

Dynamic Coupling of TMAP8 and EMERALD for Risk-Informed Fusion Fuel-Cycle Analysis

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Abstract: Accurately characterizing fuel inventory is critical for risk-informed design and operation of future nuclear fusion machines. The Idaho National Laboratory has developed a mass-balance model for fusion fuel-cycle analysis using the Tritium Migration Analysis Program (TMAP8); however, this model is inherently static, relying on fixed parameter values that do not capture the temporal effects of equipment degradation, maintenance schedules, or stochastic system failures. To address this limitation, we have developed a two-way close-coupling methodology between TMAP8 and the Event Modeling Risk Assessment using Linked Diagrams (EMERALD) dynamic probabilistic modeling tool. This framework enables the fusion fuel-cycle mass-balance model to interact with a time-dependent representation of plant performance, allowing operational states and degradation mechanisms to directly influence fuel inventory predictions.

In the coupled approach, EMERALD simulates system-level reliability behaviors—including component degradation, repair cycles, maintenance outages, and random failures—while TMAP8 computes corresponding changes in fuel-cycle flows and inventory levels. The two models exchange data iteratively, producing a fully dynamic, risk-informed representation of fuel inventory under evolving plant conditions. A case study using representative failure and degradation parameters are provided to demonstrate how integrating dynamic PRA with fuel-cycle modeling can reveal insights into operation and maintenance strategies that static analyses may overlook.

This work establishes a methodological foundation for applying dynamic PRA principles to fusion fuel-cycle design, enabling more accurate evaluation of operational margins, storage requirements, and system resilience. The resulting framework provides a pathway toward next-generation, risk-informed fuel-cycle analysis tools for advanced fusion energy systems.

1. INTRODUCTION

1.1. Nuclear Fusion Fuel Cycle

Deuterium-tritium (D-T) fusion machines are breeder systems that generate their own tritium fuel in a closed-loop cycle, which is one of the most challenging aspects of fusion energy development, consisting of two interconnected sub-cycles. As illustrated in Figure 1 [1], the fuel cycle can be visualized as a block diagram showing the main components and tritium flow rates throughout the system. Energetic neutrons from D-T fusion reactions in the plasma core breed tritium in the breeding zone, while unburned tritium is exhausted from the scrape-off layer (SOL). On the right side of the figure are two branches of the outer fuel cycle (OFC). The first, labeled “Outer Fuel Cycle – TES,” (marked in red) handles bred tritium, extracting it via the tritium extraction system (TES). The second, labeled as “Outer Fuel Cycle – CPS,” (marked in blue) manages tritium that permeates through plasma-facing components, such as the first wall and divertor, passing through heat exchanger and coolant purification system (CPS). The OFC transfers the extracted tritium to the inner fuel cycle (IFC) which processes and recirculates the fuel. The IFC comprises of a vacuum pump, fuel clean-up system, isotope separation system (ISS), exhaust and water detritiation system, and a storage and management system, all of which work in sequence to purify and recover tritium before it is re-injected into the plasma via the fueling system.

operational experience have led to impressive RAMI capabilities for fission. By contrast, fusion systems have yet to see such progress and emphasis on RAMI is therefore critical. To have the most positive impact, RAMI analyses and considerations must be included early in the design of new systems [5].

1.3. Gap Analysis

A fusion machine must be able to produce at least as much tritium as it consumes during operation. This is the underlying concept of tritium self-sufficiency. Without it, D–T fusion is not sustainable. There is not enough commercially available tritium globally to run even one 500 MW power plant for a year [6], let alone a fleet. Achieving this self-sufficiency is one of the most critical engineering challenges for future fusion systems, which is highly dependent on the machine’s availability factor [1]. This availability factor is further determined by the dynamic evolution of component states and how it affects other components’ performance. Therefore, there is a need to evaluate tritium mass balance in the fuel cycle model together with the RAMI aspect of the fusion systems.

2. METHODOLOGY

This section describes the coupling between a dynamic risk assessment tool (EMRALD) and a physics analysis tool (TMAP8).

2.1. Fuel Cycle Modeling using TMAP

TMAP8 is an open-source modeling tool designed to simulate mass and thermal transport phenomena associated with tritium migration in fusion and fission energy systems. Built on the Multiphysics Object-Oriented Simulation Environment (MOOSE) framework, TMAP8 inherits a versatile architecture that allows users to couple diverse physics models and scale simulations from small, workstation-level problems to large, high-performance computing environments, and can directly incorporate multiscale models as necessary. TMAP8 is used across research institutions to analyze tritium behavior in complex engineered systems, including breeding blankets, fuel handling components, and cooling loops. Because MOOSE provides an object-oriented modular design, TMAP8 enables users to construct custom kernels, define scalar transport systems, and integrate new phenomena as needed.

TMAP8 has been used to model the fusion fuel-cycle developed by Abdou et al. and shown in Figure 1 [1]. This model divides the fuel cycle into 11 interconnected systems, each governed by its own ordinary differential equation describing time-dependent tritium inventory. The model in TMAP8 uses scalar variables to track the tritium content in each subsystem and applies ODETimeDerivative and ParsedODEKernel objects to construct the governing equations. These terms include tritium flows, efficiencies, leak fractions, decay, residence times, and other operational characteristics specific to fusion machine designs [7].

TMAP8 is also recently equipped with the FuelCycleSystemScalarKernel to model these fuel cycle systems without manual coding that can introduce arithmetic or transcription errors. This higher-level kernel allows each subsystem to be defined with a single kernel, using Functors that encapsulate system inputs, leakage behavior, and external sources or sinks and which could be tied directly to higher-fidelity simulations. The model includes numerous constant Postprocessors representing physical parameters (e.g., efficiencies, leak fractions, residence times) and gathers subsystem outputs to compute the total tritium inventory.

2.2. Dynamic System Modeling using EMRALD

EMRALD provides an advanced framework for dynamic Probabilistic Risk Assessment (PRA) [8]. Unlike traditional PRA, which treats systems as static logical constructs, EMRALD facilitates modeling of time-dependent interactions, feedback mechanisms, and tightly integrated external simulations. EMRALD is comprised of two major tools as follows:

- Web-based model development user-interface tool
The web-based tool provides a graphical user interface (GUI) to develop dynamic models in the form of compact state diagrams. Each diagram contains multiple states which represent

different conditions of components, systems, operator actions, etc. These states are connected through events triggered by time or various conditions. Failure rates, operator actions, and system logic are incorporated into state transitions, enabling simulation of high-level operations to component-level dynamics.

- Console-based solver engine tool
EMRALD employs a three-phase discrete-event solver that samples distributions, monitors conditions and processes event queues chronologically. Upon entering a new state, immediate actions are executed, conditional triggers are evaluated, and events scheduled. This repeating loop continues until specified termination conditions are met, producing detailed timing and event sequences leading to the key states defined by the modeler. Statistical results for key states and specified variables, along with state path visualizations are provided as outputs from EMRALD.

A core strength of EMRALD lies in its modular, open-architecture coupling capabilities as follows:

- Unidirectional and bi-directional coupling capabilities
EMRALD can launch external physics-based tools (e.g., flood, fire, or thermal-hydraulic models), using outputs to inform state transitions to the external tool. In the bi-directional coupling, the external model’s outputs are fed back into EMRALD during runtime.
- Custom user interface forms
An update to EMRALD introduced a library enabling analysts to create custom user-interface forms to configure external code runs without requiring scripting expertise. This allows less specialized users to perform integrated, dynamic simulation analyses within EMRALD’s environment.

2.3. Coupling EMRALD to TMAP8

EMRALD communicates with TMAP8 through a persistent WebSocket connection that exchanges JavaScript Object Notation (JSON) messages. As illustrated in Figure 2, a WebSocket and state-machine interface was implemented to execute TMAP8 via the MOOSE *StochasticControl* utility [9], enabling seamless interaction with EMRALD. When a simulation begins, EMRALD connects to the server, specifies that TMAP8 should be executed, and synchronizes shared components and variables.

During execution, EMRALD issues actions (e.g., “start,” “modify component,” “pause,” “stop,” “restart”) to the external simulator, while the simulator responds with events (e.g., parameter updates, timer expirations, simulation completion). EMRALD processes these events through its state machine, ensuring that the external physics code and EMRALD’s logical model remain synchronized throughout the simulation.

Sets of simulations can be launched from a single input configuration to generate representative sampling statistics. These simulation sets were performed using resources from the Idaho National Laboratory High-Performance Computing Center; however, the relatively lightweight TMAP8 and EMRALD models are also suitable for execution on a modern consumer laptop while still producing statistically meaningful results.

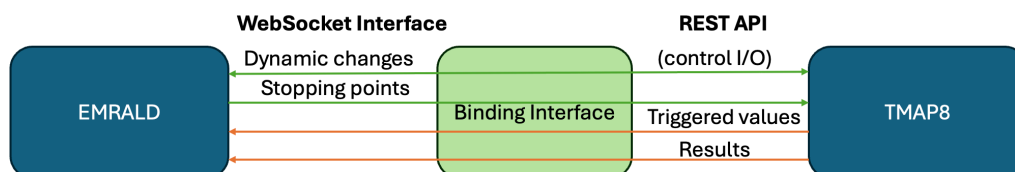


Figure 2. EMRALD/TMAP8 coupling schematic. EMRALD communicates with an interface script that converts EMRALD states into MOOSE-compatible requests and definitions.

2.4. Case Study

An example case study is provided to demonstrate the application of the EMERALD–TMAP8 coupling mechanism. The case study compares operation and maintenance (O&M) strategies and their impacts on tritium economy in the fusion fuel cycle. All numerical values used for the maintenance strategies are illustrative and do not represent any actual fusion machine.

The first strategy uses a fixed periodic maintenance schedule of 14 days every 18 months. At the start of each maintenance period, a control mechanism is assumed to purge tritium from all fuel-cycle systems except the storage system. This reduces radiological hazards for maintenance personnel. In EMERALD, this purge is modeled by temporarily setting system residence times to 1 and isolating the storage and management system from the rest of the fuel cycle during the 14-day window. These modified values are transferred to TMAP8 and then restored to normal after maintenance concludes, as shown in Figure 3.

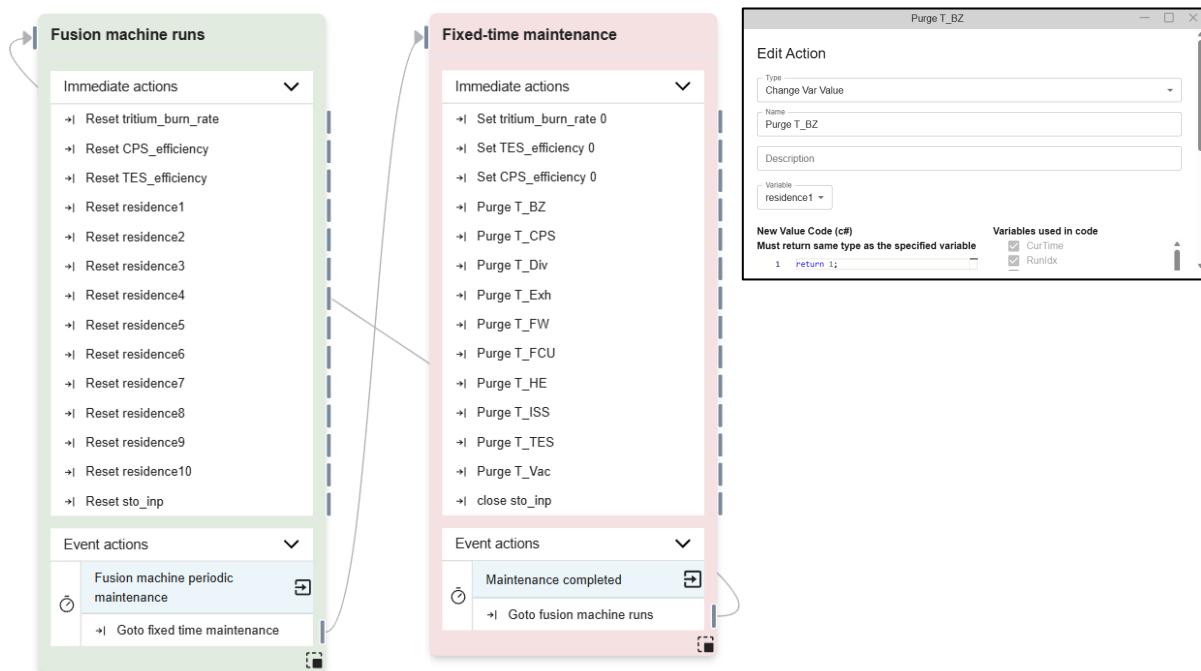


Figure 3. EMERALD diagram for the fixed-length maintenance strategy

The second strategy allows a dynamic maintenance period that may extend beyond 14 days. As shown in Figure 4, the fusion machine first enters a hot-shutdown mode at the start of maintenance. Fusion reactions cease, but the fuel-cycle systems continue operating, enabling tritium to accumulate in the storage and management system. Once tritium levels in the fuel-cycle systems are considered safe for personnel, the machine transitions to cold-shutdown mode, turning off the fuel-cycle systems and beginning the 14-day maintenance period. Additionally, if the machine becomes inoperable due to random failures in supporting systems (e.g., magnet systems or heating and current-drive systems) that do not affect the fuel cycle, only the machine is shut down (hot shutdown), while the fuel-cycle systems continue operating to recover tritium. In EMERALD, fusion machine shutdown is represented by setting the tritium burn rate to 0, and fuel-cycle shutdown is represented by setting the active systems' efficiencies (e.g., tritium extraction and coolant purification systems) to 0.

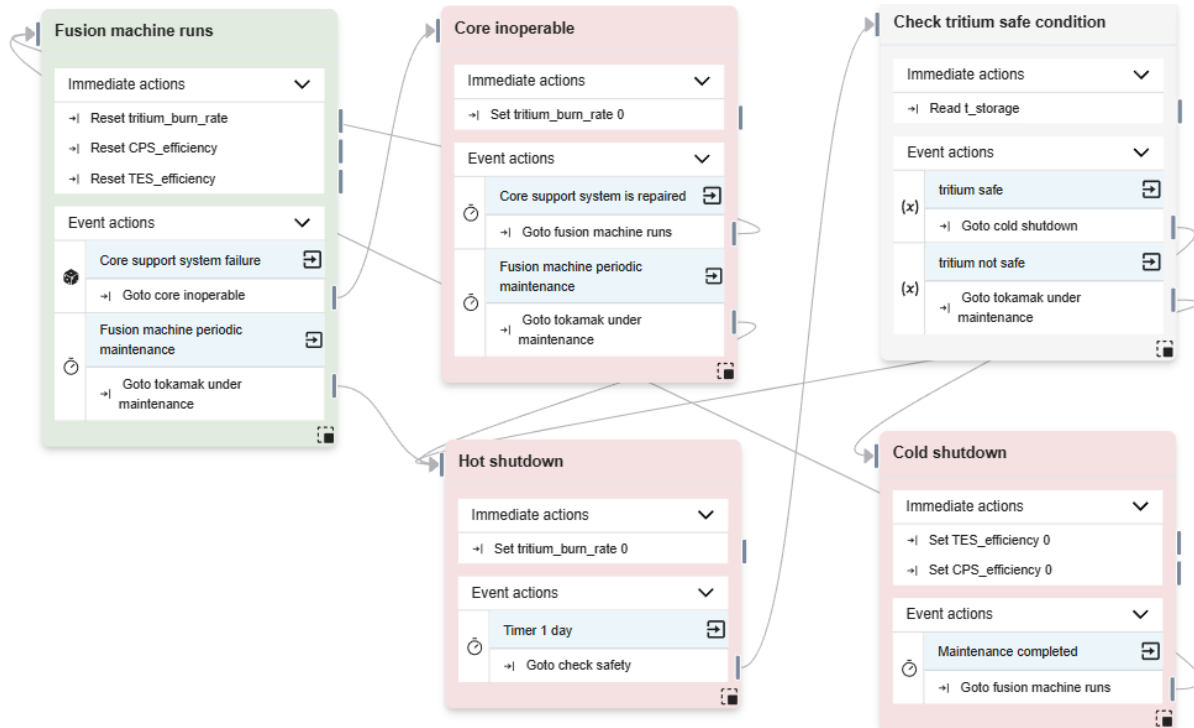


Figure 4. EMRALD diagram for the dynamic-length maintenance strategy

This second strategy also incorporates the tritium extraction system (TES) EMRALD diagram shown in Figure 5 to illustrate how the reliability of individual systems can be modeled. The underlying hypothesis is that the fusion machine and its fuel cycle may continue operating for a limited coping time even when individual fuel-cycle systems degrade or malfunction. To investigate this, isolation valves are added to the three mass-flow lines connected to the TES unit (Figure 1), and a fourth purge valve is included to empty any remaining TES inventory, simulating a full TES replacement. When the TES unit degrades, its efficiency decreases and it is temporarily isolated from the breeding zone but remains connected to the isotope separation system (ISS). This allows accumulated tritium in the TES unit to be transferred to the ISS until it reaches a safe level for workers. If the TES unit fails completely, its extraction efficiency drops to zero, it is fully isolated from all systems, and its remaining tritium inventory is purged until safe replacement conditions are met.

All fuel cycle parameters in this case study follow reference [1], except that the tritium breeding ratio is reduced from 1.9247 to 1.5.

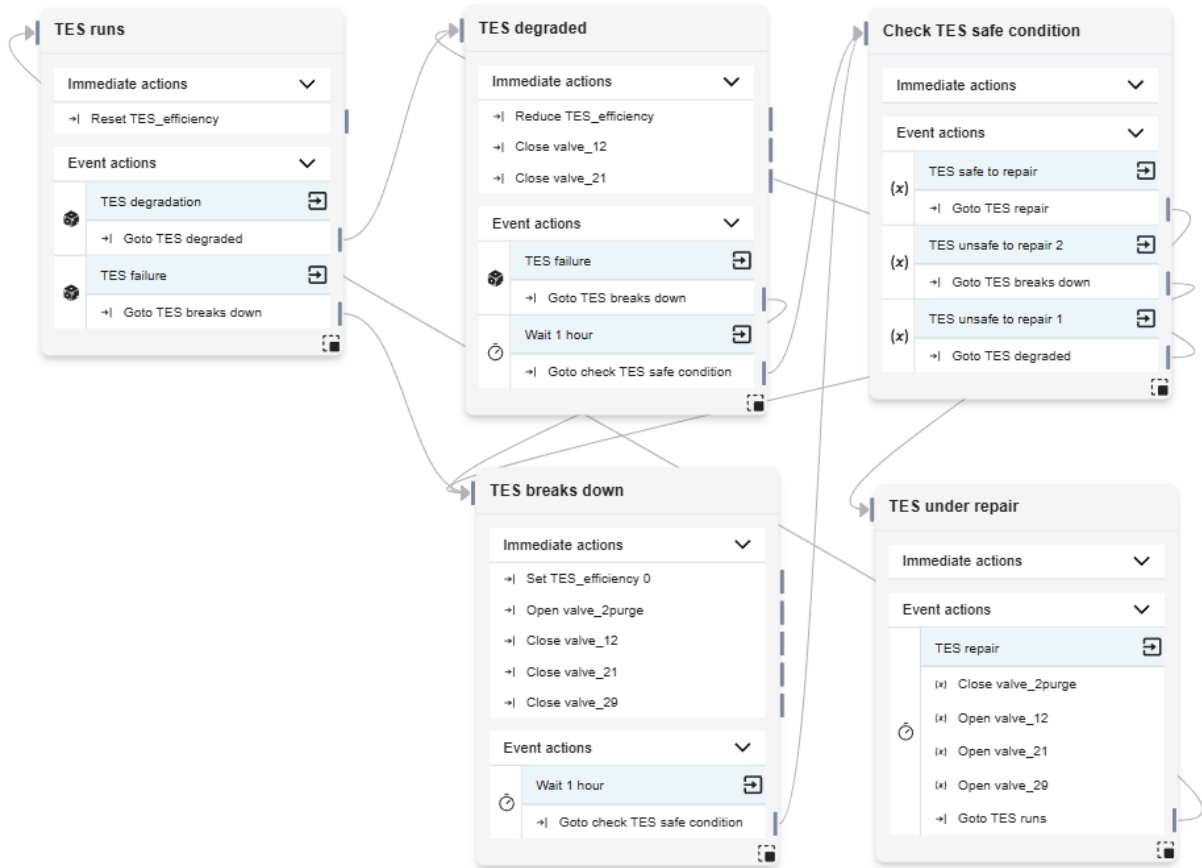


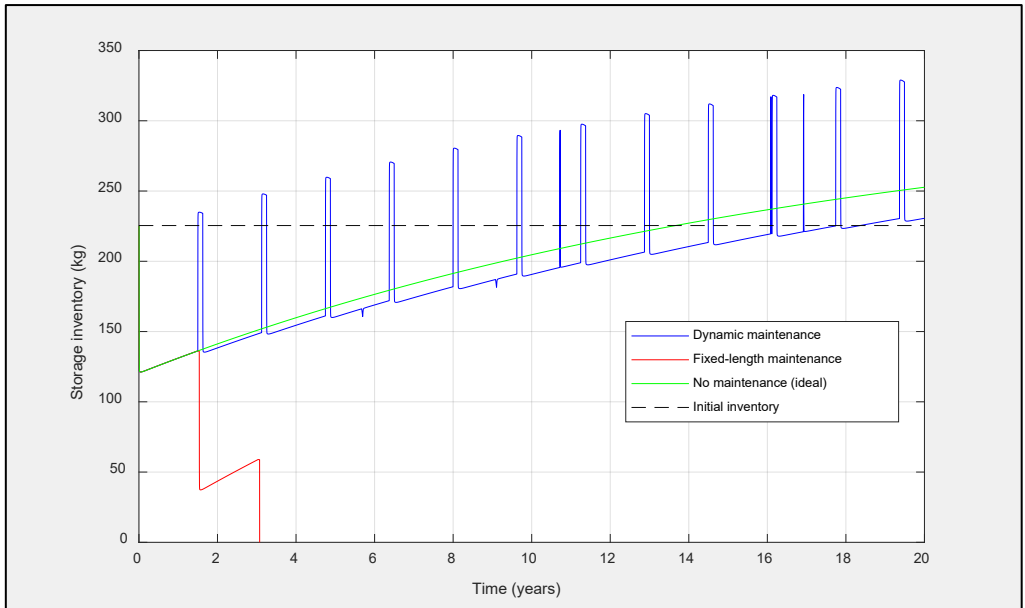
Figure 5. EMRALD diagram modelling tritium extraction system state transitions

3. RESULTS AND DISCUSSIONS

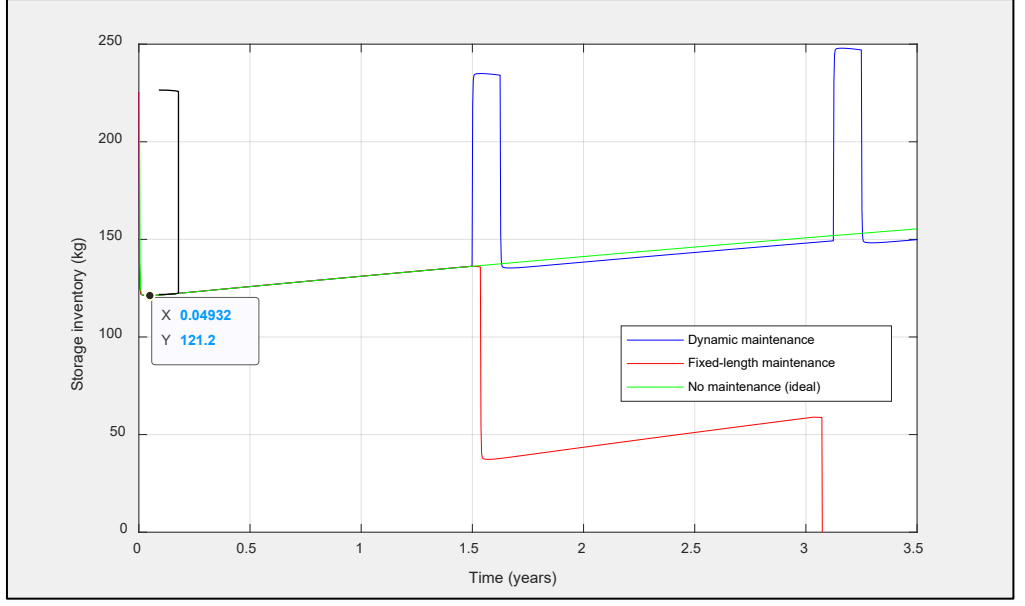
Figure 6 shows tritium inventory in the storage and management unit, where the initial inventory was 225.4215 kg. 134.2 kg of tritium was consumed within the first 18 days of tokamak operation before the storage inventory started increasing due to the breeding and recovery operations. This is the minimum amount of reserve inventory needed to restart the tokamak after shutdown. Figure 6 compares storage inventories of the case study described in the previous section with the ideal scenario where tokamak operates continuously without experiencing random failures and periodic maintenance. It shows that under ideal conditions the initial tritium inventory can be recovered in 13.5 years. The tokamak stops operating after 3 years under a fixed-period maintenance strategy because it runs out of fuel. Meanwhile, the dynamic maintenance strategy allows the tokamak to continue operating for 20 years and beyond.

Over time, radioactive decay slows the rate of increase in the storage inventory. Referring to Figure 1, inventory change over time is expressed with Equation (1), where λ is tritium decay constant. Under a steady-state operation plotted by the green curve in Figure 6, the mass flow rate terms are constant. Only the decay loss term grows as the storage inventory—and therefore time—progresses. This decay term also causes the inventory to slowly decrease during maintenance periods, producing the gap between the blue and green curves in Figure 6.

$$\frac{\partial I_{11}}{\partial t} = \dot{m}_{8-11} + \dot{m}_{9-11} - \dot{m}_{11-12} - \lambda I_{11} \quad (1)$$



(a) Storage inventory within 20 years



(b) storage inventory in the first 3.5 years

Figure 6. Comparison of tritium storage inventory across various maintenance strategies

These results illustrate how dynamic RAMI scenarios can be coupled with a system-level fuel cycle model to provide insights into strategies that enable a long-term fusion machine operation. The fixed-length maintenance strategy provides a high availability factor (AF) for the machine of 97.5%, yet limits operations for only 3.1 years. Meanwhile the dynamic-length maintenance strategy has a lower AF of 92.5% but it enables tritium self-sufficiency for a long-term operation. Another note to discuss is RAMI's effect on tritium breeding ratio (TBR). Abdou's case study utilized a required TBR (TBR_R) of 1.9247 which is overly optimistic given the current state of technology. This case study reduces TBR_R to 1.5 and shows that tritium self-sufficiency can still be achieved by using RAMI strategies.

Figure 7 shows key TMAP8 parameters that are monitored or adjusted by EMERALD in response to systems' state transitions. The figure is limited to a short time window of 4 years to better visualize the parameters' dynamics. The ex-storage inventory is the sum of tritium inventory throughout the fuel cycle systems, except the storage and management system. This parameter is monitored during repair and maintenance period to inform the safe radiological level for workers. As the figure shows, there was approximately 100 kg of tritium during a steady-state operation, which could be recovered

into the storage and management system in the order of days. The safe radiological level was achieved after 30 to 40 days following the hot shutdown state. EMRALD informed TMAP8 of the transition to this hot shutdown state by setting tritium burn rate to 0, and the transition to the cold shutdown by setting TES and CPS efficiencies to 0 after the safe working criterion is met. The figure also suggests that TES was degraded shortly after the 9th year of operation, as shown by the partial reduction in TES efficiency and the temporary isolation of the TES unit from the breeding zone. This event caused a slight temporary increase in ex-storage inventory due to tritium accumulation in the breeding zone as shown in Figure 8.

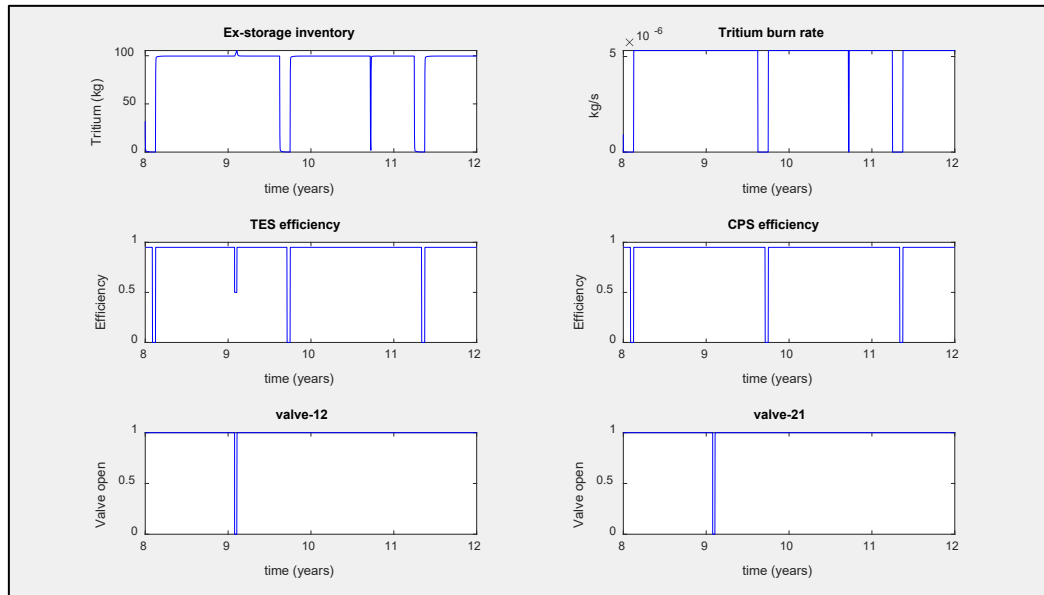


Figure 7. Key TMAP8 parameters monitored and adjusted by EMRALD

Figure 8 presents the tritium inventory across the fuel cycle systems, excluding the storage and management system. When the TES unit degraded shortly after the 9-year mark, the breeding zone inventory rose rapidly because no mass flow was being transferred from the breeding zone to the TES unit. A small portion of this accumulated tritium migrated through the cooling system into the other OFC systems, as represented by the \dot{m}_{1-5} mass-flow pathway in Figure 1. After the TES unit was repaired, its inventory increased quickly as the previously accumulated tritium in the breeding zone was transferred into it.

Results shown in Figure 6 and Figure 8 indicate that the fusion machine and fuel cycle can continue operating during TES degradation without significantly affecting the storage system's tritium inventory. Tritium inventories across all systems in Figure 8 decrease during the maintenance period. Additionally, a temporary inventory drop occurs at approximately 10.8 years, caused by a failure in the tokamak support system.

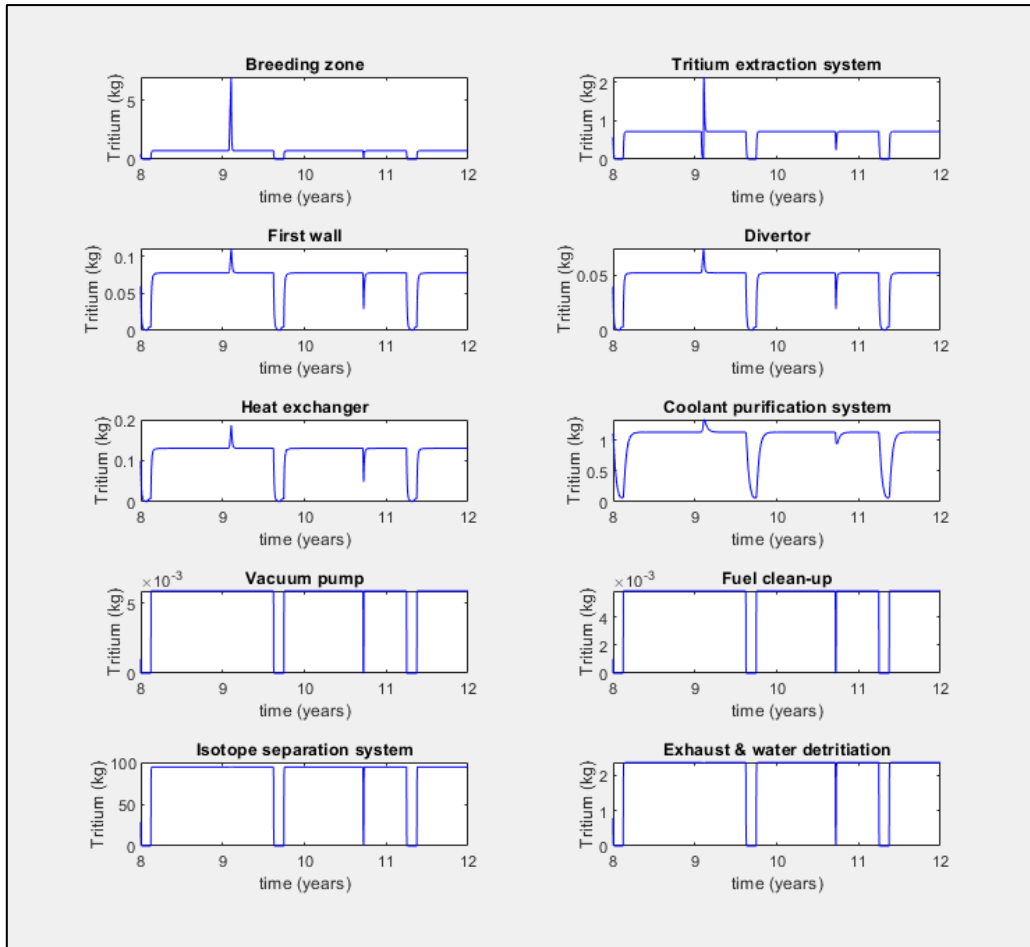


Figure 8. Tritium inventory in the fuel cycle systems

4. CONCLUSION

A bi-directional coupling capability between EMERALD and TMAP8 has been developed to support analyses of tritium self-sufficiency in D–T fusion machines while accounting for the dynamic RAMI behavior of fuel cycle systems. A case study was conducted to evaluate periodic maintenance strategies and to assess the fusion machine’s coping-time capability during degradation of the TES unit. Results indicate that a dynamic-length maintenance strategy is more effective at supporting tritium self-sufficiency than a static-length maintenance program. Findings also show that the fusion machine can continue operating during TES degradation and repair without adversely affecting overall tritium fuel cycle performance. Future work will expand RAMI modeling to remaining components of the fuel cycle.

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