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AN ASSESSMENT OF TRITIUM BREEDING REQUIREMENTS FOR FUSION POWER REACTORS

by

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AN ASSESSMENT OF TRITIUM BREEDING REQUIREMENTS FOR FUSION POWER REACTORS

J. Jung

ABSTRACT

This report presents an assessment of tritum-breeding requirements for fusion power reactors. The analysis is based on an evaluation of time-dependent tritium inventories in the reactor system. The method presented can be applied to any fusion systems in operation on a steady-state mode as well as on a pulsed mode. As an example, the UWMAK-I design was analyzed and it has been found that the startup inventory requirement calculated by the present method significantly differs from those previously calculated. The effect of reactor-parameter changes on the required tritium breeding ratio is also analyzed for a variety of reactor operation scenarios.

A FORTRAN-IV computer program, JET-I code, has been developed to implement the present method. JET-I is now in operation on the Argonne IBM-195/3033 computer system.

I. INTRODUCTION

A self-sustaining deuterium-tritium (DT) fusion reactor must breed tritium. In all fusion reactor concepts this is accomplished in a lithium-containing blanket that circumscribes the plasma. The tritium breeding ratio (TBR) as a measure of breeding capability of fusion blankets is defined as

$$TBR = N^+/N^- , \tag{I-1}$$

where N^+ is the rate of tritium production in the blanket and N^- is the rate of burning tritium in the plasma. Therefore, for a given plasma power system, the TBR is uniquely determined solely by the neutronic performance on tritium generation in the blanket.

On the other hand, the condition on the self-sustention of tritium fuel determines the tritium breeding requirement (denoted by T_o) as

$$T_o = 1 + A . \tag{I-2}$$

The extra breeding margin, A, must be positive in order to cover: (1) losses and radioactive decay of tritium during the period between production and use; and (2) supplying inventory for startup of other fusion reactors. The determination of A involves several parameters for a given fusion power system. They include: (1) tritium inventories in various system components (e.g., blanket, vacuum system, processing system and fueling/storage system); (2) fractional tritium burnup rate; (3) tritium doubling-time requirement; (4) amount of fuel reserve to guard against a temporary malfunction of the tritium recovering system; and (5) tritium loss into the environment. Thus the determination of the tritium breeding requirement, T_o, involves a substantially broader aspect of the system characteristics ranging from the plasma performance (to determine the fuel burnup rate) to the fusion power economy (to determine the doubling-time requirement). The required T_o is also strongly affected by the neutronic, chemical, and physical characteristics of the blanket performance that influence the tritium inventory in the blanket.

The viability of fusion blankets in terms of the self-sufficient fuel reproduction can therefore be decided based on a criterion,

$$\mathrm{TBR} \geq T_o . \qquad \text{(I-3)}$$

According to the heuristic arguments given in Refs. 1 and 2, the TBR that must be achieved for a conceptual blanket design exceeds the T_o by an allowance, $\delta(\mathrm{TBR})$ because of the uncertainties associated with the evaluation of TBR.

At present there are large uncertainties concerning the magnitude of tritium inventory attainable in blanket designs, particularly in solid-breeder blanket designs as addressed in Refs. 3-5. These uncertainties stem from materials characteristics not precisely known at present such as trituim diffusion and kinetic mechanisms. Of particular concern with regard to the uncertainties are the possible property changes of solid breeders caused by nuclear radiation during reactor operation. As a result, depending on the ultimate inventory realized in the blanket, the prediction of possible T_o values may substantially be altered, resulting in an uncertainty, $\delta(T_o)$, in the assessment of T_o. In consequence, the TBR that is achieved in conceptual blanket designs must satisfy the following equation:

$$\mathrm{TBR} + \delta(\mathrm{TBR}) \geq T_o + \delta(T_o) . \qquad \text{(I-4)}$$

Evaluation of $\delta(\mathrm{TBR})$ with regard to cross-section uncertainties, design uncertainties, etc., is now under way in the Blanket Comparison and Selection Study[5] which is being lead by Argonne National Laboratory. Little work[6-12] has been done so far on the evaluation of T_o and the associated uncertainty, $\delta(T_o)$.

The primary objective of the present work is to provide an analytical derivation of T_o as a function of several reactor parameters such as tritium burnup rate, doubling time and operating mode, under the assumption of:

$$\mathrm{TBR} = T_o . \qquad \text{(I-5)}$$

The tritium breeding requirement, T_o (or TBR) thus derived will provide a basis for further analysis on $\delta(T_o)$ with regard to possible variations of the reactor parameters.

In Section II a mathematical formulation of the time-dependent tritium inventories is presented assuming a pulsed-mode reactor operation. The steady-state reactor operation can be regarded as a special case of the above in which the shutdown periods are set to zero. Through this formulation, analytical formulas of T_0 (or TBR) and startup inventory requirements are derived.

Section III investigates the effect of parameter changes on the required TBR for a variety of reactor operation scenarios. The UWMAK-I design case is also examined as an example of an application of the present method. Some discussion is also given in this section, as to the computational assumptions made for the pulse-mode operation regime.

II. MATHEMATICAL FORMULATION

A. Tritium Inventory

Consider a fusion power plant consisting of a reactor complex and a system external to it. The reactor complex is assumed to include a tritium breeding blanket, vacuum-pumping system, tritium processing system, etc., while the external system (labeled as "storage system") is composed of tritium storage and fueling systems. As depicted in Fig. 1, the tritium flow in this power plant can be described, during reactor operation, as

$$\frac{dI_m}{dt} = Q_m - \frac{I_m}{\Lambda_m}, \qquad (m = 1, 2, \ldots M) \tag{II-1}$$

$$\frac{dI_p}{dt} = \sum_{m=1}^{M} \frac{I_m}{\lambda_m} - \frac{I_p}{\Lambda_p}, \tag{II-2}$$

$$\frac{dI_s}{dt} = \frac{I_p}{\lambda_p} - \frac{I_s}{\tau} - \frac{N^+}{f_b}, \tag{II-3}$$

or combining all the equations,

$$\frac{dI_T}{dt} = (N^+ - N^-) - \frac{I_T}{\tau}. \tag{II-4}$$

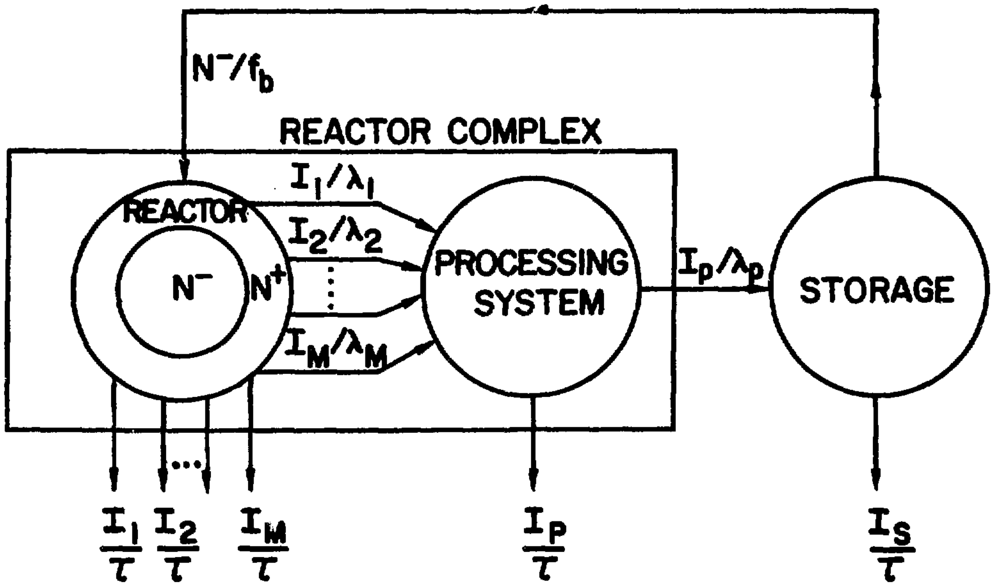

Fig. 1. Tritium flow in a fusion power plant.

The following explains the nomenclature used in the above equations:

$I_m(t)$: Tritium inventory in component other than the processing system in the reactor complex ($m = 1,2, \ldots, M$).

$I_p(t)$: Tritium inventory in the processing system.

$I_s(t)$: Tritium inventory in the storage system.

$I_T(t)$: Total tritium inventory in the plant $\left(= \sum_m I_m + I_p + I_s\right)$.

ε: Tritium loss rate into environment.

τ_o: Decay half life of tritium ($= 12.3$ y/ℓn 2).

λ_m: Mean residence time of tritium in components other than the processing system in the reactor complex ($m = 1,2, \ldots, M$).

N^-: Tritium burnup rate in the plasma.

N^+: Tritium production rate in the blanket.

f_b: Fractional tritium fuel burnup rate.

TBR: Tritium breeding ratio $\left(= N^+/N^-\right)$.

$$\frac{1}{\Lambda_m} = \frac{1}{\lambda_m} + \frac{1}{\tau}, \qquad (m = 1, 2, \ldots, M), \tag{II-5}$$

$$\frac{1}{\Lambda_p} = \frac{1}{\lambda_p} + \frac{1}{\tau}, \tag{II-6}$$

$$\frac{1}{\tau} = \frac{1}{\tau_o} + \varepsilon, \tag{II-7}$$

$$\sum_{m=1}^{M} Q_m = N^{-}\left(TBR + \frac{1 - f_b}{f_b}\right). \tag{II-8}$$

Here the leakage rate ε is assumed to be a constant for all the components for simplicity.

During reactor shutdown periods, the behavior of tritium inventories is governed by

$$\frac{dI_m}{dt} = -\frac{I_m}{\Lambda_m}, \qquad (m = 1, 2, \ldots, M) \tag{II-9}$$

$$\frac{dI_p}{dt} = \sum_{m=1}^{M} \frac{I_m}{\lambda_m} - \frac{I_p}{\Lambda_p}, \tag{II-10}$$

$$\frac{dI_s}{dt} = \frac{I_p}{\lambda_p} - \frac{I_s}{\tau}, \tag{II-11}$$

or again, combining all the equations,

$$\frac{dI_T}{dt} = -\frac{I_T}{\tau}. \tag{II-12}$$

Note that the mean residence times (λ_m's and λ_p) can be different between during operation and shutdown-time periods. The analysis here, however, assumes the same residence times for both periods to facilitate the analysis although the extension of the formulation for such different λ's is quite straightforward. The Appendix provides a brief summary of the mathematical formulation for the case of different λ's.

Define an operating time duration as Δ_0 and the following shutdown duration as Δ_D, then one complete cycle time Δ is defined as

$$\Delta = \Delta_0 + \Delta_D , \tag{II-13}$$

with the duty cycle, α, as

$$\alpha = \Delta_0/\Delta . \tag{II-14}$$

In this context a steady-state reactor operation can be dealt as a special case of $\Delta = \Delta_0$ and $\alpha = 1$. From a mathematical standpoint, one can deal with completely irregular-cycle operating modes, simply by making Δ time-dependent. In the present study, only a regular-cycle mode is considered, again, to facilitate the analysis.

During reactor operation for a time interval of

$$n\Delta \leq t \leq n\Delta + \Delta_0 , \qquad (n = 0, 1, 2, \ldots), \tag{II-15}$$

the solutions of Eqs. (II-1) through (II-4) can be written as

$$I_m(t) = I_m(n\Delta)e^{-(t-n\Delta)/\Lambda_m} + I_{mc}(\infty)\left[1 - e^{-(t-n\Delta)/\Lambda_m}\right] \qquad (m = 1, 2, \ldots, M) \tag{II-16}$$

$$I_p(t) = I_p(n\Delta)e^{-(t-n\Delta)/\Lambda_p} + I_{pc}(\infty)\left[1 - e^{-(t-n\Delta)/\Lambda_p}\right]$$

$$+\sum_{m=1}^{M}\left[\frac{I_m(n\Delta) - I_{mc}(\infty)}{\lambda_m}\right]\left[\frac{1}{\Lambda_p} - \frac{1}{\Lambda_m}\right]^{-1}$$

$$\times\left[e^{-(t-n\Delta)/\Lambda_m} - e^{-(t-n\Delta)/\Lambda_p}\right] , \tag{II-17}$$

$$I_T(t) = I_T(n\Delta)e^{-(t-n\Delta)/\tau} + I_{Tc}(\infty)\left[1 - e^{-(t-n\Delta)/\tau}\right] , \qquad \text{(II-18)}$$

and

$$I_s(t) = I_T(t) - \sum_m I_m(t) - I_p(t) . \qquad \text{(II-19)}$$

In the above,

$$I_{mc}(\infty) = \Lambda_m Q_m , \qquad (m = 1, 2, \ldots, M) , \qquad \text{(II-20)}$$

$$I_{pc}(\infty) = \sum_{m=1}^{M} \left[\frac{I_{mc}(\infty)}{\lambda_m}\right] \cdot \Lambda_p , \qquad \text{(II-21)}$$

and

$$I_{Tc}(\infty) = \tau N^{-}(TBR - 1) . \qquad \text{(II-22)}$$

Accordingly, $I_{sc}(\infty)$ can be defined as

$$I_{sc}(\infty) \equiv I_{Tc}(\infty) - \sum_{m=1}^{M} I_{mc}(\infty) - I_{pc}(\infty)$$

$$= \tau\left\{\sum_{m=1}^{M}\left[\frac{I_{mc}(\infty)}{\lambda_m}\right]\left(\frac{\Lambda_p}{\lambda_p}\right) - \frac{N^{-}}{f_b}\right\} . \qquad \text{(II-23)}$$

The $I(\infty)$'s defined above provide the respective saturation values of $I(t)$'s when the plant is operated on a continuous (steady-state) mode.

During reactor shutdown in a time interval of

$$n\Delta + \Delta_0 \le t \le (n + 1)\Delta , \qquad (n = 0, 1, 2, \ldots) , \qquad \text{(II-24)}$$

the respective inventory solutions can be given by

$$I_m(t) = I_m(n\Delta + \Delta_0)e^{-(t-n\Delta-\Delta_0)/\Lambda_m} , \quad (m = 1, 2, \ldots, M) , \qquad \text{(II-25)}$$

$$I_p(t) = I_p(n\Delta + \Delta_0)e^{-(t-n\Delta-\Delta_0)/\Lambda_p}$$

$$+ \sum_{m=1}^{M} \frac{I_m(n\Delta + \Delta_0)}{\lambda_m}\left(\frac{1}{\Lambda_m} - \frac{1}{\Lambda_p}\right)^{-1}$$

$$\times \left[e^{-(t-n\Delta-\Delta_0)/\Lambda_m} - e^{-(t-n\Delta-\Lambda_0)/\Lambda_p}\right] , \qquad \text{(II-26)}$$

$$I_T(t) = I_T(n\Delta + \Delta_0)e^{-(t-n\Delta-\Delta_0)/\tau} \qquad \text{(II-27)}$$

and

$$I_s(t) = I_T(t) - \sum_m I_m(t) - I_p(t) , \qquad \text{(II-28)}$$

The initial inventories for each pulse cycle can be found by combining the respective solutions during operation and shutdown periods. For example,

$$I_m[(n + 1)\Delta] = I_m(n\Delta + \Delta_0)e^{-\Delta_D/\Lambda_m}$$

$$= I_m(n\Delta)e^{-\Delta/\Lambda_m} + I_{mc}(\infty)\left[1 - e^{-\Delta_0/\Lambda_m}\right]e^{-\Delta_D/\Lambda_m} . \qquad \text{(II-29)}$$

By recursively solving the above equation, one finds that

$$I_m(n\Delta) = I_{mc}(\infty)G(\Lambda_m)(1 - e^{-n\Delta/\Lambda_m}) , \qquad \text{(II-30)}$$

where

$$G(x) = \frac{(1 - e^{-\Delta_0/x}) \cdot e^{-\Delta_D/x}}{1 - e^{-\Delta/x}} . \qquad \text{(II-31)}$$

It is assumed that

$$I_m(0) = 0 , \qquad (m = 1, 2, \ldots, M) . \qquad \text{(II-32)}$$

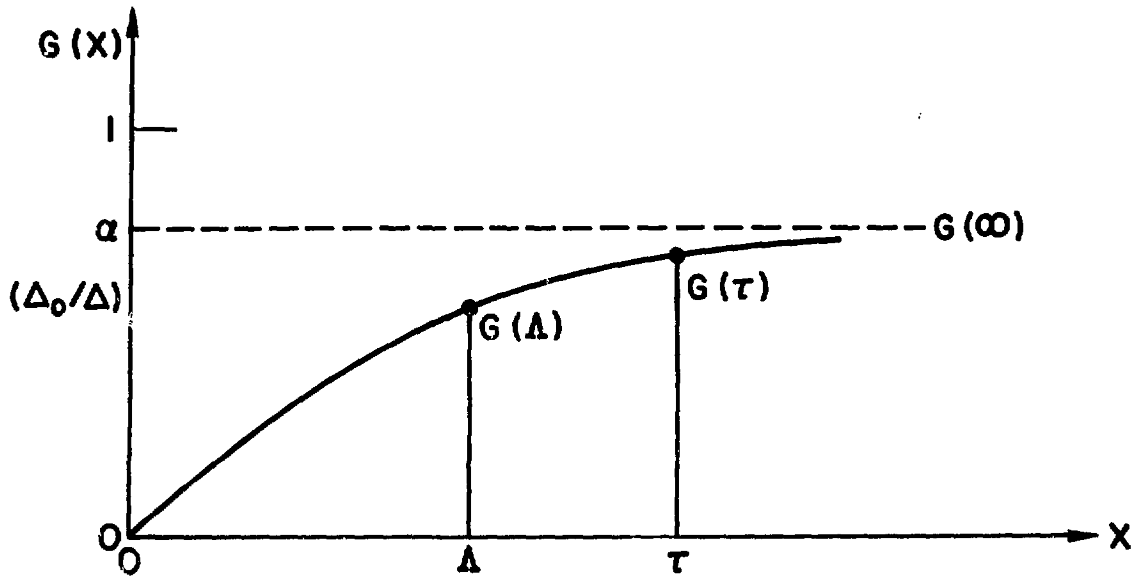

Fig. 2. The G(x) function.

The G(x) function defined above provides a measure of the effect of pulsed-mode operation on tritium inventory behavior. The funcitonal behavior of G(x) is shown in Fig. 2. In the case of steady-state operation ($\alpha = 1$),

$$G(x) = 1 . \qquad \text{(II-33)}$$

Once $I_m(n\Delta)$, $I_p(n\Delta)$, and $I_T(n\Delta)$ are solved in a similar fashion, it is easily shown that, during operation for the time interval of Eq. (II-15),

$$I_m(t) = I_{mc}(\infty)\left[1 - K_n(\Lambda_m)e^{-t/\Lambda_m}\right] , \quad (m = 1, 2, \ldots, M) , \qquad \text{(II-34)}$$

$$I_p(t) = \sum_{m=1}^{M}\left[\frac{I_{mc}(\infty)}{\lambda_m}\right]\Lambda_p\left\{\frac{\Lambda_p}{\Lambda_p - \Lambda_m}\left[1 - K_n(\Lambda_p)e^{-t/\Lambda_p}\right] - \frac{\Lambda_m}{\Lambda_p - \Lambda_m}\left[1 - K_n(\Lambda_m)e^{-t/\Lambda_m}\right]\right\}, \qquad \text{(II-35)}$$

$$I_T(t) = I_T(0)e^{-t/\tau} + I_{Tc}(\infty)\left[1 - K_n(\tau)e^{-t/\tau}\right] , \qquad \text{(II-36)}$$

and

$$I_s(t) = I_T(t) - \sum_m I_m(t) - I_p(t) , \qquad \text{(II-37)}$$

where

$$K_n(x) = G(x) + [1 - G(x)]e^{n\Delta/x} . \qquad \text{(II-38)}$$

The initial inventory of the processing system is also assumed to be zero, i.e.,

$$I_p(0) = 0 . \qquad \text{(II-39)}$$

B. Minimum Storage Inventory and Startup Inventory Requirement

Since the initial startup inventory in the storage system [denoted as $I_s(0)$ or $I_T(0)$] is an unknown to be determined rather than a given condition, one requires an additional condition on the storage inventory. As illustrated in Fig. 1, the storage system keeps supplying N^-/f_b tritium fuel to the reactor complex through a fuel injection system while an amount of I_p/λ_p tritons is fed back to the storage. In general, the outflow, N^-/f_b is substantially larger than the inflow, I_p/λ_p, shortly after reactor startup because $I_p(0) = 0$. In consequence, the storage inventory decreases in such early time periods. The storage inventory, however, must eventually increase after it reaches the minimum in order to yield extra tritium for startup of other reactors.

We define the time at which the storage inventory takes its minimum, as

$$I_s(t_0) = I_{s,min} . \qquad \text{(II-40)}$$

The $I_{s,min}$ inventory is then a minimum requirement for the fuel storage system to guard against a temporary malfunction of the tritium recovery system. Note that the time-dependent behavior of the storage inventory after it has reached the minimum value is dependent on how the extra tritium, $I_s(t) - I_{s,min}$, is handled. One can consider, for instance, a situation where the freshly bred tritium (extra to $I_{s,min}$) is continually transmitted to other reactors for rebreeding, so that the storage inventory in the reactor system in question maintains the constant $I_{s,min}$ value. The mathematical formulation shown in the following implicitly assumes all the extra tritium is reserved in the storage system until the amount of tritium becomes sufficient to be discharged for startup of another reactor, i.e., until time reaches the tritium doubling time.

In fact, the storage solution, $I_s(t)$ after the minimum value is reached strongly depends upon how one defines the doubling time as discussed in the next section.

In general, the minimum time point, t_0, can be found from

$$\left.\frac{dI_s}{dt}\right|_{t=t_0} = 0 . \qquad \text{(II-41)}$$

However, in the regime of pulsed-mode reactor operation, the relationship of Eq. (II-41) is not necessarily guaranteed because the reactor might be shut down before the storage inventory actually reaches the minimum extreme. What is guaranteed is that there exists, at least, a cycle number n_0 for which the initial storage inventory of the cycle takes the minimum, i.e.,

$$I_s(n_0\Delta) = \min\left[I_s(0),\ I_s(\Delta),\ I_s(2\Delta),\ \ldots\right] , \qquad \text{(II-42)}$$

as shown in Fig. 3.

From the relationship,

$$I_s(n\Delta) = I_T(n\Delta) - \sum_m I_m(n\Delta) - I_p(n\Delta) , \qquad \text{(II-43)}$$

one finds that

$$\frac{dI_s(n\Delta)}{dn} = \Delta e^{-n\Delta/\tau}\left\{\frac{I_{Tc}(\infty)G(\tau) - I_T(0)}{\tau} - \sum_{m=1}^{M}\left[\frac{I_{mc}(\infty)}{\Lambda_m}\right] G(\Lambda_m)e^{-n\Delta/\lambda_m}\right.$$
$$\left. - \sum_{m=1}^{M}\left[\frac{I_{mc}(\infty)}{\lambda_m}\right]\Lambda_p \cdot \left[\frac{G(\Lambda_p)}{\Lambda_p - \Lambda_m}e^{-n\Delta/\lambda_p} - \frac{G(\Lambda_m)}{\Lambda_p - \Lambda_m}e^{-n\Delta/\lambda_m}\right]\right\} . \qquad \text{(II-44)}$$

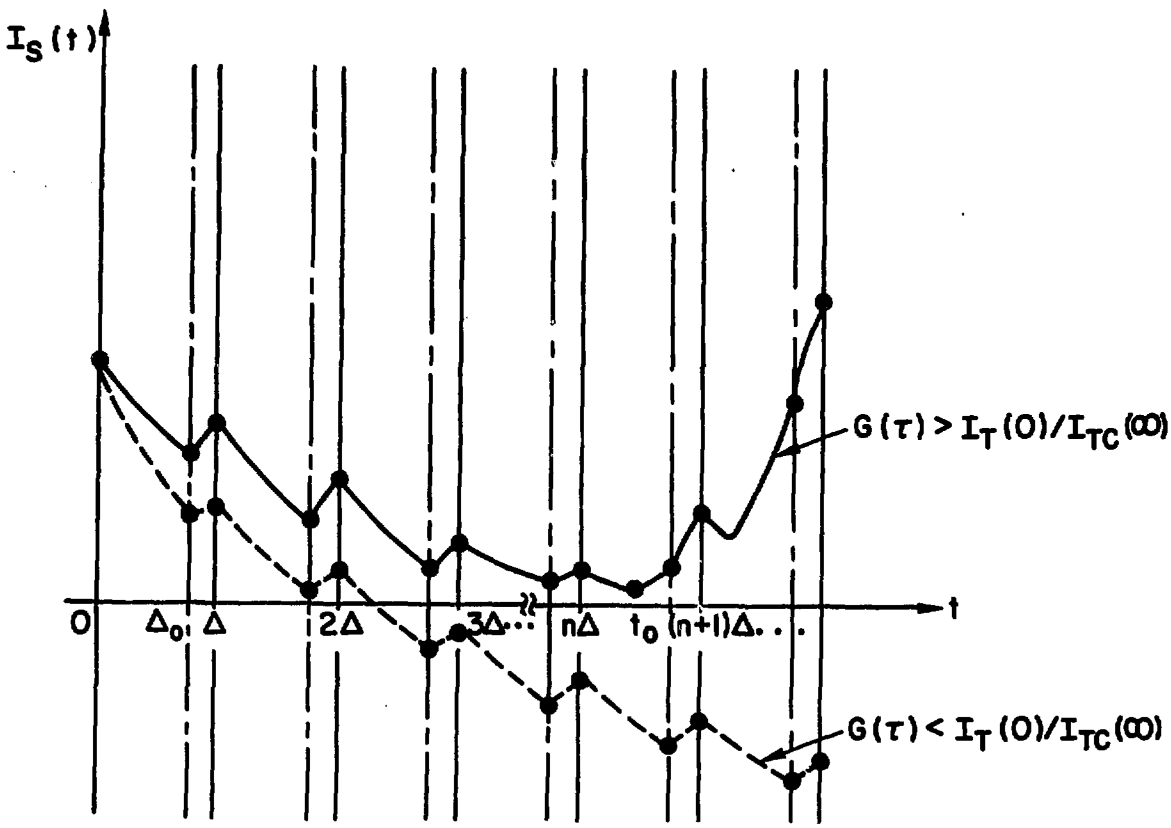

Fig. 3. Time-dependence of tritium inventory in storage.

Therefore, the cycle number n_0 can be found from

$$n_0 = \text{integer part of } \nu , \qquad \text{(II-45)}$$

where the real number ν satisfies

$$\sum_{m=1}^{M} \left\{ A_m e^{-\nu\Delta/\lambda_m} + B_m e^{-\nu\Delta/\lambda_p} \right\} = C , \qquad \text{(II-46)}$$

with

$$A_m = \frac{I_{mc}(\infty)}{\Lambda_m} G(\Lambda_m) \left\{ 1 - \frac{\Lambda_m}{\lambda_m} \cdot \frac{\Lambda_p}{\Lambda_p - \Lambda_m} \right\}, \qquad \text{(II-47)}$$

$$B_m = \frac{I_{mc}(\infty)}{\lambda_m} G(\Lambda_p) \cdot \frac{\Lambda_p}{\Lambda_p - \Lambda_m}, \tag{II-48}$$

and

$$C = \frac{I_{Tc}(\infty)G(\tau) - I_T(0)}{\tau}. \tag{II-49}$$

Consequently, the minimum time point, t_0, can be expressed as

$$t_0 = n_0\Delta + \xi\Delta_0, \qquad (0 \leq \xi \leq 1). \tag{II-50}$$

Once the cycle number n_0 is found, the variation of I_s in this cycle can be written, using Eq.•(II-3), as

$$\left.\frac{dI_s}{dt}\right|_{t=t_0} = \sum_{m=1}^{M} \left\{a_m K_{n_0}(\Lambda_m)e^{-t_0/\Lambda_m} - b_m K_{n_0}(\Lambda_p)e^{-t_0/\Lambda_p}\right\} + \frac{I_{sc}(\infty) - I_{s,min}}{\tau}, \tag{II-51}$$

where

$$a_m = \frac{I_{mc}(\infty)}{\lambda_m} \cdot \frac{\Lambda_p}{\lambda_p} \cdot \frac{\Lambda_m}{\Lambda_p - \Lambda_m} \tag{II-52}$$

and

$$b_m = \frac{I_{mc}(\infty)}{\lambda_m} \cdot \frac{\Lambda_p}{\lambda_p} \cdot \frac{\Lambda_p}{\Lambda_p - \Lambda_m}. \tag{II-53}$$

Depending on whether the $I_s(t_0)$ can really take the minimum extreme or enot, the minimum time point t_0 varies as follows: If

$$\sum_{m=1}^{M}\left\{a_m H_{n_0}(\Lambda_m)\, e^{-\Delta_0/\Lambda_m} - b_m H_{n_0}(\Lambda_p)e^{-\Delta_0/\Lambda_p}\right\} + \frac{I_{sc}(\infty) - I_{s,min}}{\tau} < 0, \tag{II-54}$$

then $\xi = 1$, or

$$t_0 = n_0\Delta + \Delta_0 . \tag{II-55}$$

Namely, the $I_s(t)$ monotonically decreases in the n_0-th cycle. Otherwise, ξ can be found from

$$\sum_{m=1}^{M}\left\{a_m H_{n_0}(\Lambda_m)e^{-\xi\Delta_0/\Lambda_m} - b_m H_{n_0}(\Lambda_p)e^{-\xi\Delta_0/\Lambda_p}\right\} + \frac{I_{sc}(\infty) - I_{s,min}}{\tau} = 0 . \tag{II-56}$$

The $H_n(x)$ function used above is defined using the $K^n(x)$ function as

$$H_n(x) = K_n(x)e^{-n\Delta/x} . \tag{II-57}$$

Once the minimum time point is obtained, the startup inventory $I_s(0)$ or $I_T(0)$ can be calculated, using

$$I_s(t_0) = I_T(t_0) - \sum_m I_m(t_0) - I_p(t_0) \equiv I_{s,min} , \tag{II-58}$$

as follows:

$$I_T(0) = I_{Tc}(\infty)K_{n_0}(\tau) - \sum_{m=1}^{M} I_{mc}(\infty)K_{n_0}(\Lambda_m)\, e^{-t_0/\lambda_m} - \left(\frac{\lambda_p}{\Lambda_p}\right)\left[I_{sc}(\infty) - I_{s,min}\right]e^{t_0/\tau} . \tag{II-59}$$

C. Doubling Time and Tritium Breeding Ratio

The tritium doubling time, t_d, can be defined in several ways depending on how bred tritium is subsequently utilized in other reactors. For example, the doubling time defined by Vogelsang[7] is equivalent to

$$I_s(t_d) = I_s(0) + I_{s,min} , \tag{II-60}$$

while Steiner's definition[8] is

$$t_d = \frac{0.693\left[I_{s,min} + I_{bc}(\infty)\right]}{\bar{N}(TBR - 1)} , \tag{II-61}$$

where $I_{bc}(\infty)$ is the blanket saturation inventory. As Vogelsang states,[7] the factor 0.693 in the above equation comes from compounding effects of continually inserting freshly bred tritium into subsequent reactors for rebreeding.

In the present study the doubling time is defined as the time at which excess tritium in the overall system becomes equal to the startup inventory, i.e.,

$$I_T(t_d) = 2\ I_T(0) . \tag{II-62}$$

The definition given above is expected to result in a somewhat long t_d comparing to a case where the extra tritium is continually fed to other reactors for rebreeding. For the definition of t_d in Eq. (II-62) takes into account a doubling delay to compensate for possible tritiium losses by the natural decay while the bred tritium is reserved in the storage system.

By inserting Eq. (II-36) into the above equation, the required tritium breeding ratio, TBR, can be written as

$$TBR = 1 + \frac{I_T(0)}{\tau \bar{N}} \cdot \frac{2 - e^{-t_d/\tau}}{1 - K_{n_0}(\tau)e^{-t_d/\tau}} . \tag{II-63}$$

Since the $I_T(0)$ is also a function of TBR, the TBR, in actuality, can be solved only by an iterative procedure. On the other hand, when a TBR is given, the doubling time, t_d can be defined as

$$t_d = -\tau\ \ell n\left[\frac{2\ I_T(0) - I_{Tc}(\infty)}{I_T(0) - K_{n_0}(\tau)I_{Tc}(\infty)}\right] . \tag{II-64}$$

Since $K_{n_0}(\tau) > 1$ for any n_0 and τ, the following must hold:

$$\frac{I_T(0)}{I_{Tc}(\infty)} < \frac{1}{2} \tag{II-65}$$

in order for t_d to be practical. Namely, the startup inventory cannot exceed one-half of the saturation value of the total tritium inventory.

In summary, the required TBR can be computed by the following algorithm. Given all relevant parameters such as ε, λ_m's, τ_p, N^-, f_b, Q_m's, $I_{s,min}$, and t_d, solve Eqs. (II-46) and (II-56) to find the minimum time point, t_0, and the cycle number n_0, starting with an initial guess of TBR. Compute $I_T(0)$ by Eq. (II-59) and revise the TBR by Eq. (II-63); then proceed to the next iteration. After all necessary parameters are determined, the respective time-dependent tritium inventories can be computed by Eqs. (II-34) through (II-37) during reactor operation, and by Eqs. (II-16) through (II-19) during reactor shutdown.

III. NUMERICAL EXAMPLES

In 1976, Okrent et al.(8) analyzed the tritium inventories, using UWMAK-I as the reference concept, in their safety analysis for tokamak-type fusion reactors. They found larger tritium inventories than previously reported by Vogelsang(7) in 1970. While Vogelsang dealt with only two components, viz., blanket and storage sustems for the inventory analysis, Okrent et al. further included a fuel processing system in between the two components. The fuel processing system can affect, as Okrent et al. stated, the total plant inventory in that a substantial amount of fuel must flow through this system, and the retention time may be significant. Assuming a retention time of one day in the processing system, Okrent and his colleagues found a startup inventory requirement of 19.4 kg compared to 5.5 kg reported by Vogelsang. These evaluations were made for the UWMAK-I design, reactor parameters of which are shown in Table I. They considered a very high TBR of 1.3, leading to somewhat unrealistic doubling times of 56 d and 127 d.

The method of Okrent and his colleagues is equivalent, in the context of the present analysis, to a case where the reactor complex consists of blanket, vacuum system, and processing system, but the vacuum system inventory is always null because of the null mean residence time Λ_v in the vacuum system. Namely, their system of equations regarding the reactor inventories, can be written as

$$\frac{dI_b}{dt} = N^{+} - \frac{I_b}{\Lambda_b} \tag{II-65}$$

$$\frac{dI_v}{dt} = N^{-}\left(\frac{1 - f_b}{f_b}\right) - \frac{I_v}{\Lambda_v} = 0 \,. \tag{II-66}$$

and

$$\frac{dI_p}{dt} = \frac{I_b}{\lambda_b} + \frac{I_v}{\lambda_v} - \frac{I_p}{\Lambda_p} = \frac{I_b}{\lambda_b} + N^{-}\left(\frac{1 - f_b}{f_b}\right) - \frac{I_p}{\Lambda_p} \,. \tag{II-67}$$

although Okrent et al. neglected the natural decay and leakage into the environment of tritium.

In general, unburned tritium in the plasma chamber must go through recovery systems such as limiter, divertor and cryogenic vacuum pumps before the tritium is reprocessed for refueling. In general, the mean residence time Λ_v in the vacuum system is not trivial. For example, the STARFIRE design(13) assumes a regeneration time of 2 h for the vacuum pumps located at the end of the limiter plenum.

In Table I five different λ_v cases $(\lambda_v = 10^{-3}, 10^{-2}, 10^{-1}, 0.5, 1.0\ d)$ by the present method are compared to the calculations by Vogelsang(7) and Okrent et al.(8) The present method assumes a steady-state reactor operation (α = 1), and $I_{s,min} = \varepsilon = 0$. The $I_{Rc}(\infty)$ shown in the table designates the total saturation tritium inventory in the reactor complex, i.e., $I_{Rc}(\infty) = I_{bc}(\infty) + I_{vc}(\infty) + I_{pc}(\infty)$. It is found that the startup inventory, $I_T(0)$, significantly varies with the vacuum mean-residence time, λ_v. It is important to note that the steady-state reactor inventory, $I_{Rc}(\infty)$ also varies accordingly.

Table II compares the startup inventories and doubling times in two reactor operating regimes, steady state and pulse mode. The cycle duration for the pulse-mode operation ranges from 0.1 d to 100 d and three duty factors,

TABLE I

A Comparison of Startup Inventory Requirement for the UWMAK-I Design

Given[a] Parameter	Method: Vogelsang[b]	Okrent et al.[c]	Present Work				
N^- (kg/d)	0.7	0.7	0.7				
λ_b (d)	13.7	13.7	13.7				
λ_v (d)	--	--	10^{-3}	10^{-2}	10^{-1}	0.5	10^0
λ_p (d)	--	1.0	1.0				
f_b	--	0.05	0.05				
TBR	1.3	1.3	1.3				
Calculated Value							
$I_{Rc}(\infty)$ (kg)	12.5	26.7	26.7	26.8	28.0	33.4	40.0
t_o (d)			21.4	21.4	21.4	21.5	21.6
$I_T(0)$ (kg)	5.5	19.4	19.5	19.6	20.8	26.1	32.8
t_d (d)			94.7	95.3	101.3	128.0	162.0

[a] $\varepsilon = I_{s,min} = 1 - \alpha = 0$.

[b] Ref. 7.

[c] Ref. 8.

TABLE II

A Comparison of Steady-State and Pulse-Mode Reactor Operations

Operating Mode		$I_T(0)$ (kg)	t_d (yr)
(A) Steady state		16.5	4.04
(B) Pulse mode			
α = 75%	Δ = 100 (d)	16.5	4.04
	10	15.7	3.81
	1	13.3	3.09
	0.1	12.4	2.85
α = 50%	Δ = 100 (d)	16.5	4.04
	10	14.5	3.48
	1	9.6	2.65
	0.1	8.4	1.81
α = 25%	Δ = 100 (d)	16.3	3.98
	10	12.3	2.83
	1	5.1	1.10
	0.1	4.2	0.90

α = 75%, 50%, and 25%, are considered. Other parameters assumed for the computation are λ_b = 10 d, λ_v = 0.2 d, λ_p = 1 d, f_b = 5%, N^- = 0.5 kg/d, $I_{s,min}$ = ε =0, and TBR = 1.03.

It is found that as the cycle duration, Δ, becomes short, the startup inventory, $I_T(0)$ and the doubling time, t_d, significantly differ from those evaluated for the steady-state operation. In general, the pulse-mode operation helps to decrease the required $I_T(0)$ and t_d values because the tritium inventories in the reactor complex can be recovered to the fueling/storage system during reactor shutdown periods. In consequence, decreasing the duty cycle (i.e., prolonging the down time) is also of assistance to realize lower requirements on $I_T(0)$ and t_d values as shown in Table II. These phenomena are due in a large part to the computational assumption that during reactor shutdown, the tritium in the reactor complex and processing system is recovered at the same rates as during operation.

In actuality, it is expected that the behavior of tritium in the reactor complex during shutdown is quite different from that during operation due to the potential temperature change in reactor components (e.g., blanket), caused by reactor shutdown. More detailed analysis on the tritium inventory evaluation remains to be carried out using the formulation presented in the Appendix, which accounts for the effect of different time constants during operation and shutdown.

Finally, Fig. 4 presents the results of a sensitivity study of required TBR with respect to possible parameter changes. We consider a reactor complex consisting of three components, viz., blanket, vacuum system, and tritium processing system. The operating mode is assumed to be steady state. The following shows the ranges of parameters studied along with the respective reference values:

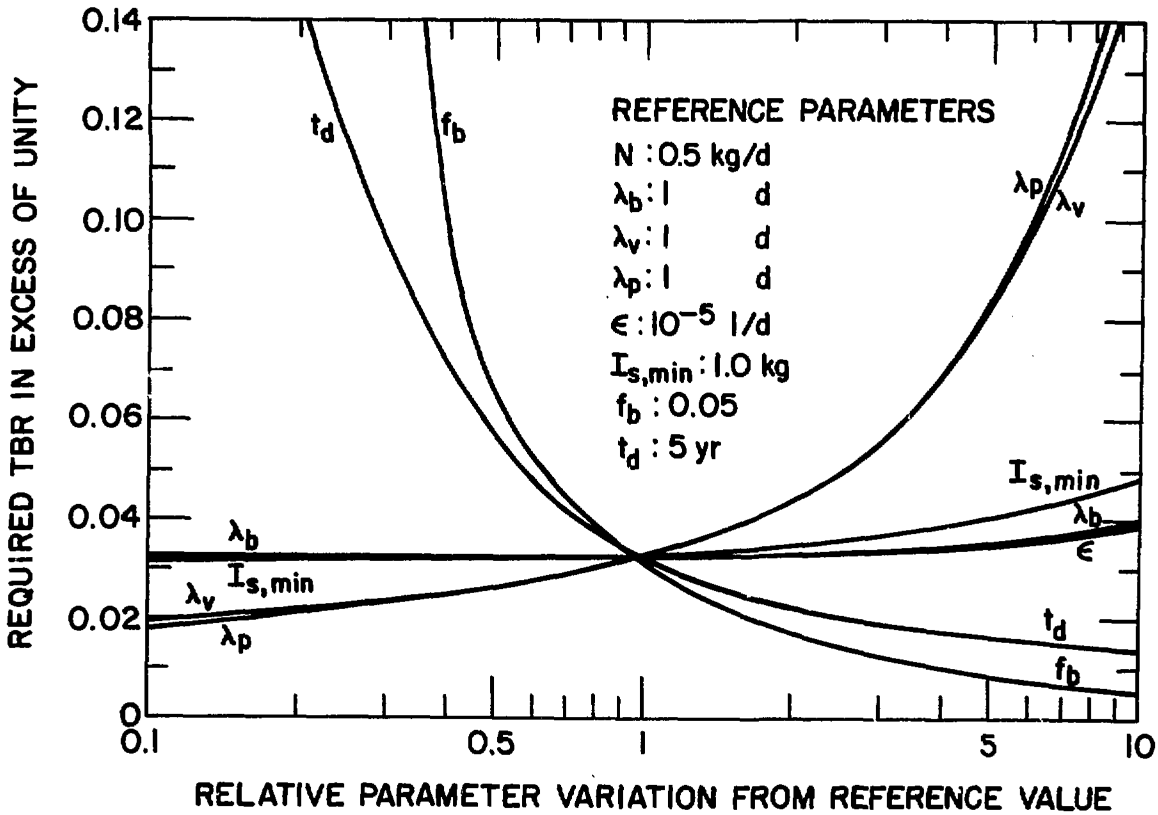

Fig. 4. Effect of parameter variation on required tritium breeding ratio.

Parameter		Range	Reference Value
λ_b	(d)	0.1-10.0	1.0
λ_v	(d)	0.1-10.0	1.0
λ_p	(d)	0.1-10.0	1.0
f_b	(%)	0.5-50.0	5.0
ε	(1/d)	10^{-6}-10^{-4}	10^{-5}
$I_{s,min}$	(kg)	0.1-10.0	1.0
t_d	(yr)	0.5-50.0	5.0

The tritium burnup rate, N^-, is fixed to be 0.5 kg/d which corresponds to a power generation rate of ~4000 MW(th) including the blanket energy multiplication. Note that the selection of N^- has no effect on the required TBR evaluation.

The set of reference values yields a tritium breeding requirement of ~1.03. The corresponding total reactor inventory, $I_{Rc}(\infty)$, is ~20.0 kg, which is broken down to ~0.52 kg, 9.5 kg, and ~10.0 kg in the blanket, vacuum system, and processing system, respectively. It is found that the impact of λ_b, ε, and $I_{s,min}$ variations on the TBR requirement is relatively small compared to other parameter variations. The ranges varied for ε and $I_{s,min}$ are equivalent respectively to: tritium loss rates of 0.02 g/d (~200 Ci/d) to 2 g/d (~20,000 Ci/d) into the environment, and 0.2 d to 20 d worth tritium fuel reserves for unexpected malfunction of the tritium supplying system. It is, therefore, expected that these variations cover the entire ranges of interest. The reference value of 1 d assumed for λ_b is a quite pessimistic assumption for any liquid-blanket designs[14] and is, even for solid-breeder designs, somewhat higher than current estimates.[5,15]

Based on the results shown in Fig. 4 it can be concluded that the most important parameters in terms of determining the required TBR are the vacuum-system time constant, λ_v, the processing-system time constant, λ_p, the fractional tritium burnup rate, f_b, and the doubling time requirement, t_d.

In order to realize a fusion blanket which requires a reasonably small TBR one has to assure that

$$\lambda_p \lesssim 1 \text{ d}$$

$$\lambda_v \lesssim 1 \text{ d}$$

$$f_b \gtrsim 5\%$$

$$t_d \gtrsim 5 \text{ yr}$$

For such a system, even a factor of two uncertainty in these parameters leads to only a few percent variation at most, in the estimated TBR requirement.

Appendix

TRITIUM INVENTORIES FOR DIFFERENT TIME CONSTANTS DURING OPERATION AND SHUTDOWN

The behavior of tritium in reactor components, particularly in the blanket, can be quite different depending on whether the reactor is in operation or shutdown. The primary driving force is the possible temperature change caused by loss of nuclear heating following reactor shutdown. This appendix provides a brief summary of analytical expressions for tritium inventories in individual components using different time constants during reactor operation and shutdown periods.

Let us assume the time constants during operation and shutdown are λ_x^O (or Λ_x^O) and λ_x^D (or Λ_x^D), respectively. Define a constant, c_m as

$$c_m = 1 - \frac{1}{\lambda_m^D}\left(\frac{1}{\Lambda_p^D} - \frac{1}{\Lambda_m^D}\right)^{-1} \Bigg/ \frac{1}{\lambda_m^O}\left(\frac{1}{\Lambda_p^O} - \frac{1}{\Lambda_m^O}\right)^{-1} , \qquad m = 1,2 \ldots, M . \tag{A-1}$$

Evidently, c_m becomes null when all the time constants are invariant during operation and shutdown. Therefore, c_m provides a measure as to the impact of the different time constants. It is easily shown that the initial tritium inventories in each cycle satisfy the following equations [analogous to Eq. (II-30)]:

$$I_m(n\Delta) = I_{mc}(\infty)G(\Lambda_m)\left[1 - e^{-n\gamma_m}\right] , \quad (m = 1,2, \ldots, M) , \tag{A-2}$$

where $G(\Lambda_m)$ and γ_m are defined as

$$G(\Lambda_m) = \frac{(1 - e^{-\Delta_O/\Lambda_m^O})e^{-\Delta_D/\Lambda_m^D}}{1 - e^{-\gamma_m}} , \tag{A-3}$$

and

$$\gamma_m = \Delta_0/\Lambda_m^0 + \Delta_D/\Lambda_m^D . \qquad \text{(A-4)}$$

Equation (A-3) is a generalized form of Eq. (II-31) previously defined to account for the effect of different time constants. Having derived equations similar to Eq. (A-2), for the processing system and storage, one finds that during reactor operation $\left(n\Delta \le t \le n\Delta + \Delta_0\right)$

$$I_m(t) = I_{mc}(\infty)\left[1 - H_n(\Lambda_m)e^{-(t-n\Delta)/\Lambda_m^0}\right] , \quad (m = 1,2, \ldots, M), \qquad \text{(A-5)}$$

$$I_T(t) = I_T(0)e^{-t/\tau} + I_{Tc}(\infty)\left[1 - H_n(\tau)e^{-(t-n\Delta)/\tau}\right] \qquad \text{(A-6)}$$

$$I_p(t) = \sum_{m=1}^{M} \frac{I_{mc}(\infty)}{\lambda_m^0}\left\{\Lambda_p^0 \frac{\Lambda_p^0}{\Lambda_p^0 - \Lambda_m^0}\left[1 - H_n(\Lambda_p)e^{-(t-n\Delta)/\Lambda_p^0}\right]\right.$$

$$\left. - \frac{\Lambda_m^0}{\Lambda_p - \Lambda_m^0}\left[1 - H_n(\Lambda_m)\, e^{-(t-n\Delta)/\Lambda_m^0}\right]\right\}$$

$$+ \sum_{m=1}^{M} \frac{I_{mc}(\infty)}{\lambda_m^0} c_m \cdot A_m \cdot e^{-(t-n\Delta)/\Lambda_p^0} , \qquad \text{(A-7)}$$

and

$$I_s(t) = I_T(t) - \sum_m I_m(t) - I_p(t) , \qquad \text{(A-8)}$$

where

$$H_n(\Lambda_x) = \left[1 - G(\Lambda_x)\right] + G(\Lambda_x)e^{-n\gamma_x} . \qquad \text{(A-9)}$$

The second term on the right-hand side of Eq. (A-7) presents a correctional inventory for the processing system due to the difference in the time constants. The term A_m included in the correction stands for

$$A_m = \left(\frac{1}{\Lambda_p^0} - \frac{1}{\Lambda_m^0}\right)^{-1} \left\{G(\Lambda_p)\left[1 - e^{-n\gamma_p}\right] + G(\Lambda_m)\left[1 - e^{-n\gamma_m}\right]\right\}$$

$$- \left(\frac{1}{\Lambda_p^0} - \frac{1}{\Lambda_m^0}\right)^{-1} \left\{e^{-\gamma_p} - e^{-\beta_m}\right\}$$

$$\times \left\{\left[1 - G(\Lambda_m)\right] \frac{1 - e^{-n\gamma_p}}{1 - e^{-\gamma_p}} + G(\Lambda_m) \frac{e^{-n\gamma_m} - e^{-n\gamma_p}}{e^{-\gamma_m} - e^{-\gamma_p}}\right\}, \qquad \text{(A-10)}$$

with

$$\beta_m = \frac{\Delta_0}{\Lambda_m^0} + \frac{\Delta_D}{\Lambda_p^D}, \qquad \text{(A-11)}$$

Once all inventories are calculated at time, $n\Delta + \Delta_0$, the inventories during a shutdown period of $\left[n\Delta + \Delta_0 \le t \le (n+1)\Delta\right]$ can be given by

$$I_m(t) = I_m(t_0)e^{-(t-t_0)/\Lambda_m^D}, \quad (m = 1, 2, \ldots, M) \qquad \text{(A-12)}$$

$$I_T(t) = I_T(t_0)e^{-(t-t_0)/\tau}, \qquad \text{(A-13)}$$

$$I_p(t) = I_p(t_0)e^{-(t-t_0)/\Lambda_p^D}$$

$$+\sum_{m=1}^{M} \frac{I_{mc}(\infty)}{\lambda_m^D} \left(\frac{1}{\Lambda_p^D} - \frac{1}{\Lambda_m^D}\right)^{-1} \left\{1 - B_n(\Lambda_m)e^{-\Delta_0/\Lambda_m^0}\right\}$$

$$\times \left\{e^{-(t-t_0)/\Lambda_m^D} - e^{-(t-t_0)/\Lambda_p^D}\right\}, \qquad \text{(A-14)}$$

and

$$I_s(t) = I_T(t) - \sum_m I_m(t) - I_p(t), \qquad \text{(A-15)}$$

where t_0 is assumed to be the shutdown time of the n-th cycle, i.e.,

$$t_0 = n\Delta + \Delta_0. \qquad \text{(A-16)}$$

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