Tritium Migration Analysis Program (TMAP8) – Enabling tomorrow's commercial fusion industry

Product/category
- Mechanical/Materials
- Software/Services

Primary submitting organization:
Idaho National Laboratory

Co-developing organization:
Oak Ridge National Laboratory

Product/services brand name:
TMAP8 (Tritium Migration Analysis Program, Version 8)

When product was introduced to the market:
January 2021

Price of product/service in US dollars:
Free and open source

Abstract:
TMAP8 tackles fusion energy's biggest hidden challenge: tritium management. It is the first open-source tritium modeling platform to meet the Nuclear Quality Assurance Level 1 (NQA-1) industry standard. The tool combines regulatory rigor; multiscale, multiphysics simulation; and broad industry accessibility and applicability to accelerate safe, commercially viable fusion power.

Additional supporting materials:
TMAP8 main paper

Website:
TMAP8 website

Video:
TMAP8 video

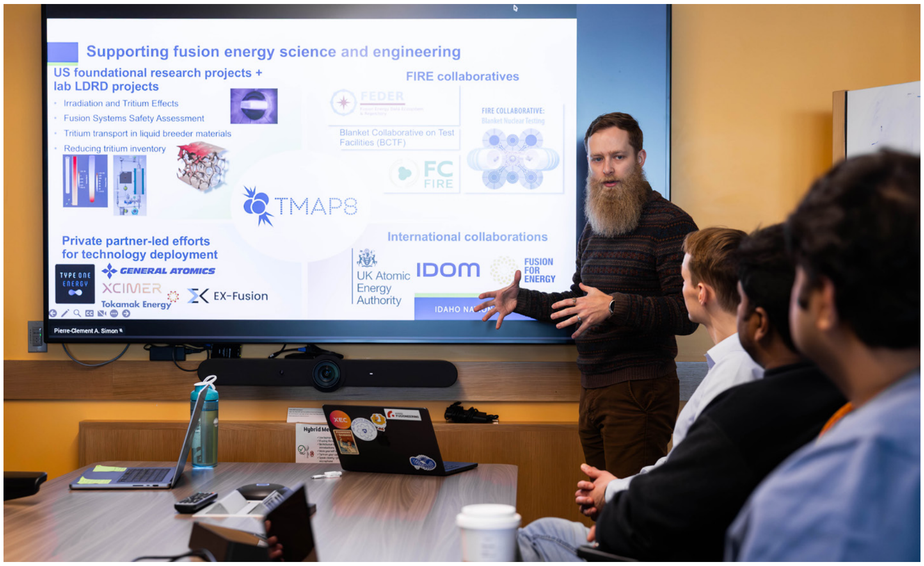

Figure 1: Dr. Pierre-Clément Simon presenting the broad ecosystem of scientific and technical projects and institutions TMAP8 supports.

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What does this product or technology do?

Nuclear energy is generated in two ways: fission, the splitting of atoms; and fusion, the joining of atoms. Fusion energy promises virtually limitless, carbon-free, reliable electricity. In 2022, after decades of research, scientists in California overcame fusion's biggest challenge: an inertial fusion ignition that produced more energy than it consumed. The experiment marked the first time a controlled fusion reaction produced a net energy gain in the laboratory. Researchers have since refined the experiment, producing even more energy and giving hope that fusion will soon produce abundant, clean commercial energy. Researchers around the world continue to produce milestones in magnetically confined fusion, with records for fusion energy generation set in 2023 and for plasma duration in 2025. The United States is now racing to deploy its first fusion pilot plants within the next decade.

But several key challenges remain before fusion lives up to its promise. One of those challenges is managing tritium, a radioactive hydrogen isotope. Along with deuterium, tritium is one of the two hydrogen isotopes that fuse together during fusion. At high temperature and pressure, fusing deuterium and tritium releases a significant amount of energy that can be used to generate electricity.

While deuterium is found in water and is relatively abundant, tritium is scarce. To overcome this challenge, fusion scientists have developed technologies to produce tritium within a system called a breeder blanket. The breeder blanket lines the plasma chamber and contains lithium. When a lithium atom is struck with a neutron, it produces the tritium necessary for fusion. Once produced, the tritium needs to be extracted, treated and reinjected into the plasma. This is called the tritium fuel cycle.

Tritium is relatively easy to produce, but difficult to track and manage. It tends to permeate through surrounding solid materials, migrate across temperature gradients, interact with radiation damage in materials and escape into coolants. Uncertainties about the quantity and location of tritium in the fuel cycle can span five to six orders of magnitude, dramatically affecting reactor design decisions. Tritium sensors are still in the experimental phase and may have limited use due to temperature, radiation and pressure constraints in a fusion plant. The ability to track and control tritium inventory determines whether a fusion power plant is safe, sustainable and economically viable.

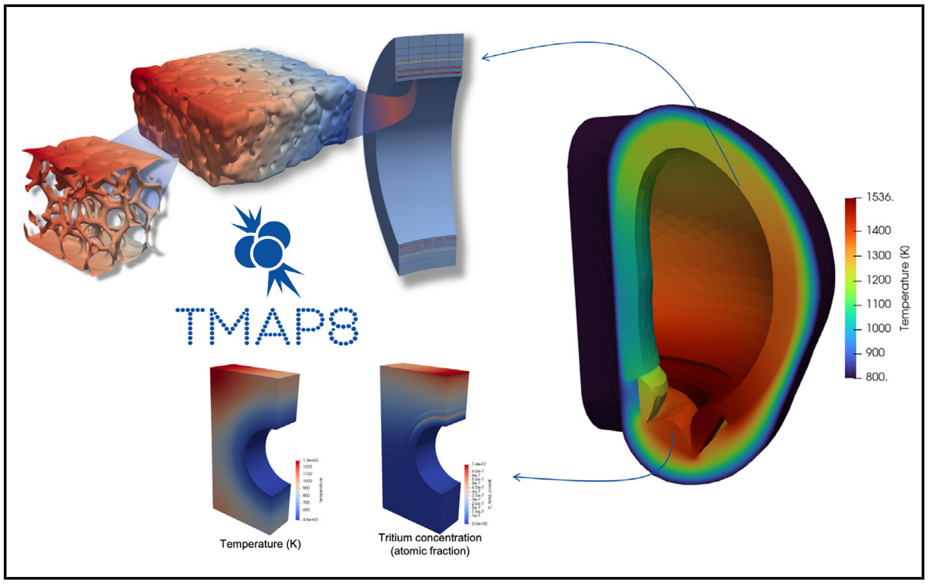

Figure 2: Illustration of TMAP8 simulation results for two key parts of a fusion energy system: multiscale capabilities for porous ceramic breeder materials and high fidelity divertor monoblock simulations, demonstrating TMAP8's flexibility, scalability, and multiphysics capabilities.

"IDOM offers its full and unqualified institutional endorsement of TMAP8 for the R&D 100 Award. We consider it an exemplary achievement in applied computational nuclear science."

—Alexandre Sureda Croguennoc, Technical Development Manager UK – Fusion Energy, IDOM

To overcome the tritium challenge, researchers have developed TMAP8, a software program that models tritium transport throughout the fusion energy system. TMAP8 represents the first open-source tritium code following NQA-1 software quality assurance standards, providing a clear regulatory pathway essential for fusion facility licensing.

For decades, researchers relied on tritium modeling codes TMAP4 and TMAP7, developed by the Idaho National Laboratory (INL). These tools served the fusion community well but were severely limited — they were restricted to one-dimensional models, capped at three material trap populations, unable to leverage modern high-performance computing, and export-controlled, which limited their availability and impact.

TMAP8 is the answer to these limitations. Developed primarily by INL in collaboration with many other institutions around the world, TMAP8 is a modern, open-source, multiscale tritium transport and fuel cycle modeling platform applicable to all fusion system designs explored by industry.

TMAP8 has been adopted by researchers at national laboratories, universities and private fusion companies in the United States and internationally. Its verification and validation cases, which ensure proper implementation and accurate predictions against real-life data, have become community benchmarks used by other tritium modeling tools worldwide. TMAP8 is central to solving tritium management challenges that are critical to enabling practical fusion energy systems.

Figure 3: Dr. Pierre-Clément Simon presenting the open-source [TMAP8 website.]

"TMAP8 is the go-to tool for us […] because it is open source, validated with rigorous software quality standards, couples seamlessly with the molten salt chemistry work we have done in the MOOSE tool, and enables us to do high-fidelity, multiphysics analysis of our breeder blanket. […] There is no alternative tool that we know of that can accomplish the same thing as TMAP8."

— Dr. Samuel Walker, Senior Nuclear Scientist, Xcimer Energy

How does the product operate?

TMAP8 is an advanced, open-source software package that addresses the critical challenge of managing tritium — the naturally scarce, radioactive fuel that must be bred on-site and meticulously tracked for reactor safety, performance and economic viability. TMAP8 is the leading tritium transport and fuel cycle modeling tool in the fusion energy field.

The modeling tool was developed using INL's Multiphysics Object Oriented Simulation Environment (MOOSE) framework, an open-source, high-performance computing platform for building and running complex multiphysics simulations. MOOSE enables researchers to couple multiple physical models in a scalable framework used across nuclear energy, materials science and other research areas.

With MOOSE, TMAP8 enables highly accurate, multiscale and multiphysics simulations of tritium transport in complex geometries, ensuring comprehensive tritium transport modeling for fusion and advanced fission systems, including molten salt reactors.

Unlike its predecessors TMAP4 and TMAP7, TMAP8 is modular, scalable and open-source, promoting transparency and collaborative development. It supports zero-dimensional to 3D simulations integrating heat transfer, surface kinetics and multispecies transport. Despite the common name with its predecessors, TMAP8 uses a completely different approach leveraging advanced computing to model tritium.

The ability to simulate multispecies transport is particularly important for modeling tritium because tritium can assume more than half a dozen specific chemical forms in normal environments, and its transport kinetics are impacted by the presence of other hydrogen isotopes.

TMAP8 leverages MOOSE's in-memory coupling for multiscale, multiphysics capabilities that span more than six orders of magnitude from nanoscale pores to full plant systems. The dimension-agnostic architecture enables seamless transition from simplified zero- and one-dimensional geometries to complex 3D system simulations without code modifications. It achieves crucial speedup on high-performance computers by intrinsically supporting massively parallel computing capabilities. TMAP8 enables simulations capturing key design features and crucial physics, which could not be previously

Figure 4: Dr. Lin Yang presenting the multiscale modeling approach leveraging surrogate modeling capabilities for accelerated design deployed for the DOE milestone program with Tokamak Energy.

"Tritium management is a top priority due to its role as fusion fuel, its scarcity, and its radioactivity. Tritium transport strongly influences both the performance and regulatory compliance of our plant design. […] Two aspects in particular make TMAP8 stand out. The first is its technical capability to model tritium transport using a multiphysics, multi-scale approach. The second is TMAP8's rigorous software quality assurance program. TMAP8 enables us to account for and control the tritium bred within our fusion energy system, an essential capability for developing a safe and regulatory-compliant fusion power plant."

— Dr. Daniel Clark, Director, Nuclear and Fuel Cycle Engineering, Type One Energy Group captured due to scale limitations. Since TMAP8 is scalable and can utilize parallel computing on hundreds of thousands of processors, it can solve computationally expensive simulation problems. Thus, TMAP8 can provide a comprehensive understanding of tritium transport in complex systems governed by multiple physics.

TMAP8's advanced capabilities extend beyond tritium transport. It can seamlessly integrate with MOOSE-based applications such as SALAMANDER and other physics and numerics modules, enhancing its ecosystem of tools and allowing for multiphysics simulations. The software currently models diffusion, multiple trapping sites, surface reactions and equilibrium, phase changes, permeation, heat transfer, and other physics. Built-in coupling with other MOOSE-based tools enables unprecedented multiphysics fidelity under realistic conditions. Moreover, integrated stochastic tools enable uncertainty quantification, sensitivity analysis, model calibration and surrogate modeling, which are essential for rapidly optimizing design and assessing safety. This is especially relevant to fusion given the large design space the industry is exploring.

Rigorous software quality assurance includes continuous integration testing, more than 90% code coverage with respect to tested lines, and comprehensive verification and validation against a growing number — currently 36 — of analytical solutions and experimental datasets. All verification and validation cases are publicly reproducible with version-controlled inputs on the TMAP8 website.

TMAP8 is developed in an open-source and agile manner, which enables broad community adoption and contribution. This is vital to international collaborations between scientists and engineers to accelerate technology deployment through advanced modeling and simulation.

TMAP8 is used in fusion and fission research — including fusion energy systems, tritium extraction technology and molten salt reactors — showcasing its success in solving real-world challenges across the nuclear energy domain.

How does the product improve upon competitive products or technologies?

TMAP8's comprehensive suite of capabilities is its most striking differentiator. Other tools often lack the ability to model the full range of tritium transport processes that TMAP8 supports, struggle to capture coupled phenomena or require substantial additional effort for multidimensional and multiscale modeling.

TMAP8 outpaces its competition by integrating modern computational techniques, high-fidelity multiphysics modeling and seamless scalability, all within an open-source framework fit for scientific endeavors, technology deployment efforts and licensing activities.

Export-controlled codes (e.g., TESSIM) face access restrictions limiting collaborations and commercial deployment. Commercial platforms (e.g., COMSOL, ANSYS) impose large annual costs, creating prohibitive barriers. Open-source alternatives (e.g., FESTIM) lack TMAP8's comprehensive suite of verification and validation cases, integrated uncertainty quantification tools, NQA-1 compliant development processes and mature modeling infrastructure, including multiscale and multiphysics capabilities. Furthermore, TMAP8's parallel capabilities and modern C++ implementation offer key speedups against alternatives.

TMAP8 is open-source and its licensing approach promotes adoption. Unlike export-controlled predecessors such as TMAP4 and TMAP7 and commercial tools like COMSOL, TMAP8 offers unparalleled flexibility, accessibility and transparency. Its permissive copyleft license, LGPL 2.1, allows proprietary extensions without disclosure, which are key for private company adoption.

The open-source model democratizes access and has enabled international adoption, eliminating export control restrictions and the large annual licensing costs typical of commercial alternatives. Adoption by Oak Ridge National Laboratory, the United Kingdom Atomic Energy Authority, IDOM, and many other national laboratories, private companies and universities for virtually all proposed fusion system designs validates its leading position and industrial readiness.

Aside from its clear advantage when it comes to capabilities, accessibility and widespread adoption in the fusion community, TMAP8 represents the first open-source tritium code following NQA-1 standards, providing a clear regulatory pathway essential for fusion facility licensing. This transparency, documentation and extensive testing exceed what alternatives can demonstrate, building unparalleled regulatory trust as the field moves from research to engineering and toward deploying energy systems that deliver electricity to the grid.

TMAP8's rapid adoption demonstrates that it addresses real industry needs. As fusion nears commercial deployment, TMAP8 provides the open, trusted foundation needed for scientific discoveries and regulatory-grade tritium modeling.

Provide a matrix demonstrating how key features compare to other products:

Category	Feature/Capability	TMAP8	Component-Scale Tools						System / Fuel Cycle Tools								
		TMAP8	TMAP4/7	FESTIM	TESSIM-X	mHIT	MHIMS	pastaFOAM	CFTSIM	FUS-TPC	SAM	ModAn/ EcosimPro	MELCOR-TMAP	RHINO	TRIMO	bluemira
Scale & Dimensionality	Pore microstructure scale	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	?	✗
	Component-level (1D)	✓	✓	✓	✓	✓	✓	✓	?	?	✓	?	✓	~	?	✓
	Component-level (2D, 3D)	✓	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✓
	Fuel cycle scale	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓
	Massively parallel HPC (10,000s of cores)	✓	✗	~[1]	✗	✗	✗	✓	?	?	✓	?	✗	?	✗	~
Physics Capabilities	Diffusion, decay, and trapping	✓	~[2]	✓	✓	✓	✓	~	~[3]	~	~	~	~	~	~	✓
	Surface kinetics	✓	✓	✓	✓	✓	✓	✗	~	~	~	~	✓	~	~	~
	Multispecies, isotope-resolved transport (H, D, T, HD, HT, DT)	✓	✓	✓	✓	✓	✓	✗	✓	?	?	?	✓	?	?	~
	Coupling with tritium generation (neutronics)	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	?
	Native coupling with other key physics (heat conduction, thermomechanics, thermal hydraulics)	✓[4]	✗	✗	✗	✗	✗	~	~	~	✓	~	~	~	~	~
	Integrated UQ, calibration, surrogate / ML coupling	✓	✗	~	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	~
	36+ open-source cases Verification & Validation	✓[5]	~	~	✗	~	~	~	✗	✗	~	~	~	✗	✗	~
Software Quality Assurance	NQA-1 compliant SQA	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	~	✗	✗	✗
	Auto-generated online documentation	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓
	Automated continuous integration testing	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓
	Formal review by change control board	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	?
Accessibility & Deployment	Open-source and free	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
	Active development & community support	✓	✗	✓	~	~	~	~	✗	✗	✓	?	✓	✗	✗	✓
	Extensible for private / proprietary builds	✓[6]	✗	✓	✗	✗	✗	✗	?	?	✓	?	✗	✗	✗	✓

This comparison matrix is accurate to the best of our knowledge, and is not exhaustive.

✓	Has the feature
✗	Does not have the feature
~	Partial feature
?	Unknown

[1] Python-based codes are not as parallelizable as C++ based ones like TMAP8, and this code has not been demonstrated on as many processors as TMAP8 has. TMAP8 scales from a laptop to national HPC facilities.

[2] TMAP4 and TMAP7 are limited to one and three trapping sites, respectively, while TMAP8 can model any number of trapping sites.

[3] Fuel cycle tools typically do not model local trapping.

[4] TMAP8 offers both loose and in-memory coupling via MOOSE; no file I/O, no external coupling scripts or infrastructure.

[5] The cases from TMAP8 are adopted as benchmarks by FESTIM, MHIMS, mHIT.

[6] The LGPL v2.1 license allows private extensions without requiring them to be open-sourced.

What are the limitations of the product/service?

One big challenge is a lack of prototypical test facilities, specifically prototypes of the fusion environment in a power plant context. The best data is experimental data, and since these prototype test facilities don't yet exist, experimental data to calibrate and validate TMAP8's capabilities are scarce. However, TMAP8 is validated across both simple and complicated validation scenarios, building users' confidence that the code is reproducing reality in a digital context.

Using AI to augment scientific workflows is more common and exploring its use in and with TMAP8 is ongoing. Since TMAP8 can simulate complex and interconnected operational environments, it allows researchers to generate high-quality data that can be used to train AI models to serve as design and engineering surrogates.

Further, the TMAP8 development team provides the input files and documentation for all verification and validation cases, allowing outside entities to reproduce their results. The validation cases could be leveraged to train AI models. Multiscale example cases in the documentation that tie component and systems-level models together are not yet available, but this is an area of active work.

Additionally, to alleviate the lack of prototypical experimental data, TMAP8's stochastic capabilities enable users to rigorously quantify and propagate uncertainties and errors, integrating them directly into design and safety assessments.

With continued experimental validation from fusion prototypes, TMAP8 will further solidify its position as the leading tritium modeling platform for the fusion research community.

Summary

Abundant and reliable fusion energy is closer than ever, but several key technical challenges remain before commercial fusion power plants become a reality.

TMAP8 addresses one of the most critical and technically complex barriers to fusion energy deployment: tritium management. Tritium is generated, extracted, processed, stored and reinjected in a tightly controlled fuel cycle. Without a viable tritium fuel cycle, a fusion power plant cannot operate safely, economically or sustainably.

Uncertainties about the fuel cycle can span five to six orders of magnitude, dramatically affecting reactor design decisions. Tritium tracking sensors are still in the experimental phase and may have limited use due to temperature, radiation and pressure constraints in a fusion plant. In the absence of comprehensive measurement systems, predictive modeling is essential.

TMAP8 represents a transformative step in advancing nuclear energy systems, with broad social and economic implications. The need for abundant, clean energy is urgent and — because building and testing fusion prototypes is so expensive — the U.S. must use modeling to accelerate deployment of commercial fusion systems.

TMAP8 models tritium transport from atomic-scale interactions and material microstructure up through full-system fuel cycle behavior within a single, integrated framework.

TMAP8 is the first open-source tritium transport code developed under NQA-1 software quality assurance standards, providing a clear regulatory pathway for future fusion facility licensing. Its rigorous verification and validation framework, open-source transparency and flexible licensing enable industry adoption with confidence.

By enabling credible, regulatory-ready modeling of tritium transport and fuel cycle performance, TMAP8 provides the technical foundation necessary to advance fusion energy from experimental systems to commercially viable power plants.