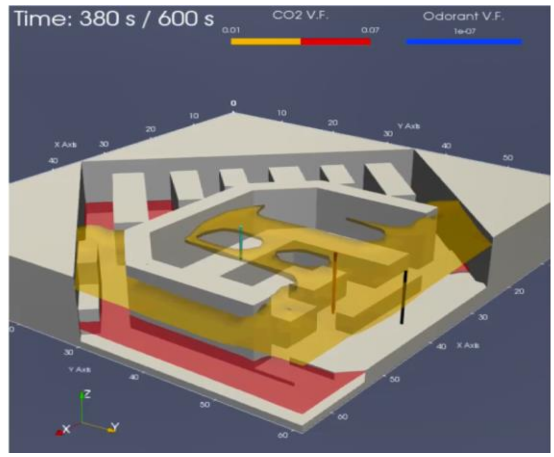
GOTHIC^{TM} for non-LWR Design & Analysis
Analysis Division

Introduction

GOTHIC is a versatile, general purpose thermal-hydraulics software package that includes a graphical user interface (GUI) for constructing analysis models, a numerical solver that includes parallel processing capabilities and a post-processor for evaluating simulation results. It solves the conservation equations for mass, momentum and energy for multicomponent, multi-phase flow in lumped parameter and multi-dimensional geometries (1, 2, or full 3D), including the effects of turbulence, diffusion and buoyancy. The diverse equation set allows GOTHIC to solve multi-physics problems and the flexible nodalization options allows GOTHIC to provide computationally efficient solutions for multi-scale applications.

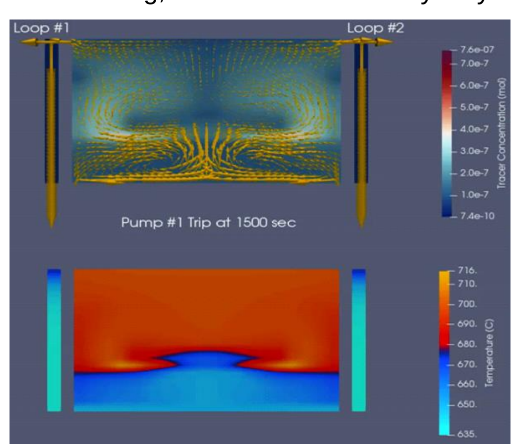


GOTHIC is an industry trusted tool for providing engineering solutions for a variety of applications to support the design, licensing, safety and operating analysis of nuclear power plant systems, containments and confinement buildings as well as spent fuel pools, spent fuel casks and waste storage tanks. GOTHIC has been used for design, licensing and safety analysis of existing plants, small modular reactors (SMR) and next generation plant designs. It has an established pedigree with verification and validation (V&V) covering a wide range of single and two-phase flow situations, which is documented and updated in the Qualification Report released with each version of the software. GOTHIC has been developed within a nuclear quality assurance (NQA) program that complies with 10CFR50, Appendix B and applicable parts of ASME NQA-1. Ongoing support and error reporting complies with 10CFR Part 21 requirements.

GOTHIC's lineage traces back to FATHOMS, COBRA-NC and COBRA-TF, but many enhancements and capabilities have been added over 30+ years of development that expand the code's applicability. GOTHIC has become a hybrid tool that bridges the gap between traditional system level thermal hydraulics analysis tools and computational fluid dynamics (CFD) analysis tools. GOTHIC's full treatment of the fluid-fluid shear as well as molecular and turbulent diffusion is consistent with that found in a CFD type code, except that GOTHIC relies on wall functions (*e.g.*, correlations for heat transfer coefficients and friction factors) rather than trying to resolve the boundary layer. As a result, GOTHIC can apply much larger computational cells than CFD type codes. The significant reduction in mesh density is one reason that GOTHIC is generally much more computationally efficient than CFD.

Non-LWR Design and Analysis

The fundamental physical models and capabilities available in GOTHIC make the software applicable for simulating many of the advanced, non-LWR concepts currently being considered. In addition to the treatment of fluid-fluid shear and turbulence, GOTHIC also includes conduction within the fluid and 2nd order accurate advection schemes to minimize numerical diffusion. These features allow GOTHIC to accurately simulate mixing, stratification and buoyancy-driven natural circulation of liquid or vapor in large open regions, which are particularly important for pool-type and high-temperature gas reactor (HTGR) designs. GOTHIC can also model jet mixing and wall-to-wall radiation heat transfer, both of which can be important in HTGRs.



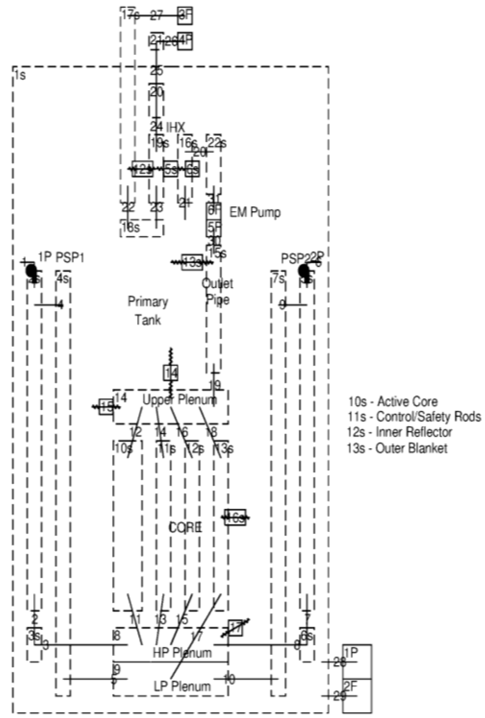
GOTHIC includes fluid properties for water (H_2O), sodium (Na), sodium-potassium (NaK) and several molten salts:

- $NaCl-MgCl_2$ (58.5%-41.5%)
- $LiF-BeF_2$ (67%-33%) - also referred to as FLiBe
- LiF-NaF-KF (46.5%-11.5%-42%) - also referred to as FLiNaK
- $NaF-ZrF_4$ (59.5%-40.5%)
- $KF-ZrF_4$ (58%-42%)
- $NaBF_4$-NaF (92%-8%)

The process developed by Zachry Nuclear to generate the fluid property files interfaces with NIST RefProp directly or can be used with a generic source to evaluate the fluid Equation of State (EOS).

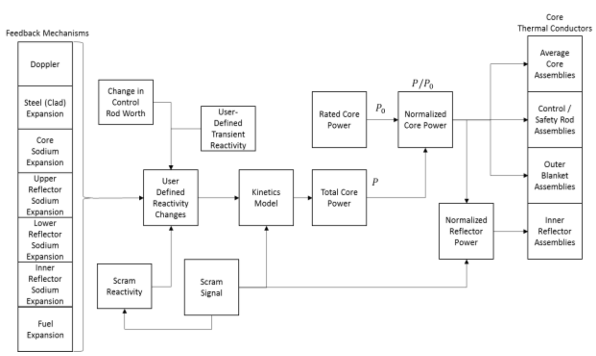
GOTHIC™ incorporates technology developed for the electric power industry under the sponsorship of EPRI, the Electric Power Research Institute.

GOTHIC Model of EBR-II

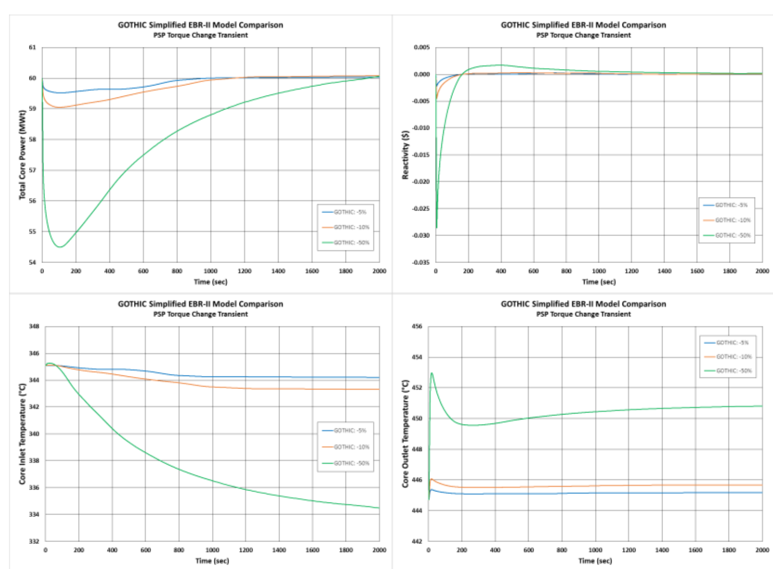


The Experimental Breeder Reactor II (EBR-II), located at the Idaho National Engineering Laboratory (INL) and operated by Argonne National Laboratory (ANL) for the US Department of Energy (DOE), was an evolutionary step toward a commercial-size fast breeder reactor. Sodium-cooled, the 62.5 MWt pool reactor was developed using metallic fuel rods, steel reflectors, and blanket assemblies. Two primary pumps transfer sodium from the pool to the core, through the electromagnetic (EM) pump and intermediate heat exchanger (IHX), and back to the pool. The core heat is transferred to the intermediate loop and ultimately to the steam generators on the secondary.

A simplified model of the EBR-II has been developed using publically available information to demonstrate GOTHIC's capabilities for non-LWR applications. Four channels are used to model the core to partition the core power between the active core (driver) assemblies, safety and control rod assemblies, inner reflector assemblies, and outer blanket assemblies. Power is applied as internal volumetric heat generation using GOTHIC's point reactor kinetics model, including reactivity feedback mechanisms shown in the figure below. Control systems are used to achieve target steady-state conditions as well as initiate transient simulations, including primary sodium pump speed changes and trips, EM pump changes, IHX secondary flow and inlet temperature upsets, control rod movement, and reactivity insertion.



GOTHIC's predictions for a 5%, 10% and 50% reduction in torque applied to one primary sodium pump are shown in the figure below. These results demonstrate the responsiveness of the GOTHIC model to rapid flow reduction transient with no control systems active (*i.e.*, constant IHX secondary inlet flow and temperature). The initial increase in core outlet temperature matches the flow reduction, causing a large negative reactivity feedback that significantly reduces core power. Core inlet temperature increases because the IHX heat removal remains high cooling the sodium pool. Core power level returns to approximately the steady-state value with the return to criticality from the reactivity feedback.

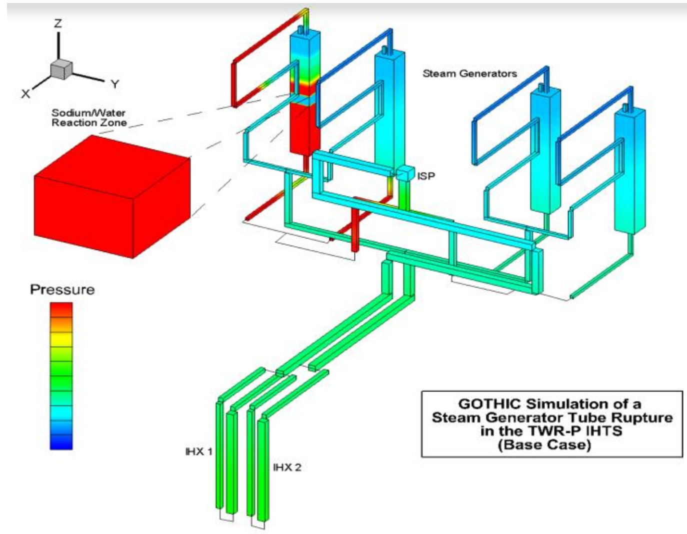


Transient simulations of various events are run using batch scripts and GOTHIC command files to automate model changes to simulate the different inputs needed (*e.g.*, pump torque vs. time, IHX flow and temperature versus time, trip activations). Development of these command files can be automated to perform sensitivity studies to evaluate the behavior to a series of plant upsets and ultimately automated responses.

A more detailed GOTHIC model of the EBR-II, which includes representations of the steam generator, feedwater inlet and steam outlet piping, as well as the shutdown cooling (SDC) system, has also been developed.

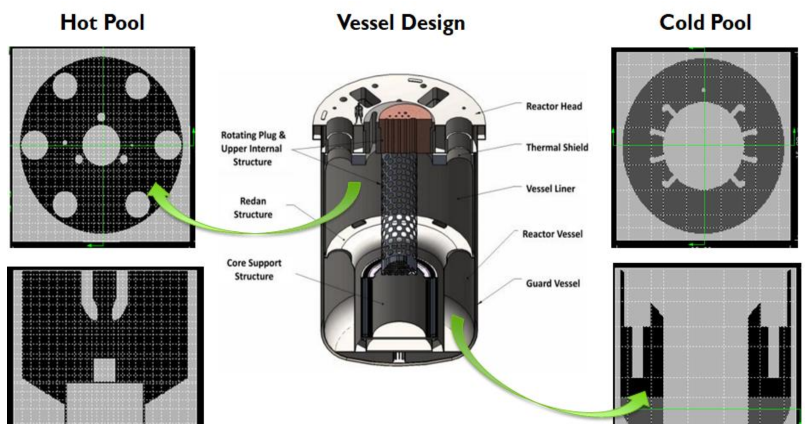
Benchmarks of this simplified GOTHIC model to SASSYS are planned.

Sodium-Cooled Reactor Design and Analysis

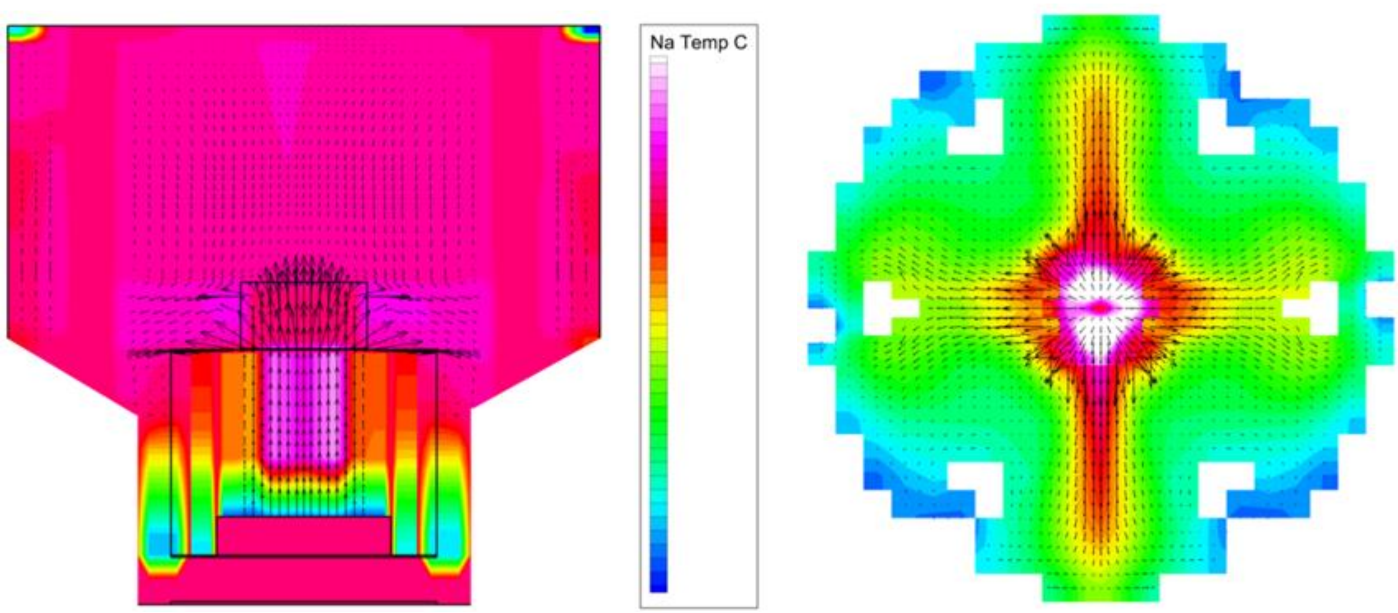


Zachry Nuclear's experience using GOTHIC for sodium-cooled reactor designs includes:

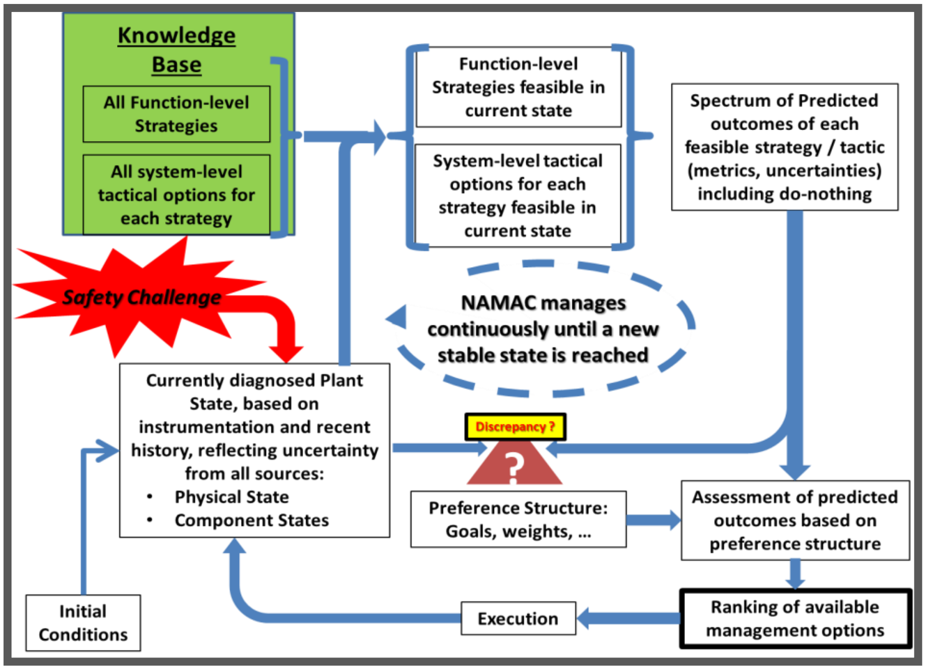
- Completed detailed GOTHIC model for Steam Generator Tube Rupture (SGTR) to examine pressure response and hydraulic loads throughout the system due to sodium-water reaction.
- Developed GOTHIC models of TerraPower's Traveling Wave Reactor (TWR) designs, including the primary and intermediate systems using sodium, the secondary-side of the steam generators using water, and the Direct Reactor Auxiliary Cooling System (DRACS) using NaK. These models were coupled using GOTHIC's Inter-process Communication (IPC) feature.
- Applied these models to evaluate flow patterns, determine loop transport time, determine air cooler requirements for the DRACS and assess various design features. GOTHIC was able to provide results that were not realizable with other system or CFD tools.
- GOTHIC has been benchmarked to Shut Down Heat Removal Test 17 (SHRT-17) from EBR-II, which represents a loss of flow due to a loss of electrical power to both the primary and intermediate-loop coolant pumps. This transient demonstrates the effectiveness of natural circulation cooling and GOTHIC compared very well with the available experimental data.
- Investigated sodium spray fires.



C. AHLFELD et. al., "Conceptual Design of a 500 MWe Traveling Wave Demonstration Reactor Plant," Proc. Int. Cong. Advances in Nuclear Power Plants (ICAPP), Nice, France, May 2-5, 2011, No. 11199 (2011).



DOE ARPA-E Project for Autonomous Control



The simplified GOTHIC EBR-II model has been used to support a DOE ARPA-E MEITNER Project that Zachry Nuclear is partnered with North Carolina State University to develop and demonstrate a nearly autonomous management and control system (NAMAC) for nuclear plants. NAMAC will be used to diagnose the plant state, project the effects of actions and uncertainties into the future behavior and make prioritized recommendations to the operator for the best strategy to cope with any situation with respect to plant safety, performance, and cost. A primary near-term goal for NAMAC is to improve plant safety by reducing operator errors, and promoting dynamic and effective management of abnormal transient and accident scenarios. Longer term goals will be to reduce operating costs and minimize the plant risk profile by affecting the system design, allowing SSC reclassification and reducing the EPZ. GOTHIC has been selected as the computational engine to satisfy the advanced modeling & simulation requirements of NAMAC. The simplified EBR-II model will be used to generate training data for the machine learning (ML) and artificial intelligence (AI) algorithms that will be used by NAMAC for diagnosis and decision making. GOTHIC will also be used as a plant simulator that can react to recommended actions and mitigation strategies. Zachry Nuclear believes NAMAC is vital to the nuclear industry and is proud to be at the forefront of developing and commercializing this technology.

Other Experience

Zachry Nuclear has performed GOTHIC simulations for a generic Molten Chloride Fast Reactor (MCFR) and a helium cooled HTGR. This work focused on physical processes and phenomena that are important in these designs, including thermodynamic and transport properties as well as the ability to represent relevant geometry and components. GOTHIC includes a neutron point kinetics model for simulation of in-core reactor kinetics and for spent fuel modeling. Recent enhancements have been made to GOTHIC for molten salt designs, including an option to specify decay heat that is released throughout the system from flowing fuel due to radioactive decay. These features were used to simulate source terms and fission product transport following a leakage event, including release to the environment, for a molten salt reactor design that uses flowing fuel. Further development to support flowing fuel designs is in-progress, but GOTHIC's ability to model flowing fuel and associated heat release has been proven.

Conclusions

GOTHIC is a computationally efficient thermal-hydraulic analysis tool that includes both system level and CFD-like attributes. The software provides an integrated analysis environment that allows for fast, flexible creation or modification of models. It is an industry trusted tool with an established QA pedigree that is capable of modeling both LWR and non-LWR designs, with demonstrated experience for sodium-cooled reactor design and analysis.

Contact Information

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