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Cooldown procedure success criteria map for the full break size spectrum of SBLOCA

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ABSTRACT

A success criteria map defining successful implementation of a cooldown procedure to mitigate small-break loss of coolant accident (SBLOCA) with failed high pressure safety injection system for the OPR1000 is generated for the full break size spectrum from 0.5 in to 2.5 in diameter breaks. The success criteria map is a multi-dimensional response surface that gives the expected peak clad temperature (PCT) as a function of break size and operator action time to start the 55.6 °C/hr reactor coolant system cooldown and depressurization involving secondary side steam dump through manual manipulation of the atmospheric dump valves (ADV). The PCT response surface is constructed through a regression analysis using a Gaussian process model (GPM) coupled to an adaptive sampling procedure that greatly reduces the computational cost and analysis time by limiting the number of required best estimate simulations of the SBLOCA with the MARS code to approximately 100. Break flow rates and times to core heat up each span several orders of magnitude when considering the full break size spectrum so an innovative solution of transforming the break size and ADV actuation time input variables using exponential and logarithm functions was implemented such that the regression could be performed on the scaled and transformed input space.

1. Introduction

Small-break loss of coolant accident (SBLOCA) with failed high pressure safety injection system (HPSI) is a risk significant event for the OPR1000 (Optimized Power Reactor 1000 MWe; formally the Korean Standard Nuclear Plant) representing 12% of the core damage frequency in the Level 1 Probabilistic Safety Assessment (PSA) model (KAERI, 2016). In order to mitigate the SBLOCA with failed HPSI, operators must successfully implement a cooldown procedure to cooldown and depressurize the reactor coolant system (RCS) so that the safety injection tanks (SITs) and low pressure safety injection system (LPSI) can makeup RCS inventory and terminate core heat up. The cooldown procedure requires operators to manually manipulate the atmospheric dump valves (ADVs) using the main control room (MCR) panel hand switches when performing a secondary side steam dump from the steam generators (SG). Detailed instructions such as recommended valve open positions and mission time to initiate the procedure are not provided in the emergency operating procedures (EOPs). Other EOPs limit the maximum allowable cooldown rate to 55.6 °C/hr (100 °F/hr) imposed for concerns over pressurized thermal shock and thermal cycling fatigue of reactor components. For some break sizes, core damage will occur even if the operators promptly establish the 55.6 °C/hr cooldown following the procedure. In these cases, an aggressive cooldown procedure must be adopted with cooldown rates that exceed the 55.6 °C/hr limit.

The purpose of the present work is to construct a success criteria map for the aggressive cooldown procedure. The success criteria map should quantify for the full break size spectrum of SBLOCA defined here as break area diameters from 0.5 in to 2.5 in, the maximum allowable time, the mission time, for operators to begin the steam dump after the reactor trip in response to the SBLOCA and the required cooldown rate needed to prevent core heat up. To make the problem more tractable, we have chosen first to only consider the normal cooldown procedure adhering to the 55.6 °C/hr cooldown rate and establish an efficient framework to generate multi-dimensional success criteria maps using data derived from best estimate simulations of the SBLOCA. The framework incorporates the Gaussian process model (GPM) for multivariate regression previously used to generate a success criteria map for the injection phase of a large-break loss of coolant accident (LBLOCA) (Fynan and Ahn, 2016a,b). However, due to the consideration of the full break size spectrum of SBLOCAs, the break flow rates and times to core heat up encountered during the analysis each span several orders of magnitude rendering the conventional black box treatment of input and output data streams provided to the regression useless. An

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innovative solution, partially motivated by the Fractional Scaling Analysis (FSA) approach (Wulff et al., 2009), of transforming the break size and ADV actuation time input variables using exponential and logarithm functions such that the regression could be performed on the transformed input space where the time-dependent thermal hydraulic (TH) system parameters are scaled such that the simulation data can be synthesized analogous to the design and comparison of experimental TH facilities to operating nuclear power plants. Secondly, an adaptive sampling strategy, although admittedly ad hoc in nature, was implemented into the GPM regression that greatly accelerated the response surface construction used to represent the success criteria map. This adaptive sampling strategy will enable the generation of additional success criteria maps for aggressive cooldown rates and inclusion of other safety systems such as charging pump flow.

The cooldown procedure using the ADVs is also very important to mitigate the station blackout (SBO), another risk significant accident, and a cooldown procedure is called for in the OPR1000 severe accident management guidelines (SAMGs) but once again detailed instructions do not exist. The cooldown procedure in the SBO or SAMG space may require manual operation of the ADV at the valve location using the handwheel and possibly performed blind without RCS temperature readings if instrumentation and control (I & C) is lost under severe accident conditions. Manual operation of the ADVs at the valve location will be challenging and performed under duress and stressful situations including darkness, smoke, high temperatures and humidity, extreme noise from cycling main steam safety valves (MSSVs), or high radiation levels. Manual operation of ADVs during anticipated operational occurrences can be nearly impossible (U.S. Nuclear Regulatory Commission, 1989). The secondary objective of the present work is to gain insight into the ADV operation, specifically valve stem positions and open fractions required to achieve specific cooldown rates, to inform EOPs and SAMGs development.

This paper is a demonstration of integrated deterministic and probabilistic safety assessment (IDPSA) (Zio, 2014). The intent is to demonstrate the practical application and integration of several tools: best estimate TH models of nuclear power plants, selection and preprocessing of input data streams, adaptive sampling, and post-processing of output data streams through regression analysis with the GPM, to the SBLOCA transient as a real-world example. The selection and implementation of specific algorithms and computational tools will be problem specific, so this paper is not putting forth a formal methodology. Due to the incorporation of many different concepts and tools in the study and the inherent complexity of IDPSA, we have organized the paper in the chronological order that the technical work was actually performed noting that the earlier steps directly inform the decisions made in the later stages. This paper is organized as follows. Section 2 describes the best estimate MARS model of the OPR1000, the specific SBLOCA modeling features and implementation of cooldown procedure in the code control function logic. Section 3 presents reference results for the SBLOCA considering the full break size spectrum and introduces a scaling and transformation procedure for break size and ADV actuation time variables, the two input parameters of the multi-dimensional success criteria map. Section 4 introduces an adaptive sampling procedure coupled to the GPM regression analysis used to optimize data generation from MARS simulations and accelerate success criteria map construction. Section 5 presents the final success criteria map and mission times for the cooldown procedure as a function of break size and discusses the application of success criteria maps in PSA.

2. Best estimate model of OPR1000 for SBLOCA simulation

2.1. Review of SBLOCA phenomena and system depressurization

Wulff et al. (2009) describes six primary agents of change that affect the depressurization of nuclear reactor primary system undergoing a LOCA in a system-level application of FSA (Zuber et al. 2007). The six agents of change in descending order of magnitude are (1) net break flow; (2) phase change by heating or cooling; (3)/(4) single-phase thermal expansion/contraction by heating/cooling; (5) expansion due to pumping power; and (6) expansion of inert gas due to wall heating. A computer analyst or experimentalist studying LOCA should consider how these agents of change are represented in their specific project presumably being performed to study a specific reactor technology or nuclear power plant and if any large deviations or deficiencies are present between the project and the actual nuclear reactor technology. For example, the experimentalist must address scale distortion between an integral experiment and a reactor. The computer analyst is faced with another layer of approximation to the physical system imposed by computer code and models. When performing a computer experiment, for example with a system TH code, the computer analyst must give careful consideration to the underlying equations of state, numerical methods, empirical submodels and correlations, and closure relations employed by the code during the calculation especially if the calculated agents of change are sensitive to these model features. The computer analyst must use engineering judgment when interpreting and applying the computer results.

The present study investigates the first four agents change on the depressurization and potential core heat up of a pressurized water reactor (PWR) during SBLOCA. Break flow is parameterized by break geometry defined by a break diameter. By considering the full break size spectrum from 0.5 in to 2.5 in diameter breaks, break flow is effectively varied and hence the depressurization. Decay heat and stored energy in the fuel causes boiling or expansion by heating of the coolant in the active core volume. Heat removal by the steam generators induces phase change by condensation or contraction by cooling dependent on the phase of the coolant leaving the core. The cooldown procedure is a mechanism by which operators can induce a desired depressurization rate by manipulating the rate of condensation or contraction occurring in the SG U-tubes volumes in competition with the boiling or expansion of coolant in the core volume.

2.2. OPR1000 plant and systems description

The OPR1000 was selected as the reference plant design for the study. The OPR1000 is based off of the Combustion Engineering (CE) System 80 technology and is a 2 × 4 plant with two hot legs, two SGs, four cold legs and four reactor coolant pumps (RCP). The rated electric and thermal power of the OPR1000 are 1000 MWe and 2815 MWt, respectively. Twelve OPR1000 units are currently in operation in Korea.

Emergency RCS makeup during SBLOCA is provided by the HPSI, LPSI, and SITs. All three systems inject to four common safety injection (SI) headers, one on each cold leg. The HPSI consists of two independent trains with one pump per train. The pump flow is split to all four SI headers. The LPSI consists of two independent trains with one pump per train. Train A pump flow is split to two SI headers while Train B pump flow is split to the other two SI headers. HPSI and LPSI draw suction from the refueling water storage tank (RWST). HPSI and LPSI are actuated by the safety injection actuation signal (SIAS). The HPSI and LPSI require alternating current (AC) electric power for the pumps and to open motor-driven isolation valves downstream of the pump discharges upon receipt of the SIAS. Electric power and some I & C are divided into two independent divisions and one LPSI train and one HPSI train are assigned to each division so there exists some common cause failure (CCF) related to electricity supply, which can fail both a LPSI train and HPSI train simultaneously. There are also system specific common cause failures that can fail both trains of a system. One SIT is provided per cold leg. The SITs are primarily passive components and will inject into the RCS when the SI header pressure is less than the nitrogen fill gas pressure.

Each SG secondary side is provided with two main steam lines