DEUTERIUM-TRITIUM FUEL SELF-SUFFICIENCY IN FUSION REACTORS

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Conditions necessary to achieve deuterium-tritium fuel self-sufficiency in fusion reactors are derived through extensive modeling and calculations of the required and achievable tritium breeding ratios as functions of the many reactor parameters and candidate design concepts. It is found that the excess margin in the breeding potential is not sufficient to cover all present uncertainties. Thus, the goal of attaining fuel self-sufficiency significantly restricts the allowable parameter space and design concepts. For example, the required breeding ratio can be reduced by (a) attaining high tritium fractional burnup, >5%, in the plasma, (b) achieving very high reliability, >99%, and very short times, <1 day, to fix failures in the tritium processing system, and (c) ensuring that nonradioactive decay losses from all subsystems are extremely low, e.g., <0.1% for the plasma exhaust processing system. The uncertainties due to nuclear data and calculational methods are found to be significant, but they are substantially smaller than those due to uncertainties in system definition.

I. INTRODUCTION

A self-sustaining fusion reactor operated on the deuterium-tritium (D-T) fuel cycle must breed tritium. In all fusion reactor design concepts, tritium is produced in a lithium-containing blanket that circumscribes the plasma. Attaining fuel self-sufficiency is a critical goal for fusion as one of a very limited number of options for a renewable energy source. Therefore, careful evaluation of the conditions for attaining self-sufficiency is necessary to define the selection criteria for design concepts and the range of acceptable performance parameters and to plan research and development (R&D) programs prudently.

In this work, we attempt to address many of the technical problems associated with attaining fuel self-sufficiency in D-T fusion reactors. The problems are found to be far more complex than can be inferred from simple calculations of the tritium breeding ratio (TBR). Attaining fuel self-sufficiency is strongly dependent on many reactor plasma physics and technology components performance parameters, many of which are presently subject to large uncertainties. These uncertainties result in a large variation in the required TBR. On the other hand, the maximum TBR achievable with present blanket concepts is limited and its prediction suffers from uncertainties in neutronics calculations. In this work, we analyze the uncertainties in both the required and achievable TBRs. This analysis is then extended to compare the risks of various candidate blanket concepts and to define the range of acceptable plasma and engineering components performance parameters necessary to enhance the potential for success in attaining fuel self-sufficiency in future D-T fusion reactors.

II. DEFINITION OF THE PROBLEM

The TBR (or Λ) is defined as:

$$\Lambda = \dot{N}^{+}/\dot{N}^{-} \ , \quad (1)$$

where $\dot{N}^{+}$ is the rate of tritium production in the system (normally the blanket) and $\dot{N}^{-}$ is the rate of burning tritium in the plasma. The *required* TBR (Λ_r) in a self-sustained fusion power economy must exceed unity by a margin, G, to: (a) compensate for losses and radioactive decay of tritium during the period between production and use, (b) supply inventory for startup of other fusion reactors, and (c) provide a

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holdup inventory, which accounts for the time delay between production and use as well as reserve storage.

We show later that G is a function of many reactor parameters as well as the doubling time, t_d. Many of these reactor parameters vary from one design to another; and, for a given design, the prediction of some of these parameters is subject to uncertainties. For example, the required TBR increases rapidly as the tritium inventory I in the reactor increases. The total inventory I includes the tritium inventory in the blanket, fueling and exhaust systems, other reactor components, and the storage inventory for use in off-normal conditions and to start up a new reactor. The magnitude of tritium inventory retained in the blanket is uncertain by about an order of magnitude for some concepts. The tritium flow rate into the plasma is inversely proportional to the tritium fractional burnup, which might vary from 0.01 to 0.5 reflecting present inventories.

We write Λ_r as:

$$\Lambda_r = 1 + G_0 + \Delta_G \ , \qquad (2)$$

where G_0 is the breeding margin for a reference conceptual design based on a given estimate of its performance parameters, and where Δ_G is the uncertainty in estimating the required breeding ratio $(1 + G_0)$.

The *achievable* TBR, Λ_a, is also a function of the reactor design with particularly strong dependence on the blanket design concept. There are two problems in providing a precise evaluation of Λ_a:

1. *Uncertainties in system definition:* Fusion reactor design concepts are evolving. The choices for many of the design features, materials, and technology options have not been made. The achievable TBR is strongly dependent on many of these choices.

2. *Inaccuracies in prediction:* For a well-specified reactor system, the prediction of the achievable breeding ratio is subject to uncertainties. These are due to approximations or errors in the various elements of the calculations, e.g., in basic nuclear data, data representation, calculational methods, and geometric representation.

Therefore, we write the achievable TBR, Λ_a, as:

$$\Lambda_a = \Lambda_c - (\Delta_s^2 + \Delta_p^2)^{1/2} = \Lambda_c - \Delta_a \ , \qquad (3)$$

where

Λ_c = TBR calculated for a specified blanket in a specified reactor system

Δ_s = uncertainty associated with system definition, i.e., the changes in Λ_c due to changes in the reference system

Δ_p = uncertainty in predicting the breeding ratio (Λ_c) for the specified system due to nuclear data uncertainties, numerical approximations, etc.

The condition to attain self-sufficiency can then be written as:

$$\Lambda_a \geq \Lambda_r \ . \qquad (4)$$

In comparing blanket concepts as well as plasma and technology choices for future fusion reactors, one needs a "figure of merit." One such figure of merit is:

$$\epsilon = \Lambda_a - \Lambda_r = (\Lambda_c - \Delta_a) - (1 + G_0 + \Delta_G) \ . \qquad (5)$$

The larger ϵ is, the higher the probability that the D-T fuel self-sufficiency condition will be met; that is, higher values of ϵ represent a lower degree of risk in not satisfying the fuel self-sufficiency requirements. An alternative figure of merit is:

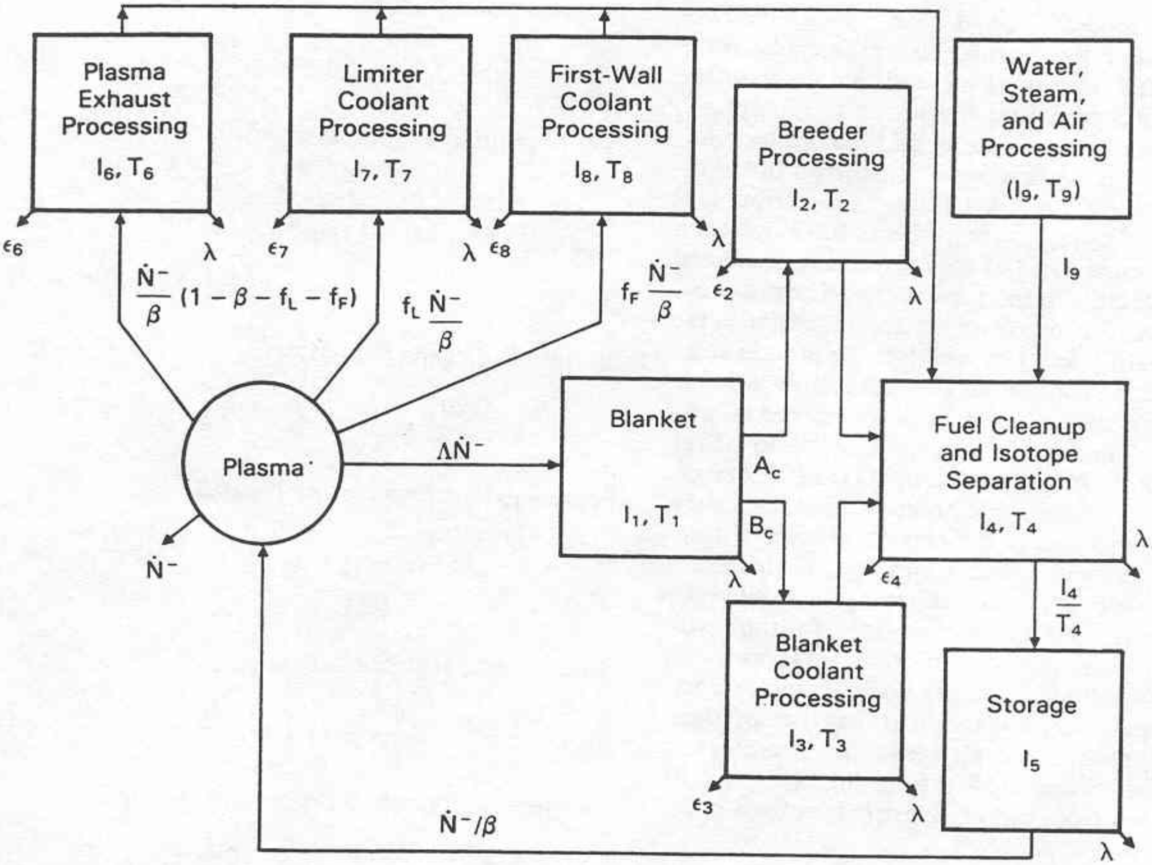
$$F = \frac{\Lambda_c - (1 + G_0)}{(\Delta_G^2 + \Delta_s^2 + \Delta_p^2)^{1/2}} \ . \qquad (6)$$

A thorough statistical treatment of the fuel self-sufficiency problem is not intended here, although it represents an excellent area for future research. Our effort in this area resulted in an expression that modifies the Δ's in the above formulas by a mix of partial derivatives of G_0 and Λ_c with regard to many of the reactor system parameters. Our present knowledge of the fusion system does not permit reasonable evaluation of the more complex expression. Therefore, in this work we maintain the above simple expressions as they are more amenable to evaluation and help provide insight into those parameters that have the largest impact on fuel self-sufficiency.

Using the expressions of Eq. (5) or (6), the problem reduces to evaluating Λ_c, G_0, Δ_G, Δ_s, and Δ_p. The evaluation of Λ_c involves three-dimensional calculation of the breeding ratio in a detailed reference design, and is not the direct focus of this work. Rather, we use values reported in literature when needed. The following sections provide an attempt to evaluate the other quantities.

III. MODEL FOR REQUIRED TBR

An analytic model was developed to describe the characteristic parameters of the various elements of the tritium cycle as a tool for evaluating the tritium breeding requirements. The basis for the model is shown schematically in Fig. 1, which describes the tritium flow through the various components of a fusion reactor system. In previous work, Carré et al.,[1] Abdou,[2] and Jung[3] reported models for deriving the tritium breeding requirement. We have found Carré's model to be a useful starting point for this work because of its explicit treatment of tritium behavior in major system components. We have expanded on Carré's original model to include the first wall and limiter coolant processing and the fuel cleanup system. The first step in developing the model was to write down a set of differential equations that relates the time-dependent tritium inventories in the various components of Fig. 1



Λ = TBR

$\dot{N}^-$ = tritium burn rate in the plasma

I_i = tritium inventory in compartment i

T_i = mean residence time of tritium in compartment i

ϵ_i = nonradioactive loss fraction of tritium in compartment i

λ = tritium decay constant

β = tritium fractional burnup in the plasma

f_i = tritium fractional leakage to compartment i

$\dot{I}_9$ = constant flow rate of tritium recovered from waste, steam, and air processing units

$$A_c = \frac{I_1}{T_1}(1 - f_c)$$

$$B_c = \frac{I_1}{T_1} f_c$$

Fig. 1. Schematic model of the fuel cycle for a D-T fusion reactor used in the present work.

to their operating parameters. These equations were then solved analytically to derive explicit expressions for the functional dependence of the tritium inventories. We then derived an exact expression for the required TBR as a function of the doubling time and the tritium cycle operating parameters. A computer program was also written and used for evaluating the dependence of the required breeding ratio on the key physics and technology parameters for fusion reactors.

The tritium permeation pathway via the in-vessel components was separated in this model from tritium permeation to the blanket coolant. In general, the limiter (or divertor) is bombarded directly by the high flux of hydrogen ions, while the first wall is exposed to a relatively modest flux of charge-exchange neutrals. Furthermore, it is possible that different coolants and their specific processing methods are used for the blanket, the first wall, and the limiters.[4] Therefore, the first-wall coolant processing and the limiter coolant processing subsystems were considered individually. Radiation effects on tritium permeation and retention in the in-vessel components have not been explicitly accounted for, but they can still be examined through adjustments in the present model parameters.

Two modes of tritium loss are accounted for in the model: radioactive decay in each but the plasma compartment, and the continuous nonradioactive losses in all processing compartments. The waste, steam, and air processing units in the fuel cycle scenario of the STARFIRE (Ref. 5) and ANL-DEMO (Ref. 6) designs are modeled here as a single compartment. Since the waste processing unit is defined to recover tritium from the wastes (continuous nonradioactive losses) in other tritium recovery compartments, the initial one-time tritium loss, such as the exchange of tritium with hydrogen, and tritium sorption on all surfaces in the system are not included. During normal reactor operation or maintenance, it is required that tritium losses to the waste, steam, and air be small. Therefore, a small constant tritium flow rate in Fig. 1 ($\dot{I}_9 = 0.01$ g/day) returned from this compartment is used in the model.

The residence times of tritium in all compartments are assumed to be constants, although this is unlikely to be accurate during startup or in fractional power operation. The residence time in the blanket is also assumed to be a constant value, which was calculated from time-averaged results of a separate time-dependent model for the blanket tritium inventory.

The governing equation for the tritium inventory I_i, in each compartment i (with compartment number and parameters as defined in Fig. 1), is written as:

blanket (i = 1):

$$\frac{dI_1}{dt} = \Lambda \dot{N}^- - \frac{I_1}{T_1} - \lambda I_1 \ ; \tag{7}$$

breeder processing (i = 2):

$$\frac{dI_2}{dt} = (1 - f_c)\frac{I_1}{T_1} - (1 + \epsilon_2)\frac{I_2}{T_2} - \lambda I_2 \ ; \tag{8}$$

blanket coolant processing (i = 3):

$$\frac{dI_3}{dt} = f_c \frac{I_1}{T_1} - (1 + \epsilon_3)\frac{I_3}{T_3} - \lambda I_3 \ ; \tag{9}$$

fuel cleanup and isotope separation (i = 4):

$$\frac{dI_4}{dt} = \frac{I_2}{T_2} + \frac{I_3}{T_3} + \frac{I_6}{T_6} + \frac{I_7}{T_7} + \frac{I_8}{T_8} + \dot{I}_9 - (1 + \epsilon_4)\frac{I_4}{T_4} - \lambda I_4 \ ; \tag{10}$$

storage and fueling (i = 5):

$$\frac{dI_5}{dt} = \frac{I_4}{T_4} - \frac{\dot{N}^-}{\beta} - \lambda I_5 \ ; \tag{11}$$

plasma exhaust processing (i = 6):

$$\frac{dI_6}{dt} = \frac{\dot{N}^-}{\beta}(1 - \beta - f_L - f_F) - (1 + \epsilon_6)\frac{I_6}{T_6} - \lambda I_6 \ ; \tag{12}$$

limiter coolant processing (i = 7):

$$\frac{dI_7}{dt} = f_L \frac{\dot{N}^-}{\beta} - (1 + \epsilon_7)\frac{I_7}{T_7} - \lambda I_7 \ ; \tag{13}$$

and first-wall coolant processing (i = 8):

$$\frac{dI_8}{dt} = f_F \frac{\dot{N}^-}{\beta} - (1 + \epsilon_8)\frac{I_8}{T_8} - \lambda I_8 \ . \tag{14}$$

Following Fig. 1, the effective residence time for each compartment τ_i is defined by letting

$$\frac{1}{\tau_i} = \begin{cases} \dfrac{1}{T_i} + \lambda \ , & i = 1 \\ \lambda \ , & i = 5 \\ \dfrac{1 + \epsilon_i}{T_i} + \lambda \ , & i = 2,3,4,6,7,8 \end{cases} \ . \tag{15}$$

The exact solutions for the time-dependent compartment inventories I_i were derived and they are expressed as:

blanket:

$$I_1(t) = I_{1\infty}\left[1 - \exp\left(-\frac{t}{\tau_1}\right)\right] \ ; \tag{16}$$

breeder processing:

$$I_2(t) = I_{2\infty}\left[1 + \frac{\tau_1}{\tau_2 - \tau_1}\exp\left(-\frac{t}{\tau_1}\right) + \frac{\tau_2}{\tau_1 - \tau_2}\exp\left(-\frac{t}{\tau_2}\right)\right] \ ; \tag{17}$$

blanket coolant processing:

$$I_3(t) = I_{3\infty}\left[1 + \frac{\tau_1}{\tau_3 - \tau_1}\exp\left(-\frac{t}{\tau_1}\right) + \frac{\tau_3}{\tau_1 - \tau_3}\exp\left(-\frac{t}{\tau_3}\right)\right] \ ; \tag{18}$$

fuel cleanup and isotope separation:

$$I_4(t) = \sum_{i=2,3}\left\{I_{i\infty}\frac{\tau_4}{T_i}\left[1 - \frac{\tau_1^2}{(\tau_i-\tau_1)(\tau_4-\tau_1)}\exp\left(-\frac{t}{\tau_1}\right) - \frac{\tau_i^2}{(\tau_1-\tau_i)(\tau_4-\tau_i)}\exp\left(-\frac{t}{\tau_i}\right)\right.\right.$$
$$\left.\left. - \frac{\tau_4^2}{(\tau_1-\tau_4)(\tau_i-\tau_4)}\exp\left(-\frac{t}{\tau_4}\right)\right]\right\}$$
$$+ \sum_{j=6,7,8}\left\{I_{j\infty}\frac{\tau_4}{T_j}\left[1 + \frac{\tau_4}{\tau_j-\tau_4}\exp\left(-\frac{t}{\tau_4}\right) + \frac{\tau_j}{\tau_4-\tau_j}\exp\left(-\frac{t}{\tau_j}\right)\right]\right\} + \dot{I}_9\tau_4\left[1-\exp\left(-\frac{t}{\tau_4}\right)\right] \; ; \tag{19}$$

storage and fueling:

$$I_5(t) = I_5^0\exp\left(-\frac{t}{\tau_5}\right)$$
$$+ \sum_{i=2,3}\left\{I_{i\infty}\frac{\tau_4\tau_5}{T_iT_4}\left[1 + \frac{\tau_1^3}{(\tau_i-\tau_1)(\tau_4-\tau_1)(\tau_5-\tau_1)}\exp\left(-\frac{t}{\tau_1}\right)\right.\right.$$
$$+ \frac{\tau_i^3}{(\tau_1-\tau_i)(\tau_4-\tau_i)(\tau_5-\tau_i)}\exp\left(-\frac{t}{\tau_i}\right) + \frac{\tau_4^3}{(\tau_1-\tau_4)(\tau_i-\tau_4)(\tau_5-\tau_4)}\exp\left(-\frac{t}{\tau_4}\right)$$
$$\left.\left. + \frac{\tau_5^3}{(\tau_1-\tau_5)(\tau_i-\tau_5)(\tau_4-\tau_5)}\exp\left(-\frac{t}{\tau_5}\right)\right]\right\}$$
$$+ \sum_{j=6,7,8}\left\{I_{j\infty}\frac{\tau_4\tau_5}{T_jT_4}\left[1 - \frac{\tau_4^2}{(\tau_j-\tau_4)(\tau_5-\tau_4)}\exp\left(-\frac{t}{\tau_4}\right)\right.\right.$$
$$\left.\left. - \frac{\tau_5^2}{(\tau_j-\tau_5)(\tau_4-\tau_5)}\exp\left(-\frac{t}{\tau_5}\right) - \frac{\tau_j^2}{(\tau_4-\tau_j)(\tau_5-\tau_j)}\exp\left(-\frac{t}{\tau_j}\right)\right]\right\}$$
$$+ \dot{I}_9\frac{\tau_4\tau_5}{T_4}\left[1 + \frac{\tau_4}{\tau_5-\tau_4}\exp\left(-\frac{t}{\tau_4}\right) + \frac{\tau_5}{\tau_4-\tau_5}\exp\left(-\frac{t}{\tau_5}\right)\right] - \frac{\dot{N}^-\tau_5}{\beta}\left[1-\exp\left(-\frac{t}{\tau_5}\right)\right] \; ; \tag{20}$$

plasma exhaust processing:

$$I_6(t) = I_{6\infty}\left[1-\exp\left(-\frac{t}{\tau_6}\right)\right] \; ; \tag{21}$$

limiter coolant processing:

$$I_7(t) = I_{7\infty}\left[1-\exp\left(-\frac{t}{\tau_7}\right)\right] \; ; \tag{22}$$

and first-wall coolant processing:

$$I_8(t) = I_{8\infty}\left[1-\exp\left(-\frac{t}{\tau_8}\right)\right] \; , \tag{23}$$

where

$$I_{1\infty} = \Lambda\dot{N}^-\tau_1 \tag{24}$$

$$I_{2\infty} = (1-f_c)\frac{\Lambda\dot{N}^-\tau_2\tau_1}{T_1} = \Lambda\cdot I_{2\Lambda} \tag{25}$$

$$I_{3\infty} = f_c\frac{\Lambda\dot{N}^-\tau_3\tau_1}{T_1} = \Lambda\cdot I_{3\Lambda} \tag{26}$$

$$I_{4\infty} = \tau_4\left(\sum_{\substack{i=2\\i\neq4,5}}^{8}\frac{I_{i\infty}}{T_i} + \dot{I}_9\right) \tag{27}$$

$$I_{5\infty} = \tau_5\left[\frac{\tau_4}{T_4}\left(\sum_{\substack{i=2\\i\neq4,5}}^{8}\frac{I_{i\infty}}{T_i} + \dot{I}_9\right) - \frac{\dot{N}^-}{\beta}\right] \tag{28}$$

$$= \tau_5\left(\frac{I_{4\infty}}{T_4} - \frac{\dot{N}^-}{\beta}\right)$$

$$I_{6\infty} = (1-\beta-f_L-f_F)\frac{\dot{N}^-\tau_6}{\beta} \tag{29}$$

$$I_{7\infty} = f_L\frac{\dot{N}^-\tau_7}{\beta} \tag{30}$$

$$I_{8\infty} = f_F\frac{\dot{N}^-\tau_8}{\beta} \; . \tag{31}$$

In this model, we have incorporated the flexibility to specify a minimum tritium inventory reserve, I_5^m. This reserve quantity is to allow continued reactor operation during operational interruption of any part of the tritium cycle. The most demanding system on the reserve inventory is the plasma exhaust processing system, whose reserve inventory is calculated in the model as the product of t_r and the tritium flow rate to the plasma, where t_r is the number of days required to supply fuel to the plasma while the plasma exhaust processing system is not operational. The tritium flow rate to the plasma is equal to $\dot{N}^-/\beta$. For low fractional burnup, this reserve quantity, or minimum inventory, turns out to be one of the more important parameters in establishing the required TBR.

The required initial startup inventory was set equal to this reserve or minimum quantity, I_5^m, plus the sum of equilibrium inventories in all reactor compartments. The initial inventory is defined to be in the storage compartment, I_5^0, with all other compartments' inventories initially set equal to zero.

The doubling time is defined as the time when the storage inventory reaches a value equaling the sum of the initial inventory, I_5^0, and the minimum inventory, I_5^m. Expressing these concepts in terms of the above equations in order to obtain the doubling time, t_d, we set the inventory in the storage unit ($i = 5$) equal to:

$$I_5(t_d) = I_5^m + I_5^0 \ . \qquad (32)$$

Since different definitions of the doubling time have been used in the literature, a doubling time defined as the time for storage inventory equal to two times the initial inventory I_5^0 has also been evaluated, as shown shortly.

The value of the minimum inventory is not readily accessible by analytic solution due to the complicated expression for storage inventory as a function of time. The minimum inventory was calculated numerically by evaluating the storage inventory as a function of time using Eq. (20). With I_5^m and I_5^0 known, their sum [by Eq. (32)] is set equal to $I_5(t_d)$ given in Eq. (20). The dependence of Eq. (20) on the required TBR, Λ_r, is related explicitly in Eqs. (25) and (26). By substituting the expressions of Eqs. (25) and (26) into Eq. (20), and rearranging, we get an explicit expression for $\Lambda_r(t_d)$:

It is important to keep in mind that the storage unit minimum inventory, I_5^m, cannot be set independently. Rather, it is a function of the initial inventory and other system parameters. For practical convenience, we have omitted an analytic expression for I_5^m, which was determined more easily by numerical means with a short computer program.

After Λ is calculated, the initial inventory is recalculated to check against the initial inventory, which was originally estimated using an assumed Λ value. Because initial inventory is weakly dependent on Λ, convergence to within 0.1% was reached with a small number of iterations.

IV. CALCULATIONS OF REQUIRED BREEDING RATIO

IV.A. Base Case

Parameter values were selected for a base (reference) case to represent the most probable or expected values in the tritium cycle. These values define the "base case" for the calculation of $1 + G_0$ and are listed in Table I. By selecting a negligible loss fraction ($f_c = 0.01$) to the coolant, the base case applies equally well to a liquid-metal blanket or to a solid breeder provided the tritium permeation from the solid breeder to the coolant is kept very low, e.g., by use of tritium permeation barriers. The blanket residence time, T_1, in the reference case is 10 days, which results in an equilibrium blanket tritium inventory of ~5 kg. This is consistent with present estimates for solid breeder blankets, but it is somewhat higher than the representative values for liquid metals. However, since the TBR varies only slightly with lower T_1, as shown later, the reference case applies to many liquid-metal

$$\Lambda_r(t_d) = \Bigg(\bigg(\bigg\{I_5^m + I_5^0\Big[1-\exp\Big(-\frac{t_d}{\tau_5}\Big)\Big]\bigg\} - \dot{I}_9\frac{\tau_4\tau_5}{T_4}\Big[1+\frac{\tau_4}{\tau_5-\tau_4}\exp\Big(-\frac{t_d}{\tau_4}\Big)+\frac{\tau_5}{\tau_4-\tau_5}\exp\Big(-\frac{t_d}{\tau_5}\Big)\Big]$$
$$+\frac{\dot{N}^-\tau_5}{\beta}\Big[1-\exp\Big(-\frac{t_d}{\tau_5}\Big)\Big]$$
$$-\sum_{j=6,7,8}\bigg\{I_{j\infty}\frac{\tau_4\tau_5}{T_jT_4}\bigg[1-\frac{\tau_4^2\exp\Big(-\frac{t_d}{\tau_4}\Big)}{(\tau_j-\tau_4)(\tau_5-\tau_4)}-\frac{\tau_5^2\exp\Big(-\frac{t_d}{\tau_5}\Big)}{(\tau_j-\tau_5)(\tau_4-\tau_5)}-\frac{\tau_j^2\exp\Big(-\frac{t_d}{\tau_j}\Big)}{(\tau_4-\tau_j)(\tau_5-\tau_j)}\bigg]\bigg\}\bigg)$$
$$\div\sum_{i=2,3}\Bigg(\bigg\{I_{i\Lambda}\frac{\tau_4\tau_5}{T_iT_4}\bigg[1+\frac{\tau_1^3\exp\Big(-\frac{t_d}{\tau_1}\Big)}{(\tau_i-\tau_1)(\tau_4-\tau_1)(\tau_5-\tau_1)}$$
$$+\frac{\tau_i^3\exp\Big(-\frac{t_d}{\tau_i}\Big)}{(\tau_1-\tau_i)(\tau_4-\tau_i)(\tau_5-\tau_i)}+\frac{\tau_4^3\exp\Big(-\frac{t_d}{\tau_4}\Big)}{(\tau_1-\tau_4)(\tau_i-\tau_4)(\tau_5-\tau_4)}+\frac{\tau_5^3\exp\Big(-\frac{t_d}{\tau_5}\Big)}{(\tau_1-\tau_5)(\tau_i-\tau_5)(\tau_4-\tau_5)}\bigg]\bigg\}\Bigg) \ . \qquad (33)$$

TABLE I

Base Case Parameter Definitions and Values

Parameter (X)	Base Case Value (X_{ref})
Tritium consumption (burn in plasma), $\dot{N}^-$ (kg/day)	0.5
Doubling time, t_d (yr)	5
Tritium fractional burnup in plasma, β (%)	5
Number of days of reserve for plasma fueling, t_r (day)	2
Nonradioactive losses (chemical tie-up in radioactive waste, etc.) in	
Breeder processing, ϵ_2 (%)	0.1
Blanket coolant processing, ϵ_3 (%)	0.1
Fuel cleanup and isotope separation units, ϵ_4 (%)	0.0
Plasma exhaust processing, ϵ_6 (%)	0.1
Limiter coolant processing, ϵ_7 (%)	0.1
First-wall coolant processing, ϵ_8 (%)	0.1
Tritium mean residence times in	
Blanket, T_1 (day)	10
Breeder processing, T_2 (day)	1
Blanket coolant processing, T_3 (day)	100
Fuel cleanup and isotope separation units, T_4 (day)	0.1
Plasma exhaust processing, T_6 (day)	1
Limiter coolant processing, T_7 (day)	100
First-wall coolant processing, T_8 (day)	100
Tritium fractional leakage from	
Breeder to blanket coolant processing, f_c (%)	1
Plasma to limiter coolant processing, f_L (%)	0.01
Plasma to first-wall coolant processing, f_F (%)	0.01
Constant tritium flow returned from the waste, steam, and air processing, $\dot{I}_9$ (g/day)	0.01

blankets as well. The selection of a tritium burn fraction equal to 0.05 or 5% is considered to be equally valid for a tokamak or for a tandem mirror design in light of present uncertainties with both confinement concepts. The three coolant processing units had residence times of 100 days, a length of time chosen to account for slow recovery processes expected in coolants. It can be much longer in the case of water. In the reference case reported here, the loss fraction from the fuel cleanup unit was set to zero, and the residence time set very short ($\leq$0.1 days) to simulate holdup in the separate compartments and a rapid channeling of tritium through the fuel cleanup unit and into storage.

In Table II, the results of the required TBR, Λ, are shown for the base case along with that for three other

TABLE II

Required Tritium Breeding Ratio, Λ, for Four Cases

Case	Doubling Time Condition[a]	Doubling Time (t_d) (yr)	Tritium Fractional Burnup (β)	Initial Inventory (kg ^{3}H)	Minimum Inventory	Λ
1 (base case)	$I_5 = I_5^0 + I_5^m$	5	0.05	35.5	21.1	1.08
2	$I_5 = 2 * I_5^0$	5	0.05	35.5	21.1	1.10
3	$I_5 = I_5^0 + I_5^m$	10	0.1	20.2	10.5	1.03
4	$I_5 = 2 * I_5^0$	10	0.1	20.2	10.5	1.04

[a]Expressed in terms of the storage unit inventory, I_5, its initial inventory, I_5^0, and its minimum inventory, I_5^m.

cases. All cases have similar parameter values except for the doubling time, burn fraction, and the inventory condition used to define the doubling time. In the base case (case 1), Λ is calculated as 1.08. If the definition of doubling time, t_d, is changed to be that at which the storage inventory is twice the initial inventory (i.e., $I_5 = 2I_5^0$), then Λ increases to 1.10. However, the definition in the base case ($I_5 = I_5^0 + I_5^m$ at t_d) is more consistent with that in the power industry and is used throughout the rest of this work. Case 3 is similar to case 1 except that the doubling time and the fractional burnup, β, in the plasma are changed from 5 yr and 5% to 10 yr and 10%, respectively. This increase in t_d and β reduces Λ to 1.03. The effect of using the alternative definition for t_d in case 3 is shown in Table II.

The time variations of the inventories by subsystem are shown for cases 1 and 3 described above in Figs. 2 and 3, respectively. As noted from the figures, the tritium inventory in the plasma exhaust processing subsystem remains constant after the first 2 days. Thereafter, because of its short residence time in that subsystem, the tritium inventory is constant at its equilibrium value. The storage inventory decreases as tritium is initially injected into the plasma and burned but it increases slowly, then rapidly, as the tritium inventories in the other subsystems build up and reach their saturation levels. We have found that the minimum inventory occurs ~30 days post-startup. It is noted from Fig. 3 for case 3 that a larger burn fraction causes the plasma exhaust processing inventory to be less than the blanket inventory. Blanket inventory variations will then appear more significant.

Case 1 above, together with the definition of the doubling time as the time when storage inventory equals the sum of the initial and minimum inventories, was selected as the base case for subsequent analysis of TBR sensitivity and uncertainty. For this base case, Λ is found to be 1.08, i.e., the breeding margin, G_0, is 0.08.

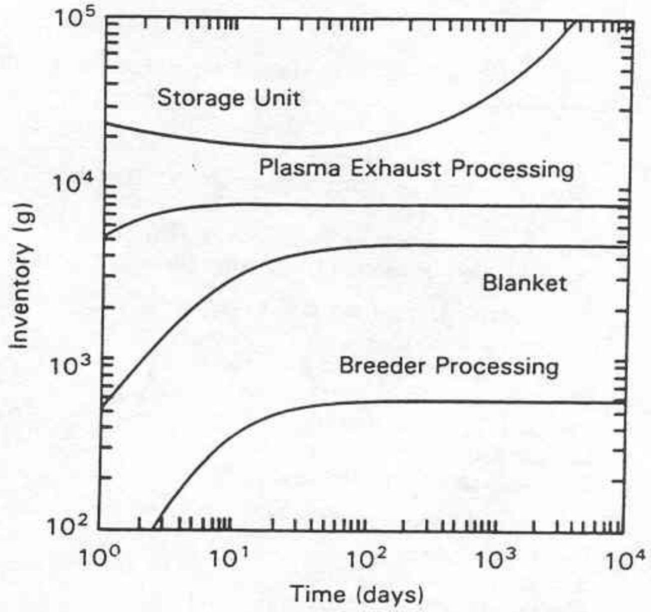


Fig. 2. Tritium inventory variation with time for the base case parameter values using $\beta = 0.05$ and $t_d = 5$ yr.

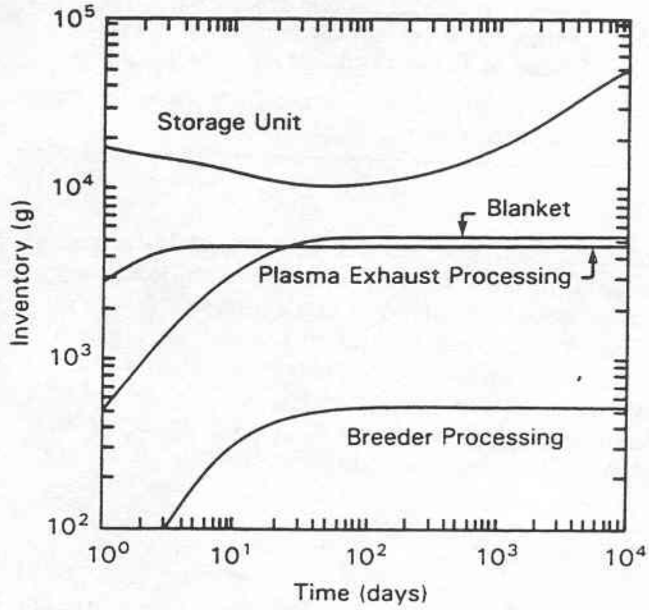


Fig. 3. Tritium inventory variation with time for the base case parameter values except $\beta = 0.1$ and $t_d =$ 10 yr.

IV.B. Sensitivity to Single Parameter Variation

The sensitivity of TBR, Λ_r, to each of the parameters of the fuel cycle was examined over a range from one-tenth to ten times the base case reference value. Table III shows the required breeding ratio, Λ_r, at the endpoints of these variations, i.e., at $x = x_{ref}/10$ and $x = 10x_{ref}$, where x_{ref} is the value of the parameter in the reference base case described in the previous section, Sec. IV.A. The rate of change in TBR due to variations in each parameter was evaluated as the slope of the TBR curve at the parameters' normalized reference value and this slope $[\partial \mathrm{TBR}/\partial(x/x_{ref})]$ is also shown in the table. The parameter slopes are summed and the percentage of total slope—or percent of the total TBR slope at the base case values that is attributable to each parameter—is calculated as shown in the last column. This column can be interpreted as the percent of the total variation in the base case due to each parameter for a small change in all the independent variables simultaneously. These values also give a relative measure of the importance of the various parameters to the required TBR in the base case. For example, the results in the table show that the number

TABLE III

Summary of Variation of the Required Breeding Ratio with a Single Change in Each of the Reference Parameters

Parameter (X)	TBR for		Slope	Percentage of Total Slope
	($X_{ref}/10$)	($X_{ref} \times 10$)		
$\dot{N}^-$	1.08(0.0%)[a]	1.08(0.0%)[a]	0.0001	0.1
t_d	1.53(41.7%)	1.04(−3.7%)	−0.0534	24.0
β	1.70(57.4%)	1.02(−5.6%)	−0.0863	38.8
t_r	1.05(−2.8%)	1.37(26.8%)	0.0322	14.5
ϵ_2	1.08(0.0%)	1.09(0.9%)	0.0011	0.5
ϵ_3	1.08(0.0%)	1.08(0.0%)	0.0000	0.0
ϵ_6	1.06(−1.8%)	1.25(15.7%)	0.0192	8.6
ϵ_7	1.08(0.0%)	1.08(0.0%)	0.0000	0.0
ϵ_8	1.08(0.0%)	1.08(0.0%)	0.0000	0.0
T_1	1.07(−0.9%)	1.19(10.2%)	0.0096	4.3
T_2	1.08(0.0%)	1.09(0.9%)	0.0009	0.4
T_3	1.08(0.0%)	1.09(0.9%)	0.0015	0.7
T_4	1.08(0.0%)	1.10(1.9%)	0.0009	0.4
T_6	1.06(1.8%)	1.22(13.0%)	0.0153	6.9
T_7	1.08(0.0%)	1.08(0.0%)	0.0002	0.1
T_8	1.08(0.0%)	1.08(0.0%)	0.0002	0.1
f_c	1.08(0.0%)	1.09(0.9%)	0.0014	0.6
f_L	1.08(0.0%)	1.08(0.0%)	0.0004	0.2
f_F	1.08(0.0%)	1.08(0.0%)	0.0004	0.2
			$\sum = 0.2231$	$\sum = 100.0$

[a]Values in parentheses represent the relative change of TBR with respect to a reference TBR of 1.08.

of days of fuel reserve, i.e., t_r, is twice as important as the mean residence time in the plasma exhaust processing system, i.e., T_6, in terms of changes in TBR due to changes in the reference values. The percentages of the total slope for t_r and T_6 are 14.5 and 6.9, respectively.

Based on extreme TBR values within this range of parameter variations and on the slope of the TBR sensitivity curve at the parameter reference value, six parameters can be identified as significantly affecting the expected TBR over that range. These parameters have an absolute slope of the TBR sensitivity curve at the base case condition of equal to or greater than 0.01, as seen in Table III. This represents a resulting 1% variation in TBR per unit change in the reference case parameter value. These six parameters were selected for further study as they accounted for over 97% of the total variation in TBR at the base case values. None of the other parameters contributed more than ~0.7% to the total variation. In order of their significance these parameters are: tritium fractional burnup in the plasma, doubling time, number of days of tritium fuel reserve, nonradioactive loss fraction, mean residence time in the plasma exhaust processing system, and, to a lesser extent, the blanket mean residence time. The TBR variation with each of these six parameters is shown in Fig. 4. Each parameter is varied in the range $0.1 \times x_{ref}$ to $10 \times x_{ref}$, where x_{ref} is the value of the parameter in the reference case.

The strong dependence of TBR on the fractional burnup and doubling time has been previously reported, and our results agree closely with those in the literature.[1-3] The number of days of tritium fuel (t_r) reserve is noted here to be very important especially for values greater than the reference case of 2 days, due to the resulting large inventory. This has not been previously noted in the literature. Figure 5 shows the required TBR as a function of the tritium fractional burnup in the plasma, β, at several values of t_r. The required Λ increases very rapidly as β decreases and t_r increases since the reserve inventory is proportional to t_r and the tritium fueling flow rate to the plasma is inversely proportional to β. For $\beta > 20\%$, the importance of t_r decreases substantially. For $\beta > 5\%$, t_r up to ~3 days can be tolerated if Λ of ~1.10 is acceptable. At lower β, it is extremely important that t_r be minimized. This means that the plasma exhaust processing system must be reliable and will require only a short time to repair. The alternative of shutting down the fusion power plant each time there is a failure in the plasma exhaust processing system is likely to be economically unacceptable.

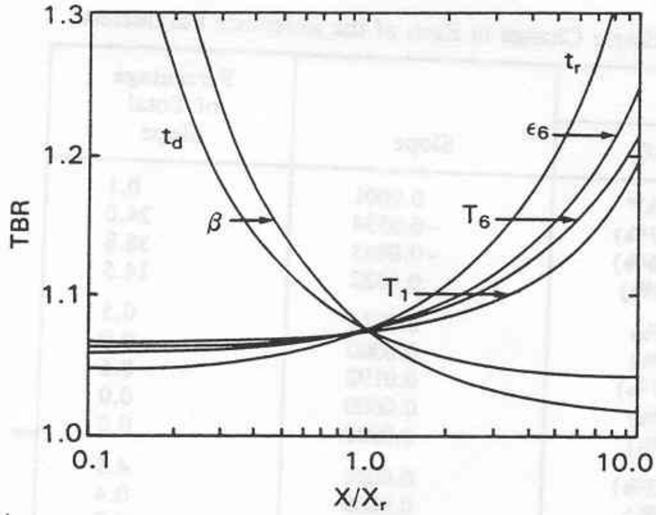


Fig. 4. Variation of the required TBR with key parameters. The horizontal axis is X/X_{ref}, where X_{ref} is the value of the parameter in the reference base case shown in Table I.

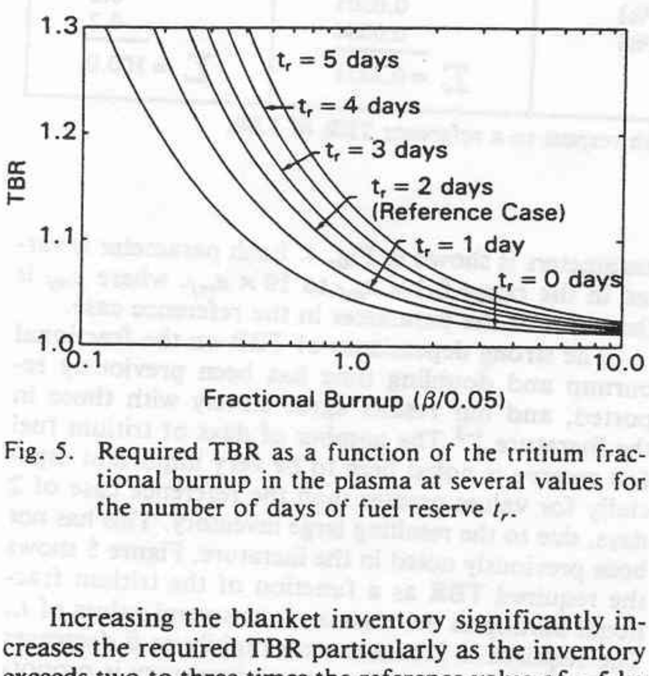


Fig. 5. Required TBR as a function of the tritium fractional burnup in the plasma at several values for the number of days of fuel reserve t_r.

Increasing the blanket inventory significantly increases the required TBR particularly as the inventory exceeds two to three times the reference value of ~5 kg (corresponding to a mean blanket residence time, T_1, of 10 days) as shown in Fig. 4. This could become a significant concern for a solid breeder undergoing chronic radiation damage with possible subsequent increases in tritium residence time and inventory.

Reactor subsystems that were modeled because of reported potential tritium permeation problems[7,8] included the first wall and limiter (or divertor) coolant systems. In the reference case, the tritium fractional leakage into the first wall and limiter coolant processing compartments was fixed at 0.01%, which is equivalent to an incoming tritium flow rate of 1 g/day. This value is consistent with recent estimates of tritium permeation[7,8] but there are very large uncertainties in this area. However, as the fractional leakage into the first wall was increased by an order of magnitude (to 10 g/day), a <1% change in the required TBR was observed. Even in the case of long residence times (100 days) representing a possibly slow tritium separation process from a water coolant, these subsystems held negligibly small inventories and thus they had negligible impact on the expected TBR. Obviously, much higher tritium permeation rates on retention inventories in the in-vessel components can significantly increase the required TBR but the safety and economic implications of such high rates are too large to be acceptable.[8]

IV.C. Sensitivity to Variations in Two Parameters

Some effort was made to examine the effect on the required breeding ratio of varying two parameters simultaneously. The combined effect is nonlinear and would have to be calculated separately for each combination of parameters. With one parameter (called a "floated" parameter) continuously varied from one-tenth to ten times of its base case reference value and the second parameter fixed at one-tenth and then at ten times of its reference value, the ranges of the TBRs for these two varied parameters are calculated. The six most important parameters discussed before were examined.

Table IV lists the required TBR values Λ for the two parameters varied from one-tenth to ten times their reference values in base case 1. One of the worst cases found is when the doubling time is short (0.5 yr) and the tritium residence time in the blanket is long (100 days). Then, as shown in the table, the required TBR value can be unrealistic, as large as several hundred. The long tritium residence time in the blanket means that a large equilibrium tritium inventory is held up in the blanket. The initial storage tritium inventory is thus increased by this large equilibrium blanket tritium inventory. To meet such a high initial tritium storage requirement within a very short period, a large tritium production rate and, therefore, large Λ must be required. The best case (Λ = 1.01) can be found when the tritium fractional burnup is high (0.5) and either the doubling time is long (50 yr), the tritium reserve fuel time is short (0.2 days), or the blanket residence time is short (1 day). Since a long doubling time may be an impractical constraint in fusion power economy, the alternatives to obtaining a small required TBR must be seriously considered as goals for fusion R&D. Such goals include attaining high tritium fractional burnup in the plasma through selection, design, and development of the impurity control and exhaust system; minimizing the tritium inventory in all reactor components, particularly the blanket; and developing reliable and efficient tritium processing systems. If the

TABLE IV

Effect on the Required TBR, Λ, Due to Simultaneous Variation in Two Parameters in the Reference Base Case

($\Lambda = 1.08$ for the reference case)

Floated Parameter		Second Parameter											
		T_1 (day)		T_6 (day)		ϵ_6		t_r (day)		t_d (yr)		β	
		1	100	0.1	10	0.0001	0.01	0.2	20	0.5	50	0.005	0.5
β	0.5	1.01	1.11	1.02	1.02	1.02	1.02	1.01	1.04	1.14	1.01	---	1.02
	0.005	1.68	1.90	1.56	3.16	1.52	3.49	1.41	4.57	5.38	1.40	1.70	---
t_d	50	1.04	1.08	1.04	1.10	1.03	1.21	1.03	1.16	---	1.04		
	0.5	1.40	>100	1.42	2.90	1.52	1.72	1.29	3.93	1.54	---		
t_r	20	1.35	1.53	1.35	1.51	1.35	1.54	---	1.37				
	0.2	1.04	1.15	1.04	1.19	1.03	1.22	1.05	---				
ϵ_6	0.01	1.24	1.37	1.24	1.39	---	1.25						
	0.0001	1.05	1.17	1.05	1.20	1.06	---						
T_6	10	1.21	1.35	---	1.22								
	0.1	1.06	1.17	1.06	---								
T_1	100	---	1.19										
	1	1.07	---										

tritium fractional burnup and doubling time are kept at the reference values, then a lower TBR requirement may be obtained by decreasing any one or two of the remaining four most important parameters simultaneously.

The required breeding ratios for the first parameter continuously varied with each of the second parameters at the reference and at the two extreme values are depicted in Figs. 6 through 11. In each of these figures, the x axis is the ratio of the new value of the first parameter to its reference value. The y axis is for the required breeding ratio, Λ_r. Several curves are displayed in each figure, with each curve for a specified value of the second parameter. Besides obtaining the required TBR within certain ranges, these figures can be used as reference maps in trade-off analysis. Several examples explaining the results of the figures are given in the following.

If the achievable tritium fractional burnup of a fusion reactor is assumed to be 0.1, then as seen from Fig. 6 the required TBR varies from 1.02 to 1.32 depending on the value of the other parameters. From Fig. 7, if the tritium fractional nonradioactive loss in the plasma exhaust processing system (ϵ_6) is no less than 0.01, no matter how the tritium doubling time is changed, the required TBR is always no less than 1.21. But, from Fig. 9, there is one possible way to obtain a TBR as low as 1.03 when $\epsilon_6 \geq 0.01$, which is attaining a high tritium fractional burnup.

As an example of trade-off considerations, suppose that the maximum achievable TBR for a fusion reactor is 1.05 and the days of tritium fuel reserve cannot be <1 day, then as seen from Fig. 8, several alternatives can be considered: designing the tritium residence time in the plasma exhaust processing subsystem at no more than 0.1 day, decreasing the tritium fractional nonradioactive loss to <0.0001, increasing the tritium doubling time to more than ~15 yr, or raising the fractional burnup to no less than ~0.1, whichever is achievable. Note that the examples shown above changed only two parameters in the reference case at one time. Changing more than two parameters simultaneously can provide additional perspective on the required TBR. However, such variations are so large that they must be considered only for specific cases.

In the parameter sensitivity study, the efficiencies of the recovery unit processes were examined and the plasma exhaust processing loss fraction was seen to affect the resultant TBR value significantly as shown in Fig. 9. For example, as a worst case, setting the plasma recovery loss fraction ϵ_6 equal to 0.02 results in a required TBR of 1.47. In Fig. 6, the importance of ϵ_6 increases rapidly at lower fractional burnup. This emphasizes the need to achieve very high efficiencies in the tritium processing subsystems, particularly that of the plasma exhaust.

Another problem arises in the recovery of tritium

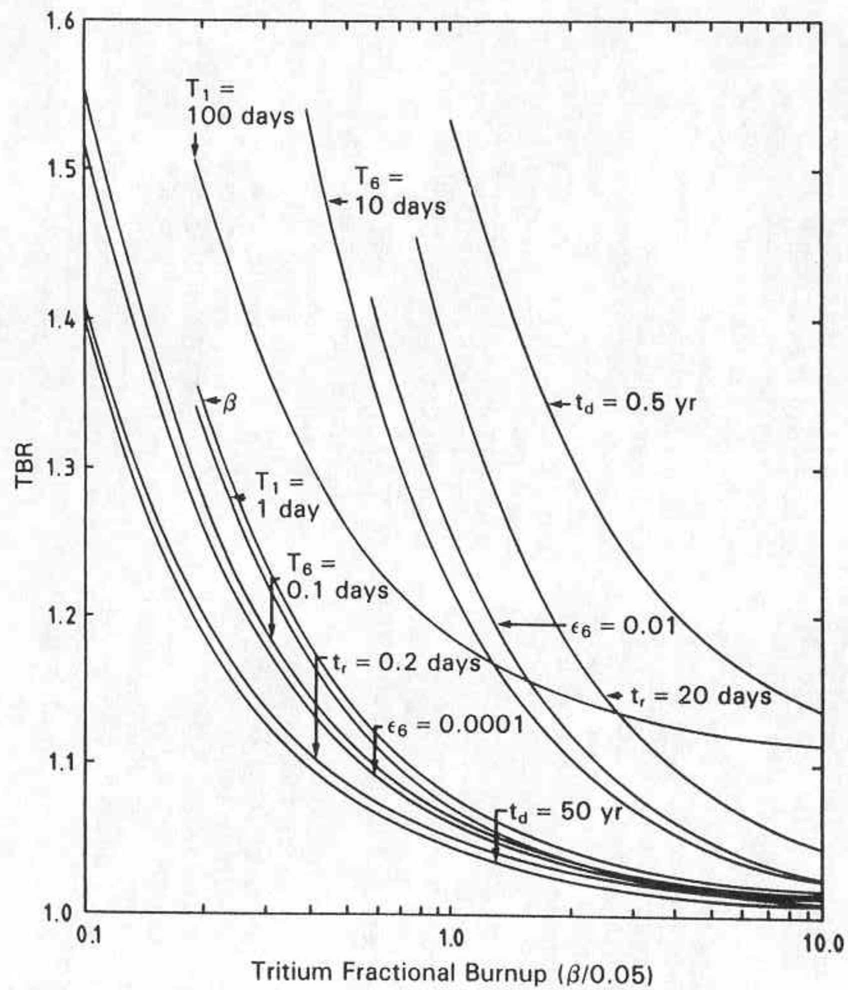


Fig. 6. The TBR sensitivity analysis of base case 1 with the tritium fractional burnup continuously varied and each of the other parameters fixed at one-tenth and at ten times its reference value.

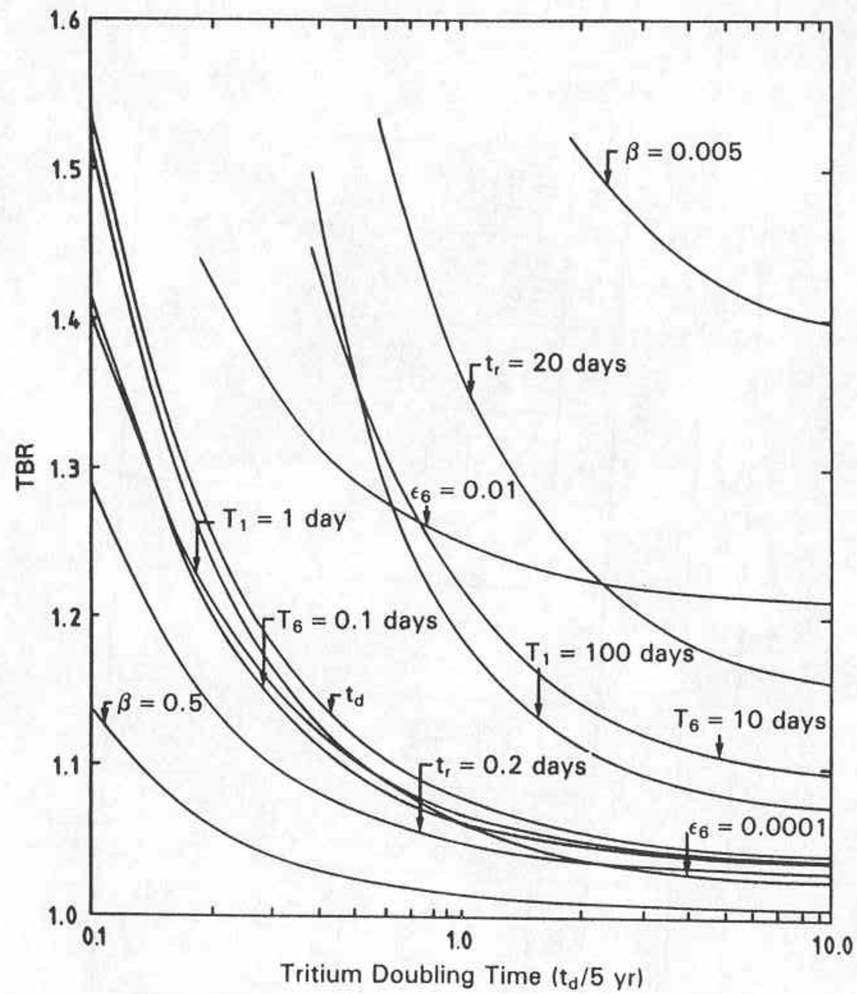


Fig. 7. The TBR sensitivity analysis of base case 1 with the tritium doubling time continuously varied and each of the other parameters fixed at one-tenth and at ten times its reference value.

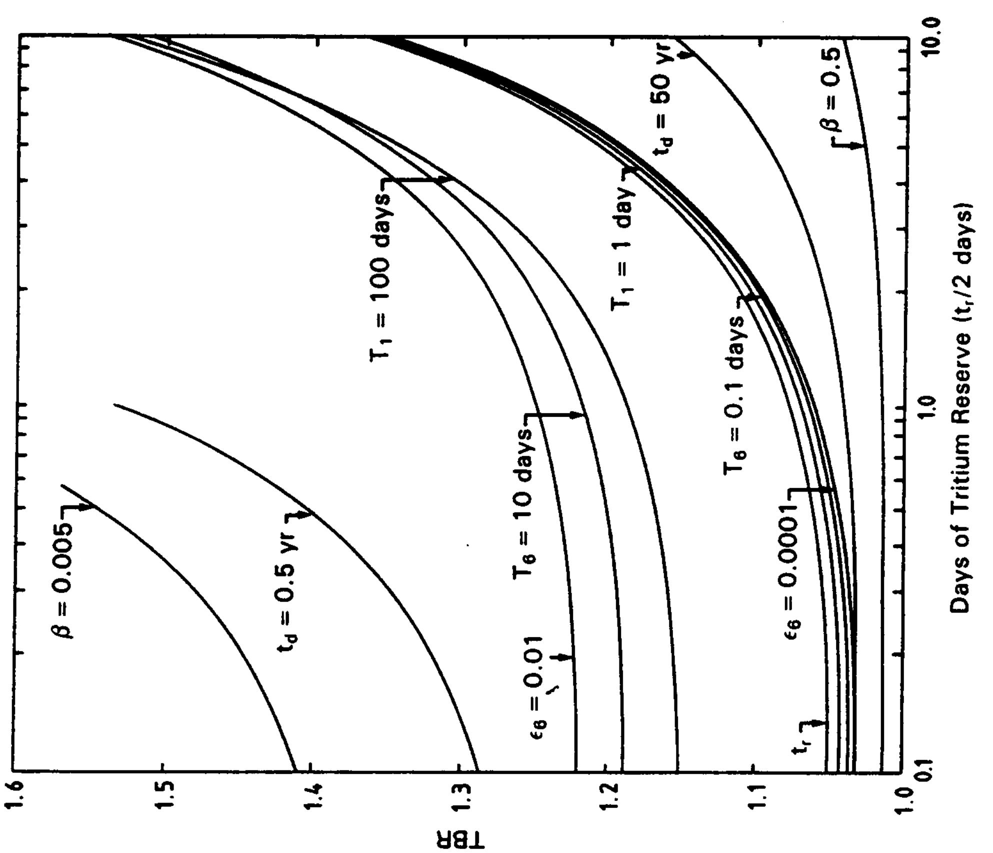


Fig. 8. The TBR sensitivity analysis of base case 1 with days of tritium reserve continuously varied and each of the other parameters fixed at one-tenth and at ten times its reference value.

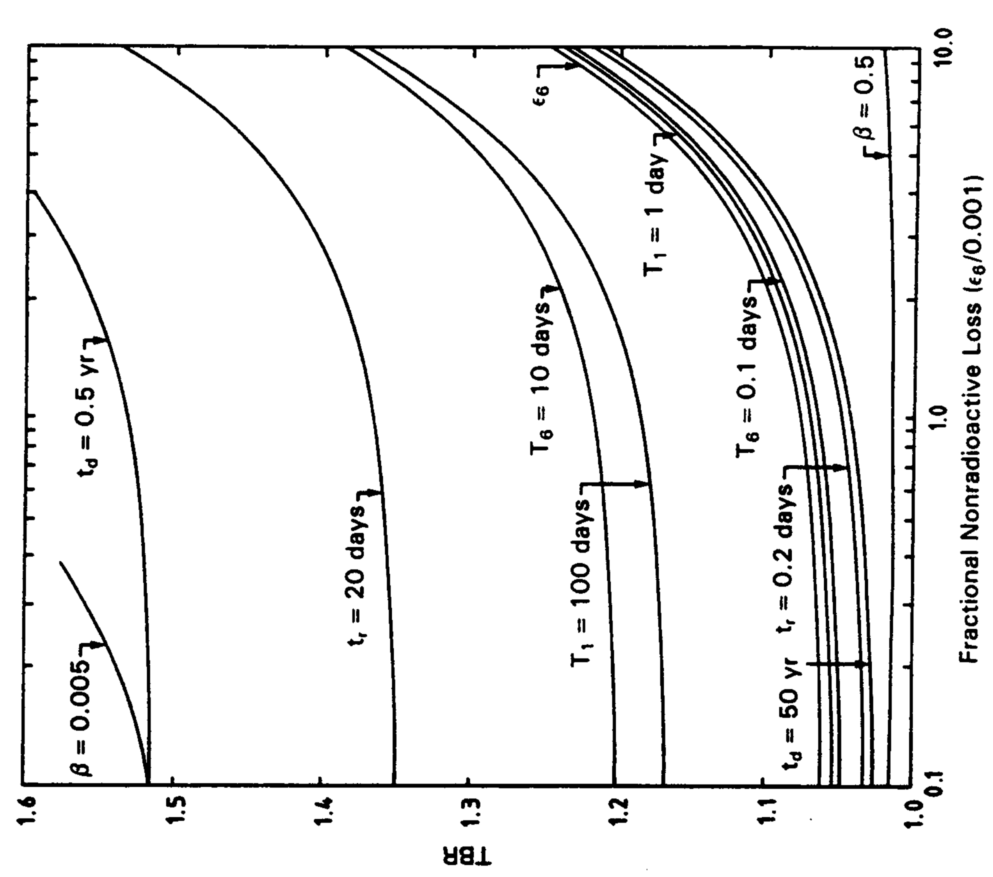


Fig. 9. The TBR sensitivity analysis of base case 1 with the tritium fractional nonradioactive loss in the plasma exhaust processing system continuously varied and each of the other parameters fixed at one-tenth and at ten times its reference value.

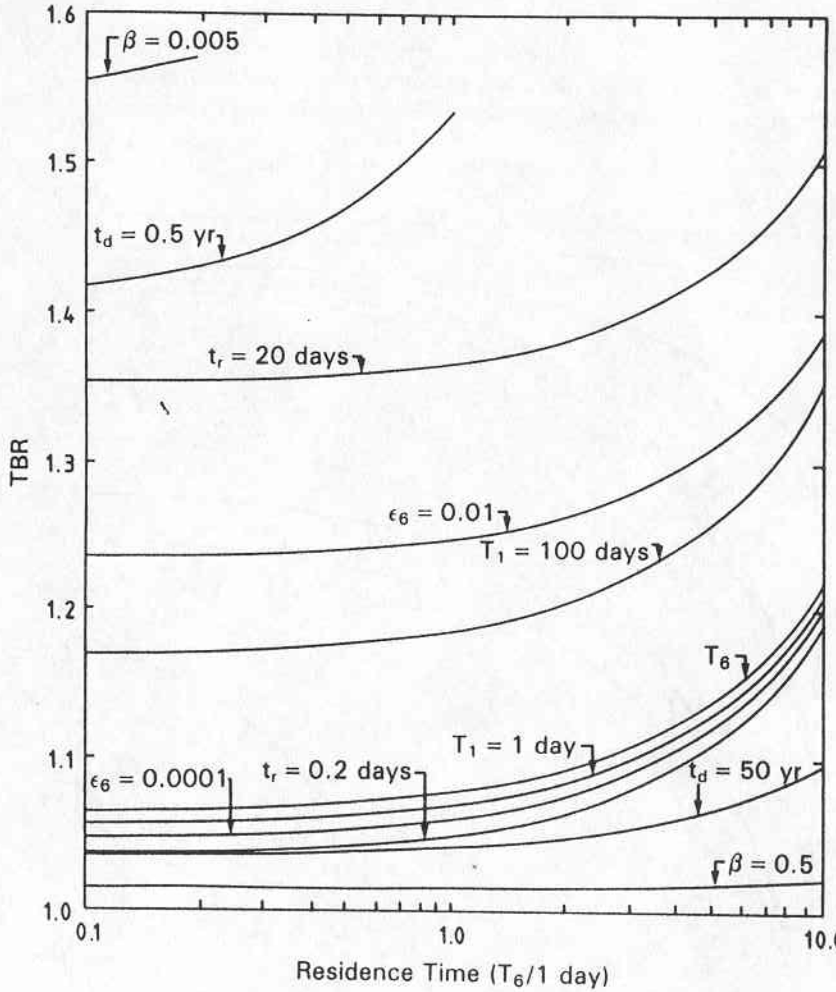


Fig. 10. The TBR sensitivity analysis of base case 1 with the tritium residence time in the plasma exhaust processing system continuously varied and each of the other parameters fixed at one-tenth and at ten times its reference value.

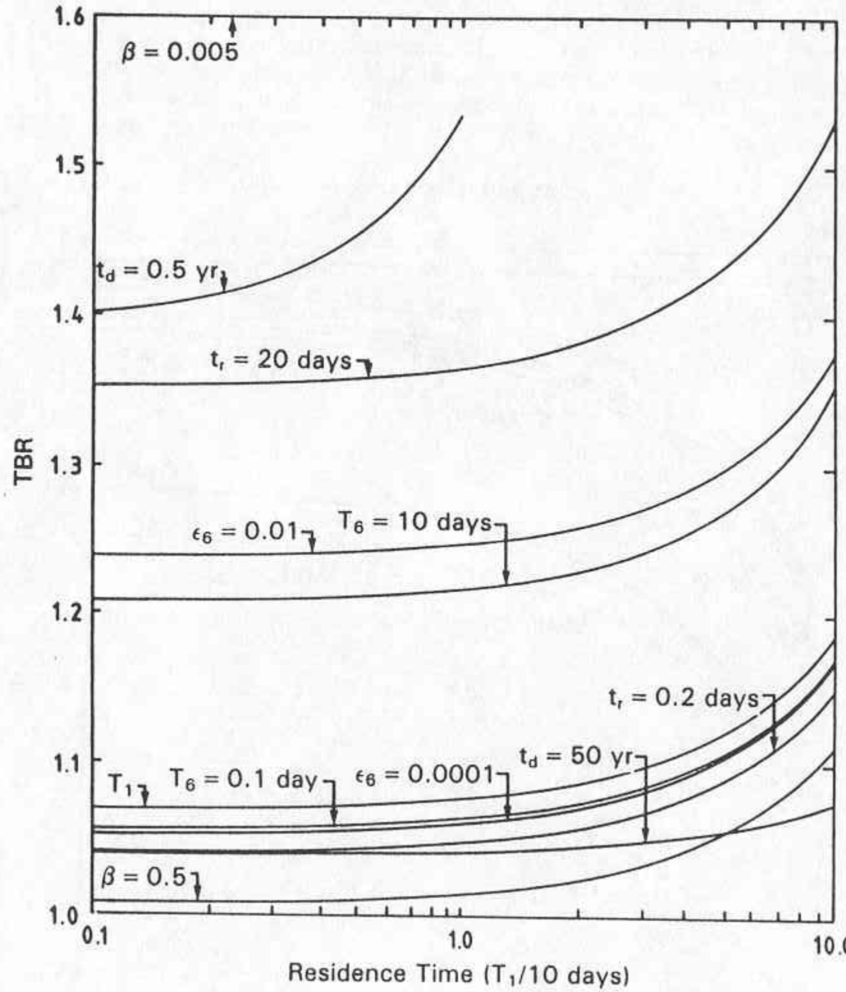


Fig. 11. The TBR sensitivity analysis of base case 1 with the tritium residence time in the blanket continuously varied and each of the other parameters fixed at one-tenth and at ten times its reference value.

from the solid breeder where the tritium in the helium purge gas may contain some fraction of tritiated water and other additives or a large fraction of the bred tritium permeates to the coolant. This tritium may need to be cycled through a long-term recovery process, which will significantly change the kinetics of the system. This possibility could be considered by setting the fraction of bred tritium that is transported to the coolant f_c (or therefore the long recovery process) equal to a large fraction, e.g., 50%. This value of transport fraction to the coolant was examined in the study, and changed the base case reference value of the required TBR from 1.08 up to ~1.13 at $f_c = 50\%$. This could be a very critical increase for breeders that have a limited achievable breeding ratio.

The model assumed that tritium in the storage unit was lost only by radioactive decay. A real system may need occasional replacement of the uranium beds, may leak, and is subject to rare accidents involving tritium loss (which may be considered as a time-averaged value in a simple analysis). This was examined briefly for the base case by adding a loss pathway in the model from the tritium storage compartment that allowed for a constant loss fraction, proportional to the stored quantity. It was found that the required TBR did not increase significantly above the base case value of 1.08 until the loss fraction was increased to about one part per one thousand, where the TBR required was ~1.13. The required TBR increases rapidly for greater loss fractions from storage. But it appears that with existing technology a realistic storage loss can easily achieve a loss of under one part per thousand.

V. UNCERTAINTIES IN SYSTEM DEFINITION

V.A. Introduction

In previous sections, we indicated the large uncertainties in estimating the required breeding ratio due to uncertainties in defining the relevant parameters, e.g., tritium inventories in the fuel cycle. This section attempts to examine those uncertainties in the definition of a fusion reactor system that leads to uncertainties in estimating the achievable breeding ratio.

The uncertainties in the fusion system definition that impact the achievable TBR, Λ_a, can be classified into two types. The first relates to the first wall/blanket and the second to the rest of the reactor. There are a diversity of blanket concepts that involve different combinations of breeder, coolant, multiplier, and structure. These concepts have different breeding potential that can be calculated for a specified blanket. However, even for a given first-wall/blanket concept there are uncertainties associated with the ability to make precise specifications of configuration details, amount and distribution of breeder, structure, coolant, and coolant manifolds. For example, future data on radiation effects on the thermophysical properties and temperature range for tritium release may require changes in our present conceptual design as to the volume percentages of the structure, coolant, and breeder, which will affect the breeding ratio.

For a given first wall/blanket, the TBR is affected by many of the reactor features that are currently uncertain. Examples are:

1. technology choices for major components, e.g., limiter versus divertor for impurity control and neutral beam versus radio-frequency (rf) for auxiliary heating
2. for a given technology choice (e.g., limiter), uncertainties as to the choice of materials and geometry and size of plates and penetrations—all of which affect TBR
3. presence of yet undefined, or poorly defined, components, e.g., penetrations for diagnostics and fueling
4. possible need for components to satisfy yet undefined, or poorly defined, requirements, e.g., passive copper coils may need[7] to be placed inside a tokamak blanket for plasma stabilization, and there may be a need for neutronically significant sector-to-sector electrical joints.[6]

The procedure adopted here is: (a) to estimate the obtainable TBR for a given blanket concept in a specified reference reactor system, e.g., STARFIRE for tokamaks[5] or MARS for mirrors,[9] and (b) to estimate the changes in TBR for the given blanket due to variations in the reference reactor system. These changes can be combined to make an estimate of Δ_s, the uncertainty in the achievable breeding ratio due to uncertainties in the system definition.

The reference calculations for a number of top-ranked blanket concepts in the reference reactor systems are provided by Jung in Sec. 6. of Ref. 10. Below, we provide the results for the sensitivity of TBR to reactor system definition. It is not practically possible, nor is it productive, to consider all types of blankets and all possible system variations. Below we consider only one blanket concept in a given reference reactor design and we examine the effect of a number of key changes in the system definition.

V.B. Geometrical Description of the Standard Model

The STARFIRE model was utilized as the reference three-dimensional tokamak reactor configuration as shown in Fig. 12. The Li_2O/He/FS blanket was used as a typical blanket. The material configurations in the outboard and inboard blanket sectors are listed in Table V. These configurations are generally similar to those in the reference model of Ref. 10, except that

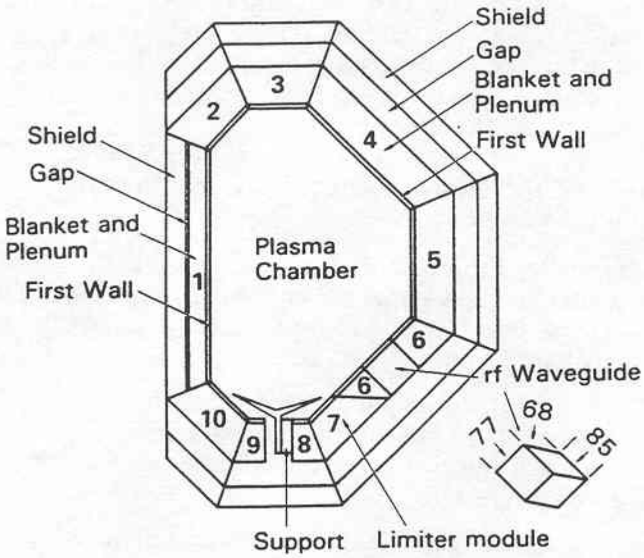


Fig. 12. A vertical cross section of the reference reactor system for tokamaks.

50-cm-thick Type 316 stainless steel was assumed here. The selection of the shield material has less impact on the TBR than other system parameters. The vacuum boundary condition was imposed at the outer surface of the shield in the radiation transport calculation.

A water-cooled limiter was assumed at the bottom of the plasma. It was taken from the Fusion Engineering Device/International Tokamak Reactor (FED/INTOR) phase 2A study.[7] The limiter was sustained at the center of the 57-cm-wide limiter duct with an HT-9 support material, which was fixed to the limiter module (see Fig. 13). Coolant channels were not considered in the support. Limiter panels extended for 1 m from the center support. They occupied an $\sim$72-m^2 area, which is $\sim$9% of the whole area of the first-wall surface. The limiter was assumed to be made of copper, which is the structural material, water coolant, and beryllium coating. The thickness of the copper structure in the panels varied from 1.5 cm at the edge to 10 cm at the center. The coolant channel regions were homogenized as shown in Fig. 13 and in Table V in the radiation transport calculation.

The rf waveguides of the STARFIRE design were employed as representative of the plasma heating and current drive systems. As shown in Fig. 12, the waveguides were located in the outboard blanket at every 30 deg along the toroidal direction. The rectangular opening of the waveguide was 77 × 68 cm. The waveguide penetrated the outboard blanket straight to the blanket bottom, but beyond this point no additional details were considered. The material compositions of the waveguide structural materials along with the water coolant were taken from the STARFIRE design. Two different compositions, which were assigned to different parts of the waveguides inside the blanket in the original design, were averaged in this calculation to get the single composition, shown in Table V. No other type of penetrations such as gaps between blanket sectors and the instrumentation relating to plasma diagnostics was included in the reference model. Contribution to the TBR uncertainty from each of these penetrations will be small, but the total values of all these contributions may not be negligible.

A uniform D-shaped plasma was assumed in the analysis. The uniform plasma distribution tends to give larger TBR values compared to a magnetohydrodynamic (MHD)-shifted distributed plasma. The atomic density composition of each material used in this analysis is summarized in Table VI.

TABLE V

Material Configuration of Reference Calculation

Blanket	
Inboard	
First wall	6 cm (0.117 HT-9)
Blanket 1	12 cm (0.079 HT-9, 0.806 Li_2O)
Blanket 2	12 cm (0.286 HT-9, 0.625 Li_2O)
Plenum	11 cm (0.20 HT-9)
Gap	2 cm
Shield	50 cm (Type 316 stainless steel)
Outboard	
First wall	6 cm (0.117 HT-9)
Blanket 1	45 cm (0.079 HT-9, 0.806 Li_2O)
Blanket 2	12 cm (0.286 HT-9, 0.625 Li_2O)
Plenum	22 cm (0.2 HT-9)
Gap	50 cm
Shield	50 cm (Type 316 stainless steel)
Limiter (71.6-m^2 Area)	
Plate (107-cm width)	
Coating	1 cm (beryllium)
Coolant passage	0.65 cm (0.385 copper, 0.615 H_2O)
Structure	1.5 to 10 cm (copper)
Coolant passage	0.65 cm (0.385 copper, 0.615 H_2O)
Coating	0.2 cm (beryllium)
Interior support	
Coating	0.2 cm (beryllium)
Coolant passage	0.65 cm (0.385 copper, 0.615 H_2O)
Structure	10.3 cm (copper)
Coolant passage	0.65 cm (0.385 copper, 0.615 H_2O)
Coating	0.2 cm (beryllium)
Duct	57-cm width
Support	22.5-cm width (HT-9)
rf Waveguide (77 × 68 cm)[a]	
Waveguide	85 cm (0.53 PCA, 0.08 H_2O)

[a]Placed at every 30 deg.

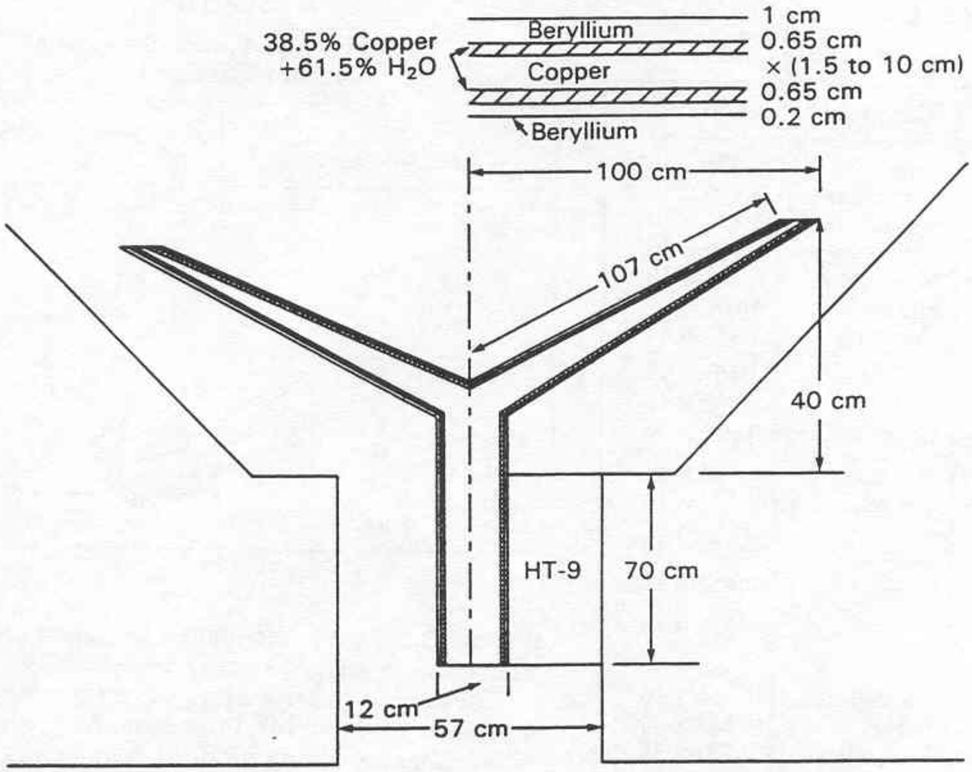


Fig. 13. A cross section of the reference limiter design.

V.C. Calculational Method and Results

The MCNP Monte Carlo code[11] was used in the uncertainty analysis along with the recently released RMCCS neutron cross-section library. The RMCSS library contains pointwise nuclear data based mainly on the ENDF/B-V evaluation,[12] and partly on the Los Alamos National Laboratory (LANL) T-2 group evaluation for iron, tungsten, and ^{7}Li. The T-2 group evaluation reproduces the secondary neutron spectra from lithium[13] more closely to a recent experiment[14] than the ENDF/B-V does.

V.C.1. Full Breeding Coverage Geometry

Calculations were performed in full blanket coverage geometries using a one- and three-dimensional geometry to serve as a reference against which the effects of system variations can be examined. The three-dimensional calculation by MCNP considered the inboard and outboard blanket configuration, but it did not account for any penetration. The one-dimensional calculation was performed using ANISN (Ref. 15) for the poloidal model of the outboard blanket. The VITAMIN-C 41B and MACKLIB-IV libraries[16] were used in the ANISN calculation. Results are shown in Table VII. As MACKLIB-IV was derived from the ENDF/B-IV library, the one-dimensional calculation resulted in a relatively large value because of the overestimated $^7\mathrm{Li}(n,n'\alpha)t$ cross section. A simple way of correction to the results derived using ENDF/B-IV data was made by reducing T_7, the tritium production rate from ^{7}Li, by 15%. This yields a breeding ratio of 1.212. Comparing this value with the three-dimensional result, the installation of the thinner inboard blanket decreased the TBR by 3%. This reduction is probably underestimated because the uniformly distributed neutron source assumes more neutrons incident on the outboard blanket than a distributed source with MHD shift does.

V.C.2. Tritium Production of Each Blanket Sector

Table VIII shows contributions to the tritium production from each blanket sector, which were obtained for the reference model with penetrations. The sector numbers referred to in the first column of the table correspond to those identified in Fig. 12.

The first wall of the inboard blanket covers ~20% of the total first-wall area. However, the relative contribution of the inboard blanket to the TBR is only 14% as seen in the table. The difference in the tritium production rate (TPR) between sectors 2 and 10 is due to the shadow effect by the limiter panel, which covers about half of the first wall of sector 10. So the limiter panel affected the TPR in sector 10 by ~20%. The TPR in sectors 8 and 9 was affected by both the

TABLE VI

Material Composition and Nuclide Density

Material	Constituent	atom/b·cm
HT-9	Iron	6.855×10^{-2}
	Chromium	9.930×10^{-3}
	Nickel	3.825×10^{-5}
	Molybdenum	4.680×10^{-4}
	Manganese	4.09×10^{-4}
	Silicon	4.00×10^{-4}
	Carbon	7.48×10^{-4}
Li_2O[a]	^7Li	7.551×10^{-2}
	^6Li	6.052×10^{-3}
	Oxygen	4.078×10^{-2}
H_2O	Hydrogen	6.686×10^{-2}
	Oxygen	3.343×10^{-2}
Beryllium		1.236×10^{-1}
Copper		8.45×10^{-2}
Tantalum		5.523×10^{-2}
PCA	Iron	5.486×10^{-2}
	Chromium	1.266×10^{-2}
	Nickel	1.282×10^{-2}
	Molybdenum	9.793×10^{-4}
	Manganese	1.710×10^{-3}
Type 316 stainless steel	Iron	5.462×10^{-2}
	Chromium	1.52×10^{-2}
	Nickel	1.121×10^{-2}
	Molybdenum	1.401×10^{-3}
	Manganese	1.232×10^{-3}
	Silicon	7.752×10^{-4}
	Carbon	2.286×10^{-4}

[a]Density is 0.8 of theoretical density.

TABLE VII

The TBR with Full Blanket Coverage

Geometry	TBR
Three-dimensional geometry[a] (outboard/inboard different)	1.182
One-dimensional cylinder[b] (outboard representative)	1.264

[a]From MCNP/RMCCS.
[b]From ANISN/MACKLIB-IV $T_6 + 0.85$, $T_7 - 1.212$.

limiter panels and the limiter duct. The opening of the limiter duct took 43% of the first-wall area of sector 3. Without the shadow effect by the limiter panels, the sum of the TPRs in sectors 8 and 9 would be ~60% of that in sector 3. Values in the table, however, show that the sum of the two sectors is ~30% of the value

TABLE VIII

Contribution to Tritium Production from Each Blanket Sector

Sector Number	Contribution (%)
1	13.8
2	5.31
3	7.8
4	23.8
5	21.5
6	15.4
7	5.37
8	1.28
9	1.32
10	4.42
Total	100.00

of sector 3. So the limiter panels decreased the tritium production in sectors 8 and 9 by ~50%.

The area of the rf waveguide opening is only 4% of the area of the sector 4 first wall. So the main factor affecting the tritium production in sectors 6 and 7, compared to sector 4, would be the shadow effect of the limiter panel. Actually, the panel covered sector 7, whose surface area is 20% of the total first-wall area of these sectors. The sum of the tritium production of sectors 6 and 7 is ~15% smaller than the sector 4 value.

V.C.3. Nonbreeding Inboard Blanket

The capital cost of a tokamak is very sensitive to the total thickness, Δ^i_{BS}, of the inboard region between the first wall and magnet, which is generally occupied by a blanket and shield. One option to reduce Δ^i_{BS} in order to improve the economics, without violating the magnet radiation protection criteria, is to reduce the thickness of or totally eliminate the inboard breeding blanket. However, this reduces the achievable TBR. The reference Li_2O/He/FS blanket design in the Blanket Comparison and Selection Study[17] (BCSS) employs a thin breeding blanket of 24 cm. The impact on the TBR due to the nonbreeding inboard blanket was examined by replacing the Li_2O in the inboard blanket with HT-9 in the reference model. The volume ratio of the helium coolant was kept the same as in the reference model. With this replacement, the TBR decreased by ~8% as shown in Table IX. The first column in the table shows the contribution of the inboard blanket to TBR in the reference model calculation. Reflection of low-energy neutrons by using HT-9 in the inboard increased the ^6Li tritium production in all other blanket sectors. This increment, however, did not cancel the decrement caused by replacing the inboard breeder with HT-9.

TABLE IX

Impact of Nonbreeding Inboard Blanket on TBR*

	Contribution of Inboard Blanket (%)	HT-9 Inboard Blanket[a] (%)	Lead Inboard Blanket[a] (%)
T_6	12.8 (±2.9)	−5.4 (±1.2)	+2.9 (±1.2)
T_7	15.2 (±3.1)	−15.8 (±1.4)	−15.8 (±1.4)
TBR	13.8 (±2.2)	−8.2 (±1.0)	−2.3 (±1.0)

*Shown is the relative deviation from the standard values.
[a]No breeding material inboard.

A neutron multiplying inboard blanket was considered. The breeding material, Li_2O, in the inboard sector was replaced with lead, which is well known as a good neutron multiplier, and the TBR calculation was repeated. The lead drastically increased the ^{6}Li tritium production by more than the decrement of T_6 caused by the removal of the inboard breeder. However, the total TBR was still lower by ~2% than the reference value because of the reduction in T_7.

V.C.4. Uncertainties Relating to Limiter Design

There are considerable uncertainties concerning the impurity control and exhaust system. There are several candidates for the type of system and many open questions as to the design of any given type. For the limiter, the open issues are the choice and amount of structural and plasma-side materials, the choice of coolant, the size of the limiter blade, the method and material for structural support, and the size of the vacuum duct. With reference to Fig. 12, it is desirable to have a nonbreeding material in the region indicated as the limiter module. Because the limiter has a short life, easy access to replace the limiter is desirable. All of these open issues result in uncertainties in estimating the achievable TBR.

The impact of the nonbreeding limiter module on the TBR was examined by the following simple model: The breeding material Li_2O was replaced with HT-9 steel in sectors 7 and 9 (see Fig. 12), the coolant being kept at the same volume as in the reference model. Results are shown in Table X. The adoption of a nonbreeding limiter module causes the TBR to drop by as much as 6%, which is significant.

The sensitivity of the TBR to the limiter duct width was analyzed by calculating the TBR for a case in which the width of the duct opening (57 cm in the reference model) was doubled. By doubling the duct width, ~3% more area of the total first-wall area was taken by the duct. The net decrease in the TBR is ~2% as shown in Table X, which is smaller than the fractional area change of the duct opening. This is because of the shadow effect of the limiter panels.

The limiter panels were coated by 1-cm-thick beryllium tile in the reference model. The coating is predicted to be eroded away by physical sputtering during reactor operation. So all the coating may be lost at the end of the short limiter lifetime. Estimation of the TBR uncertainty relating to this effect was done by testing the change in the TBR due to the removal of all the beryllium coating from the panels. Though the limiter panels covered ~10% of the total first-wall area, the absence of the beryllium coating resulted in only ~1% drop of the TBR (see Table X). It affected the T_6 value, but did not affect the T_7, as was expected by the fact that beryllium is a good neutron multiplier.

As the vacuum region surrounded by the blanket was filled with multiscattered low-energy neutrons, the use of a strong low-energy neutron absorber as a limiter coating material would have more severe effect on the TBR than the beryllium coating did. For the purpose of this analysis, a case in which the beryllium coating material in the reference model was replaced by tantalum, which is a candidate limiter material but is known to have large resonance absorption cross sections, was calculated. Results are shown in the last column of Table X. As expected, the tantalum coating affected the T_6 value much stronger than the T_7 value. The total TBR dropped by ~4%.

TABLE X

Impact of Limiter Design on TBR*

	Nonbreeding Limiter Module (%)	Limiter Duct Width (%)	Beryllium Coating (%)	Strong Absorber Coating (%)
T_6	−6.2 (±1.2)	−2.4 (±1.2)	−1.6 (±1.2)	−5.6 (±1.2)
T_7	−5.8 (±1.4)	−0.6 (±1.4)	+0.1 (±1.4)	−0.6 (±1.4)
TBR	−6.1 (±1.0)	−1.9 (±1.0)	−1.1 (±1.0)	−4.2 (±1.0)

*Shown is the relative deviation from the standard values.

V.C.5. Uncertainties Due to Plasma Heating System

The rf waveguides of the STARFIRE model were assumed in the reference model for the plasma heating as well as for the plasma current drive. To evaluate the TBR uncertainties due to the rf waveguide design, the fractional change in the TBR value from the reference case was calculated for the following two cases: (a) the area of the waveguide opening at the first wall was doubled and (b) all the materials inside the waveguide were removed, keeping the increased area of the opening. Via case 1, the size effect of the rf tubes on the TBR value can be tested. The second case will clarify two different things: effect of the structure materials as combined with the result of case 1, and the effect of void regions.

The results are shown in Table XI. The rf waveguides occupy 0.8% of the total first-wall area, which is relatively small. The T_7 results of both cases agree with this value within statistical errors. The effect of the structure materials on T_6 is very small compared to the void region effect. Roughly speaking, the magnitude of the void region effect is approximately equal to the ratio of the hole opening area to the whole first-wall area.

The STARFIRE design for the rf (lower hybrid) system attempted to minimize the penetration size and effects. Recent plasma physics and engineering results[7] on plasma heating and current drive indicate that the size of the waveguides may be even larger than what was considered above. Furthermore these results also indicate that systems other than lower hybrid, e.g., ion cyclotron resonance heating (ICRH), may have to be used to keep the circulating power requirement reasonable. Systems such as ICRH generally require antennas inside the first wall, which would have a significant negative effect on TBR.

TABLE XI

Impact of rf Waveguide Design on TBR*

	Double the rf Volume (with structure) (%)	Double the rf Volume (without structure) (%)
T_6	−1.5 (±1.2)	−1.2 (±1.2)
T_7	−1.0 (±1.4)	−1.2 (±1.4)
TBR	−1.4 (±1.0)	−1.2 (±1.0)

*Shown is the relative deviation from the standard values.

V.C.6. Homogenization Effect of Sector Side Wall

The reference calculation was performed with a homogenized material arrangement in the blanket region. The actual blanket, however, is partitioned into many sectors with an over 1-cm-thick side wall. Monte Carlo analysis was made to assess the uncertainty in the TBR due to these walls. Figure 14 shows the heterogeneous geometry model used in this analysis. The geometry is defined in x-y coordinates. The thickness of each material region is the same as in the reference outboard model of Table V except that the blanket regions identified as 1 and 2 in Table V were combined into a single 57-cm-thick breeding zone. The material composition of the breeder in Fig. 14 was the result of homogenization over the Li_2O plates, HT-9 claddings, and helium coolant channels of the BCSS design. The thickness of the side wall, which includes

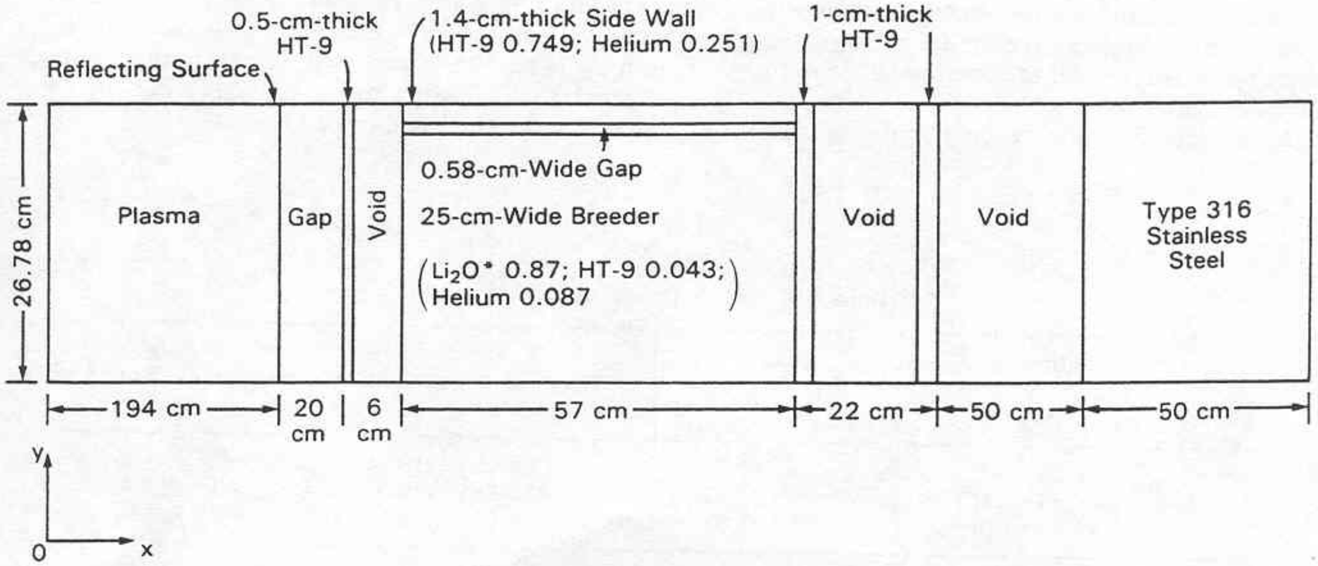


Fig. 14. Schematic of the Li_2O/He/FS blanket design.

coolant channels, and the gap width between the wall and the breeder were determined so that the overall volume ratio of the structural material (HT-9), the breeding material (Li_2O), and the void (or helium) may be the same as in blanket region 1 in the reference blanket. A homogeneous geometry model was defined just by homogenizing the three regions, i.e., the breeder, the gap, and the side wall of Fig. 14.

The results are summarized in Table XII. The homogenization seems to have resulted in some degree of overestimation of the TBR, but the degree of its magnitude is within the statistical errors of the Monte Carlo calculations. We may say within the accuracy of the Monte Carlo calculation that the homogenization of the breeding zone including the thick side wall will not result in a large uncertainty in the estimated TBR. It probably will not exceed 1.5 to 2%.

V.D. Variation in Blanket Material Composition

The effect of changes in the blanket material composition on the obtainable TBR has also been examined. The analysis was performed based on a one-dimensional cylindrical model, which represented the outboard blanket. The Li_2O/He/FS outboard blanket shown in Table V was adopted for the analysis (plasma radius = 1.94 m, first-wall radius = 214 cm) except that the shield is considered to be 30 cm thick and no gap was included between the plenum and the shield. The theoretical density of the Li_2O breeder was considered as 0.8. The plasma was assumed to be uniformly distributed. The ANISN code with 46 groups (25 neutron and 21 gamma) and the S_6P_3 approximation were used. The group constants were derived from the VITAMIN-C/MACKLIB-IV library.

The problem of interest here is to estimate the impact on the TBR of changes in the first-wall thickness, the volume fraction of the structure material in the breeder, or the Li_2O density factor. The required degree of porosity in Li_2O is currently uncertain as it is dependent on tritium transport, radiation effects, and other blanket characteristics that cannot presently be quantified exactly. A direct sensitivity analysis approach was adopted to analyze the problem. For instance, each design parameter such as the first-wall thickness was changed by a certain amount, and the direct forward transport calculation was done. Then the obtained TBR was compared to that of the reference case to get the effect of that parameter variation on the TBR. In addition to this direct approach, the impact of design variations on the TBR was also examined using first-order perturbation theory and results from both approaches were compared. In this latter approach, the forward and the adjoining fluxes were calculated for the reference design and were used to arrive at the TBR sensitivity coefficient to each design variation considered.

TABLE XII

Impact of Homogenization of Breeding Zone on TBR

Geometry	Tritium Production		
	T_6	T_7	TBR
Homogeneous	0.941	0.355	1.297 (±0.016)
Heterogeneous	0.929	0.352	1.281 (±0.016)

V.D.1. Effect of First-Wall Thickness

The volume fraction of the structure (HT-9) in the first wall is 0.117, while the thickness of the first-wall zone is 6 cm. Thus, the effective structure thickness is ~0.7 cm. To test the effect of the first-wall thickness on the TBR value, the reference structure thickness was increased to 1.05 and 1.4 cm, i.e., by 50 and 100%, respectively. The results are shown in Table XIII. The reduction in TBR in blanket 2 is twice that in blanket 1 when the first-wall thickness is changed. This is because additional scatterings that took place in the thicker first wall attenuated high-energy neutrons more than slow neutrons, and this made the depth profile of the TPR in the breeder somewhat steeper. The two cases of the 50% change and the 100% change in the wall thickness show about the same TBR sensitivity, where the sensitivity coefficient is defined as the relative change in the TBR due to a unit change in the parameter under consideration. From the results shown in Table XIII, this coefficient is -0.0244 from the direct results of the 50% change case. This indicates that the TBR will suffer a reduction of 0.0244% upon increasing the first-wall thickness by 1% (equivalent to increasing the atomic density of the first-wall constituents by 1%). The coefficient for the 100%

TABLE XIII

Effect of Change in First-Wall Thickness on the TBR

Thickness (cm)	TBR		
	Blanket 1	Blanket 2	Total
0.7 (reference)	1.200	6.389×10^{-2}	1.2639
1.05 (+50%)[a]	1.1863 (−1.14%)[a]	6.222×10^{-2} (−2.61%)	1.2485 (−1.22%)[a] (−1.02%)[b]
1.40 (+100%)[a]	1.1734 (−2.22%)[a]	6.062×10^{-2} (−5.12%)[a]	1.2340 (−2.37%)[a] (−2.03%)[b]

[a]Relative deviation from the reference values.
[b]Results obtained from perturbation theory.

change case is −0.0237 and the nonlinearity is clearly not significant up to this particular change in the first-wall thickness. This is evidenced also by examining the estimates for the change in the TBR obtained from the perturbation treatment. In this treatment, the TBR sensitivity coefficient was found to be −0.02, which translates linearly to −1.02 and −2.03% change in the TBR due to 50 and 100% change in the first-wall thickness, respectively. These values are in a good agreement to those obtained from direct evaluation as shown in Table XIII.

V.D.2. Effect of Structural Material Volume Change in the Breeding Zone

In the reference design, it has been proposed that the Li_2O breeder be packed in 1-cm-thick plates with 0.25-mm-thick HT-9 cladding. Future analysis and new data may show that the thickness of the cladding is not sufficient, for example, to accommodate excessive Li_2O swelling or to keep tritium permeation to the coolant acceptably low.

The volume fraction of the HT-9 structure in blanket 1, which was originally 0.079, was increased by 50, 100, and 300%. The increment of the structure material was compensated for by the decrease in the Li_2O volume. The reduction rates in the Li_2O volume were 4.9, 9.8, and 29.4%, respectively. Results of the TBR calculations are shown in Table XIV as well as the reference values. The TBR in both blankets 1 and 2 dropped by about the same fraction. The TBR drop in blanket 1 was a result of both the neutron flux depression caused by the increase in the structure volume and the decrease of the Li_2O volume, while in blanket 2, the TBR was influenced only by the flux depression.

TABLE XIV

Effect of Volume Fraction Change of Structure in Blanket 1 on the TBR

Volume Fraction in Blanket 1	TBR		
	Blanket 1	Blanket 2	Total
HT-9 0.079 (reference)	1.200	6.389×10^{-2}	1.2639
HT-9 0.1185 (+50%)[a]	1.1703 (−2.47%)[a]	6.220×10^{-2} (−2.65%)[a]	1.2325 (−2.48%)[a] (−2.61%)[b]
HT-9 0.158 (+100%)[a]	1.1414 (−4.87%)[a]	6.078×10^{-2} (−4.87%)[a]	1.2022 (−4.88%)[a] (−5.22%)[b]
HT-9 0.316 (+300%)[a]	1.0268 (−14.43%)[a]	5.744×10^{-2} (−10.1%)[a]	1.0842 (−14.22%)[a] (−15.67%)[b]

[a]Relative deviation from the reference values.
[b]Results obtained from perturbation theory.

The depth profile of the neutron flux became steeper by the increase in the structure volume. The sensitivity of the TBR value to the deviation in the structure volume fraction (and the compensating decrease in the Li_2O volume fraction) was estimated to be −0.050 using the case of 50% change in the structure volume. The TBR sensitivity coefficient predicted from perturbation theory is −0.052% and corresponds to a 1% increase in the structure of blanket 1. This coefficient is slightly larger (by 4%) than the corresponding value estimated from direct evaluation. The deviation from the reference TBR value resulting from the 50, 100, and 300% increases in the structure of blanket 1 are −2.48, −4.88, and −14.22%, respectively. The predicted change based on the perturbation theory is very similar to these values, even in the +300% change case, as shown in Table XIV.

Next, the volume fraction of the structure in blanket 2 was increased by 25 and 50% and, to compensate for this increment, the Li_2O volume in blanket 2 was decreased by 11.4 and 22.9%, respectively. The obtained TBR values are listed in Table XV. As the volume fraction of the structure was very large in blanket 2 compared to blanket 1, the impact of the structure increase on the TBR in blanket 2 is pronounced when it is compared to the results in Table XIV. The absolute contribution to the total TBR from blanket 2, however, is relatively small. Moreover, the increased structure in blanket 2 scatters additional neutrons back to blanket 1, so the TBR in blanket 1 was slightly increased. Consequently, the total TBR was only slightly changed.

In another case, the volume fraction of the structure was increased by 50% everywhere in the blanket. The increment of the structure was compensated for by a decrease in the helium coolant volume by 6.63% in the first wall and a volume decrease of the Li_2O of 4.9% in blanket 1, and 22.9% in blanket 2. The attained material composition after this variation is

TABLE XV

Effect of Volume Fraction Change of Structure in Blanket 2 on the TBR

Volume Fraction in Blanket 2	TBR		
	Blanket 1	Blanket 2	Total
HT-9 0.286 (reference)	1.200	6.389×10^{-2}	1.2639
HT-9 0.3575 (+25%)[a]	1.2029 (+0.24%)[a]	5.890×10^{-2} (−7.81%)[a]	1.2618 (−0.17%)[a]
HT-9 0.429 (+50%)[a]	1.2056 (+0.47%)[a]	5.371×10^{-2} (−15.9%)[a]	1.2593 (−0.36%)[a]

[a]Relative deviation from the reference values.

shown in the footnote of Table XVI. The change in the TBR in this case is about the same amount as the sum of the TBR variation observed in the 50% change cases in Tables XIII, XIV, and XV. For blanket 1, the sum of the values in Tables XIII, XIV, and XV is −3.37%, which is close to the −3.1% obtained in the present case. The sum is −21.2% for blanket 2, which is similar to the −20.3% change obtained in the present case. The total variation in the TBR that corresponds to the 50% structure increase is −3.97%. The TBR sensitivity coefficient in this case is −0.079, which gives the percentage change in the TBR value resulting from a 1% increase in the structure of the first wall and the breeding zone. The coefficient based on the perturbation treatment is −0.072 and this value is comparable to the one obtained from direct calculation.

V.D.3. *Effect of Li_2O Density Factor Change*

The assumed Li_2O density factor was 0.8 of the theoretical density in the reference design. Future experiments, however, on tritium extraction, Li_2O swelling, and other performance characteristics may show a need for a higher degree of porosity.

The Li_2O density factor in blanket 1 was decreased in two ways: from 0.8 to 0.7 and from 0.8 to 0.6, and the volume fraction of the void was correspondingly increased. The volume of the structure was not changed.

The obtained TBR values are compared with those of the reference case in Table XVII. As the amount of the Li_2O was decreased in blanket 1, the TBR value in blanket 1 decreased. But the decrease rate in the TBR was about one-third of the relative variation in the Li_2O density. The reason is that the neutron flux increased everywhere in the breeding zone because the amount of the absorber was decreased. This is also the reason why the TBR in blanket 2 was enhanced drastically. The TBR sensitivity coefficient (based on the 12.5% decrease in the Li_2O density factor) is −0.153, while the corresponding value based on perturbation theory prediction is −0.232 and is due to a 1% decrease in the Li_2O density factor. As shown in Table XVII, the perturbation treatment overestimates the predicted change in the TBR. This indicates that variation in the Li_2O density factor results in a more pronounced nonlinearity in the corresponding deviation in the TBR value as compared to the other design variations discussed above. Moreover, the TBR sensitivity coefficient is larger in this case than the corresponding ones arising from variation in the structure volume fraction.

VI. UNCERTAINTIES IN NUCLEAR DATA

The uncertainty Δp appearing in Eq. (3) includes all sources of uncertainties in the prediction of the TBR. An extensive analysis to assess the impact of the uncertainties in basic nuclear data on the achievable tritium breeding has been carried out and is the subject of a companion paper.[18] Readers interested in methods, approaches, and procedures adopted to estimate these uncertainties are referred to Ref. 18. Here, we briefly outline the results for the purpose of comparing various sources of uncertainty.

As mentioned in Sec. II, the uncertainties in predicting the achievable TBR include those uncertainties

TABLE XVI

Effect of Volume Fraction Change of Structure Throughout Blanket on the TBR

Volume Fraction	TBR		
	Blanket 1	Blanket 2	Total
Reference[a]	1.200	6.389×10^{-2}	1.2639
+50%[b]	1.1628 (−3.1%)[c]	5.093×10^{-2} (−20.3%)[c]	1.2137 (−3.97%)[c] (−3.67%)[d]

[a]First wall: HT-9, 0.117; helium, 0.883
Blanket 1: HT-9, 0.079; Li_2O, 0.806; helium, 0.115
Blanket 2: HT-9, 0.286; Li_2O, 0.625; helium, 0.089
Plenum: HT-9, 0.2; helium, 0.8.
[b]First wall: HT-9, 0.1755; helium, 0.8245
Blanket 1: HT-9, 0.1185; Li_2O, 0.7665; helium, 0.115
Blanket 2: HT-9, 0.429; Li_2O, 0.482; helium, 0.089
Plenum: HT-9, 0.3; helium, 0.7.
[c]Relative deviation from the reference values.
[d]Results obtained from perturbation theory.

TABLE XVII

Effect of Li_2O Density Factor Change in Blanket 1 on the TBR

Density Factor in Blanket 1	TBR		
	Blanket 1	Blanket 2	Total
0.8 (reference)	1.200	6.389×10^{-2}	1.2639
0.7 (−12.5%)[a]	1.1544 (−3.8%)[a]	8.528×10^{-2} (+33.5%)[a]	1.2397 (−1.91%)[a] (−2.90%)[b]
0.6 (−25%)[a]	1.0946 (−8.78%)[a]	0.1132 (+77.2%)[a]	1.2078 (−4.44%)[a] (−5.80%)[b]

[a]Relative deviation from the reference values.
[b]Results obtained from perturbation theory.

associated with the geometrical modeling, calculational methods, and nuclear data. Aside from the calculational codes that went through extensive improvements, and the refinement undertaken to model a system closely (e.g., geometrical simulation package of the MCNP Monte Carlo code[11]), there are many sources of uncertainties associated with nuclear data ranging from uncertainties in basic measurements to those introduced in data processing and representation. It has been shown that the differences among the TBR values obtained when using various neutron group structures and weighting spectra depend on the type and the thickness of the blanket under consideration.[18-20] For a blanket utilizing Li_2O or liquid lithium as a breeder, cross-section libraries that utilize a broad-group structure underestimate T_7 values and overestimate T_6 values compared to results from fine-group libraries or the MCNP (continuous energy-dependence representation for nuclear data) calculation. However, the TBR calculated using the various multigroup libraries is within 4% of the reference MCNP calculation.[20] For blankets utilizing the eutectic 17Li-83Pb as the breeder with low ^6Li enrichment, the situation is different. While excellent agreement (within ~1%) is obtained among the TBR values calculated with broad-group libraries, the difference in the calculated TBR in a thin 17Li-83Pb blanket with naturally enriched ^6Li can reach a value as high as 14% with libraries that have fewer energy groups in the low-energy range.[19] For this particular blanket type, this difference can be narrowed if an appropriate weighting spectrum representative of this blanket system is used to generate broad-group libraries.[19]

To arrive at an estimate for the uncertainty in the achievable TBR that arises from current uncertainties in measuring basic nuclear data and the systematic errors involved in these measurements, four blanket concepts were selected for this study as outlined in Ref. 18. These blankets[17] are: the Li_2O helium-cooled blanket with primary candidate alloy (PCA) structure (Li_2O/He/PCA), the 17Li-83Pb self-cooled blanket (Li-Pb/Li-Pb/PCA), the $LiAlO_2$ water-cooled blanket with beryllium multiplier and ferritic steel (FS) structure ($LiAlO_2/H_2O$/FS/Be), and the Flibe blanket (Flibe/He/FS/Be). For the latter two blankets, which utilize ferritic steel as the structural material, the TBR has been calculated using three evaluations for the $^9Be(n,2n')$ cross section: the ENDF/B-IV, ENDF/B-V, and the LANL evaluation (Be-LANL) as discussed in Ref. 18. In the latter evaluation, the energy-angle correlation for the secondary neutrons from the time sequential reaction $^9Be(n,n_1')^{9*}Be(n_2')^{8*}Be$ has been improved and presented by 33 inelastic levels[21] ($MT = 51$ to 83) although integrating the differential cross section yields essentially the same values as in the ENDF/B-IV and ENDF/B-V evaluations for the $^9Be(n,2n')$ cross section. It was found[18,22] that using the Be-LANL evaluation gives an ~4.3% reduction in the TBR value in the Flibe blanket and a corresponding reduction of ~2% in the $LiAlO_2$ blanket.

To carry out the cross-section sensitivity/uncertainty analysis [independent of the uncertainty in the energy-angle correlation for the $^9Be(n,2n')$ cross section], the concept of the relative sensitivity profile for cross-section type $\Sigma_x, P_{\Sigma_x}^{g,k}$, and the relative covariance matrices, $rcov(\Sigma_x^g, \Sigma_y^{g'})$, are employed in the manner described in Refs. 18 and 23 to arrive at the percentage standard deviation in the response $R_k \equiv \mathrm{TBR}$, $\Delta T/T$. Here, the coefficient $P_{\Sigma_x}^{g,k}$ represents the relative percent change in the response R_k due to a 1% increase in the cross section Σ_x^g at the neutron energy group g. The covariance matrices contain the correlation between the uncertainty in multigroup cross section Σ_x^g and $\Sigma_y^{g'}$ and are independent of the specific design under consideration.

The partial cross sections for each element present in a particular blanket concept were generated from the DLC41/VITAMIN-C library[24] using the AMPX module, and the SWANLAKE sensitivity code[25] was employed to generate the profiles P's in a one-dimensional geometry. The integrated relative sensitivity coefficient,

$$S_{\Sigma_x}^{T_6} = \sum_g P_{\Sigma_x}^{g,T_6} \ ,$$

was evaluated for the response $R_{T_6} = T_6$ (TBR from ^6Li) based on a 1% increase in each partial cross section Σ_x^g at all energy groups, and for the various elements present in each blanket. Corresponding results were also obtained for tritium breeding from ^7Li and both values for $S_{\Sigma_x}^k$ ($k = T_6$ and $k = T_7$) can be found in Ref. 18. Examining these integrated relative sensitivity coefficients will reveal those elements for which a slight variation in their cross section can lead to noticeable variation in the TBR (see Ref. 18).

To complete the uncertainty analysis, the profiles $P_{\Sigma_x}^{g,T_6}$ and $P_{\Sigma_x}^{g,T_7}$ were coupled with the covariance matrices for each partial cross section and the values for the relative standard deviation in the TBR, $\Delta_D = \Delta T/T$, are shown in Table XVIII. As pointed out in Ref. 18 and in contrast to other studies,[26,27] the results shown include a complete treatment for the uncertainties and correlation matrices for the elements ^6Li, lead, iron, chromium, nickel, ^{16}O, fluorine, aluminum, silicon, carbon, and hydrogen including the covariance matrices of the latest evaluation for the $^9Be(n,2n')$ cross section. Estimates for Δ_D in other blanket concepts shown in Table XVIII are based on anticipated values. As shown, the range in the uncertainty in TBR due to data uncertainties is between 2 and 6% in all the concepts considered. It was found[18] that statistical treatment used in previous work[26,27] gives larger values and can be considered as a conservative limit.

TABLE XVIII

Estimate of the Uncertainty Associated with the TBR, $\Delta_D = \Delta T/T$, in Various Blanket Concepts Due to Uncertainties Associated with Nuclear Data Base*

Number	Blanket Concept	Range of Δ_D (%)	Comments
1	Li_2O/He/PCA	~4.9	Based on extensive, detailed cross-section sensitivity/uncertainty analysis. Statistical error propagation was considered. Higher values are obtained with nonstatistical cross-section error treatment.
2	Li-Pb/Li-Pb/PCA	~3.9	See comment on blanket 1.
3	$LiAlO_2$/H_2O/FS/Be	~2.1	See comment on blanket 1.
4	Flibe/He/FS/Be	~3.4	See comment on blanket 1.
5	Li/Li/V	~6	Taken from Ref. 26. In the treatment cited in this reference, no cross-section uncertainty correlation was considered.
6	Li/Li/FS	~5.5	Assumed that the uncertainty in TBR is 0.5% less than the Li/Li/V case, since the cross section for the ferritic steel constituent (mainly iron, nickel) is better known than for vanadium.
7	Li/He/FS	~5	Assumed same as in the Li/Li/FS blanket less ~0.5% due to replacing lithium by helium coolant.
8	$LiAlO_2$/He/FS/Be	~2	Assumed same as in blanket 3 less 0.1% due to the contribution from errors associated with the H_2O cross section.
9	$LiAlO_2$/DS/FS/Be	~1.9	Based on normalizing the contribution to the TBR uncertainty in blanket 8 from beryllium, oxygen, aluminum, and FS to the weight of these materials in the draw salt (DS) blanket. Contributions from the DS coolant were not considered.
10	Li-Pb/Li-Pb/V	~4.4	Additional value of 0.5% was added to the uncertainty in TBR of blanket 2 for the reason explained in the comments on blanket 6.

*Table taken from Ref. 18.

VII. SELF-SUFFICIENCY ANALYSIS

Attaining tritium fuel self-sufficiency in a fusion reactor requires that the achievable TBR, Λ_a, be equal to or exceed the required TBR, Λ_r. Both Λ_a and Λ_r can be estimated for a given system but these estimates are subject to uncertainties arising from incomplete definition of the system, inaccurate prediction of key performance parameters for subsystems yet to be developed, and errors in the calculational methods and basic data.

Fusion is in an early stage of R&D. Therefore, the performance parameters for many of the plasma and engineering components cover a wide range of possible values with currently unknown probability distribution. Hence, a rigorous statistical treatment is not possible for many of the uncertainty terms for Λ_a and Λ_r. Previous sections provided evaluations of the sensitivity of Λ_a and Λ_r to changes in system parameters and to errors in calculations and basic data. Our purpose in this section is to develop an appreciation of the key technical problem areas in attaining fuel self-sufficiency. This is accomplished by using results from previous sections to discuss and compare the various terms in Eq. (5) for different blanket concepts and system conditions.

VII.A. Achievable Breeding Ratio

The BCSS evaluated[10,17] and compared a very large number of candidate blanket concepts based on engineering feasibility, economics, safety, and R&D requirements. The evaluation resulted in identifying nine leading blanket concepts shown in Table XIX. Extensive design and analysis effort was devoted to optimizing these blankets within two reactor reference systems, the STARFIRE tokamak reactor[5] and the MARS tandem mirror reactor.[9] Detailed three-dimensional Monte Carlo calculations were performed for the nine blanket concepts in the two reference reactor systems to calculate the TBR. These results are documented in Ref. 10 and are shown in Table XIX. The TBRs shown in Table XIX represent the most realistic estimate of Λ_c for the leading blanket concepts. While some changes can be made in these blanket designs to increase the breeding ratio, it was found

TABLE XIX

The TBR Calculated for Leading Blanket Concepts*

Blanket[a]	Breeding Ratio (Λ_c)	
	Tokamak	Mirror
A $LiAlO_2$/DS/HT-9/Be	1.24	1.29
B Li/Li/HT-9	[b]	1.14
C Li-Pb/Li-Pb/V	(1.3)[c]	1.18
D Li/Li/V	1.28	1.19
E Li_2O/He/HT-9	1.11	1.14
F $LiAlO_2$/He/HT-9/Be	1.04	1.16
G Li/He/HT-9	1.16	1.17
H Flibe/He/HT-9/Be	1.17	1.29
I $LiAlO_2$/H_2O/HT-9/Be	1.16	1.22

*See Ref. 10.
[a]Blanket concept is denoted by breeder/coolant/structure/multiplier.
[b]Not evaluated.
[c]Estimated for 90% ^{6}Li enrichment.

that the increase was generally modest and the necessary changes would, in many cases, reduce overall blanket performance or violate engineering or material constraints. Therefore, we adopt the breeding ratios in Table XIX as the reference estimates for Λ_c of Eqs. (3) and (5).

From Eq. (3), the achievable breeding ratio has two terms: the uncertainty in prediction Δ_p and the uncertainty due to system definition Δ_s. In this section, we use δ_i to refer to the relative uncertainty corresponding to the absolute uncertainty Δ_i. For example, Δ_p in Eq. (3) is equal to $\delta_p \Lambda_c$. The uncertainty in prediction comes from various sources of errors:

1. *Basic data:* The uncertainties in the TBR due to uncertainties in basic nuclear data, δ_D's, were evaluated in Sec. VI and are shown in Table XVIII for the same blanket concepts given in Table XIX. These vary from ~2 to 6%.

2. *Data processing and representation:* The experimental data undergo various processes prior to their direct use as input data to transport codes. These processes include[28,29]: (a) tabulating data at a finite number of points (e.g., energy points) or representation as an analytic function and (b) processing evaluated data to produce pointwise or multigroup data libraries; this involves approximations such as interpolation, and use of an approximate weighting spectrum. Results reported in Ref. 18 show an ~4% difference in the breeding ratio results obtained with various commonly used libraries. The values of Λ_c in Table XIX were calculated in BCSS[10] using the MCNP Monte Carlo code[11] with continuous energy treatment. Thus, the uncertainties associated with data representation should be lower than those in Ref. 18. We will assume here an approximated value for the error of ~2%.

3. *Transport calculations:* There are uncertainties associated with transport calculations for predicting the neutron flux that depend on both the particular numerical method for solving the neutron transport equation and the particular transport code. The MCNP Monte Carlo code has been thoroughly tested. Therefore, we include only the statistical error, which was estimated to be ~1%.

4. *Geometrical representation:* The modeling of the fusion reactor system for the transport calculations involves approximations in system geometry to reduce the problem to a manageable level in terms of required manpower and computer time and storage. The error from such geometrical approximations can be large. The three-dimensional geometrical modeling used for calculating Λ_c in Table XIX was sufficiently detailed so that the associated error is estimated to be only on the order of 1%.

5. *Response function:* The calculation of a nuclear response involves the use of a response function, which for TBR is the macroscopic cross section for tritium production in lithium. The uncertainty in the basic lithium cross sections was included in item 1 above. We assume that other uncertainties associated with response function calculations are negligibly small.

The largest source of uncertainty indicated above is that for basic nuclear data, Δ_D, which is ~2 to 6% depending on the blanket concepts. The other uncertainties can be larger for certain types of calculations that include crude approximations such as broad-group structure and insufficient geometrical details, and they generally depend on the specifics of the blanket concept and the reactor system. The values of Λ_c used here, however, came from unusually detailed state-of-the-art calculations and the associated errors are thought to be relatively small.

Assuming that the uncertainties listed above are uncorrelated, the prediction uncertainty δ_p is in the range of 3 to 7%.

Key uncertainties in the TBR due to uncertainties in system definition were evaluated in Sec. V. This evaluation was performed only for the Li_2O/He/HT-9 blanket. Strictly speaking, these uncertainties depend on the blanket concept. The results of a limited number of test cases indicate that, for the purpose of this work, the uncertainties estimated for the Li_2O blanket can be taken as an approximate indication of those for other blanket concepts considered here. A summary of the various uncertainties contributing to the uncertainty in the system definition, Δ_s, is given in Table XX. The largest type of change in the system is the elimination of the inboard breeding region, which

TABLE XX

Uncertainties in Achievable Breeding Ratio Due to Uncertainties in System Definition

Type of Change	Change in TBR (%)
A. No inboard blanket	14
B. Limiter	
Nonbreeding limiter module	6
Doubling limiter duct width	2
Strong absorber coating	4
C. Divertor replaces limiter	7
D. Other penetrations	
Auxiliary heating	1
Fueling, diagnostics, etc.	1
E. Other materials in blanket (10-cm-thick passive copper coils occupying 5% of the first-wall surface area)	3
F. Blanket/first-wall specification details (configuration, structure, coolant, manifolds)	2

reduces the breeding ratio by ~14%. Eliminating the inboard breeding region is desirable for all blanket concepts in tokamak reactors because of the economic penalty arising from the space limitation in the inboard region. For self-cooled liquid-metal blankets, eliminating the inboard breeding region may be necessary in order to resolve critical technical problems associated with MHD effects at high magnetic fields.

Assuming that the uncertainties in Table XX are uncorrelated, δ_s is ~18%. If the uncertainty due to the possible elimination of the inboard breeding region is excluded, δ_s becomes 11%.

VII.B. Required Breeding Ratio

In Sec. III, we developed a model for calculating the required breeding ratio Λ_r as a function of the plasma and engineering components parameters that play a key role in the tritium cycle. The model was then used in Sec. IV to evaluate the required breeding ratio at the reference parameter conditions given in Table I. The resulting reference breeding ratio, i.e., $1 + G_0$, is 1.08. The value of Λ_r was also calculated for large sets of variations in the reactor parameter. To estimate accurately the uncertainty, Δ_G in the required breeding ratio [see Eq. (2)], it is necessary to know the probability distribution, i.e., the "likelihood" of "occurrence" or "obtaining" particular sets of reactor parameters. As mentioned earlier, the early stage of R&D that fusion is in now does not permit the development of such quantitative probability distributions. A rigorous statistical treatment, or a quantitative sensitivity/uncertainty analysis of the type used in Sec. VI for nuclear data, to quantify Δ_G is not possible. Below, we attempt an approach that relies on "engineering judgment." The results are helpful in developing a better understanding of the tritium fuel self-sufficiency issue. As the fusion field progresses and a better physics and engineering data base becomes available, a more rigorous approach will be necessary.

For the present purpose, we developed a reasonable assumption that tritium cycle parameters relevant to Λ_r are lognormally distributed. Lognormal probability distributions are convenient for describing the uncertainty in parameters when that uncertainty is large or the resulting values tend to be distributed over a wide range. Such a probability distribution may be characterized by a most probable value and the uncertainty is described by a multiplier. For example, if the value of the actual parameter is expected to fall 68% of the time within a factor of 2 from the most probable value, then this situation could be appropriately characterized by a lognormal distribution with a geometric standard deviation of $\sigma_g = 2$; the most probable value being the geometric mean, X_g. These large uncertainties represent the present uncertainty in parameters of interest in future fusion reactors and thus the use of lognormals can be justified. Here, we use the lognormal distribution with a qualified judgment regarding the size of the geometric standard deviation σ_g. However, additional research will lower the parameter uncertainties. Once research has attained small uncertainties in parameter values, for example, say 10 to 20% uncertainty, then the lognormal distributions with the corresponding geometric standard deviations of 1.1 to 1.2 in this example will approach the ranges of uncertainty usually found with arithmetic normal distributions.

VII.B.1. Uncertainty Based on Probability Distribution

Consider that the parameters that most significantly affect the required TBR are assumed to be lognormally distributed. The lognormal curve for several values of the geometric standard deviation, σ_g, are shown in Fig. 15 for the example of the TBR variation with the (logarithm of) doubling time. There are a number of possible ways of determining a reasonable measure of uncertainty in the TBR value.

One possible method would use the lognormal parameter distribution as a weighting factor and calculate the weighted average of the breeding ratio, Λ_i, where i refers to a reactor parameter. This average value is given by:

$$\bar{\Lambda}_i = \int_{X1}^{X2} P_n(\ln X_i)\Lambda(X_i)\,dX_i \ ,$$

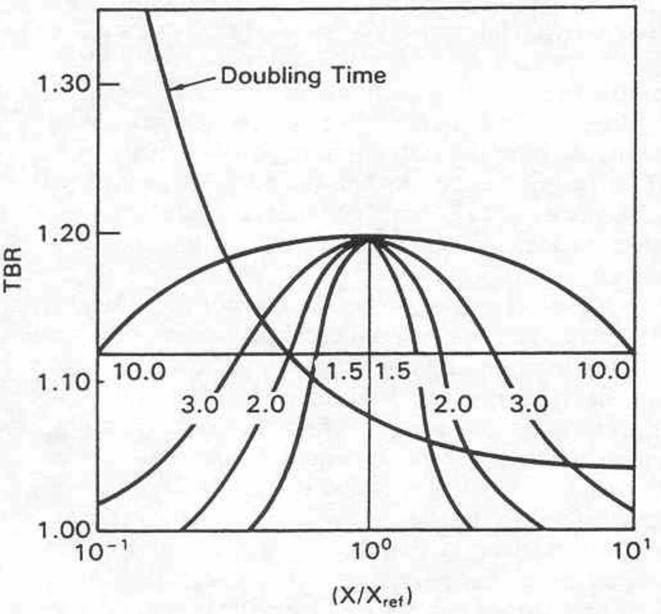


Fig. 15. A set of lognormal probability distributions for various values of geometric standard distribution to be used as weighting functions, superimposed on the variation of the TBR with doubling time.

where P_n is the normalized Gaussian probability curve with the argument, $\ln X_i$, thus reflecting a lognormal distribution of the independent parameter, X_i. This could be interpreted over any specified range of the parameter variation; that is, the integral limits $X1$ and $X2$ may define an expected range or may be extended to plus or minus infinity if no parameter range is specified. Results of such a lognormally weighted Λ_i are shown in Table XXI for each of the six most important parameters identified in Sec. IV and for several values of geometric standard deviation that range from $\sigma_g = 1$ (no variation, or equivalent to the base case) to $\sigma_g = 5$. The top Λ_i value shown in the table for each value of σ_g represents the weighted average breeding ratio when the integral limits are extended to infinity and thus extreme values in Λ_i are limited only by the decreasing probability as the parameter value departs further from its geometric mean. The bottom Λ_i value is derived by weighting only parameter values in the range within one decade from the geometric mean (setting $X1 = \bar{X}_g/10$ and $X2 = \bar{X}_g \times 10$) reflecting an assumption that we know the parameter value will not fall outside this range. The two $\bar{\Lambda}_i$ values differ significantly as σ_g increases.

These lognormal-derived values were compared to a simple weighted average taking a uniform variation or constant probability of parameter X. Because of the logarithmic range of the parameters considered (i.e., plus or minus one decade from the reference value), a uniform weighting of X will emphasize Λ values above the geometric mean and so the weighted Λ grows large only for parameters where Λ increases with the parameter value while the weighted Λ value will decrease for parameters for which Λ decreases with increasing parameter value. Alternative weighting approaches

TABLE XXI

Breeding Ratio Weighted for Lognormal Distribution of Parameter X

Parameter, X (Base Case Value)	Reference Case $\sigma_g = 1.0$	$\sigma_g = 1.5$	$\sigma_g = 2.0$	$\sigma_g = 2.5$	$\sigma_g = 3.0$	$\sigma_g = 5.0$
Doubling time, t_d (5 yr)	1.077	1.081[a] / 1.081	1.089 / 1.089	1.102 / 1.100	1.118 / 1.109	1.334 / 1.111
Burn fraction, β (0.05)	1.077	1.083 / 1.083	1.096 / 1.096	1.113 / 1.111	1.133 / 1.122	1.248 / 1.123
Days of tritium reserve, t_r (2 days)	1.077	1.079 / 1.079	1.085 / 1.085	1.093 / 1.092	1.102 / 1.097	1.155 / 1.097
Extraction inefficiency in plasma exhaust processing (0.001)	1.077	1.078 / 1.078	1.082 / 1.082	1.086 / 1.086	1.092 / 1.089	1.121 / 1.089
Residence time in plasma exhaust processing, T_6 (1 day)	1.077	1.078 / 1.078	1.081 / 1.081	1.084 / 1.084	1.089 / 1.086	1.117 / 1.086
Blanket residence time, T_1 (10 days)	1.077	1.078 / 1.078	1.080 / 1.080	1.082 / 1.082	1.086 / 1.084	1.123 / 1.083

[a]Top breeding ratio value is for lognormal parameter X weighting with no boundaries on X value. Bottom breeding ratio value is for lognormal parameter X weighting and defined boundaries on X; in this case set equal to 0.1× (base case value) and 10× (base case value).

have been considered. It was decided, however, that the lognormal distribution was a reasonably consistent method to be used for our purpose here. Also, a bounded range within one decade of the geometrical mean is assumed for the independent variable X.

The range of uncertainty varies from one parameter to another. To reflect this, one can select an appropriate σ_g for the lognormal distribution of each of the key parameters based on engineering judgment. The calculated mean breeding ratio, $\bar{\Lambda}_i$, using such selected σ_g's is a good estimate of the probable mean. Table XXII shows the selected σ_g's for the six key parameters and the corresponding $\bar{\Lambda}_i$. The relative deviation of this $\bar{\Lambda}_i$ from the required breeding ratio for the reference parameters, Λ_{ref}, which is equal to $1 + G_0$, can be taken as a measure of uncertainty δ_{Gi} in the required breeding ratio for the parameter i. Thus,

$$\delta_{Gi} = \frac{\bar{\Lambda}_i - \Lambda_{ref}}{\Lambda_{ref}} \quad .$$

These δ_{Gi}'s are also given in Table XXII. Assuming that the uncertainties are uncorrelated, the total uncertainty, δ_G, is given by

$$\delta_G^2 = \sum_{i=1}^{n} \delta_{Gi}^2 \quad ,$$

where n is the number of parameters that significantly affects Λ. For the case shown in Table XXII, this "probable" uncertainty is $\delta_G = 0.048$, i.e., ~5%.

VII.B.2. Expected Uncertainty

The procedure outlined above attempted to account for the possibility that parameters may change so as to increase or decrease the required breeding ratio. In evaluating the risks of not attaining self-sufficiency, a more conservative approach should consider the possibility that several parameters take on values that increase the required breeding ratio. One such approach is discussed below.

First, determine a most probable value for each parameter based on our present understanding and judgment of fusion reactor performance. Next, define, in a similar fashion, upper and lower bound limits for the parameter value. Assuming that the parameter distribution is lognormal, then select a geometric standard deviation, σ_g, to characterize that uncertainty. Alternatively, one may select a "2σ" value if one wants to consider 95% of the probable area, which falls within $(\sigma_g)^2$ times the mean X_g. Determine the actual parameter value, X, at the characteristic uncertainties, $X_g \times (\sigma_g^{\pm k})$. Use the two X values to calculate the largest corresponding Λ value, thus giving the maximum Λ case for that uncertainty. Determine the expected Λ value at that X which will be denoted $\Lambda_{ex,i}$ for each parameter X_i as:

$$\Lambda_{ex,i} = max[\Lambda(X_i \times \sigma_g^{\pm k})] \quad ,$$

where the maximum Λ value corresponding to one of the two cases ($+k$ or $-k$) is taken as Λ_{ex}. Calculate the parameter uncertainty δ_{Gi} before:

$$\delta_{Gi} = \frac{\Lambda_{ex,i} - \Lambda_{ref}}{\Lambda_{ref}} \quad .$$

This is repeated for each of the n parameters that significantly affects the TBR. Estimate the total δ_G; as before, $\delta_G^2 = \Sigma\delta_{Gi}^2$. The results of this procedure are illustrated in Table XXIII. The results indicate that for the σ_g values selected, the total uncertainty $\delta_G = 0.133$, i.e., 13.3%. This is a more conservative estimate of δ_G than that derived in Sec. VII.B.1. Much more conservative estimates can also be derived, for example, by selecting larger σ_g's for various parameters and by insisting on 95% confidence level. However, we attempt here to rely on engineering judgment for a proper balance between conservatism and optimism. Thus, we will use the δ_G derived above (0.133) as our basis for analysis.

TABLE XXII

Lognormal Weighted Mean Breeding Ratio and Corresponding Uncertainty with Selected Values of Standard Deviation

Parameters, X	X_g [a]	Selected[b] σ_g	$\bar{\Lambda}$	δ_{Gi}
Doubling time	5 yr	2	1.089	0.011
Burn fraction	0.05	3	1.122	0.042
Days of tritium reserve	2 days	2	1.085	0.007
Extraction inefficiency in plasma exhaust processing	0.001	5	1.089	0.011
Residence time in plasma exhaust processing	1 day	2	1.081	0.004
Blanket residence time	10 days	3	1.084	0.006
All other parameters	---	---	1.09	0.012

[a]Reference value for X_i.
[b]Weighed over range between 0.1 of reference value and 10× the reference value.

TABLE XXIII

Estimate of Required Breeding Ratio Uncertainty

Parameter	X_g	σ_g	$X_i = X_g \cdot \sigma_g^{\pm 1}$	$\Lambda_{ex,i}$	δ_{Gi}
Doubling time	5 yr	2	2.5 yr	1.120	0.040
Burn fraction	0.05	2.5	0.02	1.18	0.096
Days of tritium reserve	2 days	2	4 days	1.108	0.029
Plasma recovery loss fraction	0.001	5	0.005	1.153	0.071
Plasma recovery reserve time	1 day	2	2 days	1.092	0.014
Blanket reserve time	10 days	3	30 days	1.097	0.019
All other systems	---	---	---	1.10	0.021

VII.C. Comparison of Required and Achievable TBR

Table XXIV presents a summary of achievable and required breeding ratios and associated uncertainties for the leading blanket concepts in tokamak reactor systems that were discussed earlier in this section. The values of Λ_c are the same as those in Table XIX. The uncertainty in the achievable breeding ratio, Δ_a, is calculated as $(\Delta_p^2 + \Delta_s^2)^{1/2}$ where the uncertainty in prediction, Δ_p, and the uncertainty in system definition, Δ_s, are those described earlier in Sec. VII.A. The reference required breeding ratio, $1 + G_0$, and the associated uncertainty, Δ_G, are the same as those discussed in Sec. VII.B with one exception. The reference tritium inventory in liquid-metal and molten salt breeder blankets was lowered from 5 to 1 kg to better reflect present experimental data.

Important observations can be made about the results of Table XXIV. The TBR calculated for various candidate blanket concepts whose designs have been optimized in BCSS based on overall system considerations vary considerably, from $\Lambda_c = 1.04$ to 1.3. However, the variation in the uncertainty in the achievable breeding ratio is much less, with Δ_a in the range of 0.19 to 0.24. The required breeding ratio for the reference reactor conditions and the associated uncertainties are not very sensitive to the blanket concept. The main difference among blanket concepts is the tritium inventory retained in the blanket, but for the range of variation considered here, this is not a large discriminating factor.

In comparing blanket concepts as well as plasma and technology component choices for the reactor system as to the potential of attaining tritium fuel self-sufficiency, one needs a figure of merit (FOM). A plausible FOM was defined in Eq. (5) as $\epsilon = \Lambda_a - \Lambda_r$. Values of ϵ are also shown in Table XXIV. In calculating ϵ, the absolute magnitude of the Δ's was used.

TABLE XXIV

Summary of Achievable and Required TBRs and Associated Uncertainties for Leading Blanket Concepts in Tokamak Reactor Systems

Concept[a]	Achievable Λ_a		Required Λ_r		$\epsilon = \Lambda_a - \Lambda_r$
	Λ_c	Δ_a	$1 + G_0$	Δ_G	
A $LiAlO_2$/DS/HT-9/Be	1.24	0.22	1.077	0.143	−0.20
B Li/Li/HT-9	[b]	---	---	---	---
C Li-Pb/Li-Pb/V	(1.30)[c]	0.24	1.072	0.142	−0.15
D Li/Li/V	1.28	0.24	1.072	0.142	−0.17
E Li_2O/He/HT-9	1.11	0.21	1.077	0.143	−0.32
F $LiAlO_2$/He/HT-9/Be	1.04	0.19	1.077	0.143	−0.37
G Li/He/HT-9	1.16	0.22	1.072	0.142	−0.27
H Flibe/He/HT-9/Be	1.17	0.22	1.072	0.142	−0.26
I $LiAlO_2$/H_2O/HT-9/Be	1.16	0.21	1.077	0.143	−0.27

[a]Concept is denoted by breeder/coolant/structure.
[b]Not evaluated because of engineering feasibility constraints.
[c]Estimated for 90% ^{6}Li enrichment.

Although some uncertainties may increase or decrease Λ_a or Λ_r, our interest here is in evaluating the risk of not attaining fuel self-sufficiency.

The parameter ϵ is negative for all blanket concepts, as shown in Table XXIV and varies from −0.15 to −0.37. A simple interpretation of such an extremely important finding is that the excess margin in the breeding potential for all concepts is not sufficient to cover for all present uncertainties in basic data, calculation, performance parameters, and technology choices. An important implication is that the critical goal of attaining fuel self-sufficiency in D-T fusion reactors restricts the range of allowable physics and engineering parameters and technology choices for some subsystems. Such restrictions must be carefully considered in setting R&D goals and priorities. The detailed results reported in this paper indicate various technical areas of importance to fuel self-sufficiency. To enhance the prospects for success in attaining fuel self-sufficiency, the R&D effort should simply focus on technical areas that increase the achievable breeding ratio Λ_a and reduce the required breeding ratio Λ_r. We give some examples below of the impact of fuel self-sufficiency constraints on the choices and performance of various systems.

The achievable breeding ratio has an intrinsic upper limit, which depends most strongly on the choice of the breeder material. Elemental lithium of natural enrichment and Li-Pb highly enriched in ^6Li generally provide the highest breeding potential. Lithium compounds have a much lower intrinsic breeding potential with Λ generally less than unity except for Li_2O. A neutron multiplier is needed in this case. The low melting point, relatively poor thermal conductivity, and other material and engineering properties of lead have been shown[17] in detailed engineering analysis not to be adequate. Beryllium has been found to be the only effective nonfissionable neutron multiplier. Aside from the resource issue for beryllium, it must be recognized that the increase in the breeding ratio obtainable with beryllium is limited in actual engineering designs, as can be seen from Table XXIV.

The intrinsic upper limits on the breeding potential for all present candidate blanket concepts mandate that fusion reactor system features should be selected so as not to reduce seriously Λ_a. Results in Sec. VI and Sec. VII.A suggest the following:

1. A breeding blanket should be incorporated in the inboard region of tokamaks. For self-cooled liquid-metal blankets, the critical issue associated in the inboard (high-magnetic field) region must be solved by other means, e.g., lowering the magnetic field or the development of radiation-resistant electric insulators. Economic penalties associated with placing solid breeders in the inboard region should be minimized by techniques that do not result in significant reduction in tritium production. Concepts whose viability depends on eliminating the inboard blanket should be rejected as high risk from the fuel self-sufficiency viewpoint.

2. The R&D for subsystems that involve penetrations and nonbreeding materials in the blanket region, e.g., impurity control/exhaust and plasma auxiliary heating, should emphasize those options that result in minimum impact on the breeding ratio. In this context, a limiter is preferred over a divertor; and for the limiter, the use of strong neutron-absorbing materials should be avoided.

3. Technical areas that may result in requirements for nonbreeding materials or large void zones in the blanket region should be explored early enough to assess their implications. For example, the possibility that electromagnetic considerations for plasma stability and equilibrium might require[30] the use of passive copper coils in the blanket should be carefully evaluated.

4. Better evaluation of the magnitude of uncertainties in estimating the achievable breeding ratio is needed. For example, the use of integral neutronics experiments can provide a more reliable estimate of the uncertainties associated with nuclear data and calculations.

The required breeding ratio, Λ_r, can be minimized by focusing on the appropriate R&D related to the key reactor parameters discussed in Sec. IV. In view of the limits and uncertainties in the achievable breeding ratio, the goal for Λ_r should be kept sufficiently low to enhance the prospects for success in attaining fuel self-sufficiency. In Sec. VI, we identified six key parameters that have the largest impact on the value of Λ_r. A reasonable goal of Λ_r is ~1.08 at which these six parameters assume the following values:

1. doubling time, $t_d = 5$ yr
2. tritium fractional burnup in plasma, $\beta = 5\%$
3. number of days of tritium reserve for plasma fueling, $t_r = 2$ days
4. tritium extraction inefficiency in plasma exhaust processing, $\epsilon_6 = 0.1\%$
5. mean residence time of tritium in plasma exhaust processing, $T_6 = 1$ day
6. mean residence time of tritium in blanket $(T_1) = 10$ days.

Note that the tritium inventory retained in the blanket (I_B) is proportional to the last parameter, T_1. At $T_1 = 10$ days, I_B is equal to 5 kg. In the following discussion, I_B will be used instead of T_1 for clarity.

At this stage of fusion R&D, it is not clear whether the $\Lambda_r = 1.08$ goal is too high or too low in view of the requirements implied by the key six performance parameters. Analysis of our results shows that the permissible range for the Λ_r goal is not large. A goal of $\Lambda_r < 1.05$ implies requirements that are too demanding on the performance parameters; they seem unlikely to be achieved. On the other hand, earlier results in this section on the achievable breeding ratio and uncertainties with all present blanket concepts suggest that a goal of $\Lambda_r > 1.10$ implies that fusion R&D would be planned on a high risk of not attaining self-sufficiency.

It is instructive to examine how the requirements on the key parameters can be changed for the lower and higher goals of Λ_r. Table XXV shows the limiting values for the six key parameters in order to keep $\Lambda_r = 1.05$. A limiting value can be an upper or lower limit depending on the parameter. For example, decreasing the doubling time t_d increases Λ_r; and, therefore, the doubling time value indicated in Table XXV is a minimum value. Relative to the reference case defined above of $\Lambda_r = 1.08$ with the reference values indicated above for the six key parameters, the following observations can be made from the results in Table XXV. Lowering Λ_r from 1.08 to 1.05 places more restrictive limits on the six parameters. For example, one needs to increase the minimum value for either t_d or β to 20 yr or 8%, respectively; or alternatively reduce the maximum t_r to 0.2 days as can be seen from columns a, b, and c in the table. A factor of 10 increase in the upper limit for any of the other three parameters is not sufficient to keep Λ_r down to a 1.05 goal.

An important question is the implication of future R&D failing to achieve the indicated limit for any of the six parameters. In such a case, achieving a specified goal of Λ_r requires that such a failure be accompanied by success in obtaining better than expected performance in other parameters. Examples of such cases are indicated in columns d through h in Table XXV. Fast growth of fusion power may require a much lower doubling time than 5 yr. For $\Lambda_r = 1.05$, we find that (a) the minimum permissible doubling time without requiring more than a factor of 10 improvement in the performance of any other single parameter is 1.5 yr and (b) the only parameter that can be changed by a factor of 10 to permit such a short doubling time is β. The value of β must be >50% if t_d is to be kept at 1.5 yr. From Table XXV, the importance of β should be evident in cases d through h. For example, large changes in any one of t_r, ϵ_6, T_6, or I_B can be offset only by substantial improvement in the β limit. For example, a change in either t_r, ϵ_6, T_6, or I_B to 20 days, 0.5%, 10 days, or 22 kg requires changing β to 40, 21, 23, or 50%, in respective order. It should be noted that achieving a fractional tritium burnup β in the plasma of ~50% appears to be unlikely with present schemes for plasma operation and impurity exhaust.[30] Even if such a high value of β proves to be technically feasible, the associated economic penalty resulting from the implied high particle recycling and the buildup of impurities in the plasma appears to be very large.[5,6]

Table XXVI is similar to Table XXV except the goal for Λ_r is changed to 1.1. Relative to the reference case, increasing the goal Λ_r from 1.08 to 1.1 permits the decreasing of t_d or β to 3.5 yr or 4%, respectively; or alternatively increasing t_r to 3 days. A doubling time of 0.75 yr becomes possible if β is increased to 50%. Other than changing β, the minimum doubling

TABLE XXV

Limiting Values (Maximum or Minimum) for Key Fusion Reactor Parameters That Must Be Achieved to Keep the Required TBR, Λ_r, at 1.05

Parameter	Parameter Limit							
	a	b	c	d	e	f	g	h
Minimum doubling time, t_d (yr)	20	5	5	1.5	5	5	5	5
Minimum fractional burnup in plasma, β (%)	5	8	5	50	40	21	23	50
Maximum days of tritium reserve, t_r (day)	2	2	0.2	2	20	2	2	2
Maximum extraction inefficiency in plasma exhaust processing, ϵ_6 (%)	0.1	0.1	0.1	0.1	0.1	0.5	0.1	0.1
Maximum residence time in plasma exhaust processing, T_6 (days)	1	1	1	1	1	1	10	1
Maximum blanket tritium inventory,[a] I_B (kg)	5	5	5	5	5	5	5	22

[a]Proportional to blanket mean residence time, T_1.

TABLE XXVI

Limiting Values (Maximum or Minimum) for Key Fusion Reactor Parameters That Must Be Achieved to Keep the Required TBR, Λ_r, at 1.1

Parameter	Parameter Limit									
	a	b	c	d	e	f	g	h	i	j
Minimum doubling time, t_d (yr)	3.5	5	5	0.75	1.5	5	5	5	5	5
Minimum fractional burnup in plasma, β (%)	5	4	5	50	5	20	12	12	50	5
Maximum days of tritium reserve, t_r (day)	2	2	3	2	0.2	20	2	2	2	2
Maximum extraction inefficiency in plasma exhaust processing, ϵ_6 (%)	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.1	0.1	0.1
Maximum residence time in plasma exhaust processing, T_6 (day)	1	1	1	1	1	1	1	10	1	1
Maximum blanket tritium inventory,[a] I_B (kg)	5	5	5	5	5	5	5	5	45	22

[a]Proportional to blanket mean residence time, T_1.

time to be allowed without requiring more than a factor of 10 improvement in any particular parameter is 1.5 yr. The only such single change that can lower t_d to 1.5 yr is $t_r = 0.2$ days. As observed before, large changes in t_r, ϵ_6, T_6 or I_B cannot be offset by improvement in any single parameter except β. Increasing t_r to 20 days, ϵ_6 to 0.5%, T_6 to 10 days, or I_B to 45 kg requires increasing β to 20, 12, or 50%, in respective order, if none of the limiting values for the other parameters is to be changed.

All of the above estimates for Λ_r are based on a specific definition of the doubling time, t_d, as the time at which the tritium inventory in storage, I_5, is equal to $I_5^0 + I_5^m$ where I_5^0 is the initial tritium inventory required for starting a new reactor and I_5^m is the minimum tritium inventory that must be kept in storage for continued reactor operation. If the alternative definition of t_d as the time at which $I_5 = 2I_5^0$ is to be used, the required breeding ratio Λ_r will be higher than calculated above for any given set of reactor parameters. As shown in Sec. IV, Λ_r of 1.08 for the reference case increases to 1.10 if such change in the definition of t_d is made. This would impose more demanding requirements on the performance parameters to achieve fuel self-sufficiency.

VIII. SUMMARY

Attaining tritium fuel self-sufficiency is a critical goal for fusion reactors operated on the D-T cycle. This goal requires that the achievable tritium breeding ratio Λ_a equal or exceed the required breeding ratio Λ_r. The dependence of Λ_r and Λ_a on fusion reactor plasma and engineering components has been investigated. Since fusion energy is in an early stage of R&D, no firm choices have been made yet for design features and performance parameters. There is not yet an adequate data base to reliably predict the attainable range of parameter space or to prudently select the most attractive options. The work reported in this paper indicates that fuel self-sufficiency conditions restrict the allowable range of parameter space and are an important discriminating factor in selecting design features.

The maximum achievable TBR calculated, Λ_c, for detailed engineering designs of the leading candidate blanket concepts is in the range of ~1.05 to 1.25, subject to various types of uncertainties. Self-cooled liquid-metal designs with elemental natural lithium of natural enrichment or Li-Pb highly enriched in ^{6}Li appear to have the highest breeding potential. The largest uncertainty with self-cooled liquid-metal blankets is the possible need for eliminating the inboard blanket region in the inboard of tokamaks to resolve feasibility issues associated with MHD effects at high magnetic field. This would seriously reduce Λ_c for these concepts. Solid breeder blankets are not capable of achieving an adequate breeding ratio without the use of a neutron multiplier. The only possible exception is Li_2O, which yields $\Lambda_c \sim 1.1$. Beryllium is the only effective nonfissionable neutron multiplier. The resource limitations on beryllium indicate that the use of beryllium is not a complete solution for an indefinitely renewable fusion energy source but recycling of used beryllium should allow the construction of a large number of fusion reactors. The maximum achievable breeding ratio with beryllium remains limited to $\Lambda_c \leq 1.2$.

There are many uncertainties associated with the achievable breeding ratio Λ_a related to accuracies of prediction and incompleteness of reactor system definition. The uncertainty in prediction, Δ_p, due to uncertainties in basic data, data processing and representation, transport calculations, geometrical modeling, and response functions is in the range of 3 to 7% for the most elaborate state-of-the-art calculations. The uncertainty in system definition, Δ_s, is largely due to the uncertainties associated with selection and specifications of designs for basic reactor components, such as impurity control/exhaust and auxiliary heating, and for yet undefined component elements such as passive copper coils in the blanket region for plasma stabilization. In this analysis, Δ_s is estimated to be ~18%. Much larger or smaller changes in the achievable breeding ratio are possible if future fusion R&D yields results that have much different implications than those considered in this work.

A model to describe the tritium fuel cycle in fusion reactors was developed. The model permits calculating the required TBR, Λ_r, as a function of reactor parameters. Results show that there are six parameters whose values have the largest effect on Λ_r. These are:

1. doubling time, t_d
2. tritium fractional burnup in plasma, β
3. number of days of tritium supply that must be kept in storage for plasma fueling in case of any malfunction in the tritium processing system, t_r
4. tritium extraction inefficiency in plasma exhaust processing, ϵ_6
5. mean residence time of tritium in plasma exhaust processing, T_6
6. mean residence time of tritium in the blanket, T_1, or alternatively the steady-state inventory of tritium retained in the blanket, I_B.

A set of reference values for the above parameters that combines a judgment on what is likely to be achievable without imposing high-risk R&D requirements in any one technical area yields $\Lambda_r^{ref} \sim 1.08$. Rigorous statistical analysis of the uncertainties in various parameters requires a data base that currently does not exist. Using lognormal probability distributions for the values of various parameters as well as most probable values and standard deviations derived from engineering judgment yields an uncertainty in Λ_r of ~13%.

An FOM for the likelihood of success in meeting fuel self-sufficiency has been suggested as $\epsilon = \Lambda_a - \Lambda_r$ where $\Lambda_a = \Lambda_c - \Delta_a$ and $\Lambda_r = \Lambda^{ref} + \Delta_G$ with Δ_a and Δ_G being the uncertainties in the achievable and required breeding ratios, respectively. Values of ϵ are found to be negative and in the range of $\epsilon = -0.15$ to -0.37 for the leading candidate blanket concepts. Thus, the margin in the achievable breeding ratio is not sufficient to compensate for all estimated uncertainties in Λ_r and Λ_a. The degree of risk implied from this important result suggests that the variety of design choices and the broad range of parameter space being considered for future fusion reactors can and should be narrowed substantially by imposing constraints of fuel self-sufficiency conditions.

A number of guidelines for future R&D in various technical areas can be suggested. To maximize the achievable breeding ratio and minimize associated uncertainties, the key technical areas are:

1. Breeding blanket coverage around the plasma should be maximized. Blanket concepts that require eliminating the inboard region in tokamaks for engineering or economic feasibility must be viewed as high risk in not meeting fuel self-sufficiency conditions.

2. Efforts on subsystems that involve sizable penetrations and nonbreeding materials in the blanket region such as impurity control/exhaust, plasma heating, and current drive should emphasize options that result in minimal impact reduction in the achievable breeding ratio. Neutron slowing down and absorption characteristics of materials and the size and geometry of penetrations are key factors.

3. Technical areas that may result in identifying a need for nonbreeding materials in the blanket region should be investigated early enough to assess their implications. One notable area is the impact of electromagnetic requirements, e.g., for plasma stabilization, on blanket designs.

4. More serious effort is necessary for better evaluations of the uncertainties in the achievable breeding ratio. Integral neutronics experiments, for example, provide important input to estimates of uncertainties associated with nuclear data and calculations. Sensitivity analysis also provides a useful input.

5. Blanket concepts that yield a net TBR in detailed three-dimensional analysis with full engineering design details of <1.1 should be rejected. Concepts that result in a net breeding ratio of >1.15 should receive more R&D emphasis.

Results indicate that a goal of $\Lambda_r \leq 1.05$ imposes requirements that are too demanding on the reactor performance parameters. On the other hand, a Λ_r goal >1.1 considerably increases the risk of not attaining fuel self-sufficiency in future fusion reactors. The R&D guidance on key reactor parameters in order to keep the required breeding ratio, Λ_r, sufficiently low and enhance the probability of success in meeting fuel self-sufficiency conditions is as follows:

1. The probability of meeting the requirements of a doubling time, t_d, of <5 yr appears low at present. Therefore, the strategy for introducing fusion power

and its growth in the initial stages should be examined. In a mature fusion power economy, a typical doubling time will be ~10 yr or greater. The need for $t_d < 5$ yr is only for the initial stages of fusion power growth, but it may still represent a significant problem.

2. Every effort must be made to maximize the tritium fractional burnup, β, in the plasma. A β of >5% is necessary. Therefore, impurity control/exhaust and other subsystems that do not appear to have a high probability of meeting this goal should be rejected. A much higher β, on the order of 20 to 40%, can significantly reduce the burden on R&D in other technical areas and greatly increase the probability of success in meeting fuel self-sufficiency conditions.

3. The performance parameters for the tritium processing system are of crucial importance. Of particular importance is the plasma exhaust processing unit because of the large tritium flow rate especially at low β. The requirements on this unit are as follows:

a. Losses of tritium due to inefficiency of tritium extraction, e.g., chemical processes, must be kept to <0.1%.

b. The probability of failure and the downtime to repair the plasma exhaust processing unit must be kept as low as possible. Failure of this system requires keeping a large tritium inventory, which is inversely proportional to β, in the storage reserve for plasma fueling if power plant shutdown is to be avoided. A goal for the maximum downtime of the plasma exhaust processing unit for nonrare events should be <1 day.

c. The mean residence time of tritium should be kept as short as possible, substantially <1 day.

4. The magnitude of tritium inventory retained in the blanket, I_B, should be kept as low as possible. A goal of $I_B < 5$ kg is preferred. Candidate blanket concepts that result in $I_B > 20$ kg should be rejected, and those with $I_B > 10$ kg should be given low R&D priority.

5. The magnitude of tritium permeation into coolants and tritium inventory retained in nonbreeder elements, e.g., structure, should be minimized.

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