Benchmarking GOTHIC to the Molten Salt Reactor Experiment

Rodney Harvill, Jeff Lane, John Link, Anita Gates
Zachry Nuclear Engineering, 200 Regency Forest Drive, Suite 330, Cary, NC 27518
harvillr@zachrynuclear.com
https://dx.doi.org/10.13182/T31153

INTRODUCTION

The Molten Salt Reactor Experiment (MSRE), an outgrowth of the aircraft reactor program, was a proof-of-concept liquid-fueled, graphite-moderated, thermal reactor which operated at Oak Ridge National Laboratory from 1965 to 1969. The fuel, UF4, was dissolved in fluoride salt maintained in the liquid phase and circulated through the fuel salt loop, as shown in Fig. 1. Criticality could be achieved only in the graphite-moderated core. Heat generated in the core by fission and throughout the fuel salt loop by decay of fission products was transferred out of the fuel salt loop via a heat exchanger into a coolant salt loop, which then rejected heat to the environment through an air-cooled radiator.

This paper documents a benchmark of the fuel salt loop using GOTHIC. GOTHIC™ is a 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. The GOTHIC model of the MSRE applies reactor power using GOTHIC's neutron kinetics feature and decay heat throughout the fuel salt loop is accounted for using GOTHIC's tracer capability, which can track any number of isotopes with a user specified decay heat and progeny. The GOTHIC predictions are compared to available experimental data herein.

DESCRIPTION OF THE MSRE

Shown in Fig. 1, the MSRE was designed to operate at 10 MWt, but was limited to 8MWt by the design of its radiator. The temperatures shown in Fig. 1 are based on the design power of 10 MWt. Fuel salt with a flow rate of 75.7 l/s (1,200 gpm) enters the reactor vessel at a temperature of 908.2 K (1,175°F) and leaves it at a temperature of 935.9 K (1,225°F). The fuel salt is LiF-BeF_2-ZrF_4, with the fuel dissolved as UF_4. A heat exchanger transfers into a cooling loop the fission heat generated in the core and the decay heat generated in the fuel salt. LiF-BeF_2 coolant salt at a flow rate of 53.6 l/s (850 gpm) enters the heat exchanger at a temperature of 824.8 K (1,025°F) and leaves it at a temperature of 866.5 K (1,100°F). Heat is transferred from the coolant salt loop to the environment via a radiator, through which air at a flow rate of 94,389.5 l/s (200,000 cfm) enters at a temperature of 310.9 K (100°F) and exits at a temperature of 422.0 K (300°F) [2]. The reactor vessel and piping were constructed from Hastelloy-N, a nickel-molybdenum-chromium alloy specifically developed for compatibility with the fluoride salts used in the MSRE.

During the design phase of the MSRE, two scaled test facilities were built for hydraulic studies using water, rather than molten salt, as the working fluid. The first, a fifth-scale facility, showed that axial velocity within the flow channels in the core was a function of radial position, primarily resulting from geometric factors at the core inlet [3]. The second, a full-scale facility was almost an exact duplicate of the reactor vessel and used to measure the velocity and pressure distribution within the reactor vessel. The flow rate was 75.7 l/s (1,200 gpm), consistent with the MSRE, and the temperature range was 297.0 K (75°F) to 299.8 K (80°F) [4].

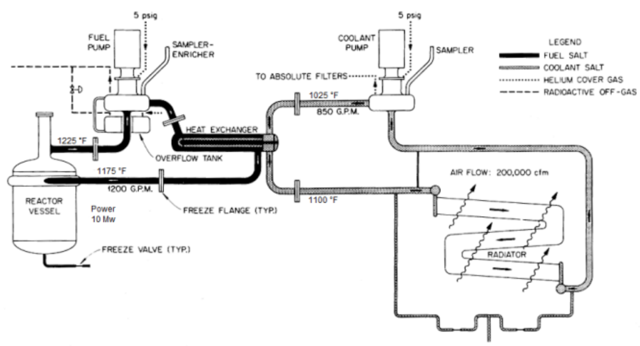

Fig. 1. Flow Diagram of the MSRE (From Fig. 1 of [1])

GOTHIC FOR NON-LWR APPLICATIONS

GOTHIC 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. It also includes the ability to track different types of materials in the flow, including radioactive isotopes, solid particles and dissolved gas.

GOTHIC bridges the gap between traditional system level thermal hydraulics analysis tools and computational fluid dynamics (CFD) analysis tools. GOTHIC includes a full treatment of the fluid-fluid shear as well as molecular and turbulent diffusion, which is consistent with what would be found in a CFD type code. GOTHIC also considers conduction within the fluid and includes 2nd order accurate advection schemes to minimize numerical diffusion. Still, GOTHIC includes the same types of features and capabilities provided by traditional system level codes, including:

- Component models for plant equipment such as pumps/fans, valves/doors, heat exchangers, fan coolers, vacuum breakers, pressure relief valves, spray nozzles, coolers and heaters, hydrogen

recombiners and ignitors, filters and sump strainer, and dryer/demisters
- Point neutron kinetics model
- Control system capability and trips

GOTHIC 8.3(QA), which represents the latest release of the software, includes a generic fluid property framework that allows the software to be used for non-LWR applications. The fluid property tables can be generated using data from NIST RefProp or using a stand-alone program to evaluate the Equation of State (EOS). GOTHIC 8.3(QA) includes property tables for water as well as property tables for six molten salts (NaCl-$MgCl_2$, LiF-BeF_2, LiF-NaF-KF, NaF-ZrF_4, KF-ZrF_4 and $NaBF_4$-NaF. A series of verification problems were prepared for each molten salt to confirm the fluid properties were implemented properly. A representative result is shown in Fig. 2, where the GOTHIC predictions are shown as solid lines and the symbols show the underlying data. These figures confirm that the temperature dependent liquid properties implemented in GOTHIC accurately represent the available data. Additional details about recent modifications to GOTHIC to support non-LWR applications can be found in [7].

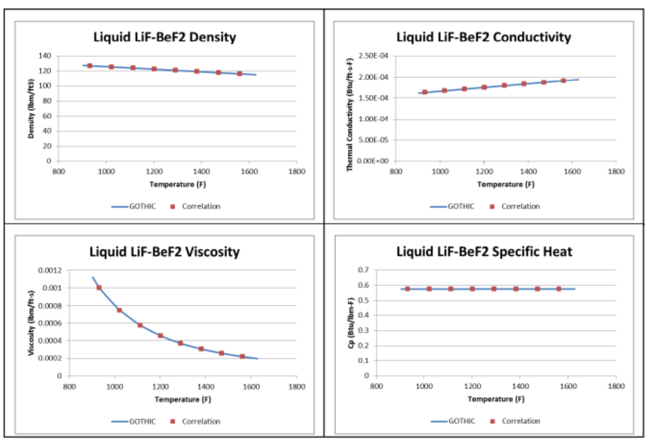

Fig. 2. LiF-BeF_2 Liquid Property Comparisons

GOTHIC BENCHMARK TO FULL-SCALE TEST FACILITY

Shown in Fig. 3, the GOTHIC model of the full-scale facility uses subdivided control volumes to represent the downcomer and core regions and lumped control volumes to represent the rest of the reactor vessel and outlet pipe. The z-axis grid lines in the downcomer and core control volumes are spaced such that their elevations match. A flow boundary condition injects 75.7 l/s (1,200 gpm) of water into the reactor vessel, and water exits the vessel into a pressure boundary condition connected to the outlet pipe. A control volume is placed between the flow boundary condition and the inlet volute for purposes of calculating the differential pressure across the vessel. As noted above, the fifth-scale facility demonstrated a radial velocity distribution in the core, and five radial core regions were identified. The GOTHIC model utilizes four control volumes to model four core regions based on the results of the fifth-scale facility studies, with the outer two regions from the fifth-scale facility combined into the fourth core region in the GOTHIC model.

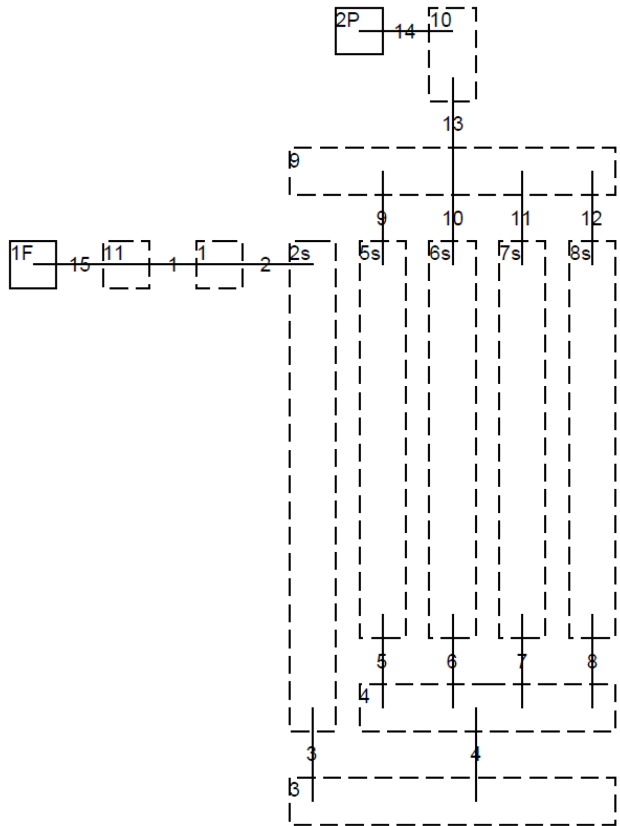

Fig. 3. GOTHIC Model of the Full-Scale Facility

Core region velocities are available for the fifth-scale facility [3]. Furthermore, core and reactor vessel differential pressures and velocities are available for a water flow rate of 75.7 l/s (1,200 gpm) at other locations in the full-scale facility [4]. Table I compares the experimental values with values calculated in the GOTHIC model of the full-scale facility for water at a temperature of 299.8 K (80°F). In general, there is very good agreement. There is, however, a significant difference between the experimental and predicted velocity at the bottom of the downcomer. The orifices between the inlet volute and the downcomer are at an angle to cause the fluid to swirl around the core container rather than flow straight down. The model currently does not include the swirl effects, and the calculated velocity represents flow straight down the annular region of the downcomer.

TABLE I. Comparison of Experimental and GOTHIC Predicted Results for the Fifth-Scale and Full-Scale Tests

Variable	Experimental	GOTHIC Predicted
V, inlet pipe (5 in. ID)	5.85 m/s (19.2 ft/s)	5.85 m/s (19.2 ft/s)
V, bottom of downcomer	1.68 m/s (5.5 ft/s)	0.64 m/s (2.1 ft/s)
V, core region 1	0.607 m/s (1.99 ft/s)	0.588 m/s (1.93 ft/s)
V, core region 2	0.18 m/s (0.60 ft/s)	0.18 m/s (0.58 ft/s)
V, core region 3	0.454 m/s (1.49 ft/s)	0.442 m/s (1.45 ft/s)
V, core region 4	0.23 m/s (0.76 ft/s) Composite value	0.23 m/s (0.74 ft/s)
ΔP, core	1.79 kPa (0.6 ft)	1.79 kPa (0.6 ft)
ΔP, vessel	44.6 kPa (15 ft)	44.6 kPa (15 ft)

Note - Velocities in this table are from the fifth-scale facility and the pressure drops are from the full-scale facility.

GOTHIC BENCHMARK TO MSRE DESIGN

Shown in Fig. 4, the GOTHIC model of the MSRE was then modified to add a fuel salt piping loop, a coolant salt loop and a radiator to the reactor vessel model components developed for the full-scale model. Thermal conductors model structural elements such as the reactor vessel shell and internal structure, the graphite moderator, piping, pump casings and the shell of the heat exchanger. Thermal conductors also transfer fission heat into the core. A pressure boundary condition maintains a 149.6 kPa (7 psig) pressure at the reactor vessel outlet, and another maintains a 584.0 kPa (70 psig) pressure at the discharge of the coolant salt pump. Volumetric pumps maintain the 75.7 l/s (1,200 gpm) fuel salt flow rate and the 53.6 l/s (850 gpm) coolant salt flow rate. A shell and tube heat exchanger component transfers heat between the fuel salt and coolant salt loops. The fuel salt loop functions as the primary side. A fan cooler heat exchanger component transfers heat out of the coolant salt loop. LiF-BeF_2 fluid properties are used for the fuel salt and coolant salt loops. GOTHIC's neutron kinetics model, in conjunction with control variable logic to account for various reactivity feedback effects (e.g., temperature coefficients, etc.), deposits fission heat into both the moderator and fuel salt in the core in the form of thermal conductor internal heat generation rates.

All fission heat is modeled exclusively in the core, neglecting the insignificant fission heat generation in fuel salt adjacent. Seven percent of the 10 MWt thermal power is modeled as decay heat by employing the eleven decay heat precursor groups from ASB 9-2 [6] in the form of tracer groups. The model is initialized with tracer concentrations representative of a long-duration full-power run, and tracers are added to model decay heat precursor generation by fission.

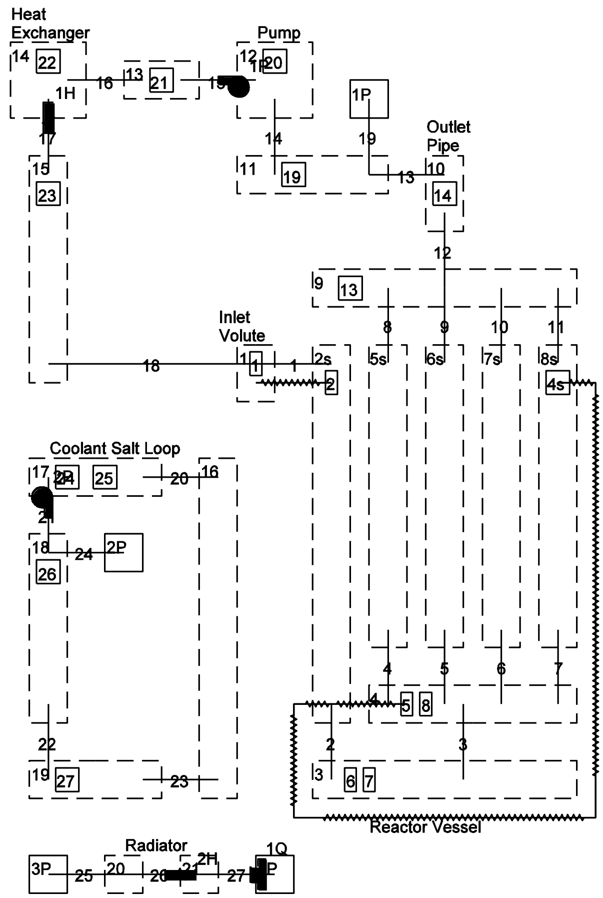

Fig. 4. GOTHIC Model of the MSRE

RESULTS

The experimental parameters consist of system temperatures from [3], density and specific heat capacity for 93% enriched uranium from [2] as specified in [3] and the percent of power deposited in the graphite moderator, as described in [3]. Table II compares the experimental and predicted values along with other relevant results. In general, the GOTHIC model yields good agreement with the experimental parameters. There is some difference in the maximum fuel and graphite temperatures, but this is to be expected since the experimental peak temperatures are point values at a radial location, while the predicted temperature represents the average value of a region of the core. The temperatures from [3] were calculated assuming that the entirety of the thermal power would be in and around the core. Because the GOTHIC model accounts for decay heat in the fuel salt, the GOTHIC model temperatures show heat-up due to decay heat in the fuel salt outside the core.

TABLE II. Comparison of Experimental and GOTHIC Predicted Results for the MSRE

Variable	Experimental	GOTHIC Predicted
Power (MW_t)	10	10
Vessel Inlet Temperature	908.2 K (1,175°F)	908.8 K (1,176.1°F)
Core Inlet Temperature	N/A	909.2 K (1,176.8°F)
Core Outlet Temperature	N/A	935.9 K (1,225.0°F)
Vessel Outlet Temperature	935.9 K (1,225°F)	935.9 K (1,225.0°F)
Heat Exchanger Inlet Temperature (°F)	N/A	936.3 K (1,225.5°F)
Heat Exchanger Outlet Temperature (°F)	N/A	908.7 K (1,176.0°F)
Fuel Salt Flow	75.7 l/s (1,200 gpm)	75.7 l/s (1,200 gpm)
Density at 922 K (1,200°F)	2,082 kg/m^3 (130 lb$_m$/ft$^{3)}$	1,964 kg/m^3 (122.6 lb$_m$/ft^3)
Specific Heat Capacity at 922 K (1,200°F)	2.008 kJ/kg·K (0.48 Btu/lb$_m$°F)	2.427 kJ/kg·K (0.58 Btu/lb$_m$°F)
Maximum Fuel Temperature	956.2 K (1,261.5°F)	943.7 K (1,238.9°F)
Maximum Graphite Temperature	975.4 K (1,296°F)	947.4 K (1,245.6°F)
Graphite Power	6.7%	6.7%
V, inlet pipe (5 in. ID)	N/A	5.82 m/s (19.1 ft/s)
V, core region 1	N/A	0.594 m/s (1.95 ft/s)
V, core region 2	N/A	0.18 m/s (0.58 ft/s)
V, core region 3	N/A	0.439 m/s (1.44 ft/s)
V, core region 4	N/A	0.22 m/s (0.73 ft/s)
ΔP, core	N/A	120.0 kPa (20.4 ft)
ΔP, vessel	N/A	2.0 kPa (0.34 ft)

The GOTHIC MSRE model currently tracks 11 different neutron precursor groups. The concentrations at two different locations within the MSRE fuel salt loop (core region and loop piping regions) for selected groups are shown in Table III. Consistent with expectations, the shorter-lived tracer groups have a lower concentration in the loop than in the core due to decay during loop transit, while the longer-lived tracer groups lose little to no concentration through decay while in transit (nearly uniform distribution). These results demonstrate GOTHIC's ability to track the time/location dependent distribution of neutron precursor groups, including decay heat, which is very important to the prediction of molten salt reactor designs with flowing fuel.

TABLE III. GOTHIC Predicted Steady-State Tracer Group Concentrations in the MSRE Fuel Salt

Precursor Group	Half-Life (s)	Concentration (mol/m^3)	
		Core	Piping
2	1.2	5.23E-6	4.85E-9
4	111.5	4.90E-5	4.35E-5
9	6.691E+6	2.69E0	2.69E0

CONCLUSIONS

GOTHIC is general-purpose thermal-hydraulic analysis tool that includes attributes of both system level and CFD-like analysis tools. This makes the software applicable to a wide-range of applications for both LWR and non-LWR designs. Also, GOTHIC includes a tracer capability to track radioactive isotopes and decay heat in flowing fuel that occurs outside the core region.

In this work, GOTHIC models of the MSRE and full-scale hydraulic test facility show good agreement with available design and experimental data for the MSRE. Future development is planned to modify the neutron kinetics in GOTHIC to account for delayed neutron precursor drift and reactivity feedback due to changing fuel salt composition.

ENDNOTES

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

REFERENCES

1. P.N. Haubenreich and J.R. Engel, Experience with the Molten Salt Reactor Experiment, Nuclear Applications & Technology, Vol. 8, February 1970.
2. R.C. Robertson, MSRE Design and Operations Report, Part I, Description of Reactor Design. Technical Report, Oak Ridge National Laboratory, Oak Ridge, TN, 1965, ORNL-TM-728.
3. J.R. Engel and P.N. Haubenreich, Temperatures in the MSRE Core During Steady-State Power Operation. Technical Report, Oak Ridge National Laboratory, Oak Ridge, TN, 1962, ORNL-TM-378.
4. R.J. Kedl, Fluid Dynamic Studies of the Molten-Salt Reactor Experiment (MSRE) Core. Technical Report, Oak Ridge National Laboratory, Oak Ridge, TN, 1970, ORNL-TM-3229.
5. *GOTHIC Thermal Hydraulic Analysis Package, Version 8.3(QA)*. EPRI, Palo Alto, CA: 2019.
6. NUREG-0800, Revision 2, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, LWR Edition, Section 9.2.5, Ultimate Heat Sink, Branch Technical Position ASB 9-2.
7. Lane, J.W., George, T.L., Claybrook, S.W., Zankowski, J.A., Kindred, T., Applicability of GOTHIC 8.3(QA) for Non-LWR Simulation, Aerosol Modeling & Hydrogen Management, NURETH-18. ANS, Portland, USA, Paper 30292, 2019.