December 2025

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TMAP8

SALAMANDER

Multiphysics Modeling of Fusion Energy Systems Using the *Software for Advanced Large-scale Analysis of MAgnetic confinement for Numerical Design, Engineering & Research* (SALAMANDER) Computational Tool

12/2025 IAEA Workshop on Digital Engineering for Fusion Energy Research

École Polytechnique IP Paris
University of Illinois Urbana-Champaign
NC State University
UK Atomic Energy Authority
VCU
Oak Ridge National Laboratory
Tokamak Energy
Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy
INL Idaho National Laboratory
INL/CON-25-85543

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Enabling Digital Engineering by Supporting:

Science

- Understand key mechanisms of material science, tritium transport, and exploring complex concepts
- Quantify uncertainty, sensitivity, and develop surrogate models
- Design and analysis of experimental systems

Technology development

- Accelerate technology development through numerical engineering, design, iterations, and safety assessments – more efficient physical testing
- Quantify the effect of new technologies on larger integrated systems
- Risk-free and cost-effective exploration
- Optimized manufacturing

- Develop virtual safety cases
- Increased accuracy
- Quantify risks and uncertainties
- Real time analysis and monitoring
- Mechanistic analysis

Licensing

- Train individuals in a risk-free environment
- Enable individuals to manipulate physics concepts and designs to accelerate learning
- Get virtual experience and develop an understanding of transport mechanisms and the impact of technologies

Education

Fusion digital engineering is best enabled by tools that support these four pillars.

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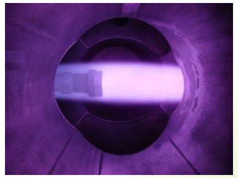
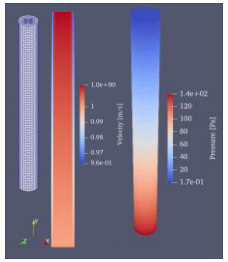
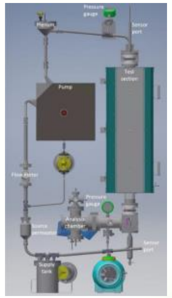
Supporting fusion energy science and engineering

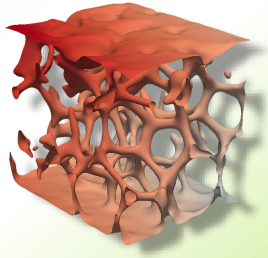
US foundational research projects + lab LDRD projects



- Irradiation and Tritium Effects
- Fusion Systems Safety Assessment
- Tritium transport in liquid breeder materials
- Reducing tritium inventory







FIRE collaboratives

FEDER
Fusion Energy Data Ecosystem & Repository

Blanket Collaborative on Test Facilities (BCTF)

FC FIRE

SALAMANDER

TMAP8

Private partner-led efforts for technology deployment

GENERAL ATOMICS

Tokamak Energy

EX-Fusion

International collaborations

UK Atomic Energy Authority

IDOM

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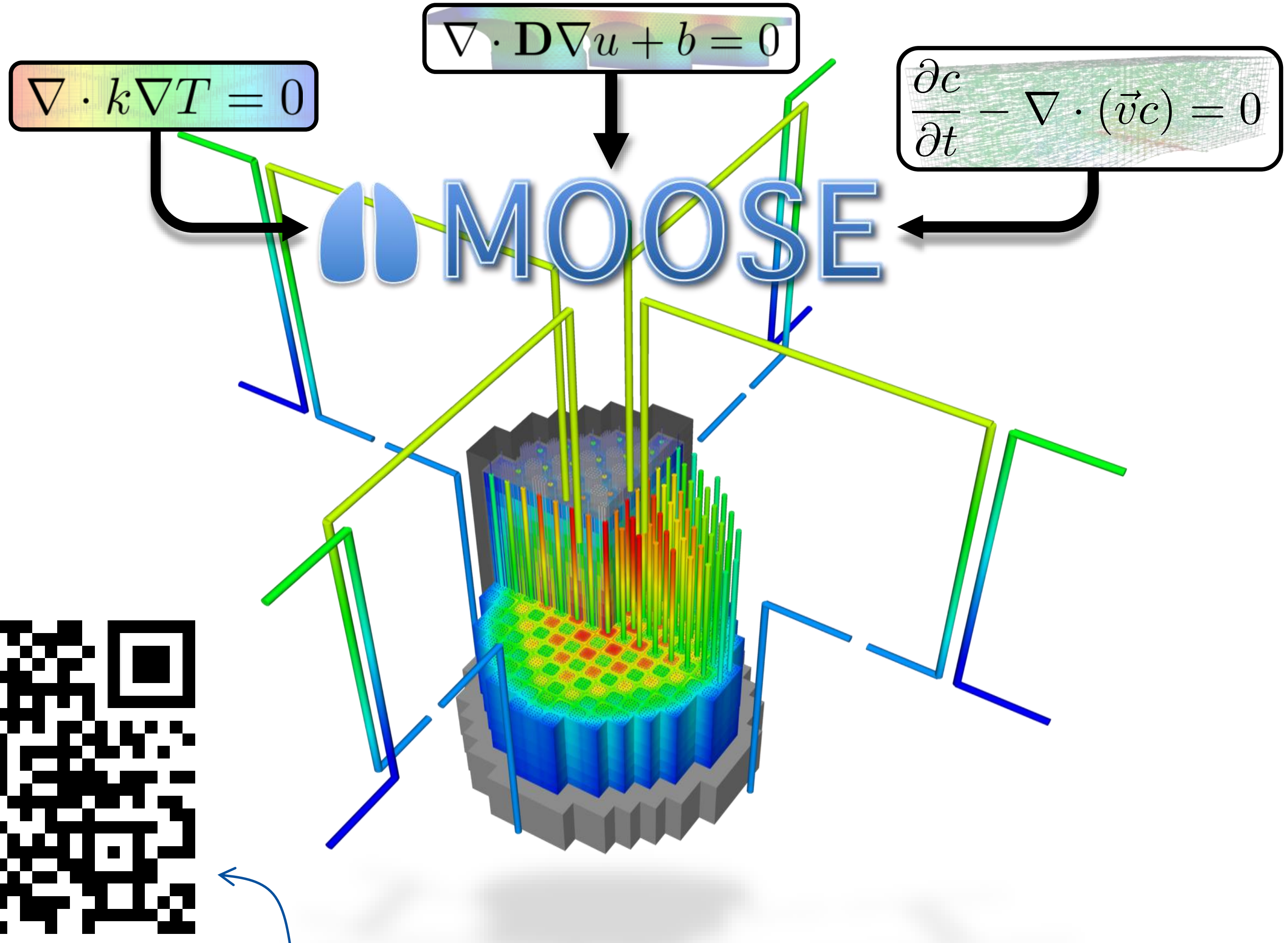
MOOSE Accelerates Development of High-Fidelity Modeling and Simulation Tools



What is MOOSE?

- Multiphysics
- Complete Platform
- Open-source
- Massively Parallel
- Flexible
- **NQA-1 Software Quality Assurance**
- **30M+ Tests per Week**
- **Stochastic Tools Module (RoMs, Surrogates, UQ)**

Website

https://mooseframework.inl.gov

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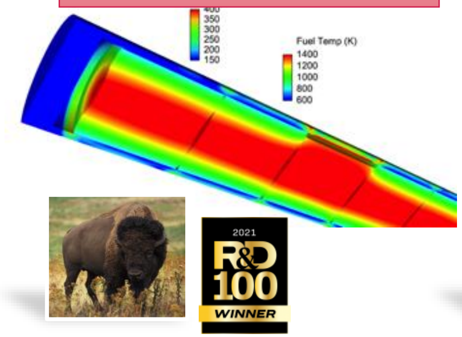
Accelerating Advanced Reactor Deployment

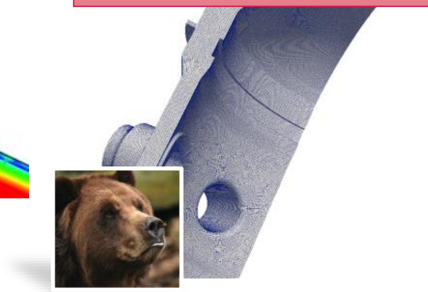
NEAMS

Accelerating Advanced Fission Reactor Deployment

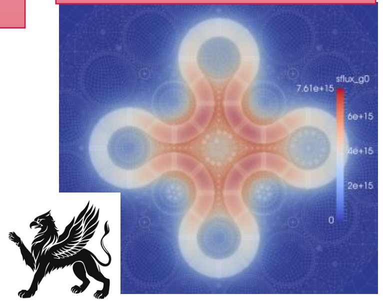
BISON
Nuclear Fuel Performance



Grizzly
Structural Mechanics for Component Aging

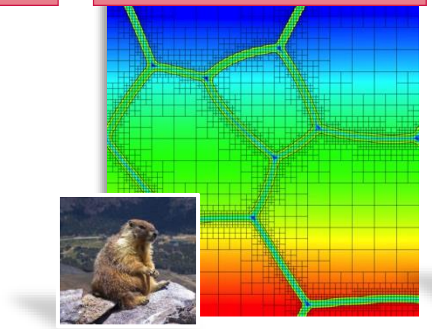


Griffin
Radiation Transport

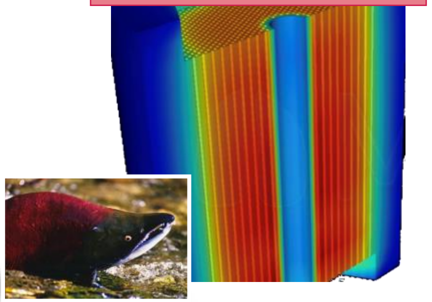


Pronghorn
Medium-fidelity CFD

Marmot
Mesoscale Materials



Sockeye
Heat pipe Simulation



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Kairos Power

RADIANT

Westinghouse

BWXT
Nuclear Energy Canada Inc.

Structural Integrity Associates, Inc.®

EPRI

The codes' modularity and licenses enable public-private partnerships

Example of impact:
Kairos Power release version 1.0.0 of KP-BISON, based on INL's BISON, used in support of NRC licensing of Hermes/Hermes 2 fission reactors

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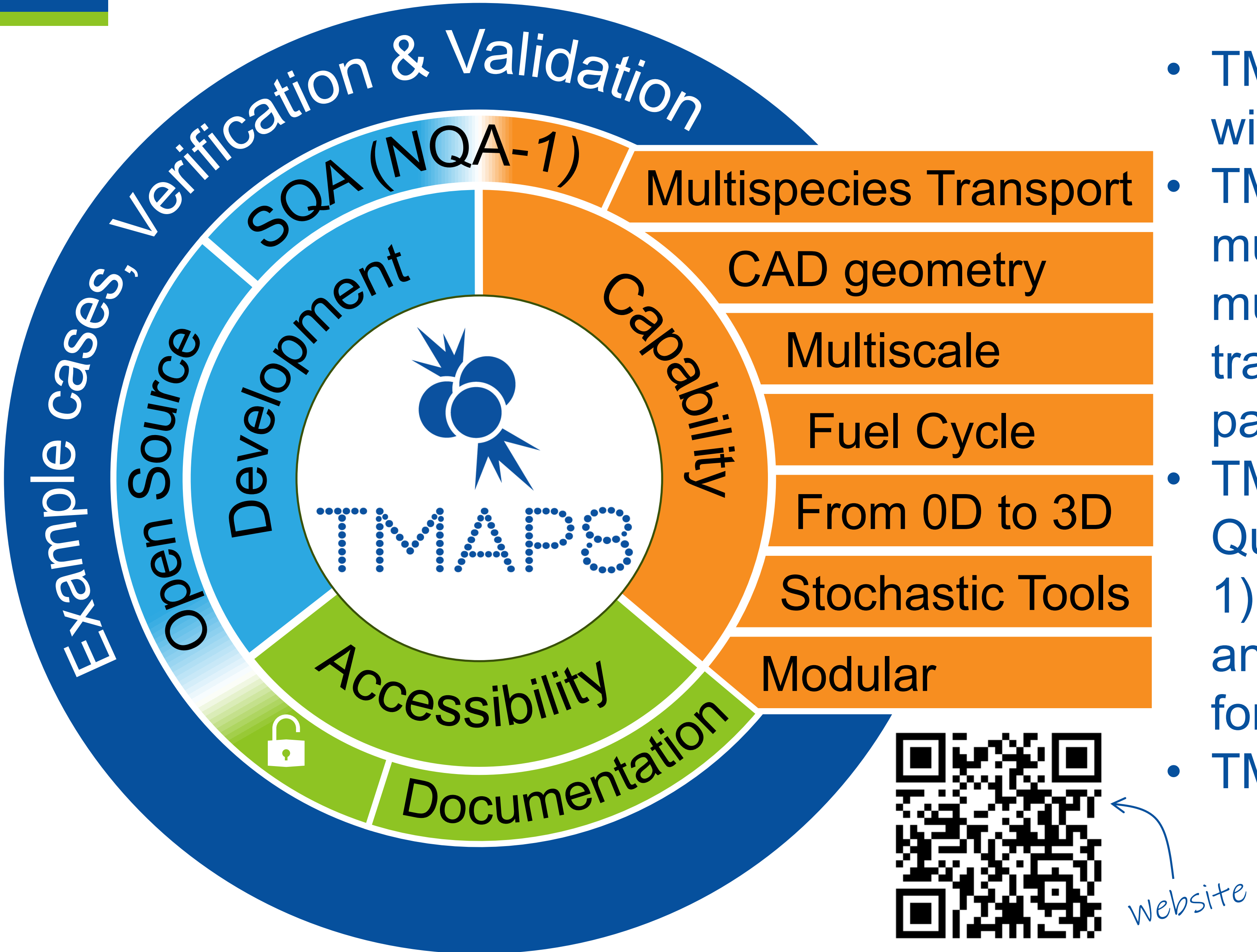
Presentation of TMAP8, the MOOSE-based version of TMAP8



- TMAP4 and TMAP7, although widely used, have limitations.
- TMAP8 enables high fidelity, multi-scale, 3D, multispecies, multiphysics simulations of tritium transport, and offers massively parallel capabilities.
- TMAP8 is open source, Nuclear Quality Assurance level 1 (NQA-1) compliant, offers user support and a licensing approach thought for collaboration.
- TMAP8 is part of SALAMANDER

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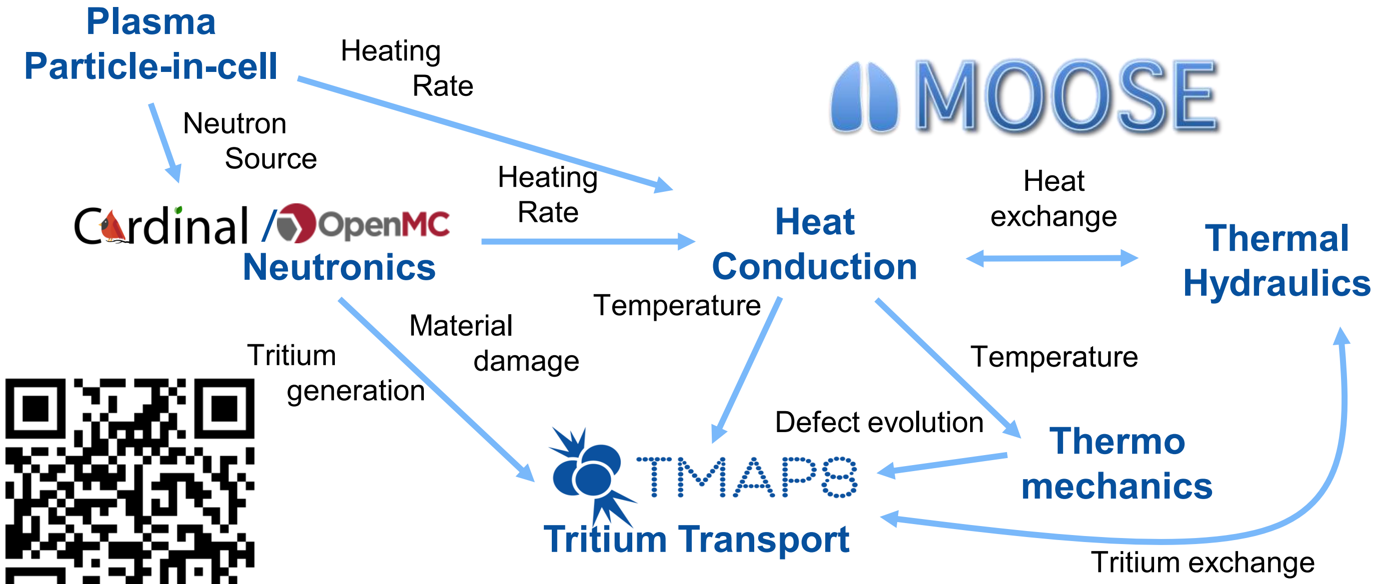
Software for Advanced Large-scale Analysis of MAgnetic confinement for Numerical Design, Engineering & Research

SALAMANDER



website

SALAMANDER is designed to perform multiphysics simulation and capture interactions between these physics.

- SALAMANDER is an open-source MOOSE-based application that integrates multiphysics capabilities for multi-fidelity calculations of fusion materials and fusion systems
- It inherits MOOSE features and contains fusion-specific capabilities.
- SALAMANDER is being developed to support design, engineering studies, and research efforts.

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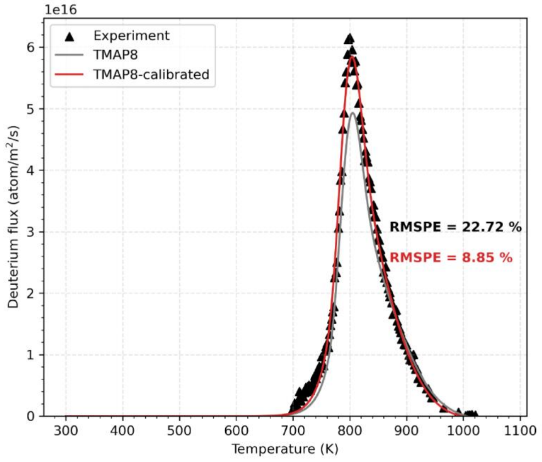
Non-exhaustive overview of SALAMANDER/TMAP8 capabilities

- TMAP8 has a Verification & Validation suite beyond TMAP4's and TMAP7's
- Additional capabilities include:

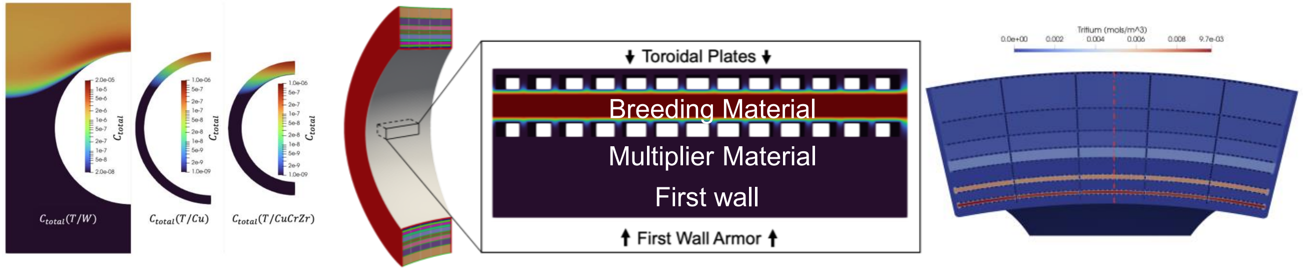
Stochastic tools

The use of stochastic tools supports model calibration, experimental analysis, and quantification of uncertainty
It can quantify experimental uncertainty, model inadequacy, and parameter uncertainty.



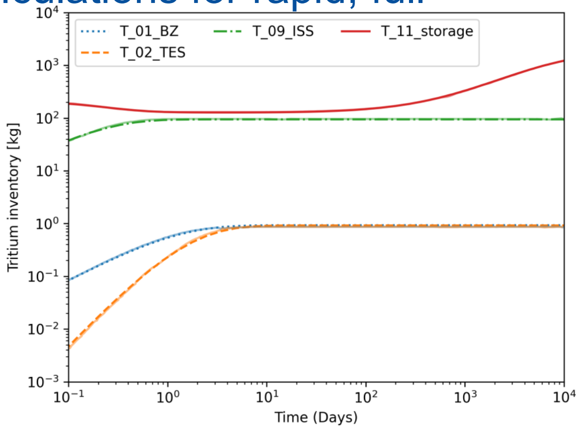
High-fidelity simulations in complex geometries

SALAMANDER/TMAP8 have been used to model complex systems such as a divertor monoblock and a breeder blanket



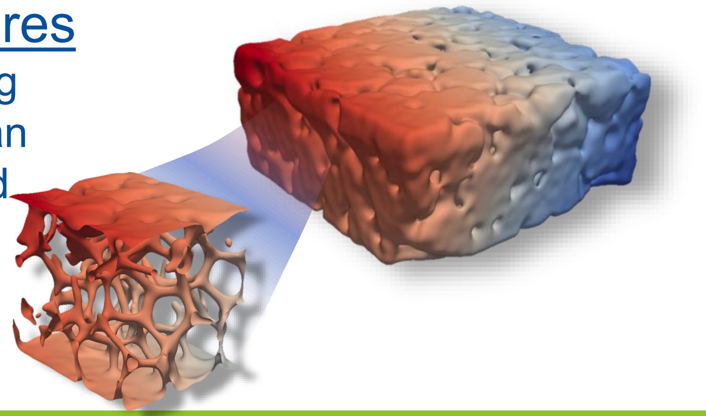
Fuel cycle

TMAP8 support fuel cycle calculations for rapid, full system analysis to track tritium inventory – going beyond TBR.
These fuel cycle models can be informed by lower lengthscale simulation in a fully integrated manner.



3D pore microstructures

Using phase field modeling capabilities, these tools can study the effect of real and simulated pore microstructure on material properties



P.-C. A. Simon, et al., Fusion Engineering and Design, Volume 214, 2025, 114874. https://doi.org/10.1016/j.fusengdes.2025.114874.

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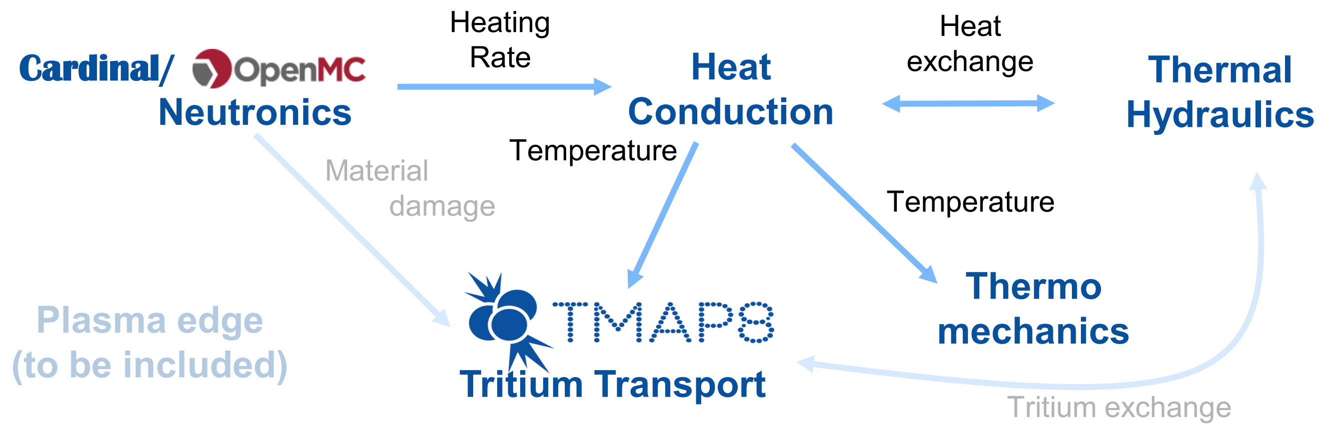
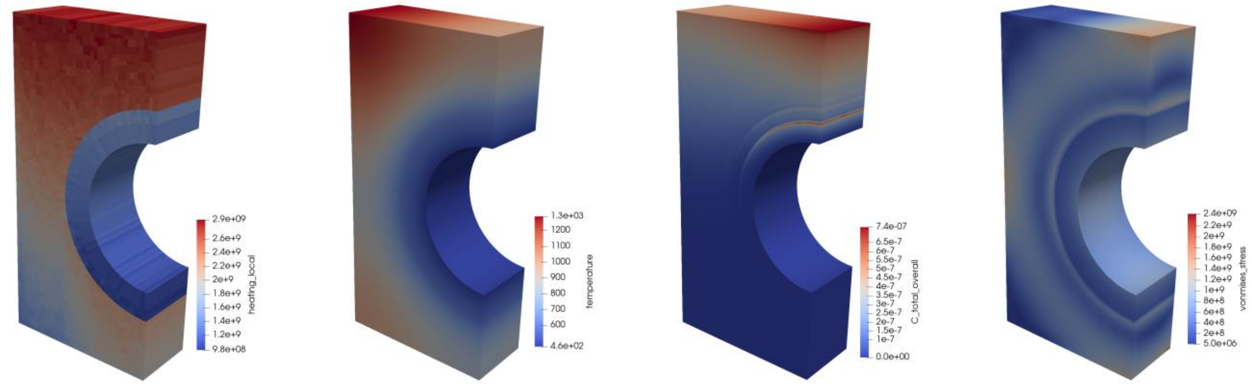
Multiphysics divertor monoblock simulations with SALAMANDER





Volumetric heating rate from neutronics (J/m^{3}s) | Temperature (K) | Tritium concentration (atomic fraction) | Von Mises Stress (Pa)

- SALAMANDER can introduce interactions between physics, and provides high-fidelity results that single physics tools do not provide
- Predictions differ from single-physics simulations done with TMAP8 alone.
- Here, the temperature distribution, dictated in part by volumetric neutron heating, is different than with common assumption of heat deposition at the top of the divertor, which affects material performance and tritium transport predictions

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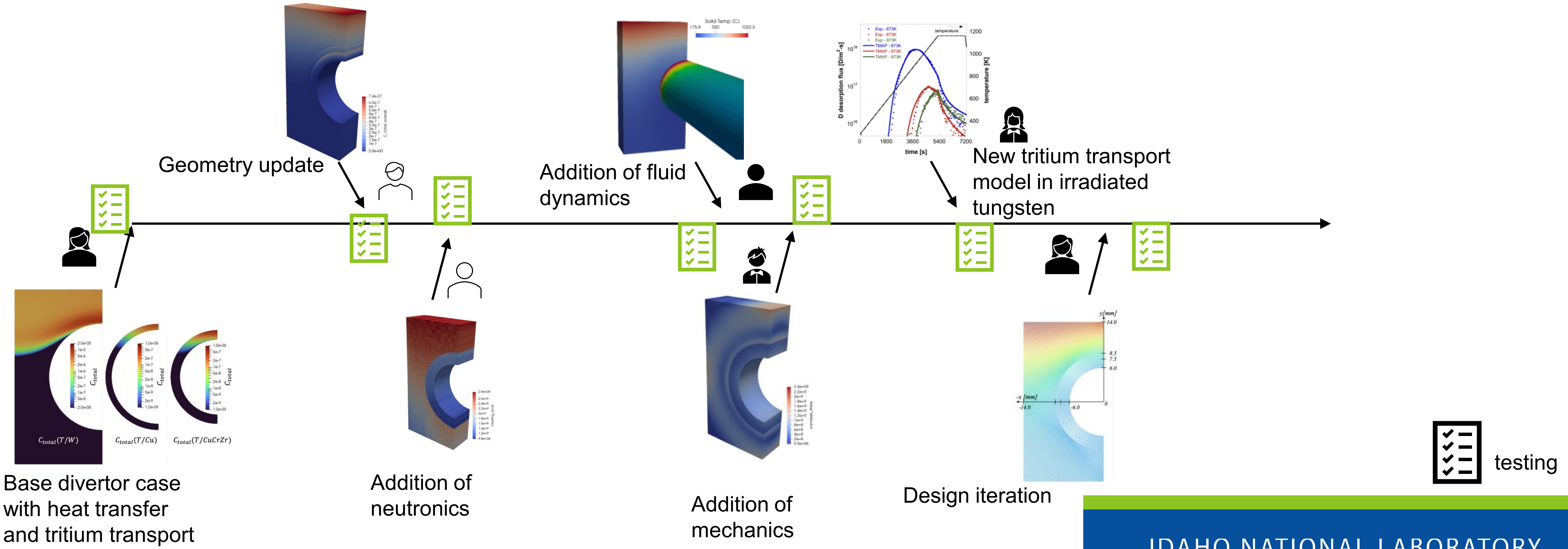
Multiphysics divertor monoblock simulations with SALAMANDER

- Collaborations and iterations is enabled thanks to automated continuous integration and the existence of a single executable for all physics.
- This approach enables experts of different fields to collaborate on a project and contribute their part while tracking how each change affects simulation results and costs.



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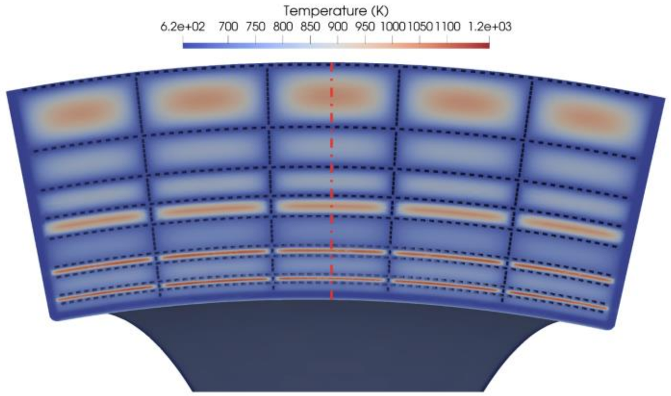
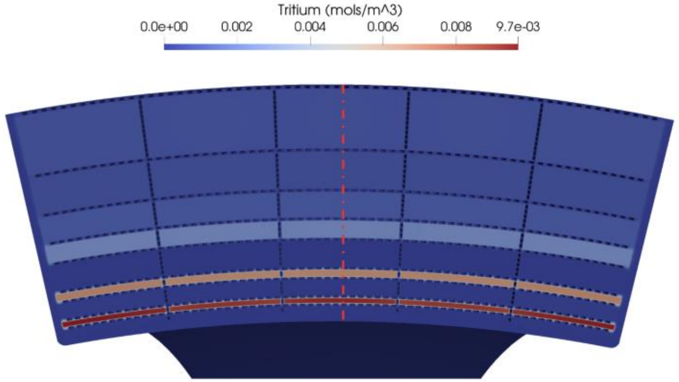
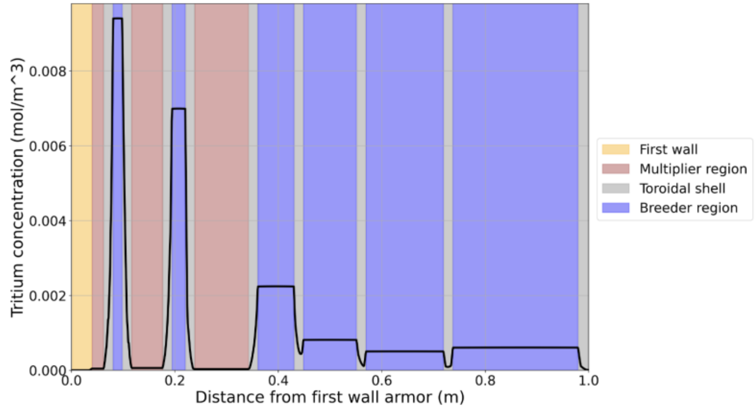
Blanket section simulation

- Large scale multiphysics simulation of a breeder blanket section
  - 36M degrees of freedom
  - Hundreds of cooling channels
  - Thermal hydraulics, heat conduction, tritium transport
  - Imports OpenMC results

Read more







T. Franklin et al., Fusion Engineering and Design, Volume 218, 2025, 115128.
https://doi.org/10.1016/j.fusengdes.2025.115128.

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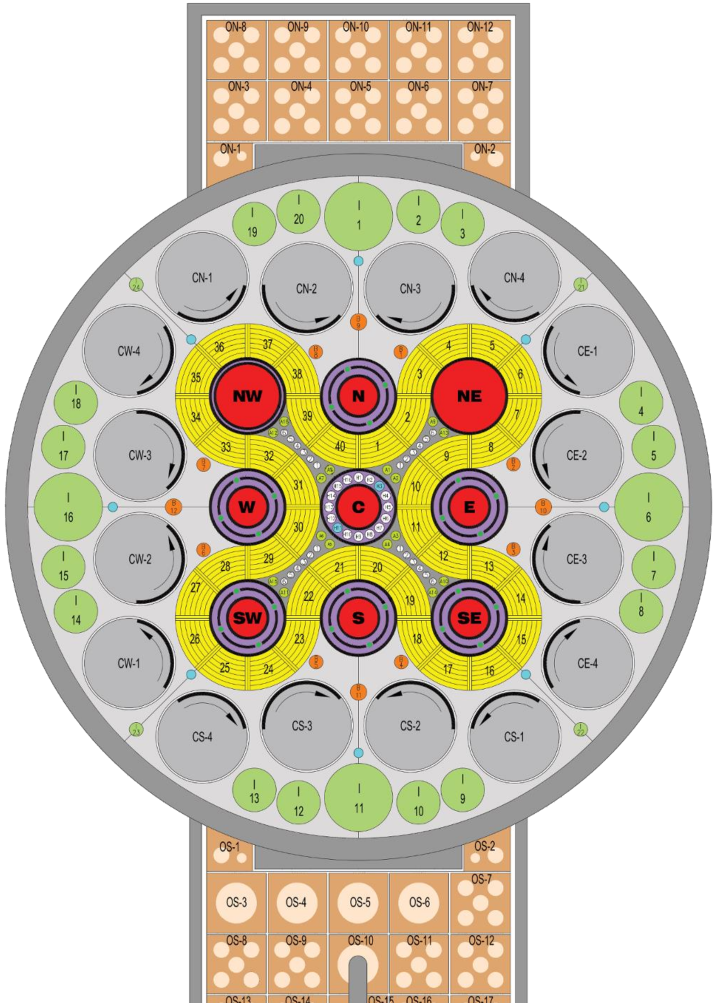
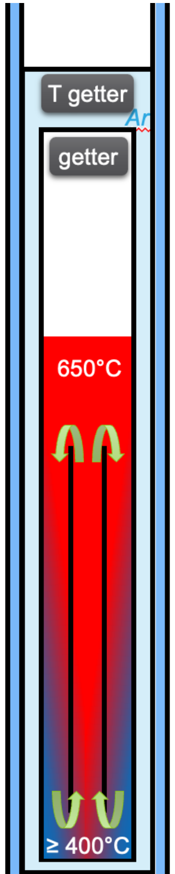
Conceptual design of liquid breeder capsule for irradiation



Advanced test reactor



- ATR (Advanced Test Reactor) irradiation of a thermal convection breeder loop (PbLi).
- Corrosion samples of fusion structural materials (CAN RAFM) will be placed in the capsule.
- Mod/Sim capabilities support the design of the capsule to ensure uniform melting of the PbLi and adequate sizing of tritium getters.

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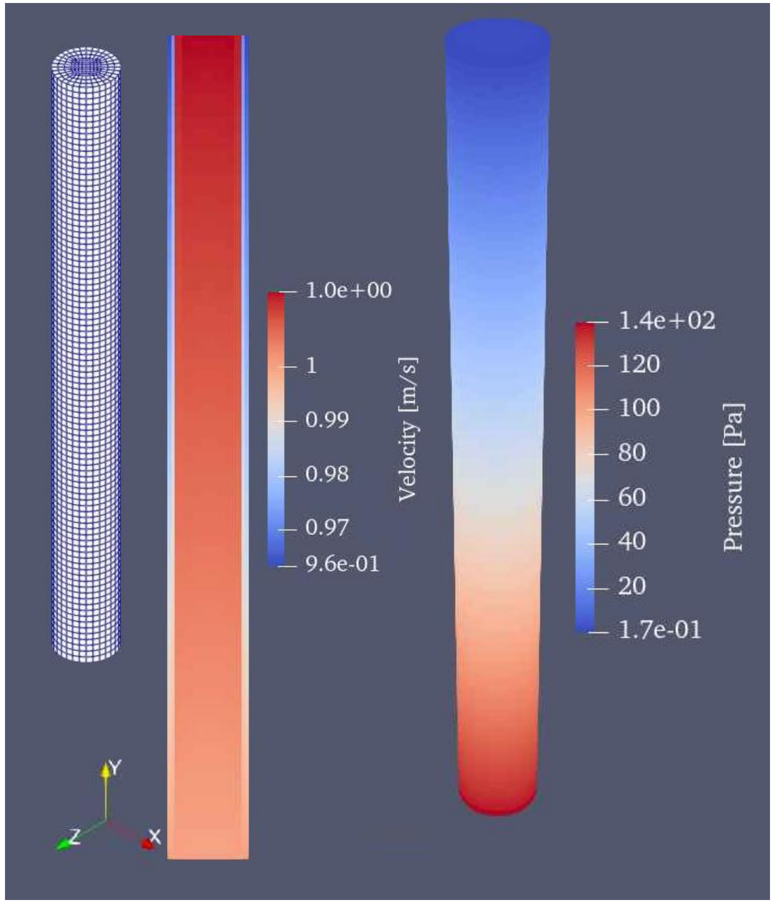
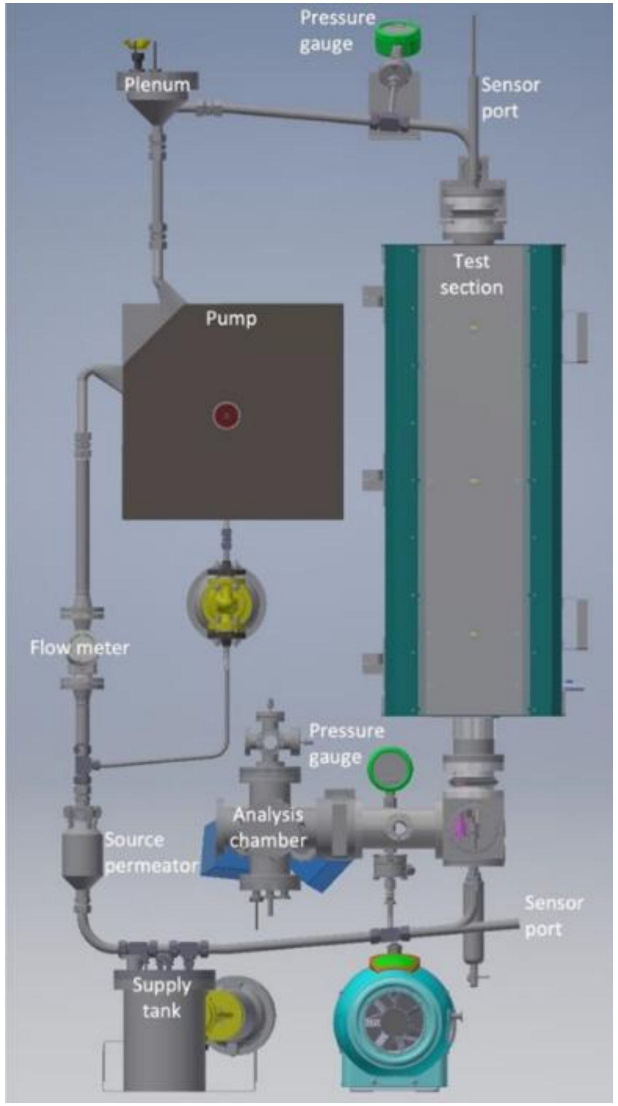
Modeling the TEX set up with SALAMANDER





- The Tritium Extraction eXperiment (TEX) set up is a forced-convection PbLi loop facility at the Idaho National Laboratory (INL) designed to test and validate technologies for extracting tritium
- Coupling the fluid flow and TMAP8 capabilities will help modeling the TEX experiments, including tritium transport through the PbLi loop and through the vanadium membrane in the test section.

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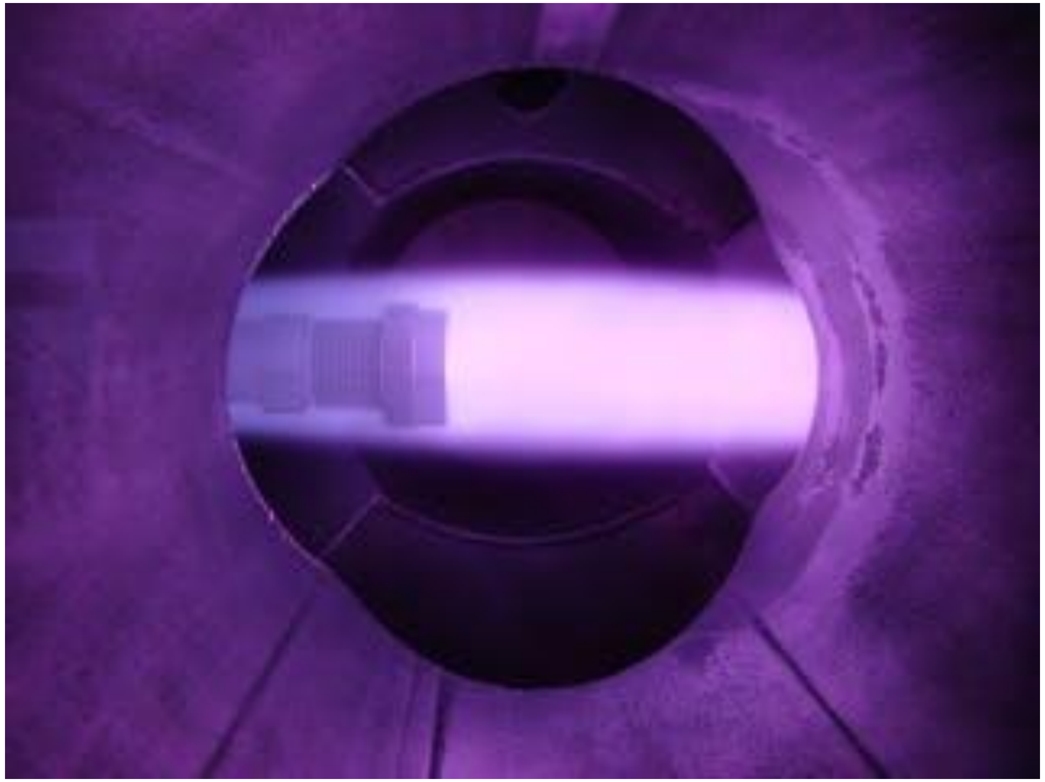
Modeling the Tritium Plasma Experiment with SALAMANDER



TPE experiment at STAR at INL

- The Tritium Plasma Experiment (TPE) is a linear plasma device to accelerate deuterium and tritium plasma ions into metal target samples.
- SALAMANDER is being developed to model the TPE experiments.
- By leveraging the heat transfer, tritium transport (TMAP8), and plasma modeling capabilities, SALAMANDER will be able to help design experiments and improve the quality of data analysis.

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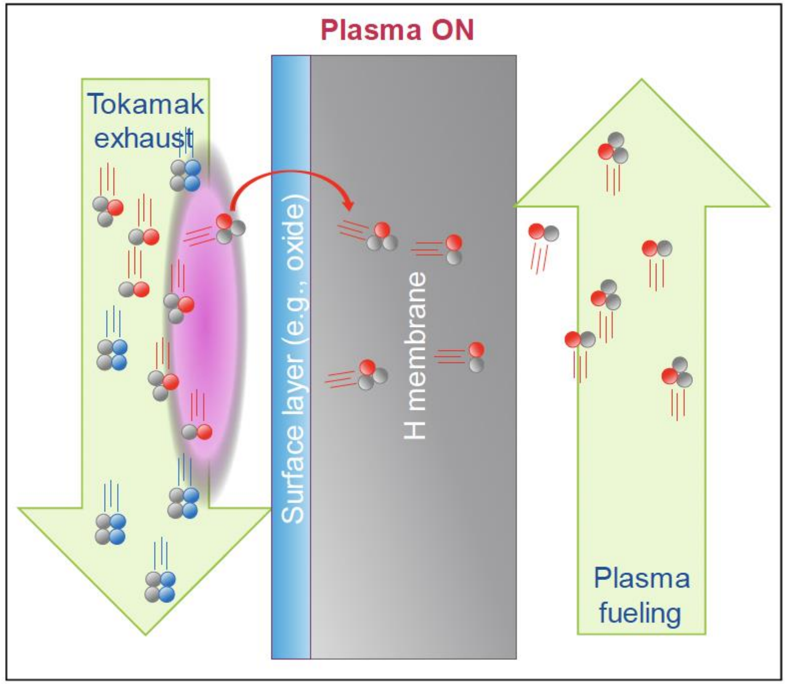
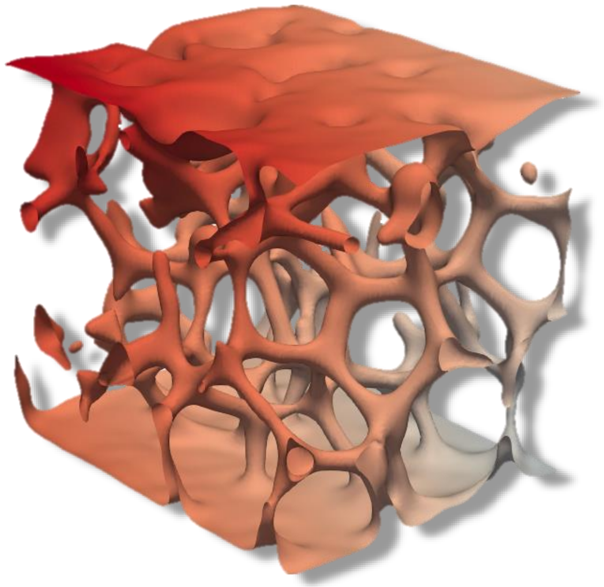
Modeling tritium extraction with TMAP8

- INL is exploring several technology for efficient tritium extraction, including metal foil pump (MFP) and reticulated capillary foam membrane
- MFP can be modeled using coupled TMAP8 with plasma and chemistry capabilities.
- Fluid flow, mechanics, and tritium transport in 3D are used to evaluate foam membranes.



Mechanism of tritium extraction by MFP



Example of a foam modeled In TMAP8

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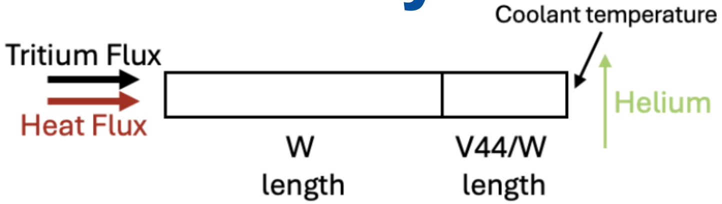
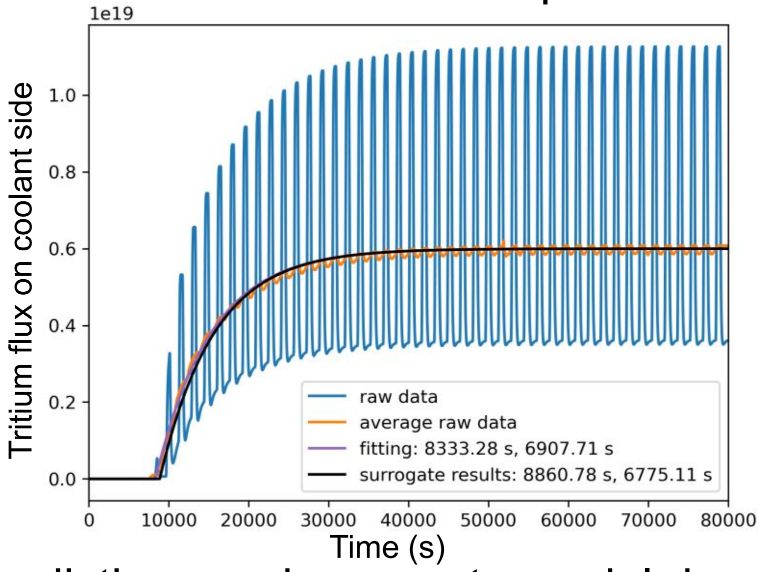
Multiscale modeling from components to system-level with TMAP8

Tokamak Energy



Geometry and conditions at the component scale (1D)

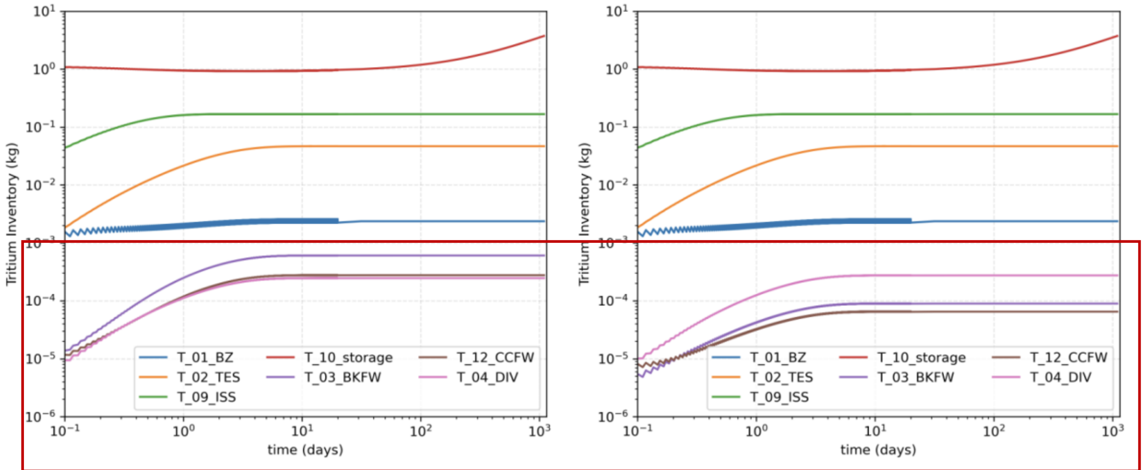
1000s such simulations are performed with different sizes, operation conditions, etc. to train a surrogate model.



Modeling predictions and surrogate model development over many design options and operational conditions.

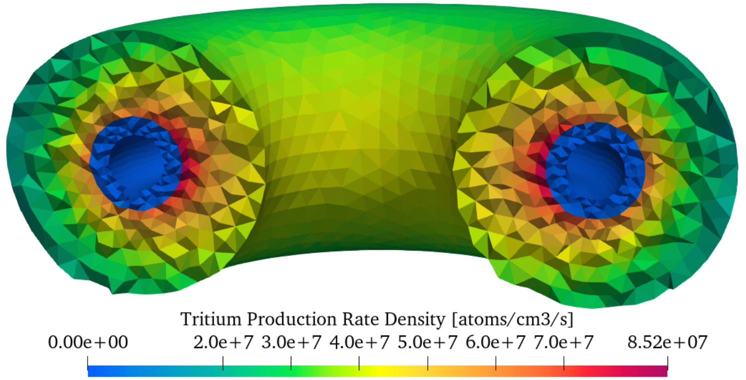
Fuel cycle calculations, where the effect of design and modeling choices on divertor, first wall, and central column retention is shown

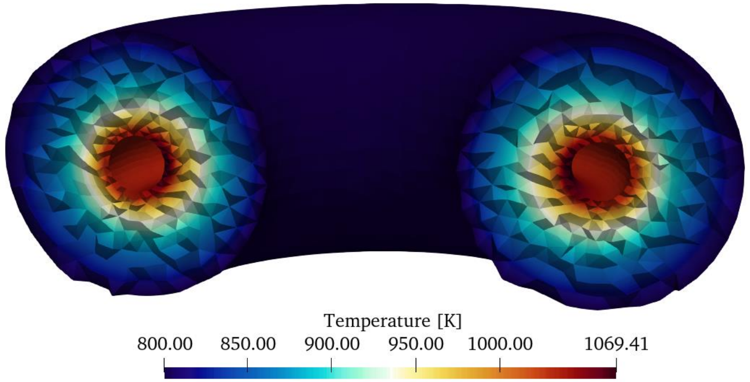
- Using TMAP8, we have investigated the tritium retention behavior of key components, developed surrogate models to capture their behavior, and we are now integrating the surrogate models into a system-scale fuel cycle model.
- We therefore capture, at the system-scale and at low computational costs, high-fidelity behavior from the component scale.
- This approach accelerates design iterations and links component-scale design and operational decisions to the fuel-cycle scale.

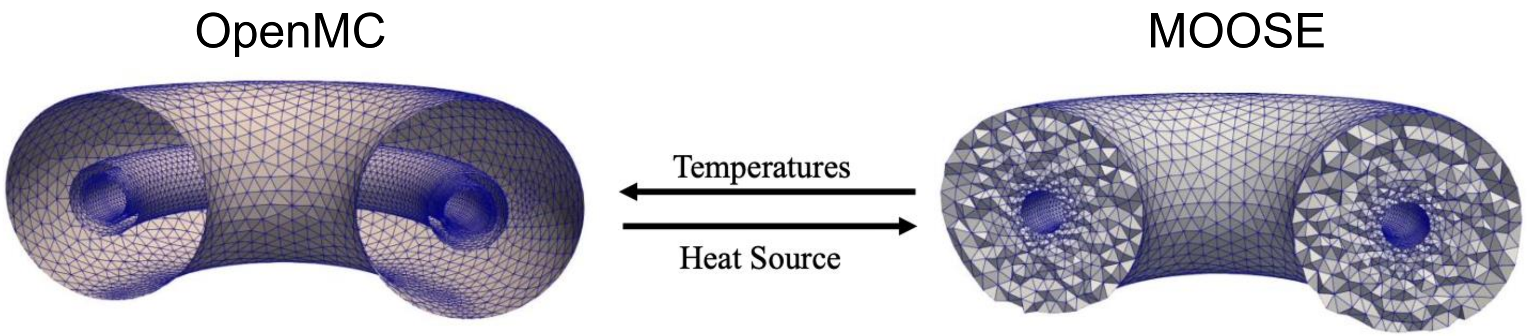


Development of a CAD-based geometry workflow for Neutronics + Multiphysics with Cardinal

- Investigated CAD-based geometry workflows and performed mesh refinement studies for:
  - DAGMC surface mesh
  - both DAGMC surface mesh and volumetric meshes used for tallying results and solving heat conduction
- Demonstrated that multiphysics results of interest could change as a result of either DAGMC model mesh not conserving the volume of the original CAD geometry, or a mismatch between the tally mesh and DAGMC particle transport mesh
- Cardinal uses MOAB skinner to regenerate DAGMC geometry on-the-fly directly from the volumetric mesh



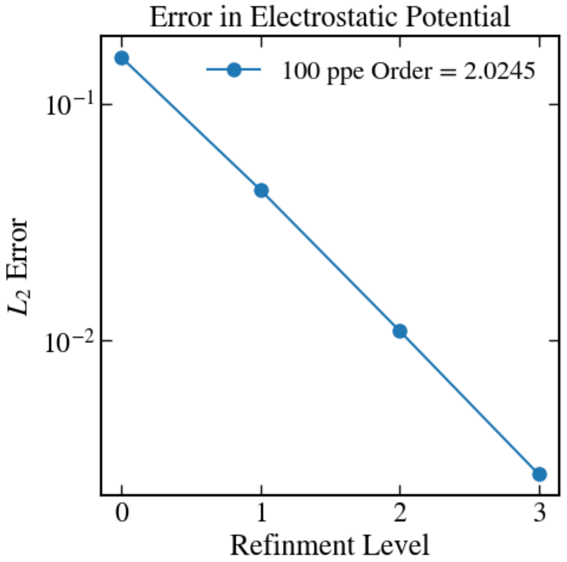


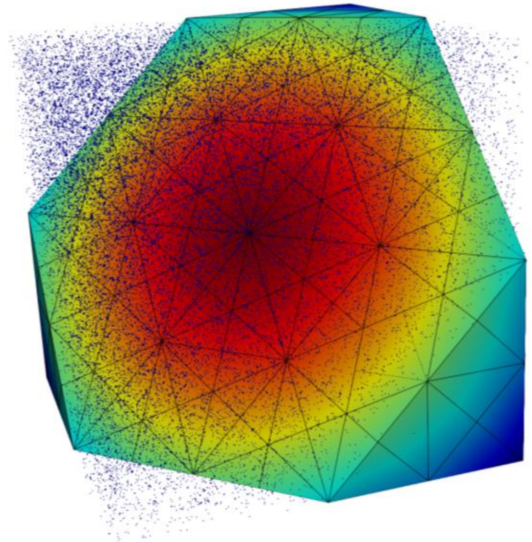


M. Eltawila et al., “Investigation of CAD-based Geometry Workflows for Multiphysics Fusion Problems Using OpenMC and MOOSE.” In Proceedings of the Pacific Basin Nuclear Conference (PBNC). American Nuclear Society, Idaho Falls, ID (2024). Pages 277-286. https://doi.org/10.13182/PBNC24-45030.

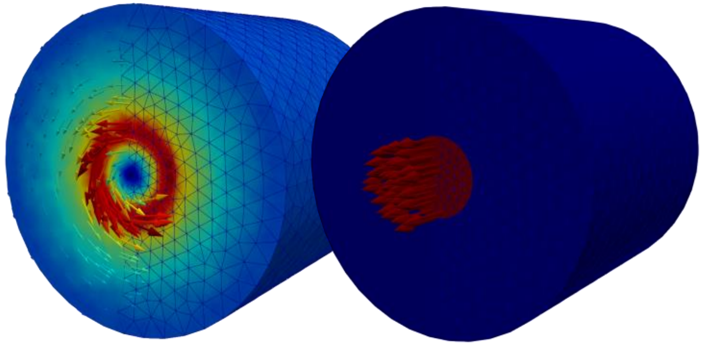
Particle In Cell (PIC) Simulations for plasma modeling

- Leverages the scalability and capability of MOOSE's Ray Tracing module
- PIC simulations can be performed in 1-, 2-, and 3-dimensional geometry with particles tracking 3 velocity components regardless of dimension
- PIC simulations can be performed on unstructured meshes
- Capabilities are being verified

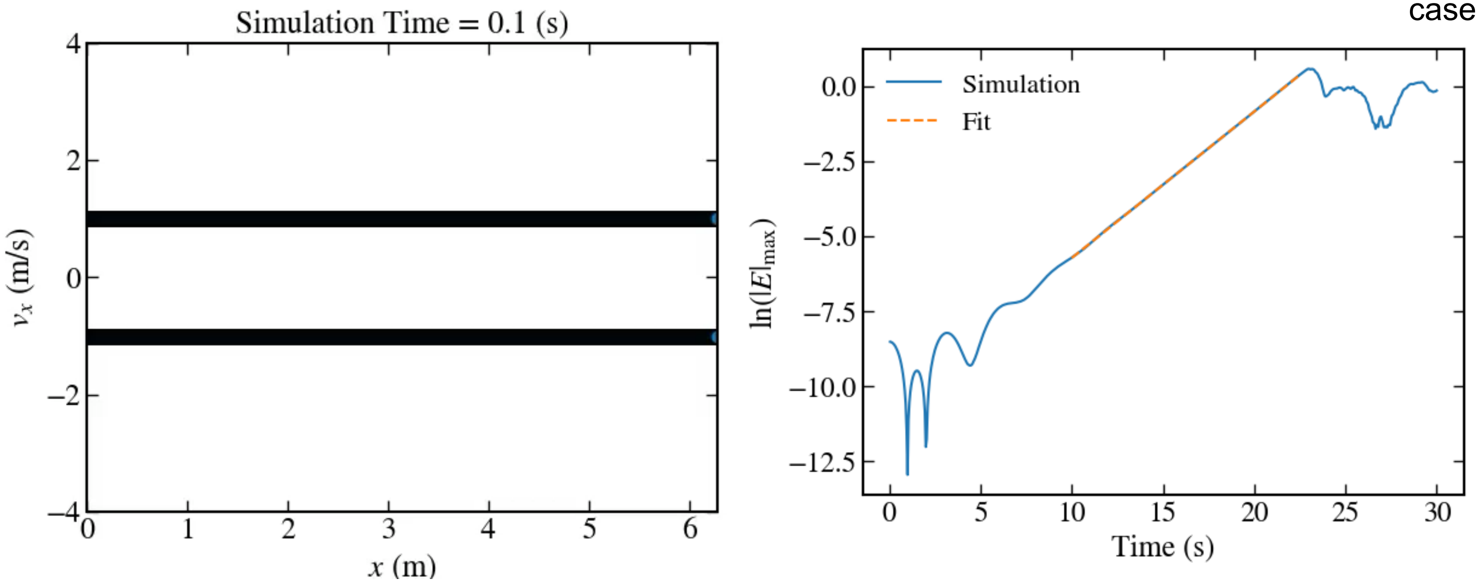




Particle Initialization: Results of a convergence study with a constant number of particles per element and the resulting 3D electrostatic potential, from a case with 1000 particles per element using tetrahedral elements.



Coupling with electromagnetics: Analytic solution for the magnetic field (left) inside and surrounding a current carrying wire produced by the current density source shown on the right.



Verification of a two-stream instability simulation

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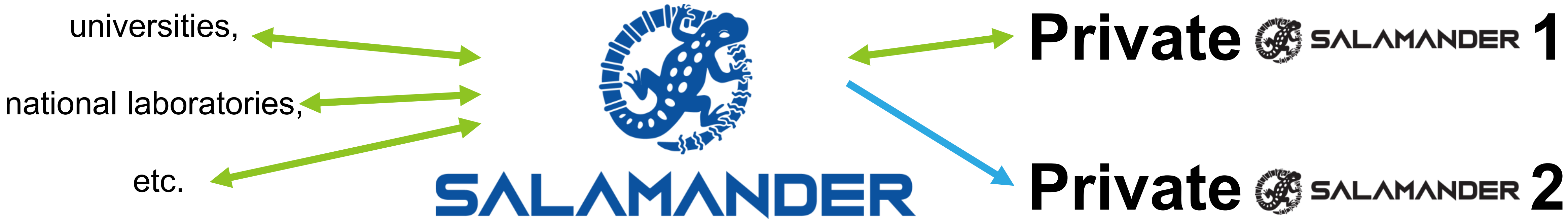
Supporting collaborative development through modularity and flexible licensing.

- TMAP8 and SALAMANDER are design-agnostic and can be used for a wide variety of systems
- TMAP8 and SALAMANDER, like MOOSE, uses the LGPL 2.1 license, which makes it very flexible

Open collaborations with



(local branches can remain private until authors decide otherwise)

Main open-source application hosted by INL

Private versions developed and controlled by private partners with proprietary data.

P.-C. A. Simon, et al., Fusion Engineering and Design, Volume 214, 2025, 114874. https://doi.org/10.1016/j.fusengdes.2025.114874.

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Conclusions

SALAMANDER TMAP8

Read more

- MOOSE is a proven system for complex multiphysics analysis to accelerate nuclear research, development, demonstration, and deployment (RDD&D)
- We are leveraging these capabilities to support multiscale, high-fidelity, multiscale modeling of fusion materials and fusion systems with NQA-1 compliant and open-source codes: SALAMANDER and TMAP8
- TMAP8 and SALAMANDER provide:
  - Multiscale / multiphysics modeling capabilities for fusion energy deployment
  - A suite of V&V and example case to establish trust, and starting points for users
  - Flexible tools supporting the transition from science to engineering. They are applicable to experimental design and analysis, science and engineering studies, safety analysis, etc.
- Ask to the community: Identifying Mod/Sim needs, contribute capabilities, and validation data.

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Acknowledgements

- This work was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, and authored by Battelle Energy Alliance, LLC under Contract No. DE-AC07-05ID14517.
- This work was supported through the INL's Laboratory Directed Research & Development (LDRD) Program under DOE Idaho Operations Office Contract DE-AC07-05ID14517.
- This research made use of Idaho National Laboratory's High Performance Computing systems located at the Collaborative Computing Center and supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract No. DE-AC07-05ID14517.

Idaho National Laboratory

Oak Ridge National Laboratory

VCU

UK Atomic Energy Authority

École Polytechnique

Institut Polytechnique de Paris

University of Illinois Urbana-Champaign

Tokamak Energy

NC State University

TMAP8

SALAMANDER

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Website

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TMAP8

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TMAP8 Verification & Validation (V&V) cases

Case Name	Case Title	TMAP4	TMAP7	TMAP8
	verification			
ver-1a	Depleting Source Problem	✓	✓	✓
ver-1b	Diffusion Problem with Constant Source Boundary Condition	✓	✓	✓
ver-1c	Diffusion Problem with Partially Preloaded Slab	✓	✓	✓
ver-1d	Permeation Problem with Trapping	✓	✓	✓
ver-1dc	Permeation Problem with Multiple Trapping		✓	✓
ver-1dd	Permeation Problem without Trapping		✓	✓
ver-1e	Diffusion in Composite Material Layers	✓	✓	✓
ver-1fa	Heat Conduction with Heat Generation	✓	✓	✓
ver-1fb	Thermal Transient	✓	✓	✓
ver-1fc	Conduction in Composite Structure with Constant Surface Temperatures		✓	✓
ver-1fd	Convective Heating		✓	✓
ver-1g	Simple Forward Chemical Reaction	✓	✓	✓
ver-1gc	Series Chemical Reactions		✓	✓
ver-1ha	Convective Gas Outflow Problem in Three Enclosures	✓	✓	✓
ver-1hb	Convective Gas Outflow Problem in Equilibrating Enclosures		✓	✓
ver-1ia	Species Equilibration Problem in Ratedep Condition with Equal Starting Pressures		✓	✓
ver-1ib	Species Equilibration Problem in Ratedep Condition with Unequal Starting Pressures		✓	✓
ver-1ic	Species Equilibration Problem in Surfdep Conditions with Low Barrier Energy		✓	✓
ver-1id	Species Equilibration Problem in Surfdep Conditions with High Barrier Energy		✓	✓
ver-1ie	Species Equilibration Problem in Lawdep Condition with Equal Starting Pressures		✓	✓
ver-1if	Species Equilibration Problem in Lawdep Condition with Unequal Starting Pressures		✓	✓
ver-1ja	Radioactive Decay of Mobile Tritium in a Slab		✓	✓
ver-1jb	Radioactive Decay of Mobile Tritium in a Slab with a Distributed Trap Concentration		✓	✓
ver-1ka	Simple Volumetric Source		✓	✓
ver-1kb	Henry's Law Boundaries with No Volumetric Source		✓	✓
ver-1kc-1	Sieverts' Law Boundaries with No Volumetric Source			✓
ver-1kc-2	Sieverts' Law Boundaries with No Volumetric Source		✓	✓
ver-1kd	Sieverts' Law Boundaries with Volumetric Source		✓	✓
	validation			
val-2a	Ion Implantation Experiment	✓	✓	✓
val-2b	Diffusion Experiment in Beryllium	✓	✓	✓
val-2c	Test Cell Release Experiment	✓	✓	✓
val-2d	Thermal Desorption Spectroscopy on Tungsten		✓	✓
val-2e	Co-permeation of H_2 and D_2 through Pd		✓	✓
val-2f	Modelling self-damaged tungsten effects on deuterium transport			Ongoing
val-2g	Analyzing FLiBe permeation experiment			Ongoing

- Verification ensures that the models are properly implemented.
- Validation ensures that the models reproduce experimental data.
- The validation cases show how TMAP8 can be used to analyze experimental measurements
- V&V cases can also be used as starting points for other analysis since input files and documentation are provided.
- TMAP8's V&V surpasses those of TMAP4 and TMAP7.
- A recently published journal paper presents the first half of TMAP8's V&V cases.

 P.-C. A. Simon, et al., Fusion Engineering and Design, Volume 214, 2025, 114874. https://doi.org/10.1016/j.fusengdes.2025.114874.

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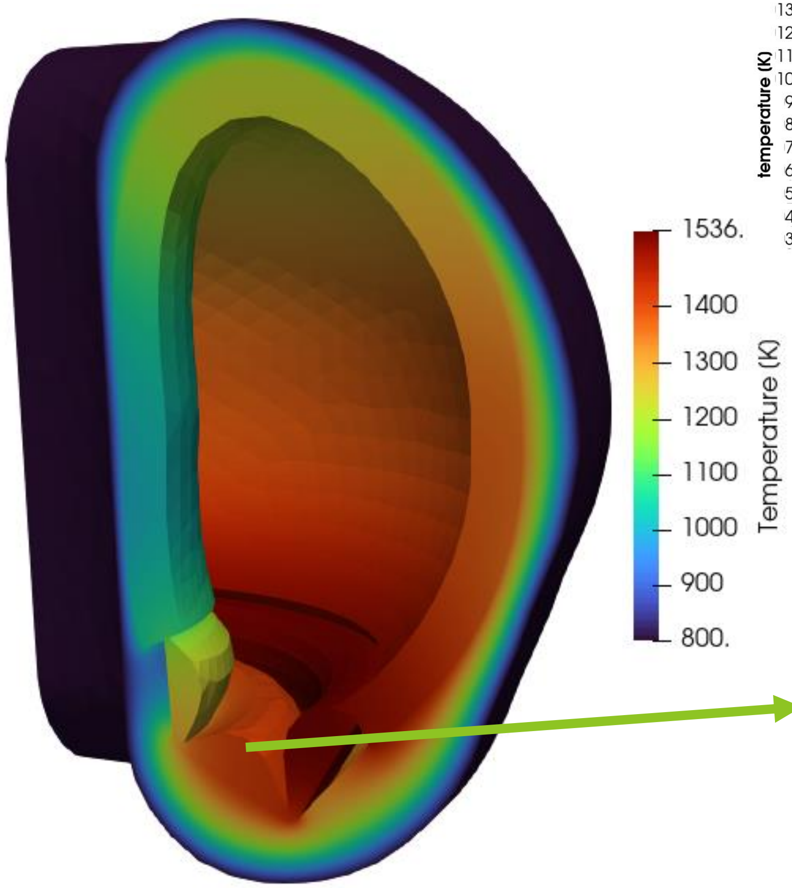
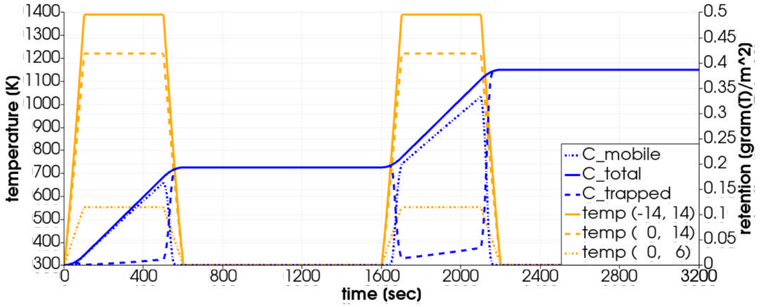
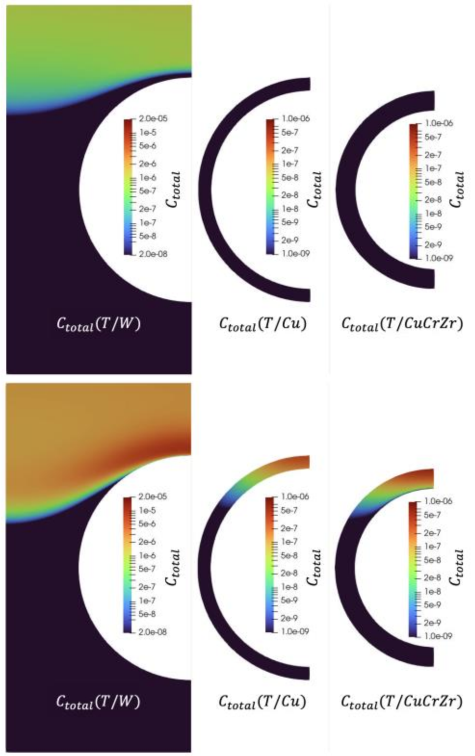
Modeling a divertor monoblock with TMAP8







- The divertor extracts heat and ash produced by the fusion reaction while protecting the main chamber from thermal loads
- Due to plasma exposure, tritium implantation is expected
- The ITER-type divertor monoblock is composed of three different materials with water coolant at its center
- TMAP8 models the temperature and tritium distribution
- This simulation is extended to multiphysics

M. Shimada et al., Fusion Engineering and Design, Volume 203, 2024, 114438, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2024.114438.

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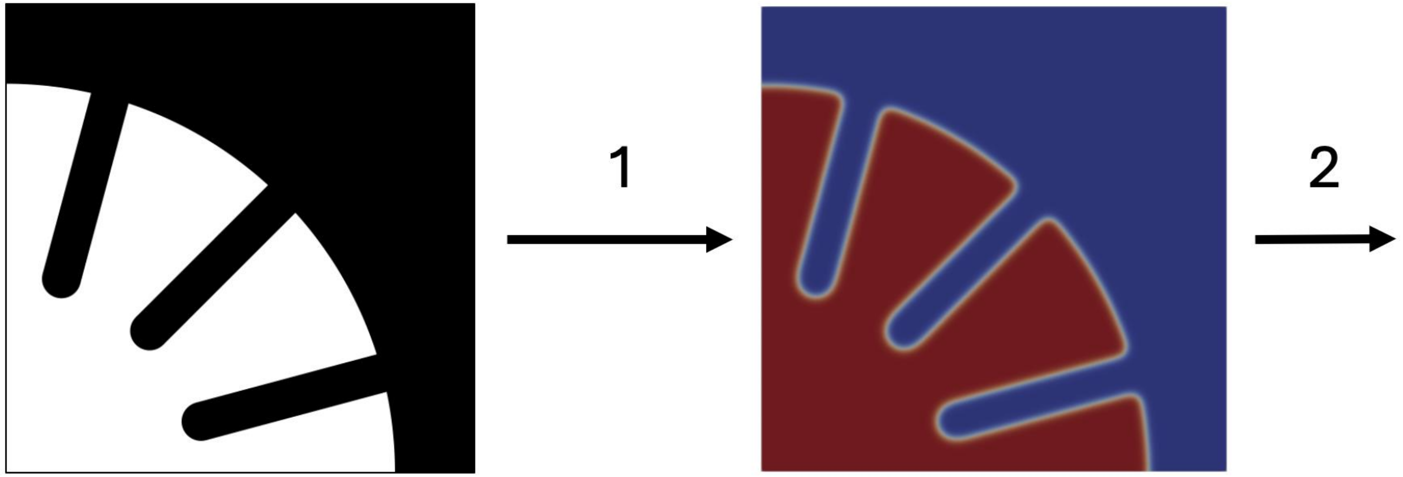
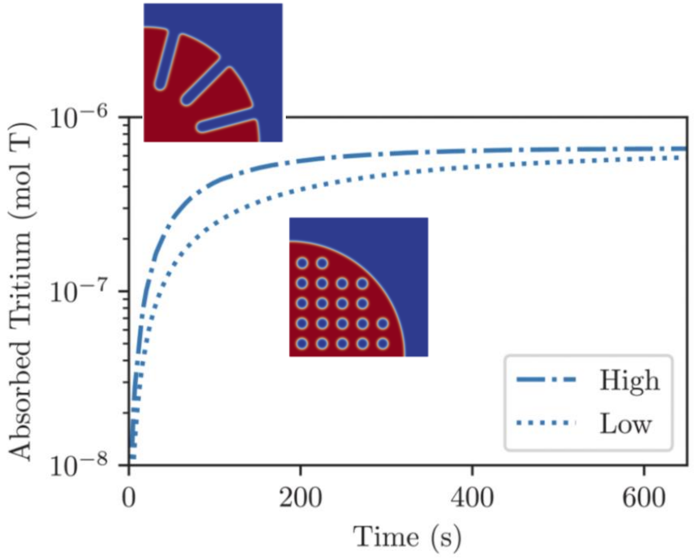
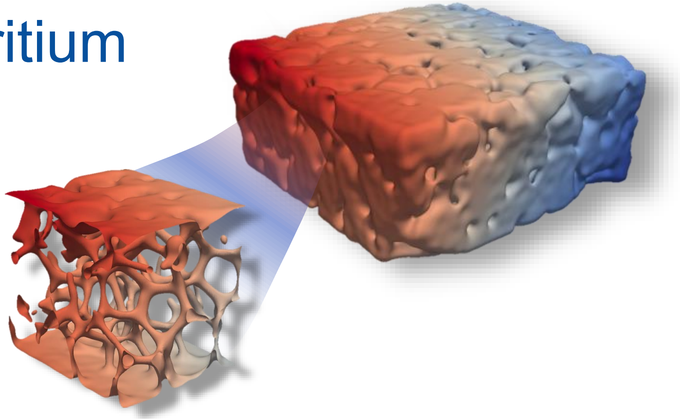
Mesoscale simulation with TMAP8 for breeder material development



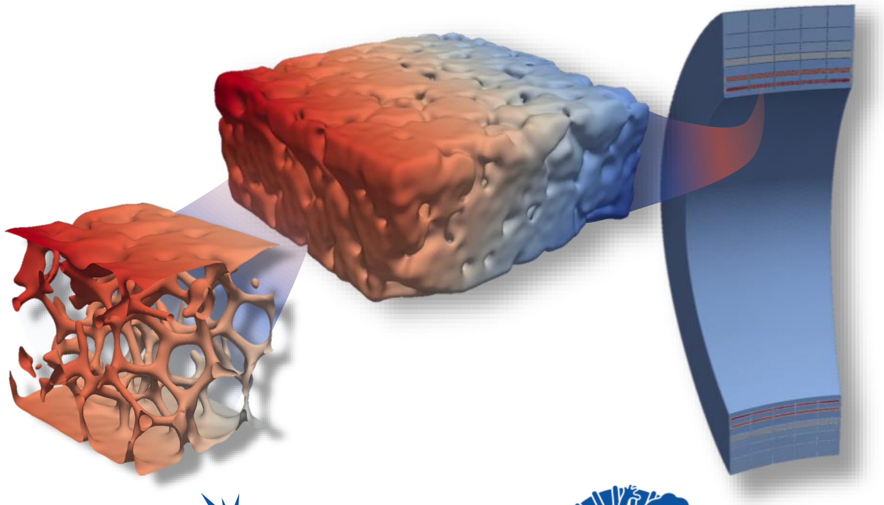


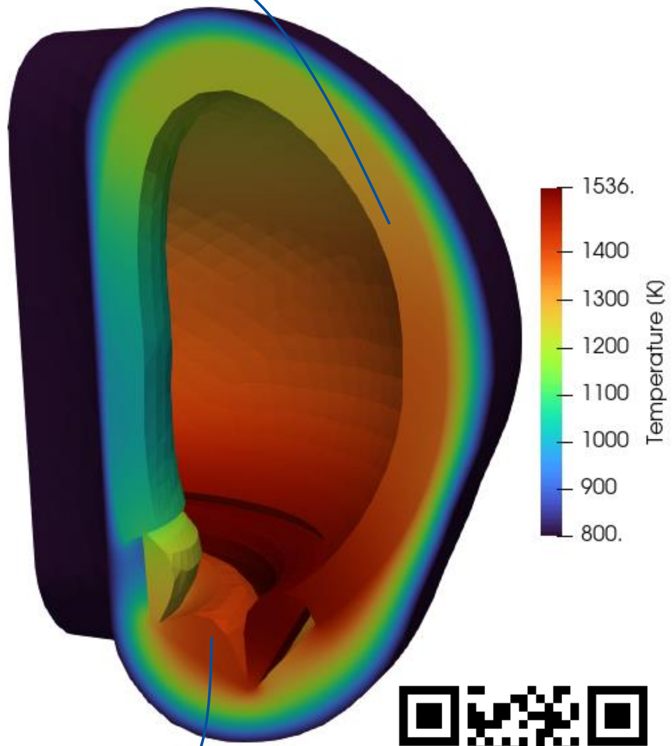
- TMAP8 can model tritium transport at the mesoscale.
- It can import microstructural images and perform tritium transport calculation.
- This enhances comparison against experiments since the microstructure can be accurately captured in the simulation
- It can then be used for microstructure optimization



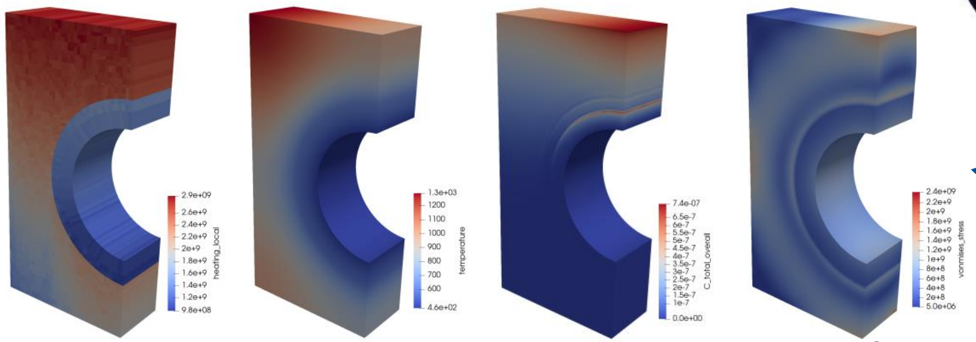
P.-C. A. Simon, P. W. Humrickhouse, A. D. Lindsay, "Tritium Transport Modeling at the Pore Scale in Ceramic Breeder Materials Using TMAP8," in IEEE Transactions on Plasma Science, 2022, doi: 10.1109/TPS.2022.3183525.

MOOSE-based capabilities for fusion modeling





TMAP8 SALAMANDER



Volumetric heating rate from neutronics (J/m^3s) | Temperature (K) | Tritium concentration (atomic fraction) | Von Mises Stress (Pa)

- Advanced MOOSE-based modeling and simulations are being developed and deployed for blankets and plasma facing components.
- Stemming from multiscale tritium transport capabilities through TMAP8, SALAMANDER provides integrated multiphysics capabilities.
- TMAP8 and SALAMANDER are open-source, NQA-1 compliant, and have a permissive license to enable public-private partnerships.

Website

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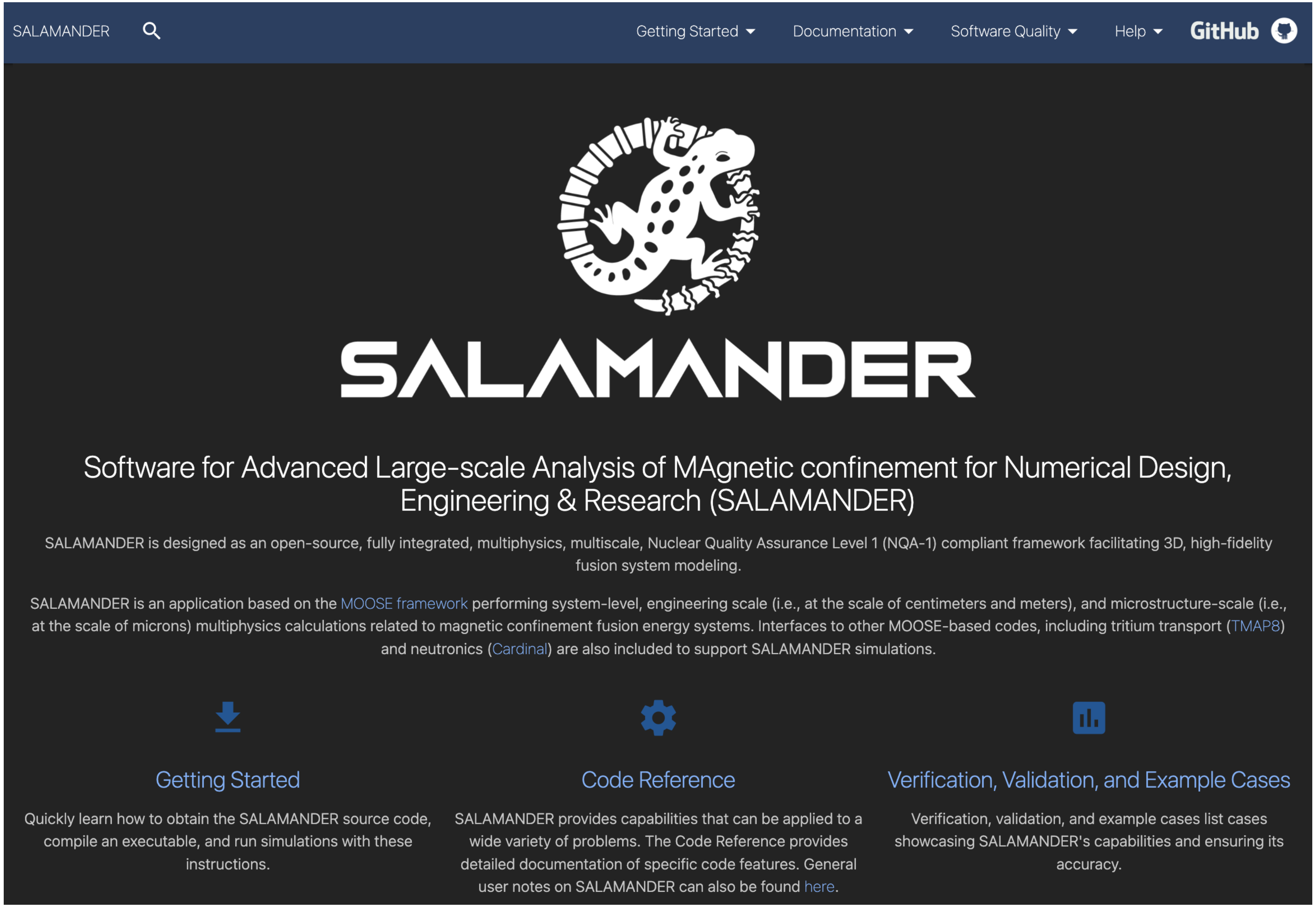
Getting started with SALAMANDER

website


SALAMANDER

Getting Started ▾ Documentation ▾ Software Quality ▾ Help ▾ GitHub

SALAMANDER

Software for Advanced Large-scale Analysis of MAgnetic confinement for Numerical Design, Engineering & Research (SALAMANDER)

SALAMANDER is designed as an open-source, fully integrated, multiphysics, multiscale, Nuclear Quality Assurance Level 1 (NQA-1) compliant framework facilitating 3D, high-fidelity fusion system modeling.

SALAMANDER is an application based on the MOOSE framework performing system-level, engineering scale (i.e., at the scale of centimeters and meters), and microstructure-scale (i.e., at the scale of microns) multiphysics calculations related to magnetic confinement fusion energy systems. Interfaces to other MOOSE-based codes, including tritium transport (TMAP8) and neutronics (Cardinal) are also included to support SALAMANDER simulations.

Getting Started

Quickly learn how to obtain the SALAMANDER source code, compile an executable, and run simulations with these instructions.

Code Reference

SALAMANDER provides capabilities that can be applied to a wide variety of problems. The Code Reference provides detailed documentation of specific code features. General user notes on SALAMANDER can also be found here.

Verification, Validation, and Example Cases

Verification, validation, and example cases list cases showcasing SALAMANDER's capabilities and ensuring its accuracy.

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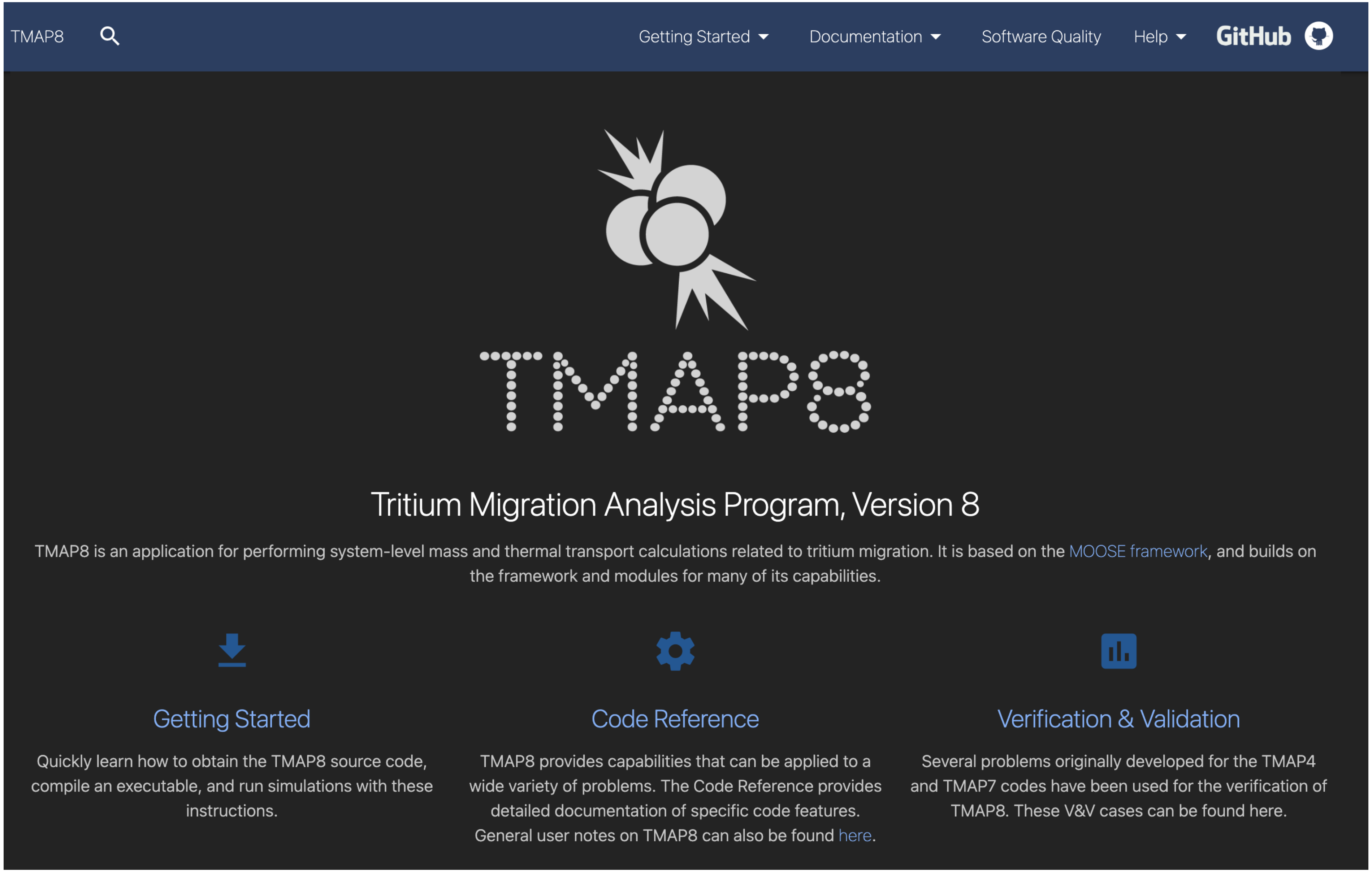
Getting started with TMAP8

website



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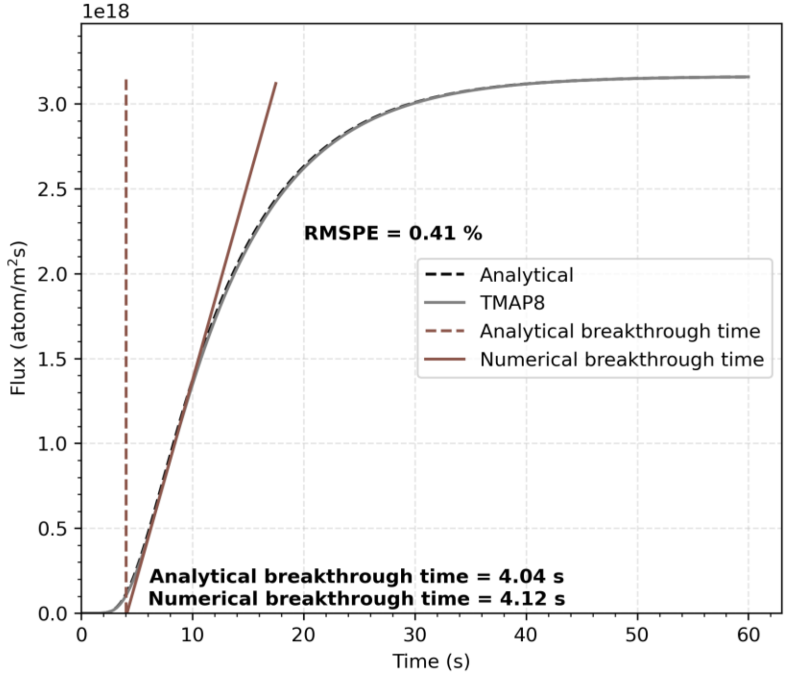
TMAP8 Verification highlight:

In ver-1dc, we model tritium transport in a slab with three trapping site populations with different energies and densities.

Comparison against analytical solution

$$\frac{dC_M}{dt} = \nabla D \nabla C_M - \text{trap\_per\_free} \cdot \sum_{i=1}^{3} \frac{dC_{T_i}}{dt},$$

$$\frac{dC_{T_i}}{dt} = \alpha_t^i \frac{C_{T_i}^{empty} C_M}{(N \cdot \text{trap\_per\_free})} - \alpha_r^i C_{T_i},$$



A small root mean square percentage error (RMSPE) quantifies a good agreement.

Method of Manufactured Solutions

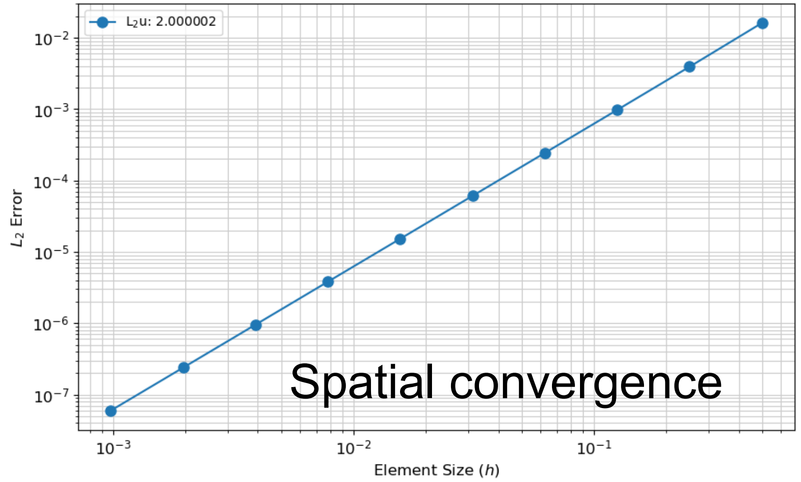
Manufactured Solutions:

$$u(x,t) = \cos(x)t, \quad u_i(x,t) = \frac{N u_{i,0}}{2}(t\cos(x) + 1),$$

New equations with forcing functions:

$$\frac{\partial u}{\partial t} - \nabla \cdot (D \nabla u) + \sum_{i=1}^{3} \frac{\partial u_i}{\partial t} - f = 0,$$

$$\frac{\partial u_i}{\partial t} - \alpha_t^i \frac{u_i^{\text{empty}} u}{N} + \alpha_r^i u_i - f_i = 0.$$



P.-C. A. Simon, et al., Fusion Engineering and Design, Volume 214, 2025, 114874. https://doi.org/10.1016/j.fusengdes.2025.114874.

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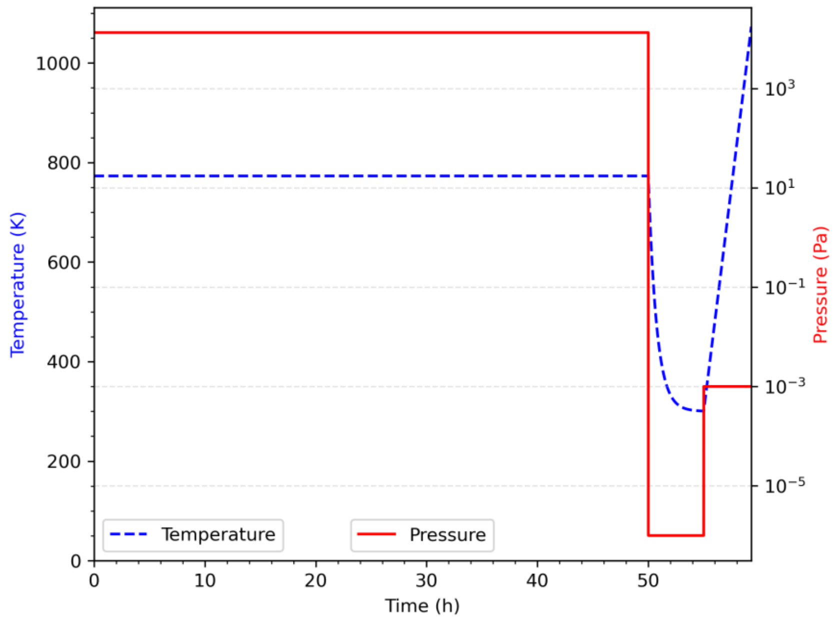
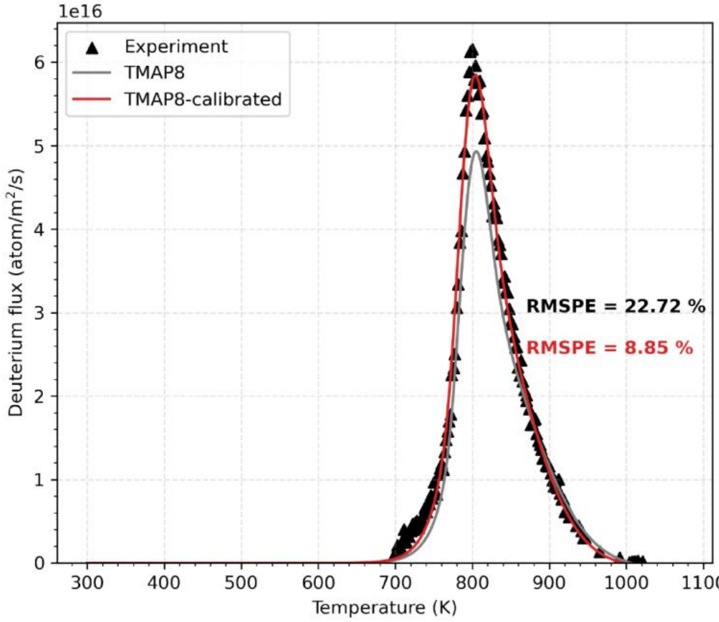
TMAP8 Validation highlight

Case Name	Case Title	TMAP4	TMAP7	TMAP8
	validation			
val-2a	Ion Implantation Experiment	✓	✓	✓
val-2b	Diffusion Experiment in Beryllium	✓	✓	✓
val-2c	Test Cell Release Experiment	✓	✓	✓
val-2d	Thermal Desorption Spectroscopy on Tungsten		✓	✓
val-2e	Co-permeation of H_2 and D_2 through Pd		✓	✓
val-2f	Modelling self-damaged tungsten effects on deuterium transport			Ongoing
val-2g	Analyzing FLiBe permeation experiment			Ongoing





- Validation cases show how TMAP8 can accurately reproduce experimental results
- The stochastic tools module is available for model calibration, uncertainty quantification
- They can be used as starting points for other studies.
  - In val-2a, we reproduce an experiment of ion implantation and desorption
  - Using model parameters from literature provides reasonable results
  - Calibration increases accuracy

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TMAP8 example cases

Examples

Inputs which demonstrate potential applications for TMAP8 capabilities, along with walk-through guides which should in theory allow users to leverage prior work.

Fuel cycles from Abdou et al. and Meschini et al.

Because TMAP8 is built on MOOSE, it brings MOOSE's capacity to solve ordinary differential equations using ScalarKernels. These can be quite useful to model parts of the system at high levels of abstraction while working with detailed models of specific components. As examples, we propose two fuel cycle models. The first model re-creates the fuel cycle model described in Abdou et al. (2021) as a high-level abstraction of a fuel cycle in a potential fusion power plant. The second model re-creates the fuel cycle model described in Meschini et al. (2023), which models the tritium fuel cycle for ARC-and STEP-class DT fusion power plants.

Divertor Monoblock

TMAP8 is used to model tritium transport in a divertor monoblock to elucidate the e
and cool-down cycles) on the tritium in-vessel inventory source term and ex-vessel
This example reproduces the results presented in Shimada et al. (2024).

Pore-Scale Tritium Transport in Imported Microstr

This example demonstrates TMAP8's capability to (1) generate pore structures from
transport on these pore structures based on the model described in Simon et al. (20
tritium transport.

- Example cases are intended to show how TMAP8 can be used, and how to perform key studies.
- They can be used as starting points for other analysis.

Kernels

For the mass conservation equation, we use ADTimeDerivative and ADMatDiffusion to represent the 1st and 3rd terms of Eq. (3). The TMAP8 kernels TrappingNodalKernel and ReleasingNodalKernel represent the 4th and 5th terms of Eq. (3), respectively, and simulate the trapping/release behavior of hydrogen isotopes in/from trap sites. For the conservation of energy equation, SpecificHeatConductionTimeDerivative and HeatConduction solve the 1st and 3rd terms of Eq. (4). `ADTimeDerivative` and `ADMatDiffusion` are kernels from the core MOOSE framework, and `SpecificHeatConductionTimeDerivative` and `HeatConduction` are kernels from the MOOSE Heat Transfer Module. These pre-made kernels are commonly re-used to represent time derivative, diffusion, and heat conduction terms in a given material within a variety of MOOSE-based simulations.

```
[Kernels]
  ############################## Kernels for W (block = 4)
  [diff_W]
    type = ADMatDiffusion
    variable = C_mobile_W
    diffusivity = diffusivity_W
    block = 4
    extra_vector_tags = ref
  []
  [time_diff_W]
    type = ADTimeDerivative
    variable = C_mobile_W
    block = 4
    extra_vector_tags = ref
  []
  [coupled_time_W]
    type = ScaledCoupledTimeDerivative
    variable = C_mobile_W
    v = C_trapped_W
    factor = 1e0
    block = 4
    extra_vector_tags = ref
  []
```

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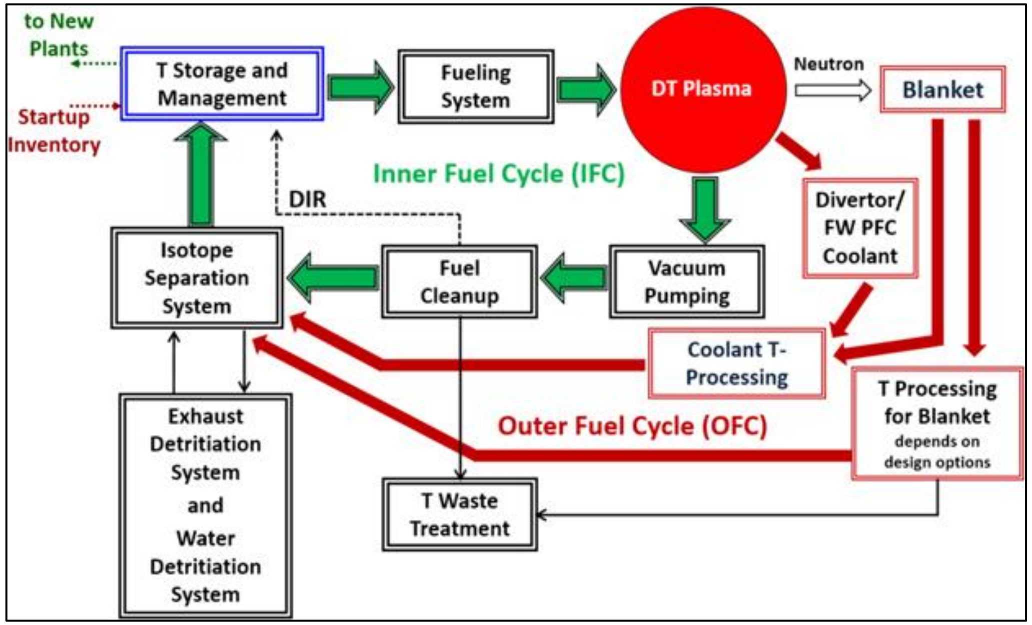
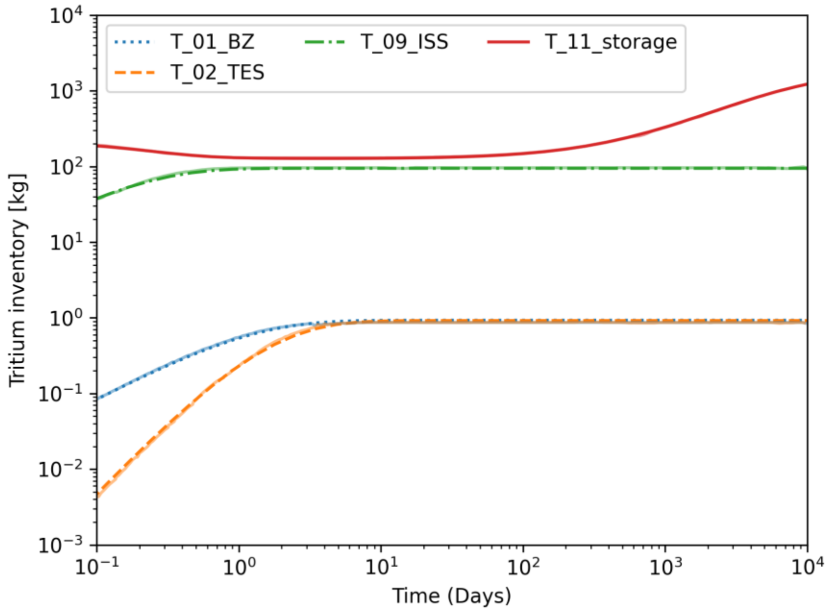
TMAP8 example cases – The tritium fuel cycle



System Name	System number	Tritium inventory variable	system equation
Breeding zone	1	T_01_BZ	Eq. (1)
Tritium Extraction System	2	T_02_TES	Eq. (2)
First Wall	3	T_03_FW	Eq. (3)
Divertor	4	T_04_DIV	Eq. (4)
Heat Exchanger	5	T_05_HX	Eq. (5)
Coolant Purification System	6	T_06_CPS	Eq. (6)
Vaccum Pump	7	T_07_vacuum	Eq. (7)
Fuel Clean-up	8	T_08_FCU	Eq. (8)
Isotope Separation System	9	T_09_ISS	Eq. (9)
Exhaust and Water Detritiation System	10	T_10_exhaust	Eq. (10)
Storage and Management	11	T_11_storage	Eq. (11)

- TMAP8 can perform 0D simulation of the fuel cycle and evaluate the tritium inventory in each part of the system.
- It can also be coupled with lower length-scale simulations to derive on the fly the behavior of subsystems.



[1] Abdou, Mohamed, et al. "Physics and technology considerations for the deuterium–tritium fuel cycle and conditions for tritium fuel self sufficiency." *Nuclear fusion* 61.1 (2020): 013001.
[2] Riet, Adriaan Anthony. "Systems Level Fuel Cycle Modeling in TMAP8 - A Demonstration." , Oct. 2024.
[3] Simon, Pierre-Clément, et al. "MOOSE-based Tritium Migration Analysis Program, Version 8 (TMAP8) for advanced open-source tritium transport and fuel cycle modeling." Fusion Engineering and Design (2025)