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DEVELOPMENT OF A FUSION FUEL CYCLE SYSTEMS CODE[1]

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ABSTRACT

The tritium inventory in a D-T fusion experiment, like ITER, may be the major hazard onsite. This tritium is distributed throughout various systems and components. A major thrust of safety work has been aimed at reducing these tritium inventories, or at least at minimizing the amount of tritium that could be mobilized.

I have developed models for a time-dependent fuel cycle systems code, which will aid in directing designers towards safer, lower inventory designs. The code will provide a self-consistent picture of system interactions and system interdependencies, and provide a better understanding of how tritium inventories are influenced. A "systems" approach is valuable in that a wide range of parameters can be studied, and more promising regions of parameter space can be identified. Ultimately, designers can use this information to specify a machine with minimum tritium inventory, given various constraints.

Here, I discuss the models that describe tritium inventory in various components as a function of system parameters, and the unique capabilities of a code that will implement them. The models are time dependent and reflect a level of detail consistent with a systems type of analysis.

The models support both a stand-alone Tritium Systems Code, and a module for the SUPERCODE, a time-dependent tokamak systems code. Through both versions, we should gain a better understanding of the interactions among the various components of the fuel cycle systems.

1 Introduction

One of the major hazards at the site of a fusion experiment, such as ITER[2], is likely to be tritium. The ITER team has estimated the inventory of tritium in the various systems and components of this machine to be several kilograms.[1] Safety work in the past has focused on reducing these inventories, or reducing the mobile fraction of these inventories. Future safety work should continue in this direction. This paper describes a new tool that can be applied to that end.

An initiative to develop a time-dependent Fuel Cycle systems code is now underway. I have developed a set of models that describe various components of the fuel cycle, and which should ultimately be part of a stand-alone Tritium Systems Code and a module of the SUPERCODE, a tokamak systems code. The models are safety oriented, with the aim of better understanding systems interactions and interdependencies. A self-consistent picture will describe the global impact of parameter changes on tritium inventories. This will provide a better understanding of how inventories, particularly those in vulnerable locations, are influenced by various systems parameters. A "systems" type of approach is appropriate, where the impact of a wide range of parameter values on the system as a whole can be studied. A systems analysis can be used to scope out relevant regions of parameter space in a self-consistent way, making the trade-offs evident. Ultimately, we in the fusion community will be able to use this information to arrive at a design with minimum tritium inventory, given various constraints. Or, if the user specifies mobility fractions for the various locations of tritium, the analysis will lead to the design with the minimum mobilizable tritium inventory.

Figure 1 depicts the tritium or fuel cycle systems for a tokamak fusion machine. Individual components have been studied in detail and the tritium inventory in components as a function of their own design parameters is fairly well understood.[2 - 10] This is true, with the exception perhaps of the plasma facing components, where researchers have not yet established much of a data base for materials such as tungsten and beryllium. Despite the depth of knowledge about most of the tritium systems components, we do not understand interactions among the various components of the system as a whole very well. It is this gap in knowledge that I hope can be breached with the present work.

The models are described in more detail in Reference [11]. The implementation of these models into code will be underway in the near future. This code (both the stand-alone and SUPERCODE versions) will be unique in that it will provide a complete picture (complete in the systems sense, i.e. all major components are included) of the tritium systems, and it also will provide the capability to vary many systems parameters. In this way, the designer has a great range of flexibility for examining system behavior. Other codes exist, which describe components of the fuel cycle systems in detail, but these are too cumbersome for use as part of a systems code. Existing systems codes do not allow for study of the parameters we think are important for safety. For example, the work of

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[2] International Thermonuclear Experimental Reactor

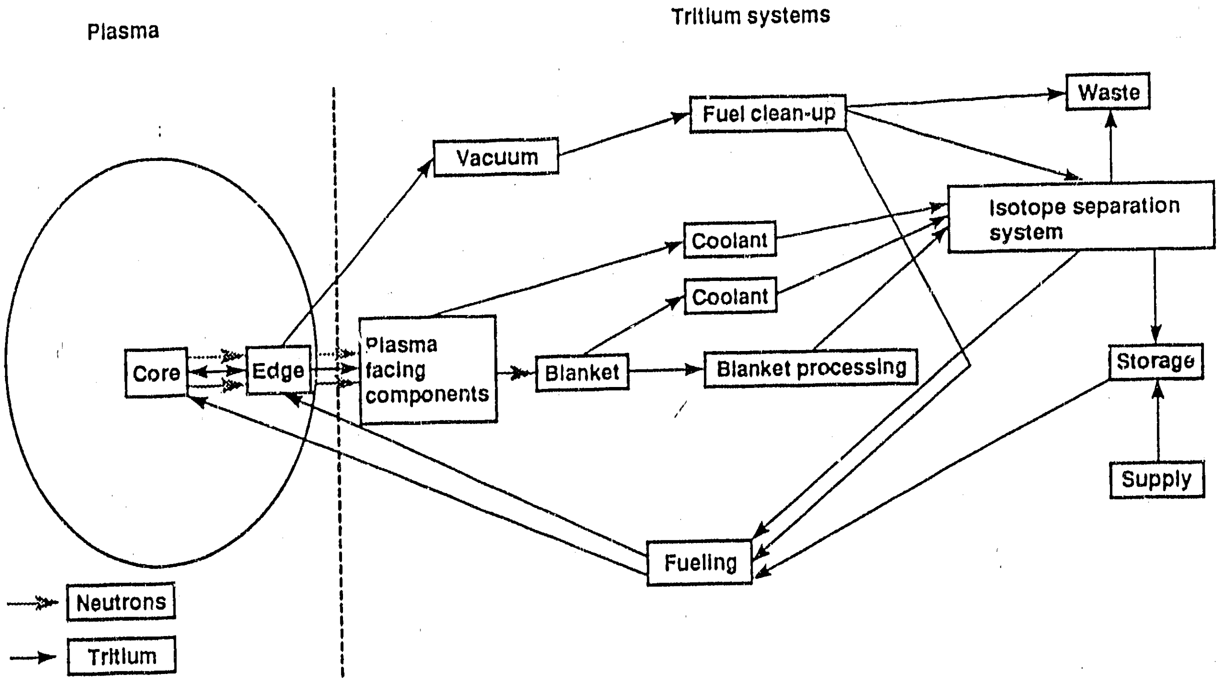

Figure 1: Tritium systems flow diagram

Abdou et al., [12] focused on the required Tritium Breeding Ratio for self-sufficiency. Instead, the present work is aimed at better understanding how we can reduce tritium inventories in fusion machines. Table 1 lists some existing codes and the reasons why they are unsuitable for present purposes.

In the body of this paper, I discuss models that describe tritium inventories and flows for various components as a function of system parameters. I do not specifically give the models here. Instead, I discuss their characteristics and refer the reader to Reference [11], which is the more detailed report on this topic. I also discuss applications of this work, plans for implementing the models into code, and future work to complete this undertaking.

2 Tritium Systems Models

The components I have examined are: plasma facing components, vacuum system, fuel clean-up system, buffer tank, isotope separation system, fueling components (gas puffers, pellet injectors, and neutral beams), and storage. Figure 1 illustrates the interactions among these components. I have not included the blanket, blanket processing and coolant clean-up systems in the discussion of models here. The TETRA systems code effort provided steady state models for these components.[14] Time dependent versions of these models could be developed in the future and used with my time dependent models to form a complete set.

The models in Reference [11] compute both a total and a mobile tritium inventory. Presently, the user must specify the mobility fraction for specific component inventories. In the future, further development can allow for internal computation of mobility fractions. Species tracked in addition to tritium include deuterium, protium (normal hydrogen) and helium.

2.1 Plasma Facing Components

The Plasma Facing Components (PFC) model allows the build-up of tritium in plasma facing materials to be followed in a systems analysis. It is important that we understand how we can reduce this inventory, as it may dominate the total tritium inventory, and it is one of the most vulnerable inventories. Three plasma facing materials can be investigated with this model: carbon, beryllium, and tungsten.

The inventory in the plasma facing materials consists of three components: bulk inventory, codeposited inventory, and inventory in dust. Bulk inventory is estimated by the use of look-up tables. Some information is already available from computer calculations and I have assembled this into an initial data base.[11] More simulations are needed to expand the library, especially for beryllium and tungsten. Values not specifically listed in the data library can be obtained by interpolation. Because of the different conditions to which they are exposed, the first wall and divertor are treated separately. It is possible to take surface temperature variations and thermal gradients into account. Currently, the data base is limited in its range of temperatures and edge conditions (tritium pressure or flux), so the user will have to assume values for which there are data, or provide more data. Ultimately, it should be possible to use the library with information from a plasma facing component thermal model and a plasma edge model, which would provide direct input on component temperatures and edge conditions. I evaluate the codeposited and dust inventories from simple algorithms based on user specified material and temperature dependent codeposition

Table 1: Summary of Existing Codes for Tritium Systems

Code Name, Institution, or Author	Application	Reasons why not suitable for Fuel Cycle systems studies
ITER/NET Fuel Cycle Unit uses CHEMCAD[13]	all fuel cycle components	- steady state only - IBMPC compatible - not transportable to crays, MAC, SUN workstation i.e. not easily linked to SUPERCODE - does not optimize
TETRA[14]: USDOE/FEDC/LLNL tokamak systems code	some fuel cycle components	- steady state only - some models too simple, some too complex
TSTA[15,16]	some fuel cycle components	- no model for complete loop - steady state models for catalytic reactors, pipe flows - stand-alone dynamic model for ISS - monte carlo model for cryopump - either too detailed or require too much time - no optimization
DIFFUSE[17]: Sandia, TMAP[18]: INEL	plasma facing components	- time requirements too large - do not optimize
FLOSHEET[19]: Ontario Hydro	isotope separation system	- too complex for present needs and may require too much computer time - no optimization
Work of Abdou et al.[12]	main fuel cycle components	- contain insufficient details for components of interest - objective was to determine required tritium breeding ratio - no optimization

and erosion rates. In the future, more detailed models of these inventories could be developed, with perhaps a direct linkage to the plasma edge model, which would provide erosion and codeposition rates.

2.2 Vacuum System

The vacuum system model describes the build-up of tritium on cryogenic primary vacuum pumps and the regeneration of these pumps. Because of the potential safety benefits of continuous regeneration of cryopumps, I have included two advanced schemes for continuous regeneration, in addition to batch regeneration. Future work should include development of models for turbomolecular pumps as primary vaccum pumps, and models for backing pumps, as they may contain significant inventory.

2.3 Fuel Clean-up System

The model I describe for the Fuel Clean-Up (FCU) system is based on the reference fuel clean-up system for ITER.[20] This system consists of molecular sieve beds and a palladium membrane reactor. I include three sets of molecular sieve beds, each consisting of one ambient and one cryogenic bed. At any time, one set of beds will be purifying, one will be in standby mode, and the other will be regenerating.

Although the clean-up system will receive feed streams from the plasma, neutral beams, pellet injectors, and breeder blanket, I have focused only on the stream from the plasma, as it contains the most tritium and most impurities. Since neither the stand-alone Tritium Systems Code nor the plasma model of the SUPERCODE accounts for impurities, the user must provide a suitable impurity composition. The model redistributes the hydrogens in the plasma exhaust as the various species corresponding to the impurity levels. The time dependence of the different species and total hydrogen isotopes on the molecular sieve beds during all three modes is followed, as are the flows in and out of the beds. I model the flow to the palladium membrane reactor during regeneration, and the inventory in the reactor itself. I describe the flow out of the palladium membrane reactor by a simple time constant.

The code will allow for optimization of the FCU in terms of bed size and cycling time. Future work should include the development of models for different fuel clean-up schemes. This would allow comparison of the relative safety merits of different approaches to fuel clean-up.

2.4 Buffer Tank

I provide for the use of a buffer tank upstream of the Isotope Separation System (ISS). The ISS is sensitive to flow variations. If the flow is greater than what the ISS is design for, a stream is directed to the buffer tank; if the flow is less than what the ISS is designed for, a stream is drawn from the buffer tank. The user will be able to study the behavior of the tritium inventory in the buffer tank, as this component interacts with flows from various other components and the operation of the ISS. It will be important to understand how we can alter system parameter values in such a way as to keep the inventory in the buffer tank as low as possible, considering the function it must perform. Future work should explore the need for buffer tanks at other locations, and if these are determined as necessary, additional models should be included in the code.

2.5 Isotope Separation System

The separation of hydrogen isotopes is a complex process, which requires a complicated model for accurate description. In the model I developed in Reference [11], I have made many simplifications. The model is based on a simple mass balance around the entire ISS. This approach was taken in the past by Abdou et al. [12]. However, they only followed one component (tritium), and they did not have multiple exit streams of varying concentrations. In my model, I follow all three hydrogen isotopes, and in addition to flow variations, I am able to examine the impact of different stream compositions and product purities.

The ISS can receive feed from the FCU, the neutral beam, the pellet injectors, the blanket processing system, and the coolant systems. The user must completely specify the product composition. Three product streams are provided, each rich in either tritium, deuterium, or protium. The outflow from the ISS depends on the inventory in this component, and on a residence time. The residence time is dependent on the product composition. With a purer product, the number of stages for separation will be greater, and hence, a longer residence time is necessary to achieve the separation.

The model does not follow the initial transient behavior of the ISS. Instead, the ISS is given an initial inventory, which should be equivalent to that expected at steady state. The initial steady state can be found by running the systems code in steady state first to determine the required design values. The system is assumed to be run in total reflux prior to start-up of the tokamak, so that column profiles are established. Once the simulation begins, perturbations of flow and composition about the steady state design value can be followed.

2.6 Neutral Beams

Deuterium neutral beams are not expected to be a large contributor to the total tritium inventory, but since this component interacts with other components of the fuel cycle systems and provides some amount of fueling (~ 5%), I have included it. I do not separately account for separate modules or the ports; the calculations are for the neutral beam system as a whole.

The neutral beams make use of large cryopumps, which may build-up a tritium inventory over time. This is the primary sink for tritium in the neutral beams; small quantities may accumulate on the walls and the neutral beam dump. The model follows the build-up of species in these three sinks. The tritium can enter the neutral beam either as the feed to this system, or backflow from the plasma. The neutral beam feed is delivered from the deuterium rich stream of the ISS, deuterium storage, and from a recycle stream. The idea of recycling regenerated material from the neutral beam cryopumps is new, and it will be interesting to examine the impact this has on the system. This will have the benefit of reducing demands on the isotope separation system.

2.7 Pellet Injectors

I have developed models for two types of pellet injectors: a moderate velocity (1 - 1.5 $\frac{\text{km}}{\text{s}}$) single stage injector for shallow core fueling, and a high velocity (4 - 5 $\frac{\text{km}}{\text{s}}$) two stage injector for deep core injection. For continuous fueling, I consider two extruders per injector. I have modeled the change of inventory in the extruders, as one is depleted by providing feed to the plasma, and as the other fills up and forms DT ice. Feed to the extruders is provided from storage, from the ISS, and from the FCU. The direct feed to the fuelers from the FCU, without first purifying the isotopes in the ISS, is a new concept. This has the benefit of reducing demands on the ISS, and therefore its inventory. It will be interesting to study the impact of this scheme on plasma and component performance.

Propellant requirements are based on a fixed number of moles of protium per pellet (user specified). A different value can be used for the two types of injectors. Contamination of the propellant gas by eroded pellet is monitored, although it does not impact the effectiveness of propelling the projectile. The two stage injector has two propellant streams, one for each stage. For both of these, and also for the single stage propellant, some fraction is directed to the ISS after propelling the projectile. The remainder is mixed with purified protium and recycled for use as propellant again.

2.8 Gas Puffer

I provide a simple model for edge fueling with a gas puffer. This consists of a reservoir, connected to the plasma chamber by a fast acting puffing valve. Feed to the gas puffer comes from the ISS, storage, and direct recycle from the FCU (after impurities have been removed). The flexibility in the gas puffer and two pellet injector models will be useful for exploring the impact of fueling different compositions to different depths in the plasma.

2.9 Storage

I provide three storage systems in my model: one is tritium rich, one is deuterium rich, and one is protium rich. As a further subdivision of this, I keep separate account of what flows into storage from the ISS (if any), as well as the pure inventory provided directly from external sources. It is possible to calculate the number of shipments to the site necessary to meet the external supply. This may be important when assessing the overall risk, as transportation of tritium to the site presents a risk to the public.

3 Applications of this Work

The potential applications of the Tritium Systems Code are wide ranging. I anticipate significant use of this tool during the early stages of the Engineering Design Activity of ITER. In addition to a better understanding of established systems and systems interactions, we will be able to study the impact of some new innovative ideas on tritium inventories.

Once coded, the Tritium Systems Code, or the SUPERCODE with its Tritium Systems Module, will be able to optimize the fuel cycle systems of a tokamak design. In optimization studies, a figure of merit is chosen and the objective is to minimize or maximize its value. From a safety perspective, the figure of merit could be the mobilizable tritium inventory, and the objective would be to minimize this, subject to other constraints on the design[3]. The models I have described here will quantify safety and enable safety to be brought in as a constraint in design optimization.

To follow, I list a variety of studies that should be possible once the models in this report are coded.

1. Study the global impact of varying isotope separation system product purity (tritium and protium).
2. Examine the global impact of relaxed protium requirements (i.e. impact of increasing allowable protium in the feed to the plasma).
3. Determine the extent to which partial processing (by FCU only) of plasma exhaust is feasible.
4. Study the effect of varying fuel composition and means of fueling.
5. Examine different cryopump regeneration methods.
6. Study ways of increasing fraction burn-up in the plasma.
7. Examine schemes for FCU cycling/bed sequencing.
8. Optimize use of isotope separation system buffer tank.
9. Examine risks of onsite storage versus external supply of tritium.
10. Determine the extent to which recycle of neutral beam exhaust from its cryopump is practical.
11. Determine the extent to which recycle of pellet injector propellant is practical.
12. Study the impacts of various operating scenarios, plasma conditions, and fueling schemes on tritium inventories in plasma facing components.

4 Implementation of the Models

The models are complete and described in detail in Reference [11]. The next task is to implement them into a working computer code.

Ultimately, the models can be used for both a stand-alone Tritium Systems Code, and for a module in the SUPERCODE, a tokamak systems code. The stand-alone version will be used to gain a better understanding of component-to-component relationships, where there would be no need to run an entire tokamak systems code. We will be able to optimize the tritium systems parameters to minimize mobilizable tritium inventory. In Reference [11], I suggest a very simple plasma chamber model, which serves to close the loop, for the stand-alone code. The SUPERCODE has a plasma model. This version of the Tritium Systems Module will be useful in gaining a better understanding of how plasma parameters impact tritium inventories in fuel cycle systems and how plasma performance is impacted by variations in tritium systems parameters.

The fusion safety group at the University of California, Berkeley plans to undertake the task of coding the models. This work will be underway in the near future.

5 Future Work

This work has established the basis for quantification of safety in systems analysis, and provides the opportunity to gain a better understanding of interactions among fuel cycle systems components. This effort is incomplete and there is much to be done. I summarize future needs below.

(A) Complete a working Computer Code:

1. Provide an independent review of the models and data bases.
2. Complete coding of the models.
3. Integrate with the SUPERCODE.

(B) Improve Inventory Models and Data Bases:

1. Expand the Plasma Facing Components data library.
2. Add turbomolecular pumps as an option for primary vacuum pumping.
3. Add backing pumps to the vacuum system.
4. Improve modeling of FCU System palladium membrane reactor.
5. Add other FCU options.
6. Develop time dependent models for the TETRA blanket, blanket processing systems, and water clean-up system.
7. Develop steady state equations for other components, from the time dependent models provided.

(C) Expand Scope:

1. Add models for different pellet injector propellants.
2. Examine models for applicability during non-DT phases of experiments; make required additions to the present models.
3. Add costing models.
4. Add uptake in first wall/divertor structure and coolant loss pathway for plasma facing components.
5. Add models for atmospheric processing and develop models for effluents.
6. Add models to describe mobility fractions.

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[3] Because of time considerations, we would probably not want to optimize at every time step during the transient.

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