Nuclear Engineering and Technology 48 (2016) 975–981

Available online at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Effect of Spray System on Fission Product Distribution in Containment During a Severe Accident in a Two-Loop Pressurized Water Reactor

Mehdi Dehjourian [a], *Mohammad Rahgoshay* [a,*], *Reza Sayareh* [b], *Gholamreza Jahanfarnia* [a], *and Amir Saied Shirani* [c]

[a] *Department of Nuclear Engineering, Science and Research Branch, Islamic Azad University of Tehran, Iran*
[b] *Faculty of Electrical and Computer Engineering, Kerman Graduate University of Technology, Kerman, Iran*
[c] *Faculty of Engineering, Shahid Beheshti University, Tehran, Iran*

ARTICLE INFO

Article history:
Received 18 November 2015
Received in revised form
25 February 2016
Accepted 9 March 2016
Available online 5 April 2016

Keywords:
CONTAIN
Loss-of-Coolant Accident
Pressurized Water Reactor
RELAP5/SCDAP
Severe Accident

ABSTRACT

The containment response during the first 24 hours of a low-pressure severe accident scenario in a nuclear power plant with a two-loop Westinghouse-type pressurized water reactor was simulated with the CONTAIN 2.0 computer code. The accident considered in this study is a large-break loss-of-coolant accident, which is not successfully mitigated by the action of safety systems. The analysis includes pressure and temperature responses, as well as investigation into the influence of spray on the retention of fission products and the prevention of hydrogen combustion in the containment.

1. Introduction

In the event of a large-break loss-of-coolant accident (LB LOCA) in a pressurized water reactor (PWR), coolant mass and energy are first released from the reactor coolant system to the containment through the break. This type of accident occurs in a high-pressure cold-leg pipe in its worst condition, which is a guillotine type of break. In such accidents, the primary system envelope is breached [1].

If the accident is not successfully mitigated by the action of safety systems, core meltdown, relocation and release of radioactive material to the containment through the break, followed by reactor vessel failure and debris ejection will eventually occur. To prevent early containment overpressurization due to heat load in an accident scenario, spray systems and fan coolers are provided in the design of nuclear power plants. They also have the function of enhancing the early depletion of radionuclides from the atmosphere.

The applicability of CONTAIN for the determination of radiological source terms of a PWR under conservative release conditions is demonstrated [2].

---

* *Corresponding author.*
E-mail address: m.rahgoshay@gmail.com (M. Rahgoshay).

http://dx.doi.org/10.1016/j.net.2016.03.007

The containment response during the first 24 hours of such a cold-leg LB LOCA in Beznau nuclear power plant with a two-loop Westinghouse PWR was simulated with the CONTAIN 2.0 computer code [3], which was developed by Sandia National Laboratories under U.S. Nuclear Regulatory Commission sponsorship. Initial and boundary conditions, which result from processes not modeled by CONTAIN, were obtained from simulation with the RELAP5/SCDAP code [4].

Core–concrete interaction, including the attack of the basemat concrete by molten core material, was modeled with the CORCON code, which is included in CONTAIN.

The analysis is focused on the thermal–hydraulic aspect of the containment response. Pressure and temperature responses, as well as the influence of spray on the depletion of fission products from the atmosphere and hydrogen distribution in the containment, are considered.

In support of the analysis for Beznau nuclear power plant (Switzerland), a safety analysis report, and detailed RELAP5/SCDAP and CONTAIN models of the plant are developed [5].

The Beznau PWR is a Westinghouse-designed nuclear power station with a rated thermal power of 1,130 MW. There are two primary coolant loops. Each loop contains a U-tube steam generator, a reactor coolant pump, and associated piping. A single pressurizer is attached to the hot-leg piping in one of the two loops. Two accumulators are attached to each cold leg. A large, dry, subatmospheric containment building surrounds the reactor systems. Specifications of the containment are shown in Table 1. Beznau has two separate spray systems in the containment. The two spray systems operate independently, with a capacity of 45 kg/s [5], via spray nozzles located in the upper compartment of the containment. The actuation time of the spray system is determined by an overpressure signal (the set value is 2.0 bara). Operation of the spray system is helpful in decreasing the average pressure by condensing steam. Additionally, the cold droplets from spray nozzles, as heat sinks, also lower the average temperature in the containment.

2. Materials and methods

2.1. CONTAIN code description

The CONTAIN 2.0 computer code is an integrated analysis tool used for predicting the physical conditions, chemical compositions, and distributions of radiological materials inside a containment building following the release of material from the primary system in a light water reactor accident. It can also predict the amount of source term released to the environment [3].

The fission product behavior modeled in CONTAIN includes radionuclide decay, decay heating, atmosphere transport processes, transport in liquid pathways, iodine scrubbing, release of fission products from hosts, and release of fission products during core–concrete interactions.

CONTAIN allows the analyst to subdivide the containment into any number of nodes or cells, each of which consists of a well-mixed repository of gases (the atmosphere) as well a number of solid heat transfer structures that exchange heat with the atmosphere through an appropriate array of heat transfer correlations [3].

The CONTAIN code includes developmental models for melt ejection from the reactor pressure vessel (RPV) and dispersal from the cavity.

Table 1 – Specification of Beznau containment.

Parameter	Value
Free volume (m^3)	47,500.0
Containment elevation (m)	55.0
Containment inner radius (m)	19.0
Concrete wall thickness (m)	1.1
Steel liner thickness (m)	0.006
Cavity concrete floor thickness (m)	4.0

2.2. CONTAIN input model—containment compartments

The model of the containment is presented by 15 cells in Fig. 1. The containment dome is defined as Cell 12. Cell 15 represents the RPV, which is inactive in the present calculations and is treated as a dummy cell. Cells 3 and 10 are the crane wall annulus. The cavity and instrument tunnel volumes are represented by Cell 2, while the containment sump is modeled as Cell 1. Reactor pool is modeled by Cell 11. The steam generator rooms on the left and right sides are represented by Cells 4 and 8. The reactor coolant pump rooms on the left and right sides are represented by Cells 5 and 7. The free volumes below the steam generators are modeled as Cells 6 and 9. Cells 13 and 14 model gap volume and environment, respectively.

Fourteen flow paths and 22 engineering vents are modeled. Connections between compartments are shown schematically in Fig. 1 (each connection may represent several flow paths or engineering vents). Flows between compartments are modeled by applying the hybrid flow solver [3].

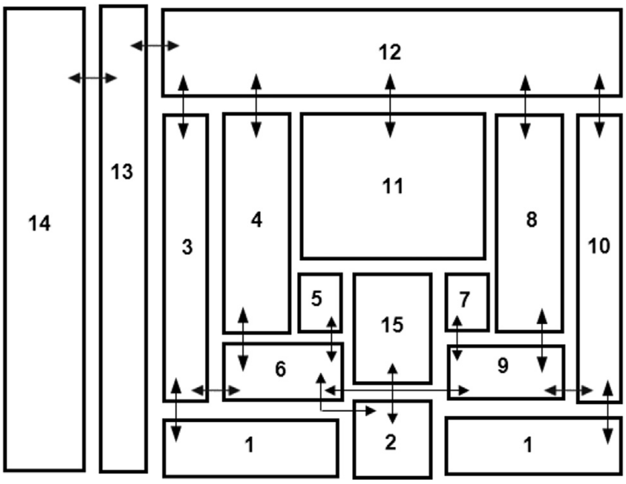

Fig. 1 – Containment compartments and flow paths.

The containment walls, floors, and other structures were modeled by steel or concrete rectangular heat structures, as appropriate. These heat structures, particularly the masses of concrete that form the containment walls, act as passive heat sinks during accident conditions. The containment shell is modeled by heat structures with adiabatic outer surfaces. Heat transfer to the environment and the annulus area between the double containment shells are not modeled. Heat is ultimately removed from the containment through the containment spray system and through the transfer of heat from the containment sump liquid in the heat exchangers.

Two spray systems were modeled. Sprays were initiated when the containment pressure reached approximately 2.0 bara. The CONTAIN code does not model phenomena that take place in the reactor coolant system.

To obtain time-dependent sources of coolant, gases, fission products, and molten core material, which could be included in the CONTAIN input, an LB LOCA with no safety injection actuated is simulated with the severe accident code RELAP5/SCDAP [4].

The RELAP5/SCDAP codes is a severe accident analysis code capable of modeling all important severe accident phenomena (reactor coolant system response, core material chemical reactions, oxidation, ballooning and rupture of the fuel rod cladding, core heat-up, degradation and relocation to the lower plenum, etc.). The code is a combination of the RELAP5 code for thermal hydraulics calculation, the SCDAP code for severe accident-related phenomena, and the COUPLE code for a finite element treatment of the RPV lower head. The RELAP5/SCDAP can only model the in-vessel phase of the severe accident. RELAP5/SCDAP is characterized by its detailed, mechanistic models of severe accident phenomena; however, the calculations can be rather time consuming [4].

The sequence of events during the development of the accident in the primary system is summarized in Table 2.

The following sources were obtained:

- Liquid and vapor coolant
- Gases: N_2, O_2, H_2
- Fission products: Xe, Te, Cs, I
- Molten core material: UO_2, ZrO_2, Zr, Fe, Cr, Ni

Table 2 – Sequence of events during LB LOCA.

Event	Time (sec)
Large break in the cold leg	0
Reactor scram	2
Start of accumulator feed	5
End of accumulator feed	65
Failure of cladding (cladding exceeds the temperature of 1,173 K)	620
Molten corium starts to form the molten pool	2,230
Dry core (no water in the active core)	2,790
Start of melt material slump in the lower head of the vessel	3,670
Pressure vessel failure	5,100

LB LOCA, large-break loss-of-coolant accident.

The majority of the core material inventory is released to the cavity at low pressure after vessel creep rupture at approximately 5,100 seconds. The reactor coolant system pressure at the time of vessel breach is an important parameter controlling direct containment heating. At very low reactor coolant system pressures, as seen in LOCA, the prerequisites of efficient dispersal and fragmentation are not present for efficient direct containment heating interactions. Consequently, there are no heat transfer and chemical reactions that may lead to containment overpressurization [6].

3. Results and discussion

Two different simulations were performed: (i) with no spray in the containment; and (ii) with spray in the containment.

The initial time (t = 100 seconds) was defined by the occurrence of the large break. The initial pressure in the containment was assumed to be 0.98 bara. The initial temperature of the containment atmosphere and heat structures was 322 K.

Hot hydrogen, produced by metal steam reactions in the reactor cavity or subcompartment, vents into the upper dome of the containment, where it can burn as a diffusion flame.

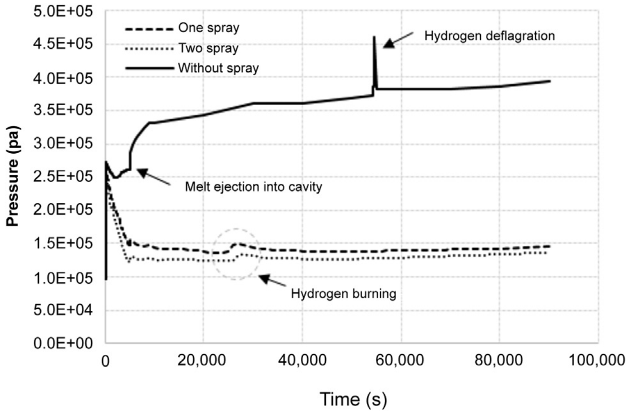

Fig. 2 – Containment pressure.

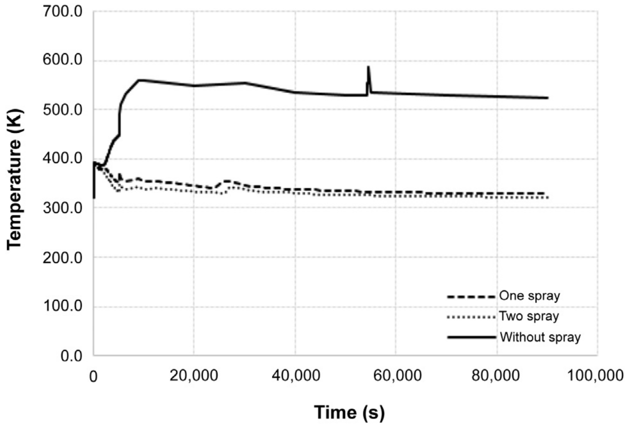

Fig. 3 – Containment temperature.

In the present analysis, the effect of hydrogen ignition source is not taken into account and the diffusion flame model, in the presence of conditions for low autoignition criteria, simply burns the combustible gas flowing into a cell through a flow path utilizing the oxygen in the cell.

Fission product retention in the primary system and on containment structures is more effective if these elements can be maintained at a lower temperature. For this purpose, containment sprays using cool water with the use of residual heat removal heat exchangers can be utilized. Water addition via containment sprays can be used to scrub fission products from the containment atmosphere and thus reduce fission product releases.

The containment sump is located inside the containment and provides an additional source of water for long-term containment cooling by spray.

Water from the containment sump passes through a heat exchanger and, after cooling, is used as spray water in the containment.

In case of hydrogen release inside the containment, sprays homogenize the hydrogen distribution and may lead to "de-inerting" of the mixture through condensation of steam on water droplets. In case of ignition, the water spray can affect flame propagation. Two antagonizing effects can be expected: (i) flame acceleration due to the turbulence induced by spray actuation; and (ii) flame quenching due to the cooling effect of water spray [7].

In the absence of spray, pressure in the main compartment of the containment (Cell 12) first increases sharply due to the coolant released from the primary system, and then decreases as the coolant condenses on heat structures or aerosols. At 5,100 seconds, with failure of RPV molten material ejected to cavity, an increase in pressure occurs.

Especially with the use of spray systems, hydrogen combustion is possible, as steam inertization is lost and combustible conditions are more probable. Without operation of the spray system, steam acts as an inerting gas, unless inertization gets lost and accumulated hydrogen burns. As seen in Fig. 2, at 54,400 seconds after the start of an accident, a stronger deflagration of hydrogen leads to an increase of pressure to about 4.5 bara. This value is more than the design pressure of the containment (4.0 bara) [8] but is less than the failure pressure (8.0 bara) [8], and containment integrity is maintained. At the end of the calculation, the pressure reaches approximately 3.93 bara, which is close to the design pressure of the containment.

Spray acts when containment pressure reaches 2.0 bara (half of design pressure) at about 5 seconds after the initiation of accident. With the operation of the spray, pressure in the containment is less than the previous case (without the spray), and slow burning of hydrogen is predicated. The pressure reaches about 1.5 bara after 24 hours, which is less

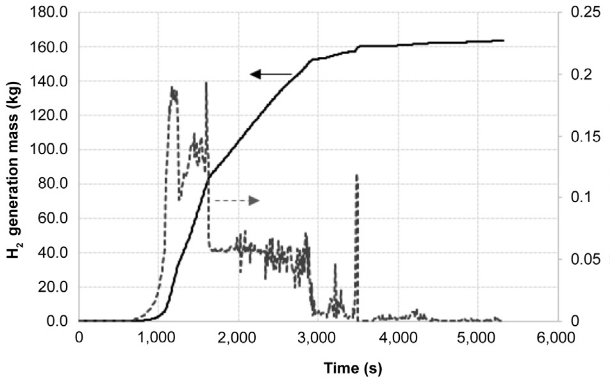

Fig.4 – Hydrogen generation during the in-vessel phase.

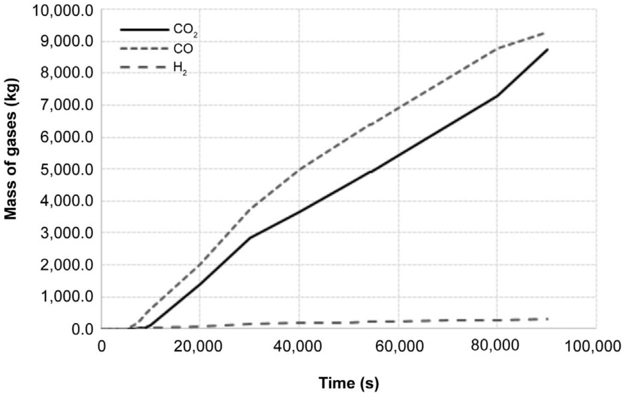

Fig. 5 – Mass of the gases released in the cavity due to CCI. CCI, core–concrete interaction.

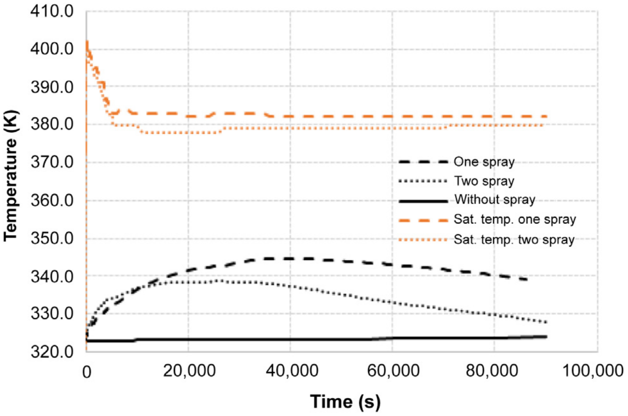

Fig. 6 – Containment sump water temperature.

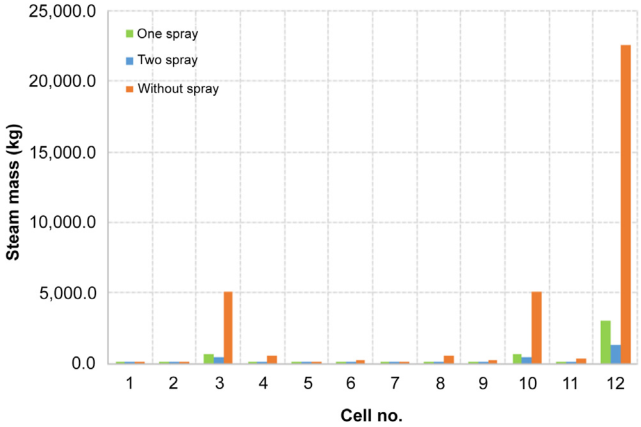

Fig. 7 – Steam mass in the cells of the containment.

than the maximum allowable pressure. The impact of spray capacity on the containment response is assessed as a sensitivity study, which is shown in Figs. 2 and 3.

Fig. 3 depicts the atmospheric temperature in Cell 12. With the operation of the spray system and absorption of heat from the containment atmosphere, the temperature decreases; however, in the case without spray, the containment temperature is higher because there is no heat removal from the containment.

The values of hydrogen mass calculated by RELAP5/SCDAP due to oxidation of clad during the in-vessel phase are shown in Fig. 4. After RPV failure and ejection of molten materials into the cavity, hydrogen generation from ablation of concrete is calculated by CONTAIN code, using CORCON model. The long-term pressurization is mostly due to the generation of noncondensable gases (H_2, CO, and CO_2) caused by molten core–concrete interaction (Fig. 5).

The temperature of the containment sump water should be maintained below the saturation temperature during long-term cooling of the containment. The temperature of the sump calculated during the analysis is shown in Fig. 6.

There are various potential challenges to containment integrity during a severe accident in a light water reactor. Generation of hydrogen and its combustion pose significant risk for severe accidents. For the prevention of hydrogen combustion, the concentration of hydrogen should be kept low, especially in the dome of the containment where most of the hydrogen accumulates.

The mechanisms of condensation and entrainment by operation of spray have opposite consequences for hydrogen combustion. On the one hand, atmosphere mixing due to entrainment caused by falling droplets (that is, momentum transfer from the droplets to the atmosphere) causes a more uniform hydrogen concentration in the containment. On the other hand, steam condensation on droplets causes a decrease of steam concentration in the atmosphere and a corresponding increase in hydrogen concentration.

After 24 hours, steam concentration in the cells of the containment decreases with the operation of spray, as shown in Fig. 7. In the case of spray operation with respect to low criteria for autoignition of hydrogen dominant slow burning occurs in Cell 6 (source compartment) from the beginning of the analysis, and burning in the other cells are negligible.

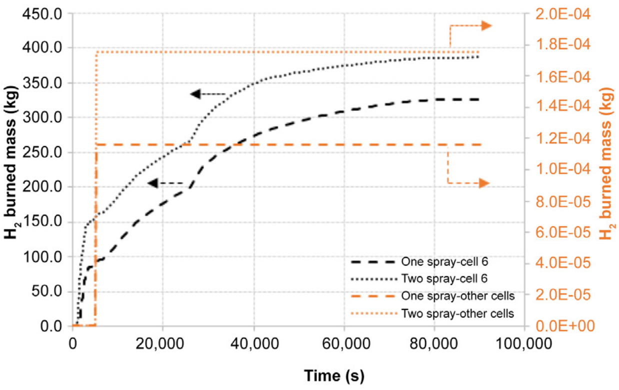

Fig. 8 – **Mass of hydrogen burned in the containment cells with one and two sprays in operation.**

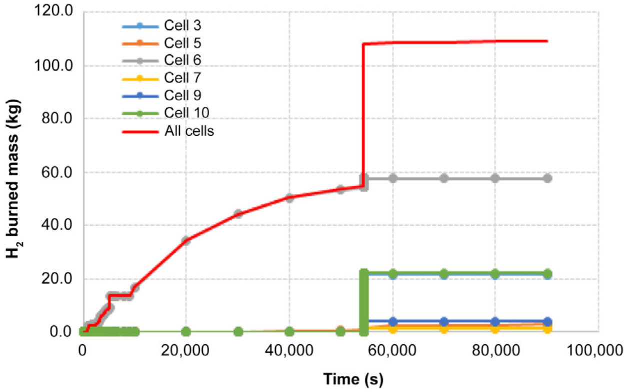

Fig. 9 – **Mass of hydrogen burned in the containment cells without spray in operation.**

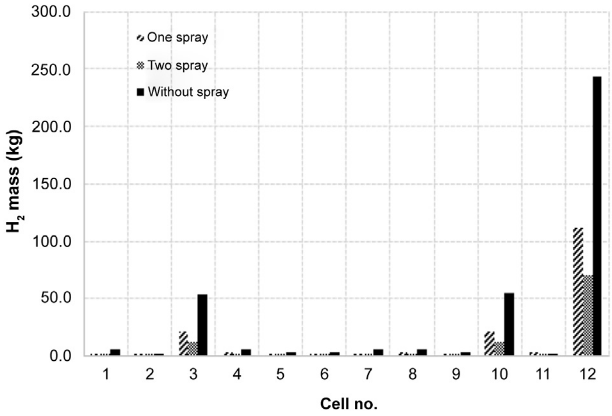

Fig. 10 – **Hydrogen mass in the cells of the containment.**

Hydrogen burning under different spray conditions in cells of the containment is shown in Fig. 8. In the case without spray, because of the high steam concentration only in Cell 6 (source compartment), burning of hydrogen occurs with less value than with spray operation from the beginning of the analysis, as shown in Fig. 9. In the other cells, hydrogen burning starts at 54,400 seconds, when accumulated hydrogen reaches combustible threshold value. Therefore, implementation of hydrogen counter measures is needed in different locations of the containment.

Table 3 – **Release of fission product mass into the containment.**

Elements in group	Initial inventory (kg)	Mass released into the containment (kg)	
		In-vessel phase	Ex-vessel phase
Xe, Kr	103.1	43.41	59.6
Cs, Rb	53.6	24.55	29.08
I	3.74	1.71	2.02
Te	8.61	3.94	4.65

Results of the analysis, shown in Fig. 10, indicate that with actuation of spray and large-scale burning of hydrogen, the remaining hydrogen mass in the main compartment of the containment reduces and so the possibility of hydrogen deflagration decreases.

In a severe accident, evaluation of the source term is required to assess the radiological hazards to the public. As a result of an accident, these fission products can escape to the environment following containment venting, to prevent containment failure.

In this analysis, four fission products that are most important radiologically, Xe, Te, Cs, and I, are considered. The initial inventory of the fission products and their released mass into the containment, during the in- and ex-vessel phases of severe accident progression, are shown in Table 3. Typically in the ex-vessel phase, most fission products remain in the melt that is released into the cavity, while some fission products are released through core–concrete interaction.

In this work, the mass of released fission products in the in-vessel phase is calculated by RELAP5/SCDAP, and for simplification, all remaining fission products are immediately released from the fuel, at the time of RPV failure, into the containment as vapor becomes airborne. Steam is considered as an aerosol component that can be a host of airborne fission products.

Mitigation of noble gas release into the environment is extremely difficult due to the low reactivity of these gases. Noble gases have an important contribution to the whole-body dose as well as the gamma dose [9].

Most of the isotopes of iodine and cesium have radiological effects and hazardous effects on health. Mitigation of radioiodine is required in the case of severe accidents. Mitigation of radioiodine is also important for reactor licensing.

The containment spray model allows for the removal of aerosols, aerosolized fission products, elemental iodine, and less reactive organic iodine compounds from the containment atmosphere. With the operation of the containment spray, aerosols and fission products are removed from the atmosphere and transferred to the pool of the containment sump.

When elemental iodine is transferred to the containment sump, control of radiological effects is easier, while iodine and cesium accumulated in the dome of the containment can be released into the environment by venting the containment.

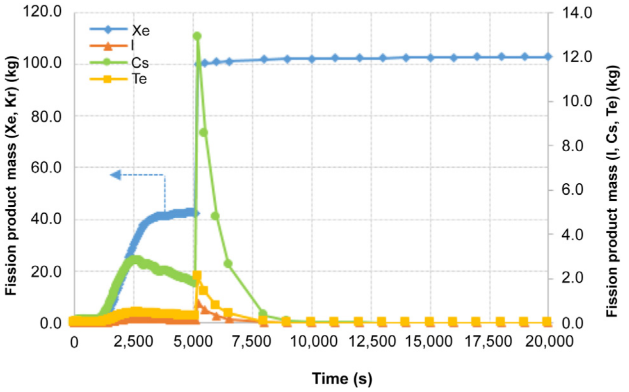

Fig. 12 – Fission product mass in the atmosphere of the containment with operation of sprays.

Masses of the fission products solved in the sump water of the containment by operating the spray system are shown in Fig. 11. Masses of the fission products transported back into the containment atmosphere with the contaminated spray water are shown in Fig. 12.

As the release of the fission products during in-vessel phases ends, the remaining fission products with RPV failure are released into the containment, so there is an increase in the mass of fission products. After 24 hours, the distribution of fission products in different cells of the containment when spray is not operated is shown in Fig. 13. The results show significant quantities of Te, Cs and I, which are airborne fission products, as vapor deposited in the steam as aerosol, and which accumulated in the upper compartment of the containment, in a similar way to Xe and Kr gases.

These fission products can escape into the environment when containment venting occurs for prevention of containment failure, which is not acceptable from the safety point of view. When the spray system is operated, as shown in Fig. 14, all fission products including I, Cs, and Te, except noble gases are washed and scrubbed away in the pool of the containment sump.

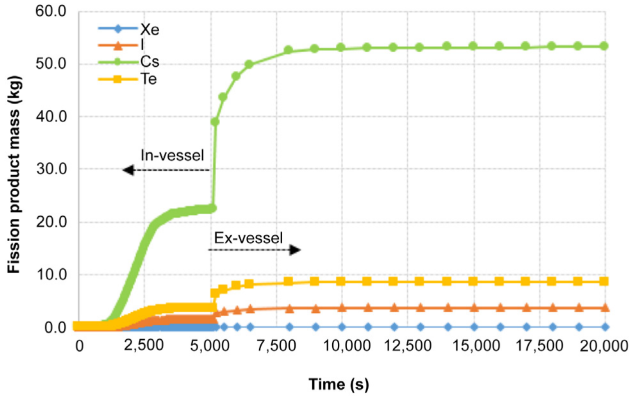

Fig. 11 – Fission product mass in sump water of the containment with operation of sprays.

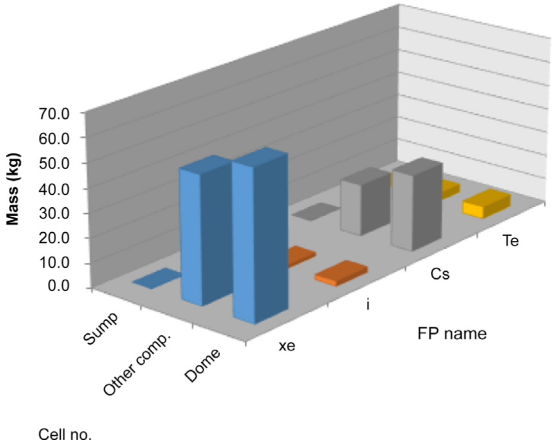

Fig. 13 – Fission product distribution in the containment without spray in operation.

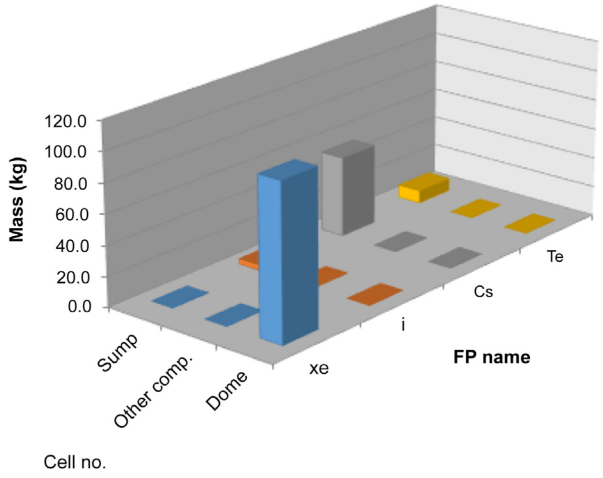

Fig. 14 – Fission product distribution in the containment with one spray and two sprays in operation.

4. Conclusion

Containment phenomena during an LB LOCA with low-pressure vessel failure in a two-loop Westinghouse PWR were simulated with the CONTAIN code. The following conclusions can be drawn:

- After an accident, the short-term containment pressurization is due to coolant release, whereas the long-term pressurization is determined mostly by gas generation caused by molten core–concrete interaction.
- Containment spray system operation leads to a decrease in pressure in the long term and to hydrogen burning in the containment.
- Most of the hydrogen generated by molten core concrete interaction is entrained into the containment's main compartment (dome) via natural circulation.
- With the operation of the spray system in the containment, aerosols and fission products are removed from the atmosphere and transferred to the pool of the containment sump.
- With the use of spray systems, hydrogen combustions occur as steam inertization is lost.
- Without the operation of the spray system, steam acts as an inerting gas, and accumulated hydrogen burns when inertization is lost.
- For the case without spray, hydrogen burning does not occur from the beginning of the analysis in all the cells, and so implementation of hydrogen countermeasures is required in different locations of the containment.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgments

This study was performed as a part of the long-term research on nuclear safety supported by the Nuclear Engineering Department of Science and Research Branch Islamic Azad University. The authors are pleased to acknowledge the support of the technical input for the present work from the Safety Department of Beznau Nuclear Power Plant.

REFERENCES

[1] F.C. Rahim, M. Rahgoshay, S.K. Mousavian, A study of large break LOCA in the AP1000 reactor containment, Prog. Nucl. Energy 54 (2012) 132–137.

[2] R. Frutos, D. Gido, G. Henneges, P. Schmuck, Calculation of fission product behaviour in an advanced containment in case of a severe accident, Nucl. Eng. Des. 202 (2000) 173–178.

[3] CONTAIN 2.0 Code Manual, A Computer Code for Nuclear Containment Analysis, Prepared for the U.S. Nuclear Regulatory Commission, Patent, 1997.

[4] RELAP5/SCDAP//MOD3.2 Code Manuals, A Computer Code for Best-Estimate Transient Simulation of Light Water Reactor Coolant Systems During Severe Accidents, Prepared for the U.S. Nuclear Regulatory Commission, Idaho National Engineering and Enjvironmental Laboratory, NUREG/CR-6150, 1997.

[5] Nordostschweizerische Kraftwerke (NOK) AG, Beznau (KKB), Safety Analysis Report, 2003.

[6] B.R. Sehgal, Direct containment heating (DCH), in: Nuclear Safety in Light Water Reactors, first ed., Ch. 3, British Library Cataloguing in Publication Data, London, 2012, pp. 228–254.

[7] OECD, Status Report on Hydrogen and Related Computer Codes, Nuclear Energy Agency Committee on the Safety of Nuclear Installations, NEA/CSNI/R (2014)8, 2014.

[8] OECD, Documentation of the Use of Severe Accident Computer Codes in Selected Level-2 PSAs for Nuclear Power Plants, NEA/CSNI/R (97)19, Nuclear Energy Agency Committee on the Safety of Nuclear Installations, 1998.

[9] K. Mehboob, C. Xinrong, Source term evaluation of two-loop PWR under hypothetical severe accidents, Ann. Nucl. Energy 50 (2012) 271–284.