DYNAMIC SIMULATION OF A PROPOSED ITER TRITIUM PROCESSING SYSTEM

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ABSTRACT

Dynamically simulating the fuel cycle in a fusion reactor is crucial to developing a better understanding of the safe and reliable operation of this complex system. In this work, we propose a tritium processing system for ITER's plasma exhaust. The dynamic simulation of this proposed system is then performed with the TRUFFLES (TRitiUm Fusion Fuel cycLE dynamic Simulation) model. The fuel management, storage, and fueling operations are developed and coupled with previous cryopump and fuel cleanup unit subsystems to fully realize the complete torus exhaust flow cycle. Results show that tritium inventories will vary widely depending upon reactor operation, individual subsystem and unit operation designs. A diverse collection of batch-controlled subsystems with changes in their processing parameters are simulated in this work. In particular, the effects from the fuel management subsystem's fuel reserve and tank switching times are quantified using sensitivity studies.

I. INTRODUCTION

The design and operation of the fuel cycle tritium processing system needs to be reliable and safe to fully realize the advantages of fusion power. In order to achieve such a design, an accurate dynamic simulation of its operation during reactor operation needs to be performed to aid in the understanding of the complex behavior of the fuel cycle for any design configuration and any reactor operating scenario. TRUFFLES was developed for this purpose and to fully investigate the parametric space governing the fuel cycle. TRUFFLES is able to model existing fuel cycle tritium systems and their corresponding unit operations in code "modules" that can be easily replaced and/or extended. A flowsheet can thus be built around these modules to offer maximum flexibility in the simulation of the fuel cycle.

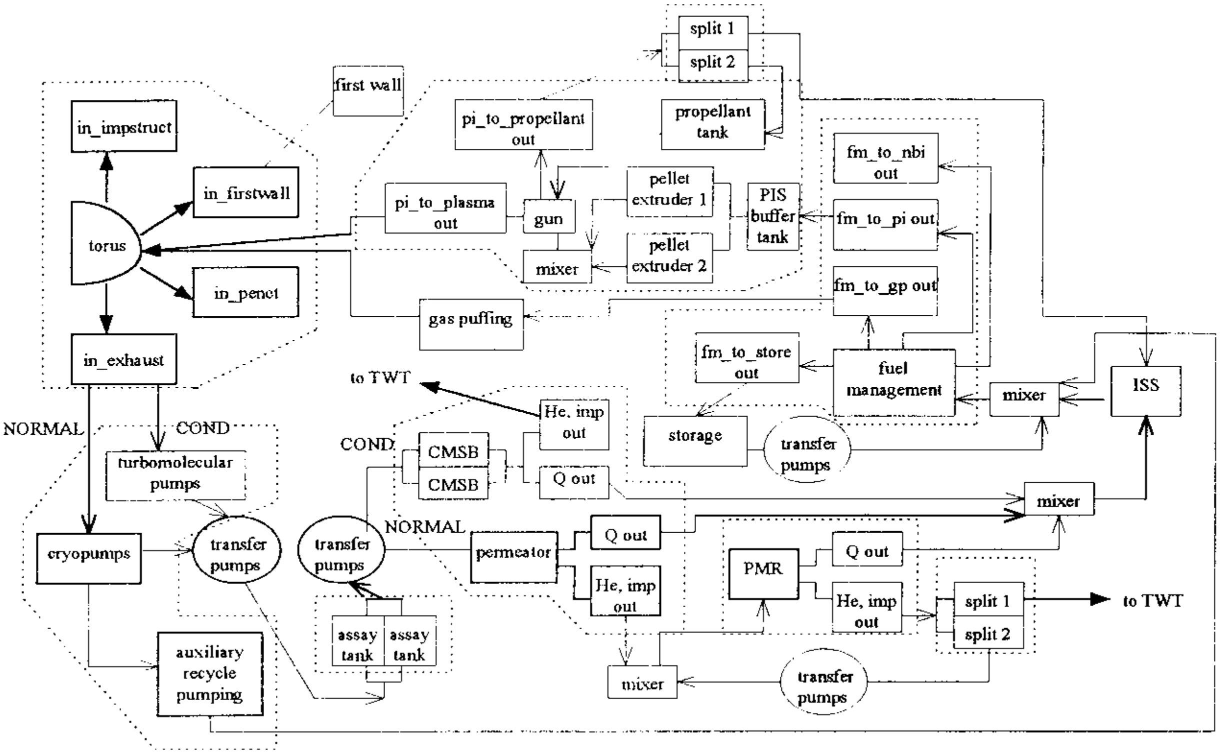
The author's past work on this subject focused on the CDA-design cryopump and fuel cleanup unit subsystems.[1,2] This work will expand on subsystem development to complete the primary flow cycle representing the processing of the torus exhaust. As a result, models for the fuel management, storage, and fueling subsystems are developed and studied. The latest proposed fuel cleanup unit and impurity processing subsystems for ITER are also included.

II. MODEL STRUCTURE OF TRUFFLES

A. SUBSYSTEMS AND UNIT OPERATIONS

TRUFFLES is a hierarchical process model which can be subdivided into subsystems and further into unit operations that define the fuel cycle. Subsystems serve a specific function in the fuel cycle and can be made up from a sum of unit components. Diverse configurations can thus be implemented. For example, the fuel cleanup unit has undergone various modifications in its design so that several submodules have been implemented to model these distinct subsystem designs.

Finally, the unit operation is the basic working unit in this model. It includes both individual component models and scheduling operations. Reactors, permeators, electrolysis units, and cold traps are examples of physical component models.



ISS = Isotope Separation System
PMR = Palladium Membrane Reactor
TWT = Tritium Waste Treatment
CMSB = Cryogenic Molecular Sieve Bed
PIS = Pellet Injection System

Figure 1: Proposed ITER Tritium Processing System Flowsheet

Regeneration, pumping, and reactor mode switching represent scheduling operations.

To model multiple outflows, it is necessary to specify fictional modules whose outflow rate and composition are governed by the operation and physical processes of their parent unit. For example, the fuel management subsystem is defined by various different outflows to separate fueling components.

The methodology used in the modelling approach is based on shortcut blackbox models representing each unit operation whereby Euler's method is utilized at this module level in order to significantly decrease computing time.[1] This approximation can be used for the purpose of this dynamic model because most of the subsystems are governed by batch processes with corresponding batch schedules controlled by the fuel cycle designer. Shortcut models must then be used on subsystems that do not behave in an algebraic manner, such as the ISS.

III. PROPOSED ITER TRITIUM PROCESSING SYSTEM

Figure 1 shows a schematic of the flowsheet representing the proposed tritium processing system as defined in this section. The dashed boxes represent a specific subsystem whose unit operations are included inside its boundary. Fictional outflow units are specified by the *unit1_to_unit2* boxes and the *species out* boxes. Torus plasma outflows are designated by the *in_unit* box, which include:

1) in_exhaust = inflow to exhaust processing
2) in_impstruct = inflow through divertor/limiter
3) in_firstwall = inflow through first wall
4) in_penet = inflow through penetrations

A. TORUS OUTFLOWS

Torus outflows will depend upon the reactor operating scenario and their scheduling. TRUFFLES is able to account for 5 different operating conditions: 1) steady-state fusion burn (power production), 2) pulsing (burn-dwell), 3) conditioning with various gases, 4) downtime, and 5) preloading of the fuel cycle.

In the case of pulsed operation, the historic behavior of the fusion power and torus exhaust outflow rates during one cycle can be simplified by assuming that the rampup and pumpdown times are negligibly small compared to the burn and dwell times. This assumption can be used because the pumpdown time when calculated using the vacuum pumping speed and conductances with the required start-up pressures and burn pressures will yield typical pumpdown durations in the order of a few seconds (~10-30 seconds) compared to the expected burn and dwell times in the hundreds of seconds (500-1000 seconds). Figure 2 shows this modeling assumption.

H_2 & He Impurities	**Mole Fraction from Total Exhaust Rate**
H_2	0.5 %
He	2 %
Impurity Species	**Mole Fraction from Total Impurities**
Ar	5 %
O_2	5 %
N_2	5 %
CQ_4	30 %
CO	5 %
CO_2	5 %
NQ_3	5 %
Q_2O	35 %

Table 1: Representative Species Composition of Impurities Entering Primary Vacuum Pumps with Typical Mole Fraction Values

The torus outflow composition can be modeled using either a fixed concentration profile in the torus exhaust or using vacuum vessel material parameters. The second option is the subject of another paper.[3] For this study, a fixed representative impurity concentration profile is utilized as given in Table 1. This list represents a likely average concentration profile in the exhaust. Other possible species, such as higher hydrocarbons (e.g. C_2Q_6) may be easily incorporated into this list resulting in slightly different inventories.

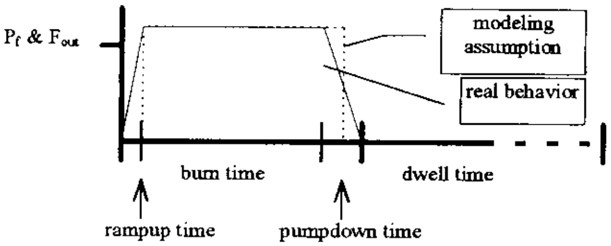


Figure 2: Power and Fuel Outflow Cyclic History

B. PRIMARY VACUUM PUMPING (CRYOPUMPS)

The CDA Fuel Cycle Report provides details on the operation and dynamic tritium inventory characteristics of this subsystem.[4] Direct recycle (with or without an intermediate set of auxiliary sorption pumps) can also be modeled.[2] The reference case for the proposed processing system is a 1 [min] stagger time, an 8 [min] pumping time, a 12 [min] partial regeneration time, and a 32 [min] complete regeneration time.

C. FUEL CLEANUP UNIT AND IMPURITY PROCESSING

Past studies using TRUFFLES have analyzed the CDA fuel cycle unit design.[1,2] In the current proposed design which differs from the CDA design, impurity separation is accomplished using hydrogen permeators during normal operation and molecular sieve beds during conditioning operation. This flow type separation is necessary due to different flow compositions. Impurity processing is performed by a palladium membrane reactor. For both of these unit operations, it is assumed that the inventory is negligible in comparison to other fuel cycle components due to its continuous operation and relatively small size. Other similar fuel cleanup units and impurity procesing configurations have also been modeled.

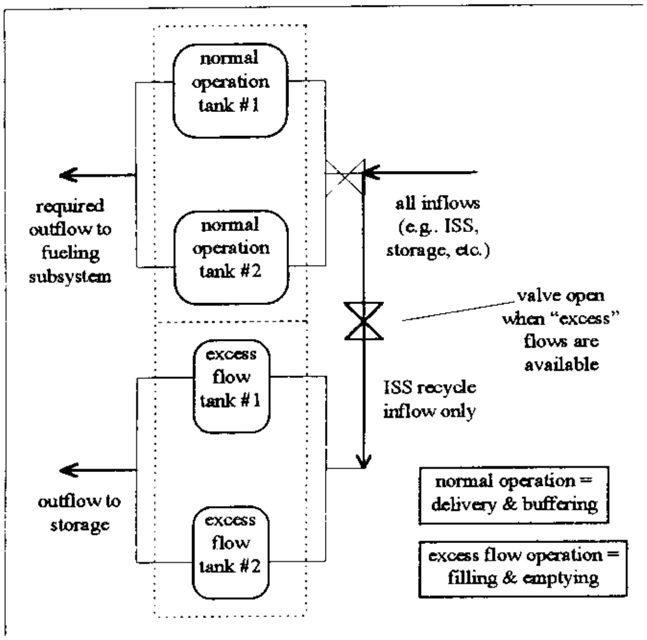


Figure 3: Fuel Management Configuration for Fuel Species j

D. ISOTOPE SEPARATION SYSTEM

For this initial investigation, this complex subsystem is modeled as a tank with a characteristic residence time (45 min. for the proposed design). The complexity of this subsystem will necessitate the future inclusion of a detailed model to account for separation factors, reflux rates, and cryogenic unit size. Such a model has been developed using a supertray concept to reduce the order of the equations involved in solving the distillation model.[5]

E. FUEL MANAGEMENT

The proposed design for the fuel management subsystem incorporates a set of buffer tanks operating with a batch strategy so that this subsystem is able to meet the fueling requirements for the specified tokamak operating scenario. Figure 3 illustrates the configuration for one type of fuel species. The fuel species consist of all the Q_2 isotopes and He to account for both normal and conditioning operation. Each of the fuel species is processed with its own buffer tank configuration. The constraint to obtain fresh fuel from storage as needed and recycled fuel from the ISS when available governs its operation.

A detailed look at the system for one fuel species shows a 4 buffer tank configuration, 2 for normal operation while the other 2 are used in the case of flows arriving after the maximum capacity for a normal operation tank is reached. Both normal operation tanks operate in such a way that one is always delivering the required fuel while the other is available for the buffering of recycled flows. When the "delivery" tank reaches a preset "minimum" value of pressure or inventory set by the tank switch reserve time, the "buffering" tank is required to contain a preset quantity of fuel before their roles are switched. If this "fuel reserve" quantity is not available at the time when the "delivery" tank reaches its preset "minimum" value, the makeup fuel necessary to reach this level must be routed from the storage subsystem. The fuel reserve time (10 min) and tank switch reserve time (5 min) parameters govern the inventory behavior.

The "excess" tanks act much the same way as the normal operation tanks except that they receive only recycled gas flows during the time when the "buffering" tank has reached its full capacity. The roles of these excess tanks are the "filling" and "emptying" of recycled fuel flows. When the "filling" tank reaches its maximum capacity, it switches roles with the other tank and delivers fuel to storage units that act as receivers of excess fuel. These "excess" tanks are especially important when the tritium breeding ratio, TBR, is greater than 1.

F. STORAGE

The storage subsystem is linked with the fuel management subsystem for the transfer of fuel during fuel makeup of the "buffering" tank and for the storage of excess fuel from the "excess" tanks. As with the fuel management subsystem, the storage is capable of providing any fuel type. The designer can control the quality of fuel delivered through the fuel management and fueling subsystems and ultimately to the torus chamber for fusion or conditioning. The fuel flows that originate from the storage subsystem are driven by suitable transfer pumps.

G. FUELING

The fueling subsystem consists of various fueling submodules which belong to either: a) pellet injection or b) gas puffing. The amount of fueling that is delivered by each of these methods (if both are used in the design) can be fixed in addition to the D:T ratio for control of the plasma profile in the torus (e.g isotopic tailoring).

1. Pellet Injection. Its unit operations include: a) the extruder system (2 extruders for each injector are used in this design), b) and the injector gun. The extruder system's function is to freeze the incoming fuel flow into frozen pellets for injection into the torus. At least 2 extruders are needed for continuous operation due to the exhaustion of fuel in one extruder and corresponding freezing time associated with each batch of incoming gas. A fueling time of 6 [min] and a freezing time of 3 [min] are used as the performance parameters. This freezing time is slightly lower than the 5-10 [min] used in current experiments, in order to reduce the tritium inventory in the PIS system.[6] A continuous one-extruder gas stand has also been proposed. Plasma backflow and propellant contamination are introduced in the injection gun model to determine the required fuel flow coming from the fuel management subsystem. The inventory is assumed to be negligible in this unit.

2. Gas Puffing. The gas puffing module is modeled as a single continuous stirred tank (manifold) which takes the required discharge from the fuel management subsystem and delivers this fuel through fast-acting valves into the torus.

H. AUXILIARY UNIT OPERATIONS

1. Catalytic Reactor. Reactors in general are modeled with any possible reactions that are expected to occur in the reactor. This flexibility allows the user to model any type of reactor proposed to be used in the flow configuration. A representative overall efficiency for each modeled reactor is used to account for the incompleteness of reactions.

2. Permeator. In this operational unit, various species that are expected to fully permeate the permeator are modeled. With respect to the tritium fuel cycle, these permeating species are most likely to be hydrogen isotopes. Similarly to catalytic reactors, an overall efficiency rating is assigned to each permeator to estimate the fraction of permeating species that actually permeate through the component.

3. PMR. This component is modeled as a combination of a permeator and a catalytic reactor. An efficiency value to account for reaction "completeness" of expected chemical reactions is included as for the catalytic reactor module.

4. Assaying Tank System. In a tritium processing system, a means for accurately measuring the composition of the flow content at various points in the fuel cycle must be performed during operation of the system. In order to perform this function as well as acting as a buffering mechanism, an assaying tank system was developed using two tanks operating in a batch process with each other. One tank is used for temporary buffering of flows, while the other is used for recirculation and analysis of its contents using one of several experimental methods before discharging its contents downstream through a transfer pump. A parametric assaying time defines this recirculation time. When one tank fills up to a maximum level, then the roles are switched.

5. Transfer Pumps. For our model, a general type of transfer pump is used whereby the pumping speed coupled with the pressures from the upstream and downstream units is estimated using representative pumping curves.

6. Mixers and Splitters. These modules are self-explanatory and are utilized in great abundance throughout the fuel cycle to be able to simulate multiple inflows and recycle flows.

IV. RESULTS AND ANALYSIS OF SIMULATIONS

A. DYNAMIC TRITIUM INVENTORIES

Dynamic behaviors of localized tritium inventories in the major subsystems of the torus exhaust fuel cycle stream are tracked for a 2-day simulation period consisting of initial pulsing operation (i.e. 1000 sec burn and 1000 sec dwell) on the 1st day followed by steady-state operation on the 2nd day. Different burn and dwell times can be acommodated in the code. Figures 4-10 display these time-dependent inventories. About half of the tritium inventory in this primary fuel cycle stream can be seen to be located in 2 subsystems: 1) the cryopump primary vacuum pumping, and 2) the ISS. The remaining inventory is located in buffer units such as tanks and pellet extruders.

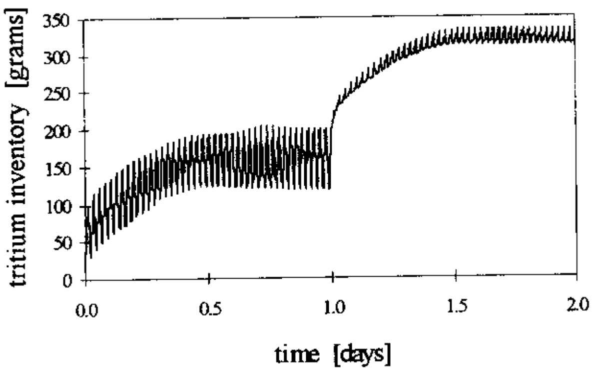


Figure 4: Dynamic Tritium Inventory in Cryopumps

For the cryopumps subsystem, its tritium inventory (in Figure 4) can be seen to vary approximately with an overall residence time determined by its operation cycle. The jump at t = 1[day] is due to the doubling of the average flow rate exiting the torus, which leads to a corresponding doubling of the tritium inventory. This figure, as do all the subsequent figures, shows the dramatic effect on the range of inventory fluctuations due to pulsing operation.

The next major subsytem in this processing system is the assaying tank system used for experimental validation of the flows inside the reactor. Figure 5 shows the behavior in this subsytem as governed by batch spikes which depend upon the operational unit design parameters. A small increase in the average inventory occurs during steady-state. Figure 6 presents a detailed view showing the spikes during 1 hour of the pulsing phase, where the small plateau is the assaying time. The different shapes on the rising portion of the curve is due to the complex behavior of the inlet flow.

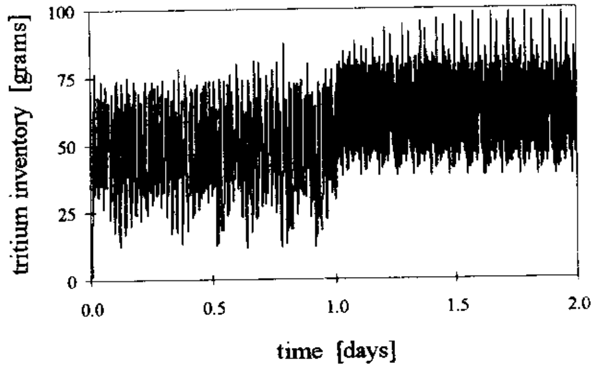


Figure 5: Dynamic Tritium Inventory in Assaying Tank System

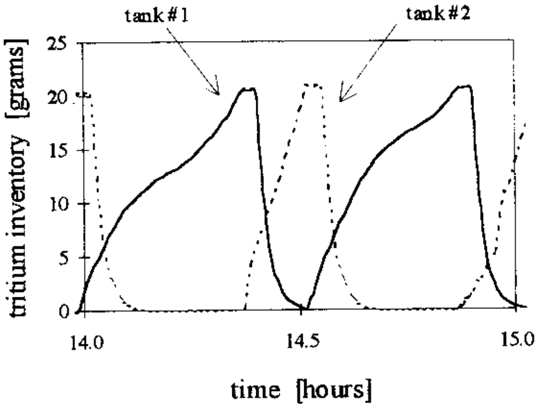


Figure 6: Close-Up of Dynamics in Assaying Tank System

However, the dwell during pulsing can be seen in the tank #2 plot, because this dwell time is greater than the pumping time of the cryopumps. The inventory in the FCU is assumed to be negligible. The ISS inventory is illustrated in Figure 7 where the behavior is similar to the cryopumps.

The fuel management tritium inventory in Figure 8 shows the effects from upstream holdups. In the first 2 [hours], the storage subsystem provides the only source of fuel because recycle flows are not being discharged yet from the ISS. This will result in a greater drop in tritium inventory due to the "delivery" tank's inventory slowly decreasing while the "buffering" tank is not able to balance it with holdup of incoming recycled flows. However, when recycling is available, the inventories in the "delivery" and "buffering" tanks will decrease and increase at almost the same rate so that the aggregate inventory appears constant. Again, at t=1[day], there is a discontinuity due to the operating scenario change. At the start of steady-state operation,

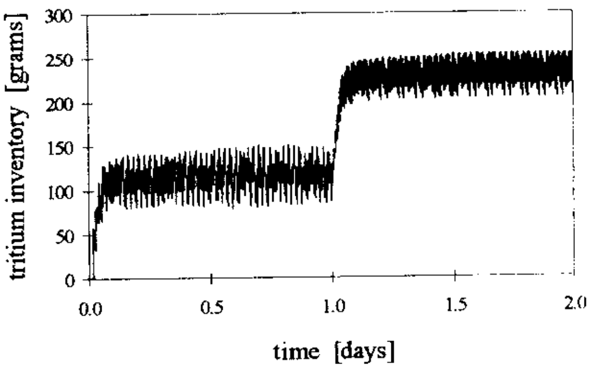


Figure 7: Dynamic Tritium Inventory in the ISS

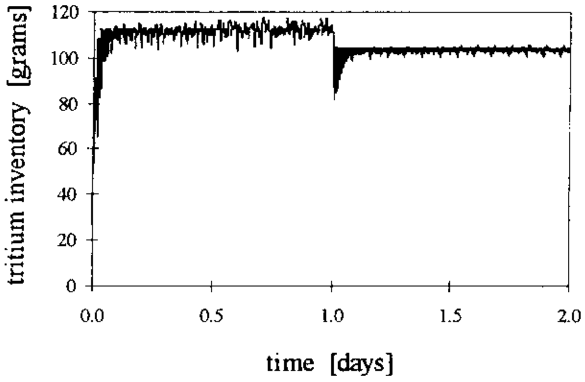


Figure 8: Dynamic Tritium Inventory in Fuel Management

the higher required flow rates out of fuel management and into fueling will cause a temporary imbalance on the fuel management net flow. Thus, it will take approximately 2 [hours] (i.e. the average upstream residence time) for the balance to be regained as shown in the figure .

The corresponding storage tritium inventory appears in Figure 9, where the sharp drops in inventory appear at the beginning of each new phase of operation as expected from Figure 8. These sharp drops define the non-recycling phase of the simulation when inventory rises in other subsystems. Additionally, the storage tritium inventory must decrease by an amount equal to the fuel fusion burnup during the recycling phase. This is shown in the figure where the slopes are equal to the corresponding average fusion burnup (9.6 [g/hr] during steady-state and 4.8 [g/hr] during pulsing).

Regarding the fuel management subsystem, the amount of preloading required before reactor startup for this configuration is not large. In fact, as long as the preloaded tritium inventory is above the minimum value set by the switch reserve time, then the fuel management will operate as designed. For our simulation parameters, the fuel management preloaded inventory value can be as low as 60 [g]. Still, other fuel subsystems (e.g. the pellet injection extruders), will need to be preloaded with enough fuel to start and operate the unit because of fueling requirements.

The PIS extruders operate on a batch cycle for the 2-extruder system governed by the fueling and freezing times and is composed of a cyclical rise and fall in inventory. The rise is due to the faster required extruder system inflow rate for constant fueling while the associated drops occur when no inflow enters the standby extruder when freezing of the fuel is performed. The maximum and minimum inventories will depend upon the amount of required freezing time for a given batch of fuel. Figure 10 shows this behavior. As expected, during pulsing the inventory fluctuations increase from the mismatch of the pulsing and the fueling/freezing behavior.

B. DESIGN PARAMETER SELECTION

Fuel cycle design parameters (e.g. assaying time, fuel reserve time of the fuel management "delivery" tank, fuel reserve time during fuel management tank switching, pellet injection fueling and freezing times) must have values so that the fuel cycle is optimized and operate reliably. Table 2 lists some fuel cycle

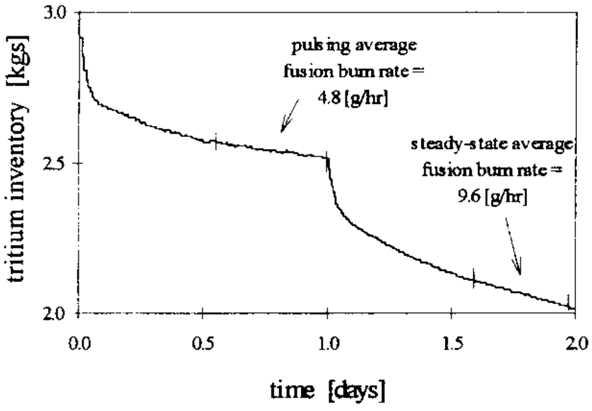


Figure 9: Dynamic Tritium Inventory in Storage

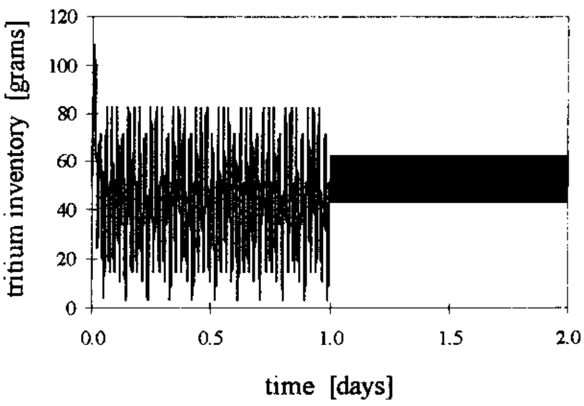


Figure 10: Dynamic Tritium Inventory in Pellet Injection Extruder System

Parameter	⇐⇐	⇐	**Selected Design Value**	⇒	⇒⇒
ISS τ_{res}	15 [min]	22.5 [min]	30 [min]	37.5 [min]	45 [min]
ISS avg trit. inv	56.4 [g]	84.2 [g]	111.6 [g]	138.8 [g]	165.6 [g]
FM fuel reserve time	5 [min]	8 [min]	10 [min]	12 [min]	15 [min]
FM avg trit. inv	47.2 [g]	70.6 [g]	110.5 [g]	126.0 [g]	152.6 [g]
Assaying Time	X	1 [min]	2 [min]	3 [min]	4 [min]
Assaying Tank System avg trit. inv	X	39.6 [g]	43.4 [g]	47.2 [g]	51.0 [g]

Table 2: Tritium Inventory Sensitivity to Various Fuel Cycle Design Parameters

design parameters and their associated influence on the local tritium inventory. From this table, it appears that the assaying time has a very small effect on the tritium inventory when changed from 1 [min] to 4 [min]. However, longer assaying times must include a corresponding increase in the value of the maximum allowable gas for the assaying operation to function reliably.

However, the ISS residence time as well as the fuel management fuel reserve time greatly affect the average tritium inventory in their corresponding subsystems. Again, for the case of the fuel reserve time, a decrease in its value must include an associated decrease in the switch reserve time if they become equal. Decreasing the fuel reserve time to fueling from fuel management will lower the amount of fuel necessary in the "delivery" tank and thus its inventory. However, this change will effect a faster cycling of fuel from storage to make up for burned fuel. This cycling will be limited by the pumping speed of the storage transfer pumps to transport the required fuel.

V. SUMMARY

A computer model, TRUFFLES, which accurately characterizes a fusion fuel processing system has been developed. Results have been obtained which elucidate the dynamic behavior of such a system. The code has been shown to be useful for determining the effect of processing parameter changes on tritium inventories. It is believed that this model will be useful for ITER process design and safety analysis.

In this work, the effects from pulsing were investigated. Steady-state and pulsing [1000 sec burn - 1000 sec dwell) scenarios were compared, where a change toward higher reactor availability can be examined. The logic for a fuel management subsystem was presented and it was found that for different maximum allowable tritium inventory requirements, the fuel reserve time must change correspondingly. For example, if the tritium inventory must not be allowed to be higher than 100 [grams] inside fuel management, the fuel management fuel reserve time must be lower than 9 [min]. Other fuel cycle design parameters will be affected by such a requirement. Analysis of the dynamic tritium inventories showed that the required preloading of fuel in the fuel management is about 60 [g] for this configuration.

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