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A NEW APPROACH FOR ASSESSING THE REQUIRED TRITIUM BREEDING RATIO AND STARTUP INVENTORY IN FUTURE FUSION REACTORS

TRITIUM SYSTEMS

KEYWORDS: *tritium fuel cycle, required tritium breeding ratio, startup inventory*

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Accurately estimating the required tritium breeding ratio (TBR) Λ_r in fusion reactor systems is necessary to guide fusion research and development and to assess the feasibility of fusion reactors as a self-sufficient energy source. This is especially true when one considers the limits imposed by the present-day breeding performance of breeder blanket candidates. Studies of this subject have been performed in the past, with particular emphasis on developing appropriate dynamic simulations of the fuel cycle. In the last few years, development of new dynamic and integrated fusion fuel cycle tritium computer codes has moved away from general residence-time models and instead incorporated more comprehensive and realistic models. Furthermore, detailed and rigorous computer codes that model the dynamic retention behavior of individual components inside the fuel cycle, in particular the torus plasma-facing components in a tokamak, have been vastly improved with uncertainties identified.

A more efficient and intuitive methodology for tritium self-sufficiency analyses is developed based on an analytical scheme that makes use of different types of tritium inventories inside the fuel cycle as calculated from detailed numerical simulations. Short-term and long-term tritium inventories are differentiated as well as tritium lost through waste material. Also, the tritium fuel cycle is split into a number of independent tritium migration paths to aid in the development of an integrated tritium balance for which Λ_r or other parameters of interest can be solved analytically. Tritium startup requirements are also examined. An important side benefit derived from using the aforementioned methodology is that the uncertainty in Λ_r for a given reactor design can easily be calculated from uncertainty ranges characterizing a number of relevant reactor operation and fuel cycle parameters. Maximum tritium inventory limits were considered from safety and operational standpoints. A wide range of parametric studies were conducted with various scenarios to forecast changes in Λ_r when the reactor design is modified. For example, it was determined that with most current estimates of the achievable TBR Λ_a, ranging from 1.04 to 1.07, a small design window for both the fuel fractional burnup and the downtime of tritium reprocessing components severely limits any proposals for a reactor operating scenario that will be valid for a reasonably paced fusion growth rate.

I. INTRODUCTION

The scarcity of natural tritium leads directly to the need to breed tritium from manufactured sources. In a future grid of DT fusion reactors, such breeding will most likely be performed primarily inside the reactors themselves rather than from any available outside sources. Moreover, a significant tritium startup inventory will be required during the initial period of their operation. The fuel self-sufficiency condition for a DT fusion reactor, $\Lambda_a \geq \Lambda_r$, was defined and analyzed in detail by Abdou et al.[1] The value Λ_r is the required tritium breeding ratio (TBR), and Λ_a is the achievable TBR given a particular reactor and blanket design. For this previous work, Λ_r was derived using a simplified first-order linear system model, which made use of mean tritium residence times

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to simulate the tritium dynamics. In addition, other related efforts to evaluate DT fuel self-sufficiency have been conducted, although they have adapted more or less the same methodology.[2–5]

The purpose of this work is to develop a more detailed, accurate, and efficient methodology for tritium self-sufficiency analyses, based on detailed numerical simulations that evaluate tritium inventories both locally and globally. The main reason for using such detailed numerical schemes [e.g., Kuan et al.,[6–9] CFTSIM (Ref. 10), DYNSIM (Ref. 11), TMAP4 (Ref. 12), and coupled erosion and plasma codes as in WBC/REDEP/DEGAS+ (Ref. 13)] is to model different parts of the fuel cycle in a more realistic manner to more accurately quantify the impact of changes on tritium self-sufficiency caused by subsystem operation. As a result, the use of localized subsystem tritium residence times is replaced by calculated tritium inventories. An important side benefit, derived from using the aforementioned methodology, is the ability to easily calculate the uncertainty in the required TBR and the startup inventory requirement for a given reactor design based on the uncertainties from a number of relevant reactor and fuel cycle parameters. In short, an alternative approach to the tritium self-sufficiency problem is proposed and developed in this work using an analytical scheme for which a quantitative evaluation of the tritium breeding and startup requirements is then conducted.

II. FUEL CYCLE DYNAMIC MODELING

A key part of the evaluation of Λ_r is the calculation of time-dependent tritium flow rates and inventories throughout the entire fuel cycle—in other words, the modeling of the fusion fuel cycle. In past fuel cycle dynamic models, average tritium residence times, average nonradioactive loss fractions, and the tritium decay time were all utilized within a coupled system of first-order linear differential equations as follows (see Nomenclature on p. 350):

$$\frac{dI_i}{dt} = \sum_{j \to i} \left(\frac{I_j}{\tau_j} \right) - (1 + a_i) \frac{I_i}{\tau_i} - \lambda I_i \qquad (1)$$

where

i = subsystem of interest

j = other subsystems.

In the aforementioned linear model, the nonradioactive loss fraction is formulated as a linear function of the processing rate I_i/τ_i. More-general formulations for this loss fraction can also be used, for example, by relating this loss fraction to the subsystem inventory by adding another proportionality constant b_i as in $a_i(I_i/\tau_i) + b_i I_i$ (Ref. 5).

A block diagram of the tritium fuel cycle has proven to be a valid tool in the understanding of both integrated dynamic modeling schemes and tritium self-sufficiency analyses. It is thus worth summarizing the block diagram of the fuel cycle briefly. The fuel cycle can be decomposed into various subsystems that are linked in various ways to one another through various processing lines. The major subsystems that can be represented as independent blocks are

1. plasma
2. plasma exhaust vacuum pumping
3. impurity separation
4. impurity processing
5. plasma-facing components (PFCs)
6. PFC coolant
7. hydrogen isotope separation
8. fuel management
9. long-term storage
10. fueling
11. breeding blanket
12. blanket coolant.

A few more minor fuel cycle subsystem blocks (e.g., the tritium waste treatment and the blanket tritium processing) can also be included in the preceding list. Each of these subsystem blocks provides a specific function in the gradual processing and eventual recycling of the DT fuel. More detail on the actual processing tasks can be obtained from Refs. 6, 7, and 10.

It is also worthwhile to briefly discuss the current status of integrated fuel cycle dynamic models, as well as localized models, that are being used in the estimation of the tritium inventories. With respect to integrated models, as previously mentioned, computer simulations using a system of linear differential equations characterizing each subsystem were the starting point (with progressively more species being tracked). With more-detailed fuel cycle designs becoming readily available, such as International Thermonuclear Experimental Reactor (ITER) designs, it became possible to model each subsystem, in addition to the components inside each subsystem, in a more rigorous manner to capture the essential dynamics of the subsystems. It was found that most components that made up the tritium plant, i.e., outside the vacuum vessel, were dynamically driven by batch operations that controlled their inventories.[6,7,10]

Localized tritium inventory models have also undergone more rigorous modeling to understand and predict the inventories and flow rates inside single fuel cycle components. Such localized models have been applied to the breeding blanket,[14–17] a variety of relevant PFC tritium retention processes,[18–20] and the Isotope Separation System[11] (ISS). Great improvements in modeling (dynamic and steady state) have gradually been attained, with the result that inventory predictions for many components are now much more accurate than past models. The calculations of these models, both integrated and local, have thus been used for the analysis in this work.

III. A NEW ANALYTICAL APPROACH UTILIZING INVENTORY PREDICTIONS FROM OTHER MODELS

With the development of more-accurate integrated models of the fuel cycle that make use of component operating parameters, which are optimized for runs that normally simulate fuel cycle operations up to about a few days or weeks, simulation runs up to typical values of the doubling time will require a fair amount of time. Furthermore, rigorous localized dynamic models that most likely model the retention levels in the spatial dimension as well as in time are also characterized by long execution times. The large divergence in values between characteristic time constants in fuel cycle processing lines and the tritium radioactive decay constant, as well as the iteration needed to solve for the appropriate Λ_r, will result in the direct use of current simulation models for tritium self-sufficiency analyses. This is an inordinately inefficient process. More efficient methods should then be pursued for self-sufficiency studies that make use of current capabilities in tritium inventory prediction. Working with this view in mind, an analytical approach was developed that directly solves for a number of tritium self-sufficiency parameters of interest, such as Λ_r, by utilizing direct values of quasi-steady-state tritium inventories that can be calculated from current levels of inventory predictions for future DT fusion reactors. Iterations of many simulation runs are thus skipped while a more thorough analytical formulation is provided, making parametric analyses more practical.

The best approach, then, toward the advancement of a more efficient solution of the tritium self-sufficiency problem, as encountered in feasibility, safety, and economic analyses, is to use an analytical approach without the use of general average residence times characterizing each subsystem. Thus, we take advantage of the detail and accuracy available from present numerical solutions for estimating the tritium inventory while making use of efficient and fast analytical solutions. Some reasons for this choice are as follows:

1. Because we are dealing with the fuel cycle as a whole in this study and the accumulation of inventory for a specific period of time, it would be expected that only the total inventory and the accumulated loss to unrecoverable sinks for the period of interest, $\sum_i I$ and $\int\left(\sum_{i\rightarrow to\ env} F\right)$, would directly affect self-sufficiency problems. This total fuel cycle inventory $\sum_i I$ can be further subdivided into inventories located within various tritium flow paths as discussed later in this paper.

2. Present dynamic models are normally used for simulating short periods of time when the tritium inventory reaches a quasi-stable regime, with the notable exception of fuel cycle components exposed to long-term irradiation.

3. A much better understanding of the tritium dynamic behavior throughout the fuel cycle with respect to tritium self-sufficiency is obtained. This is especially true with regard to the different tritium migration paths and their comparative importance in self-sufficiency analyses.

With regard to tritium self-sufficiency, only the inventory still held in the reprocessing units at specific points in time are of interest, and the actual dynamics are unimportant. However, in most instances found throughout the fuel cycle, the tritium inventory will never stabilize to a single value due to various batchwise operations and also due to regular maintenance and/or accident conditions. Because of such expected inventory fluctuations, the inventory at any point in time as described by quasi-steady-state operation will range in values driven by the batchwise operations in use. As a result, both a minimum and a maximum inventory condition will exist in the tritium reprocessing subsystems $\sum_i I_{min}$ and $\sum_i I_{max}$, respectively. An average quasi-steady-state inventory can also be calculated, $\sum_i I_{avg}$. Therefore, these fluctuating inventories will have some significance in tritium breeding requirement studies. These inventory fluctuations will also add another condition that has not been included in previous work done in this area. This condition is the minimization of the tritium inventory during the quasi-stable regime of the entire fuel cycle tritium inventory, which may affect the initial required supply of tritium. The difference between $\sum_i I_{min}$ and $\sum_i I_{max}$ will be the primary driver for the aforementioned minimization condition.

In summary, a two-step process can be identified in the aforementioned scheme for solving tritium self-sufficiency problems. The first step is to identify the quasi-stable regime found in tritium inventory dynamics and to calculate such quasi-steady-state tritium inventories. Long-term irradiation tritium retention processes will also need to be taken into account, though they may also be described by quasi-steady-state values as discussed in Sec. IV.C. Thus, tritium inventory prediction codes are used within this tritium self-sufficiency framework to provide such quasi-steady-state inventories as well as average losses to the environment and to waste material. In addition, the effect from changes in operating parameters characterizing fuel cycle components on $\sum_i I_{min}$, $\sum_i I_{max}$, and $\sum_i I_{avg}$ can be more readily analyzed with these more detailed codes. The second step will then make use of such tritium data to obtain the required TBR Λ_r or other tritium fuel self-sufficiency-relevant parameters using an analytical approach.

Before discussing the details of the analytical method used in the preceding framework, the different migration paths of the tritium flow must be understood, because breaking up the fuel cycle into such flow paths will help in analyzing the tritium fuel self-sufficiency problem. During reactor operation, tritium will migrate through four possible retention/processing lines that make up the fusion fuel cycle as pictured in the simplified flow schematic of Fig. 1. From a tritium self-sufficiency point of view, only the aggregate inventories inside each of these processing lines are of concern. In other words, localized tritium inventories, retained in individual subsystems or components that are part of a specific processing line, will affect tritium self-sufficiency issues on equal terms. This observation will be used in the upcoming fuel cycle analysis.

In conventional fusion reactors, most of the tritium will flow through the plasma fueling/exhaust line because the tritium fractional burnup in the plasma is relatively small, for example, on the order of a few percent. Because of this burnup inefficiency, most of the tritium fuel does not participate in fusion reaction burn but is exhausted through the divertor/limiter and onto the plasma-exhaust-reprocessing components. The tritium in the long-term storage subsystem will feed this loop during the start of operation when the tritium produced in the breeder has yet to flow through this loop. Moreover, tritium on or within PFCs may be processed within this same plasma fueling/exhaust line during various wall-conditioning intervals, so a noncontinuous flow will characterize tritium trapped inside PFC materials. For our purposes, the subsystems within this processing line can further be categorized into either critical or noncritical subsystems with regard to the capability of the reactor to operate continuously even when process interruptions caused by component or operational failure occur.

The breeder line only interfaces with the plasma fueling/exhaust line through either in-line storage or common reprocessing equipment, such as the ISS, and so is independent of reactor operation except for the neutron load to the blanket. This is not so for the coolant line, which interfaces with both the fusion reactor chamber, acting as the tritium source, as well as the plasma fueling/exhaust line. Note that both the breeder- and coolant-processing lines can be served by a single processing line, as in the case of a design incorporating a liquid breeder simultaneously serving as the PFC coolant. Last, an impurity-processing line branches out from and back into the plasma fueling/exhaust line. This line carries only tritiated impurities, so the tritium flow rate within this tritium path is low. The breeder-, coolant-, and impurity-processing lines are considered noncritical with regard to operational interruptions. For example, if the helium purge flow is lost in a solid breeder, flow of tritium through the blanket breeder subsystem will stop, so the breeder line will not process any tritium during this time. However, the fusion reactor can still be operated in a normal manner. Figure 2 shows a schematic of the fuel cycle subsystem network and illustrates the subsystems that are part of each processing line. Much of the subsequent discussion focuses on the different effects on tritium self-sufficiency and startup inventories due to these four processing lines.

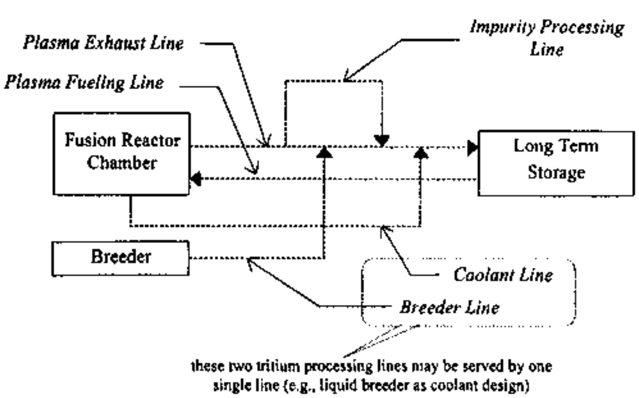

Fig. 1. Tritium migration paths in the fuel cycle.

IV. FUEL CYCLE INTEGRATED TRITIUM BALANCE

The calculation of the required TBR has been modified to utilize the quasi-steady-state tritium inventories and integrated tritiated losses in the fuel cycle as opposed to tritium residence times used in previous work. Integrated nonradioactive losses (e.g., those that are not due to tritium decay) can be found by keeping track of the accumulated loss of tritium that is discharged to the environment as well as that which is retained as waste. More simply, the environmental losses can be estimated from the safety limits imposed by operation standards. These losses will be negligible compared to the inventory present in the fuel cycle at any given time. The loss due to waste material is more difficult to estimate, and a method for estimating such waste is presented later. The analytical methodology presented here is based on an integrated tritium balance during any given period of interest, i.e., a doubling time, with the fuel cycle/reactor system as the control volume. This approach requires accounting for all sources and sinks that will affect tritium flow during said period of interest. Note that, unlike the previous modeling effort focusing on the operational aspects of the fuel cycle and for which all molecular species were tracked, only tritium, whether in molecular form or held up in impurities, is to be tracked during the discussion in this section.

Table I lists the general initial and final inventory conditions found in the fuel cycle within a specified time period. This list applies to all self-sufficiency problems

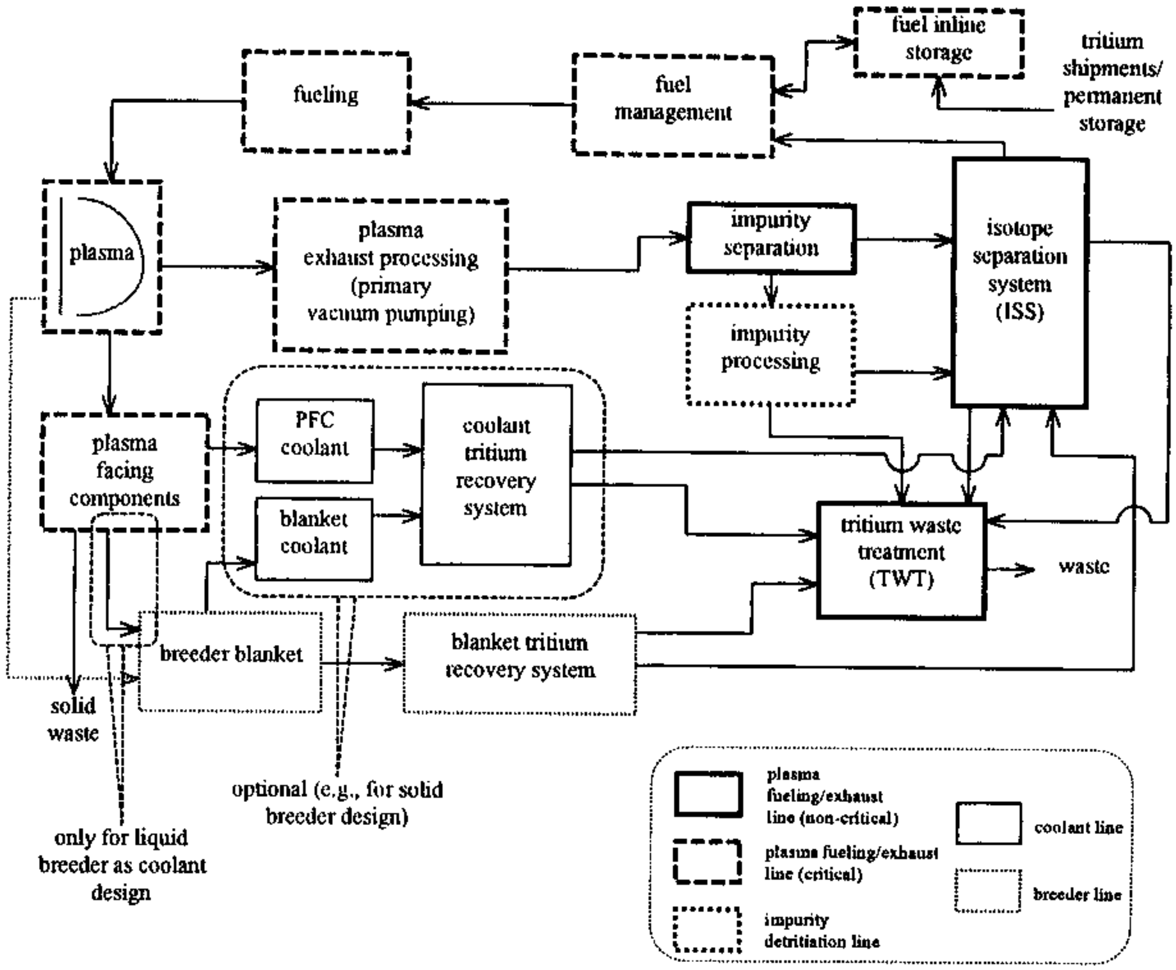

Fig. 2. Fuel cycle schematic with tritium-processing lines.

TABLE I

Fusion Fuel Cycle Initial and Final Tritium Inventories

Initial inventory conditions	Startup storage inventory, $I_{i,0}$
Final inventory conditions	Required inventory in storage, I_{req} (doubling-time requirement = $I_{i,0}$)
	Reserve inventory in storage, I_r
	Total short-term quasi-steady-state inventory, $\sum_i^{short\ term} I$
	Total long-term steady-state inventory, $\sum_i^{long\ term} I$

that are constrained within this time period. During startup of the reactor, the only initial inventory originates from the long-term storage subsystem. This initial condition assumes a clean reactor chamber, especially the vacuum vessel walls, with regard to tritium. It is expected that during startup, protium, deuterium, and impurities will most probably exist in some form in the fuel cycle, but tritium should not be present. The integrated tritium balance is as follows:

$$\text{net production} = \text{required production} \tag{2}$$

$$\text{sources} - \text{sinks} = \text{required production} \tag{3}$$

$$\overset{A}{\int_0^{t_f} F_{net}\,dt} + \overset{B}{\int_0^{t_f} \left(\frac{dI_{i,0}}{dt}\right) dt} - \overset{C}{\sum_i^{long\ term} I} - \overset{D}{I_{waste}|_0^{t_f}} = \overset{E}{I_{req}} \ , \tag{4}$$

where A through E are labels corresponding to each term of Eq. (4). The net production is that production from all tritium sources minus the losses to all significant tritium sinks during reactor operation.

The tritium source terms in the fuel cycle originate mostly from both breeder production or external sources. It is assumed that most of the tritium necessary to start the reactor for continuous operation is initially stored in the storage subsystem, with the remaining tritium fed from external sources, if at all. Conversely, many different tritium sinks exist throughout the fuel cycle. These can be grouped into the following:

1. tritium decay (12.3-yr half-life)
2. fusion reactions
3. loss to environment
4. loss to waste material $I_{waste}|_0^{t_f}$
5. long-term retention inside the fuel cycle $\sum_i^{long\ term} I$.

Tritium decay affects tritium sources and startup tritium inventories, which will gradually be redistributed throughout the fuel cycle in a dynamic manner. The required production is that production necessary to satisfy various conditions within a certain period of interest, so it is governed by the desired rate of accumulation of next-generation fusion reactors.

The right side of Eq. (4) is thus made up of I_{req}, the required inventory that is located in the storage subsystem for subsequent removal to another reactor. The startup tritium inventory inside the reactor plant, $I_{i,0}$, which is initially in storage, will be redistributed to the plasma exhaust-line-processing units and so is not included in the aforementioned balance because it will cancel out on both sides of the equation. Each term is discussed separately in Secs. IV.A through IV.E, corresponding to labels A through E in Eq. (4).

Inclusion of pulsing, maintenance, and shutdown periods in simulated reactor operating scenarios are taken into account in this analytical scheme with both general pulsing and downtime availability parameters as provided by the following definitions. Total reactor availability is calculated by multiplying these parameters together:

$$\alpha_p = \frac{t_{burn}}{t_{burn} + t_{dwell}} \qquad \alpha_{op} = \frac{t_{on}}{t_{on} + t_{off}} \ . \tag{5}$$

Both parameters are utilized only in calculations involving sources or sinks, which are associated with the reactor power level, to account for its time-dependency. During shutdown, it is assumed that all the mobile inventory will be returned to the storage subsystem for subsequent use during the next startup phase.

IV.A. Net Tritium Production Due to Continuous Sources and Sinks

The net production of tritium during a given time period because of continuous production or loss of tritium inside the fuel cycle will gradually be accumulated and transferred into the storage subsystem. Therefore, we need to account for all continuous sources and sinks of tritium in the fuel cycle. Tritium breeding inside the breeder blanket as a result of n, Li reactions is the major, and possibly the only, local source of tritium in the fuel cycle. If plasma-facing walls are made of beryllium, this will serve as another source of tritium, though a minor one relative to the blanket breeder source. In a breeding blanket, the tritium production rate is the product of the actual net TBR Λ and the rate of DT fusion reactions in the plasma. This breeding is thus coupled by way of the neutron flux to the reactor power level P_f. The reactor operation scenario must also be taken into account through α_p and α_{op} to provide an average rate of tritium production. For the special case of a steady-state power level with no reactor downtime, $\overline{F_{bred}}$, the average tritium production rate in the breeder, will be constant because $\alpha_p = 1$ and $\alpha_{op} = 1$. In the following equation, Q_f is the energy produced in a fusion reaction:

$$\overline{F_{bred}} = \Lambda\left(\frac{\alpha_p \alpha_{op} P_f}{Q_f}\right) \ . \tag{6}$$

Fusion inside the plasma is considered a continuous tritium sink due to nuclear burnup of tritium. This burning process is again coupled to the reactor power level. Therefore, the equation is similar to the Eq. (6) bred tritium source equation, where now $\overline{F_{fus}}$ is the average tritium loss from fusion reactions:

$$\overline{F_{fus}} = \alpha_p \alpha_{op}\left(\frac{P_f}{Q_f}\right) \ . \tag{7}$$

These two equations are coupled through Λ, which is defined as the ratio of the rate of tritium bred in the breeding blanket versus that of the rate of tritium lost through fusion reactions. Nonradioactive losses will likely exit from the reactor plant through the heat transport coolant line and then to the environment. They may also be trapped inside replaced material that is not processed for detritiation. However, only environmental losses are continuous or nearly continuous in nature, whereas waste tritium is lost only during specific periods, which are few in the lifetime of a commercial reactor. Therefore, waste tritium is taken into account separately in the integrated tritium balance, so only environmental losses concern us here. These environmental material tritium losses can be calculated for specific simulation scenarios using integrated simulations or from operating limits set for safety reasons. Again, continuous natural tritium decay will have an impact. Thus, we can estimate an average rate of the nonradioactive tritium loss to the environment $\overline{F_{env}}$ for this purpose. This can be accomplished by averaging the accumulated losses during a specified period of operation t_{sim}:

$$\overline{F_{env}} = \frac{\int_0^{t_{sim}} F_{env}\, dt}{t_{sim}} \quad . \tag{8}$$

With the integrated simulations as used in Eq. (8), it is assumed that the short simulation scenario that is characteristic of any integrated simulation run is duplicated on a larger scale for the time period of interest such as doubling time. With respect to environmental losses, a more straightforward way of estimating this rate of loss is to use the imposed environmental loss limits on reactor operation. Such environmental losses are very small and so are expected to be negligible in tritium self-sufficiency problems. For typical reactor design concepts, $\overline{F_{env}}$ is taken to be ~10 Ci/day, which corresponds to a loss of only ~1 g of tritium during 1000 days of operation.

Fuel from external sources may be added to the reactor's fuel cycle after the reactor has started operating. Such external fuel may originate from dedicated tritium production plants, fission reactors, military stockpiles, or concurrently operating fusion reactors. This external fueling rate can be any general function with respect to time. In fact, it will most likely be introduced into the reactor's fuel cycle at discrete time periods during the course of operation. Nevertheless, since such discrete time periods will most likely be much shorter than the timescale of any tritium self-sufficiency problems, it can be assumed that the fuel is fed to the fuel cycle at a constant or nearly constant rate $\overline{F_{ext}^{in}}$, relative to t_f. The value $\overline{F_{ext}^{in}}$ is thus considered an additional continuous source of tritium for the fuel cycle. Conversely, a continuous or nearly continuous flow of tritium can be extracted from the fusion reactor, $\overline{F_{ext}^{out}}$, to aid in the tritium needs of any external operation such as starting another reactor or for supplying tritium for other applications such as weapons replenishment.

The dynamic behavior of the loss rate is not needed in this analysis because only the initial and final conditions contribute to the problem. As a result, the net rate of tritium production, including all of the aforementioned continuous sources and sinks in the fuel cycle, is

$$F_{net} = \overline{F_{bred}} - \overline{F_{fus}} + \overline{F_{ext}^{in}} - \overline{F_{ext}^{out}} - \overline{F_{env}} \quad . \tag{9}$$

When we substitute the $\overline{F_{bred}}$ and $\overline{F_{fus}}$ relations of Eqs. (6) and (7), respectively, we then have

$$F_{net} = \alpha_p \alpha_{op}\left[\Lambda\left(\frac{P_f}{Q_f}\right)\right] - \alpha_p \alpha_{op}\left(\frac{P_f}{Q_f}\right) + \overline{F_{ext}^{in}} - \overline{F_{ext}^{out}} - \overline{F_{env}} \quad . \tag{10}$$

In Eq. (10), α_p and α_{op} remove the time-dependency of the right side for both $\overline{F_{bred}}$ and $\overline{F_{fus}}$. In addition, $\overline{F_{ext}^{in}}$, $\overline{F_{ext}^{out}}$, and $\overline{F_{env}}$ are time-averaged values because their time-dependency is not important for the timescale in the studies conducted here. When tritium decay is included in the net accumulation of tritium as previously defined, the accumulated net production tritium gain $\int F_{net} dt$ is governed by the following first-order differential equation:

$$\frac{d\left(\int F_{net}\, dt\right)}{dt} = F_{net} - \lambda\left(\int F_{net}\, dt\right) \quad . \tag{11}$$

When we substitute the equation for F_{net}, we then have

$$\frac{d\left(\int F_{net}\, dt\right)}{dt} = \alpha_p \alpha_{op}\left[\Lambda\left(\frac{P_f}{Q_f}\right)\right] - \alpha_p \alpha_{op}\left(\frac{P_f}{Q_f}\right) + \overline{F_{ext}^{in}} - \overline{F_{ext}^{out}} - \overline{F_{env}} - \lambda\left(\int F_{net}\, dt\right) \quad . \tag{12}$$

The solution to this nonhomogeneous linear differential equation when solving for $\int_0^{t_f} F_{net}\, dt$ within the period of interest (limits 0 and t_f) becomes

$$\int_0^{t_f} F_{net}\, dt = \left[(\Lambda - 1)\alpha_p \alpha_{op}\left(\frac{P_f}{Q_f}\right) + \overline{F_{ext}^{in}} - \overline{F_{ext}^{out}} - \overline{F_{env}}\right] \times \frac{(1 - e^{-\lambda t_f})}{\lambda} \quad . \tag{13}$$

IV.B. Loss from Startup Storage Inventory

IV.B.1. Startup Storage Inventory Dynamics

Now, with respect to the net production term in the integrated tritium balance in Eq. (4), the problem is reduced to calculating the correct value for $I_{i,0}$. Physically, $I_{i,0}$, the startup tritium inventory in the reactor plant, will subsequently diffuse out throughout the plasma exhaust line of the fuel cycle (with a trace amount in the coolant line) and ultimately achieve a quasi-steady-state condition during the reactor lifetime. In addition, it will subsequently experience losses to sinks in the fuel cycle during the period of interest t_f. In this methodology, the loss will originate from both tritium decay and tritium losses to the environment and waste, which are nonradioactive. However, nonradioactive losses are taken into account separately as formulated in the expression for F_{net}. Thus, only tritium decay must be included to estimate

$dI_{i,0}/dt$, which can be expressed with a simple exponential decay behavior as follows:

$$\frac{dI_{i,0}}{dt} = -\lambda I_{i,0} \ , \tag{14}$$

with the integrated solution given by

$$\int_0^{t_f} \left(\frac{dI_{i,0}}{dt} \right) dt = -I_{i,0}(1 - e^{-\lambda t_f}) \ . \tag{15}$$

Now the problem is reduced to calculating the correct value for $I_{i,0}$. Note that $I_{i,0}$ can be any value as long as the inventory in storage does not run out before the bred tritium is able to replace this startup fuel supply for fueling the plasma. In other words, I_s, the inventory located inside the storage subsystem, should not drop to a negative value during reactor operation. The goal should then be to estimate $I_{i,0}^{opt}$, the lowest tritium inventory that allows continuous operation of the reactor, taking into account any resupply from outside sources.

IV.B.2. Optimal Startup Inventory

Mathematically, $I_{i,0}^{opt}$ will be satisfied when $I_s = 0$ at the storage inventory inflection point t_s^{infl} (i.e., when the storage subsystem switches from a role as an effective source to one of an effective sink), as illustrated in Fig. 3. This can be formulated as follows:

$$I_{i,0}^{opt} \Rightarrow I_s(t_s^{infl}) = 0 \quad \text{and} \quad \frac{d^2 I_s(t_s^{infl})}{dt} > 0 \ . \tag{16}$$

For such an optimized condition, a satisfactory startup inventory will have enough tritium during startup within the storage subsystem to compensate for the initial holdup in all relevant processing lines before bred tritium from the breeder line can be used and recycled as fuel, e.g., a short-term global inventory $\sum_i^{short\ term} I$. Fuel cycle inventories will thus reach a quasi-steady-state short-term inventory level in a relatively short time at the start of reactor operation as compared to typical times of interest for tritium self-sufficiency problems such as doubling time. Relevant processing lines in the fuel cycle include the plasma-exhaust-processing line and the coolant line but not the breeder line, so we only need to account for $\sum_{pl+il}^{short\ term} I$ and $\sum_{cl}^{short\ term} I$. This is because the breeder line's source of tritium is not the tritium originally exhausted or permeated from the storage subsystem but that which is newly generated from nuclear transmutation processes in the lithium breeder. Stated another way, during the early phase of reactor operation, the plasma exhaust line's tritium holdup originates solely from the startup inventory in the storage subsystem.

The startup storage tritium inventory will be redistributed solely throughout the plasma exhaust line. This statement holds true because the tritium holdup in the coolant line is negligible during the period when the storage subsystem acts as the sole supplier of fuel to the reactor. The tritium is considered to be short term because the bred tritium is recycled into the plasma exhaust line for refueling back into the torus in a much shorter time than any long-term (i.e., radiation-induced trapping) tritium inventories that exist in the fuel cycle. We can separate short-term from long-term tritium inventories because of relatively fast batchwise operations for the reprocessing of tritium. Table II lists the short-term tritium inventory characteristics for the tritium-processing lines found in the fuel cycle along with tritium inventory estimates for an ITER-type reactor. Similarly, Table III lists the corresponding long-term tritium inventories.

Tritium can be lost to the following processes during this all-storage source fuel phase: fusion burnup, tritium decay, tritium lost to the environment, and tritium lost to waste material recovered from the fuel cycle. Now, tritium decay is already accounted for in Eq. (15) so that only the first and third process losses need to be included in a formulation for $I_{i,0}^{opt}$. Moreover, availability considerations in different areas of the fuel cycle need to be quantified. A total reserve inventory I_r, implemented to account for operational interruption scenarios, is thus included for availability considerations. The following equation will hold true in this case:

$$I_{i,0}^{opt} = \sum_{pl+il}^{short\ term} I + \sum_{cl}^{short\ term} I + \int_0^{t_s^{infl}} (\overline{F_{fus}} + \overline{F_{env}} - \overline{F_{ext}^{in}} + \overline{F_{ext}^{out}})\, dt + I_{waste}\big|_0^{t_s^{infl}} + I_r \ . \tag{17}$$

The tritium inventories in Eq. (17) originate only from the plasma-exhaust- and coolant-processing lines, and not

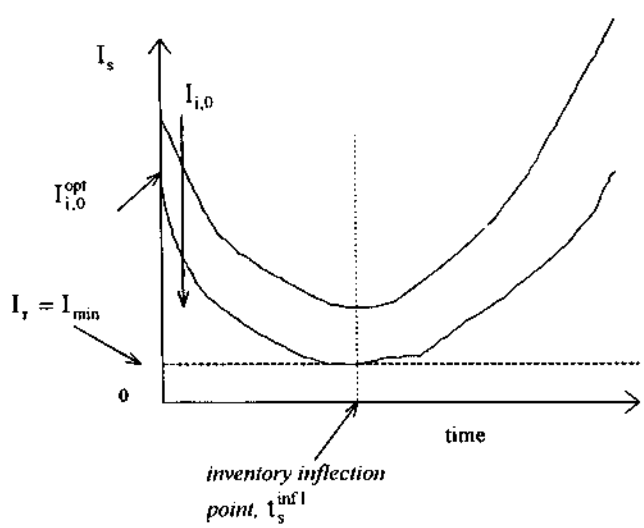

Fig. 3. Optimal startup inventory in storage.

the breeder line. The breeder line is not relevant in calculating the optimal startup inventory because none of the tritium from startup will flow through the breeder line. Only the tritium generated inside the breeder blanket during normal reactor operation will flow through the breeder line, which is of no concern for startup calculations. In addition, each of the processing lines is characterized by short-term and long-term retention of tritium. For the plasma exhaust line, the long-term tritium retention is due only to the trapping of tritium on the surface or inside the bulk of PFC materials. The portion of the plasma exhaust processing line that exists outside the plasma environment contains no long-term tritium inventory because of the fast processing rates for all subsystems within this processing line and the existence of most of the components here outside the vacuum vessel, e.g., in the tritium plant complex and hence outside the radiation environment that causes radiation-induced trapping of tritium.

With respect to variables that depend on t_s^{infl}, one needs to first estimate the time for the tritium bred in the blanket to make its way into the plasma exhaust line so that it is available for refueling in addition to the tritium fed from storage. One way to estimate this characteristic time in the breeding blanket τ_{bl} is to divide the quasi-steady-state short-term inventory in the breeder (not taking into account any radiation-induced trapped inventories) by the tritium generation rate, which is equal to $\Lambda(\alpha_p \alpha_{op} P_f / Q_f)$:

$$t_s^{infl} \cong \tau_{bl} \cong \frac{\sum_{bl}^{short\ term} I}{\dfrac{\Lambda \alpha_p \alpha_{op} P_f}{Q_f}} \quad . \tag{18}$$

Now, the continuous nonradioactive losses due to fusion burnup and environmental losses, in addition to any continuous source of tritium from outside the fuel cycle, during the period of nonrecycling of tritium from the breeder line, can be included by multiplying the corresponding loss rates by τ_{bl}:

$$\begin{aligned} I_{i,0}^{opt} \cong & \sum_{pl+il}^{short\ term} I + \sum_{cl}^{short\ term} I \\ & + \tau_{bl}\left(\frac{\alpha_p \alpha_{op} P_f}{Q_f} + \overline{F_{env}} - \overline{F_{ext}^{in}} + \overline{F_{ext}^{out}}\right) \\ & + I_r + I_{waste}\big|_0^{\tau_{bl}} \quad . \end{aligned} \tag{19}$$

As a result,

$$\begin{aligned} I_{i,0}^{opt} \cong & \sum_{pl+il}^{short\ term} I + \sum_{cl}^{short\ term} I + \left(\frac{1}{\Lambda}\right) \sum_{bl}^{short\ term} I \\ & + \left(\frac{Q_f \sum_{bl}^{short\ term} I}{\Lambda \alpha_p \alpha_{op} P_f}\right)(\overline{F_{env}} - \overline{F_{ext}^{in}} + \overline{F_{ext}^{out}}) \\ & + I_r + I_{waste}\big|_0^{\tau_{bl}} \quad . \end{aligned} \tag{20}$$

Due to the relatively long time it takes for tritium to permeate through solid walls and into the coolant for conventional fusion reactors, $\sum_{cl}^{short\ term} I \cong 0$. Furthermore, if we note that any tritium loss to the environment is negligible compared to the tritium burn rate (i.e., $\overline{F_{env}} \ll (\alpha_p \alpha_{op} P_f / Q_f)$) and that no waste material is likely to be removed (i.e., $I_{waste}|_0^{\tau_{bl}} = 0$) during this short initial all-storage-source fuel phase, then we can approximate $I_{i,0}^{opt}$ with the following:

$$\begin{aligned} I_{i,0}^{opt} \cong & \sum_{pl+il}^{short\ term} I + \left(\frac{1}{\Lambda}\right) \\ & \times \left[\sum_{bl}^{short\ term} I - \frac{Q_f \sum_{bl}^{short\ term} I(\overline{F_{ext}^{in}} - \overline{F_{ext}^{out}})}{\alpha_p \alpha_{op} P_f}\right] + I_r \quad . \end{aligned} \tag{21}$$

Note that the quasi-steady-state tritium inventories, as calculated by more detailed integrated or stand-alone codes, are only used for the calculation of this initial inventory estimate. The variable τ_{bl} is the characteristic holdup time in the breeder line, which has been redefined for our purposes to include the inventory variable $\sum_{bl}^{short\ term} I$. The aforementioned short-term inventories will be time-averaged values when quasi-steady-state conditions are reached in the various fuel cycle components. Most fuel-reprocessing components are operated or are characterized as having such quasi-steady-state inventory levels. However, components that are directly affected by radiation, e.g., the PFCs and breeding blanket, will only reach such a level in a characteristic time much higher than the fuel-reprocessing line due to slow trapping processes. Thus, $\sum_{pl+il}^{short\ term} I$, $\sum_{cl}^{short\ term} I$, and $\sum_{bl}^{short\ term} I$ must be properly accounted for by estimating the inventory levels during this short-term period. In conventional tokamak fusion reactors, $\sum_{pl+il}^{short\ term} I$ will be dominated by codeposition processes, while $\sum_{bl}^{short\ term} I$ will be dominated by the mobile inventory in the breeder. Figure 4 shows the general dynamic behavior from such short-term inventories.

IV.B.3. Allowable Reserve Inventories and Reduction of Reactor Availability

Due primarily to economic reasons, increasing reactor availability is desirable during the lifetime of the reactor. This leads to implementing operating scenarios that will lead to increased operational availability. One such solution is to introduce additional tritium fuel for on-line storage in the tritium plant building at the start of operations. This tritium inventory, which can be quickly and easily connected to the fuel cycle, can then be available throughout the reactor campaign to safeguard against possible component failure conditions by allowing for continued reactor operation. Such an auxiliary or reserve inventory of tritium has been termed the "minimum

TABLE

Fuel Cycle Subsystems with Estimated/Calculated

Processing Line	Major Subsystems in ITER	Type of Processes Involved	Failure/Availability Considerations
Plasma exhaust line	Codeposition	Plasma/wall interactions	Safety limits (~5 h = 18 1000-s shots)
	Wall saturation	Plasma/wall interactions	Frequency of conditioning
	Cryopumps	Batchwise	Stagger operation
	FCU (permeators)	Continuous holdup	Multiple stages
	ISS	Continuous holdup	Multiple columns, flexible operation
	Storage beds	Mostly batchwise operations	Multiple storage beds
	Fueling	Mostly batchwise operations	Flexible extruder operation
	Buffer tanks	Mostly batchwise operations	Multiple tanks (e.g., for assay)
Breeder line	Solid breeder blanket	Continuous holdup	Temperature constraints
	Dedicated reprocessing units	Mostly batchwise operations	Multiple stages
Impurity processing line	Dedicated reprocessing units	Mostly batchwise operations	Multiple stages

*Based on the latest (early 1998) ITER design considerations.

TABLE

Fuel Cycle Subsystems with Estimated/Calculated

Processing Line	Major Subsystems in ITER	Type of Processes Involved	Failure/Availability Considerations
Plasma exhaust line	Dust	Plasma/wall interactions	Frequency of conditioning
	Bulk soluble	Solubility	Wall replacement frequency
	Bulk trapped	Radiation-induced	Wall replacement frequency
	Neutron transmutation	Radiation-induced (for Be only)	Wall replacement frequency
	Codeposition	Plasma/wall interactions	Frequency of conditioning
Breeder line	Neutron multiplier	Radiation-induced	Blanket replacement frequency
Coolant line	Coolant	Continuous holdup	Coolant loss
	Dedicated reprocessing units	Continuous holdup	Multiple columns, flexible operation

*Based on the latest (early 1998) ITER design considerations.

tritium inventory reserve" in past work.[1] This is because the reserve inventory can be as high as needed but must be above a certain minimum quantity set by the dynamics of the fuel cycle. Obviously, such a minimum tritium inventory reserve is equivalent to an optimum quantity for minimizing the amount of scarce and radioactive tritium located in the plant. However, the drawback to this design implementation, as a means of increasing reactor availability, is that it may lead to a very large increase in the amount of tritium needed at startup. This may significantly affect the global tritium supply for first-generation fusion reactors. The question is thus raised regarding how much of a reserve inventory of tritium is needed for reliable, safe, and economic reactor operation. We try to analyze this question with emphasis on trying to quantify optimum inventory values for a reserve supply.

Once more, the reserve inventory I_r is the inventory that is set aside for continuous reactor operation during any fuel cycle component failure under normal reactor operation. For instance, if one of the reprocessing components in the plasma exhaust line fails and is not able to function, the gas can then be rerouted to an alternate

II

Short-Term Tritium Inventories in ITER*

ITER Reference Inventory (g T)	Inventoary Quasi-Steady-State Fluctuations (g T)	Uncertainty in Inventory Estimate (g T)	Dynamic Model Used
360	±10	±180	CFTSIM, DEGAS/REDEP
5	Negligible	Negligible	CFTSIM, PERI
150	±10	±10	CFTSIM
5	Negligible	Negligible	CFTSIM
245	±50	±100	FLOSHEET
1000	±50	±500	ITER baseline design
50	±50	±25	Kuan et al.
100	±50	±50	Kuan et al.
25	±30	±20	ITER baseline design
50	±50	−50/+100	Estimated
50	±50	−50/+100	Estimated

III

Long-Term Tritium Inventories in ITER*

ITER Reference Inventory (g T)	Quasi-Steady-State Fluctuations (g T)	Uncertainty in Inventory Estimate (g T)	Dynamic Model Used
1000	±1000	±1000	Estimated (safety limit)
210	Negligible	−200/+1000	TMAP4
1425	Negligible	±900	TMAP4
96	Negligible	±30	ITER baseline design
820	±820	±820	Safety limit
800	Negligible	±800	Various beryllium models
5	Negligible	±5	Estimated
12	Negligible	±10	ITER baseline design

pipeline from which it can be stored in some temporary storage device. Accordingly, this gas, containing tritium, is lost during this off-normal phase of the processing line (though reactor operation continues normally). The scenario to be avoided will then occur when such operational interruptions take place at the same time as the tritium inventory in the storage subsystem, as calculated from the previously derived optimal startup inventory with $I_r = 0$, reaches a value near zero. Not enough fuel is then available to continue normal fusion burn reactor operation. A makeup tritium inventory must then be included until the component is fixed, replaced, or an alternate component is brought on-line.

Previous analyses have made use of a general time for reserve fueling that accounts for the number of days required to supply fuel to the plasma while the plasma-exhaust-processing subsystem is not operational to calculate the required reserve inventory.[1,4,5] This time for reserve fueling is equal to the time it takes to replace or repair a failed fuel-cycle-reprocessing component. For example, if redundancy of a particular component is used in the design, then the time for reserve fueling constitutes

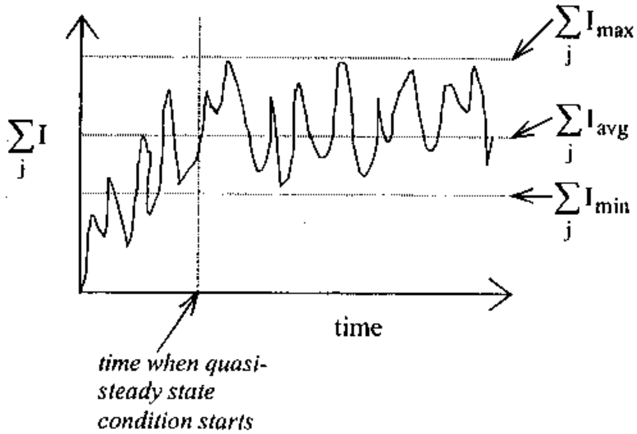

Fig. 4. General short-term tritium inventory dynamic behavior.

the time it takes to switch to the new component from the failed one. Now, the tritium inventory, if any, in the component at the time of failure or nonoperability can either be recycled back into the fuel cycle during the replacement/repair duration, recycled back into the fuel cycle at a later time, or, in the worst case, not recycled at all. If a conservative approach is undertaken in this analysis, then the worst case must be included in the analysis.

In this work, we expand on the concept of a required time for reserve fueling by further making a distinction between failures occurring within different processing lines of the fuel cycle. As discussed previously, the fuel cycle can be subdivided into four distinct tritium pathways: the plasma exhaust vacuum pumping line, the plasma exhaust impurity line, the breeder line, and the coolant line. Correspondingly, a reserve inventory should account for operational interruptions in each of these tritium pathways separately. In other words, times for reserve fueling that are appropriate to each of these processing lines will have varying impacts on tritium self-sufficiency issues. Note also that reserve inventories may be constrained by a localized tritium inventory limit, applied to the flow and diversion of the resulting inventory into temporary storage devices, as determined from safety analyses rather than from any characteristic repair or replacement times. It may be more valid to think of a maximum level of tritium storage capability during off-normal events. Hence, in some cases, it may be more relevant to make use of the allowable reserve inventories as parameters rather than the corresponding times for reserve fueling. These multiple interpretations in defining the reserve inventory lead to the adoption of a more flexible approach when incorporating a reserve inventory in tritium self-sufficiency calculations.

For each processing line in the fuel cycle, an overall line reserve inventory is coupled to the time for reserve fueling by way of the average flow rate flowing through the line during normal operation. If t_r^{vl}, t_r^{il}, t_r^{bl}, and t_r^{cl} correspond to the times for reserve fueling in the plasma exhaust, impurity-processing, blanket, and coolant lines, respectively, then the reserve inventory appropriate for each line is as given in Table IV. The reserve inventories required for failures in the plasma exhaust line, impurity-processing line, blanket line, and coolant line are I_r^{vl}, I_r^{il}, I_r^{bl}, and I_r^{cl}, respectively, while $\overline{F^{vl}}$, $\overline{F^{il}}$, $\overline{F^{bl}}$, and $\overline{F^{cl}}$ correspond to the average flow rates in each line. The instantaneous tritium flow rate will, in fact, vary in an oscillating manner for the typical batchwise reprocessing units. The average tritium flow rates flowing through these four processing lines can be calculated from the reactor power level and are also given in Table IV. In these flow rate estimates, α_{op} is not necessary in the calculation (i.e., $\alpha_{op} = 100\%$) because it is implicit that no downtime occurs during such operational interruptions when a reserve inventory is to be provided. However, pulse operation, characterized by α_p, is part of normal operation and so needs to be included.

The value $\overline{F^{vl}}$ corresponds to the fueling rate to the reactor during normal operation. Though the downstream reprocessing subsystems experience a lower flow rate, through loss of tritium in fusion reactions and any surface trapping processes, the storage subsystem needs to provide the full fueling rate to continue reactor operation in the event of a failure causing operational interruption within the processing line. The $\overline{F^{vl}}$ value will thus take care of any failures in fuel cycle components downstream of the torus. A failure in the fueling subsystem or fuel management subsystem, i.e., upstream of the torus subsystem, though part of the plasma-exhaust-processing line, will result in automatic stoppage of reactor operation. The value for $\overline{F^{cl}}$ can be estimated from permeation studies for the case of solid breeders with coolant channels. The trapping rate of tritium on the PFCs during normal reactor operation is $\overline{F^{PFC}}$, which will be governed by codeposition in carbon-lined tokamaks. The radiation-induced tritium inventory need not be included because of its long timescale compared to that of tritium reprocessing units in the plasma exhaust line and breeder line. For solid breeders, we can thus neglect $\overline{F^{cl}}$, because the typical timescale of tritium holdup in the plasma exhaust and breeder processing line is on the order of a few hours to a day, while during this same period, only surface layer saturation takes place in the PFCs. In other words, permeation into the coolant line is assumed to take much longer than it takes for bred tritium to be recycled into the plasma exhaust line. This assumption also leads to neglecting $\sum_{cl}^{short\ term} I$. For liquid breeders, the coolant-processing line is equivalent to the breeder line.

Two ways to define the reserve inventory I_r can be formulated using the reserve inventories required for each of the processing lines: (a) a reserve inventory to account for single-component failures I_r^s, meaning that only one component can fail at any one time in the fuel cycle, or (b) a reserve inventory to account for compound

TABLE IV

Estimation of Tritium Reserve Inventories Using Time for Reserve Fueling

Tritium Processing Line	Average Flow Rate of Tritium	Reserve Inventory Using t_r	Likely Reserve Inventory Limitations	Relevant Partial Derivatives
Plasma fueling/exhaust loop	$\overline{F^{vl}} = \left(\frac{1}{f_b}\right)\frac{\alpha_p P_f}{Q_f}$	$I_r^{vl} = \overline{F^{vl}} t_r^{vl}$	Localized inventory limit	$\frac{\partial I_r}{\partial t_r^{vl}} = \left(\frac{1}{f_b}\right)\frac{\alpha_p P_f}{Q_f}$ $\frac{\partial I_r}{\partial f_b} = -t_r^{vl}\left(\frac{1}{f_b^2}\right)\frac{\alpha_p P_f}{Q_f}$
Impurity bypass	$\overline{F^{il}} = f_{imp}\left[\left(\frac{1-f_b}{f_b}\right)\frac{\alpha_p P_f}{Q_f} - \overline{F^{PFC}}\right]$	$I_r^{il} = \overline{F^{il}} t_r^{il}$	Time for replacement/ repair	$\frac{\partial I_r}{\partial t_r^{il}} = f_{imp}\left[\left(\frac{1-f_b}{f_b}\right)\frac{\alpha_p P_f}{Q_f} - \overline{F^{PFC}}\right]$ $\frac{\partial I_r}{\partial f_b} = -t_r^{il} f_{imp}\left(\frac{1}{f_b^2}\right)\frac{\alpha_p P_f}{Q_f}$
Breeder	$\overline{F^{bl}} = \frac{\Lambda \alpha_p P_f}{Q_f}$	$I_r^{bl} = \overline{F^{bl}} t_r^{bl}$	Time for replacement/ repair	Need to solve for the required TBR explicitly
Coolant	$\overline{F^{cl}} \cong 0$ (for solid PFC walls)	$I_r^{cl} = \overline{F^{cl}} t_r^{cl}$	Time for replacement/ repair	---

component failures I_r^c, whereby more than one component can fail simultaneously:

$$I_r^s = \max(I_r^l) + \sum_{l \in \max(I_r^l)}^{short\ term} I \tag{22}$$

and

$$I_r^c = \sum_{\text{all } l} I_r^l + \sum_{\text{all } l}^{short\ term} I \ , \tag{23}$$

where l represents a tritium processing line.

As noted earlier, a conservative formulation must include the inventory at the time of failure $\sum_{i=m}^{short\ term} I$, which may or may not be recycled back into the fuel cycle. The value I_r^s utilizes the worst-case scenario for a single-component failure mode, which is equivalent to the processing line with the largest specified reserve inventory. For this case, failure modes from other processing lines with smaller reserve inventories are addressed by I_r^s. On the other hand, I_r^c is a more restrictive definition of the reserve inventory due to the less likely occurrence of compound failure modes.

Whichever definition for I_r is used, one can specify which processing line requires an inventory in reserve for any process upsets. Some processing lines may be deemed to have too great an impact on the startup inventory if the capability for continuous operation during operational interruptions is to be included in the reactor design. Such a capability may not be advantageous, so operational interruptions and component failures will, in fact, lead to a reduction in the operational availability of reactor power production. Now, however, a significant reduction in the required startup inventory may be achieved. This consideration will mainly affect the main plasma-exhaust-processing line, where most of the tritium is reprocessed, as opposed to the other low-throughput flow lines. For instance, a failure in the impurity-processing line will not affect α_{op} because of the very low tritium throughput through this processing line. During such operational interruptions of the impurity-processing system, this flow may be stored inside a temporary storage vessel without interfering with the main plasma exhaust flow.

Multiple component failures are unlikely to happen, so we use the aforementioned definition of a single-component failure to help quantify this design variable. Now, any of the four processing lines can determine the amount of reserve fuel required for reactor operation. As discussed earlier, this will depend on which processing line deserves to be buffered by a reserve inventory during failure modes. Table V lists four possible options in determining the reserve inventory where a localized inventory limit is also included. However, as noted earlier, the coolant line is not expected to contribute any retained tritium during the short-term period when a reserve is needed, so this processing line is neglected. The effect on the startup inventory is very likely the determining factor in deciding which option is selected in a given fuel cycle design. For next-generation commercial fusion reactors with low burnup, i.e., low f_b, the throughput in the plasma exhaust line is much higher than that in the breeder line. The impurity line throughput will be much lower than the plasma exhaust line's throughput because fusion reactors require low impurity concentration. The plasma exhaust line will thus determine the reserve inventory, unless it is decided that continuous operation during failure modes in this line are not worth incorporating in the design, which will make either the breeder line or impurity line the maximum reserve inventory line, depending on the corresponding component reliabilities. The reserve inventory can thus be formulated with different design options as follows:

$$I_r = \begin{cases} \left(\dfrac{t_r^{pl}}{f_b}\right)\left(\dfrac{\alpha_p P_f}{Q_f}\right) + \displaystyle\sum_{pl(nc)}^{short\ term} I \\ \qquad \text{for reserve inventory option 1} \\ f_{imp}\left[\left(\dfrac{1-f_b}{f_b}\right)\dfrac{\alpha_p P_f}{Q_f} - \overline{F^{\text{PFC}}}\right] t_r^{il} + \displaystyle\sum_{il}^{short\ term} I \\ \qquad \text{for reserve inventory option 2} \\ \Lambda_r\left(\dfrac{\alpha_p P_f}{Q_f}\right) t_r^{bl} + \displaystyle\sum_{bl}^{short\ term} I \\ \qquad \text{for reserve inventory option 3} \\ I_{local}^{limit} + \displaystyle\sum_{i}^{short\ term} I \\ \qquad \text{for reserve inventory option 4} \end{cases} \tag{24}$$

Note that only noncritical tritium inventories are used in the estimation of the lost inventory in the nonoperational subsystem. Once more, critical subsystems or components in the fuel cycle are required to operate in a satisfactory manner to provide continuous reactor operation. For example, failures in vacuum vessel components will result in reactor shutdown. An example of this discrepancy are cryopump failures, because the cryopump plasma exhaust subsystem is operated using a number of pumps. Failure in a number of cryopumps that does not significantly affect the total pumping speed will not hinder reactor operation. Equation (24) can thus be substituted back into Eq. (21) to obtain a relationship using reserve inventories or times for reserve fueling, whichever definition is appropriate for the respective processing line. This relationship is optimal in terms of minimizing the fuel required to start up a reactor with the operating scenario selected. Finally, the use of a single quasi-steady-state average inventory for each modeled subsystem may be inadequate due to the inherent wide-ranging fluctuations characterizing each subsystem. Thus,

TABLE V

Four Design Options for a Tritium Reserve Inventory

Reserve Inventory Design Option	Characteristics	Design Requirements
1	If plasma-fueling/exhaust-processing line is to be buffered with an adequate reserve inventory	$\begin{cases} \left(\frac{t_r^{pl}}{f_b}\right) > \Lambda_r t_r^{bl} \\ \left(\frac{t_r^{pl}}{f_b}\right)\left(\frac{\alpha_p P_f}{Q_f}\right) > f_{imp}\left[\left(\frac{1-f_b}{f_b}\right)\frac{\alpha_p P_f}{Q_f} - \overline{F}^{\mathrm{PFC}}\right] t_r^{il} \end{cases}$
2	If impurity processing line is to be buffered with an adequate reserve inventory	$\begin{cases} f_{imp}\left[\left(\frac{1-f_b}{f_b}\right)\frac{\alpha_p P_f}{Q_f} - \overline{F}^{\mathrm{PFC}}\right] t_r^{il} > \Lambda_r \left(\frac{\alpha_p P_f}{Q_f}\right) t_r^{bl} \\ f_{imp}\left[\left(\frac{1-f_b}{f_b}\right)\frac{\alpha_p P_f}{Q_f} - \overline{F}^{\mathrm{PFC}}\right] t_r^{il} > \left(\frac{t_r^{pl}}{f_b}\right)\left(\frac{\alpha_p P_f}{Q_f}\right) \end{cases}$
3	If breeder processing line is to be buffered with an adequate reserve inventory	$\begin{cases} \Lambda_r t_r^{bl} > \left(\frac{t_r^{pl}}{f_b}\right) \\ \Lambda_r \left(\frac{\alpha_p P_f}{Q_f}\right) t_r^{bl} > f_{imp}\left[\left(\frac{1-f_b}{f_b}\right)\frac{\alpha_p P_f}{Q_f} - \overline{F}^{\mathrm{PFC}}\right] t_r^{il} \end{cases}$
4	If localized inventory limit (from safety design limits) is used for estimate of reserve inventory	$\begin{cases} I_{local}^{limit} > \Lambda_r \left(\frac{\alpha_p P_f}{Q_f}\right) t_r^{bl} \\ I_{local}^{limit} > \left(\frac{t_r^{pl}}{f_b}\right)\left(\frac{\alpha_p P_f}{Q_f}\right) \\ I_{local}^{limit} > f_{imp}\left[\left(\frac{1-f_b}{f_b}\right)\frac{\alpha_p P_f}{Q_f} - \overline{F}^{\mathrm{PFC}}\right] t_r^{il} \end{cases}$

design factors could be included in the preceding calculations for the short-term inventories.

The previous discussion focused on making sure that the reactor does not run out of fuel by having a reserve inventory available for any process upsets. Nevertheless, this reserve inventory is necessary in only a small time frame when the inventory available in storage is near its minimum value. When the storage inventory is large enough due to bred inventory above that needed for any tritium losses, the reserve inventory included during startup does not contribute to the prevention of reactor stoppage during fuel cycle component failures.

If no reserve inventory is used in the operating design of the fusion reactor, then reliability considerations for each of the components in the fuel cycle will need to be addressed along with the reduction in overall availability of the reactor. In more general terms, if we consider each of the subsystems separately, then the availability of each subsystem during reactor operation can be calculated by the following relationship, which makes use of subsystem failure rates:

$$\alpha_i = \frac{\mathrm{MTBF}_i}{\mathrm{MTBF}_i + \mathrm{MTTR}_i} \tag{25}$$

The mean time between failures (MTBF) for subsystem i, MTBF_i, and the corresponding mean time to replacement MTTR_i will be determined by the components used within the subsystem's design. Consequently, different parts of the fuel cycle will be characterized by different values for availability, which will have varying effects on Λ_r and will depend on the design approach toward a reserve inventory. For example, if one is required to design a fuel cycle system to handle a given Λ_r, a minimum requirement for the availability for different subsystems can be calculated using this approach. A minimum impurity-processing line availability can be estimated and compared to a minimum torus availability. As predicted, the minimum torus availability is much more restrictive than the corresponding availability in the impurity-processing line. We will return to availability considerations later when we examine the variation of the required TBR against changes in reactor availability.

IV.C. Long-Term Tritium Retention Processes

Long-term tritium retention processes, as exemplified by radiation trapping, will affect the tritium self-sufficiency problem differently from short-term inventories. As discussed previously, such short-term inventories are characterized by a rapid rampup to quasi-steady-state inventories. In contrast, long-term inventories possess a different timescale and are likely to stay trapped and localized without migrating throughout the fuel cycle. Thus, they will not be transferred to the storage subsystem and subsequently will be unavailable to new reactors as a part of the startup inventory unless active removal of this tritium is effected. From an integrated tritium balance point of view, long-term inventories $\sum_i^{long\ term} I$ will mainly originate from the tritium that is bred inside the breeder during reactor operation. Again, the startup inventory does not need to take into account the value of $\sum_i^{long\ term} I$ because long-term retention is negligible during the short time that the tritium bred from the breeder line is unavailable for recycling. Thus, $\sum_i^{long\ term} I$ can be considered as a tritium production requirement of the breeder, or equivalently a loss of tritium, and so is taken into account on the right side of Eq. (4).

Most of this long-term tritium inventory is located inside the vacuum vessel, where the irradiation environment is important. The long-term tritium inventory in the plasma-fueling/exhaust-processing line will then all be retained inside a few of the critical components, namely, the torus PFCs. The long-term coolant inventory will be due to typical fuel-processing equipment and not to irradiation trapping because the coolant is not affected by irradiation damage, and the coolant-reprocessing equipment exists outside the radiation enclosure. Impurity processing is only characterized by short-term inventories. Thus,

$$\sum_{i}^{long\ term} I \cong \sum_{pl(c)}^{long\ term} I + \sum_{bl}^{long\ term} I + \sum_{cl}^{long\ term} I \ .$$

The main physicochemical processes that play a role in this long-term retention of tritium are radiation-induced trapping within the bulk of the vacuum vessel materials and surface interactions, such as tritium codeposition and tritiated dust formation. Radiation-induced trapping inside the bulk material is a slow process that can take a fairly long time to reach steady state, depending on the quantity of traps created through irradiation. Tritium codeposition, which seems to apply to only carbon-based materials, will be very significant because large quantities of tritium can be retained at a relatively fast rate, thus making active removal a necessity for adequate reactor operation. Depending on the plasma and material conditions, tritium codeposition can vary within a large range of inventory values. Estimates from 5 to 10% of the fueling rate have been given[20] or from 20 and up to a possible 100 g per ITER pulse, depending mostly on the assumed chemical sputtering yield.[13] Finally, a fundamental lack of understanding is currently the state of affairs with regard to tritiated dust formation. To summarize, Table VI presents the nomenclature associated with each type of tritium inventory.

IV.D. Tritium Lost to Waste Material

Tritium losses also arise from waste disposal that has not undergone tritium detritiation or have very low tritium decontamination factors. Such fuel cycle waste material will be removed periodically during reactor operation. An approximate relationship of the dynamics of this tritiated waste (most likely retained in the bulk of solid material) can be provided using the following parameters:

1. $\epsilon_{replace}$, the fraction of the total long-term inventory $\sum_i^{long\ term} I$ that is removed during one material/component replacement interval
2. $\epsilon_{recycle}^{waste}$, the fraction of tritium in the removed tritium that can be recycled back into the fuel cycle
3. $\nu_{replace}$, the average rate of periodic replacements.

The total tritium loss to waste material during a specified period of time can then be formulated as follows:

$$I_{waste}\Big|_0^{t_f} = (1 - \epsilon_{recycle}^{waste})\epsilon_{replace} \sum_{i}^{long\ term} I \, \nu_{replace} t_f \ . \tag{26}$$

It is expected that $\nu_{replace}$ will be infrequent, i.e., on the order of a few replacements during the lifetime of the reactor. In addition, with respect to estimating long-term inventories, tritiated waste material and processing components removed from the fuel cycle are assumed to be infrequent enough that all of $\sum_i^{long\ term} I$ will build up again to its steady-state value.

IV.E. Storage Gain Requirements

IV.E.1. Doubling Time Inventory

For this study, a general inventory requirement I_{req} is used in tritium breeding requirement calculations. The value for I_{req} will depend on different requirement objectives. Previous work has focused on the doubling time inventory I_{dbl} as the required inventory buildup in storage to produce enough tritium to fuel another equivalent fusion reactor. The definition of the doubling time inventory was given as either

$$I_{dbl} = 2I_{i,0} \quad \text{or} \quad I_{dbl} = I_{i,0} + I_{min} \ . \tag{27}$$

For our case, where we have developed a procedure to estimate I_{min}, it is the second definition that will be

TABLE VI

Tritium Inventory Classifications and Definitions

Tritium Processing Line	Effect on Continuous Reactor Operation During Operational Interruptions	Subsystems	Short-Term Inventory		Long-Term Inventory	
Plasma fueling/exhaust loop	Critical	Fueling, vacuum pumping, fuel management	$\sum_{pl}^{short\ term} I$	$\sum_{pl(c)}^{short\ term} I$	$\sum_{i}^{long\ term} I$	$\sum_{pl(c)}^{long\ term} I$
	Noncritical	FCU, ISS, fuel storage, TWT		$\sum_{pl(nc)}^{short\ term} I$		$\sum_{pl(nc)}^{long\ term} I \cong 0$
Impurity bypass	Noncritical	Impurity processing (e.g., PMR, HITEX, etc.)	$\sum_{il}^{short\ term} I$			$\sum_{il}^{long\ term} I \cong 0$
Breeder	Noncritical	Solid breeder/liquid breeder, breeder reprocessing	$\sum_{bl}^{short\ term} I$			$\sum_{bl}^{long\ term} I$
Coolant	Noncritical	Coolant, coolant reprocessing	$\sum_{cl}^{short\ term} I \cong 0$			$\sum_{cl}^{long\ term} I$

used in this work. Note that the second definition gives a more accurate representation of the inventory needed to fuel a single new reactor when no improvements in system reliability, e.g., I_{min} for the new reactor is equal to I_{min} for the current reactor, are taken into account as illustrated in Fig. 3. For use in the integrated tritium balance, $I_{req} = I_{i,0}$ with respect to doubling time considerations. This is because I_{req} is the required net inventory bred in the fuel cycle as opposed to the total storage subsystem inventory I_s, which already includes I_{min}. In other words, when the optimal startup inventory is used, I_{dbl} is the inventory located in the storage subsystem when the doubling time is reached, which is at most $I_{i,0}^{opt} + I_{min}$.

In more general terms, it is possible that the reliability of next-generation fuel cycle systems will improve during the time needed to meet the inventory objective. Mathematically, this will cause all the reserve times in future reactors to be reduced, e.g., $t_r^{pl'} < t_r^{pl}, t_r^{il'} < t_r^{il}, t_r^{bl'} < t_r^{bl}, t_r^{cl'} < t_r^{cl}$. Thus, I'_{min} in future reactors will be lower than the I_{min} used for the current reactor's tritium breeding requirement calculations. As a result, a formulation for I_{req}, which includes the effects of improvements in reliability, can be reformulated by simply substituting the improved reserve times in the equation for $I_{i,0}^{opt}$.

IV.E.2. Other Inventory Requirement Considerations

Another inventory requirement of interest, from a tritium self-sufficiency perspective, is the inventory needed for the self-sustaining operation of a single reactor. Such a requirement will most likely characterize first-generation commercial power reactors such as DEMO, where the primary goal is the achievement of reliable and safe operation in a fusion reactor. For this case, $I_{req} = 0$, because no net breeding requirement is needed for external use. On the other hand, inventory requirements that lead to a more rapid pace in the introduction of new fusion reactors than the doubling-time concept may be relevant if fusion is widely accepted as an energy source in combination with the decline or reduced viability of other energy sources and an increased global energy demand. To generalize and quantify such varying rates of introduction, the following relationship can be used: $I_{req} = (n-1)I_{i,0}^{opt}$, where n is the rate of introduction of new DT fusion reactors. For the self-sustaining operation of a single reactor, $n = 1$; for a doubling-time inventory, $n = 2$. Accordingly, the required inventory in the storage subsystem will be $I_s = (n-1)I_{i,0}^{opt} + I_{min}$. Again, we need to always have at least I_{min} stored in the storage subsystem to account for component failure scenarios in the current reactor even after $(n-1)I_0^{opt}$ is removed to fuel new reactors. As noted earlier, I'_{min} inside $I_{i,0}^{opt}$ can be different from the aforementioned I_{min}. Last, another possibility is the requirement for a particular inventory value at a specific point in time. For example, 5 kg of net bred inventory may be specified as an objective requirement for availability 1 yr into the future. For this case, values for I_{req} as well as t_f are then provided with no reserve inventory needed for consideration.

IV.E.3. Lag-Time Considerations

If a lag time t_1 is included that takes into account the inventory loss to tritium decay between reaching I_{req} and its transfer and startup use in a new reactor, then the required inventory needs to be increased from $I_{i,0}^{opt}$ to a higher value using the following relations, where I_{trf} is the reactor-to-reactor transfer inventory:

$$\frac{dI_{trf}}{dt} = -\lambda I_{trf}$$

with boundary conditions:

$$\begin{cases} I_{trf} > I_{req} & \text{at } t = t_f \\ I_{trf} = I_{req} & \text{at } t = t_f + t_1 \end{cases} . \quad (28)$$

Then the solution to Eq. (28) with the given boundary conditions is

$$I_{trf} = I_{req} e^{-\lambda(t-t_f)} . \quad (29)$$

Time variable t starts when the storage tritium inventory reaches I_{req}. If we now solve for I_{req}, the variable of interest, by using the second boundary condition, we then obtain

$$I_{req} = I_{i,0}^{opt} e^{\lambda t_1} . \quad (30)$$

V. SOLUTIONS OF INTEREST

All the previous independent solutions calculated for each of the terms in Eq. (4) can be substituted back into the balance equation to solve for those variables of interest in tritium self-sufficiency problems. Previous work has focused on estimating the required TBR, which can be accomplished by solving Eq. (4) for the TBR. Required tritium startup inventories can be estimated from $I_{i,0}^{opt}$ in Eq. (21). Due to the direct dependence of the required TBR on the estimated reserve inventory, an estimate of the required TBR will depend on which reserve inventory design approach is selected, as given in Table V. It can be observed from this table that the reserve inventory is only a function of the required TBR when the breeder processing line is selected for buffering. All other options do not involve the required TBR. Therefore, two slightly different solutions can be derived to account for all reserve inventory options.

Such a formulation involves solving a quadratic equation for Λ_r, the required TBR, so two separate solutions will exist. However, one of the two solutions will always result in a negative value, a physical impossibility, so we use only the (+) solution. Using the approximation for $I_{i,0}^{opt}$ in Eq. (21), the positive solution for the Λ_r quadratic equation becomes

$$\Lambda_r = \begin{cases} \dfrac{\Omega + \Phi}{\dfrac{2\zeta\psi}{\lambda}} & \text{for reserve inventory options 1, 2, and 4} \\ \dfrac{\Omega + \Phi}{2\left(\dfrac{\zeta\psi}{\lambda} - (\varphi + \psi)\dfrac{t_r^{bl}\zeta}{\alpha_{op}}\right)} & \text{for reserve inventory option 3} \end{cases} , \quad (31)$$

where

$$\zeta = \alpha_p \alpha_{op}\left(\frac{P_f}{Q_f}\right) \quad (32)$$

$$\varphi = (n-1)e^{\lambda t_l} \quad (33)$$

$$\psi = 1 - e^{-\lambda t_f} \quad (34)$$

$$\Omega = \begin{cases} (\varphi + \psi)\left(\sum\limits_{pl+il}^{short\ term} I + I_r\right) + \sum\limits_{i}^{long\ term} I + I_{waste}\big|_0^{t_f} + \dfrac{\psi}{\lambda}\left(\zeta + \overline{F_{env}} - \overline{F_{ext}^{in}} + \overline{F_{ext}^{out}}\right) \\ \quad \text{for reserve inventory options 1, 2, and 4} \\ (\varphi + \psi)\left(\sum\limits_{pl+il}^{short\ term} I + \sum\limits_{bl}^{short\ term} I\right) + \sum\limits_{i}^{long\ term} I + I_{waste}\big|_0^{t_f} + \dfrac{\psi}{\lambda}\left(\zeta + \overline{F_{env}} - \overline{F_{ext}^{in}} + \overline{F_{ext}^{out}}\right) \\ \quad \text{for reserve inventory option 3} \end{cases} \quad (35)$$

and where

ζ = factor containing the effective power production

φ = factor that accounts for the lag time and introductory rate of new reactors

ψ = factor that accounts for the time requirement objective

Ω = effective inventory term.

For simplification purposes, Φ represents the square root term in the quadratic equation for Λ_r as follows:

$$\Phi = \begin{cases} \sqrt{\Omega^2 + \dfrac{4(\varphi + \psi)\zeta\psi}{\lambda} \sum\limits_{bl}^{short\ term} I\left(1 - \dfrac{(\overline{F_{ext}^{in}} - \overline{F_{ext}^{out}})}{\zeta}\right)} & \text{for reserve inventory options 1, 2, and 4} \\ \sqrt{\Omega^2 + 4(\varphi + \psi)\left(\dfrac{\zeta\psi}{\lambda} - (\varphi + \psi)\dfrac{t_r^{bl}\zeta}{\alpha_{op}}\right) \sum\limits_{bl}^{short\ term} I\left(1 - \dfrac{(\overline{F_{ext}^{in}} - \overline{F_{ext}^{out}})}{\zeta}\right)} & \text{for reserve inventory option 3} \end{cases} . \quad (36)$$

More specifically, the main tritium pathways for typical next-generation fusion reactors will exist in the plasma-exhaust-processing line and the breeder line. Including an inventory reserve to account for interruptions in the impurity line and coolant line can thus be neglected in this assumption. If component reliabilities in the processing lines do not differ by a large margin and if localized inventories are not limiting, then the condition $f_b^{-1} > \Lambda_r$, i.e., when the plasma-fueling/exhaust-processing line dominates, is easily met in most future fusion reactors. This is because f_b^{-1} is much greater than any achievable TBR in candidate breeding blankets. On the other hand, if a localized inventory limit characterizes the plasma-fueling/exhaust-processing line and this limit is less than the inventory needed to buffer the breeder line, then the solution calculated for reserve inventory option 3 must be used.

We note that the short-term inventory variables in Eq. (36) are related to the ζ variable, which is, in turn, a function of α_p, P_f, and f_b. It is not related to α_{op} because any reactor downtime is assumed to take place at a much later time than the attainment of the quasi-steady-state inventories characterizing short-term inventories. Therefore, any changes in the aforementioned three variables are also translated into changes in $\sum_{pl(c)}^{short\ term} I$, $\sum_{pl(nc)}^{short\ term} I$, and $\sum_{bl}^{short\ term} I$. Thus,

$$\sum_{pl+il}^{short\ term} I = \sum_{bl}^{short\ term} I = f(\alpha_p, P_f, f_b) \ .$$

Conversely, long-term retention is not a function of ζ because inventory in this category is governed by trapping mechanisms that are not related to reactor operating variables but are rather related to material properties. We assume that the trapped tritium inventory, due to irradiation, will reach steady state before the time to satisfy the inventory requirement objective is reached.

Now, consider the case where the achievable TBR Λ_a is known for a certain reactor design. Since we are interested in finding out how much inventory is allowed to be held up in the critical plasma-line-reprocessing units to produce a given doubling time, then we would need to solve for $\sum_{pil}^{short\ term} I$ and $\sum_{pl}^{long\ term} I$. Reformulating the fuel cycle balance from Eq. (4), the equations for the allowable inventory holdup in the plasma-exhaust/impurity-processing line are then, for the case when the plasma exhaust processing line determines the reserve inventory,

$$\begin{aligned}\sum_{pl}^{long\ term} I_{allow} &= \frac{1}{1 + (1 - \epsilon_{recycle}^{waste})\epsilon_{replace}\nu_{replace}t_f} \\ &\times \left\{\Lambda_a\left(\frac{\zeta\psi}{\lambda}\right) - \frac{\psi}{\lambda}(\zeta + \overline{F_{env}} - \overline{F_{ext}^{in}} + \overline{F_{ext}^{out}}) \right. \\ &\quad - (\varphi + \psi)\left(\sum_{pl}^{short\ term} I + I_r + \frac{1}{\Lambda_a}\left(1 - \frac{(\overline{F_{ext}^{in}} - \overline{F_{ext}^{out}})}{\zeta}\right)\sum_{bl}^{short\ term} I\right) \\ &\quad \left. - \sum_{bl}^{long\ term} I - \sum_{cl}^{long\ term} I - I_{waste}\big|_0^{t_f}\right\}\end{aligned} \tag{37}$$

and

$$\begin{aligned}\sum_{pil}^{short\ term} I_{allow} &= \Lambda_a\left(\frac{\zeta\psi}{(\varphi + \psi)\lambda}\right) - \frac{\psi}{(\varphi + \psi)\lambda}(\zeta + \overline{F_{env}} - \overline{F_{ext}^{in}} + \overline{F_{ext}^{out}}) \\ &\quad - \left(I_r + \frac{1}{\Lambda_a}\left(1 - \frac{\overline{F_{ext}^{in}} - \overline{F_{ext}^{out}}}{\zeta}\right)\sum_{bl}^{short\ term} I\right) \\ &\quad - \frac{1}{(\varphi + \psi)}\left(\sum_{i}^{long\ term} I + I_{waste}\big|_0^{t_f}\right) \ .\end{aligned} \tag{38}$$

Other inventory variables in the equation can be solved in a similar manner. Calculation of the startup inventory is given in Eq. (21), where the optimal startup inventory was discussed. Accordingly, a high level of flexibility is achieved by way of the tritium balance formulation of Eq. (4). Table VII lists reference values for the fuel cycle parameters used in this analytical scheme. The short-term inventory reference values were obtained from the Table II ITER reference inventory column. On the other hand, the reference value for the long-term inventory was estimated by adding the ITER reference inventories and the upper-limit inventory uncertainties of Table III (corresponding to more conservative values).

For validation purposes, the solution for Λ_r using this analytical formulation is compared with a few scenarios from Abdou et al.'s[1] tritium self-sufficiency research. Base parameters from this previous work were used and reformulated when necessary. For example, this previous work utilized a burn rate of tritium, i.e., 500 g T/day, as a reference parameter for which conversion to the fusion power and associated parameters was required. In addition, the quasi-steady-state tritium inventories that characterize the scenario were needed, for which only two cases were mentioned. Values for the quasi-steady-state tritium inventories were taken from the time-dependent inventory plots of the major subsystems. These two scenarios with the fuel cycle parameters that were used are listed in Table VIII, where entries in bold are values that are different for each case. The value for Λ_r was the same for the two different scenarios examined, namely, $\Lambda_r = 1.08$ and $\Lambda_r = 1.03$, as given

TABLE VII

Fuel Cycle Parameters Used in the Analytical Tritium Balance Scheme

Fuel Cycle Parameter	Reference Value	Fuel Cycle Parameter	Reference Value
t_f t_r^{pl} P_f	5 yr 2 days 1.5 GW	$\epsilon_{recycle}^{waste}$ $\epsilon_{replace}$ $\nu_{replace}$	0.9 0.9 0.2/yr
f_b	2%	$\sum_{i}^{long\ term} I$	8930 g T
α_p	100%	$\sum_{pil}^{short\ term} I$	1965 g T
α_{op}	100%	$\sum_{bl}^{short\ term} I$	75 g T
t_l	0 yr (no lag)	$\overline{F_{ext}^{in}}$ and $\overline{F_{ext}^{out}}$	0 kg T/yr (no external sources/sinks)
ϵ_{env}	0 g T/day (negligible)	n	2

TABLE VIII

Values of Parameters Used in the Analytical Scheme Corresponding to the Ref. 1 Values

Scenario (doubling time $n = 2$)	α_p (%)	α_{op} (%)	P_f (GW)	t_l (yr)	t_f (yr)	$\overline{F_{env}}$ (g T/day)	$\overline{F_{ext}}$ (g T/day)	$I_{waste}\vert_0^{t_f}$ (g T)	$\sum_{i}^{long\ term} I$ (g T)	$\sum_{pl+il}^{short\ term} I$ (g T)	$\sum_{bl}^{short\ term} I$ (g T)	f_b (%)	t_{pl}^r (day)
$f_b = 5\%$, $t_f = 5$ yr	100	100	3.27	0	**5**[a]	**11**	0	0	0	**10450**	5400	**5**	2
$f_b = 10\%$, $t_f = 10$ yr	100	100	3.27	0	**10**	**5.5**	0	0	0	**5200**	5400	**10**	2

[a]Values in bold are those that are different for each case.

TABLE IX

Comparison of Present Analytical Scheme with the Ref. 1 Model

Scenario (doubling time $n = 2$)	Results from Ref. 1 Modeling Scheme			Results from Present Analytical Scheme		
	I_r (g T)	Λ_r	$I_{i,0}^{opt}$ (g T)	I_r (g T)	Λ_r	$I_{i,0}^{opt}$ (g T)
$f_b = 5\%$, $t_f = 5$ yr	20000	1.08	35500	20000	1.08	35500
$f_b = 10\%$, $t_f = 10$ yr	10000	1.03	20500	10000	1.03	20500

in the comparison of the two models in Table IX. The required tritium startup inventories and minimum inventories also matched. The nonradioactive loss rates that were used in both scenarios in the previous work were quite high, equivalent to a loss of 5.5 and 11 g T/day. The quasi-steady-state inventories used in our scheme were taken from the convergence of all the dynamic inventories to a steady-state value, as calculated using general tritium residence times in the aforementioned work.

VI. UNCERTAINTIES IN FUEL CYCLE PARAMETERS

Uncertainties in parameter values along with inventory fluctuations characterizing fuel cycle component operation (i.e., batch operation) will produce an uncertainty in the calculation of Λ_r. We can obtain a relationship for this uncertainty in the required TBR, $\delta\Lambda_r$, by propagating uncertainty and inventory fluctuations into all the parameters of Eq. (31). The inventory uncertainties, $\delta \sum_i I$, will be composed of both operational fluctuations as well as uncertainties in their calculation. Operational fluctuations in tritium inventories can be gathered from integrated fuel cycle simulations,[6,7,10] while uncertainties in calculations, i.e., as when physicochemical processes are involved, can be obtained from detailed simulations or estimations.[12,13]

The general formula for random error propagation in a function that is composed of several variables, $q(x,\ldots,z)$, where $(\delta x,\ldots,\delta z)$ are the uncertainties in the independent variables $(x,\ldots,z)$, is given as

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x}\,\delta x\right)^2 + \ldots + \left(\frac{\partial q}{\partial z}\,\delta z\right)^2}\ , \tag{39}$$

which assumes that the uncertainties in $(x,\ldots,z)$ are all independent and behave in a random fashion, so quadrature addition is used. In our problem, the primary variables $(x,\ldots,z)$ are as follows:

1. α_p
2. α_{op}
3. P_f
4. t_l
5. t_f
6. f_b
7. $\overline{F_{ext}^{in}}$
8. $\overline{F_{ext}^{out}}$
9. $I_{waste}\big|_0^{t_f}$
10. I_r
11. $\sum_{bl}^{short\ term} I$
12. $\sum_{bl}^{long\ term} I$
13. $\sum_{pl(c)}^{short\ term} I$
14. $\sum_{pl(nc)}^{short\ term} I$
15. $\sum_{pl}^{long\ term} I$
16. $\sum_{il}^{short\ term} I$
17. $\sum_{cl}^{long\ term} I$.

Moreover, I_r can be further decomposed into other variables, depending on the reserve inventory design option selected. However, for the inventory uncertainties, we must take into account the inventory fluctuation inherent in the design because we have no knowledge of where the actual inventories will be during the quasi-steady-state cycle when the time to reach the inventory requirement is reached. Furthermore, reserve inventory design option 2, when the impurity-processing line dominates, can be neglected. A general solution for I_r accounts for reserve inventory design option 4, which makes use of a localized inventory design limit. The partial derivative calculations for the variables in the quadratic equation for the required TBR are as follows:

$$\frac{\partial\Lambda_r}{\partial\varphi} = \left(\frac{1}{\Phi}\right)\sum_{bl}^{short\ term} I\left(1 - \frac{(\overline{F_{ext}^{in}} - \overline{F_{ext}^{out}})}{\zeta}\right) + \left(\frac{\lambda}{2\zeta\psi}\right)\left(\sum_{pl+il}^{short\ term} I + I_r\right)\left(1 + \frac{\Omega}{\Phi}\right)\ , \tag{40}$$

$$\frac{\partial\Lambda_r}{\partial\psi} = \left(\frac{1}{2\zeta\psi}\right)\left(1 + \frac{\Omega}{\Phi}\right)\left[\zeta + \overline{F_{env}} - \overline{F_{ext}^{in}} + \overline{F_{ext}^{out}} + \lambda\left(\sum_{pl+il}^{short\ term} I + I_r\right)\right] + \left(\frac{\varphi + 2\psi}{\Phi\psi}\right)\sum_{bl}^{short\ term} I\left(1 - \frac{(\overline{F_{ext}^{in}} - \overline{F_{ext}^{out}})}{\zeta}\right) - \frac{\lambda}{2\zeta\psi^2}(\Omega + \Phi)\ , \tag{41}$$

$$\frac{\partial\Lambda_r}{\partial\zeta} = \frac{1}{2\zeta}\left(1 + \frac{\Omega}{\Phi}\right) + \left(\frac{\varphi + \psi}{\Phi\zeta}\right)\sum_{bl}^{short\ term} I - \frac{\lambda}{2\zeta^2\psi}(\Omega + \Phi)\ , \tag{42}$$

$$\frac{\partial\Lambda_r}{\partial \sum_{bl}^{short\ term} I} = \begin{cases} \dfrac{(\varphi+\psi)}{\Phi}\left(1 - \dfrac{(\overline{F_{ext}^{in}} - \overline{F_{ext}^{out}})}{\zeta}\right) & \text{for reserve inventory options 1, 2, and 4} \\[2ex] \dfrac{(\varphi+\psi)}{\Phi}\left(1 - \dfrac{(\overline{F_{ext}^{in}} - \overline{F_{ext}^{out}})}{\zeta}\right) + \dfrac{\lambda(\varphi+\psi)}{2\zeta\psi}\left(1 + \dfrac{\Omega}{\Phi}\right) & \\ & \text{for reserve inventory option 3} \end{cases}\ , \tag{43}$$

$$\frac{\partial\Lambda_r}{\partial\overline{F_{ext}^{in}}} = -\frac{\partial\Lambda_r}{\partial\overline{F_{ext}^{out}}} = -\frac{1}{2\zeta}\left(1+\frac{\Omega}{\Phi}+\left(\frac{2}{\Phi}\right)(\varphi+\psi)\sum_{bl}^{short\ term} I\right) , \tag{44}$$

$$\frac{\partial\Lambda_r}{\partial\sum_{pl(c)}^{short\ term} I} = \frac{\partial\Lambda_r}{\partial\sum_{pl(nc)}^{short\ term} I} = \frac{\partial\Lambda_r}{\partial I_r} = \frac{\lambda(\varphi+\psi)}{2\zeta\psi}\left(1+\frac{\Omega}{\Phi}\right) , \tag{45}$$

$$\frac{\partial\Lambda_r}{\partial\sum_{i}^{long\ term} I} = \frac{\lambda}{2\zeta\psi}\left(1+\frac{\Omega}{\Phi}\right)[1+(1-\epsilon_{recycle}^{waste})\epsilon_{replace}\nu_{replace}t_f] , \tag{46}$$

and

$$\frac{\partial\Lambda_r}{\partial I_{waste}|_0^{t_f}} = \frac{\lambda}{2\zeta\psi}\left(1+\frac{\Omega}{\Phi}\right) . \tag{47}$$

The uncertainty in the required TBR can then be obtained from the following quadrature relation using tritium self-sufficiency variables when no uncertainty is associated with λ, the tritium decay constant, and the loss of tritium to the environment, namely, $\overline{F_{env}}$, is neglected:

$$\begin{aligned}\delta\Lambda_r = \Bigg[&\left(\frac{\partial\Lambda_r}{\partial\varphi}\delta\varphi\right)^2 + \left(\frac{\partial\Lambda_r}{\partial\psi}\delta\psi\right)^2 + \left(\frac{\partial\Lambda_r}{\partial\zeta}\delta\zeta\right)^2 + \left(\frac{\partial\Lambda_r}{\partial\overline{F_{ext}^{in}}}\delta\overline{F_{ext}^{in}}\right)^2 + \left(\frac{\partial\Lambda_r}{\partial\overline{F_{ext}^{out}}}\delta\overline{F_{ext}^{out}}\right)^2 \\ &+ \left(\frac{\partial\Lambda_r}{\partial I_{waste}|_0^{t_f}}\delta I_{waste}|_0^{t_f}\right)^2 + \left(\frac{\partial\Lambda_r}{\partial\sum_{bl}^{short\ term} I}\delta\sum_{bl}^{short\ term} I\right)^2 + \left(\frac{\partial\Lambda_r}{\partial\sum_{pl(c)}^{short\ term} I}\delta\sum_{pl(c)}^{short\ term} I\right)^2 \\ &+ \left(\frac{\partial\Lambda_r}{\partial\sum_{pl(nc)}^{short\ term} I}\delta\sum_{pl(nc)}^{short\ term} I\right)^2 + \left(\frac{\partial\Lambda_r}{\partial\sum_{i}^{long\ term} I}\delta\sum_{i}^{long\ term} I\right)^2 + \left(\frac{\partial\Lambda_r}{\partial I_r}\delta I_r\right)^2\Bigg]^{1/2} .\end{aligned} \tag{48}$$

These equations can then be further decomposed to more basic parameters by the chain rule of integration. For some parameters of interest, we have the following:

$$\frac{\partial\Lambda_r}{\partial t_l} = \frac{\partial\Lambda_r}{\partial\varphi}\frac{\partial\varphi}{\partial t_l} = (n-1)\lambda\exp(\lambda t_l)\frac{\partial\Lambda_r}{\partial\varphi} , \tag{49}$$

$$\begin{aligned}\frac{\partial\Lambda_r}{\partial t_f} &= \sqrt{\left(\frac{\partial\Lambda_r}{\partial\psi}\frac{\partial\psi}{\partial t_f}\right)^2 + \left(\frac{\partial\Lambda_r}{\partial I_{waste}|_0^{t_f}}\frac{\partial I_{waste}|_0^{t_f}}{\partial t_f}\right)^2} \\ &= \sqrt{\left(\lambda\exp(-\lambda t_f)\frac{\partial\Lambda_r}{\partial\psi}\right)^2 + \left((1-\epsilon_{recycle}^{waste})\epsilon_{replace}\sum_{i}^{long\ term} I\nu_{replace}\frac{\partial\Lambda_r}{\partial I_{waste}|_0^{t_f}}\right)^2} ,\end{aligned} \tag{50}$$

and

$$\frac{\partial\Lambda_r}{\partial\alpha_p} = \sqrt{\left(\frac{\partial\Lambda_r}{\partial\zeta}\frac{\partial\zeta}{\partial\alpha_p}\right)^2 + \left(\frac{\partial\Lambda_r}{\partial\sum_{bl}^{short\ term} I}\frac{\partial\sum_{bl}^{short\ term} I}{\partial\alpha_p}\right)^2 + \left(\frac{\partial\Lambda_r}{\partial\sum_{pl+il}^{short\ term} I}\frac{\partial\sum_{pl+il}^{short\ term} I}{\partial\alpha_p}\right)^2 + \left(\frac{\partial\Lambda_r}{\partial I_r}\frac{\partial I_r}{\partial\alpha_p}\right)^2} . \tag{51}$$

We must now evaluate $\partial\zeta/\partial\alpha_p$, $(\partial\sum_{bl}^{short\ term} I/\partial\alpha_p)$, $(\partial\sum_{pl+il}^{short\ term} I/\partial\alpha_p)$, and $\partial I_r/\partial\alpha_p$. The partial derivative $\partial\zeta/\partial\alpha_p$ is simply equal to $\alpha_{op}(P_f/Q_f)$. On the other hand, $(\partial\sum_{bl}^{short\ term} I/\partial\alpha_p)$ and $(\partial\sum_{pl+il}^{short\ term} I/\partial\alpha_p)$ are dependent on the tritium reprocessing line design and can be obtained from more detailed simulations. From integrated fuel cycle simulations,[6,7,10] it has been observed that the short-term inventories will vary as $(1/100)\sum_{bl}^{short\ term} I$ and $(1/100)\sum_{pl+il}^{short\ term} I$ (for α_p given in percentages), respectively, where this linear relationship is due to the batch operations that characterize the buildup of short-term inventories. For example, in a vacuum pump system that is operated in stagger mode, as in the ITER cryopump baseline design, there exist two distinct dynamic modes of its inventory corresponding to changes in α_p. First, as α_p is reduced from a maximum of 100%, the dynamic fluctuations diverging from a maximum short-term inventory for the vacuum pumps gradually become greater until the inventory fluctuations reach a level of zero inventory. Reducing α_p further results in burn periods with fluctuating inventories that are separated by longer and longer periods of zero inventory. Both of these dynamic modes result in an average linear reduction in $\sum_i^{short\ term} I$ with α_p. On the other hand, for continuous holdup subsystems such as distillation columns in the ISS, the tritium holdup is more stable against changes in α_p. However, for our purposes, the overall $\sum_i^{short\ term} I$ is taken to decrease linearly with α_p, as outlined previously. Finally, $\partial I_r/\partial\alpha_p$, for the time when the plasma-fueling/exhaust-processing line is to be buffered by a reserve inventory and when a time for reserve fueling is used, is given by the following relationship:

$$\frac{\partial I_r}{\partial \alpha_p} = \left(\frac{1}{f_b}\right)\left(\frac{P_f}{Q_f}\right) . \tag{52}$$

Note that some relationships of the tritium inventories against some fuel cycle parameters will most likely depend on the particular fuel cycle system design. As a result, variations in these relationships are to be expected when comparing one design with another.

VII. PARAMETRIC ANALYSIS OF THE TRITIUM SELF-SUFFICIENCY PROBLEM

In this section, we examine the tritium self-sufficiency problem through the analyses of a large number of widely varying cases. Each of these cases is based on the reference design with the relevant fuel cycle parameters as given in Table VII. Unless otherwise stated, it will be assumed that any fuel cycle parameter not explicitly mentioned in the discussion has a value corresponding to the reference design from Table VII.

VII.A. Dominant Parameters

It is found that two fuel cycle parameters dominate the calculation of the required TBR: the time to fulfill a given inventory objective t_f (e.g., the doubling time) and the reserve inventory needed to buffer operational interruptions I_r. All other parameters have only a fraction of the influence that these two parameters have on tritium

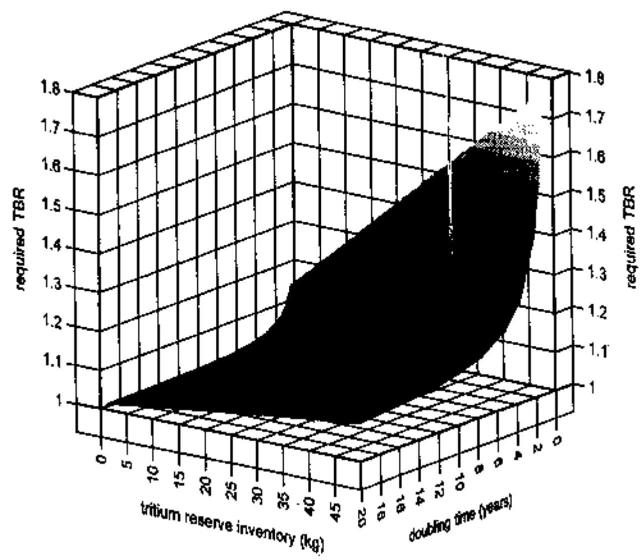

Fig. 5. Variation of required TBR compared with the tritium reserve inventory and the doubling time.

fuel self-sufficiency variables, namely, the required TBR and the required tritium startup inventory, for realistic parameter ranges. Figure 5 shows a three-dimensional surface plot of the required TBR compared with the doubling time (i.e., $n = 2$) and the tritium reserve inventory. It can be seen from this plot that the required TBR starts to increase dramatically for values of the doubling time less than ~8 yr. In addition, the effect from the tritium reserve inventory starts to slowly increase as the doubling time is reduced, although there exists a linear relationship between the required TBR and the reserve inventory. As a result, if the required TBR is limited to a particular value, then there exists a curved area within the doubling time–reserve inventory plane that satisfies this limiting condition. This is most easily presented using a contour plot corresponding to the three-dimensional surface as illustrated in Fig. 6. If the doubling time is relaxed to a longer duration, then a higher reserve inventory can be used. Conversely, if the reserve inventory must be reduced to low values (e.g., for safety or tritium availability reasons) while the TBR is kept constant, then the doubling time is accordingly reduced and next-generation reactors can be introduced at a faster pace. However, this condition may lead to a reduction in reactor availability because insufficient fuel is available during operational interruptions.

If the plasma exhaust line tritium throughput is used as the buffer condition, the fuel fractional burnup plays a large role as does the estimated time to fix any problems that produced the operational interruption. This is the scenario that was analyzed in earlier work; now, t_d, f_b, and t_r^{pl} are the dominant parameters. However, as discussed earlier, I_r is a direct function of t_r^{pl}, while it is indirectly

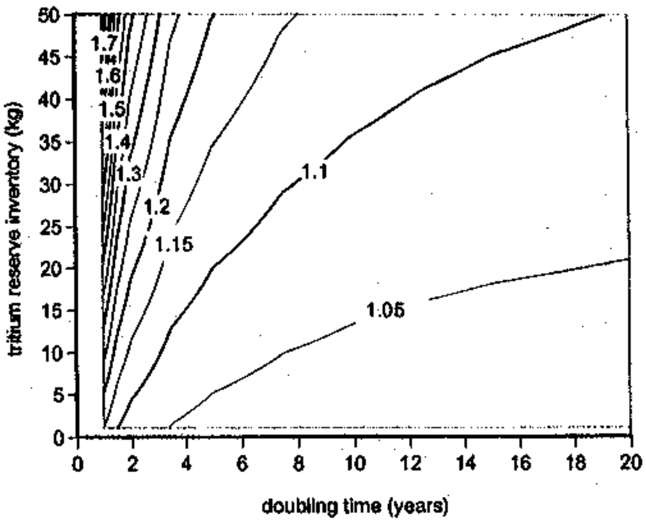

Fig. 6. Contour plot of required TBR compared with the tritium reserve inventory and the doubling time.

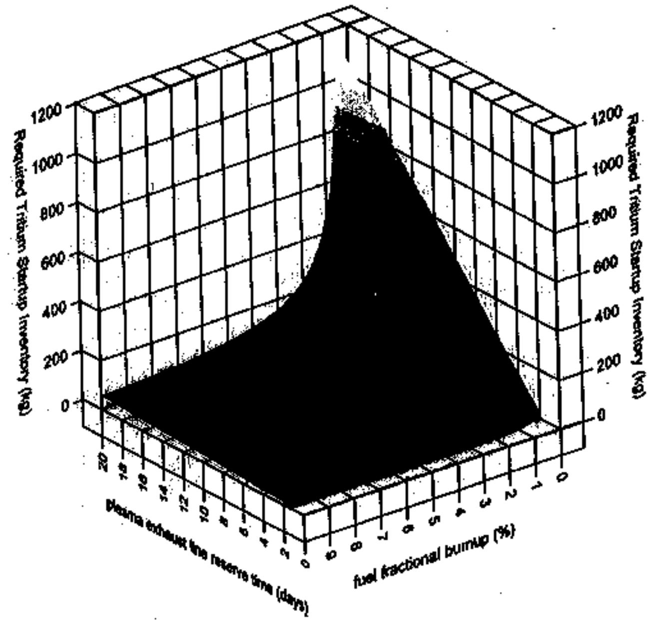

Fig. 8. Variation of the required tritium startup inventory compared with the plasma-exhaust-line time for reserve fueling and the fuel fractional burnup.

proportional to f_b. Note that f_b does not play a role in the estimation of the required TBR if this buffer/reserve option is not selected for the fuel cycle design. Figure 7 shows a plot of the required TBR compared with the fuel fractional burnup and the plasma-exhaust-line reserve fueling time. This plot clearly shows the direct relationship between Λ_r and t_r^{pl} in addition to the $1/f_b$ relationship. Any values lower than ~4% for f_b give rise to large Λ_r when the reserve time is set to values >8 days. A similar relationship also characterizes the estimation of the required tritium startup inventory $I_{t,0}$, as in Fig. 8. In this figure, the plot is reversed to more clearly show the invariance of $I_{t,0}$ with changes in the reserve time for high f_b. Values of $I_{t,0}$ of less than ~50 kg of tritium can be achieved by $f_b > 5\%$ and $t_r^{pl} < 10$ days. Again, a curved area can be obtained to satisfy a required TBR.

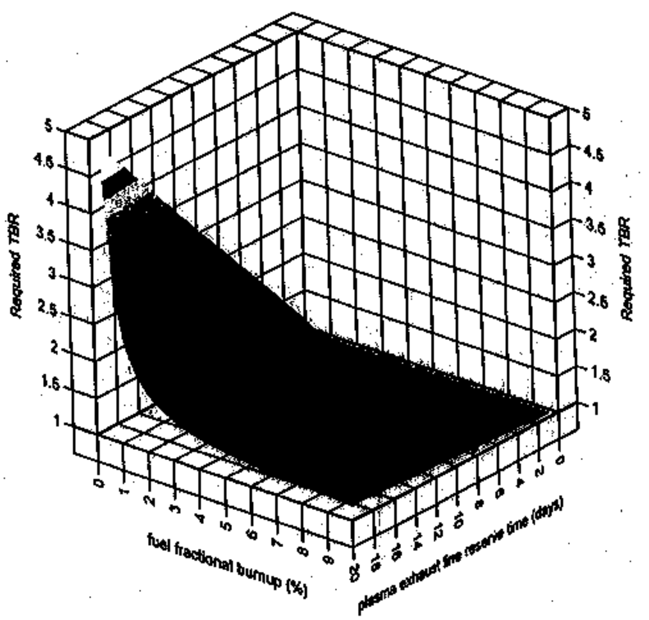

Fig. 7. Variation of the required TBR compared with the plasma-exhaust-line time for reserve fueling and the fuel fractional burnup.

VII.B. Alternate Reserve Inventory Design Options

The best way to dramatically relax the tritium fuel self-sufficiency problem is to incorporate a plasma-exhaust-line-reprocessing system, which can operate at 100% availability. Either no failures arise during the lifetime of the reactor or if a failure does occur, then the flow can be routed to an alternate local reprocessing system, which can handle the flow during such operational failures. If the fuel cycle features such a failure-resistant exhaust-processing-line design, then the reserve inventory can be planned to buffer other processing lines with much lower tritium flow rates. Figures 9 through 16 show the effects from provision of a different tritium reserve scenario as outlined in Table V for three different reserve inventory design options.

Figure 9 shows a contour plot of the required TBR compared with the fusion power and the time for reserve fueling for reserve inventory option 1, i.e., buffering the plasma-exhaust-processing line. It can be observed that the required TBR is relatively insensitive

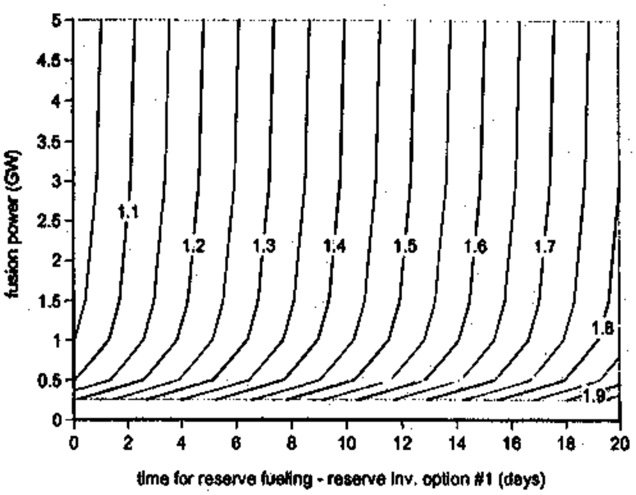

Fig. 9. Variation of the required TBR compared with the time for reserve fueling (using reserve inventory design option 1, i.e., the plasma-exhaust-processing line) and the fusion power.

to changes in fusion power. A significant change in the required TBR for a given time for reserve fueling will occur only for reactors producing very low fusion power (on the order of <0.5 GW). This variation seems to apply to any value of t_r^{pl}. Thus, to keep the TBR at a particular value, the time for reserve fueling must be accordingly reduced as the fusion power is reduced. Here, the overall behavior of the variation characteristics can be explained by noting that although the extra tritium produced from fusion reactions and the reserve fueling are both proportional to the fusion power, their slopes will differ. For low-fusion-power cases, the extra tritium gained from fusion reactions is not enough to counterbalance the extra tritium required for reserve fueling. Therefore, a higher Λ_r is needed. As P_f is increased (while keeping t_r^{pl} constant), however, the higher rate of extra tritium gained from fusion reactions serves to reduce the TBR needed to produce the extra tritium for reserve fueling. Eventually, for high enough P_f, the tritium gained from fusion reactions will balance out the tritium needed for reserve fueling so that Λ_r will not be significantly affected by further increases in P_f. In other words, for high enough fusion power, Λ_r will be a function of fuel cycle parameters other than P_f. Quantitatively, the change in Λ_r against changes in t_r^{pl} is almost insignificant for operations with $P_f > 3$ GW. A reduction from 3 to 1 GW must be balanced by a reduction in t_r^{pl} of ~0.7 days. From 1 GW down to 0.5 GW, the balancing amount of reduction in t_r^{pl} is increased to ~1.3 days. Finally, for very low power fusion reactors, i.e., from 0.5 to 0.25 GW, t_r^{pl} must be further shortened by ~2.5 days.

In contrast, changes in fusion power have a significant effect on the required tritium startup inventory, as observed in Fig. 10, which shows a similar contour plot again for option 1. An inverse relationship between fusion power and the time for reserve fueling characterizes this plot; in other words, increases in both P_f and t_r^{pl} will result in an increase in the tritium startup inventory (the fusion fractional burnup is assumed constant in this case). The tritium startup inventory surfaces with constant values are seen to be equally spaced. A large change in the required tritium startup inventory, on the order of hundreds of kilograms of tritium, is thus seen to occur for alternate scenarios in fusion power and time for reserve fueling.

Buffering of the tritiated impurity flow is now considered, where the time for reserve fueling is now given by t_r^{il} rather than t_r^{pl}, with failure and replacement characteristics due to reprocessing components in the impurity-processing line as opposed to that from the many reprocessing components found in the plasma exhaust line. Tritium throughput in the dedicated impurity-processing line is a small fraction of the tritium flowing through the main plasma-exhaust-processing line, for which the average tritiated fractional impurity content f_{imp} is the driving parameter. Figures 11 and 12 show contour plots of the required TBR compared with fusion power and the time for reserve fueling for reserve inventory option 2, i.e., buffering the impurity-processing line, with $f_{imp} = 2$ and 5%, respectively. Similarly, Figs. 13 and 14 represent similar contour plots of the required startup tritium inventory. Thus, both Figs. 11 and 12 correspond to Fig. 9, whereas Figs. 13 and 14 correspond to Fig. 10 but with a different reserve inventory option.

Figures 11 and 12 are characterized by an insensitivity of Λ_r against changes in the time for reserve fueling, which is in contrast to Fig. 9, which shows Λ_r insensitive to fusion power for most of the parameter range

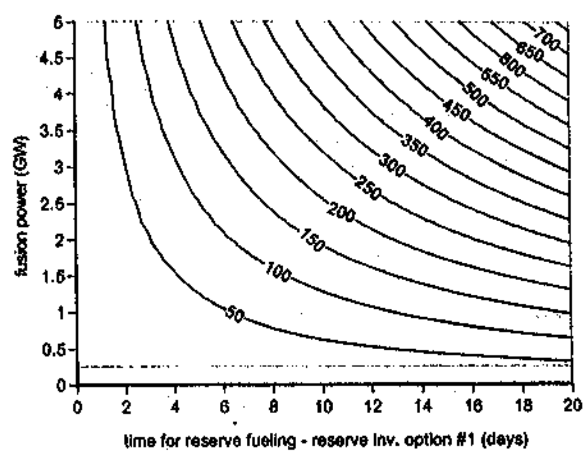

Fig. 10. Variation of the required tritium startup inventory (in kilograms) compared with the time for reserve fueling (using reserve inventory design option 1, i.e., the plasma-exhaust-processing line) and the fusion power.

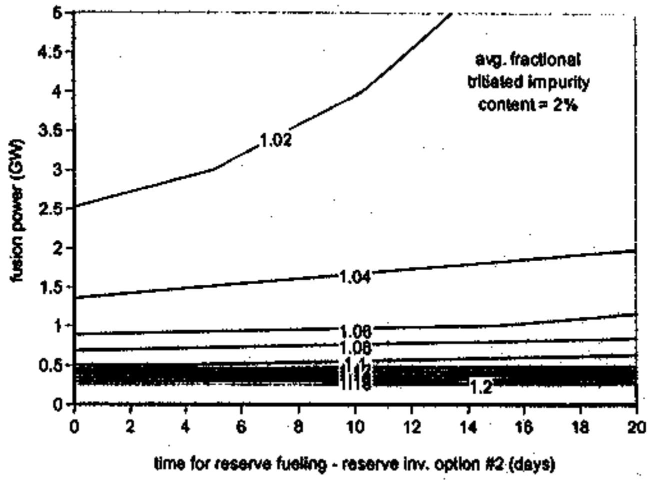

Fig. 11. Variation of the required TBR compared with the time for reserve fueling (using reserve inventory design option 2, i.e., the impurity-processing line) and the fusion power with f_{imp} = 2%.

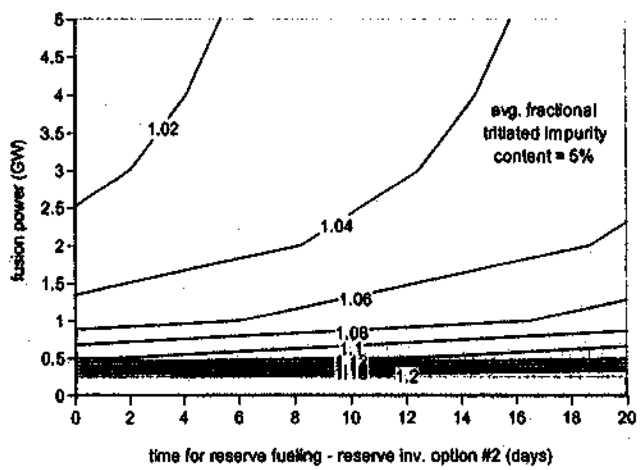

Fig. 12. Variation of the required TBR compared with the time for reserve fueling (using reserve inventory design option 2, i.e., the impurity-processing line) and the fusion power with f_{imp} = 5%.

of interest. The reason for this change in sensitivity is mainly due to the low reserve inventory required for option 2 as opposed to option 1. This can be attributed to the fact that the driving force to a change in Λ_r due to variations in P_f, namely, the tritium throughput for the processing line that is designed to be buffered, is characterized by very different values for both cases. The tritium throughput in the impurity-processing line is much smaller than that of the plasma-exhaust-processing line, thereby reducing the reserve inventory for the former case. Thus, increasing the time for reserve fueling for option 2 does not have much of an effect because only a small reserve inventory is required. Only when P_f is increased to values above ~1 to 2 GW do we see a variation with t_r^{II}. Accordingly, as the fusion power is increased, changes in fusion power gradually exert a greater influence, so increasing the fusion power reduces the required TBR. In addition, a greater average fractional tritiated impurity content slightly increases Λ_r for changes in t_r^{II} when P_f is held constant. For instance, increasing P_f from 1.5 GW to ~3 GW when f_{imp} = 2% and t_r^{II} = 16 days reduces Λ_r from 1.04 to ~1.03, whereas if f_{imp} is

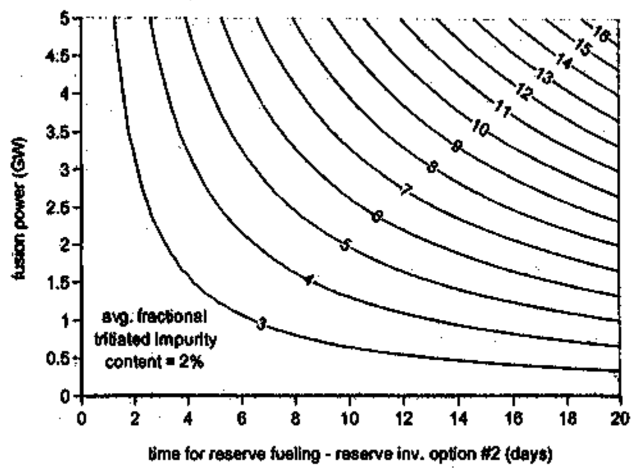

Fig. 13. Variation of the required tritium startup inventory (in kilograms) compared with the time for reserve fueling (using reserve inventory design option 2, i.e., the impurity-processing line) and the fusion power with f_{imp} = 2%.

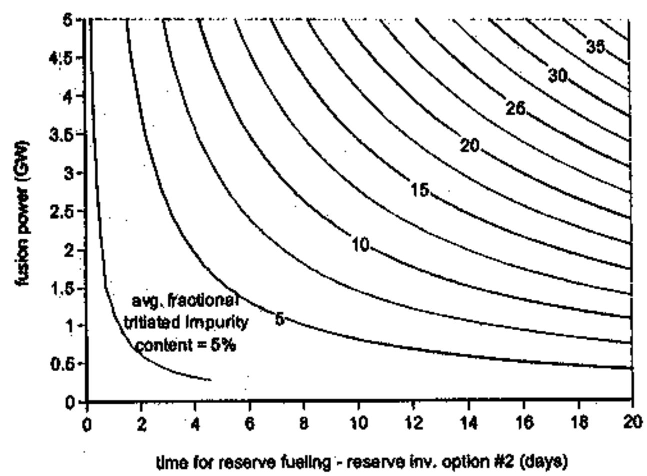

Fig. 14. Variation of the required tritium startup inventory (in kilograms) compared with the time for reserve fueling (using reserve inventory design option 2, i.e., the impurity-processing line) and the fusion power with f_{imp} = 5%.

changed to 5% for the same parameter range, Λ_r is reduced from 1.06 to only ~1.045. Increasing the tritiated impurity fraction will thus result in a slight increase in Λ_r as expected. The relatively low values of Λ_r, i.e., up to 1.2 when P_f is reduced to 0.25 GW, are attributed to the low reserve inventory required. From Figs. 13 and 14, the required tritium startup inventory reflects the same variation pattern as in Fig. 10, except for much smaller values. Moreover, we see an increase in the required tritium startup inventory, which roughly corresponds to the increase in f_{imp}; i.e., when f_{imp} is roughly doubled, the required tritium startup inventory is also roughly doubled. Again, this is expected from the corresponding increase in the tritium throughput inside the impurity-processing line as f_{imp} is increased.

Finally, we examine the effects from the third design option for the reserve inventory, buffering of the breeding blanket processing line with a time for reserve fueling given by t_r^{bl} this time. Again, similar contour plots are shown as in the previous two design options. Figure 15 shows a contour plot of the required TBR compared with the fusion power and the time for reserve fueling for reserve inventory option 3, i.e., buffering the breeding-blanket-processing line, whereas Fig. 16 shows a similar contour plot for the required startup tritium inventory. Figure 15 is also characterized by an insensitivity of Λ_r to changes in the time for reserve fueling, which is similar to Figs. 11 and 12. This is again due to the low tritium breeding production and the resulting low required reserve inventory for this design option. Only when P_f is increased to values above ~2 GW do we see a variation with t_r^{bl}. Similar to the results of design option 2, increasing P_f from 1 to 3 GW reduces Λ_r from 1.06 to between 1.02 and 1.03 for a wide range of times for reserve fueling. The relatively low values of Λ_r, i.e., up to 1.2 when P_f is reduced to 0.25 GW, are very similar to design option 3, which is due to the small influence that the low reserve inventories for such low-throughput processing lines have on Λ_r. From Fig. 16, the required tritium startup inventory again reflects the same variation pattern as in the previous startup inventory contour plots and with values similar to design option 2.

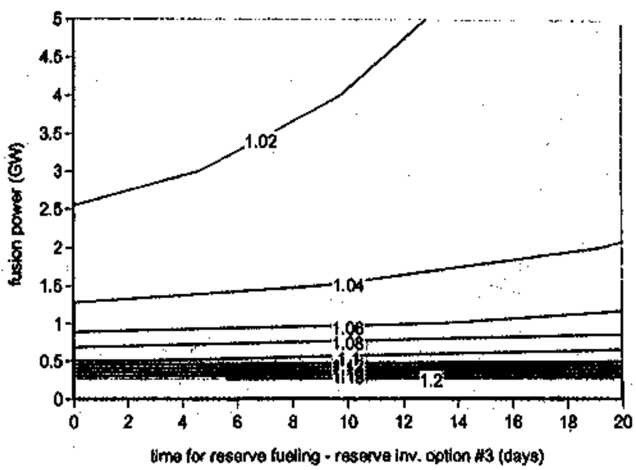

Fig. 15. Variation of the required TBR compared with the time for reserve fueling (using reserve inventory design option 3, i.e., the breeder blanket processing line) and the fusion power.

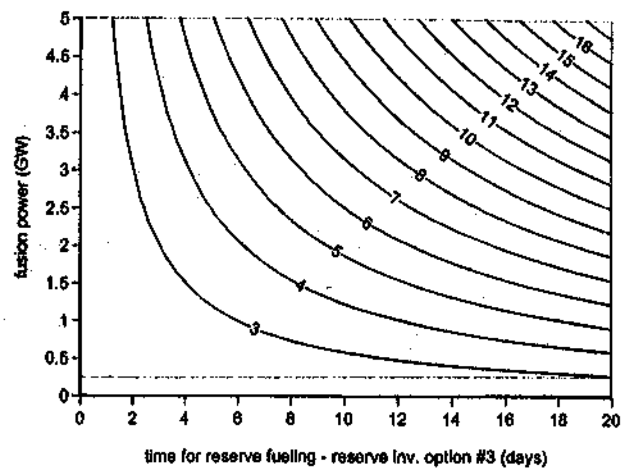

Fig. 16. Variation of the required tritium startup inventory (in kilograms) compared with both the time for reserve fueling (using reserve inventory design option 3, i.e., the breeder blanket processing line) and the fusion power.

Different buffering designs have been examined for the three major independent tritium-processing lines in the fuel cycle. Nonetheless, a constant supply of electrical energy from fusion power is expected to be necessary to meet energy demands. If a 100% reliable and available plasma-exhaust-processing line is not available (which is most likely since a 100% reliable processing component is very difficult), then a tritium inventory reserve needs to be stored that takes failure operations into account in the plasma-exhaust-processing line. Thus, the figures that show the results using reserve inventory design option 1 are more likely to be used than the figures for options 2 and 3. However, the large tritium startup requirements must be considered if other parameters cannot be improved, such as the fuel fractional burnup.

VII.C. Non-Steady-State Considerations

The fuel fractional burnup can either have a direct influence on the fuel cycle short-term tritium inventories, or the fuel cycle design can be modified to address the higher throughput without increasing the tritium inventory by changing the size or operating strategy of the processing components. For example, if a cryopump design is used as the plasma-exhaust-processing subsystem, a stagger operating strategy is most likely to be used to reduce the tritium inventory. However, if the reactor is

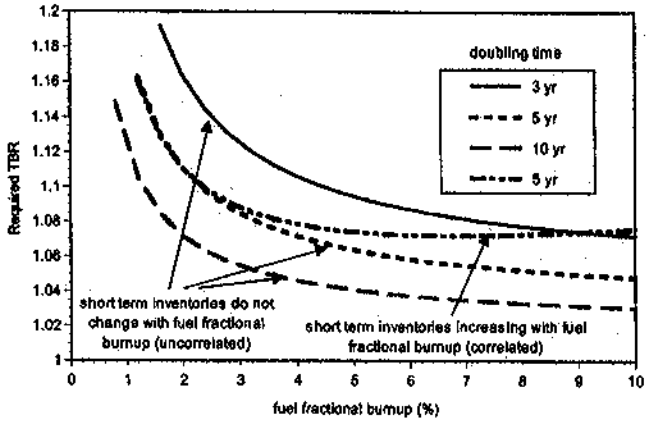

Fig. 17. Variation of the required TBR compared with fuel fractional burnup for various values of the doubling time.

modified to be operated at lower f_b, then a more frequent stagger operation with faster regeneration times may be implemented to reduce the dynamic tritium inventory. If no modification is performed, the higher tritium throughput will result in a linear increase in the quasi-steady-state short-term inventory, as verified from CFTSIM simulation runs. Thus, in Figs. 17 and 18, the variation of Λ_r against f_b for different reactor operating scenarios is examined with both a linear relationship between the short-term inventory and f_b (short-term inventory increasing) and no correlation between them (short-term inventory constant). Figure 17 shows the Λ_r curves for different doubling times—3, 5, and 10 yr—and shows an $\sim 1/f_b$ relationship for all noncorrelated curves with the curves displaced toward larger values of Λ_r for lower t_d. Furthermore, the 5-yr doubling time is shown for both the correlated and the uncorrelated cases. As can be seen from the figure, a correlated scenario produces a small increase in Λ_r after the initial fast drop in Λ_r. Specifically, Λ_r does not gradually drop from $\sim$1.08 to 1.04 when f_b is increased from 3 to 10% as in the noncorrelated case but reaches a minimum value of $\sim$1.07 at 6% f_b and increases to 1.08 at 10% f_b for the correlated case.

Figure 18 shows Λ_r curves for different operating fusion power scenarios when f_b is varied as in Fig. 17. This time, however, all the curves correspond to the correlated case (a more realistic scenario). The displacement of the curves when the fusion power is reduced from 5 to 3 GW is small. However, when it is further reduced to 1.5 GW, Λ_r is observed to be further displaced to higher values, and the curve exhibits a minimum Λ_r point, $\sim$1.075 for this case, as opposed to the other curves. The reason for this behavior is that the increase in bred tritium that results from higher fusion power outweighs the need to increase the tritium reserve inventory with respect to Λ_r calculations. The variation of Λ_r with changes in P_f at f_b lower than $\sim$1.5% does not seem to be significant.

Figure 19 shows the impact of the short-term inventory correlation with reactor variables. This figure shows the variation of both the required TBR and the required tritium startup inventory with changes in the fusion power. Both correlated (linear function of power) and uncorrelated (constant short-term inventory with changes in fusion power) curves are plotted in the figure. The sharp rise in Λ_r when P_f is lower than $\sim$1 GW is due to the corresponding reduction in neutron flux into the breeder blanket, which affects the tritium production rate and the time to reach the inventory objective (e.g., a doubling time). Thus, fusion reactors that produce <1 GW of fusion power will require higher Λ_r than higher power reactors. In fact, any reactors with fusion power greater than $\sim$1 GW will be characterized by the same Λ_r if other reactor parameters are kept constant. Correlation of the total short-term inventory is observed to have an insignificant effect on modifying the value of Λ_r, so uncertainties

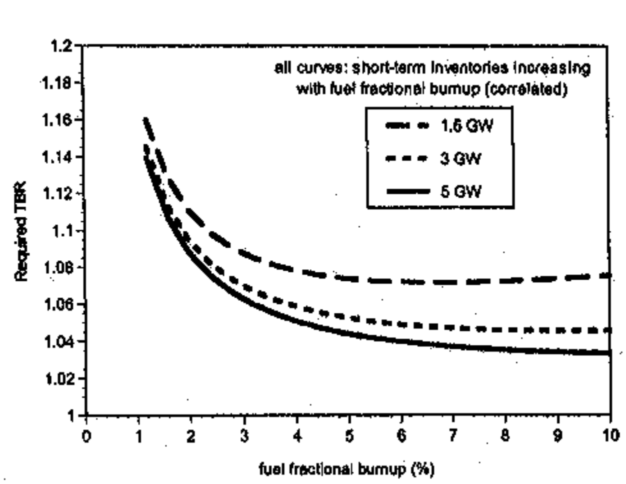

Fig. 18. Variation of the required TBR compared with fuel fractional burnup for various values of fusion power.

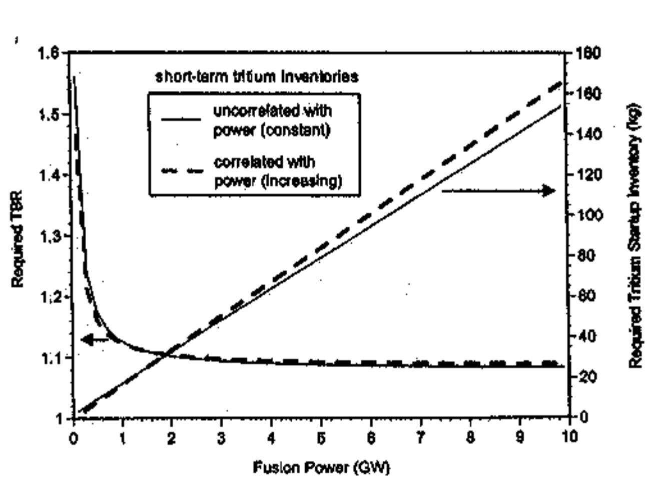

Fig. 19. Variation of both the required TBR and the required tritium startup inventory compared with fusion power.

with regard to fuel cycle design changes can be neglected in the calculation of Λ_r for reactors with different fusion power. The required startup tritium inventory $I_{i,0}$ is seen to have a strong linear correlation with fusion power. Reactors with P_f greater than ~3 GW will result in an $I_{i,0}$ > 50 kg, a significant amount that may be restricted by safety analyses. Again, the correlation of the short-term inventory is seen to have a very small effect, though for P_f > 5 GW, a significant divergence of a few percent (increasing linearly with P_f) is observed.

Reactor availability and burn-cycle effects on tritium fuel self-sufficiency are now considered. Reactor availability (due to both scheduled and nonscheduled reactor downtime) will affect tritium fuel self-sufficiency through any relations involving the fusion power. Figure 20 depicts the variation of Λ_r with changes in the doubling time for fueling next-generation fusion reactors. As before, a $1/t_d$ behavior is observed, and the rise in Λ_r starts when the doubling time becomes less than ~8 yr. A change in Λ_r of less than ~4% for all cases is the result when t_d > 8 yr. In this figure, three different curves with different reactor availabilities are produced. A significant divergence of the Λ_r curves occurs for availabilities ranging from 60 to 100%. Thus, loss of reactor operation due to scheduled and nonscheduled maintenance is seen to have a significant effect on the required TBR, especially as the desired rate of fusion growth is increased. Note that these curves are produced using a buffering of the plasma-exhaust-processing line of 2 days, which result in no loss of reactor operation from failures in the processing lines. If the achievable TBR is limited to ~1.3 to 1.4 for any candidate breeder material and design, then the fastest rate of introduction of next-generation fusion reactors (i.e., n = 2 for the doubling time) will be limited to those with doubling times ≳1.5 to 2 yr, as given by the figure. Faster introductory rates will not be possible.

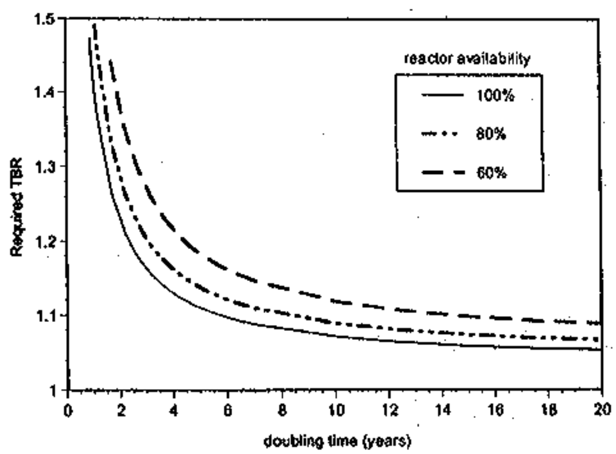

Fig. 20. Variation of the required TBR compared with the doubling time for various reactor availabilities.

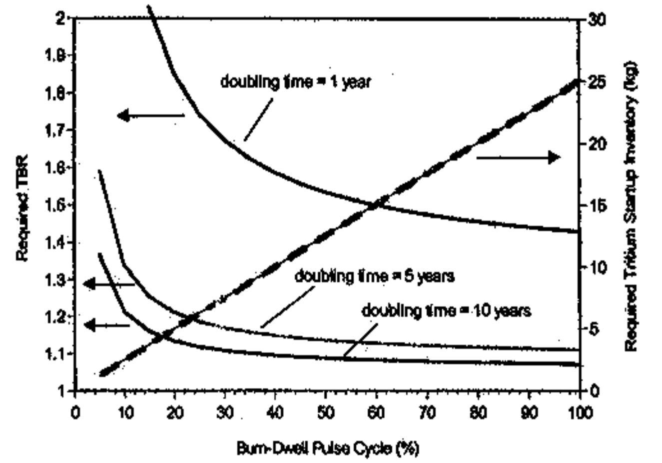

Fig. 21. Required TBR and tritium startup inventory as a function of the pulse cycle, assuming the fuel cycle inventory remains the same (i.e., fuel cycle is changed accordingly to accommodate more tritium throughput).

Figure 21 shows both the Λ_r and required tritium startup inventory curves when the burn-dwell pulse cycle (i.e., for tokamaks) is varied. All the curves were produced with the assumption that the short-term inventory remained the same for all pulse-cycle scenarios. This is a safe assumption because redesigning the fuel cycle components to keep the short-term inventory constant may be required. The Λ_r curves again show an inverse relationship that is characteristic of previous parameter variations, which is again due to the reduction in neutron fluence. Three curves with different doubling times ranging from 1 to 10 yr are shown. The change in Λ_r when t_d changes from 5 to 10 yr is only ~15% of the change from 1 to 5 yr in t_d (though most of the discrepancy occurs as t_d nears 1 yr). With regard to any limitations imposed by a reduced pulse cycle, the figure shows that for most value sets of the doubling time, the pulse cycle does not have much of an effect when α_p > 50%. Significant variations of Λ_r occur when α_p is less than ~25% for all doubling times. The variation due to changes in the pulse cycle are greater as t_d is reduced to values of less than or near 1 yr. Finally, $I_{i,0}$ is not a function of the doubling time, as can be seen by the single constant slope line in the figure. A required tritium startup inventory of 25 kg will be required for all cases when the pulse cycle reaches 100% (i.e., steady state). Thus, a significant reduction in $I_{i,0}$ may result from the adoption of a shorter burn period (or, equivalently, a longer dwell period) in the burn-dwell pulse cycle.

Effects on tritium self-sufficiency due to reductions in both on-line availability and in the burn-dwell cycle are combined in Fig. 22. This figure again shows the inverse Λ_r relationship, where the abscissa is now reactor on-line availability α_{op}. A realistic range in the

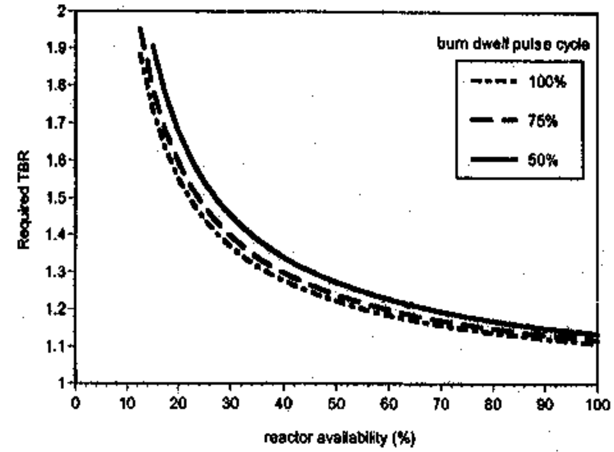

Fig. 22. Variation of the required TBR compared with reactor availability for various pulse cycles.

burn-dwell pulse cycle (50 to 100%) is seen to have a negligible effect for the entire range of α_{op}, particularly in the range from ~50 to 100%. For instance, the increase in Λ_r as α_p is reduced accordingly from 100 to 50% is less than ~5%. For $\alpha_{op} < 50\%$, the effect on Λ_r is slightly augmented, as shown in the figure. Nevertheless, practical operation of future commercial DT fusion reactors will probably experience at least 70% reactor online availability, whereby designs with different α_p will be characterized by very small differences in Λ_r.

VII.D. Economic Growth Rate

As noted previously, various inventory breeding objectives (i.e., other than a doubling time inventory) may be met during reactor operation. Such objectives will depend on the desired rate of introduction of next-generation reactors. Obviously, economic considerations point toward a faster introductory rate of reactors, though, of course, other factors will limit this rate. To quantify the effects from any future fusion growth rate, Fig. 23 shows the TBR that is required for different values of n, the number of future reactors descending from the current parent reactor. Five different slopes are plotted, each one corresponding to a different time for reserve fueling, which ranges from 0 (i.e., no reserve tritium inventory available) to 20 days. A constant slope is characteristic of all curves because the quantity of required tritium is simply a multiple of n. The longer is the time for reserve fueling for the reactor design, the higher is the TBR required. Effects from restrictions in blanket performance can be visualized by including a horizontal line in Fig. 23. For example, if the achievable TBR in the blanket for a particular design is limited to 1.3, then the number of reactors that can be built for the next generation of fusion reactors will be limited, depending on the amount of reserve fuel available. If $t_r = 0.5$ days, then at most two new reactors can take the place of a previous reactor, whereas if t_r is increased to 2 days, then at most four to five reactors can be constructed for the next-generation line. In addition, if no next-generation reactors need be built, i.e., $n = 1$, as when enough tritium is available externally, then a high-performance breeding blanket need not be used in the design where $\Lambda_r < 1.1$ would suffice for most reserve inventory designs. The doubling time inventory objective is given by $n = 2$.

VII.E. Effects from Different Tritium Inventory Types

The effects from variations in the tritium inventory located inside the fuel cycle, as simulated by a great number of numerical codes (both integrated and localized simulations), can be seen in Fig. 24. Variations in tritium inventory are set against the reference ITER-like design mentioned previously. Since the reference case is characterized by different inventories for each inventory category, e.g., short-term inventories have a much lower tritium inventory than long-term inventories, the curves in Fig. 24 are staggered from each other. Four different types of tritium inventories are examined in Fig. 24: the total long-term tritium inventory, the short-term tritium inventory inside the plasma-exhaust/impurity-processing line, the short-term tritium inventory inside the breeding blanket-processing line, and the tritium inventory lost as waste during periodic replacements of wall materials and processing components. All four types of tritium inventory are seen to have a similar linear effect on the required TBR. In fact, three of the four inventory types produce almost equivalent Λ_r variation slopes, i.e., an increase in Λ_r of ~0.003 for every kilogram increase of retained tritium. The short-term plasma-exhaust/impurity-processing line, however, produces a slightly higher change in Λ_r with equivalent changes in the retained

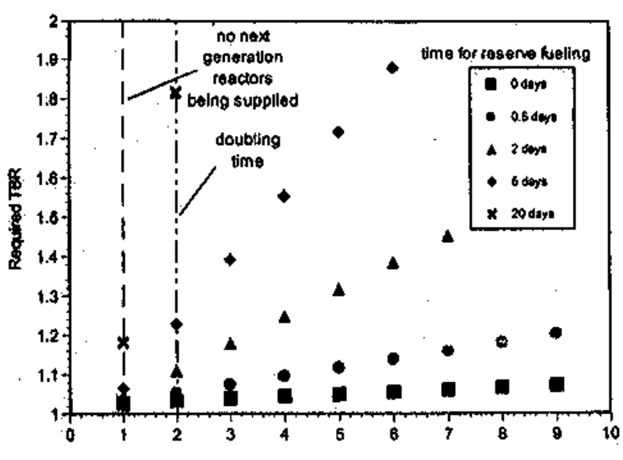

Fig. 23. Variation of the required TBR compared with n, the rate of introduction of new reactors.

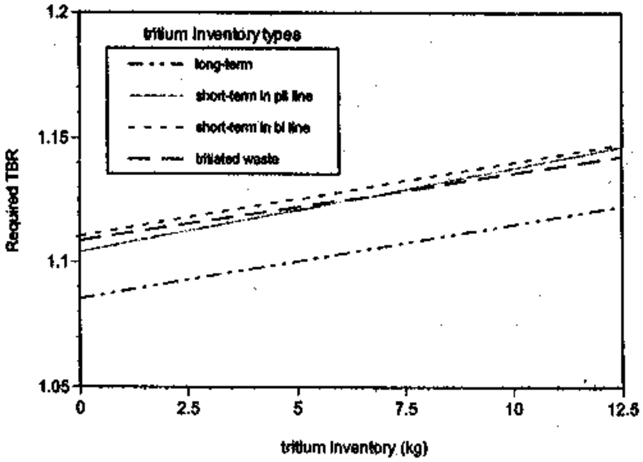

Fig. 24. Variation of the required TBR compared with various types of tritium inventories found in the fuel cycle.

tritium inventory. This discrepancy leads to an increase of only ~15% in Λ_r from the three other tritium inventory types. Thus, even if the uncertainty in breeding blanket performance is small, on the order of a few percent, a large range in fuel cycle tritium inventory can be accommodated. Tritium inventories in the fuel cycle are thus seen to produce a relatively small effect on Λ_r compared to other variables. However, if the margin between the achievable TBR and the required TBR is small, changes in the fuel cycle design that considerably reduce the tritium inventory may be sufficient to close the gap.

As formulated in this work, the waste tritium inventory is a function of the replacement schedule and efficiency in detritiation of the removed waste. Figure 25 shows the effect from changes in these variables. The reference case indicates that the fraction of tritiated waste removed is 0.9, from which, then, a fraction of this removed tritiated waste that is recycled back into the fuel cycle is also 0.9. The values are expected to be high for both parameters in order to efficiently process tritium inside the fuel cycle during reactor operation. Two separate curves are plotted in Fig. 25 for variations in each of the preceding fractional parameters. These two curves correspond to different rates of periodic replacement: one full replacement every 5 yr of operation and one full replacement every year. As the figure shows, the effect of changes in the fraction recycled is much greater than changes in the amount removed during such full replacement periods. Such changes are greatly enhanced when the replacement rate is increased from one in 5 yr to one per year. The value Λ_r drops significantly as the waste that is recycled is increased, whereas it rises less steeply as the amount of material removed is increased. It is significant that if none of the tritium in the waste that is removed is recycled but is left in the removed material or components, then Λ_r can increase to ~10% for a schedule of one replacement per year. However, it is expected that replacements will occur very infrequently during reactor operation due to power-grid availability considerations.

A further parametric study is shown in Fig. 26, which shows the effects from changes in the quantity of retained long-term tritium inventory on the variation of Λ_r compared with the rate of full replacement periods. For the reference case of 0.9 fraction of material removed and 0.9 fraction of tritium in the waste material recycled, the variation of Λ_r compared with the number of replacement periods during reactor operation is seen to be quite insensitive if the long-term inventory is less than ~5 kg. If this long-term inventory rises to 10 and then 20 kg, Λ_r increases more as the replacement rate is increased.

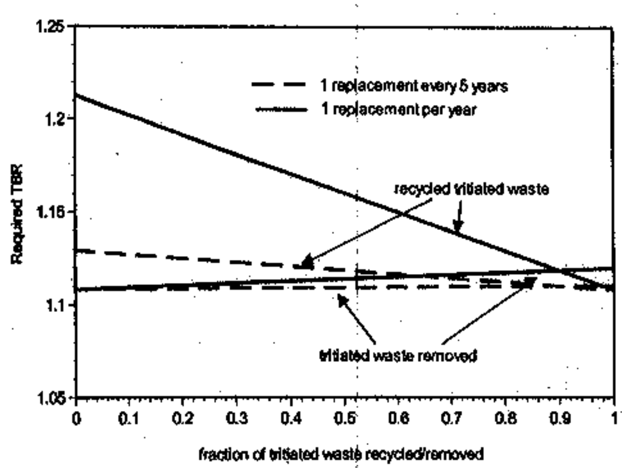

Fig. 25. Variation of the required TBR compared with the fraction of tritiated waste removed and/or recycled.

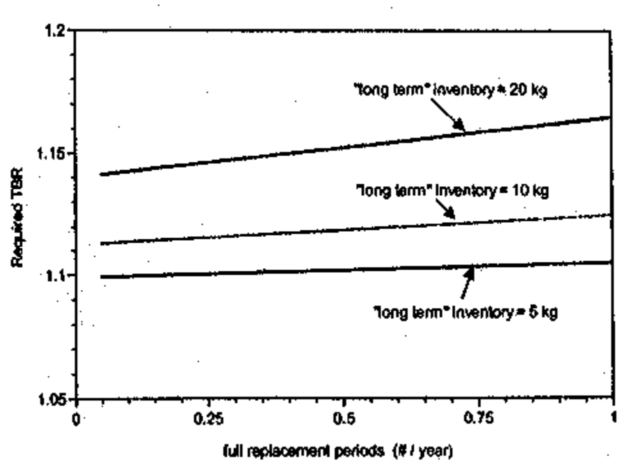

Fig. 26. Variation of the required TBR compared with the frequency of full replacement periods.

Nevertheless, the long-term inventory is expected to be restricted to a few kilograms for safety reasons, so Λ_r should be somewhat insensitive in this respect.

VII.F. Effects from External Fueling Sources and Delays

Dedicated tritium production reactors are already being planned for the near future that will lead to a drastic increase in the tritium available to drive power fusion reactors.[21–24] If such dedicated tritium production is indeed available and concurrently operating with commercial power fusion reactors, it is very likely that some of the tritium generated externally will be shipped and fed to the reactor. If we assume that such an external tritium fueling rate is continuous (or almost continuous, e.g., shipped every day or so), then such an external feed will alleviate the tritium breeding requirements to be met by the breeding blanket inside the reactor. Figure 27 shows the effects from variations in this external tritium fueling rate when it is varied from 0 to 10 kg T/yr. Curves that characterize different doubling time periods are presented in the figure. It is apparent that the required TBR is reduced at a constant rate of ~0.05 for every 5 kg T/yr of externally derived tritium fuel. A variation in the doubling time has no effect on the downward slope.

Conversely, tritium can be continually extracted from the reactor. The fusion reactor will act as a tritium source for any external operations that require tritium, as in weapons replenishment. Thus, Fig. 27 shows the appropriate curve for a doubling time of 5 yr, which is increasing at a constant rate. This curve mirrors the corresponding curve for the external tritium source. Predictions that take into consideration the near-term tritium supply result in an external tritium supply ranging from ~1.5 to 2 kg T/yr, as is shown in the figure.[21] Coincidentally, it is estimated that if weapons replenishment is needed, a similar rate of

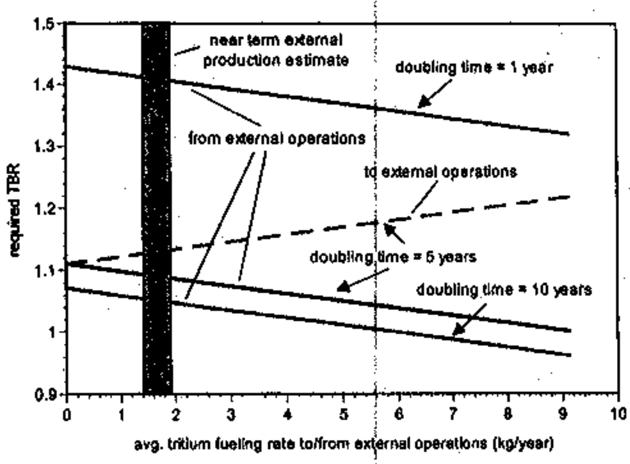

Fig. 27. Variation of the required TBR compared with the average tritium rate to and from external operations for various doubling times.

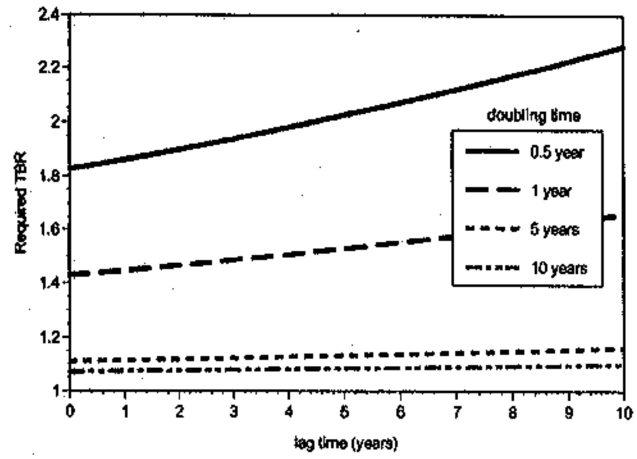

Fig. 28. Variation of required TBR compared with lag time for various doubling times.

~2 kg T/yr will be required.[24] For this range, a reduction or augmentation in Λ_r is seen to be small, at most 0.02. However, if the margin between the required TBR and the achievable TBR is small, then including an external tritium source may be helpful. Extruding tritium to feed external operations will have the opposite effect. Again, note that increasing the doubling time to periods longer than 5 yr have only a small impact on the value of Λ_r.

If unforeseen events occur that delay the use of the bred tritium of the parent reactor in the child reactor, then such a delay must be included in the analysis. As a result, the impact from any lag time, i.e., delay, during transfer of the tritium from the current reactor to next-generation reactors is shown in Fig. 28. A lag time of less than a year has a negligible impact on Λ_r. However, if the doubling time is reduced to 1 yr or less, the effect from such a lag-time period is increased and may be significant in tritium fuel self-sufficiency analyses. One can then conclude that any delay in the use of the bred tritium will be important only for very fast rates of introduction of next-generation reactors.

VII.G. Allowable Tritium Inventories

As noted earlier, another way of framing the problem of tritium self-sufficiency in fusion reactors is to determine how much allowable tritium inventory can be retained when the achievable TBR for a particular breeding blanket design is known, as depicted in Fig. 29. Four separate cases are considered here. The allowable plasma exhaust line long-term retention is examined for doubling times of 5 and 3 yr, while the plasma exhaust line short-term retention is also examined for doubling times of 5 and 4 yr. As indicated by the figure, a linear relationship with almost equivalent slopes characterizes all four cases, as has been observed in previous results involving fuel cycle tritium inventories and their effects.

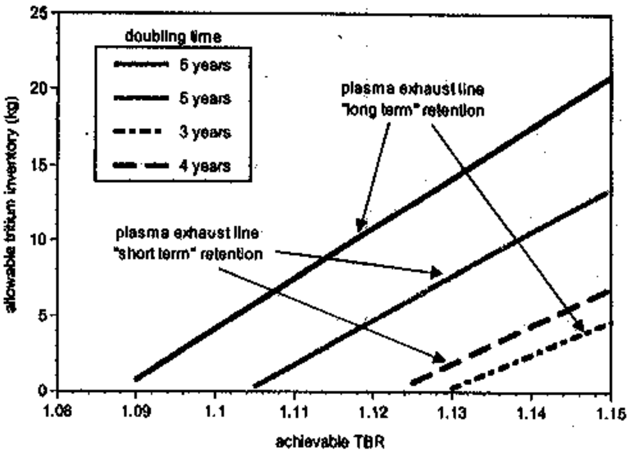

Fig. 29. Variation of allowable tritium inventory for various inventory types as a function of the achievable TBR.

More tritium inventory is allowed for long-term retention than for short-term retention with the same doubling time and for a given achievable TBR. Furthermore, as the doubling time is reduced, the tritium inventory allowed in all cases is correspondingly reduced. For instance, when a breeding blanket is able to achieve a TBR of 1.13 at most, then the allowable tritium inventories for the reference case are ~15 kg for long-term retention and 7 to 8 kg for short-term retention. It is likely that the long-term retention will be more restrictive in most future reactor designs. However, if the doubling time is reduced to 3 yr for this particular case, then the design does not allow for any long-term tritium retention in the entire fuel cycle. One can also determine the lowest TBR required when any type of tritium inventory becomes negligible. For a doubling time of 5 yr, the lowest required TBR when the tritium inventory reaches negligible values is ~1.09.

VIII. ANALYSIS OF UNCERTAINTY IN PARAMETERS INFLUENCING TRITIUM SELF-SUFFICIENCY

Uncertainty (due to system definition, random processes, and an uncertainty in process behavior) is an important parameter to consider in any systemwide analysis. The tritium self-sufficiency problem is also characterized by such uncertainties, so the required TBR will have uncertainties because of the many parameters influencing its calculation. Previous papers have discussed uncertainties in the achievable TBR, but so far none have considered uncertainties in the calculation of the required TBR. As outlined in Sec. VI, the uncertainty in the calculation of the required TBR can be expressed as a quadrature relation involving the uncertainties for each parameter and the partial derivatives associated with the parameter.

TABLE X

Reference Values for Uncertainties in Fuel Cycle Parameters

Fuel Cycle Parameter Uncertainty	Reference Value for Uncertainty
$\delta \sum_{bl}^{short\ term} I$	20 g T
$\delta \overline{F_{ext}^{in}}$	2 g T/day
$\delta \sum_{pll}^{short\ term} I$	0.5 kg T
δI_r	15 kg T
$\delta \sum_{i}^{long\ term} I$	2 kg T
δI_{waste}	5 kg T
δt_l	0.5 yr
δt_f	2 yr
$\delta \alpha_p$	10%

Reference values for the uncertainties used in this analysis are shown in Table X. With these reference values and with the reference tritium self-sufficiency parameters given in Table VII, the uncertainty in Λ_r ($\delta\Lambda_r$) was calculated as 0.02. Moreover, it is of interest to determine $\delta\Lambda_r$ for various values of the uncertainties in the long-term tritium, tritium reserve, and tritiated waste inventories. Such a study is of value because all three of these tritium-retention processes characterizing the fuel cycle have large uncertainties associated in the calculation of their tritium inventories.

Figures 30 and 31 present contour plots of Λ_r as a function of the aforementioned variables. The variation of $\delta\Lambda_r$ as a function of δI_r and $\delta \sum_i^{long\ term} I$ is shown in

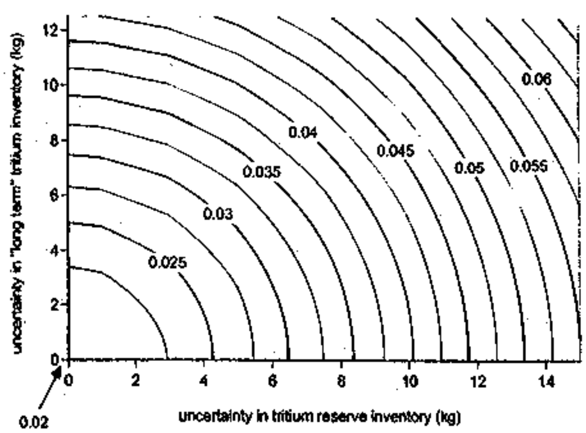

Fig. 30. Variation of the uncertainty in calculating the required TBR compared with the uncertainties in both the reserve and the long-term tritium inventories.

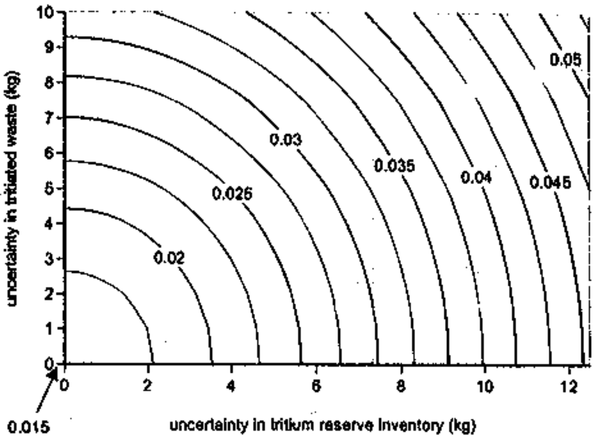

Fig. 31. Variation of the uncertainty in calculating the required TBR compared with the uncertainties in both the reserve and waste tritium inventories.

Fig. 30, while its variation as a function of δI_r and δI_{waste} is shown in Fig. 31. Both figures are characterized by similar changes in $\delta\Lambda_r$ compared with changes in either axis, resulting in a wavelike expansion from the origin, at which $\delta\Lambda_r$ is not zero but 0.020 for Fig. 30 and 0.015 for Fig. 31. This is due to uncertainties in other reference parameters when the uncertainties in the tritium inventories for the types associated with both axes are zero. We observe that there exists a slight difference in $\delta\Lambda_r$ when either $\delta \sum_i^{long\ term} I$ or δI_{waste} is changed as a function of changes in δI_r, which accounts for the asymmetry of the curves with the origin as reference. As an example, if $\delta\Lambda_r$ must be below ± 0.025 for a certain fuel cycle design, then the allowable uncertainty for the tritium retained as long-term inventory is approximately ± 5 kg, whereas it is only approximately ± 4 kg for that held in reserve, as illustrated in Fig. 30. On the other hand, Fig. 31 shows an increased tolerance to changes in tritium inventory for both tritium-retention mechanisms associated with the plot; i.e., if $\delta\Lambda_r < \pm 0.025$, then the allowable uncertainty in the tritiated waste estimate is ± 7 kg, whereas it is approximately ± 6 kg for that held in reserve. Again, all other uncertainties are held constant with their reference value for both cases. The reason for this discrepancy is that the reference uncertainty in the long-term inventory is different from that in the waste inventory. If all three tritium inventories are reduced to zero, then $\delta\Lambda_r$ is only reduced to a value of 0.0147.

IX. A STUDY ON THE EFFECTS OF TRITIUM CODEPOSITION ON THE REQUIRED TBR

Predictions that the tritium located inside the torus will dominate the overall fuel cycle inventory, coupled with the fact that the availability of the fusion reactor will be dictated by the frequency of conditioning and maintenance of the PFCs, will lead to significant effects on the calculation of the required TBR. This is especially true when the PFCs (especially the divertor) are designed to be composed of carbon, e.g., carbon fiber composites and graphite, with the associated recent estimates on the possibly very large tritium inventories found in the codeposited layer inside the torus walls. If there exists an inventory limit for tritium inside the torus during normal operation I_{wall}^{limit}, then a conditioning time given by the efficiency and rate of cleaning will lead to reduced reactor operation availabilities. For the TBR studies of this work, and by relating wall inventory limits, codeposition rates, and finally conditioning parameters to the overall availability, we can observe the effect on the required TBR from changes in torus wall design for PFCs composed of carbon.

The time to reach the inventory limit if we assume that all the inventory is held up in the codeposited layer is then

$$t_{codep}^{retention} = \frac{I_{wall}^{limit}}{\alpha_p F_{codep}^{retention}} \ . \tag{53}$$

The value $F_{codep}^{retention}$ is directly related to the plasma density and the effective reflection coefficient. The plasma density can be controlled by changing the fueling and exhaust rates through fast-acting valves and feedback loops. The overall reflection coefficient is related to the implantation rate, which is determined by the plasma regime of operation. However, a simplified relationship is valid because of the high uncertainties characteristic of the codeposition process. In detailed studies, the codeposition rate of tritium has been predicted to be ~20 g/shot for ITER using beryllium and some carbon.[13] This corresponds to an equivalent rate of $F_{codep}^{retention} = 72$ g/h for continuous fueling.

Conditioning that is performed to release this codeposited tritium can be performed either during the dwell phase for the pulsing case within normal operation of the reactor or during separate conditioning scenarios following buildup of the inventory to the inventory limit. The conditioning time is then

$$t_{codep}^{removal} = \frac{I_{wall}^{limit}}{F_{codep}^{removal}} \ . \tag{54}$$

The downtime availability can then be related to the codeposition and conditioning parameters as follows:

$$\alpha_{op}^{codep} = \frac{t_{codep}^{retention}}{t_{codep}^{retention} + t_{codep}^{removal}} \ . \tag{55}$$

For required TBR calculations, the inventory limit given as a design parameter will become the maximum possible inventory due to codeposition during the lifetime of the reactor. Note that the other types of tritium holdup inside the torus (e.g., tritium trapped in the bulk, mobile tritium in the bulk, and tritium trapped in dust) will

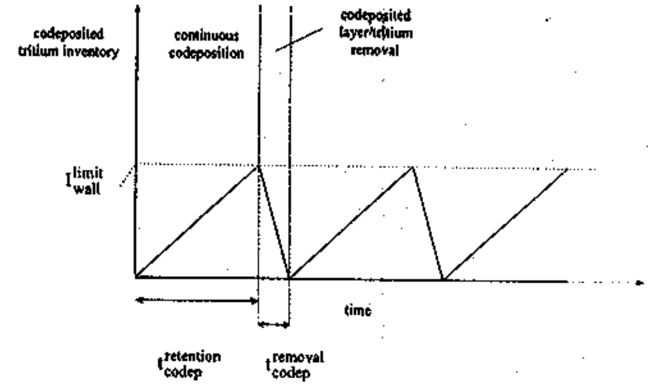

Fig. 32. Characteristics of tritium codeposition dynamics.

still need to be accounted for using other methods of calculation.

Figure 32 is a schematic of the expected tritium codeposition retention-and-release dynamics during operation of a carbon-lined tokamak. The required TBR can then be related to both $F_{codep}^{retention}$ and $F_{codep}^{removal}$ for which a contour plot is shown in Fig. 33, where the variation of the required TBR can be observed as a function of the rate of codeposition and the rate of tritium release from periodic conditioning of the plasma-facing walls. In this figure, the behavior of the required TBR can be explained through reactor availability arguments. For instance, the required TBR decreases for low $F_{codep}^{retention}$ and high $F_{codep}^{removal}$ because of increased reactor availability as it takes longer for the tritium limit to be reached. Conversely, a reduction in reactor availability occurs when the tritium codeposition rate is high, which leads to more frequent conditioning periods.

As can be seen in the figure, a wide range of required TBRs (i.e., from ~1.15 to 1.5) is possible with

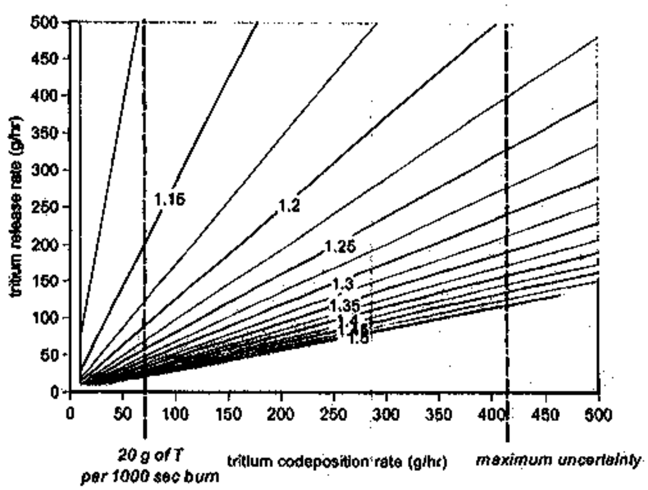

Fig. 33. Variation of required TBR as a function of tritium codeposition and tritium release rates.

the uncertainty that currently is associated with predictions of the codeposition process. Research focusing on the codeposition process and, in particular, the tritium retention associated with this process has predicted a value of ~20 g T/1000 s burn for ITER. However, the uncertainty (mainly that due to chemical sputtering yields) is very high, leading to estimates as high as 120 g T/1000 s burn for ITER (Ref. 13). The 20 g T/1000 s burn estimate as well as the associated very high uncertainties are included in the figure for comparison. The performance requirement of a breeder blanket design in a carbon-lined tokamak is then expected to be influenced considerably by the codeposition process. Note that the maximum allowable tritium codeposition inventory used in the analysis does not have an effect on the required TBR because both the tritium codeposition rate and the tritium release rate are equally affected by a change in the maximum tritium limit. Only if I_{wall}^{limit} is increased to very high levels, e.g., 10 kg, will there be a small impact on the required TBR through a change in the short-term inventory in the plasma-exhaust-processing line.

X. A STUDY ON THE VARIATION OF THE REQUIRED TBR FOR CHANGES IN THE MTBF AND MTTR OF MAJOR REACTOR COMPONENTS

The reliability and availability of the major components inside the reactor will have a large impact on the required TBR associated with a particular fuel cycle design. Since the components that make up the reactor are critical in the successful operation of the reactor, the MTBF and MTTR values associated with the major components will have a significant impact. As a result, buffering of failures in these components is not possible as opposed to failures from noncritical processing components, as discussed previously. Reactor on-line availability, namely α_{op}, is a factor of the number of major components as well as the MTBF and MTTR associated with each of these components. In reality, the different components will each have a different value for MTBF and MTTR. However, for our purposes, we can assume that each of these components will have an equal outage risk. For this simplified case, the required TBR can then be related to the average MTBF and MTTR for the reactor components as well as to the total number of major reactor components.

Figure 34 shows a contour plot of the Λ_r variation as a function of the MTTR (in months) and the MTBF [in full-power years (FPY)]. Reference-case parameters are used to obtain this figure. Six major components in the reactor are assumed. The required TBR is seen to increase with higher MTTR and lower MTBF values. In particular, very low values for MTBF, i.e., 3 FPY or lower, will cause a very high increase in Λ_r. Increasing the MTBF to values higher than ~6 yr does not significantly alter the required TBR in the design.

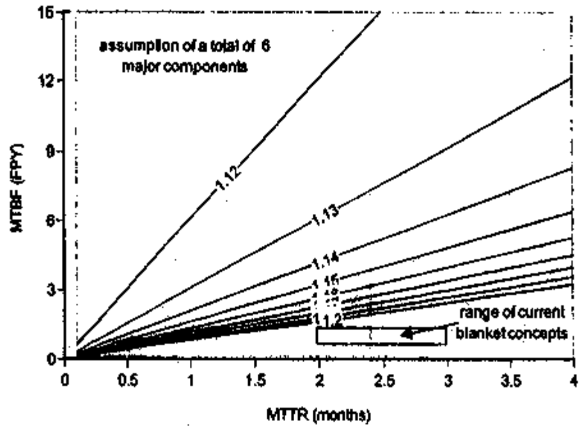

Fig. 34. Variation of required TBR as a function of MTTR and MTBF for a single major reactor component (assuming equal outage risk).

For comparison, the range of MTBF and MTTR values of current blanket concepts is also shown in the figure, which corresponds to a blanket availability of ~87%. It is apparent that the current state of reliability in tokamak components leads to very high values for the required TBR. In fact, studies have shown that different solid breeder blanket concepts have very similar values for blanket availability—between 85 and 88% (Ref. 25). Therefore, increases in reliability for solid breeder blanket designs may be difficult, so liquid breeder blanket designs may be better candidates from this perspective.

XI. RANGE OF ACHIEVABLE TBR

The primary purpose of tritium self-sufficiency analyses is to investigate the interrelationships between the required TBR and the achievable TBR for different scenarios. One then needs to compare these two TBR parameters to see if tritium self-sufficiency is possible. In addition, one must also consider the confidence level with respect to achieving tritium self-sufficiency and economic breakeven conditions. This can be accomplished by considering the large number of uncertainties involved in the calculations. This is especially true for calculating the achievable TBR for specific breeding blanket design concepts. Such factors as the blanket geometry, the blanket multiplier/breeder composition, and the selected neutronic calculation method will have a large influence on the operational TBR; in fact, a detailed study on the effects of such uncertainties has been conducted.[1]

The variation of the achievable TBR and the energy multiplication factor M for a large number of different tritium breeding lithium-containing materials (both liquid and solid breeders) has been examined recently.[26] Liquid breeding materials (e.g., lithium and $Li_{17}Pb_{83}$) offer vastly improved TBRs (>1.6) as compared to solid breeding materials (e.g., Li_2O, Li_2ZrO_3, and $LiAlO_2$) with TBRs ~ 0.9 to 1.4. FLiBE is seen to be an exception for liquid breeders because the TBR that can be reasonably achieved is only ~1.2. This low TBR for the FLiBE material will be an important issue in determining the more attractive materials from the standpoint of tritium self-sufficiency. Such achievable TBRs have been calculated for an idealized one-dimensional cylindrical geometry with a 100% dense natural breeder blanket at room temperature. For a more realistic evaluation, a range of achievable TBRs can be estimated for various candidate breeding blanket design concepts. The ranges of achievable TBRs for these design concepts are lower than for previous concepts. These uncertainty margins show the effect of the design on tritium breeding.

For lithium zirconate, the ITER reference breeding material, a value between 1.04 and 1.07 is the current range, with an uncertainty of ~15%. For DEMO, a first-generation commercial fusion power plant concept, the particular blanket design is still under consideration with emphasis on enhanced safety, environmental, and economic features. As a result, tritium breeding requirements will be a major consideration in DEMO. Figure 35 is identical to Fig. 6, except that it only shows the curve associated with the present maximum achievable TBR of 1.07. Within the constraint of a reference doubling time of 5 yr or less, the required tritium reserve inventory is found to be a maximum of ~12 kg. This tritium reserve inventory is related to both the fuel fractional burnup and the plasma exhaust line time for reserve fueling, and a design window for both parameters with the constraint of 12 kg of tritium inventory in reserve is shown in Fig. 36.

The design window is observed to be small with a corresponding reduction in the required time for reserve fueling as the fuel fractional burnup is reduced. ITER is

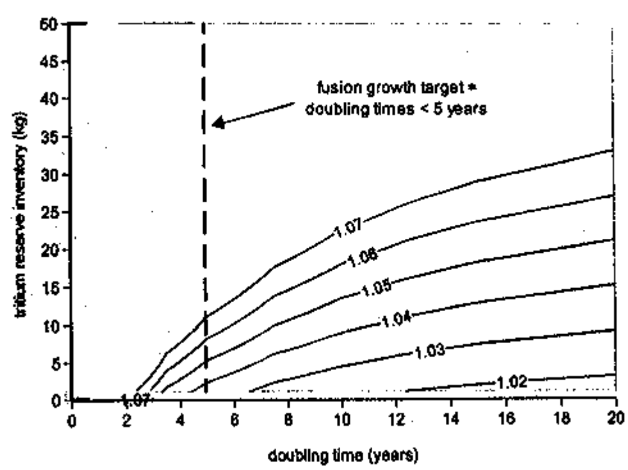

Fig. 35. Design window with current estimates of the achievable TBR.

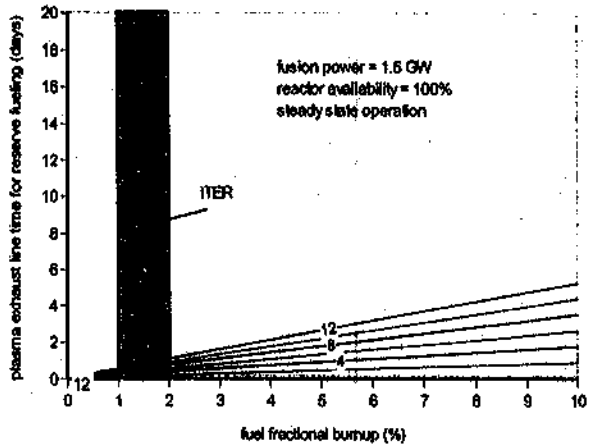

Fig. 36. Design window for a maximum tritium reserve inventory of 12 kg (corresponding to an achievable TBR of 1.07 and doubling time periods <5 yr).

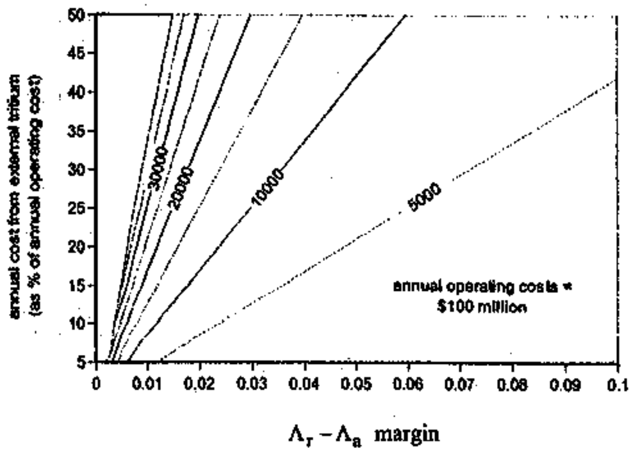

Fig. 37. Variation of the required cost of external tritium in dollars per gram of tritium (annual operating costs = $100 million—solid breeder design).

currently set to operate with f_b in the range of 1 to 2%, and this is shown in the figure for comparison. A value of the MTTR for noncritical tritium-reprocessing components in the plasma-exhaust-processing line, i.e., the fuel cleanup unit and the ISS, of <1 day may not be possible with current technology. From these two figures, it can be deduced that the current state of the art in breeding blankets does not offer enough breeding to fuel commercial fusion reactors and their required associated growth rate for a wide range of the dominant parameters as determined using this analysis.

XII. THE EFFECT OF TRITIUM COSTS FROM EXTERNAL SOURCES

A final study was performed on the evaluation of tritium costs associated with external sources. Figures 37 and 38 illustrate the variation of the required annual cost from external tritium for various breeding margins. As observed in Fig. 27, the external fueling rate has a linear correlation with the required TBR. If a breeding margin is given, i.e., where the required TBR is slightly higher than the achievable TBR, then it may be possible to close this margin by continuously adding tritium fuel from external sources to the reactor during its lifetime. If the annual operating cost with this external tritium fuel is not to exceed a certain cost (in this example, we formulate this cost as a percentage of the annual operating cost of the reactor), then the required cost of external tritium that can satisfy the aforementioned requirements can be calculated. Figure 37 thus shows this variation of the required cost of external tritium compared with the annual cost of external tritium and the breeding margin when the annual reactor operating cost is $100 million, whereas the plot of Fig. 38 shows the variation for an annual re-

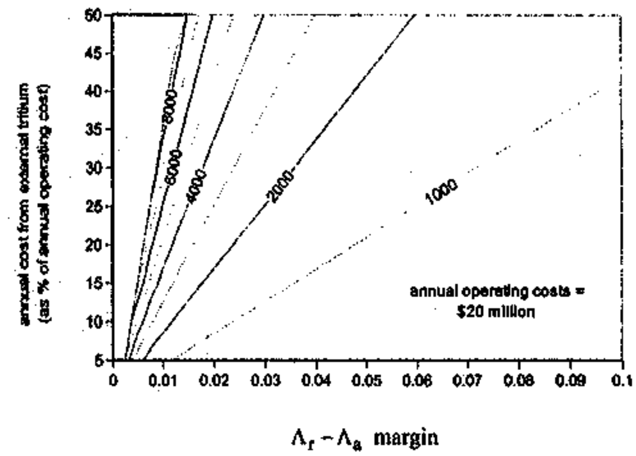

Fig. 38. Variation of the required cost of external tritium in dollars per gram of tritium (annual operating costs = $20 million—liquid breeder design).

actor operating cost of $20 million. These values have been predicted to correspond to a typical solid breeder and a typical liquid breeder, respectively.[23]

It is apparent that for a solid breeder design concept (corresponding to Fig. 37), the cost of external tritium must be below approximately $30 000/g T to be cost-effective. If external fueling is to be used, then the prices of tritium from external sources must be reduced to these levels. Typical values of the price of tritium at present range from $30 000 to $100 000/g T (Ref. 23). On the other hand, for a liquid breeder design (corresponding to Fig. 38), the required cost of external tritium must be less than $8000/g T. External tritium must then be further reduced in price to be cost-effective for liquid breeder designs.

XIII. DISCUSSION OF TRITIUM SELF-SUFFICIENCY ANALYSES

Accurately predicting the tritium breeding inventories throughout the fuel cycle as well as the tritium losses during a specified period of time when tritium breeding is taking place serves to evaluate the research and development (R&D) areas that gain most from technical improvements. During the startup of commercial fusion activity, the tritium doubling time is expected to be a major factor in the continuing success of fusion energy production due to the scarcity of tritium. The objective from an economic viewpoint is then to shorten the tritium doubling time as much as possible or otherwise to achieve a lower tritium breeding requirement for given fusion energy production scenarios. Realizing such objectives must be balanced with the limited resources available in R&D as well as the finite time period before a tritium breeding fusion reactor is constructed.

The importance of shortening the tritium doubling time, or any other tritium inventory objective, as well as achieving lower tritium breeding requirements was discussed. Considerable attention was paid to evaluating the effects from technical R&D areas in the tritium plant and the fusion reactor. Parametric studies using this analytical approach, in addition to detailed computational results for individual subsystems and components from other numerical models, were performed. As a result, we selected some technical R&D areas where a range of improvements, which are feasible in the future, had the greatest effect on tritium breeding economic considerations.

We found that variation of the TBR does not change much with changes in the tritium retained in any of the different types of tritium inventory categories mentioned in this paper. However, since the long-term tritium inventory estimated to be trapped inside bulk material in the radiation environment is found to be much higher than the short-term inventories due to processing inside dedicated tritium reprocessing components (mostly due to batch operations), evaluation of the long-term inventory plays a larger role in the determination of the required TBR and startup tritium inventory. Since the accountancy of this trapped tritium is highly uncertain due to effects as varied as irradiation, helium bubbles, impurity effects, sputtering, plasma disruptions, conditioning, and blistering, which affect the generation of traps in the first wall and blanket, it is recommended that R&D be focused in this area.

More research is needed on the effects from downtime, in particular glow-discharge conditioning, bakeout, and PFC replacement schedules. The side effects due to tritium codeposition will be especially important. Though it is the goal of a commercial reactor to operate at steady state, this may not be possible with current designs that incorporate tritium retention inside the first wall. The loss of tritium during t_l and its effect on Λ_r provide a measure of the economic loss due to delays in the construction of new reactors and the need to start actual construction of new reactors during operation of first-generation reactors.

Future improvements in plasma performance will drastically affect the R&D emphasis for the fuel cycle. Increasing the fuel fractional burnup will reduce the load into the plasma exhaust line but will keep the load into the breeder line the same for a given fusion power operation. As a result, R&D may need to be siphoned off from the plasma exhaust line into the breeder line. Moreover, due to the coolant line's relatively low tritium load as well as the long tritium appearance in this path, the coolant line is not expected to have much of an impact on tritium self-sufficiency issues if the tritium is reprocessed in the tritium plant.

An investigation of the possible parameter space of cryopumps[6,7,9] shows that design changes may lead to a $\pm$300-g change in its tritium inventory. Conversely, the pellet injection subsystem will only change approximately $\pm$100 g T when its parameters have been changed during appropriate simulations. Both subsystems exhibited fluctuations in their inventory during the quasi-stable regime of between $\pm$50 and $\pm$100 g T. By examining the variation of Λ_r due to changes in the short-term tritium inventory in the plasma-exhaust-processing line, we found that such design changes will have negligible effects on Λ_r. Therefore, from a tritium self-sufficiency perspective, such design changes in these individual subsystems will hardly change the required tritium breeding in the blanket.

An investigation of the impact on the tritium self-sufficiency problem from design trade-offs can also be performed. For example, if no coolant-reprocessing subsystem is included in the fuel cycle configuration in order to cut costs, then the permeation of tritium into the coolant must be minimized. This can be accomplished by somehow ridding the PFCs of the trapped and diffused tritium before permeation reaches a critical rate. Such an action requires a shutdown-and-maintenance period that will in turn increase TBR for a given doubling time. Therefore, if the shutdown frequency of the reactor due to tritium bakeout in the PFCs is known,[27] then the increase in TBR can be estimated from Fig. 22 relating the variation of Λ_r to changes in α_{op}. The economic effect of such a design change can then be weighed against the fuel cycle configuration, which includes coolant-reprocessing components.

The loss rate of tritium to waste material was found to have an almost equivalent effect in the calculation of the required TBR as the inventories held up in the fuel cycle if enough material (e.g., PFC armor) needs to be removed during the lifetime of the reactor. However, the greater uncertainties in estimating such tritiated waste material make this more of a determining factor than other types of inventories. This is slightly counterbalanced by the slightly higher tolerance of uncertainties in the estimation of the total tritium inventory lost as waste when compared to corresponding uncertainties in other types of tritium inventories. Therefore, research on the prevention of such losses should be examined more closely. Waste material is expected to be high in first-generation fusion reactors.

A proposal for a more efficient use of multiple fusion reactors from a tritium breeding perspective may be to utilize one such reactor as an external tritium source to feed the rest of the self-breeding DT fusion reactors. A significant reduction in the required TBR may be achieved this way, as shown in the analysis section. As an example, we will assume that a DT reactor can produce ~240 g of excess tritium per day. Now, if there exist ten other similarly operated DT fusion reactors in the grid, this single reactor would be able to reduce the required TBR in the rest of the DT-fueled reactors by ~0.10.

XIV. RECOMMENDATIONS FOR R&D

All fusion reactor studies that have been conducted have provided a list of top-level objectives that must be fulfilled for the successful operation of a particular reactor design. A closed fuel cycle has always been included within this list. This is due to the scarcity of tritium and the need to show that a reactor can be self-sufficient. However, from previous results, for the case when there are several fusion reactors in operation, it may be more advantageous to have some reactors that are slightly more than self-sufficient while the others are less than self-sufficient. The excess tritium from the self-sufficient reactors can then be used to continuously provide the other reactors with the needed tritium so that they will not run out of fuel. The required TBRs for the reactors that are selected to operate without self-sufficiency can then be much lower and more than balance the increase in the required TBR of the slightly more than self-sufficient reactors.

The blanket tritium release and inventory have often been cited as important from both safety and economic standpoints. However, as the results from the current parametric study on TBR requirements show, the blanket tritium inventory dynamics actually do not have much of an effect on the estimation of the required TBR for realistic blanket inventory predictions. Variations in the kilogram range will only affect the required TBR a few percent. Furthermore, a variation of the tritium inventory and release inside the blanket is not much more significant than corresponding changes in other parts of the fuel cycle. Other variables, such as the burnup of fuel and availability considerations, are more significant.

Previous magnetic fusion energy (MFE) designs over the past three decades estimated low tritium fractional burnups (of <5%), but the ARIES-I and ARIES-RS MFE reactor designs attempted to obtain higher values that are much greater than 5% (reflecting different designs as well as different assumptions). Specifically, the ARIES-I tokamak reactor study performed in 1991 resulted in a design value of the fuel fractional burnup of 19.3% (Ref. 28). Later in 1997, the evaluation of another reactor design based on an advanced reversed shear configuration of the previous ARIES-II design, named ARIES-RS, improves on the tritium burnup performance up to a design value of ~30% (Ref. 29).

Similarly, conceptual inertial fusion energy (IFE) reactors are also designed to achieve high fuel fractional burnups and are actually expected to achieve higher burnup than MFE designs. For instance, the HYLIFE-II inertial confinement reactor design of 1994 operates at an f_b of ~50% (~900 g T/day of fueling required for a steady-state fusion power of ~2.8 GW, equivalent to ~430 g T/day lost to fusion reactions).[30] One can thus infer that fusion reactor designers believe that $f_b > 20\%$ may be necessary in a commercial environment. This compares to the current design value of the ITER experimental device of ~1 to 2%. A preliminary study of tritium breeding requirements for IFE designs has been performed using Abdou et al.'s[31] model. This work furthers such studies of alternate and advanced designs.

Increasing f_b from 1 to 2% to the 20% level will require advanced plasma confinement regimes in addition to divertor operation with high particle recycling, which may be hard to achieve in a real setting. For instance, increasing the effective confinement of D and T to achieve high fuel burnup may also lead to a related high confinement of He particles, ultimately leading to unacceptable levels of He ash in the plasma. In summary, the confidence level in reaching high f_b will depend on the plasma physics progress in the near future. However, one can conclude that R&D for reactor systems that can access and maintain higher f_b is a key issue.

The great complexity of current MFE and IFE reactor designs, in particular as they compare to the fission reactor core, cannot be understated when commercial development of fusion energy is discussed. This issue is related to the low power density of current design concepts for fusion and the need to develop higher power density schemes. For instance, IFE offers the advantage over MFE of possibly less complexity, higher power densities, and correspondingly higher reliability and availability of the reactor core. It has thus been argued that this advantage of higher capacity factors inherent in the IFE system design over MFE (even if all problematic physics issues have been solved) make IFE reactor systems more desirable from an economic perspective.[32] The results from the tritium breeding requirement study in this work further lend support to this perspective, primarily because of the higher fuel fractional burnups possible with IFE (on the order of 30 to 50%) and the higher availabilities inherent in a simpler design. Limitations of MFE availabilities because of engineering considerations is another key issue here. However, one perceived IFE advantage, the employment of liquid walls to shield the blanket and so reduce operational interruptions due to radiation damage, is currently also being used for more advanced MFE designs.[33] Thus, availability reductions due to radiation damage may not be an issue for both IFE and MFE concepts. A greater focus on R&D effort in liquid-wall design is therefore encouraged.

A volumetric neutron source for testing nuclear components under fusion-relevant conditions is deemed an important step toward resolving critical issues of fusion nuclear technology.[34] Such a device would be much smaller than an experimental tokamak reactor, such as ITER, and can provide meaningful results, especially in the testing of components in a relevant fusion environment and under relevant values of neutron fluences. Since the behavior of tritium retention under irradiation is expected to affect tritium breeding requirements as much as other parameters when the fuel fractional burnup and availabilities are high, R&D focus in this area will contribute to the reduction of uncertainties in the estimation of the required TBR. Because engineering constraints, as in reliabilities of the reactor vessel components, may pose serious questions regarding the validity of MFE design concepts for commercial use, experiments (as in a volumetric neutron source) related to the effective availability of a reactor should be studied more extensively. In addition, quantitative studies of tokamak reactor availability are to be promoted.

A significant trend from the discussion in Sec. XIII is that the effects of various fuel-cycle-relevant parameters on the required TBR will reach an asymptotic level whereby a further increase or decrease in the parameter of interest will not lead to much of a change in the required TBR. This is similar to an exponential behavior. It is thus meaningful to explore the extent of this level of insensitivity for various parameters that lead to large changes in the required TBR. Table XI thus lists the parameter ranges for fuel fractional burnup, fusion power, and reactor availability, which do not yield much sensitivity in the corresponding variation of the required TBR; i.e., they only lead to an ~5% change in the required TBR. In addition, an approximate set of realistic parameter ranges, taking into account current technological limitations, possible future advances in plasma science and reactor design technology, as well as the many types of possible fusion reactor designs (i.e., not limited to MFE), is also shown in the table.

It is apparent that for realistic variations in the value of the fuel fractional burnup, the required TBR will change significantly. Similarly, all values of fusion power will lead to possible significant variations in the required TBR. On the other hand, the realistic parameter range and the insensitive parameter range for reactor availability almost match, which does not lead to much change in the required TBR for realistic variations in reactor availability. We can thus conclude that any technological advances or design changes that lead to variations in f_b or P_f will drastically affect the reactor's Λ_r, as opposed to changes in α_{op}. As discussed prviously, tritium inventory changes result in a linear dependence of the required TBR. The particular range of inventory changes, whether low or high, will then not have an effect on the variation of the required TBR. Only the magnitude of the inventory will be important.

In this section we examined the R&D areas that should be more extensively pursued from the perspective of reducing the tritium-breeding requirement of commercial fusion plant concepts. Predictions or top-level requirements for such first-generation commercial power plants have been discussed in many conceptual reactor studies of fusion. Such studies help provide estimates of plant operation that are thought to be necessary for commercial use. A discussion of R&D needs and minimum levels of performance needed to provided adequate tritium-breeding requirements will aid in more efficiently advancing the development of an optimized design for a commercial fusion power reactor. This work has tried to separate the evaluation of future DT fusion reactors from physics issues that currently and severely limit the operation of fusion reactors. Walker and Haines[35] have assessed the prospects of DT tokamak fusion in a commercial setting and have stated that "such a study should address the macroscopic, engineering and economic issues alongside the physics." This work was conducted with such a philosophy in mind.

TABLE XI

Insensitive Parameter Ranges for Required TBR Calculations

Parameter	Realistic Parameter Range	Insensitive Parameter Range
Fuel fractional burnup, f_b	2 to 50%	70 to 100%
Fusion power, P_f	0.25 to 5 GW	All values of fusion power can affect the required TBR significantly.
On-line reactor availability, α_{op}	50 to 100%	65 to 100%

XV. CONCLUSION

A new approach to solving tritium fuel self-sufficiency problems has been developed to realize more efficient and accurate solutions. An analytical scheme was chosen that makes use of inventories calculated from more detailed and rigorous dynamic models. Using the approach developed in this work, a direct relationship between inventories and general fuel cycle parameters is provided. Such a scheme can more fully account for reliability and availability considerations. An integrated tritium balance was discussed to determine analytical solutions for tritium self-sufficiency-relevant variables such as the required TBR and startup inventories for specific reactor designs.

The effect from changing various fuel cycle parameters was investigated. Dominant parameters again proved to be the time in fulfilling the inventory objective (e.g., doubling time) and the reserve inventory. The reserve inventory is related to the fuel fractional burnup and the time for reserve fueling if the plasma-exhaust-processing line is to be buffered against any operational interruptions. This work also examines the possibility in buffering other distinct processing lines in the fuel cycle with reduced tritium throughput. These other reserve inventory design options provided a much lower required TBR and, in particular, a much reduced required tritium startup inventory. However, a future fusion reactor is expected to operate in steady state for commercial reasons, so more stringent buffering of the plasma-exhaust-processing line may be required.

Availability effects were also studied in relation to the reserve inventory requirements. A small impact can be seen from changes in reactor availability and the pulse cycle selected. The variation of the required TBR and the required tritium startup inventories as a function of fusion power was also examined for a number of scenarios. For reference parameters assumed in this work, the required TBR for an ITER-type commercial fusion reactor is 1.11 ± 0.02, and the required tritium startup inventory is 25 kg. The impact from tritium inventories of all types was found to be small, though it may be significant when small margins between the required TBR and the achievable TBR exist. In particular, tritiated waste may have a more significant impact. A number of more focused studies were conducted with respect to tritium codeposition and the MTBF-MTTR for major reactor components.

Using the aforementioned methodology, the uncertainties in the required TBR and the startup inventory requirement for a given reactor design were easily calculated. Uncertainties in tritium breeding requirements due to predicted parameter variations were evaluated, and we found that an uncertainty of 0.02 in the required TBR existed for reference uncertainties. Parametric studies of the impact from uncertainties in tritium inventories found in the fuel cycle were performed. Finally, an investigation on the cost-effectiveness of a design incorporating external tritium fueling during the lifetime of a DT reactor was conducted.

NOMENCLATURE

I_i^j = inventory of species j, either in elemental (e.g., T) or molecular form (e.g., T_2, DT) in fuel cycle compartment i

τ_i^j = residence time of species j, either in elemental (e.g., T) or molecular form (e.g., T_2, DT) in fuel cycle compartment i

λ = tritium decay rate (s^{-1})

a_i^j = local nonradioactive processing loss parameter (chemical and/or nuclear) due to the rate of processing of species j, either in elemental (e.g., T) or molecular form (e.g., T_2, DT) in fuel cycle compartment i

b_i^j = local nonradioactive processing loss parameter (chemical and/or nuclear) due to the local inventory of species j, either in elemental (e.g., T) or molecular form (e.g., T_2, DT) in fuel cycle compartment i

t_f = period to satisfy the tritium inventory requirement objective when the starting time is set as $t = 0$

t_d = doubling time period (i.e., when $I_s = I_{i,0}^{opt} + I_{min}$)

t_s^{infl} = time when the storage subsystem reaches a minimum value

t_{sim} = period of simulation for more detailed simulation models

t_l = lag time between reaching the required doubling-time inventory and its transfer and use in the next-generation reactor

I_{dbl} = required doubling-time inventory, including lag time

I'_{dbl} = required doubling-time inventory with no lag time

I_{min}^s = minimum inventory in the storage subsystem

I_r = reserve inventory to buffer operational interruptions in the fuel cycle

$\overline{F_{bred}}$ = average tritium breeding rate during the period t to t_f

$\overline{F_{fus}}$ = average fusion reaction rate during the period t to t_f

$\overline{F_{ext}^{in}}$ = average feed rate from external fuel sources during the period t to t_f

$\overline{F_{ext}^{out}}$ = average rate of tritium delivery to external needs during the period t to t_f

$\overline{F_{env}}$ = rate of tritium loss to the environment during the period t to t_f

$\overline{F_{net}}$ = average net production of tritium due to all sources and sinks in the fuel cycle during the period t to t_f

$I_{i,0}$ = startup tritium inventory within the reactor power plant

$I_{i,0}^{opt}$ = optimized (i.e., minimum) startup tritium inventory within the reactor power plant for a given reserve inventory design option

$\overline{F^{PFC}}$ = average rate of tritium inflow from the PFCs into the coolant

t_r^{pl} = time for reserve fueling during plasma-fueling/exhaust line operational interruptions (days)

t_r^{il} = time for reserve fueling during impurity processing operational interruptions (days)

t_r^{bl} = time for reserve fueling during breeder line operational interruptions (days)

t_r^{cl} = time for reserve fueling during coolant line operational interruptions (days)

τ_{bl} = average breeder line tritium holdup time (h)

P_f = fusion power (GW)

f_b = fuel fractional burnup (%)

f_{imp} = average tritiated fractional impurity content (%)

t_{burn} = burn time (s)

t_{dwell} = dwell time (s)

t_{on} = reactor on-line (h)

t_{off} = reactor off-line (h)

α_p = ratio of burn time to burn-dwell cycle time

α_{op} = ratio of time that the reactor is on-line to the total time

α_t = total reactor availability

Q_f = energy from a fusion reaction

$\sum_i I$ = tritium inventory summed over all tritium reprocessing subsystems i

$\sum_{pl} I$ = tritium inventory summed over all tritium reprocessing subsystems in the plasma-fueling/exhaust line

$\sum_{cl} I$ = tritium inventory summed over all tritium reprocessing subsystems in the coolant line

$\sum_{bl} I$ = tritium inventory summed over all tritium reprocessing subsystems in the breeder line

$\sum_{pl}^{short\ term} I$ = tritium inventory summed over all tritium reprocessing subsystems in the plasma-fueling/exhaust line during the short-term period of reactor operation

$\sum_{pl(c)}^{short\ term} I$ = tritium inventory summed over all critical tritium reprocessing subsystems in the plasma-fueling/exhaust line during the short-term period of reactor operation

$\sum_{pl(nc)}^{short\ term} I$ = tritium inventory summed over all noncritical tritium reprocessing subsystems in the plasma-fueling/exhaust line during the short-term period of reactor operation

$\sum_{il}^{short\ term} I$ = tritium inventory summed over all tritium reprocessing subsystems in the impurity processing line during the short-term period of reactor operation

$\sum_{pl+il}^{short\ term} I$ = tritium inventory summed over all tritium reprocessing subsystems in the plasma-fueling/exhaust line + impurity processing line during the short-term period of reactor operation

$\sum_{bl}^{short\ term} I$ = tritium inventory summed over all tritium reprocessing subsystems in the breeder line during the short-term period of reactor operation

$\sum_{cl}^{short\ term} I$ = tritium inventory summed over all tritium reprocessing subsystems in the coolant line during the short-term period of reactor operation

$\sum_{pl}^{long\ term} I$ = tritium inventory summed over all tritium reprocessing subsystems in the plasma-fueling/exhaust line during the long-term period of reactor operation

$\sum_{il}^{long\ term} I$ = tritium inventory summed over all tritium reprocessing subsystems in the impurity processing line during the long-term period of reactor operation

$\sum_{bl}^{long\ term} I$ = tritium inventory summed over all tritium reprocessing subsystems in the breeder line during the long-term period of reactor operation

$\sum_{cl}^{long\ term} I$ = tritium inventory summed over all tritium reprocessing subsystems in the coolant line during the long-term period of reactor operation

$\sum_i I_{min}$ = quasi-steady-state minimum tritium inventory summed over all tritium reprocessing subsystems i

$\sum_i I_{max}$ = quasi-steady-state maximum tritium inventory summed over all tritium reprocessing subsystems i

$\sum_i I_{avg}$ = quasi-steady-state average tritium inventory summed over all tritium reprocessing subsystems i

$\sum_{pl} I_{allow}$ = allowable tritium inventory summed over the reprocessing units in the plasma-fueling/exhaust line

$\delta \sum_i I$ = uncertainty in the tritium inventory summed over components i, including average fluctuations during normal operation

Λ = TBR

Λ_r = required TBR

Λ_a = achievable TBR

φ = tritium self-sufficiency timescale factor

ζ = tritium self-sufficiency reactor power factor

Ψ = tritium self-sufficiency time objective factor

Ω = tritium self-sufficiency effective inventory factor

Φ = square root term in the solution of the tritium self-sufficiency quadratic equation

$MTBF_i$ = mean time between failures for component i (yr)

$MTTR_i$ = mean time to replacement for component i (months)

I_{wall}^{limit} = allowable tritium inventory due to codeposition in the vacuum vessel

$F_{codep}^{retention}$ = rate of tritium codeposition

$F_{codep}^{removal}$ = rate of tritium removal from codeposited layers

$t_{codep}^{retention}$ = total time of tritium retention due to tritium codeposition for a continuous fueling period

$t_{codep}^{removal}$ = total time of tritium removal from codeposited layers for a continuous removal period

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