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Changing the World's Energy Future

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Development and Validation of a Probabilistic Risk Assessment Model for a Generic Modular High Temperature Gas-Cooled Reactor

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Abstract

This study looks to develop and validate a probabilistic risk assessment (PRA) model for the modular high temperature gas-cooled reactor (MHTGR) using INL's Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) software. Validation against a General Atomics design involves matching event and fault trees to historical frequencies, with a goal of under 15% difference. The research aims to deliver a reliable PRA model to assess the safety of MHTGRs for use within high-temperature industrial applications.

Introduction

The concept of the modular high temperature gas-cooled reactor (MHTGR) primarily took shape in the 1980s (1). This innovative configuration of the MHTGR is engineered to depend minimally on active safety mechanisms. Instead, the reactor's core size, its geometric design, and chosen power density are strategically determined to enable decay heat to dissipate from the core through natural processes of radiation and conduction alone (2). Consequently, this design ensures that even in the event of a total loss of primary coolant, the core effectively contains radionuclides, preventing their significant release.

The following validation of the probabilistic risk assessment (PRA) of the MHTGR is based upon a generic design by General Atomics (GA) (2). The plant consists of four reactor modules connected in parallel to two turbine generators. Major components of each module include a reactor core made up of TRISO fuel in a prismatic hex-block configuration, steam generator, helium circulator, shutdown heat exchanger, and control rods.

Renewed interest in the MHTGR comes from the theorized exceptional safety and the potential coupling of thermal and electrical energy to an industrial facility. Preliminary evaluations of the very high temperature gas-cooled reactor configurations suggest achievable outlet temperatures reaching 900 °C, surpassing the 850 °C threshold necessary for standard thermochemical cycles (3).

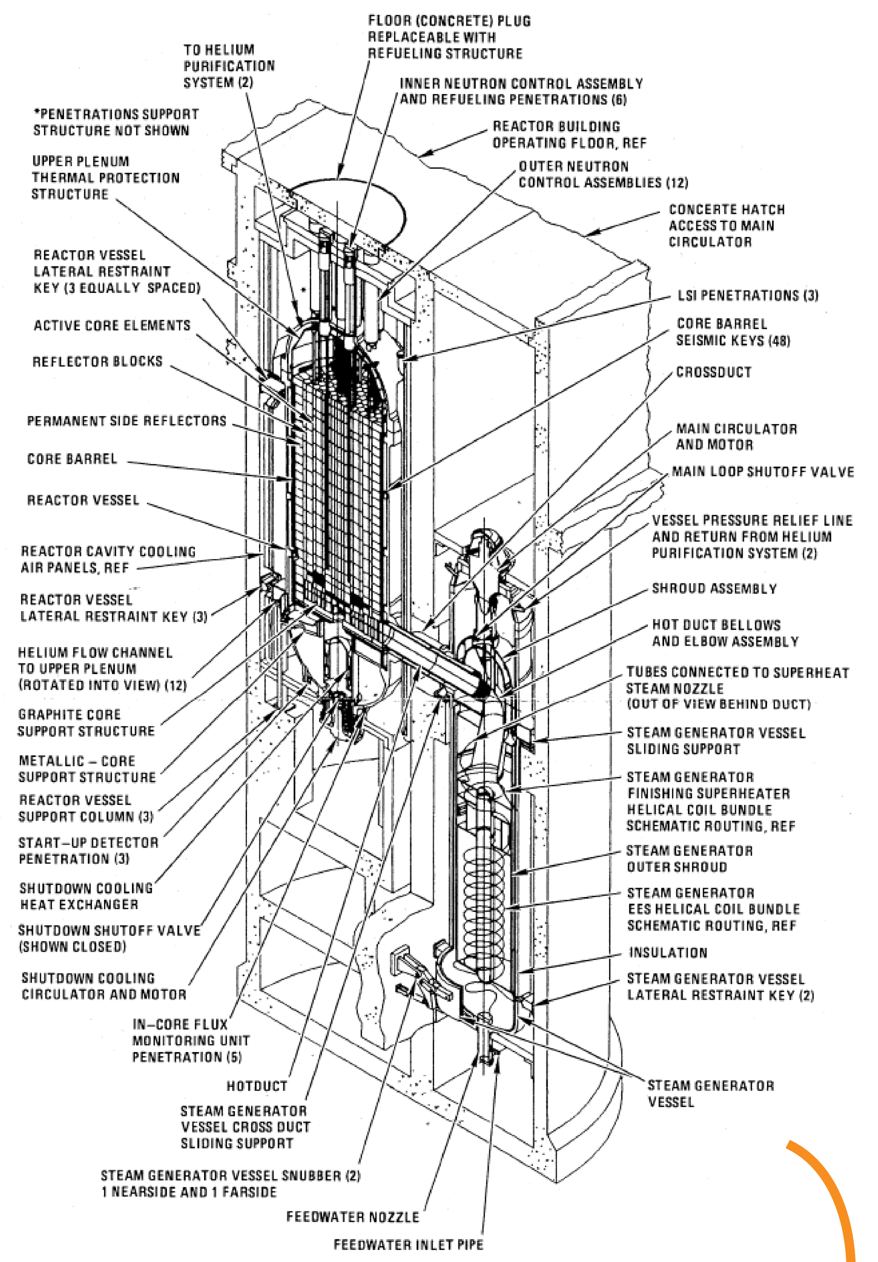

Fig 1. Single module of the MHTGR.

Objective

While PRA has previously been conducted for the MHTGR the foundational event and failure data used in these assessments are now considered outdated. Generic advanced reactor PRAs are required for research as to avoid propriety concerns and ensure that the reactor's safety is accurately evaluated using current data. It is imperative to develop and validate a new, computer-based PRA model that reflects the latest failure and safety information. This PRA is a representative design that will be modified to include modern passive safety features, once verification is complete.

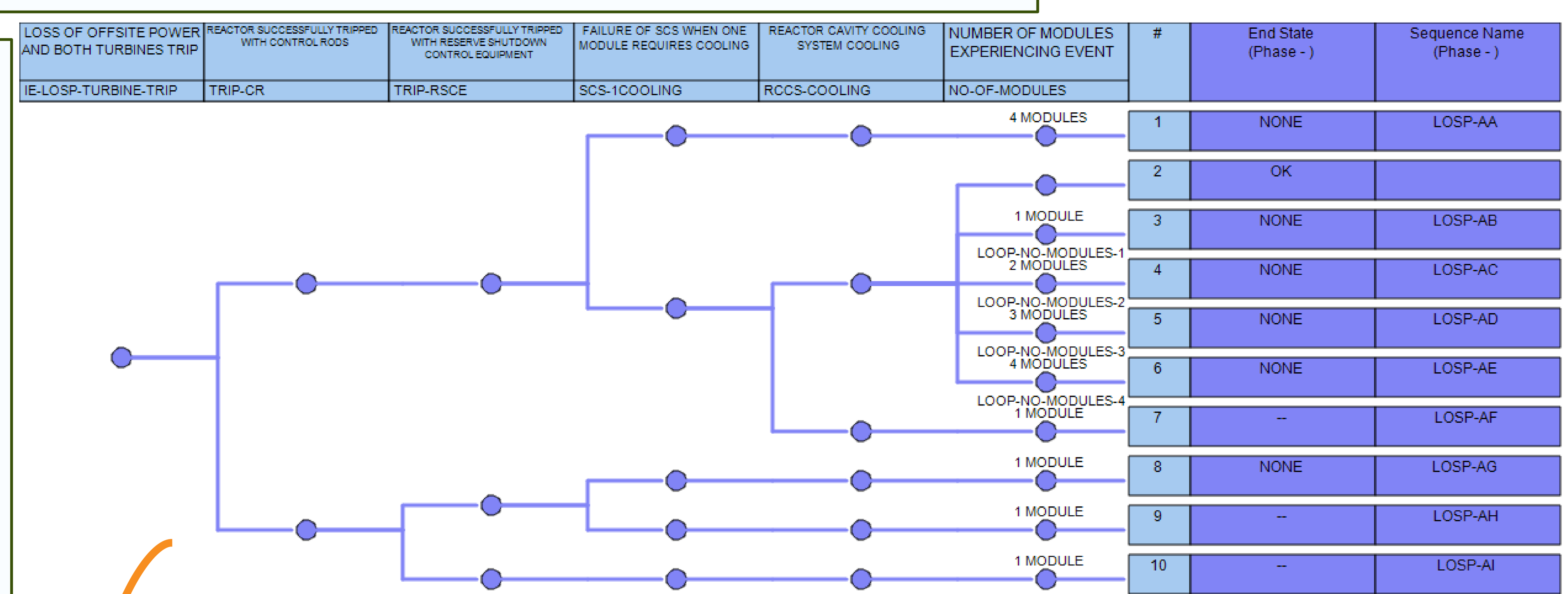

Fig 2. Event tree of the initiating event loss of offsite power.

Methodology

The selected model is based upon the MHTGR paper published by GA (2). Within the publication, event and fault trees are presented as they were used for their analysis, and final event frequencies were tabulated.

SAPHIRE is an INL developed PRA software, developed for the Nuclear Regulatory Commission, used primarily for existing nuclear power plants. Validation of the SAPHIRE model was performed by constructing GA's event and fault trees and quantifying the results. A simple absolute percent difference calculation was performed between GA's and SAPHIRE's frequency outputs, and the validation was considered successful if values were under 15%.

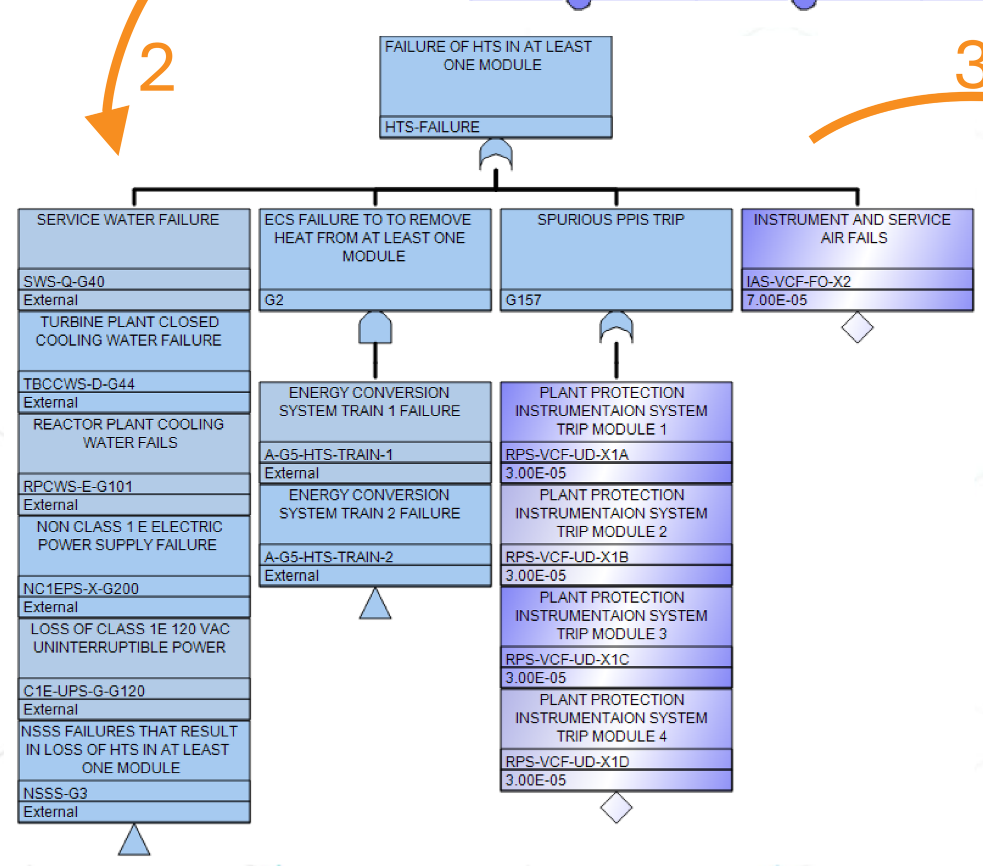

Fig 3. Fault tree of the heat transport system.

Top Event	Published Result	SAPHIRE Result	% Difference
Heat Transport System Failure	1.70E-01	1.81E-01	6.5
Shutdown Cooling System Failure	3.00E-02	2.82E-02	6.0
Intentional Depressurization Failure	1.00E-03	1.06E-03	6.0

Table 1. Comparison of top event probabilities published results versus those obtained from SAPHIRE.

1. Identify initiating events and sequences to failure or release of radionuclides.
2. Construct fault trees and input basic event data.
3. Determine event probability for event tree sequence quantification.

Validation

Basic event data was selected from tables included in GA's analysis as well as their cited sources. This was done to ensure proper validation and non-addition of current data. GA did not quantify event tree logic by simply assuming independence between each event. The publication also does not use simple point values, and repair times are included. Within the SAPHIRE model, care was taken to match appropriate mission times, repair times, and uncertainties using primarily lognormal distributions with 90% confidence intervals. A selection of results from the fault tree analysis is presented in **Table 1**.

Conclusion

The validation process for the PRA is currently underway, with essential work still pending. Difficulties have emerged, particularly in the selection of basic event data presented by GA and their interdependencies. In PRA, acknowledging the influence of system interdependencies on event tree outcomes is crucial. SAPHIRE adeptly factors in these dependencies, ensuring that the sequence of events is accurately reflected in the calculation of top event probabilities. Despite these challenges, substantial progress has been achieved, with most unvalidated sequences aligning closely—within 20%—of previously published results.

The aim is to establish a reliable model of a generic MHTGR suitable for integration with an industrial facility. The utilization of high-temperature steam from nuclear reactors in industrial processes is a concept that is gaining popularity. Given the enhanced safety features expected of the MHTGR, such an application is increasingly viable. This supports the Department of Energy's Integrated Energy Systems (DOE IES) program to evaluate the safety case of these industrial applications.

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