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Time-dependent tritium inventories and flow rates in fuel cycle components of a tokamak fusion reactor

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Abstract

Time-dependent inventories and flow rates for several components of the fuel cycle are modeled and studied through the use of a new modular-type model for the dynamic simulation of the fuel cycle in a fusion reactor. The complex dynamic behavior in the modeled subsystems is analyzed using this new model. Preliminary results using fuel cycle design configurations similar to ITER are presented and analyzed. The inventories and flow rates inside the primary vacuum pumping, fuel cleanup unit and isotope separation system are studied. Ways to minimize the tritium inventory are also assessed. This was performed by looking at various design options that could be used to minimize tritium inventory for specific components.

1. Introduction

The International Thermonuclear Experimental Reactor (ITER) Project has led to detailed studies of many preliminary designs in the various engineering areas of a fusion reactor including the fuel cycle. Currently, the fuel cycle for ITER is undergoing various changes in its design to meet the latest requirements. One way of providing relevant data to these design studies is by computer simulations.

In the past, steady state codes have been produced where the main emphasis was on the calculation of design flow rates, such as the TETRA systems code by Reid et al. [1]. However, these steady state models do not take into account the changing tritium inventory throughout the fuel cycle system, which impacts the economic and safety aspects of reactor design. The accuracy of fuel cycle dynamic modeling especially has been stagnant due to the limitations encountered in previous dynamic models. These past models utilized general tritium residence times to determine the tritium inventory in each modeled subsystem, in part due to the fact that a detailed preliminary design of a fusion reactor was not available. Although parametric studies of these dynamic models using the residence time approach, such as from Sarigiannis et al. [2], provided new insight into the behavior of the fuel cycle, these models have not been accurate enough to provide relevant data for the current phase of engineering design work.

As a result, in the summer of 1992 a collaboration between UCLA, UC Berkeley, and Los Alamos National Laboratory was initiated for the development of a new modular dynamic model for the fuel cycle in a fusion reactor, with ITER being used as the reference design. This work details the objectives of the new

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model, a short summary of how the model is structured, capabilities of the new model and preliminary results.

2. Fuel cycle design objectives

One of the major objectives of fuel cycle design in a fusion reactor is to lower its tritium inventory, primarily mobile inventories, as summarized by Anderson and Bartlit [3] and also Finn and Sze [4]. Currently, an overview of the ITER fuel cycle design and objectives has been reported by Dinner [5,6]. ITER tritium inventories will be measured in kilograms with the objective being to reduce this as much as is reasonable from other design constraints. Other objectives are the sizing of fuel cycle components to handle the wide range of plasma exhaust flow rates migrating throughout the fuel cycle and the exploration of tritium system alternatives.

A dynamic model of the fuel cycle which tracks tritium flow rates and inventories in the reactor plant in real time will be instrumental in achieving these objectives. Such a time-dependent code enables design engineers to better understand transient system behavior such as startup, standby, shutdown, and process upsets and changes.

3. The new dynamic model

3.1. Theory

Previous fuel cycle dynamic models, as developed by Abdou et al. [7], Gabowitsch and Spannagel [8] and Sarigiannis [9], have utilized the residence time approach. They all have admitted the high uncertainty involved in estimating a residence time for each modeled fuel cycle subsystem. The calculation of inventories basically involved solving

$$\frac{\partial I}{\partial t} = \text{Inflows} - \text{Losses} - \frac{I}{T_{\text{res}}} \qquad (1)$$

where I is the subsystem inventory and T_{res} is the subsystem residence time. Losses result from permeation and nuclear transmutations such as tritium decay. These residence time models then utilized a linear equations solver, such as the Runge–Kutta scheme, to solve the resulting matrix of linear differential equations. The next step was then taken by Brereton [10] who summarized what was needed to develop a more accurate fuel cycle dynamic model, while preliminary simulation results using ITER parameters were established by Busigin et al. [11].

In the dynamic model presented in this work, several important improvements in modeling capabilities over past models have been formulated and implemented, which are:

- The use of real unit design parameters in place of a general tritium residence time to define each subsystem.
- The inclusion of actual tokamak fusion reactor operating scenarios.
- The inclusion of the major impurities, hydrogen isotopes and state variables.
- The inclusion of fuel cycle component operating modes and their associated scheduling.
- Flexibility of the modular approach in this new model that is able to account for changes in fuel cycle design and modeling improvements.

These new capabilities serve to increase the accuracy of the model. As a result, the calculation of the tritium inventory is more complex because of the many operating parameters that come into play. This can be thought of as:

$$\frac{\partial I}{\partial r} = f(\text{inflows, operating schedule, operating parameters}) \qquad (2)$$

where the inventory is then a function of the operating scenario that is selected.

The solution to the inventories and concentrations is performed by an Euler approximation scheme in order to drastically decrease the amount of computer time needed to solve the large number of resulting differential and algebraic equations. Since most of the equations for plasma exhaust modeling are either algebraic or for differentials change slowly, a more complicated differential equations solver is not needed. As a result, the simulation results from this new model can be obtained quickly.

The general fusion fuel cycle flowsheet for use in this new dynamic tritium modeling code is illustrated in Fig. 1. As mentioned above, this flowsheet schematic is purposely made to be as general as possible in order for the modules representing the various options in the subsystem blocks to be incorporated as the design warrants. Various levels of detail are thus incorporated into the model; these consist of: (1) the integrated fuel cycle, (2) the subsystems in the fuel cycle and (3) unit operations found in these subsystems.

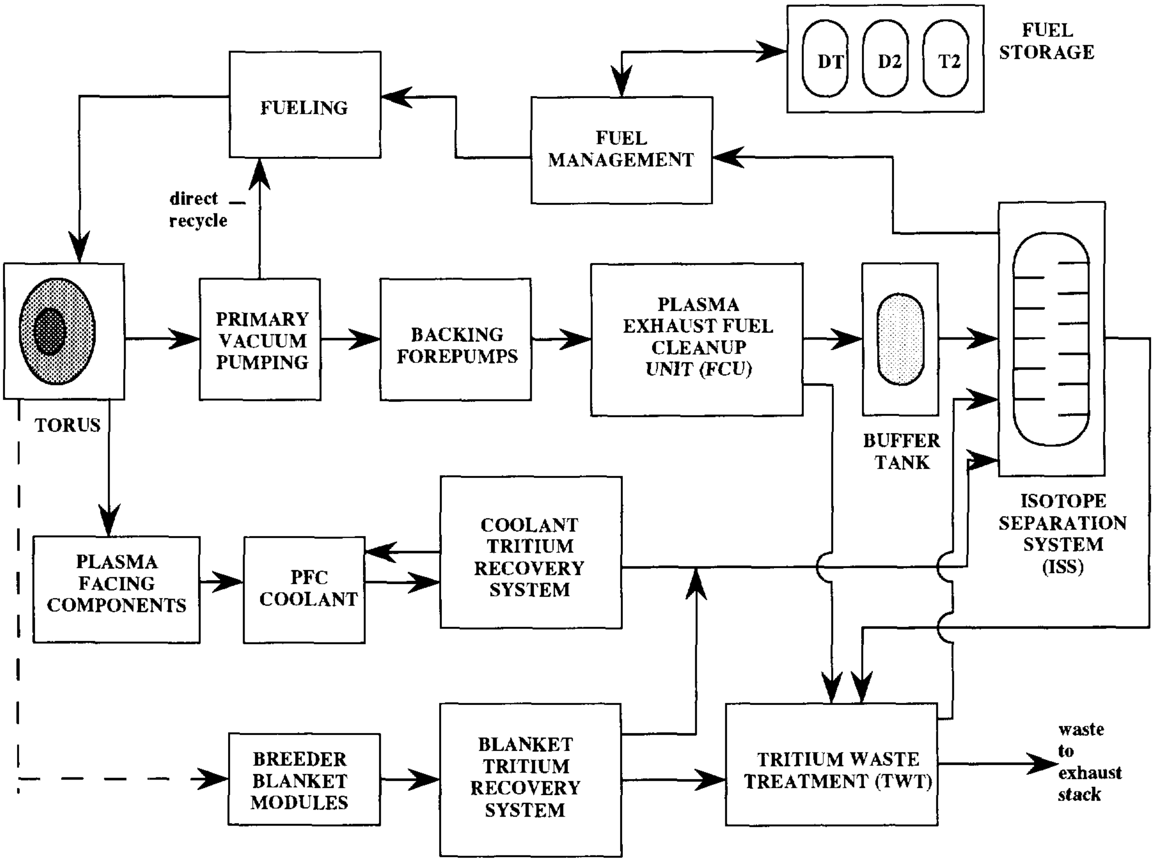

Fig. 1. General fusion fuel cycle flowsheet.

3.2. *Input/output parameters*

A major departure from previous models is the ability to specify an increasing number of input parameters in the model. They consist of:

- Reactor operating parameters (power, fuel burnup, tbr etc.)
- Plasma exhaust composition
- Individual subsystem operating parameters (duty cycle, regeneration time etc.)
- Subsystem design parameters (sieve bed capacity, catalytic reactor volume etc.)
- Design configuration of fuel cycle to be simulated
- Operating mode (steady state, pulsing, conditioning etc.)

The reference values for these parameters, design configurations, and operating schedules were derived from the ITER CDA Fuel Cycle Report by Leger et al. [12].

The only species accounted for in previous models was tritium, but in recent models deuterium and protium flows have also been incorporated. However, impurities were not tracked. Nevertheless, impurities account for a significant portion of the tritium inventory in several fuel cycle components and in fact may constitute the majority of its tritium inventory. This model includes the 10 major molecular species in the plasma exhaust from CDA specifications: He, Q_2, Ar, O_2, N_2, CQ_4, CO, CO_2, NQ_3, Q_2O. With regard to Q_2, this model tracks all six hydrogen isotope molecules, namely T_2, D_2, H_2, DT, HD, and HT. Therefore the output parameters of the model include the following: (1) inventories of all molecular species in each subsystem, (2) mole fractions of each species in the outflow from each subsystem and (3) hydrogen isotopic ratios in the outflow.

4. Fuel cycle component modules

A quick overview of the primary vacuum pumping and the fuel cleanup unit is now presented. Kuan [13] provides a more comprehensive review of the above components and their corresponding subroutine modules in addition to the breeder blanket, storage and isotope separation system. Modules for these fuel cycle components are written with enough detail to describe reality, but not too much to slow down the code.

4.1. Plasma exhaust primary vacuum pumping

The plasma exhaust primary vacuum pumping subsystem determines the subsequent behavior of the plasma exhaust flow into the downstream components, and thus controls their input state. From the ITER CDA Fuel Cycle Technical Report, cryopumps were chosen as the reference design with their batch operation determined by a variety of cycle times (pumping time, partial regeneration time, complete regeneration time, warm-up time) and by the backing forepump characteristics.

The CDA Report specifies a stagger operating schedule for these cryopumps with both partial and complete regeneration stages for each pump. During pumping, it is assumed that the flow is equally partitioned for all cryopumps in pumping mode and that Q_2 is condensed on the 4.2 K surface cryopanels, while all other impurities are frozen on the 80 K surface cryopanels inside the vacuum pumping unit. Helium is trapped by cryosorption in a charcoal surface. Then, during partial regeneration, the cryopump chamber is warmed to 20 K to drive off the Q_2 and He. Impurities stay trapped in the liquid nitrogen-cooled cryopanel during partial regeneration. However, during complete regeneration, the cryopump is heated to about 400 K to exhaust everything from the cryopumps, mainly impurities that have accumulated over time.

In the code, these stage operations are simulated directly by providing three separate subroutines to process a specific operation. For example, during pumping of the exhaust gas by an individual pump, the following equation simulates its behavior:

$$\frac{\partial I}{\partial t} = \frac{\text{plasma exhaust flow}}{\text{number of pumps in operation}} \qquad (3)$$

The plasma exhaust flow is calculated from the reactor fusion power, fuel burnup and losses to plasma-facing components. When partial regeneration occurs, the He and Q_2 that have been accumulated will be evacuated from the cryopump chamber by backing forepumps. The pumping speed of these backing pumps and the pressure inside the cryopump chamber during warm-up will determine the evacuation time of the gas. The regenerated outflow is then:

$$\frac{\partial I_t}{\partial t} = -\left(I_{t-\mathrm{d}t} - \frac{P_t V_{\text{cryopump}}}{R T_{\text{cryopump}}}\right) \qquad (4)$$

I_t represents the inventory at time t, $I_{t-\mathrm{d}t}$ represents the inventory at time $t - \mathrm{d}t$, P_t is the pressure at time t, which is calculated from the pumping speed at the cryopump chamber outlet, V_{cryopump} is the cryopump chamber volume, R is the gas constant and T_{cryopump} is the cryopump chamber temperature. The process of complete regeneration is equivalent to partial regeneration, except that all the gaseous species are to be exhausted.

4.2. Plasma exhaust fuel cleanup unit (FCU)

The CDA reference design incorporates a semi-batch mode of operation consisting of three ambient molecular sieve beds (AMSBs) and three cryogenic molecular sieve beds (CMSBs). These beds are cycled through three modes of operations governed by stages of purification, standby, and regeneration. The molecular sieve beds serve as selective impurity traps for various molecular species depending upon their molecular weight. The only species that flows continuously through these traps is He. Q_2 is initially adsorbed in the cryogenic beds, however, incoming impurities gradually displace this sorbed Q_2. This process is simulated by the following conditional equation:

IF (amount of adsorbed species > sieve bed capacity)

THEN switch FCU operating mode (5)

As a result, the frequency of FCU mode cycling will depend upon the inflow rate to the FCU. During regeneration of a bed, the trapped impurities are routed to a palladium membrane reactor (PMR) for tritium detritiation. Other FCU configurations can and have been implemented.

5. Preliminary results of new modular dynamic model

Many preliminary results have been obtained with the aid of this new modular model for the study of the dynamic behavior of the fuel cycle. Dynamic simulation of the primary vacuum pumping subsystem is now presented in the form of a parametric study exploring its tritium inventory. In addition, the effect of direct fuel recycle from the cryopumps subsystem is examined.

5.1. Effect of various fuel cycle parameters on the cryopumps' dynamic tritium inventory

In this example case, we study the way that various fuel cycle parameters may affect the tritium inventory in the cryopumps subsystem. This example emphasizes the capability that this model has for predicting the change in behavior of the dynamic tritium inventory when a different reactor scenario is defined and how this tritium inventory can then be minimized by changing other fuel cycle parameters. The scenario definitions are listed in Table 1. In addition, the CDA plasma exhaust impurity composition is described in Table 2.

For Scenario 1, we first examined the tritium inventory in the cryopumps vacuum subsystem with CDA-valued parameters. Fig. 2 illustrates the correspondingtritium inventory dynamic behavior. This behavior is

Table 1
Definition of scenarios for fig. 2

Scenario	Operating conditions
1	• 1.5 GW • 3% Burnup fraction • CDA values for cryopump cycle parameters • 2% impurity mole fraction
2	Burnup fraction changed from 3% to 1%
3	Same as Scenario 1 except values for cryopump cycle parameters changed from CDA values to one-fifth their CDA value
4	Same as Scenario 1 except 2% impurity mole fraction decreased to 0% impurity mole fraction

Table 2
Plasma exhaust impurity composition

Impurity species	CDA reference value
Total Impurities	2% of total plasma exhaust
Individual impurity species	% of impurities
Ar	4
O_2	8
N_2	8
CQ_4	56
CO	8
CO_2	4
NQ_3	4
Q_2O	8

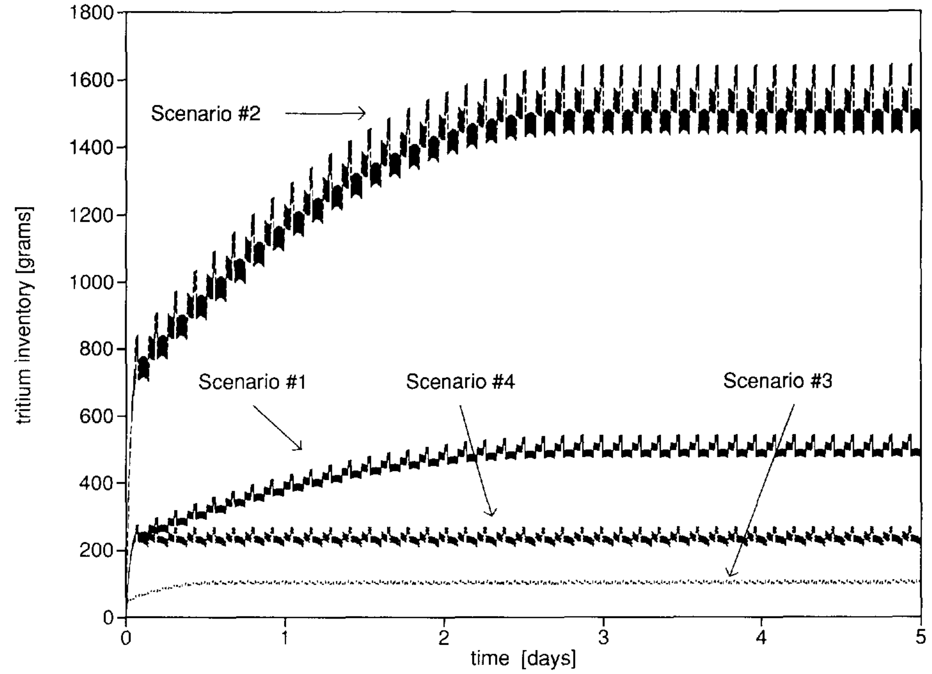

Fig. 2. Effect of various fuel cycle parameters on the cryopumps' dynamic tritium inventory

determined by the type of operating schedule of the cryopumps and the reactor fueling scenario. After the initial rise in inventory during the first 2 h due to the stagger operation of the pumps, several cyclic patterns are observed. The sharp drops in inventory are caused by the complete regeneration of one cryopump. The sharp rises in inventory are due to the skip of the partial regeneration period for the cryopump that is undergoing complete regeneration. Finally, the dark bands are actually very fast fluctuations caused by the rapid pumping into and pumpout from different pumps.

Next, for Scenario 2, a decrease in the fuel fractional burnup effected an increase in the steady state tritium inventory from about 500 g to 1500 g, as expected. In addition, we learn from this dynamic study that the tritium inventory quickly reaches a value equal to about half its steady state value in about 2 h and that it then slowly increases to its steady state value in the next 2.5 days.

For the fuel cycle designer, one of the top priorities is to minimize the tritium inventories. After this large increase in the cryopumps' tritium inventory, it is then desirable to examine other options that will lower it. First, a local subsystem variation is realized by increasing the frequency of operation of the cryopumps from Scenario 1 by a factor of 5, as in Scenario 3. This causes the steady state tritium inventory to be decreased by the same factor of 5 to about 100 g. Also, the time to reach steady state is reduced from about 2.5 days to 0.5 days and the temporal fluctuations become negligible.

Finally, in Scenario 4, decreasing the value of the impurity concentration in the plasma exhaust to the lower limit of zero impurities reduces the steady state tritium inventory in the cryopumps to about half the Scenario 1 value. Dynamically speaking, the time to reach steady state is almost instantaneous or about 2 h, because the complete regeneration operation becomes unnecessary when there are no impurities to flush out of the cryopump system.

5.2. Dynamic tritium inventories in the primary fuel cycle loop with fuel recycling option

In Fig. 3, the dynamic tritium inventories in the cryopumps, FCU and ISS are illustrated for the case of direct fuel recycle from the cryopumps. The operating

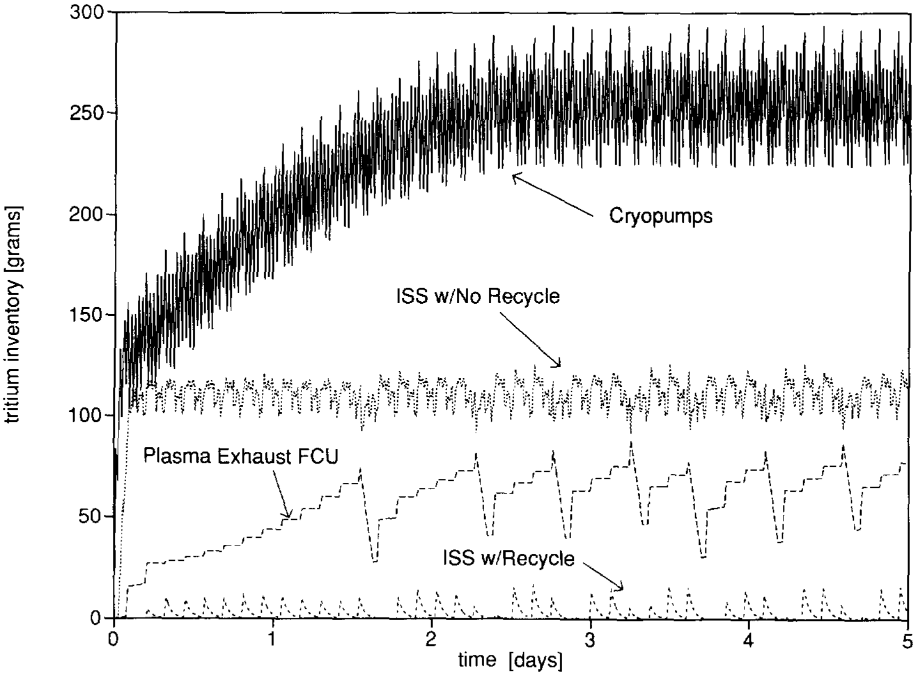

Fig. 3. Dynamic tritium inventories with fuel recycling option and pulsing mode.

scenario simulated is a pulsing fueling operation with 1.5 GW, 3% fuel burnup, an ISS characteristic residence time of 45 min and a DT escape rate from the 4.2 K surface of the cryopumps of 10%. This DT escape rate denotes the small amount of DT that is pumped with the He.

When recycle is used, the tritium outflow issuing from the primary vacuum pumping toward the FCU is dependent on the DT escape rate, since this is the only sourisece of tritium tied up in hydrogen isotopes. When this escape rate is small, then just a small amount of tritium flows through the remaining downstream components. This dependence can be observed by comparing the small tritium inventory inside the ISS when recycling is performed with the ISS inventory without recycling. The FCU is generally unaffected by recycling because it deals mostly with impurities. In this recycling scenario, the cryopumps become the major source of tritium inventory, where it levels out to about 2.5 kg in approximately 2.5 days. The fast fluctuations in inventory in the vacuum pumping systems are a result of the pulsing operation.

In addition to the two example cases mentioned above, many other studies have been performed. For example, studies concerning the effect of fuel cycle parameters on the FCU tritium inventory and the storage tritium inventory have been performed.

6. Conclusions

This new fuel cycle dynamic model for a tokamak fusion reactor gives more time-dependent tritium inventory and flow rate information throughout the fuel cycle than has been previously reported. Because the basic physical parameters of each unit operation are included, this model should be more accurate than most previous models. In addition, its flexibility provides the fusion community with a tool for describing the fuel cycle that can be easily modified and utilized. In this work, dynamic tritium inventories in several fuel cycle components were examined and ways to minimize these inventories were explored.

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