Conceptual Design of Underground Toroidal Containment Extension Building for Increased Containment Integrity and Natural Decontamination Capability of Radioactive Materials during Nuclear Severe Accident Mitigation

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1. Introduction

The occurrence of Fukushima Daiichi Accident in 2011 taught many that even the unimaginable severe accidents could happen. Nuclear power experts and the regulators began to consider severe accident scenarios that were not previously considered seriously, and the industry has begun to develop not only preventive but also mitigative technologies that can limit the environmental spread of radioactive materials. One such commercialized technology is containment filtered venting system (CFVS), which would vent the containment pressure through filtered system into the environment so that the chance of containment failure would be reduced [1].

The nuclear power plants (NPPs) are already equipped with many active safety systems to mitigate the accident consequences. Active systems generally have much better efficiency in performance compared with passive systems. A passive system depends on some kind of gradient (e.g. gravitational, temperature, or pressure gradient) [2]. However, as time passes, the gradient may decrease, thereby decreasing the overall system efficiency over a long-period. Nonetheless, in case of when loss of both AC and DC power occurs in the NPP along with unavailability of other off-site power sources, application of passive accident mitigation systems would be important to improve the overall NPP system reliability [3].

The purpose of this research is to introduce a containment building extension as an underground toroidal structure to further improve the NPP safety by enhancing its capabilities to withstand beyond design basis accidents through use of a passive severe accident mitigation system.

2. Conceptual Design

Improvement in the NPP severe accident mitigation capability by the underground toroidal structure is achieved mainly by providing additional volume and thus extension of the containment survival time even during unforeseen severe accident scenarios. Additional response time provided should allow better onsite and offsite responses. Also, appropriate measures of cesium and iodine control could be included to enhance radiological emergency preparedness. In particular, as iodine-131, one of the most important radionuclides of concern [4] has half-life of approximately 8 days, even withholding I-131 inside the toroidal structure to decay would significantly reduce the short-term health risks of NPP accidents by prohibiting uptake of iodine-131 into thyroid for the public, thereby reducing the thyroid cancer risks [5].

2.1 Conceptual Design of the Underground Toroidal Building

The conceptual design of the underground toroidal containment extension structure is shown as Figures 1 and 2 [6]. It is to be installed underground at the basement of the NPP containment building site, so that in case of NPP severe accident, radioactive releases would passively flow through safety valves into the toroidal structure and allow most radioactive isotopes with short half-life to naturally decay away inside the structure.

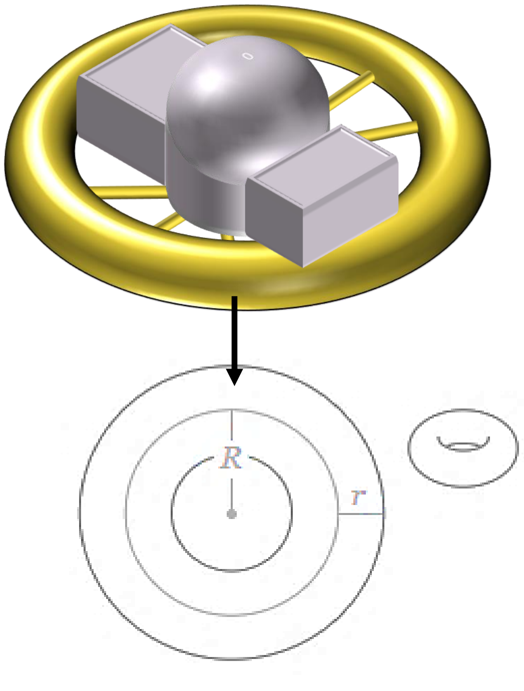

Fig. 1. Conceptual design of the underground toroidal building

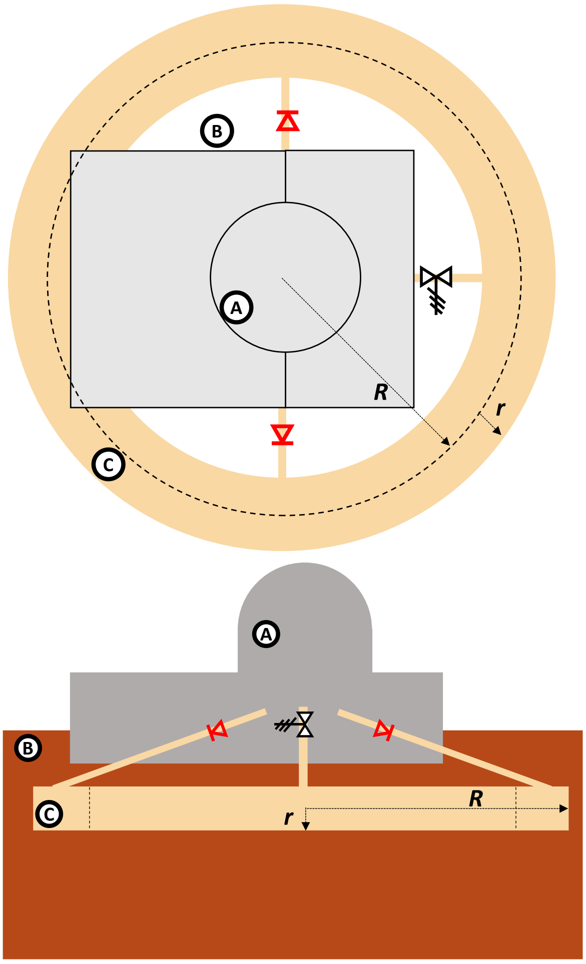

Fig. 2. Top and side views of the underground toroidal containment extension building (not drawn to scale)

In the Figure 2, symbols A, B, and C represent a typical NPP containment & auxiliary building, the NPP site, and the underground toroidal building, respectively. There would be check valve lines from the containment to the toroidal building and safety valve lines from the toroid to the containment. The letters *R* and *r* represent the horizontal distance from the center of the NPP containment building and inner radius of the toroidal extension, respectively. The volume of the toroidal structure can be found using a simple equation.

$$V_{toroid} = 2\pi^2 R r^2 \qquad \text{[Eq. 1]}$$

If *R* and *r* are 88.65 m and 20 m, the volume of the toroidal structure would become roughly 10 times the free volume of the NPP containment building, and because the structure is designed underground, it would be sturdier against pressure increases. If the toroid can have inner radius (*r*) of 25 m, then the distance (*R*) can be decreased to 60 m and can still have over 10 times the free volume of the containment. Therefore, depending on the site, *R* and *r* may be adjusted to fit the safety design needs of the power plant. As a reference, a typical Korean Standard NPP (OPR1000) has a containment height and inner diameter of 66.8m and 43.9m, respectively [7].

3. Methods and Results

3.1 Methods for a Preliminary Analysis

MAAP4 code, a fast-running integrated computer code that can simulate the severe accident sequences in pressurized water reactors, was used to simulate the effects of having toroidal containment extension. The original plant file for OPR1000 was provided by Korea Atomic Energy Research Institute (KAERI) for research purposes.

An additional compartment was added to the original plant file to simulate the additional toroid compartment with *R* of 88.65 m and *r* of 20 m, at 30 m below the ground level. A check valve connecting the containment to the toroidal extension was designed so that it would open and close if the differential pressures between the containment and the toroid are greater than $1\text{x}10^5$ Pa (~1atm) and 34,474 Pa (~5 psi for a typical check valve), respectively. Aerosol sedimentation area inside the toroidal building was assumed to occupy 1/3 of the total area. The largest characteristic total cross-sectional area in the toroid was assumed $20^2\pi$ m^2. It was assumed that no passive autocatalytic recombiner (PAR) exist inside the reactor building.

For the accident scenario, unmitigated long-term station blackout (LTSBO) accident was used from the State-of-the-Art Reactor Consequence Analyses (SOARCA) report for both OPR1000 without and with the underground toroidal containment extension [8]. The containment pressure was simulated to see when the containment failure would occur in case loss of AC along with DC power occurs with failed operator actions.

3.2 Results of the Simulation

The results of the simulations are shown in the Figures 3 and 4. Figure 3 shows the simulated containment pressure during unmitigated long-term station blackout accident with no underground toroid extension. Figure 4 is the simulated containment pressure for the same accident sequences but with the aforementioned toroid extension attached to the containment through check valves.

As shown in Figure 3, the examined nuclear reactor with unmitigated station blackout accident would result in a containment failure in roughly 2~3 days (about 49 hours according to the simulation). This is as expected for a typical 1000 MWe pressurized water reactor [8].

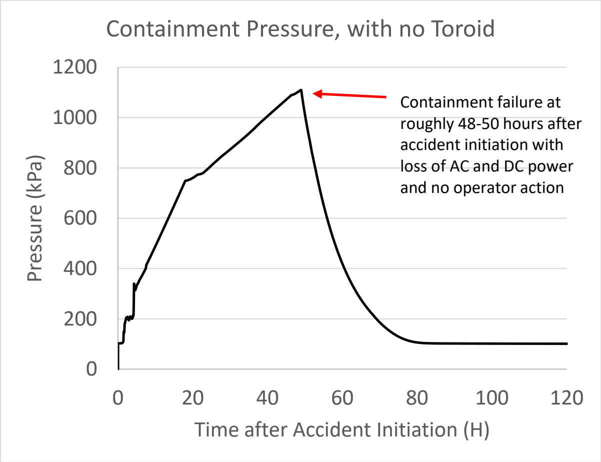

Fig. 3. Containment pressure during unmitigated long-term station blackout accident, with no underground toroid extension

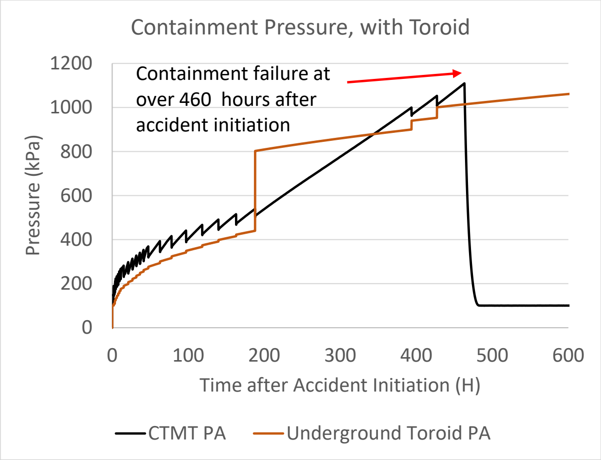

Fig. 4. Containment pressure during unmitigated long-term station blackout accident, with underground toroid extension

However, just by having large additional volume underground with passive check valve system connecting it from the containment, much more significant time (roughly 460 hours from the simulation as shown in Figure 4) can be secured for additional response before the containment fails. This additional time would also allow short-lived radionuclides (including I-131) to decay significantly inside the closed structure without being released into the environment.

Although this is a preliminary analysis, the results may warrant more future research of this technology.

4. Conclusions and Discussions

The underground toroidal containment extension building as proposed in the study may result in the improvement in the NPP severe accident mitigation capability through providing much larger additional volume and thus extension of the containment survival time. Such improvement is expected even during unexpected severe accidents in the future. Additional response time provided should allow better onsite and offsite responses. To reduce the costs, it is also possible to build one toroidal structure underground with connections to multiple reactor buildings at a site, so that any one of the connected reactor buildings can use the toroidal structure in case of a severe accident with containment over-pressurization.

However, additional research is required to further show the feasibility of this technology. For example, although it is expected that an underground structure would be much more advantageous in case of over-pressurization, more extensive structural analysis should be performed. The limitations of the soil/rock conditions to use underground toroidal structure should also be defined. As additional safety systems (e.g. PAR, radioactive iodine/cesium filters, cooling system, etc.) inside the toroid may also impact its capability of holding the radioactive gas inside, technoeconomic analysis should also be performed to better predict the cost of using this structure. Nonetheless, the proposed underground toroidal containment extension strategy may prove to be useful to enhance both actual and perceived safety of nuclear power plants.

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