational settling and diffusion significantly affect the behavior of aerosols. Gas viscosity and particle density are the major parameters that govern gravitational settling. Deposition velocity according to diffusion is greatly affected by the structural geometry and flow conditions. It decreases when particle diameter increases, while the deposition velocity according to gravitational settling shows the opposite trend. Inertial deposition occurs when particles are captured or accelerated in their motion toward obstacles. In such circumstances, if the aerosol particles are sufficiently large, they collide with the obstacle surfaces and remain deposited thereafter. Another important mechanism in aerosol deposition is phoretic deposition. Thermophoretic and diffusiophoretic depositions are detailed mechanisms; the former is caused when the temperature gradient produces a movement of the particles towards the lower temperature zone and the latter appears in the direction of flux of a condensed vapor such as steam. The thermophoretic process can be significant when high temperature aerosols and gases confront a large area of cold structures, for instance containment walls or floors.

Resuspension: Aerosols deposited in a pool or on the surface of a structure can be physically entrained or evaporated with changes of gas flow, temperature, or concentration. A resuspension may occur in the core, the RCS, or the containment. Aerosols deposited on the surface of the primary system can be resuspended by turbulent flow. A sudden increase in steam flow due to core cooling or relocation of core debris is the main source of potential resuspension of aerosols. Aerosols transported to the containment can be deposited on the surface of the containment, and on structures and water pools in the containment. The gas turbulent flow due to hydrogen deflagration or steam explosion can be the main source that induces aerosol resuspension. In addition, aerosols deposited in the containment can also be resuspended if there is a sudden change of containment pressure due to the failure of the containment pressure boundary or containment discharge. Modeling of aerosol resuspension is based on adhesion and removal forces. For the dry aerosols, the van der Waals force, electrostatic force, and chemical cohesive force are the important adhesion forces to be taken into account. In the meantime, the lift force perpendicular to the surface and drag force parallel to the surface should be considered as important removal forces. The deposited aerosols are removed layer by layer by agitation on the surface and moved with a rolling behavior [17,18].

3.1.1.3. Pool scrubbing. When gases including radioactive materials are ejected into the pool, some radioactive aerosols and gases are captured in the pool by pool scrubbing. This phenomenon is taken into account by defining the decontamination factor (DF), which is the ratio of the initial mass of the specific radioactive material to the final mass after it passes through the water pool, in a wet-type filtered containment venting system (FCVS), as well as in other gas sparging systems. When the carrier gases including radioactive aerosols and gases enter the pool through a vent, the carrier gases leaving the vent form large globules that break up into a swarm of small bubbles. Several physical processes are involved in transporting aerosols to the liquid-gas interface (equal bubble surface) when steam/gas mixtures are bubbled through a water pool [19]. The DF of aerosols can be calculated in three regions, that is, gas injection, bubble rising, and pool surface regions [20]. The total DF is obtained by the product of the values calculated in those regions. In the injection zone, aerosol removal occurs through several mechanisms such as: Stefan flow from steam condensation during gas equilibration to pool conditions; inertial impaction of aerosols in a rapid gas velocity decrease; and centrifugal, diffusional, and gravitational aerosol deposition during gas injection through small orifice or multihole vents. In the rising zone, aerosol removal occurs from centrifugal, diffusional, and gravitational aerosol deposition within a bubble. The pool scrubbing phenomenon has been modeled and embedded in several computer codes, such as SPARC (Suppression Pool Aerosol Removal Code), BUSCA (BUbble SCrubbing Algorithm), and SUPRA (SUppression Pool Retention Analysis) [19]. These codes aim at simulating the pool scrubbing process and estimating the DFs of the radioactive aerosols and of iodine gas in the water pool.

3.1.1.4. Leaching. During the Fukushima accident, radionuclides from the damaged fuel were continuously dissolved in the coolant and then accumulated in the containment and turbine building in the form of contaminated water. Thus, there could be leakage paths for these radionuclides that leached out from the turbine building to the sea. In particular, compared to the case of Cs-137, Sr and Ba releases into water were much higher than those into the atmosphere. However, knowledge of the leaching mechanism and accurate models for the prediction of release rates are limited [16].

3.1.2. Gaseous behavior

3.1.2.1. Chemistry. Cs, I, and Te species caused most of the airborne dose during past severe accidents at NPPs due to their high volatilities in the containment under severe accident conditions. It was observed from PHÉBUS-FP tests that a large amount of gaseous iodine was released from the RCS to the containment when nuclear fuel was degraded. The existence of Cs in the absence of other elements allows the quick production of CsI, because there is no obstacle in the reaction of $CsOH + HI \leftrightarrow CsI + H_2O$. CsI can be produced even without the existence of gaseous I_2 because a much larger amount of Cs exists compared to the I species. However, when Mo is added to the Cs-I system, the reaction changes completely due to the high affinity of Mo for Cs; as a result, partial cesium molybdates make a complex to Cs_xMoO_y, which is the most stable gaseous molybdate. Nevertheless, Cs_xMoO_y cannot be produced in a hydrogen atmosphere, and this result is very similar to the case of the nonexistence of Mo, in which CsI aerosol production is dominant. In experiments with a steam atmosphere, a maximum of 80% of the iodine transferred from the primary circuit, under a steep temperature gradient and with a small fraction, was in the form of aerosols. Gaseous iodine is mostly composed of molecular iodine; the remaining portion is HI or HOI. When boron (B) is added to the Cs-I system, gaseous iodine is activated due to the production of $CsBO_2$, but the degree is smaller than it is in the case of Mo. With control-rod materials such as Ag and Cd, it is surmised that Ag and Cd react with iodine and prevent the production of gaseous iodine [9,11,14,21].

Iodine aerosols released from the RCS to the containment may sediment and settle on the walls in the containment. If they are soluble, they can be dissolved in the sump or become plated out on wet surfaces as ions in the form of I^-. Then, the behavior of I^- changes according to time and the pH of the aqueous solution. Several FPs dissolved in the solution cause water radiolysis and decrease the pH in the pool. At this time, a large amount of the dissolved I^- changes to elemental iodine and moves to the containment atmosphere. Organic iodide is also produced by the reactions of I_2 and I^- with paints on the containment surfaces, and with organic materials decomposed radiolytically in solution. Gas-phase radiolysis is an important decomposition route, as well as solution phase radiolysis. Thus, radiolytic products of air, such as NO_2, O_3, or HNO_3, oxidize molecular and organic iodine and produce I_xO_y in the containment atmosphere. However, the I_xO_y aerosols are deposited on the containment surface, and are then partially decomposed to molecular iodine under irradiation. Decomposition of I_xO_y by CO produced from degradation of B_4C (control rod) may also affect the amounts of gaseous iodine [9,11,14,22,23].

3.1.2.2. Adsorption and desorption. Volatile iodine can be adsorbed by surfaces in the containment over time to form organic iodides. Painted surfaces act as sinks for I_2 and as a source for volatile organic iodine. The I_2 adsorption on surfaces depends on the gas and water temperatures and the gas flow velocity along the walls. Under wet conditions, the wall condensation rate drives I_2 diffusion towards the surfaces. Radiation induces fast radiochemical reactions between iodine and the paint [22]. Models for the adsorption of I_2 on paint, steel, and aerosols have been developed, but uncertainties remain concerning the effect of paint aging on the iodine volatility, deposition of iodine oxides on the surface and the subsequent decomposition and volatilization of iodine species, iodine adsorption kinetics on representative multicomponent aerosols, and temperature and loading effects from H_2 phenomena on FPs deposited on the wall [14].

3.1.2.3. Revaporization. After condensed species are deposited in the RCS, they can be revaporized by the displacement of the thermodynamic equilibrium in case of changes in temperature or carrier gas composition, or decreases in partial pressures in the gas phase. The reasons for the equilibrium vapor pressures exceeding the ambient partial pressures of the vapor species may include decay heating of deposited materials and changes in the chemical environment within the RCS. For instance, in a high pressure scenario, natural circulation with high temperature can cause a creep rupture of the RCS and revaporization of volatile material such as species formed from cesium and iodine. Furthermore, rupture of the RCS can radically change the chemical environment of deposits and raise the oxygen potential of the atmosphere, which can produce various volatile species of FP elements. Therefore, revaporization may be a source of delayed release to the containment. The revaporized materials may be redeposited in cooler regions of the RCS or be swept out of the system [9,24]. PHÉBUS FP tests demonstrated this type of revaporization of several elements, with other evidence such as reaction of the deposited species with the substrate, stratification of deposits in the upper plenum samples, different stages of release, and effects of changes in the atmosphere. Recently, revolatilization and distribution of ruthenium deposited on the surfaces under irradiation and ozone action have been studied in several international programs [9].

3.2. Issues relevant to FP behavior

In this section, three stages of FP release, from the core, the RCS, and the containment, are considered. Another type of containment breach, i.e., containment bypass, is also considered, while filtered containment venting is dealt with as a countermeasure against FP release. The identified technical issues concerning FP behavior at each stage are described in Tables 1–3. They are divided into aerosol release (Table 1) and gaseous release (Table 2). Since iodine and ruthenium behave in aerosol and gaseous forms, issues specific to them were dealt with separately, as shown in Table 3.

3.2.1. Release from the core

When fuel rods heat up, some FPs are released from the fuel rods. FP release in the RCS can be divided into two modes: gap release and fuel meltdown release. The FPs are released from the gap between the fuel pellet and the cladding when cladding rupture occurs. The temperature of the cladding rupture depends on the increasing rate of the cladding temperature, the internal pressure, and the mechanical characteristics of the cladding. The gas release rates of the FPs are determined by considering the release fractions and escape fractions, which depend on the fission species. The FP release rate during fuel meltdown is related to the fuel temperature, fuel burn-up, and fuel type and shape, to mention a few characteristics. If the fuel rods are exposed to high temperature and high steam environment with large surface area, then the FPs are released largely during the fuel meltdown. Most of the noble gases and halogen gases are released during the fuel meltdown.

Since the TMI-2 accident, much effort has been devoted worldwide to gaining knowledge on core melt accident phenomenology. Several experimental programs, including large scale tests, have been performed; new physical modeling has been developed and implemented in integral accident simulation codes such as MELCOR, MAAP, and ASTEC. Among the integral test programs related to in-vessel severe accident progression, several important ones are the CORA and QUENCH out-of-pile experiments and the PHÉBUS Severe Fuel Damage and PHÉBUS FP in-pile experiments. These experiments were performed at large scale, typically with 20–25 fuel rods of up to 1 m heated length enclosed by an insulating shroud, with control rod material present (Ag-In-Cd or B4C). The QUENCH experiments were more specifically focused on the study of water reflooding of (slightly) degraded cores [16]. Several models have been proposed to evaluate the releases of FPs from the core, such as CORSOR, CORSOR-M, CORSOR-O, CORSOR-BOOTH, and ORNL-BOOTH [25]. Currently, some issues remain to resolve the mechanism of FP release from the core, for example, FP releases such as Cs and I from high burn-up and MOX fuels [6].

3.2.2. Release from the RCS

After the FP release from the core, mainly by vaporization, various phenomena affect the FP transport in the RCS conditions. For instance, in the vapor phase, chemistry, condensation, and evaporation onto or from surfaces and aerosols play major roles in the FP transport, whereas in the aerosol phase, nucleation in the gas or suspended phase, aerosol growth, deposition, and resuspension are important. Especially, the PHÉBUS FP program reveals that the gaseous phase chemistry among I, Cs, Cd, and Mo in the RCS has a great influence on gaseous iodine release into the containment [26].

Regarding the FP release from the RCS, major phenomena resulting in breaches in the RCS boundary are reactor vessel breach and pipe rupture or valve opening. FPs are released from the RCS to the containment during reactor pressure vessel failure. Reactor pressure vessel failure modes can be divided into localized vessel failure, global vessel failure, penetration tube heat-up and rupture, and penetration tube ejection due to welding spot ablation. When the molten core and iron penetrate the pressure vessel and run into the reactor cavity with high pressure in the reactor vessel, the molten corium could result in the scattering of finely divided UO_2 (containing FPs) into the containment atmosphere. The UO_2 particles cool down and experience a reaction with oxygen to form U_3O_8 at temperatures below about 1,500°C. The reaction is

Table 1
Knowledge level, significance, and research period for aerosol behavior issues.

Technical issues			Knowledge level			Significance (urgency)			Research period			
			High	Mid	Low	High	Mid	Low	Short (2–3 yr)	Mid (3–5 y)	Long (5–10 y)	N/A
Aerosol release	Release from core	FP release in accordance with fuel type and burnup	W,D				O				O	
		Improvement of the model for degradation of core structure (mainly control rods) and release of material including aerosols		W	D	O				O		
		Effect of reflooding and hydrogen generation at high burnup(≥60 MWd/kgU)/MOX fuel	W		D			O				O
	Release from RCS	Aerosol resuspension in the RCS (mechanical resuspension)	W		D		O			O		
		Aerosol deposition in singularities and complex structures		W	D			O		O		
		Particle break-up in highly turbulent flows		W	D			O		O		
		Influence of chemistry on aerosol release		W	D		O			O		
	Containment issue	Phenomena related to formation, growth, and deposition of aerosols including growth through coagulation and condensation, condensation on the containment surface	W	D		O				O		
		Charge effects		W	D			O	O			
		Mixed aerosols in condensing atmospheric conditions		W	D		O			O		
		Re-entrainment from pools (including resuspension with pool scrubbing in the sump)		W	D	O			O			
		Influence of recombiners		W	D		O			O		
		Hydrogen-burn effects on suspended aerosols		W	D		O			O		
		Release from MCCI pool	W		D	O				O		
		Fire aerosols		W	D		O			O		
		FP (Sr, Cs, Ba, Sb, Ce/Pr, Eu and actinides) releases to cooling water			W,D		O			O		
	Resuspension	Model improvement and additional validation for aerosol resuspension in the containment (mechanical resuspension)	W		D		O			O		
		Transport and deposition of aerosols through turbulence effect when corium is ejected		W	D		O			O		
	Washout	Model improvement for the aerosol removal by spray		W	D	O				O		
	Pool scrubbing	Experiments with higher gas temperature, steam flow rate and hydrogen concentration in the carrier gas than those of the current tests		W	D	O				O		
		Pool tests enlarged to the saturated condition and comparison of the decontamination capability with that of the subcooled pool		W	D	O				O		
		Effect of the high pressure condition on the pool surface, and the effect of water pH on the retention of aerosols and gaseous iodine	W		D	O				O		
		Integrated effect tests using the representative aerosol materials with well-defined severe accident conditions to examine the resuspension phenomena		W	D	O				O		
		Establishment of the systematic experimental database to validate stand-alone or integral code models		W	D	O				O		
	MCCI	Re-evaluation of the current experimental results and additional validation of the codes related to MCCI, characterization of aerosols in terms of the concrete type		W	D		O			O		

(*continued on next page*)

Table 1 (*continued*)

Technical issues			Knowledge level			Significance (urgency)			Research period			
			High	Mid	Low	High	Mid	Low	Short (2–3 yr)	Mid (3–5 y)	Long (5–10 y)	N/A
		Quantity of FPs and non-radioactive aerosols carried by the gas products from MCCI		W	D		O			O		
	Containment bypass accident	Aerosol retention in the SG	W		D	O				O		
		Development of the measures and strategies for mitigation of the radiological consequences from ISLOCAs and SGTRs		W,D			O			O		
	Leaching	Experimental study (separate, integral) on the scenarios and phenomena for the development and validation of models concerning the FP transport along the leak paths		W	D		O			O		
		Confirmation of available models and experimental study on the reaction between corium and water beneath the basemat		W	D		O			O		

"O" is an indication of the corresponding column for each item.
D, domestic; FP, fission product; ISLOCA, interfacing system loss of coolant accident; MCCI, molten core concrete interaction; N/A, not applicable; RCS, reactor coolant system; SG, steam generator; SGTR, steam generator tube rupture; W, worldwide.

exothermic and is accompanied by the release of FPs that are volatile under these conditions [27].

FP gas and aerosols can also be released into the containment through pipe rupture and opening events. During this procedure, some aerosols deposited on the RCS inner walls can be re-entrained and released into the containment. After vessel failure, if oxygen is entrained in the RCS, some FPs such as RuO_4, might be generated from the aerosols deposited on the RCS inner walls by the oxidation process.

3.2.3. *Release from the containment*

Direct failure of the containment occurs in typical modes such as isolation/penetration failure, steam explosions, combustion processes, steam overpressurization, direct containment heating, and basemat melt-through. A leak or rupture of the containment, either at the time of the accident or resulting from the failure to close isolation paths, may result in a significant release pathway for radioactive FPs, especially if the path is in direct contact with the containment atmosphere. However, in most probabilistic safety analysis studies for Korean NPPs [28], hydrogen combustion and overpressurization by steam and the noncondensable gases generated during molten core concrete interaction (MCCI) are treated as the most important direct modes for containment failure in the cylinder wall (for example, hoop failure due to membrane stresses in the cylinder wall).

From an ST perspective, if the containment is not intact, release characteristics of radionuclides from the plant are different, mainly depending on the size of the containment opening. Typically, a failure size of about 1 ft^2 (0.1 m^2), called a "rupture", arrests a gradual pressure buildup and will depressurize the containment

Table 2
Knowledge level, significance, and research period for gaseous release behavior.

Technical issues			Knowledge level			Significance (urgency)			Research period			
			High	Mid	Low	High	Mid	Low	Short (2–3 yr)	Mid (3–5 yr)	Long (5–10 yr)	N/A
Gaseous release	Release from core	Analysis and evaluation with consideration for the plant conditions based on the existing experimental results	W	D		O			O			
		Experimental study of the gaseous nuclides produced in the core and RCS	W		D	O					O	
		Modeling of critical nuclides and relevant reactions	W		D	O				O		
	Release from RCS											
	Release from containment											
	Leak from containment boundary	Quantification of FPs leaked through the containment penetrations with cracks formed and released into the environment, based on the dynamic behavior of the containment		W	D		O			O		
	Washout	Review and evaluation of the existing experimental and theoretical research results, and further study using experiments and modeling		W	D		O			O		

"O" means an indication of the corresponding column for the issue.
D, domestic; FP, fission product; N/A, not applicable; RCS, reactor coolant system; W, worldwide.

Table 3
Knowledge level, significance, and research period for iodine and ruthenium behavior issues.

Technical issues		Knowledge level			Significance (urgency)			Research period			
		High	Mid.	Low	High	Mid.	Low	Short (2–3 yr)	Mid (3–5 yr)	Long (5–10 yr)	N/A
Release from RCS	Cs, I release models	W	D		O				O		
	Gaseous iodine formation and release from the core and RCS	W		D		O				O	
	Iodine adsorption kinetics on representative multicomponent aerosols and their radiolytic stability		W	D		O				O	
	Degradation of I_xO_y by CO that is produced from B4C control rod degradation		W	D		O				O	
	Effect of control rod materials on the transport of iodine in the RCS	W		D	O					O	
	Possibility of revaporization of the metallic iodide deposited along the RCS	W		D		O				O	
Release into containment	Transport of iodine species adsorbed onto or desorbed from the metallic or painted surface, or aerosol particles in gaseous phase	W		D	O				O		
	RI heterogeneous formation from the reaction between iodine and paint in gaseous phase/effect of the paint aging on the iodine volatility and the ST		W	D	O				O		
	RI radiolytic destruction in gaseous phase		W	D		O			O		
	Volatile iodine adsorption due to steam condensation	W		D		O			O		
	I_xO_y size and composition, and radiolytic stability of deposited I_xO_y on the containment surface		W	D	O				O		
	Formation and destruction of volatile iodine inside the pool: effect of the boundary conditions such as thermal-hydraulics, oxidation, pH, concentration of chemical additives, mass transfer, radiolytic condition / formation of organic iodides in the aqueous phase due to radiolytic decomposition of organics such as paint/oxidation and reduction of iodine species (I^-, I_2, IO_3^-) / iodine retention in pool under pH variation	W		D		O			O		
	Iodine partitioning: production rate of volatile iodine from the aqueous phase / mass transfer rate among the iodine species at the water surface of pool / mechanism for releasing volatile iodine as the pool dries out	W		D	O				O		
	modifications of iodine speciation (gas-particle) in the environment during its transport in the atmosphere		W	D			O			O	
Leaching	Analytical model for the removal (adsorption) rate along the release path		W	D		O			O		
Aerosol behavior	Acquisition of experimental data on the Ru aerosol release from fuel under oxidic condition		W	D	O			O			
	Revaporization of Ru (^{103}Ru,^{106}Ru) deposits in the RCS / revolatilization of Ru species in accordance with RCS temperature and gas composition, and their distribution: revolatilization fraction, effect of deposition of nuclides other than Ru, surface examination of the oxidation state of the deposits	W		D	O				O		

“O” means an indication of the corresponding column for the issue.
D, domestic; N/A, not applicable; RCS, reactor coolant system; RI, organic iodide; SAMG, severe accident management guidelines; ST, source term; W, worldwide.

within 2 hours in a large dry containment [29]. Another consideration is the timing of the FP release from the containment relative to the in-vessel and ex-vessel release periods. If the release from the containment is delayed after the in- and ex-vessel releases, more FPs in the containment atmosphere can be removed through various mechanisms including the deposition, and less will be discharged into the environment. For instance, if early and large containment failure occurs at or soon after reactor vessel failure, FPs will be easily released without passing through a variety of deposition processes.

In this situation, the next important consideration regarding the ST is both the mechanism of natural removal processes and the availability of engineering safety features that can affect the FP behavior inside the containment.

3.2.4. Containment bypass

A bypass of the containment occurs in typical modes such as V-sequence [interfacing system loss of coolant accident (ISLOCA)] and steam generator tube rupture (SGTR) sequences that are not isolated by the containment. The containment bypass sequences are quite different from the non-bypass sequences. There exists a direct flow pathway from the primary system to the outside of the containment boundary, bypassing the main containment region. Hence, holdup and attenuation of radionuclides (released from the core/primary system prior to vessel failure) are not significantly affected by the natural processes and engineered safety systems in the containment. Consequently, bypass sequences can result in large ST releases soon after the onset of core damage.

The SGTR sequences in this paper assume that isolation of a broken steam generator (SG) is not achieved. Thus the release pathway could be the RCS, the SG secondary side, the secondary steam line, and the safety/relief valves (which are usually assumed to be stuck open after several cycles of opening and closing). This SGTR event is a typical bypass event because the primary coolant is directly released into the SG secondary side and the FPs could potentially escape from the secondary side into the environment. However, recent experimental data obtained in the **A**e**r**osol **T**rapping **I**n **S**team Genera**T**or (ARTIST) project [30] on FP behavior in the SG secondary side during SGTR-type severe accidents show significant retention of FPs along the release paths. Furthermore, in an ISLOCA, if the break in the interfacing system is located low enough in the primary auxiliary building, the original water in the RCS and refueling water tank (RWT) water injected into the RCS can escape through the break and will form a pool that covers the break location. This indicates that the ST can become smaller as the released FPs experience scrubbing in the pool, in which the break point outside the containment is determined by the time at which radioactive releases commence.

3.3. Issues relevant to countermeasures against FP release

This section describes technical issues relevant to the countermeasures against the release of FPs, such as mitigation features, mitigation strategies, and regulatory requirements, all of which are summarized in Table 4.

3.3.1. Mitigation features

3.3.1.1. Filtered containment venting. In cases in which the integrity of the containment pressure boundary is threatened by the containment pressurization during a severe accident, the FCVS can be used to prevent containment damage by controlled discharge of the containment atmosphere with filtration of the FPs. As this has been considered practical after the Fukushima accident, many countries, including Korea, have decided to install the FCVS in their respective operating NPPs. The FCVS typically consists of an inlet piping from the containment penetration, filtration devices, and outlet piping to the environment. There are two types of commercialized FCVS. One is a wet scrubber system consisting of filtration components with pool scrubbing. The other is a dry scrubber system consisting of filtration components without pool

Table 4
Knowledge level, significance, and research period for severe accident countermeasure issues.

Technical issues			Knowledge level			Significance (urgency)			Research period			
			High	Mid.	Low	High	Mid.	Low	Short (2–3 yr)	Mid (3–5 yr)	Long (5–10 yr)	N/A
Mitigation features	FCVS	Review and evaluation of the existing experimental and theoretical research results, and further study using experiments and modeling: FCVS actuation time or actuation pressure; FCVS operation in the SAMG range (continued open or repetitive open/close); capability of containment pressure reduction; DFs for aerosols and gaseous iodine; duration for passive operation; on- and off-site doses	W	D		O				O		
	ECSBS	Effectiveness of containment pressure reduction, actuation timing, operation duration		W,D			O			O		
Mitigation strategies and regulatory measures	AST	Integrated study by the industry, universities, and research institutes to determine the STs enveloping all realistic accident sequences	W	D		O				O		
	ST methodology	ST modelling improvement	W		D	O					O	
		Analytical methods to identify and resolve uncertainties in source term assessments: chemical forms of suspended iodine in the containment, mechanisms of FP removal such as spray and natural deposition, etc.		W	D	O					O	
		Analysis of Fukushima specific data to identify the uncertainties in FP behavior		W	D	O				O		

"O" means the corresponding column for the issue.
AST, accident source term; D, domestic; DF, decontamination factor; ECSBS, emergency containment spray backup system; FCVS, filtered containment venting system; FP, fission product; N/A, not applicable; ST, source term; W, worldwide.

scrubbing. FPs in aerosol and gaseous forms can be physically and chemically removed in the filtration components.

The amount of FPs inside the containment is closely related to the accident scenario and the availability of safety features. It may also be sensitive to the design of the FCVS, for instance, the capability of the filtration components to remove radioactive material, and the operation principles of the system, including the time to actuate the system. A relatively large portion of radioactive aerosols will be loaded in the case of early venting. By contrast, the portion of nonactive aerosols will relatively increase in the case of late venting due to the MCCI. A small amount of gaseous iodine will also exist in the containment; most of it will be elemental and organic iodine, with composition varying according to the venting time.

The actuation and operation of the FCVS will be reflected in the SAMGs. The actuation of FCVS should be carefully considered to minimize the release of FPs into the environment. Thus, SAMG action to actuate the FCVS should generally be delayed as long as possible if the containment integrity is maintained [31]. Regulatory requirements of the system are different among countries. The most important principle is that release of FPs into the environment should be controlled within a certain limit. In this respect, regulatory requirements need to be established for the following aspects:

- Actuation time or pressure.
- Operation method within SAMG: open through or periodic.
- Containment depressurization performance.
- Scrubbing efficiency for aerosol and gaseous iodine.
- Passive operation period.
- On site and off site dose during operation.

The system efficiency is currently being studied to estimate it under irradiation and to better evaluate gaseous iodine and ruthenium ST [8,32].

3.3.1.2. *Spray.*

The pressure control of containment using the spray system has some advantages, namely, minimizing the release of FPs and securing a margin for containment failure pressure. In the case of an optimized power reactor (OPR1000) type NPP, the spray system is activated automatically when the containment pressure exceeds the set point pressure. In the early stage, the water source for the spray is supplied from the RWT; later it is supplied from the recirculation operation. In addition to the spray system, the emergency containment spray backup system (ECSBS) is installed as a containment depressurization measure for the advanced power reactor (APR1400) type NPP during a severe accident. The ECSBS activates 24 hours after an accident occurs, and removes the decay heat and depressurizes the containment for 48 hours. Since the ECSBS uses a water source outside the containment, such as fire pumps and fire pump vehicles, this system is available when no electric power source is available, even within the plant.

When the spray system is activated, it is effective at reducing soluble FPs such as elemental iodine and CsI. The activation of the spray system is likely to affect various phenomena in the containment according to the aspects below.

- It can reduce the containment pressure by condensing the steam; as such, for containment integrity, it can eliminate the threat of overpressurization. However, if hydrogen is already accumulated in the containment, the activation of the spray system may increase the possibility of hydrogen burn or explosion by reducing the steam fraction in the containment atmosphere.
- It is expected that MCCI can be prevented or mitigated by cavity flooding. Therefore, it is reasonable to assume that the spray system can effectively reduce the release of FPs by MCCI and the subsequent basemat melt-through possibly caused by MCCI.
- It is very effective at removing aerosol particles by mechanisms such as diffusiophoresis, impaction, interception, and diffusion.

If two trains of the PWR spray system are activated, they can reduce the floating radioactivity concentration level to 1/100 of the initial level within 30 minutes. After this sharp drop of the radioactivity level, the effectiveness of the removal rate for the remaining FPs markedly decreases, since the distribution of particle size is shifted to small particle sizes. Thus, the technical background for the revised ST [7] suggests that the mission time for the operation of the spray system should be greater than 10 hours.

In general, the spray system injects the coolant outside the RCS, and it is thought that there is no direct effect on the behavior of FPs inside the RCS. However, it is clear that this system can indirectly affect the FP behavior in the RCS, as follows:

- The cooling of the RCS exterior by the spray decreases the pressure and temperature inside the RCS, so it affects the generation rate and the behavior of FPs inside the RCS. In addition, the consequential changes in the progression of a severe accident, such as the failure time of the reactor vessel, can also indirectly affect the behavior of FPs.
- It is necessary to consider the effect of injection into the RCS or spray system by the recirculation operation. In the recirculation operation, the FPs releasable into the containment atmosphere or onto the floor can be injected again into the RCS. Therefore, it is clear that this process can affect the behavior of FPs.

3.3.1.3. *Cavity flooding.*

The primary purpose of cavity flooding is to cool the corium relocated in the cavity basement. Since the relocated corium contains abundant FPs, cavity flooding can also play an important role in retaining the FPs inside the containment. In fact, this cavity flooding strategy is implemented in the generic Korean SAMG as a fourth applicable action if the RCS injection is unsuccessful in returning the reactor core to a coolable state. Spray, gravitational discharge from the RWT, and injection by the fire protection system are methods of cavity flooding. However, the practicability of this strategy differs according to the design of the nuclear reactor because some old NPPs (models prior to the GEN-III reactors) were not fully equipped with such flooding measures.

Ideally, since the cavity space can be fully filled with water, pool scrubbing may become an inherent mechanism to mitigate the FP release from the corium. Depending on the water level, temperature, and pressure of the cavity pool, diverse FP removal mechanisms are expected. In addition, fragmentation of the corium and spreading of the debris may affect the FP removal mechanism. More importantly, the MCCI phenomenon may generate additional aerosols, which should be taken into account in analyzing the overall behavior of aerosols during cavity flooding.

3.3.2. *Mitigation strategy for containment bypass*

For containment bypass, there are two representative events, SGTR and ISLOCA. In an SGTR, FPs can be released to the SG through a leak or through damaged locations in the SG tube, and to the environment through the unisolated main steam safety valve, main steam atmosphere dump valve, or a leak in the steam supply systems.

In an ISLOCA, the FPs released into an auxiliary building can be released into the environment through the venting system. For the mitigation of such a bypass event, countermeasures for mitigation of FP release begin from the emergency operation procedure, and the strategy for the control of FP release, which minimizes release to the environment in the SAMG. This strategy consists of two steps: (1) finding the release path; and (2) isolating it.

FP release by an ISLOCA event can occur due to failure of the containment isolation system, penetration, or leakage during the long-term operation of the safety injection or spray system. In these cases, it is necessary to consider interruptions of the safety injection or spray system operation, and the adverse effects of these interruptions. Afterwards, the operation of the auxiliary building venting system should take into account that the FPs were already released into the auxiliary building through the filter.

The control of the FP release due to SGTR is performed through the following actions. First, it is necessary to determine that this release occurred during the process of SG depressurization strategy execution. In this case, the transition to another sound SG for depressurization should be executed. Then, the damaged SG should be isolated. In this process, the water level should be secured above the damaged location in order to reduce the FP release. Sometimes, steam dump from a damaged SG to the condenser becomes an effective method to reduce FP release to the environment, even though there are some adverse effects.

3.3.3. Reference ST

The Technical Information Document 14844 ST [10], which specifies a release of FPs from the core to the reactor containment in the event of a postulated accident involving a “substantial meltdown of the core,” has been used since 1962 in the United States (U.S.) and Korea to evaluate reactor siting and plant performance. The revised ST NUREG-1465 (1995) [7] was developed based on up-to-date research results on severe accidents. It provides more realistic estimates of the release of FPs into the containment, in terms of timing, nuclide types, quantities, and chemical forms [7]. A review of this ST in comparison with the PHÉBUS-FP (Fission Products) program shows that while similarities exist concerning early in-vessel releases and the amount of net release of noble gases, iodine, etc., there are major discrepancies with respect to cesium and tellurium releases and a possible massive iodine release under specific conditions. New insights gained from recent studies may lead to a need to revisit the NUREG-1465 element grouping [11]. By contrast, the French regulatory body developed a Reference ST [33] for beyond design-basis accidents with different conditions for the releases of radionuclides. This ST was also reviewed and the results showed the effectiveness of the S3 levels [34]. Now, in Korea, a reasonable way to prepare a reference ST for evaluation of the mitigation capability against severe accidents is under discussion.

3.3.4. Regulatory criteria for radioactive material release

In response to public opinion in Korea and an international cooperative drive [35] to promote nuclear safety since the Fukushima accident, the Korean regulator has recently established a set of new requirements that domestic licensees must follow in the design, construction, and operation of NPPs [36]. The deterministic criterion requires that an accident accompanied by significant core damage should not result in a radiation dose of an individual residing near a reactor site in excess of 250 mSv for the whole body and 3 Sv for the thyroid from iodine exposure, as required by 10 CFR100.11 in the U.S. [37]. In addition, the targets of the risk evaluated with probabilistic safety assessment are the following: (1) the individual risk of prompt cancer fatalities that might result from reactor accidents to the public in the vicinity of an NPP should not exceed 0.1% of the corresponding total risk; or, plant performance targets equivalent to the above objective should be met; and (2) the sum of the occurring frequencies of accidents that can cause a release of Cs-137 exceeding 100 TBq should be less than 1.0×10^{-6}/y. Therefore, elaboration of regulatory guidelines and consolidation of methodology applied to confirm that the above criteria are met are under way.

4. Proposals for future research

Tables 1–4 describe the research needs, their current knowledge level, their significance, and the expected research period for each identified technical issue. The collected opinions show that the domestic technical level needs to be upgraded further through organized research to resolve those issues. The common perception of the subcommittee concerning FP behavior is that the most important and urgent technical issues are as follows: (1) improvement of the model of degradation of the core structure (mainly control rods) and release of material including aerosols; (2) acquisition of experimental data on Ru release from fuel under oxidic conditions; (3) improvement of the model for Cs and I release from the RCS; (4) understanding of the phenomena related to formation, growth, and deposition of aerosols, including growth through coagulation and condensation, and condensation on the containment surface; (5) experimental study and modeling of transport of iodine species adsorbed onto or desorbed from metallic or painted surfaces or of aerosol particles in gaseous phase or heterogeneous organic iodide (RI) formation from reaction between iodine and paint in gaseous phase; (6) experimental study and modeling of aerosol release from the MCCI pool; (7) experimental study on pool scrubbing: pool tests enlarged to the saturated condition and comparison of the decontamination capability with that of the subcooled pool/effects of the high pressure conditions on the pool surface, and effects of water pH on retention of aerosols and gaseous iodine; integrated effect tests using representative aerosol materials with well-defined severe accident conditions to examine resuspension phenomena; (8) review and evaluation of existing research results and further study with experiments and modeling of FCVS: its actuation time or actuation pressure; operation in the SAMG range (continued open or repetitive opening/closing); capability of containment pressure reduction; DFs for aerosols and gaseous iodine; duration of passive operation; on- and off-site doses; and (9) determination of STs encompassing all realistic accident sequences. In addition, the group was interested in the following issues as relatively important and urgent technical issues: (10) analysis and evaluation with consideration of plant conditions based on existing experimental results; (11) understanding of iodine partitioning in the containment: production rate of volatile iodine from the aqueous phase; mass transfer rate among the iodine species at the water surface of pool; mechanisms for releasing volatile iodine as the pool dries out; and (12) understanding of revaporization of Ru deposits in the RCS; revolatilization of Ru species in accordance with RCS temperature and gas composition, and their distribution; revolatilization fraction; effect of deposition of nuclides other than Ru; surface examination of oxidation state of deposits.

Some of these issues are related to the Fukushima action items, such as installation of the FCVS [9]. Most of the issues are expected to require mid-term and long-term research periods to approach the international level, while some, such as item (2), parts of item (7), FP re-entrainment from the containment pool, and item (10) may need short-term research of perhaps 2–3 years. However, the group did not deal with FP release from damaged fuel in detail. Behavior of FPs after release into the environment is currently outside the scope of this study. These deficiencies will be made up for through periodic updates of the report in the future. Furthermore, this study did not cover the specific issues for the CANDU pressurized heavy water reactors. Nevertheless, most of the items are considered relevant to that type of reactor.

5. Conclusion

Voluntary efforts by Korean researchers to develop a domestic research roadmap for severe accidents came to fruition with the establishment of a special committee on the "Development of a Research Roadmap for Examination of a Severe Accident Phenomena and Establishment of a Countermeasure System" by the KNS in early 2015. One of its three subcommittees dealt with FP behavior and operated effectively until the end of August 2016. The group discussed the characteristics of FP release and examined the technical issues relevant to the release stages and to the physical forms of radionuclide release and transport. Through brainstorming and referring to the EU PIRT, they developed a tree for FP release phenomena by tracing failures of the defense-in-depth barriers. In addition, countermeasures were added to the tree. For each element, they determined the phenomena, accident management actions, and regulatory aspects relevant to the mitigation features in the containment and the mitigation strategies against containment bypass accidents. Regulatory concerns about the ST and the acceptance criteria for radionuclide release were also included in the tree. Then, the group identified further research needs for important technical issues based on the degree of the current knowledge level in Korea and in foreign countries, the significance and urgency of those issues, and the expected research period required to reach an advanced level of knowledge.

The group identified the 12 most important and urgent technical issues, including "improvement of the model for degradation of core structure and release of material including aerosols." Most of the issues are expected to require mid-term and long-term research periods, while some of them might need a short period, for example, the issue of pool scrubbing has seen very active study. The group activity did not deal with the FP release from damaged fuel in detail. Furthermore, behavior of FPs after release into the environment was outside the scope of this study. These deficiencies will be remedied through periodic updates of the report in the future.

Conflicts of interest

All authors have no conflicts of interest to declare.

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