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Original Article

Bayesian Optimization Analysis of Containment-Venting Operation in a Boiling Water Reactor Severe Accident

Xiaoyu Zheng, Jun Ishikawa, Tomoyuki Sugiyama, and Yu Maruyama*

Nuclear Safety Research Center, Japan Atomic Energy Agency, 2–4, Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki-ken, 319–1195, Japan

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ABSTRACT

Containment venting is one of several essential measures to protect the integrity of the final barrier of a nuclear reactor during severe accidents, by which the uncontrollable release of fission products can be avoided. The authors seek to develop an optimization approach to venting operations, from a simulation-based perspective, using an integrated severe accident code, THALES2/KICHE. The effectiveness of the containment-venting strategies needs to be verified via numerical simulations based on various settings of the venting conditions. The number of iterations, however, needs to be controlled to avoid cumbersome computational burden of integrated codes. Bayesian optimization is an efficient global optimization approach. By using a Gaussian process regression, a surrogate model of the "black-box" code is constructed. It can be updated simultaneously whenever new simulation results are acquired. With predictions via the surrogate model, upcoming locations of the most probable optimum can be revealed. The sampling procedure is adaptive. Compared with the case of pure random searches, the number of code queries is largely reduced for the optimum finding. One typical severe accident scenario of a boiling water reactor is chosen as an example. The research demonstrates the applicability of the Bayesian optimization approach to the design and establishment of containment-venting strategies during severe accidents.

1. Introduction

The establishment of strategies in response to severe accident conditions is fraught with various choices, usually with the involvement of many academic disciplines and influential factors. Effective severe accident management measures can ensure the prevention of reactor core damage, containment vessel failure, and the final mitigation of radiological consequences. Because of the complexity of the overall situation, most decisions for severe accident management measures are

* *Corresponding author.*
E-mail address: zheng.xiaoyu@jaea.go.jp (X. Zheng).
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currently made by expert judgement. Mathematically, the optimization of the design of a specific accident countermeasure can be converted to an equivalent task of finding the optimal solution of an objective function [1]. When the objective function has no explicit form, as is especially the case in many engineering fields, it is called a "black-box" objective function, such as an integral severe accident code for an experimental facility. The only way to obtain corresponding outputs of the "black-box" function is to evaluate it, and this usually requires computational/practical effort, which is sometimes so expensive as to be unaffordable. To overcome the inefficiency of random or grid searches for optimal solutions, we can adopt methods of deterministic global searching [2] or stochastic methods using Bayesian theory [3]. A simulation-based framework using the latter approach has been proposed; then, as a demonstration, a containment-venting operation under severe accident conditions in a boiling water reactor (BWR) is optimized to reduce the total release of fission products from the containment of a nuclear reactor. To simplify the problem, the venting system analyzed does not include the installation of any filter. The outputs from the present optimization analysis are equivalent to the amount of fission products introduced into a filtered venting system.

In general, BWR containments use suppression chambers (S/Cs), also known as wetwells, to condense water vapor. Under severe accident scenarios, venting of a containment vessel (involving the removal of steam, hydrogen, and other gases) might be required to prevent containment failure resulting from overpressure [4]. One primary requirement in Order EA-13-109 issued by the United States Nuclear Regulatory Commission is that Mark I and Mark II containments must have S/C venting systems that remain functional during severe accident conditions [5]. The establishment of containment-venting activation rules directly affects the containment integrity, and likewise the environmental fission-product release. The venting operations are affected by, for example, the timing of activation/deactivation and the duration of each phase. The problem is complex and affected by many factors. When containment-venting rules are designed, their effectiveness at ensuring containment protection and consequence mitigation needs to be inspected. To find the optimal setting of these influential factors with a minimization of fission-product release, queries via computer simulations using integrated severe accident codes are required.

The Japan Atomic Energy Agency has been developing the THALES2 code to analyze severe accident progression and estimate source terms for Level 2 probabilistic risk assessment [6]. In recent years an independent computer code for iodine chemistry simulation, KICHE [7,8], has been coupled with THALES2 through an interface program developed for the exchange of input/output between the two codes [9]. THALES2/KICHE is an integrated and fast-running severe accident code that simulates the progression of severe accidents in light water reactor nuclear power plants, including simplified modeling of thermal–hydraulic response, core melt progression, and in-vessel and ex-vessel transport behavior of radioactive materials with a consideration of iodine chemical reaction kinetics in aqueous phase, etc.

This paper is organized as follows. In Section 2 we describe the analysis of a typical BWR severe accident using the THALES2/KICHE code. In Section 3 we demonstrate the Bayesian optimization framework. In Section 4 the venting strategy is optimized under severe accident conditions to mitigate radioactive release from the containment vessel.

2. Severe accident analysis via THALES2/KICHE

A BWR4 plant model with a Mark I containment is discretized with control volumes, as shown in Fig. 1. The reactor cooling system is divided into seven volumes: reactor core, upper plenum, steam dome, downcomer, lower plenum, and recirculation loops A and B. The containment vessel model comprises the drywell (D/W), S/C, pedestal, and vent pipes that connect the D/W and S/C. The environment volume is connected to the reactor building and S/C, which represent the paths of containment leaks and the S/C vent.

After a severe accident occurs, fission products released from a degraded core can transfer to the reactor cooling system, containment, and reactor building. During this process, vigorous physical and chemical processes take place and the fission products are drastically transformed [10]. The activation timing and operational duration of the venting system are crucial for consequence mitigation: fewer fission products will be released if the concentration of the in-containment gaseous radionuclides is low and the filtering function of the S/C works favorably, otherwise more fission products will be released. The transportation and release of representative fission products are simulated using the THALES2/KICHE code; methods to establish effective venting operations will be discussed.

As an example, one of several typical BWR severe accident sequences [11], TQUV (a transient (T) followed by failure of the feedwater system (Q), the high-pressure coolant injection system (U), and the low-pressure coolant injection system (V) with depressurization of reactor coolant system), is chosen to

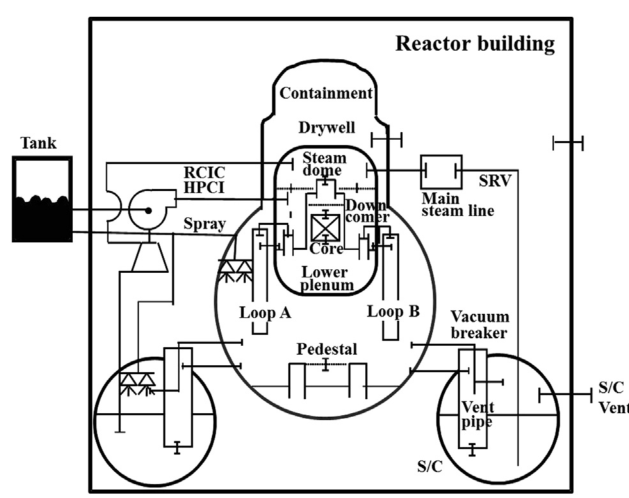

Fig. 1 – Control volume nodalization for THALES2/KICHE modeling. HPCI, high pressure coolant injection system; RCIC, reactor core isolation cooling system; S/C, suppression chamber; SRV, safety relief valve.