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Changing the World's Energy Future

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ABSTRACT

Fusion energy research is growing quickly, responding to a worldwide need for clean, sustainable, baseload-capable sources of energy. According to some experts, a fusion pilot power plant could even be capable of delivering power to the grid by the 2040s. To achieve this aggressive goal, however, strong investment in safety systems and analysis is required to ensure new materials, device concepts, and technologies are both effective and safe for the public. Idaho National Laboratory (INL) has performed research on fusion safety for over 45 years, and the laboratory took part in the design and analysis of many fusion concepts, including the Advanced Research Innovation and Evaluation Study (ARIES), Compact Iginition Tokamak, and ITER. This history is discussed through the lens of electromagnetic simulation tools—Magnetic System Circuitry Analysis Program (MSCAP) and MAGARC (a portmanteau of "magnet arcing")—developed to evaluate superconducting magnets for fusion tokamaks. To achieve the goal of rapid commercial deployment, the fusion community will need to draw on and learn from this large body of work and apply it to new computing paradigms and modern supercomputers. To update INL's legacy for such an effort, ongoing and planned research will use the Multiphysics Object-Oriented Simulation Environment (MOOSE)—a multiscale, multiphysics framework originally developed for nuclear fission reactor simulation—to design and develop future fusion concepts.

Keywords: Fusion, computational electromagnetics, MSCAP, MAGARC, MOOSE

1. INTRODUCTION

Fusion energy research and development proceeds at an ever-increasing rate, spearheaded and promoted by governments and the fusion industry as an answer to a global requirement for clean, sustainable, baseload-capable sources of energy. The proposed timelines are bold; the United States Department of Energy (U.S. DOE) Fusion Energy Strategic Advisory Committee (FESAC), in their recent long-range report, set a goal of a fusion pilot plant (FPP) by the 2040s [1]. In this same report, FESAC also asserted that such an FPP would require significant advances in modern safety systems and that strong theory and computational programs focused on highly coupled multiphysics models will be required to effectively predict the performance and behavior of new fusion concepts. DOE's national laboratories have been at the forefront of research in this space for over 70 years, and it is vital to learn and draw from such a large body of work as the fusion energy research community moves into a new age of rapid, iterative design and possible commercial deployment.

What became the Idaho National Laboratory (INL) Fusion Safety Program (FSP) was established in 1979 by the U.S. DOE to lead fusion safety research in the DOE laboratory complex. The program, then at

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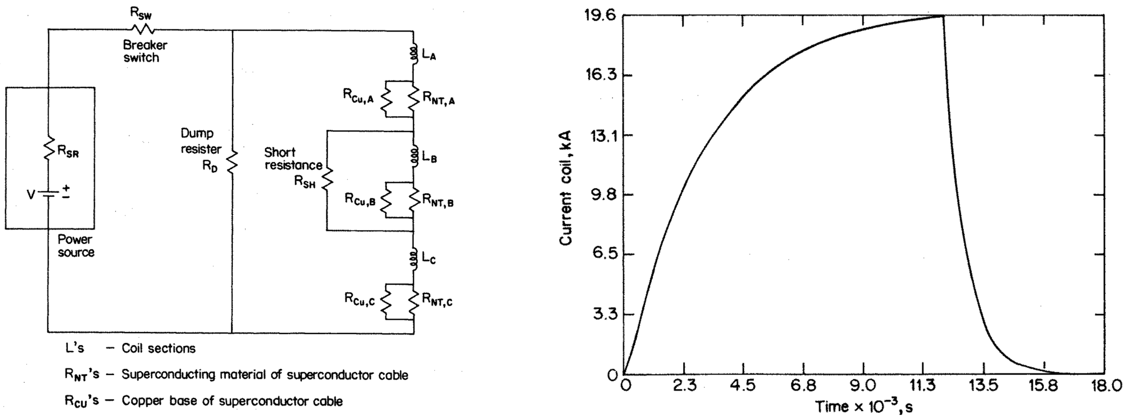
the Idaho National Engineering Laboratory (INEL), was charged with the following broad objectives: "(1) assist DOE in the management of the Fusion Reactor Safety Research Program, and (2) provide timely information to support fusion power development" [2]. To that end, the INEL FSP focused on a number of research areas: tritium handling and safety; activation product generation, control, and release; lithium safety considerations; magnet safety concerns for magnetic confinement fusion (MCF); plasma and coolant disturbances; auxiliary heating safety concerns; cryogenic, vacuum, and electrical safety; toxic materials; accident and safety analysis techniques; safety in design (of codes and standards, quality assurance); and waste management [3]. Over the next 45 years, the FSP continued to carry out research in these areas, with new experimental facilities—in particular the world-renowned Safety and Tritium Applied Research (STAR) Facility [4]—and modeling and simulation capabilities that have covered a wide range of systems, including system-level thermal hydraulics and fluid flow [5, 6], tritium migration [7, 8, 9], chemistry [10], plasma disruptions [11], and electromagnetics [12, 13].

This paper will focus most of its discussion on a review of magnet safety modeling and simulation efforts undertaken by the INL FSP. Specifically, it will describe the modeling of the electrical systems and electromagnetic configurations for modern superconducting magnets using the Magnetic System Circuitry Analysis Program (MSCAP) and MAGARC (a portmanteau of "magnet arcing") codes in Section 2 and Section 3, respectively. In Section 4, discussion will then move to ongoing and future projects continuing and expanding these legacy efforts within the INL-developed Multiphysics Object-Oriented Simulation Environment (MOOSE) framework [14], with the end goal of enabling whole device modeling and digital twin development of fusion energy systems and concepts.

2. SIMULATION OF MAGNET CIRCUIT AND ELECTRICAL SUPPLY EQUIPMENT TRANSIENTS USING MSCAP (1985)

The underlying methodology for MSCAP was developed by Kraus and Jones of the INEL FSP in 1985. It focused on the study of normal and off-normal electrical events for superconducting magnets in MCF systems [15, 16]. At the beginning, this effort emphasized so-called nonlinear, fast-response transients, such as impacts from electrical system disruptions/instabilities and internal magnet shorts and arcs. The significant amount of stored energy within these magnets—for example, up to 41 GJ for the ITER toroidal field (TF) magnet [17]—can lead to a catastrophic rapid failure of both the magnet and the surrounding structures and systems. The first version of the code, Mod 0, was a hybrid finite difference/finite element code, capable of modeling transient circuit components (e.g., voltage sources, resistors, capacitors, and inductors) based on Kirchoff's voltage loop and current node laws [16, 18]. Figure 1 shows an MSCAP example of a simplified circuit representing a TF coil charge and discharge system alongside MSCAP simulation results of coil current over time for a "slow dump" (meaning small dump resistance, R_D, in Figure 1a) transient after a magnet short.

Even early on, MSCAP was used for safety evaluation and testing for design studies of domestic fusion concepts, including the Advanced Research Innovation and Evaluation Study (ARIES) design program [19] and the Compact Ignition Tokamak [20], as well as part of experimental studies abroad, including the TESPE toroidal magnet set at Kernforschungszentrum Karlsruhe (now Karlsruhe Institute of Technology [KIT]) [21]. In 1990, a new version of the code, Mod 1, was released. This had several improvements over the original version, including improved voltage calculations for inductors, a code restart capability, current source elements, circuit element power and energy output, improved equation assembler output, and other user-experience improvements [22]. Collaborations with KIT using MSCAP continued into the 1990s as the code became a component of the MAGnet System (MAGS) code [23] to study magnet quenching (a concept discussed in more detail in Section 3). MAGS/MSCAP was later used through the 1990s and 2000s as part of the ITER safety basis in the TF model coil project [24, 25, 26].



(a) Simplified tokamak TF coil circuit. **(b) Coil current vs. time for a "slow dump" transient.**

Figure 1. MSCAP analysis of a tokamak superconducting magnet protection circuit, from [16]. © 1986 by John Wiley and Sons, Ltd and reprinted with permission from the publisher.

3. UNMITIGATED THERMAL QUENCH EVENT MODELING IN FUSION MAGNETS USING MAGARC (1999)

Superconducting materials, where the operating electrical resistivity is near zero, only remain superconducting in a small range of temperatures, magnetic fields, and currents. As an example, the ITER TF coil conductor operates in the 7–8 K range in a high-magnetic-field region of the coil and up to 15 K in the low-field region [27]. A significant potential safety case for superconducting magnets is the magnet thermal quench event. This occurs when a portion of a superconducting material falls outside of this ideal region and transitions from a superconducting state to that of a regular conductor with finite resistivity. Because of the high magnet currents, the material can then warm quickly via resistive heating. Examples of the causes of a quench include cracked or compromised conductor insulation, electrical system faults, or changes in magnetic flux or heat deposition due to plasma operation [28, 13]. Mitigation of a quench focuses on either routing current around the quench region using a stabilizer conducting material (such as copper) with a lower resistivity than the superconductor in its normal conductor state, thereby cooling the superconductor material and allowing it to return to a superconducting state, or rapidly discharging the stored energy in the coil using an auxiliary system. An unmitigated quench occurs when the quench is otherwise undetected because of safety system failures, and heating occurs rapidly (copper stabilizers can melt within 30-40 seconds). In the localized quench region, coil current would then arc between solid regions of the stabilizer, leading to more localized heating and further melting, expanding the quench region quickly. The quench would halt when the magnetic energy is dissipated or when the arcs leave the magnet through the magnet leads. The molten material generated by the event could impinge on the vacuum vessel or cryostat, potentially leading to a failure of safety containment barriers. During the ITER Engineering Design Activity (EDA), it was determined that an unmitigated thermal quench was extremely unlikely (frequency less than 1×10^{-6} per year) as a possible accident scenario [27, 29].

However, considering the high stored magnet energy (10s of GJ) and possibility of severe damage to the ITER safety containment barriers should the accident occur, it needed to be investigated. In 1999, the (now) Idaho National Engineering and Environmental Laboratory (INEEL) FSP developed a modeling capability to investigate the consequences of such an accident—MAGARC [30]. It contained several multidimensional, multiphysics, coupled models—three-dimensional heat conduction for the thermal response of radial plates, coil casing, and insulation; quasi-two-dimensional heat conduction to model the conductor of the superconducting cable; a three-dimensional resistive circuit model for the radial plates (structures that hold the conductors in place) and coil case to simulate arcing behavior; and a one-dimensional coolant flow model using helium. Example output of the MAGARC code circa the year 2000 is shown in Figure 2, where an unmitigated quench is modeled at a location farthest away from the magnet leads; there is no external helium cooling, which was identified by Merrill as the most conservative study case [30]. It is important to note the representation shown in Figure 2a for clarity; the MAGARC calculation of the radial plate heat conduction model was performed on a three-dimensional regular rectangular grid, where each node—in i, k, j coordinates rather than the traditional Cartesian coordinates in x, y, and z—is mapped to their physical location on the D-shaped TF magnet geometry.

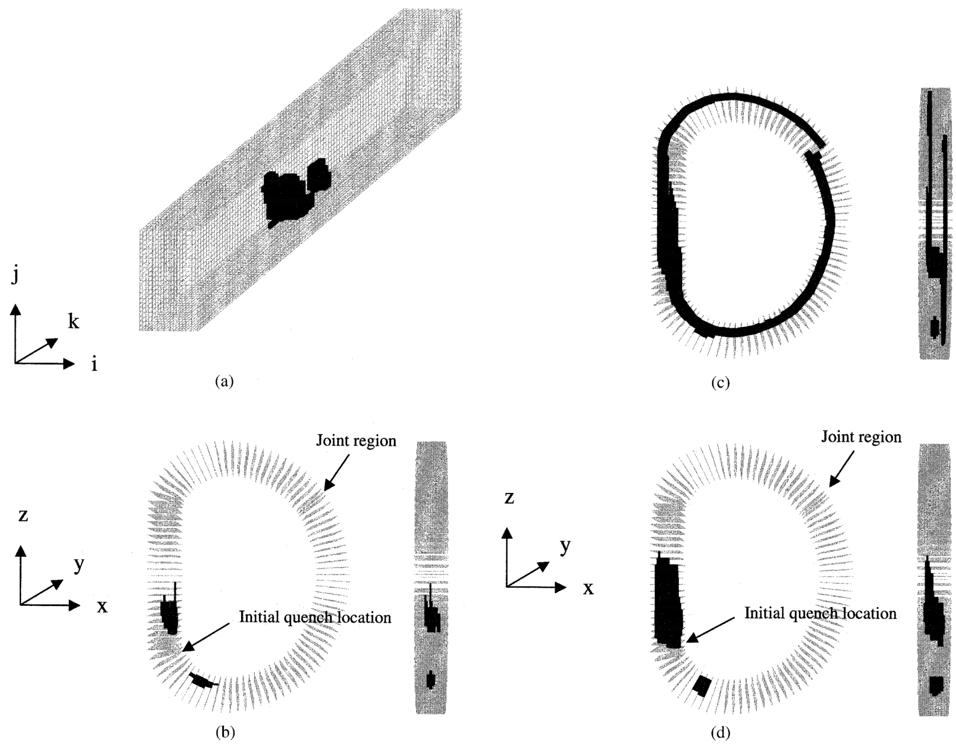


Figure 2. Early MAGARC analysis of an ITER TF coil undergoing an unmitigated thermal quench event: (a) 50 s (regular grid), (b) 50 s (magnet geometry), (c) 300 s, and (d) 7115 s, from [30]. Reprinted with permission of the publisher (Taylor & Francis Ltd, https://www.tandfonline.com).

MAGARC was used as part of the ITER magnet safety assessment and EDA on several occasions from 2004 to 2016, with improvements made to MAGARC to model the TF and poloidal field (PF) coil of the 2003 ITER design, add models for insulation failure behavior, and apply the code to more accident scenarios identified by ITER International Organization. These were completed by 2009 [31]. In 2015, a similar unmitigated quench analysis of an updated MAGARC code was performed on the DEMO (post-ITER demonstration power plant) concept, using a new arcing behavior model based on Maxwell's equations [13]. By 2016, benchmarking and sensitivity studies of MAGARC were being performed against another ANSYS-based ITER magnet safety package under development at the Culham Centre for Fusion Energy in the United Kingdom in order to validate previous safety analyses, and this led to several stability and performance improvements for the code, as well as continued benchmarking of the new arcing behavior model [32]. In this era, the fusion nuclear science community also identified MAGARC as extensively-used in the assessment of fusion plant behavior during an accident (alongside MELCOR and TMAP), and they recommended that it be updated and expanded to better meet the increasing complexity of ITER, and eventually DEMO [33]. Complex engineering often requires equally complex multiphysics simulation and analysis, and the remainder of this paper will discuss how INL is pursing the goal of fusion device simulation using MOOSE.

4. FUSION DEVICE MODELING AND SIMULATION AT INL USING THE MOOSE FRAMEWORK (2020)

The MOOSE framework is an open-source modeling and simulation platform developed at INL since 2008. It has predominantly focused on the creation of modular, high-fidelity, massively-parallel, multiscale, multiphysics models for the nuclear fission space [14]. Most recently, this effort occurred under the U.S. DOE Nuclear Energy Advanced Modeling and Simulation (NEAMS) program, through which applications have been developed for nuclear fuel performance (BISON [34]), system-level thermal hydraulics [35], medium-fidelity computational fluid dynamics (CFD) [36], high-fidelity neutron transport and CFD (Cardinal [37]), and many other areas. Being built on a single, modular platform has an obvious advantage: easy interoperability. All MOOSE-based codes can be natively coupled together to form large multiphysics simulations and, as in the case of Cardinal (with its OpenMC and NekRS dependencies), even non-MOOSE-based applications can be "MOOSE wrapped," enabling closer coupling and integration. This tight integration enabled a path to fission reactor digital twin development, and fusion could follow a similar path.

Fusion energy devices share many physics and scenarios with nuclear fission systems: e.g., neutronics and material activation, thermal-hydraulics, fluid flow, heat transfer, chemical reactions, structural degradation, transient off-normal events. Thus, many of the tools mentioned above could be repurposed or reconfigured for fusion use. Furthermore, commercial fusion energy devices will need well-tested, verified, and validated computational toolkits with high software quality assurance standards for licensing and governmental review; MOOSE and many of its applications are Nuclear Quality Assurance Level 1 (NQA-1) standard compliant [38]. This last capability has attracted the attention of such nuclear regulators as the U.S. Nuclear Regulatory Commission, which seeks to use MOOSE-based NEAMS tools to assist in its mission.

Funded research and development for a "MOOSE for Fusion" concept began in earnest at INL in 2020 when fusion breeding blanket modeling based on MOOSE was begun as part of a U.S. DOE Office of Science Early Career Research Program Award [39]. This project began with an initial proof-of-concept study of a ceramic breeding blanket, based on that of the Fusion Nuclear Science Facility (FNSF) design [40], where a computer-aided design (CAD)-to-simulation workflow was developed for rapid design iteration and optimization of future blanket concepts. This coupled model contained heat generation based on neutronics calculations (using OpenMC), heat conduction within each layer of the blanket (first wall armor, neutron multiplier, and breeder material), and thermal hydraulics for the blanket cooling system—the latter two using MOOSE physics modules [41]. In this work, a 22.5-degree section of an outboard FNSF-style blanket was assembled using a configuration of material layers chosen to optimize tritium breeding, modeled using multiphysics capabilities, and then evaluated against a design criterion (in [41], the maximum temperature limits of the materials). Once a design has been evaluated against a desired metric, simulation parameters can be adjusted quickly and reevaluated on the fly. An example of the model output is shown in Figure 3. More-recent developments have focused on adding tritium generation and diffusion using the MOOSE-based Tritium Migration Analysis Program, Version 8 (TMAP8) code [9], which will be presented in a forthcoming publication [42] and released as an open-source code within the MOOSE repository as the *MOOSE fusion module*.

Ongoing research using MOOSE for fusion modeling and simulation includes coupled electro-thermo-mechanical modeling of superconducting magnets for safety evaluation and scrape-off layer plasma dynamics at INL [43, 44, 45] as well as collaborations with the United Kingdom Atomic Energy Agency, which has

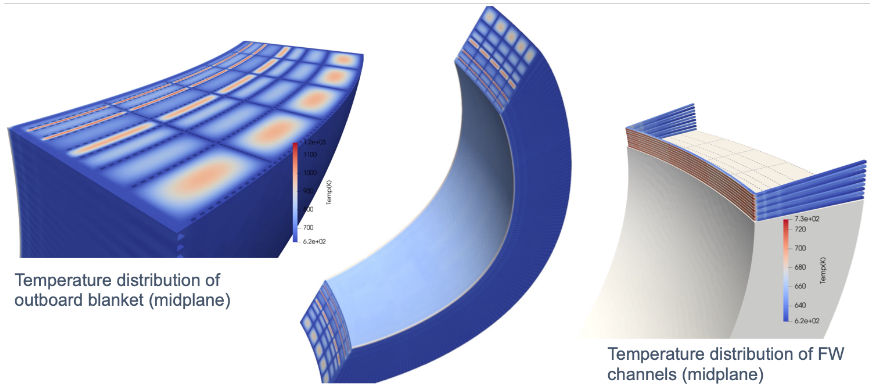


Figure 3. MOOSE simulation of the temperature distribution of an FNSF-style ceramic breeder blanket. 0093-3813 © 2022 IEEE. Reprinted with permission from [41].

developed its own MOOSE-based suite of tools for fusion research [46]. In the remainder of this section, the current electromagnetic capabilities of MOOSE in the context of the superconducting magnet modeling effort are described and summarized; a description of the other components of the project is left for future communications.

The electromagnetics modeling capability within MOOSE results from a recent development effort, enabling coupled computational electromagnetics simulations across all MOOSE-based applications [47]. The MOOSE electromagnetics module focused, thus far, on complex-valued, multidimensional wave-propagation scenarios, such as those encountered in antenna design, radio-frequency low-temperature plasma systems, and waveguide simulation. Conductors within the module have also been considered perfect, or idealized. Thus, the foundational basis of many module examples can be modeled with a vector-variable wave equation, shown in transient form in Equation (1), with a generic complex-valued vector field, $\vec{u}$, and scalar coefficients, a and b. The vector $\vec{r}$ represents the spatial dependence of the scalar coefficients, and t represents their time dependence.

$$\nabla \times \nabla \times \vec{u} + a(\vec{r}, t)\frac{\partial^2 \vec{u}}{\partial t^2} = -\left(b(\vec{r}, t)\vec{F}\right) \tag{1}$$

An expression of this form, or similar, for both electric and magnetic fields can be derived directly from Maxwell's equations and is sufficient for vacuum and dielectric material wave-propagation problems of many types. However, this current module formulation will likely not be sufficient for the modeling of electromagnetic fields within imperfect conductors, where free charge and free current density is non-zero and there is greater electromagnetic wave attenuation; therefore, new development effort will be required. Indeed, MAGARC, for example, uses a vector-potential formulation of Maxwell's equations, where the electric and magnetic fields ($\vec{E}$ and $\vec{B}$, respectively) can be calculated based on a combination of a magnetic vector potential $\vec{A}$ and an electrostatic potential ϕ [32], in general given by

$$\vec{B} = \nabla \times \vec{A} \tag{2}$$

and

$$\vec{E} = -\nabla\phi - \frac{\partial \vec{A}}{\partial t}. \tag{3}$$

This formulation is not currently available in the MOOSE electromagnetics module, but its implementation is under development. Further, electrical and thermal material-property libraries for superconducting materials of interest, such as yttrium barium copper oxide (YBCO) and rare-earth barium copper oxide (REBCO), are also under development. Property libraries for other materials, such as stainless steel, glass epoxy coil insulation, and copper, will initially be obtained from those of MAGARC for code benchmarking purposes [13, 32].

5. CONCLUSIONS

This paper briefly reviewed and outlined the history of electromagnetic modeling for fusion superconducting magnets within the INL FSP—in particular, the development efforts and usage of the MSCAP and MAGARC codes, from 1985 to roughly 2016. This computational research is representative of only one portion of the work undertaken by the program over the last 45 years, yet it is vital to the safe and stable long-term operation of future FPPs. More-recent developmental activities at INL using the MOOSE framework since 2020 show great promise in updating INL legacy modeling and simulation capability in the areas of tritium accountancy (TMAP8); development of new models for coupled neutronics, heat conduction, and thermal hydraulics for ceramic breeding blankets (MOOSE fusion module); and in modeling of the scrape-off layer plasma and first wall (Fusion ENergy Integrated multiphys-X [FENIX]). The recently-created MOOSE electromagnetics module is also currently under further development as a base on which to update the legacy fusion magnet simulation capabilities mentioned in this work. A MOOSE-based application ecosystem will provide a cutting-edge, coupleable, and modular base on which workflows for fusion safety analysis and whole-device modeling can be built and run on world-class supercomputing systems. The MOOSE-based fusion modeling capability will enable the FSP to effectively serve its original mission well into the coming decades and support the broader fusion research and development community.

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