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ARC-class tokamaks: Preliminary design, system modeling and safety assessment

Primary cooling system, fuel cycle and machine learning for safety applications

By

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Fusion power plants will play a crucial role in sustainable energy production if their technological maturity and economic feasibility are demonstrated in the next decades. In this regard, ensuring safety during nominal operations, and expected or unexpected transients is of paramount importance for the development (and deployment) of fusion reactors. Lack of operational experience and data, absence of detailed design, and a safety framework still under development make preliminary safety analysis of fusion reactors extremely challenging. Nevertheless, preliminary safety analysis can be carried out alongside the design process to produce a robust, safety-oriented design. This work focuses on the methodological and modeling part of a preliminary safety analysis for fusion reactors. Modeling is a persistent need throughout the whole safety analysis, since most of the safety-critical systems in fusion reactors has not been previously modeled. The methodological part deals with strengthening the deterministic approach by integration with a probabilistic framework and the investigation of machine learning (ML) algorithms for nuclear safety. The ARC (Affordable, Robust, Compact) tokamak is exploited as case study. ARC is an innovative, compact tokamak design that features demountable, high-temperature superconducting magnets, a replaceable vacuum vessel, and a molten salt liquid immersion blanket (LIB). The work presents a preliminary design, modeling, and safety analysis of two critical systems, the fuel cycle and the primary cooling loop. Components of the fuel cycle contain the largest radiological source terms in the plant, i.e. tritium inventories that span from grams to kilograms. The time dependent tritium inventories are quantified by a dynamic, system-level model of the fuel cycle implemented in MATLAB Simulink®. The fuel cycle analysis targets minimization of tritium inventories and reactor self-sufficiency simultaneously. Results show that the start-up inventory can be lower than 1 kg and the required TBR to ensure self-sufficiency within the achievable range (TBR = 1.05 - 1.10). Accidents occurring in the primary cooling system (i.e., the FLiBe loop) are a major pathway for the release of tritium. The FLiBe loop is indeed part of the fuel cycle itself because FLiBe works as coolant, breeder and tritium carrier in ARC. A considerable amount of tritium is therefore found in the FLiBe loop and related components. A preliminary design of the primary cooling system is proposed by means of a functional analysis, and the most likely accidental scenarios are identified by an FMEA and simulated by a thermal-hydraulics model of the primary cooling loop. The model is developed in OpenModelica and exploits OMPython to be effectively coupled with machine learning algorithms. The safety analysis is carried out by integrating deterministic analysis in a probabilistic framework, which allows to deeply investigate the space of possible accidents that might occur in a fusion reactor. The results from the thermal-hydraulic simulations are used to build a dataset of safe and accidental transients. Lastly, ML algorithms are applied to the safety analysis. Supervised and un-supervised models are trained on the dataset built by the thermal-hydraulic model, and used to perform tasks of increasing complexity (clustering, identification of the end states, prediction of thermal-hydraulic variables and remaining time before system failure). Results show that ML models can be effectively used for safety purposes, they can execute tasks in times that are compatible with on-line monitoring, and with relative errors on the target variables as low as 10^{-5}. Nevertheless, many criticalities are identified during the process (from the synthetic data generation to the interpretation of the results). A framework for the development and strengthening of ML models for nuclear safety is therefore proposed. The outcomes of the work can be summarized as follows. (1) An ARC-class tokamak minimizes the radiological hazard related to tritium inventories thanks to its compact size, and an optimal operational region has been identified by the fuel cycle model developed in this work. (2) The functional analysis and the FMEA allowed to draw a conceptual layout of the primary cooling system, and the thermal-hydraulic model of the primary cooling system can be exploited to build a database of safe and accidental transients. (3) Machine learning algorithms (especially deep neural networks) are effective tools to strengthen the safety analysis and to support operations and decision making. To further improve their applicability to nuclear safety analysis a framework to compensate the lack of data and the development of numerical simulation tools compatible with ML integrations is proposed.