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Adaptive simulation for failure identification in the Advanced Lead Fast Reactor European Demonstrator

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ABSTRACT

The identification undesired or abnormal states of a nuclear power plant is of primary importance for defining accident prevention and mitigation actions. To this aim, computational models and simulators are frequently employed, as they allow to study the system response to different operational conditions. For complex systems like the nuclear power plants, this is in general challenging because the simulation tools are i) high-dimensional; ii) black-box; iii) dynamic and iv) computationally demanding.

In this paper, an adaptive simulation framework recently proposed by some of the authors is tailored for the analysis of accident scenarios involving the control system of the Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED).

The results confirm that the adaptive simulation framework proposed is effective in identifying critical regions of operation with a limited number of calls to the computationally expensive model. The time of occurrence and magnitude of the failures of the components of the control system are identified as key factors to characterize the critical regions. In particular, it is shown that the order of occurrence of the components' failures strongly affects the evolution of the accident scenarios.

1. Introduction

The Lead-cooled Fast Reactor (LFR) has been selected by the Generation IV International Forum as one of the candidates for the next generation of Nuclear Power Plants (NPPs). This innovative nuclear system can offer a great potential for plant simplification and reach higher operating efficiency compared to nuclear concepts employing other coolants. On the other hand, it introduces new and different safety concerns and design challenges. To address these, computational models are used particularly for identifying undesired or abnormal states (Turati et al., 2015, 2017a; Zio, 2016).

Indeed, modeling and simulation allows investigating the response of the system in different scenarios and transients, under uncertain conditions, including possibly hazardous ones. Design-Of-Experiment (DOE) approaches have been proposed to analyze the system response with respect to specified performance criteria, e.g. of safety, reliability, resilience, business continuity, etc. (Santner et al., 2003; Simpson et al., 2001; Zeng and Zio, 2017). The interest lies in the identification of the factors, parameters and variables values that lead the system to undesired conditions or deviations from operational limits (Bier et al., 1999; Zio, 2016).

In this paper, we focus on system responses represented by mathematical models of the form $Y = f(X)$. Within this setting, we are interested in identifying the Critical Region (CR) formed by the set of input configurations X that lead the output safety-significant parameters Y to cross a given safety threshold, i.e., $CR = \{x \in D_X \ s.\ t.\ f(x) > Y_{thres}\}$, where Y_{thres} represents the physical threshold beyond which the system fails in an undesired state. For example, for the safe operation of a steam generator it is necessary that the pressure does not exceed an upper design limit value.

Indeed, a possible strategy to discover the CRs is to resort to a large number of model simulations and a posteriori retrieve the information of interest. Several types of DOE have been proposed to span as uniformly as possible the input space, in order to have a global exploration of the I/O relation. Latin Hypercube Sampling (LHS) (Iman, 2008; McKay et al., 1979) and Quasi Monte Carlo (QMC) sampling such as Sobol' sequences (Sobol, 1976), are among the best known (Chen et al., 2006). However, although they have been designed for efficiently

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Acronyms

Acc	Accuracy
AK-MCS	Adaptive Kriging-Monte Carlo Simulation
ALFRED	Advanced Lead Fast Reactor European Demonstrator
COV	Coefficient Of Variation
CR	Critical Region
CROD	Control Rod
DOE	Design Of Experiment
FA	Fuel Assembly
HP	High Pressure
HT	High Temperature
I/O	Input/Output
kNN	k Nearest Neighbors
LAR	Least Angle Regression
LFR	Lead Fast Reactor
LHS	Latin Hypercube Sampling
LHT	Lead Highest Temperature
LLT	Lead Lowest Temperature
LT	Low Temperature
MC	Monte Carlo
NPP	Nuclear Power Plant
PCE	Polynomial Chaos Expansion
QMC	Quasi Monte Carlo
RME	Relative Misclassification Error
SG	Steam Generator
SHP	Steam Highest Pressure
SISO	Single Input Single Output
SPLOM	Scatter PLOt Matrix
SR	Safe Region
SROD	Safety Rod

filling high-dimensional spaces (Sobol et al., 2011), still they do not represent a viable solution when the computational cost per simulation is high with respect to the computational resources available. In practice, models of nuclear system responses are: i) high-dimensional, i.e., involve large number of inputs and/or outputs; ii) black-boxes, i.e., the mathematical function $f(X)$ underlying the I/O relation is not known explicitly and is usually nonlinear; iii) dynamic, i.e., evolve in time; iv) computational demanding, i.e., require a long time to run a simulation compared to the available computational resources (Kernstine, 2013). Then, intelligent adaptive sampling strategies have been proposed to progressively guide the simulations towards the regions of interest (i.e., the CRs in our case), making the best use of the information and knowledge gained at previous steps and iterations of the search (Cadini et al., 2014; Li et al., 2011; Picheny et al., 2010; Turati et al., 2017a).

In the present paper, we apply an adaptive simulation framework recently proposed in (Turati et al., 2017b) to explore accident scenarios of a LFR with a limited number of simulations. The study considers the Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) (Frogheri et al., 2015), developed within the European FP7 LEADER project and the control strategy proposed in (Ponciroli et al., 2015a). Specifically, we focus on failures related to control variables that lead the system controlled variables to cross given operational thresholds. For example, the temperature of the lead in the reactor pool must be kept between two reference values to avoid its solidification and material damages. It is to be noted that in the accident scenarios studied, we consider the control system in operation without the activation of any safety systems. This kind of analysis entails spanning a large number of parameters related to both the model and the control system, and hence calls for efficient simulation-based exploration methods. On the other hand, the selected transients represent very severe conditions for the system, which remains "unprotected" because no action is taken for mitigating the failure. Such type of analysis then allows focusing on the non-trivial role of the control system during accident transients (Passerini et al., 2017; Ponciroli et al., 2017).

The rest of the paper is organized as follows: in Section 2, a global overview of ALFRED is given with a specific focus on the control, the uncertainties embedded in the model and the types of accident scenarios simulated; in Section 3, a brief description of the simulation-based exploration framework is provided, followed by a detailed analysis of its application to ALFRED. Finally in Section 4, some conclusions are drawn.

2. Advanced Lead Fast Reactor European Demonstrator (ALFRED)

ALFRED is a small-size (300 MWth) pool-type LFR and its primary system current configuration is depicted in Fig. 1 (Frogheri et al.,

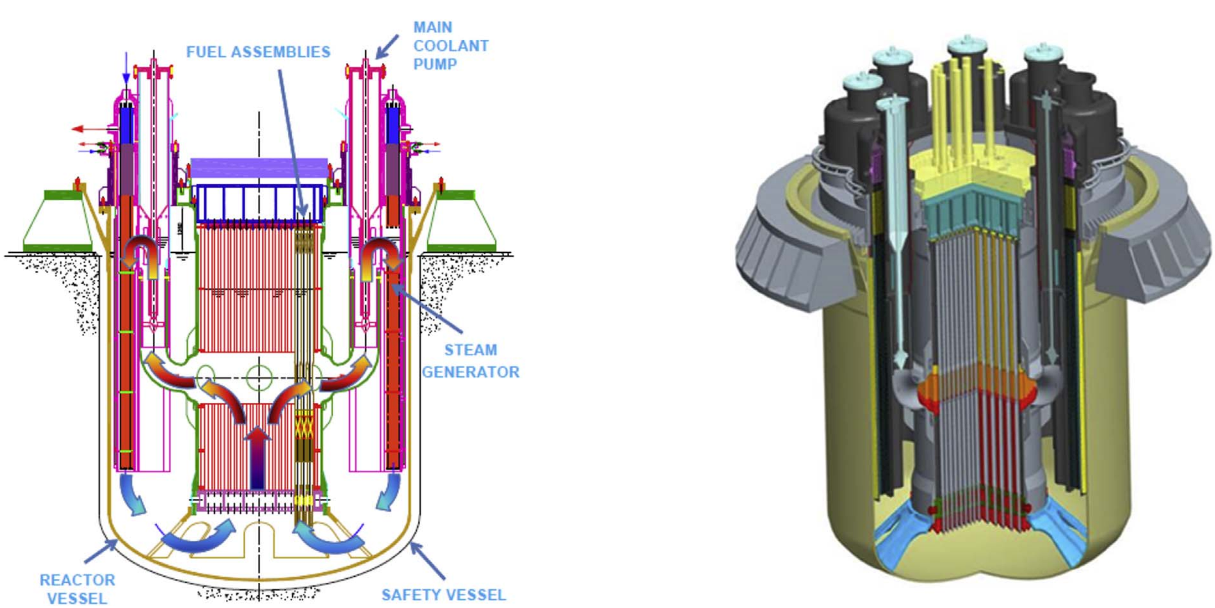

Fig. 1. ALFRED nuclear power plant layout.