OVERVIEW OF ANALYTICAL AND EXPERIMENTAL EFFORTS ON TRITIUM BREEDING

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ABSTRACT

Models have been developed and utilized to examine the conditions necessary for attaining tritium fuel self-sufficiency in fusion reactors. Results show that these conditions define important limits on the parameter space in which the plasma and various reactor components have to operate. In addition, these conditions indicate preference for some material, design and technology choices. Results on conditions of fuel self-sufficiency can be used to guide experimental and analytical R&D efforts not only in neutronics, but also in a number of physics and technology areas.

1. INTRODUCTION

Attaining tritium fuel self-sufficiency is clearly a necessary requirement for future fusion reactors operated on the DT fuel cycle. The evolution of fusion reactor designs and the availability of some new data in physics and technology over the past several years have made it possible to model the performance of various subsystems in the fuel cycle of DT fusion reactors. Such models have been utilized recently to examine the conditions required for attaining tritium fuel self-sufficiency.[1] These conditions can be used as a powerful tool in screening material and design options, defining the allowable parameter space for the performance of plasma and technology components, and identifying important areas of research and development (R&D).

The purposes of this paper are to provide: 1) an interpretive summary of recent results on the conditions for attaining fuel self-sufficiency; 2) an indication of R&D areas in fusion reactor physics and technology that are most important to fuel self-sufficiency; and 3) summary of ongoing experimental and analytical efforts in fusion neutronics related to fuel self-sufficiency.

2. SELF-SUFFICIENCY CONDITION

The tritium breeding ratio (TBR or Λ) is defined as:

$$\Lambda = \dot{N}^{+}/\dot{N}^{-} \tag{1}$$

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 <u>required</u> tritium breeding ratio (Λ_r) in a self-sustained fusion power economy must exceed unity by a margin, G, to: 1) compensate for losses and radioactive decay of tritium during the period between production and use, 2) supply inventory for startup of other fusion reactors, and 3) provide hold-up inventory which accounts for the time delay between production and use as well as reserve storage.

The required TBR is found to be 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 tritium breeding ratio 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 uncertainties. We write Λ_r as:

$$\Lambda_r = 1 + G_o + \Delta_G \tag{2}$$

where G_o is the doubling time 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 $(1 + G_o)$.

The achievable tritium breeding ratio, 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 in an evolving process. The choices for many of the design features, materials and technology options have not been made. The achievable tritium breeding ratio 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 tritium breeding ratio, Λ_a, as:

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

where

Λ_c = tritium breeding ratio 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.

Δ_a = total uncertainty in achievable breeding ratio.

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:

$$\varepsilon = \Lambda_a - \Lambda_r = (\Lambda_c - \Delta_a) - (1 + G_o + \Delta_G) \qquad (5)$$

The larger ε is, the higher is the probability that the D-T fuel self-sufficiency condition will be met, i.e., higher values of ε represent a lower degree of risk in not satisfying the fuel self-sufficiency requirements.

The following three sections evaluate Λ_a, Λ_r and ε for parameter range and design options presently under investigation for fusion reactors with particular emphasis on tokamaks.

3. ACHIEVABLE BREEDING RATIO

The Blanket Comparison and Selection Study (BCSS)(5, 6) evaluated 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 1. Extensive design and analysis effort was devoted to optimizing these blankets within two reactor reference systems, the STARFIRE(7) tokamak reactor and the MARS(8) tandem mirror reactor. Detailed three-dimensional Monte Carlo calculations were performed for the nine blanket concepts in the two reference reactor systems to calculate the tritium breeding ratio. These results are documented in Ref. 6 and are shown in Table 1. The tritium breeding ratios shown in Table 1 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 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 1 as the reference estimates for Λ_c of Eqs. (3) and (5).

Table 1. Tritium breeding ratio calculated for leading blanket concepts (see Ref. 6).

Blanket[a]	Breeding Ratio (Λ_c)	
	Tokamak	Mirror
A $LiAlO_2$/DS/HT9/Be	1.24	1.29
B Li/Li/HT9	[b]	1.14
C LiPb/LiPb/V	(1.3)[c]	1.18
D Li/Li/V	1.28	1.19
E Li_2O/He/HT9	1.11	1.14
F $LiAlO_2$/He/HT9/Be	1.04	1.16
G Li/He/HT9	1.16	1.17
H Flibe/He/HT9/Be	1.17	1.29
I $LiAlO_2$/H_2O/HT9/Be	1.16	1.22

[a] Blanket concept is denoted by breeder/coolant/structure/multiplier.

[b] Not evaluated.

[c] Estimated for 90% ^{6}Li enrichment.

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 will 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:

a. Basic Data: The uncertainties in the tritium breeding ratio due to uncertainties in basic nuclear data, δ_D, were evaluated in references 1 and 9. They were found to vary from ~2% to 6%.

b. Data Processing and Representation: The experimental data undergoes various processes prior to its direct use as input data to transport codes. These processes include: a) tabulating data at a finite number of points (e.g., energy points) or representation as an analytic function, 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. 8 show ~4% difference in the breeding ratio results obtained with various commonly used libraries. The values of Λ_c in Table 1 were calculated in BCSS using the MCNP Monte Carlo code[10] with continuous energy treatment. Thus, the uncertainties associated with data representation should be lower than those in Ref. 9. We will assume here an approximated value for the error of ~2%.

c. Transport Calculations: There are uncertainties associated with transport calculations for predicting the neutron flux which 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%.

d. 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 1 was sufficiently detailed so that the associated error is estimated to be only on the order of 1%.

e. 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 (a) 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 tritium breeding ratio due to uncertainties in system definition were evaluated in Ref. 1. 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 2. The largest type of change in the system is the elimination of the inboard breeding region which 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 to resolve critical technical problems associated with MHD-effects at high magnetic fields.

Assuming that the uncertainties in Table 2 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%.

4. REQUIRED BREEDING RATIO

A model was developed in Ref. 1 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 also used to evaluate the required breeding ratio at the reference parameter conditions given in Table 3. The resulting reference breeding ratio, i.e., $1 + G_o$, is 1.08. the value of Λ_r was also calculated[1] for large sets of variations in the reactor parameter. Six parameters are found to have the largest effect on Λ_r. The variation of Λ_r with each of these parameters is shown in Fig. 1.

Table 2. Uncertainties in achievable breeding ratio due to uncertainties in system definition (for a tokamak reactor).

Type of Change	% Change in TBR
A. No inboard blanket	14
B. Limiter:	
Non-breeding 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

In order to accurately estimate 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 "occurence" or "obtaining" particular sets of reactor parameters. 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 Ref. 9 for nuclear data, to quantify Δ_G is not possible. This is a fruitful area for future investigation.

A number of approaches to quantify Δ_G were explored in Ref. 1. Results were found to be very sensitive to assumptions on probability distributions for reactor parameters. A plausible value of δ_G was derived as 0.133 based on a combination of uncertainty analysis and engineering judgement as to the most likely probability distributions. Table 4 provides a summary of the procedure used to calculate this plausible value of δ_G. The six key reactor parameters of Fig. 1 were considered. Log-normal probability distributions were assumed for the probability of occurence of various values for each reactor parameter. The most probable value for each parameter is designated as x_g in Table 4. Values of x_g were taken as the reference values from Table 3. Each log-normal probability distribution had a standard deviation, σ_g, as shown in Table 4. For each parameter, the difference between the breeding ratio at $x_g \cdot \sigma_g$ or x_g/σ_g and the breeding ratio at the reference parameters was taken as an estimate of δ_g for this parameter. The uncertainties due to various parameters were assumed to be statistically uncorrelated and the total uncertainty was calculated as the square root of the sum of the squares of partial uncertainties.

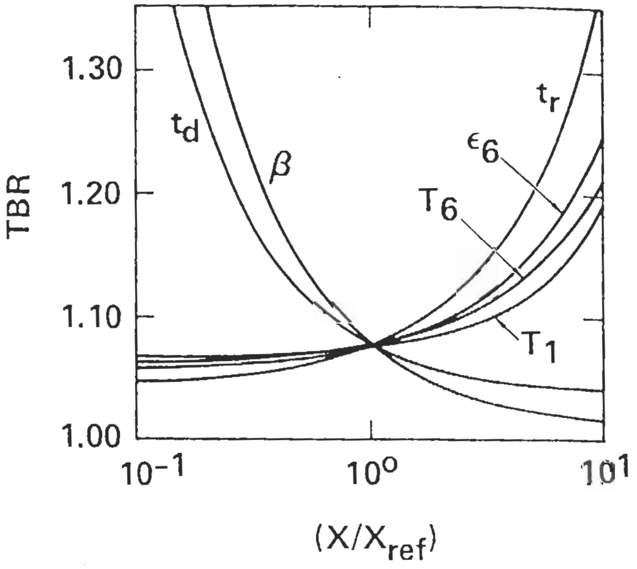

Figure 1. Variation of the required tritium breeding ratio with key parameters. The horizontal axis is x/x_{ref}, where x_{ref} is the value of the parameter in the reference base case shown in Table 3.

5. COMPARISON OF REQUIRED AND ACHIEVABLE TBR

Table 5 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 1. The uncertainty in the achievable breeding ratio, Δ_a, is calculated as $\sqrt{\Delta_p^2 + \Delta_s^2}$ where the uncertainty in prediction, Δ_p, and the uncertainty in system definition, Δ_s, are those described earlier. The reference required breeding ratio, $1 + G_o$, and the associated uncertainty, Δ_G,

Table 3. Reference parameters used for evaluating Λ_r.

Parameter (X)	Base Case Value (X_{ref})
Tritium Consumption (Burn in Plasma) ($\dot{N}^-$)	0.5 kg/day
Doubling Time (t_d)	5 yr
Tritium Fractional Burnup in Plasma (β)	5%
Number of Days of Reserve for Plasma Fueling (t_r)	2 days
Non-Radioactive 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)	10 days
Breeder Processing (T_2)	1 day
Blanket Coolant Processing (T_3)	100 days
Fuel Cleanup and Isotope Separation Units (T_4)	0.1 days
Plasma Exhaust Processing (T_6)	1 day
Limiter Coolant Processing (T_7)	100 days
First Wall Coolant Processing (T_8)	100 days
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 ($\dot{I}_9$)	0.01g/day

Table 4. Estimate of uncertainty in required breeding ratio.

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	.05	2.5	0.02	1.18	0.096
Days of T reserve	2 d	2	4	1.108	0.029
Plasma recovery loss fraction	0.001	5	.005	1.153	0.071
Plasma recovery reserve time	1.0 d	2	2 d	1.092	0.014
Blanket reserve time	10 d	3	30	1.097	0.019
All other systems	—	--	—	1.10	0.021

Table 5. Summary of Achievable and Required Tritium Breeding Ratios and Associated Uncertainties for Leading Blanket Concepts in Tokamak Reactor Systems

		Achievable Λ_a		Required Λ_r		
	Concept[a]	Λ_c	Δ_a	$1 + G_o$	Δ_G	$\varepsilon = \Lambda_a - \Lambda_r$
A	$LiAlO_2$/DS/HT9/Be	1.24	0.22	1.077	0.143	-0.20
B	Li/Li/HT9	[b]	--	--	--	--
C	LiPb/LiPb/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/HT9	1.11	0.21	1.077	0.143	-1.32
F	$LiAlO_2$/He/HT9/Be	1.04	0.19	1.077	0.143	-0.37
G	Li/He/HT9	1.16	0.22	1.072	0.142	-0.27
H	Flibe/He/HT9/Be	1.17	0.22	1.072	0.142	-0.26
I	$LiAlO_2$/H_2O/HT9/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% Li enrichment.

are the same as those discussed in the previous section with one exception. The reference tritium inventory in liquid metal and molten salt breeder blankets was lowered from 5 kg to 1 kg to better reflect present experimental data.

Important observations can be made on the results of Table 5. The tritium breeding ratio 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 components choices for the reactor system as to the potential of attaining tritium fuel self-sufficiency one needs a figure of merit. A plausible figure of merit was defined in Eq. (5) as $\varepsilon = \Lambda_a - \Lambda_r$. Values of ε are also shown in Table 5. In calculating ε, the absolute magnitude of the Δ's was used. Although some uncertainties may increase or decrease Λ_a or Λ_r, of 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 5 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 DT 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.

6. SELF-SUFFICIENCY IMPACT ON R&D

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 LiPb highly enriched in ^{6}Li 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(5) in detailed engineering analysis not to be adequate. Beryllium has been found to be the only effective non-fissionable 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 5.

The intrinsic upper limits on the breeding potential for all present candidate blanket concepts mandate that fusion reactor system features be selected so as not to seriously reduce Λ_a. Results summarized in previous sections 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 requires eliminating the inboard blanket should be rejected as high risk fuel self-sufficiency viewpoint.

2. The R&D for subsystems that involve penetrations and non-breeding 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 non-breeding 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[11] 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 are 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 shown in Table 3. 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. 4, 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:

- Doubling time (t_d) = 5y
- Tritium fractional burnup in plasma (β) = 5%
- Number of days of tritium reserve for plasma fueling (t_r) = 2 days
- Tritium extraction inefficiency in plasma exhaust processing (ε_6) = 0.01%
- Mean residence time of tritium in plasma exhaust processing (T_6) = 1 day
- 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 Λ_r = 1.08 goal is too high or too low in view of the requirements implied on 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 too demanding requirements on the performance parameters that seem unlikely to be achieved. On the other hand, results on the achievable breeding ratio and uncertainties with all present blanket concept suggest that a goal of $\Lambda_r > 1.10$ imply 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 6 shows the limiting values for the six key parameters in order to keep Λ_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 6 is a minimum value. Relative to the Reference Case defined above of Λ_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 6. 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 2 oy or 8%, respectively; or alternatively reduce the maximum t_r to 0.2 days as can be

Table 6. Limiting values (maximum or minimum) for key fusion reactor parameters that must be achieved to keep the required tritium breeding ratio, 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), days	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 7. Limiting values (maximum or minimum) for key fusion reactor parameters that must be achieved to keep the required tritium breeding ratio, 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), days	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), days	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.

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-h in Table 6. Fast growth of fusion power may require a much lower doubling time than 5 years. 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 year, 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 6, the importance of β should be evident in cases d-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 d, 0.5%, 10 d, or 22 kg require 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.(11) 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 appear to be very large.(7, 12)

Table 7 is similar to Table 6 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 permit decreasing t_d or β to 3.5 y or 4%, respectively; or alternatively increasing t_r to 3 days. A doubling time of 0.75 y becomes possible if β is increased to 50%. Other than changing β, the minimum doubling time to be allowed without requireing more than a factor of 10 improvement in any particular parameter is 1.5 y. The only such single change that can lower t_d to 1.5 y is t_r = 0.2 d. 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 d, ϵ_6 to 0.5%, T_6 to 10 d, 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.

7. PRESENT EFFORT ON TRITIUM BREEDING

Present efforts on tritium breeding are focused on: 1) reducing uncertainties in a) required TBR, and in b) achievable TBR; and 2) improving the predictability of uncertainties. The level of effort in the world fusion program in these areas can be viewed as modest.

A key part of the effort to reduce uncertainties in required TBR is the development of models[1-4] to describe the fusion fuel cycle. Improvements in these models permit better estimates of the required TBR. In addition, results from parametric studies using these models can be utilized to identify the allowable range of parameter space and the preferred physics and technology design options from fuel self-sufficiency viewpoint. As shown in previous sections, such effort is very useful in guiding R&D activities.

Reducing uncertainties in achievable TBR requires 1) reducing uncertainty due to system definition, Δ_s, and 2) reducing uncertainty in predicting TBR for a given system, Δ_p (see Eq. 3). Uncertainties in system definition can be reduced by narrowing material and design options that are being considered for fusion reactor components and by providing greater engineering details in describing the selected design options. Examples of such effort for the blanket component are BCSS[5, 6] and the European Blanket Study.[2] Similar effort is required for other components such as those for plasma impurity control and plasma heating.

The uncertainty in prediction, Δ_p, can be reduced by improvement of calculational methods and nuclear data. Present effort in the world program is very limited for two reasons: 1) sophisticated neutronics methods and data developed in the nuclear fission program are available and applicable for fusion, 2) uncertainties in prediction of TBR are now thought to be significantly less than those from other sources of uncertainties in evaluating self-sufficiency (this assumption needs to be validated experimentally). However, there remains a need for some effort on methods and data in a number of specific areas.[3]

Improving the predictability of uncertainties in both the achievable and required breeding ratios is an area that has received considerable attention recently. As can be seen from results in previous sections, such effort is justified as it is crucial to evaluating the degree of risk in not attaining the fuel self-sufficiency goal in future fusion reactors.

Predicting the uncertainty in the required TBR requires a new methodology. As discussed in Sec. 4, the required TBR depends on many choices for reactor components and on the achievable performance parameters for each component. Quantifying the probable range for the required TBR and deriving an estimate of the probable total uncertainty requires a new methodology that combines statistical methods and the science/art of predicting the outcome of R&D for new technologies. Suggested approaches and areas for future investigations are discussed in Ref. 1.

Improving the predictability of the uncertainty in the achievable TBR is a problem that belongs almost solely to the field of neutronics. Methods for improving the prediction of uncertainty are available in this case from the fission reactor R&D experience and they have begun to be applied in the fusion field. An important element in this effort is performing integral neutronics experiments with point neutron sources. In these experiments, assemblies that simulate the blanket are irradiated for a relatively short time to measure the tritium production rate. A comparison between calculated and measured tritium production rates yields useful information on uncertainties in methods and data. An example of present integral blanket neutronics experiments is the FNS activity described in Ref. 13.

Sensitivity analysis is also a powerful tool in providing estimates of uncertainties. Present efforts in this area are summarized in Ref. 9.

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