Effect analysis of the intentional depressurization on fission product behavior during TMLB' severe accident

HUANG Gaofeng* LI Jingxi TONG Lili CAO Xuewu

School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai 200240, China

Abstract It has been found that the pressure in the reactor coolant system (RCS) remains high in some severe accident sequences at the time of reactor vessel failure, with the risk of causing direct containment heating (DCH). Intentional depressurization is an effective accident management strategy to prevent DCH or to mitigate its consequences. Fission product behavior is affected by intentional depressurization, especially for inert gas and volatile fission product. Because the pressurizer power-operated relief valves (PORVs) are latched open, fission product will transport into the containment directly. This may cause larger radiological consequences in containment before reactor vessel failure. Four cases are selected, including the TMLB' base case and the opening one, two and three pressurizer PORVs. The results show that inert gas transports into containment more quickly when opening one and two PORVs, but more slowly when opening three PORVs; more volatile fission product deposit in containment and less in reactor coolant system (RCS) for intentional depressurization cases. When opening one PORV, the phenomenon of revaporization is strong in the RCS.

Key words Fission product behavior, Depressurization, TMLB' accident, Severe accident

1 Introduction

In a severe accident of a pressurized water reactor (PWR), the core might melt down under high pressure[1]. Molten corium might eject and disperse from the lower head into the containment atmosphere, causing direct containment heating (DCH). The potential hydrogen deflagration or detonation and thermal shock could damage the containment and cause releases of fission products in great dose rates. To prevent DCH, intentional depressurization is used[2,3], when the power-operated relief valves (PORVs) are latched open by the core exit thermocouple at 922 K. Depressurization of the reactor coolant system, however, can give rise to enhanced release of fission products, which transport through the reactor coolant system and cause accelerated core degradation, perhaps, due to the loss of more coolant through the PORVs. The opening of PORVs lowers the pressure, and the fission products, especially the inert gas and volatile fission products, may behave differently.

Mitigation and elimination of the fission product release by pressure-driven expulsion of the reactor vessel can be achieved by reducing the pressure difference between the reactor vessel and the reactor containment[4]. In a long time after opening the PORVs, effects of the fission product release include aerosol sedimentation, aerosol inertial impaction, aerosol thermophoresis, revaporization, etc[5]. Distribution of the fission products in the primary system and the containment, and radioactivity in the containment, can be different, hence different ways to treat a severe accident of PWR.

In this paper, a typical high pressure core melts sequence, TMLB' station blackout scenario, is studied for the depressurization analysis, assuming that the accident is initiated by the loss of offsite and onsite

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* Corresponding author. *E-mail address:* huanggaofeng@sjtu.edu.cn

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AC&DC power without recovery of steam generator auxiliary feedwater. Behaviors of inert gas and volatile fission products are evaluated with the severe accident analysis code, so as to determine the depressurization affecting the fission product behaviors.

2 Calculation model

2.1 Phenomenological model

The modeled fission product phenomena include aerosol sedimentation, aerosol inertial impaction, aerosol thermophoresis and aerosol revaporization. The models, except the aerosol revaporization, are traditional, but they are important, too, for the calculation.

In an aerosol sedimentation, the aerosol deposits on surfaces by gravity. The deposition rate is given by

$$\Lambda=\lambda[\gamma\chi^2\mu h^2/(k_0 g\rho)]^{1/2} \tag{1}$$

where Λ is non-dimensional deposition rate, λ is removal rate, γ is agglomeration shape factor, χ is Stokes correction factor, μ is carrier gas speed (m/s), h is equivalent deposition length (m), k_0 is Brownian coefficient, g is acceleration due to gravity (m/s^2), and ρ is theoretical particle density (kg/m^3).

Thermophoresis occurs when an aerosol particle is transported to a surface as a result of temperature gradient between the surface and the gas. The deposition speed u_d in m/s is given by

$$u_{\mathrm{d}}=\frac{\mu\cdot\beta}{x\cdot\rho_{\mathrm{g}}\cdot L}\left(\frac{T_{\mathrm{g}}}{T_{\mathrm{wall}}}-1\right)\left[\frac{1-(\beta\cdot Pr)^{1.25T_{\mathrm{wall}}/T_{\mathrm{g}}}}{1-(\beta\cdot Pr)^{1.25}}\right]Nu \tag{2}$$

where, β is deposition coefficient, ρ_g is gas density (kg/m^3), L is length of thermophoretic surface (m), T_g is gas temperature (K), T_{wall} is wall surface temperature (K), Pr is gas Prandtl number, and Nu is Nusselt number.

In an inertial impaction, aerosols are removed from flow field by impaction on surfaces. The deposition speed u_i in m/s is given by

$$u_{\mathrm{i}}=Eu_{\mathrm{g}} \tag{3}$$

where E is the collector efficiency, and u_g is the gas velocity (m/s).

Revaporization occurs when the deposited aerosol becomes hot enough heated by the decaying fission products. The revaporization mass flux is calculated from[6,7]

$$J=\frac{p_{\mathrm{s}}\cdot Q\cdot M}{R\cdot T}\left[1-\exp\left(\frac{Sh\cdot D\cdot S}{Q\cdot d_{\mathrm{h}}}\right)\right] \tag{4}$$

where J is revaporization mass flux (kg/s), P_s is saturation vapour pressure (Pa), Q is volumetric flow rate of gas (m^3/s), M is molar mass of vapor (kg/mol), R is gas constant 8.31(J·K^{-1}·mol^{-1}), T is temperature (K), Sh is Sherwood number, D is binary diffusion coefficient (m^2/s), S is area of revaporization surface (m^2), and d_h is hydraulic diameter of tube (m).

2.2 Plant model

For a 3-loop PWR of 900 MWe, the severe-accident code is used to analyze the effect of intentional depressurization on fission product behavior. The code, an analysis tool for an integral system, simulates the response to accident initiation events in a light water reactor. The reactor coolant system consists of a reactor vessel, active core region and two reactor coolant loops — the broken and unbroken loops (Fig.1). The broken loop models a single hot leg, steam generator, intermediate leg, reactor coolant pump and cold leg. The pressurizer is located on the broken loop hot leg. The unbroken loop combines the remaining two reactor coolant loops and steam generators. The pressurizer PORVs comprise of three groups of individual relief valves, which open either automatically at the set pressure or by the operator. The fission products pass through the relief valves and go to the quench tank, and the containment after the quench tank rupture disk fails.

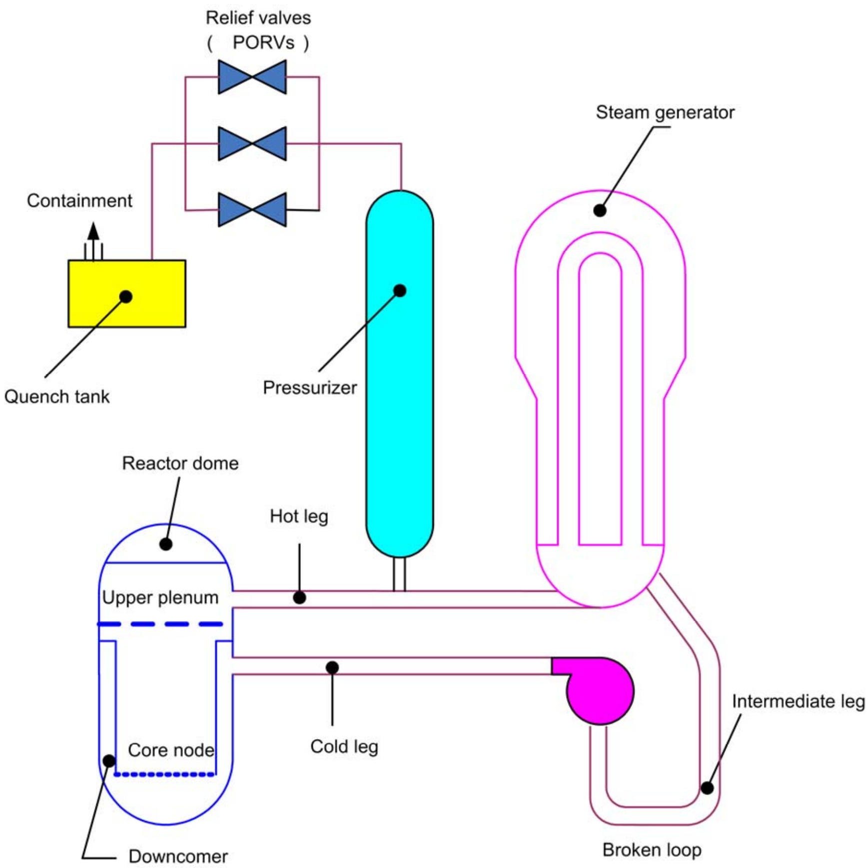

Fig.1 RCS and pressurizer PORVs model.

3 Fission products and the initial mass

The fission products are divided into 12 groups (Table 1), including inert gases in Group 1; volatile fission products in Groups 2, 3, 6, 10 and 11; and nonvolatile fission products in other groups. The fission products in each group have the similar physical and chemical characteristics. Masses of the initial fission products are calculated with the hypothesis that the fuel elements are of three categories for 1, 2 and 3 years of use, respectively.

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Table 1 Fission product groups

Groups	Fission product
1	Xe, Kr (Inert Gas)
2	CsI, RbI
3	TeO_2
4	SrO
5	MoO_2, RuO_2, TcO_2, RhO_2
6	CsOH, RbOH
7	BaO
8	La_2O_3, Pr_2O_3, Nd_2O_3, Y_2O_3, ZrO_2, NbO_2, AmO_2, CmO_2
9	CeO_2
10	Sb
11	Te_2
12	NpO_2, PuO_2

4 Analysis of fission product behavior

4.1 Accident progression analysis

Four cases of the TMLB accident, i.e. the base case and depressurization of Cases 1, 2 and 3, are considered. In Case 1, one PORV is latched open by the operator at 922 K at the core exit. In Case 2, the operator latchs open two PORVs. And in Case 3, all the three PORVs are latched open during intentional depressurization. The time of core melting and RPV low head failure are decided by two factors, i.e. the number of opened PORVs and the time of accumulator injection. Effect of the intentional depressurization on behaviors of the fission products, especially for inert gas and volatile fission product, are analyzed, in terms of the fission product release, transport and distribution affected by different depressurization cases.

The key events of the four accident sequences evaluated are shown in Table 2.

Table 2 Time (in s) of the key event for TMLB sequences, with the zero second at the station blackout

Events	Base case	Case 1*	Case 2	Case 3
PORVs reach the set pressure	3,871	3,871	3,871	3,871
Rupture disk failed	6,430	6,430	6,430	6,430
Sore uncovery starts	8,128	8,128	8,128	8,128
PORVs lathed open	–	9,205	9,205	9,205
Gap release starts	9434	9,478	9,531	9,563
Accumulator injection starts	–	11,447	10,366	9,945
Core melt starts	11,563	10,623	10,378	22,131
Core support plate fails	18,016	24,033	37,159	26,037
Accumulators empty	–	29,273	33,130	22,005
RPV lower head fails	19,008	29,259	48,326	35,462
Computation ends	19,208	29,459	48,526	35,662
RCS pressure at lower head failure / MPa	16.37	1.91	0.48	0.40

* Case 1, 2 and 3 are with 1, 2 and 3 PORVs, respectively.

4.2 Inert gas

For the base case, PORV set pressure is reached with increasing pressure of the reactor coolant system (RCS), the PORV open/close cycles keep the RCS pressure at 16.37 MPa (Fig.2a), and the rupture disk of quench tank fail at 6,430 s. After the core is uncovered, gap release starts at 9,434 s, and inert gases released from the core accumulate in the RCS. In the PORV open/close cycles, part of the inert gas mass goes to the quench tank, and to the containment then. The residual inert gases in the RCS go to the containment after failure of lower head of the reactor pressure vessel (PRV). Fig.2b shows three quick releases of inert gases into the containment. The first occurs when the core begins to melt. Within 1000 s, 132 kg inert gases go to the containment through the failed rupture disk. The second occurs when the core support plate fails, a large amount of molten core materials drops into the lower head and interacts with the coolant, with an immediate increase of the RCS pressure, and the PORV opens more frequently, such that in 300 s about 42 kg inert gases go to the containment through the PORV. The last quick release is at the time of RPV lower head failure, and at once about 92 kg inert gases flow into the containment through the RPV lower head. Altogether, 297.3 kg inert gases go to the containment, while only 1.7 kg inert gases retain in the RCS. About 31% of the inert gas mass goes to the containment through the RPV lower head.

For all the four depressurization cases, the accident progression is the same before the PORVs are latched open. PORVs set pressure is reached at 3,871s and the rupture disk fails at 6,430 s. At ~9,205 s when the thermocouple at core exit exceeds 922 K, PORVs are latched open by the operator. In Case 1 and 2, due to coolant loss *via* the PORVs, and in sufficient accumulator injection with one or two opened PORVs, the core melt and inert gas releases occur earlier than the base case (Table 2 and Fig.2a). In Case 3, the RCS pressure decreases quickly and accumulators start earlier to inject coolant, so the progression of core melt is very slow. Unlike the base case, inert gases in the three depressurization cases do not accumulate in the RCS for a long time. On manual opening of the PORVs, inert gases released from the core flow into the containment through the PORVs. The more opened PORVs, the less inert gas mass retains in the RCS before the RPV fails. For Case 3, it is after 22,000 s that a large amount of inert gases begins to release from the core and go to the containment quickly, and very little is retained in the RCS during the accident. It can be seen that for Cases 1, 2 and 3, almost 99% of the inert gas mass flow directly into the containment through the PORVs.

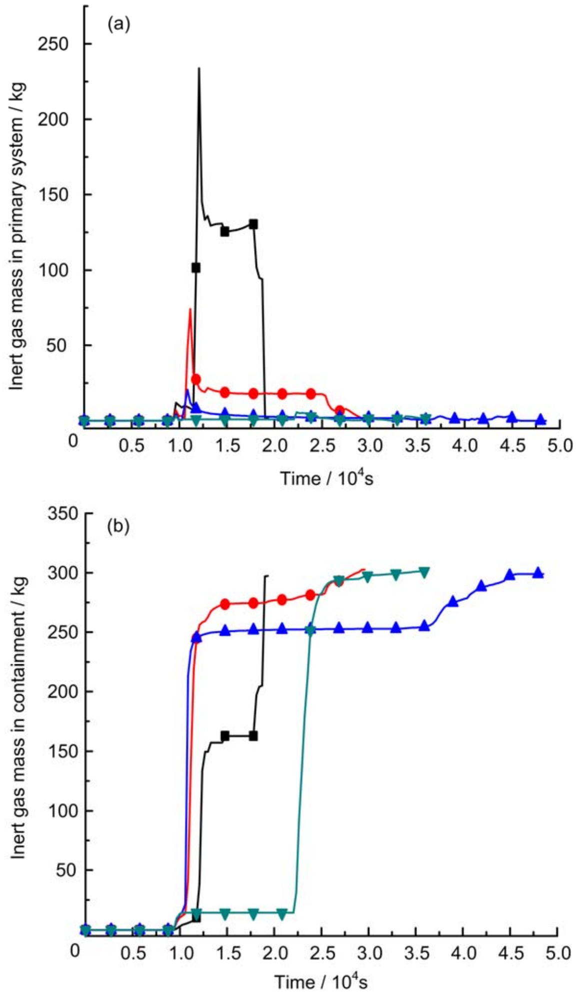

Fig. 2 Inert gas mass in RCS (a) and in containment (b) for different cases.
■ Base Case, ● 1 PORV, ▲ 2 PORVs, ▼ 3 PORVs

The analysis results indicate the effect of depressurization on inert gas behavior. The first effect is that less inert gas mass retains in the RCS for the depressurization cases, and opening more PORVs decreases the retaining inert gas mass in the RCS before the RPV fails. Another effect is the different fractions of inert gases going through the PORVs, i.e. 99% and 59% for the depressurization cases and the base case, respectively.

4.3 Volatile fisssion products

Because of similar physical and chemical characteristics of all volatile fission products, Group 2, i.e. CsI and RbI, which are the main form of iodine during an accident[8], was chosen to analyze the fission product behavior. These volatile fission products are in states of vapor, aerosol or deposition.

For the base case, CsI and RbI are released from the melting core. Most of them deposit on surfaces of the RCS heat sink, only a little suspended CsI/RbI are of vapor and aerosol (Fig.3). In a PORV open/close cycle, CsI/RbI particles flow through the PORV to the containment (Figs.4b and 4c). At low temperature and pressure, the CsI/RbI particles deposit gradually on the walls, floors and other heat sinks in the containment (Fig.4a). There is sedimentation, thermophoresis and inertial impaction for aerosol in this process. The RCS pressure stays high during the accident, so the deposition mass in the RCS is larger than that in the containment. Altogether, 26.3 kg CsI/RbI is released from the core (Table 2), with 24 kg CsI/RbI, almost all in the form of deposition, retaining in the RCS, while 2.3 kg of released CsI/RbI is in the containment, with 0.28 kg of suspended CsI/RbI and 2.02 kg of deposit.

In Case 1, the PORV is opened at 9,200 s, with great coolant loss through the PORV, and the core melt begins earlier than the base case. At 11,447 s, the accumulators work to slow down the core melt. Most of the released CsI/RbI deposits on surface of the RCS heat sink, while the aerosol and vapor go to the containment *via* the PORV, and deposit gradually in the containment. With decreasing RCS pressure, revaporization occurs for deposited CsI/RbI in the RCS (Fig.3a), and most CsI/RbI vapor is generated from deposition, flowing to the containment through the PORV to become deposit finally in the containment (Figs.4a and 4c). About 26.5 kg CsI/RbI is released from the core, with only 3.9 kg CsI/RbI, almost all in the form of deposition, retaining in the RCS. There is 3.2 kg suspended CsI/RbI, and deposit for the rest, in the containment.

In Case 2, the accumulators are initiated at 10,366 s. During the core melting, part of the released CsI/RbI deposits gradually in the RCS, and others go to containment to become the deposit. The revaporization is not strong. About 26.7 kg CsI/RbI is released from the core, with only 8 kg CsI/RbI retaining in the RCS. There are 0.68 kg and 2.31 kg suspended CsI/RbI in the RCS and containment, respectively.

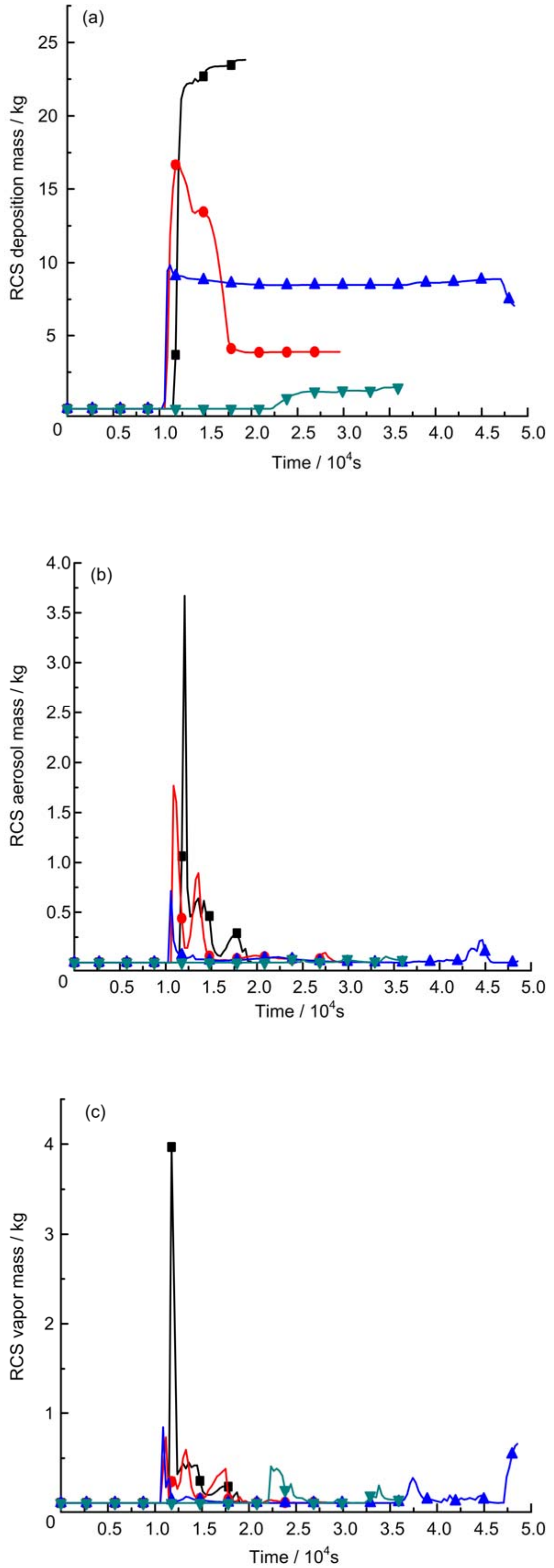

Fig.3 CsI&RbI deposition mass (a), aerosol mass (b) and vapor mass (c) in RCS for different cases.
■ Base Case, ● 1 PORV, ▲ 2 PORVs, ▼ 3 PORVs

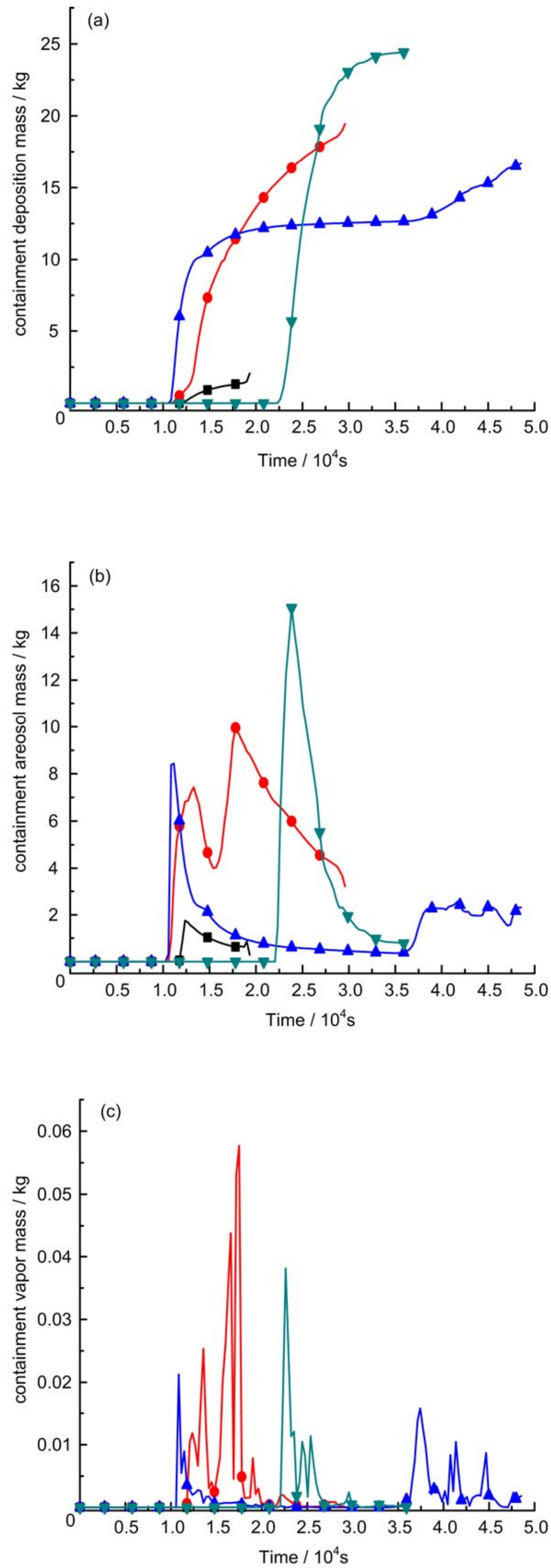

Fig.4 CsI&RbI deposition mass (a), aerosol mass (b) and vapor mass (c) in containment for different cases.
■ Base Case, ● 1 PORV, ▲ 2 PORVs, ▼ 3 PORVs

In Case 3, RCS pressure is low in early stage, hence no re-vaporization, and the least CsI/RbI retaining in RCS. About 26.7 kg CsI/RbI is released, with only 1.5 kg in the RCS. There are 0.06 kg and 0.78 kg suspended CsI/RbI in the RCS and containment, respectively.

5 Conclusion

The effect of intentional depressurization on fission product behavior is analyzed. According to the analytical results, it is concluded: (1) Before the RPV fails, less inert gas is retained in the RCS for the depressurization cases, and the more pressurizer PORVs that are latched open, the less inert gas that is retained in the RCS. The fraction of inert gas that transports through the PORVs is, respectively, 99 percent and 59 percent for depressurization cases and base case. (2) In the intentional depressurization cases, because of low RCS pressure during the accident, less volatile fission product deposits in RCS and more volatile fission product deposits in containment, and there is the least deposition in RCS for the case of opening three PORVs. When opening one PORV, the phenomenon of revaporization is strong in the RCS.

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