MODELLING AND ANALYSIS OF DT FUEL SELF-SUFFICIENCY IN FUSION REACTORS

Mohamed A. Abdou
UCLA

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Purpose of Effort

- Understand and quantify conditions necessary to achieve DT self-sufficiency in fusion reactors
- Identify R&D areas in physics and engineering of critical importance to fuel self-sufficiency

Approach

- Develop mathematical models to describe tritium behavior in all components in the fuel cycle

- Develop probability distributions for possible outcome of fusion physics and engineering R&D

- Perform sensitivity analysis to determine importance of parameters

- Estimate range of uncertainties

- Identify critical R&D needs for fuel self-sufficiency

TRITIUM BREEDING PROBLEM

- A part of DT fuel self-sufficiency issue

- Self-sufficiency condition:

  Λ_r = Required tritium breeding ratio

  Λ_a = Achievable breeding ratio

  $\Lambda_r > \Lambda_a$

- Key question:

  Magnitude of uncertainties in Λ_r, Λ_a

  - Conventional types of uncertainties
  - Unconventional type

REQUIRED TBR

$$\Lambda_r = 1 + G_o + \Delta_G$$

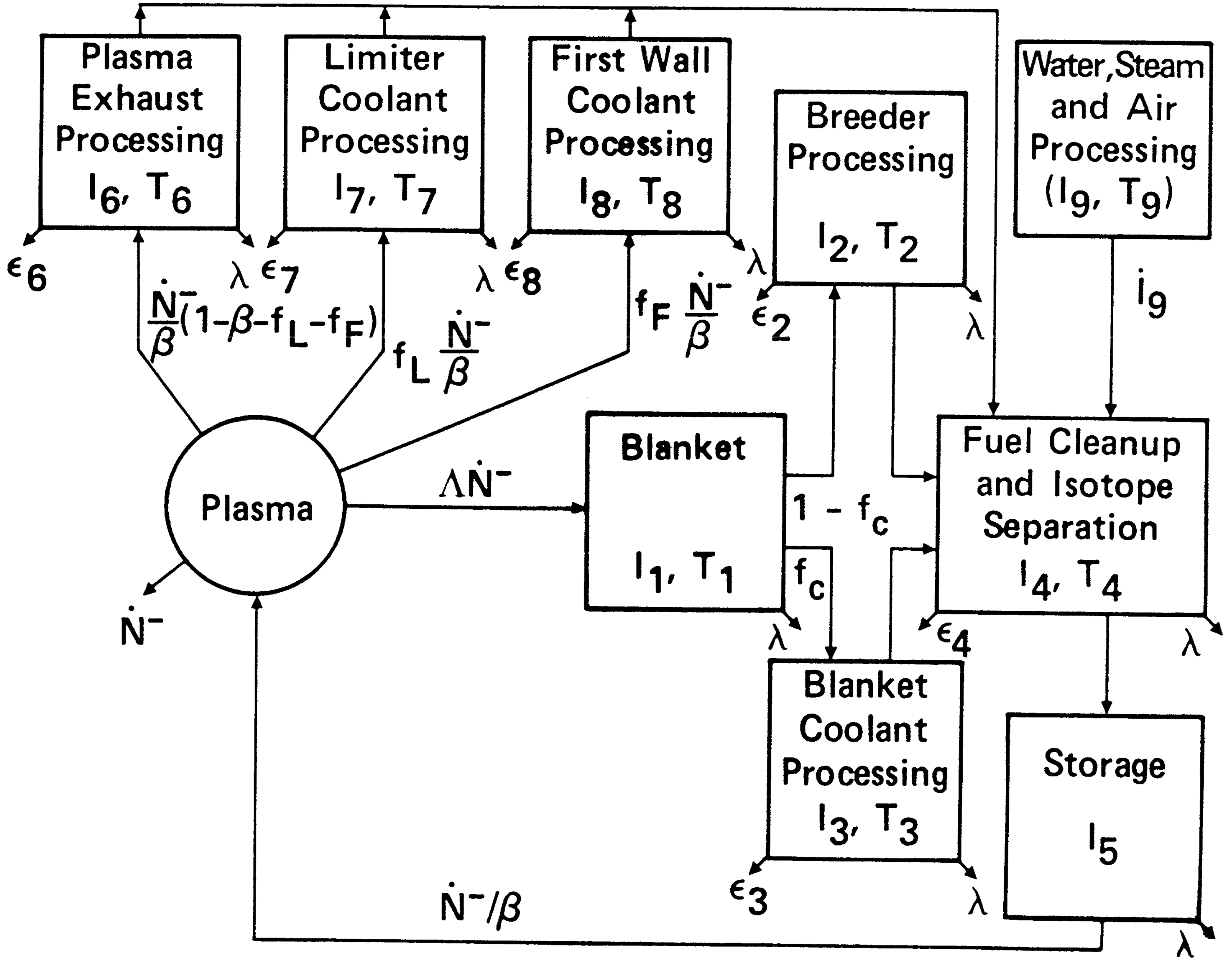
G_o = doubling time margin for a reference conceptual design

Δ_G = uncertainty associated with G

Model

- Model was formulated and used to evaluate dependence of Λ_r on reactor parameters.
- Methods for estimating Δ_G are under development. Initial results are available.

Schematic model of the fuel cycle for a DT fusion reactor used in the present work



Λ = tritium breeding ratio

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

I_i = tritium inventory in compartment i

T_i = tritium mean residence time in compartment i

ε_i = nonradioactive loss of tritium in compartment i

λ = tritium decay constant

β = tritium fractional burnup in the plasma

f_i = tritium fractional leakage in compartment i

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

TRITIUM INVENTORY VARIATION WITH TIME
FOR THE BASE CASE PARAMETER VALUES
USING β = 0.05 and t_d = 5 YR

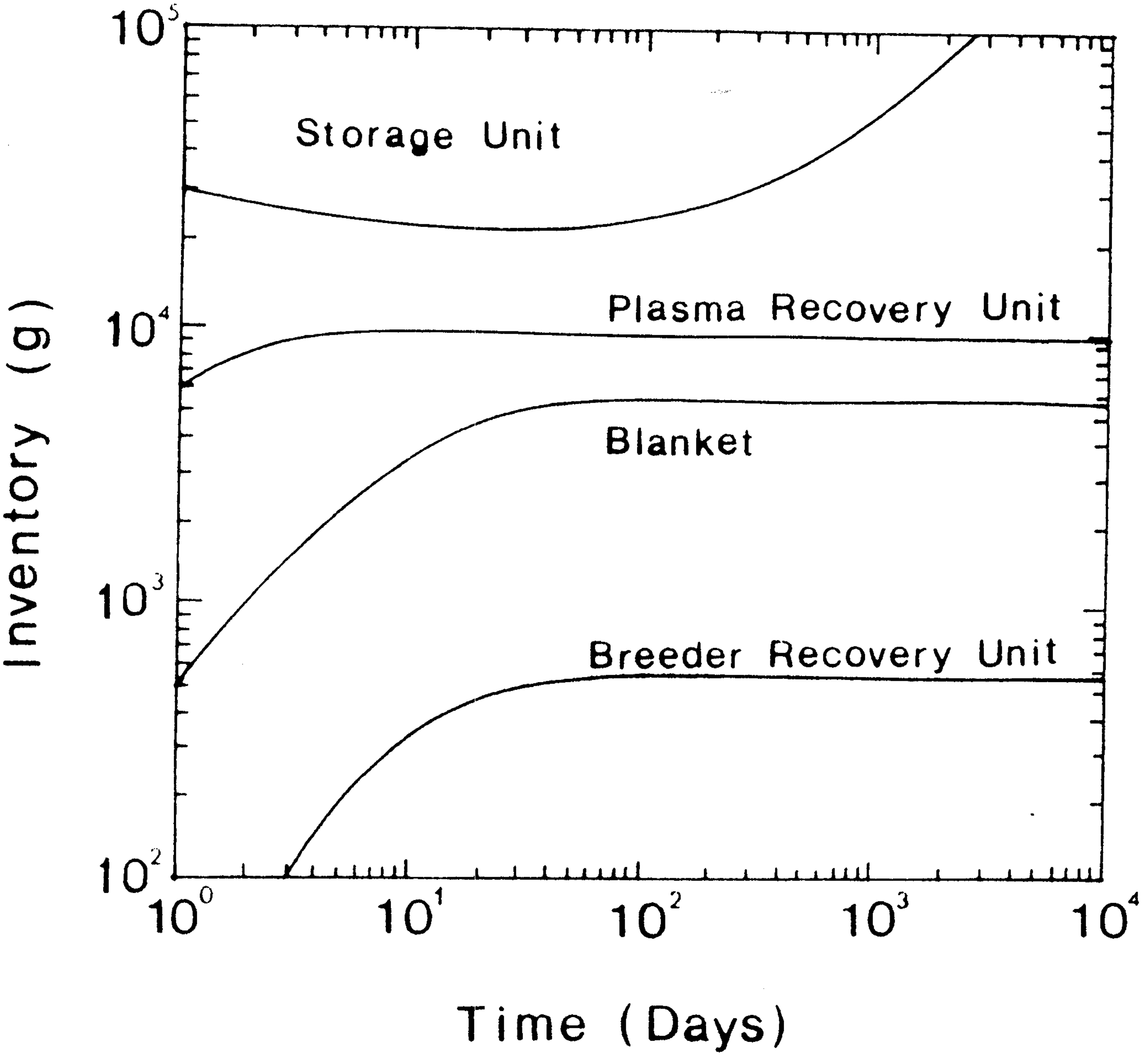


Table 3. Summary of Variation of the Required Breeding Ratio with a Single Change in Each of the Reference Parameters

Parameter (X)	TBR for		Slope	Percentage of Total Slope
	$(X_{ref}/10)$	$(X_{ref} \cdot 10)$		
$\dot{N}^-$	1.08(0.0%)*	1.08(0.0%)*	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
			$\sum = 0.2231$	$\sum = 100.0$

* Values in parenthesis represent the relative change of TBR with respect to a reference TBR of 1.08.

REQUIRED TBR IS FOUND TO BE STRONGLY DEPENDENT ON SIX KEY PARAMETERS

β = tritium fractional burnup in plasma

t_d = doubling time

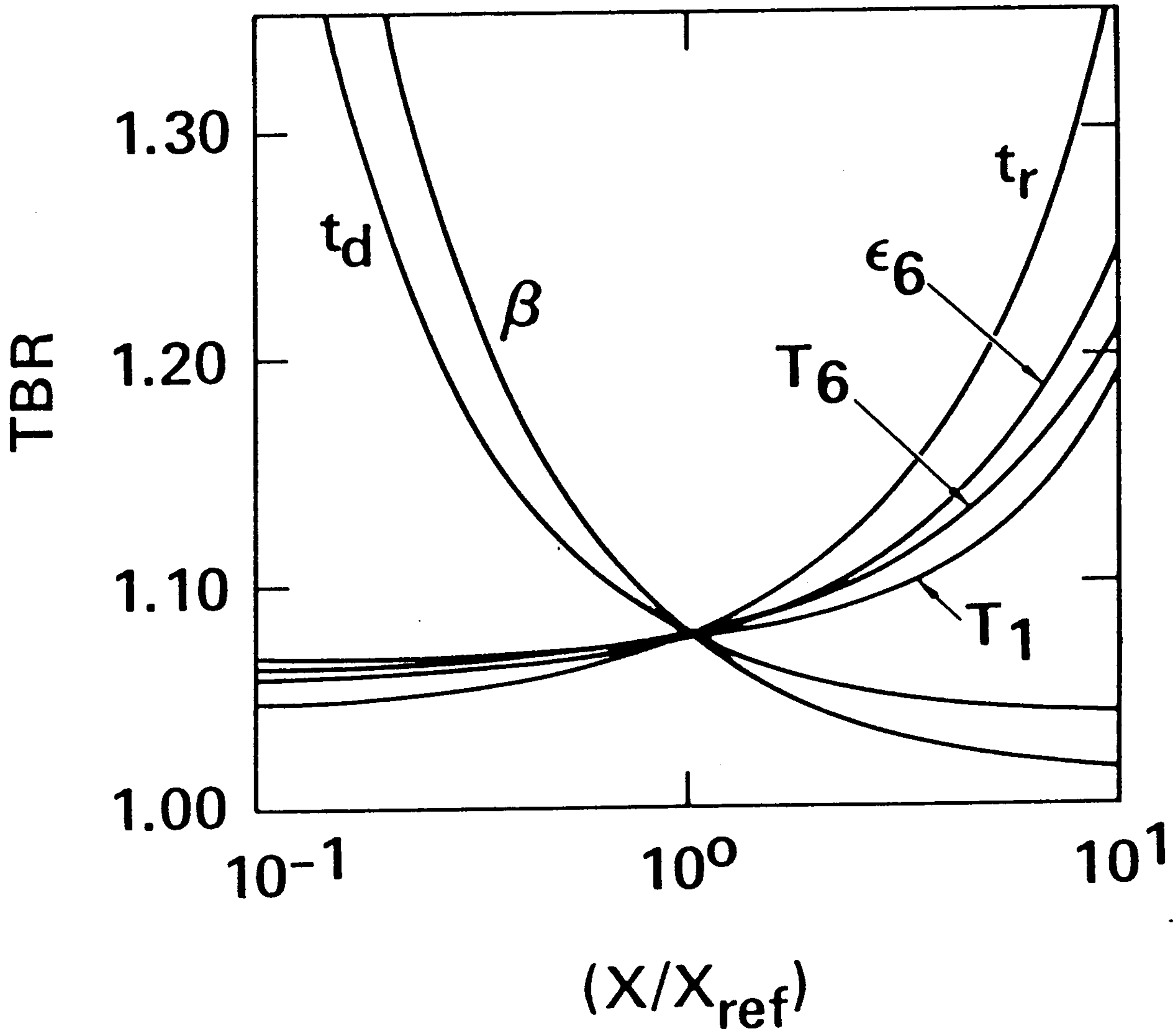
T_1 = tritium mean residence time in blanket

T_6 = tritium mean residence time in plasma exhaust processing

t_r = number of days of tritium reserve

ϵ_6 = tritium extraction inefficiency in plasma exhaust processing

Dependence of Required TBR on Plasma, Engineering Parameters



Reference Case (X_{ref})

β = 5%
T_1 = 10d
t_r = 2d

t_d = 5y
T_6 = 1d
ϵ_6 = 0.1%

METHODS FOR CALCULATING Δ_G

Problem

- We know from mathematical models how to calculate

  $\Lambda_r = f(x_1, x_2 \ldots, x_n)$

  where x_i = reactor parameter

- x_i can not be defined now; we can only estimate a range

Approach

- Estimate expected values of x_i's

- Calculate $\Lambda_r^o = f(x_1^o, x_2^o, \ldots, x_n^o)$

  x_i^o = reference reactor parameter

- Define

  $$\Lambda_r = \Lambda_r^o + \Delta_G$$

- Develop probability distribution for x_i around x_i^o (Key problem)

- Estimate Δ_G

Log-Normal Probability Distributions Used as Weighting Functions, Superimposed on the Variation of the Breeding Ratio with Doubling Time.

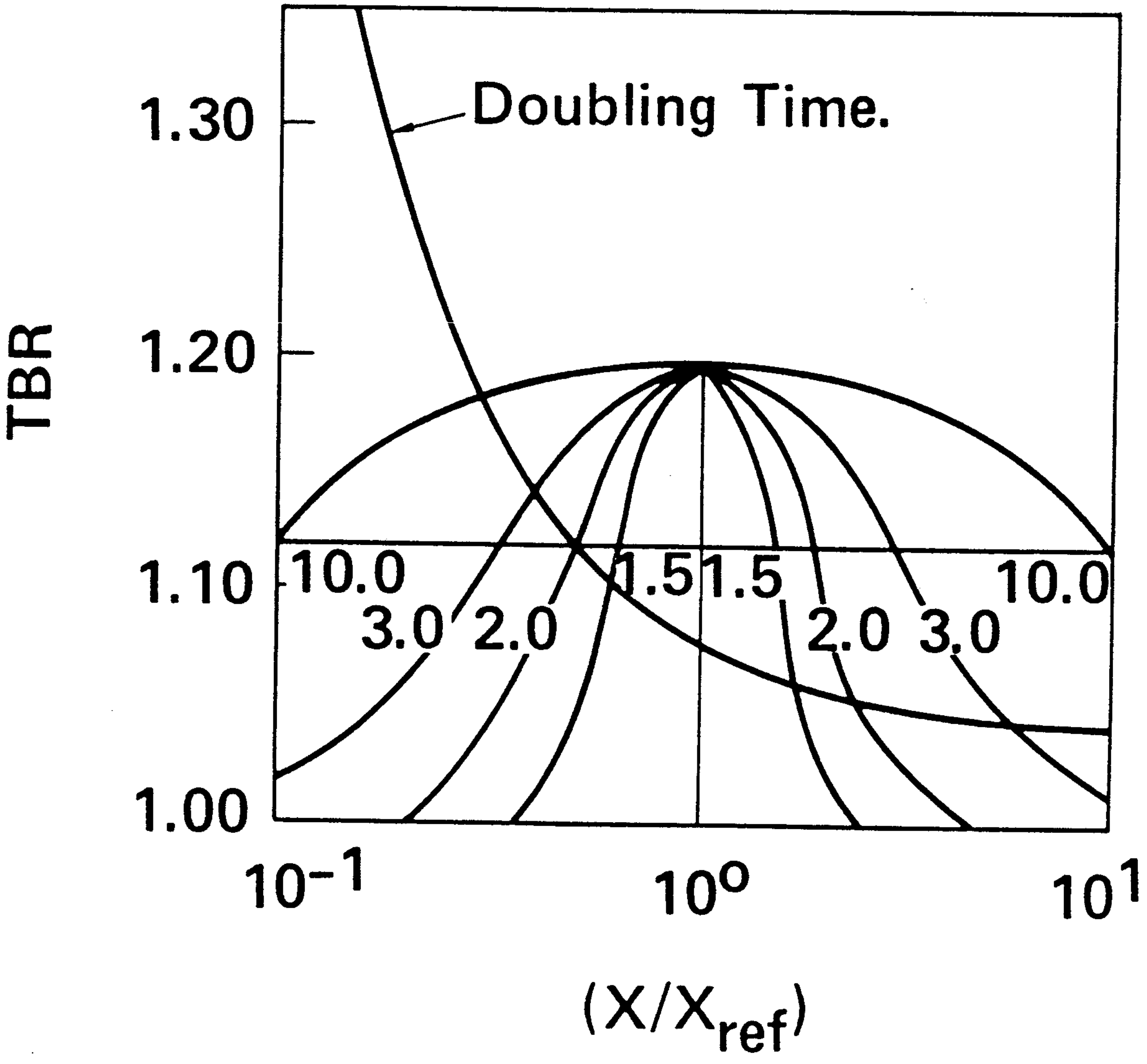


Table 21. Breeding Ratio Weighted for Log-Normal Distribution of Parameter, x

Parameter, x (Base Case Value)	Ref. Case σ_g = 1.0	σ_g = 1.5	σ_g = 2.0	σ_g = 2.5	σ_g = 3.0	σ_g = 5.0
Doubling time, t_α (5 yr.)	1.077	1.081 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 T-reserve, t_r (2 d)	1.077	1.079 1.079	1.085 2.085	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 d)	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 d)	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 log-normal parameter x weighting with no boundaries on x value. Bottom breeding ratio value is for log-normal parameter x weighting and defined boundaries on x; in this case set equal to 0.1x (base case value) and 10x (base case value).

Table 22. Log Normal 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	.05	3	1.122	0.042
Days of T reserve	2 d	2	1.085	0.007
Extraction inefficiency in plasma exhaust processing	.001	5	1.089	0.011
Residence time in plasma exhaust processing	1 d	2	1.081	0.004
Blanket residence time	10 d	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 ten times the reference value.

REQUIRED BREEDING RATIO UNCERTAINTY
(95% CONFIDENCE LEVEL)

Parameter	x_g	σ_g	$\Lambda_{ex,i}$	Δ_{Gi} (%)
Doubling time	5 yr	2	1.120	4
Burn fraction	.05	2.5	1.18	9.6
Days of T reserve	2 d	2	1.108	3
Plasma recovery loss fraction	0.001	5	1.153	7
Plasma recovery time	1 d	2	1.092	1.4
Blanket inventory	5 kg	3	1.097	2

ACHIEVABLE TBR

- Problem - We cannot predict precisely Λ_a because:
    - We do not know the exact specifications of what to build
    - For given reactor specifications, we cannot predict precisely the performance

- We can only calculate a TBR for a reference system with assumptions about its specifications

$$\Lambda_a = \Lambda_c - \sqrt{\Delta_s^2 + \Delta_p^2}$$

Λ_c = TBR calculated (the best we know how today, 3D, etc.) for a specified blanket in a specified reactor

Δ_s = Uncertainty associated with system definition [changes in calculated TBR resulting from changes in the reference reactor system (e.g., reference reactor system has limiter and reactor to be built could have a divertor)]

Δ_p = Uncertainties in predicting TBR for a given system

$$\Delta_p = \sqrt{\Delta_m^2 + \Delta_d^2 + \Delta_c^2}$$

Δ_m = Uncertainties associated with geometric modeling

Δ_d = Uncertainties associated with nuclear data

Δ_c = Uncertainties associated with calculational methods

TYPES OF UNCERTAINTIES IN PREDICTING ACHIEVABLE TBR

Uncertainties Associated with System Definition (Δ_s)

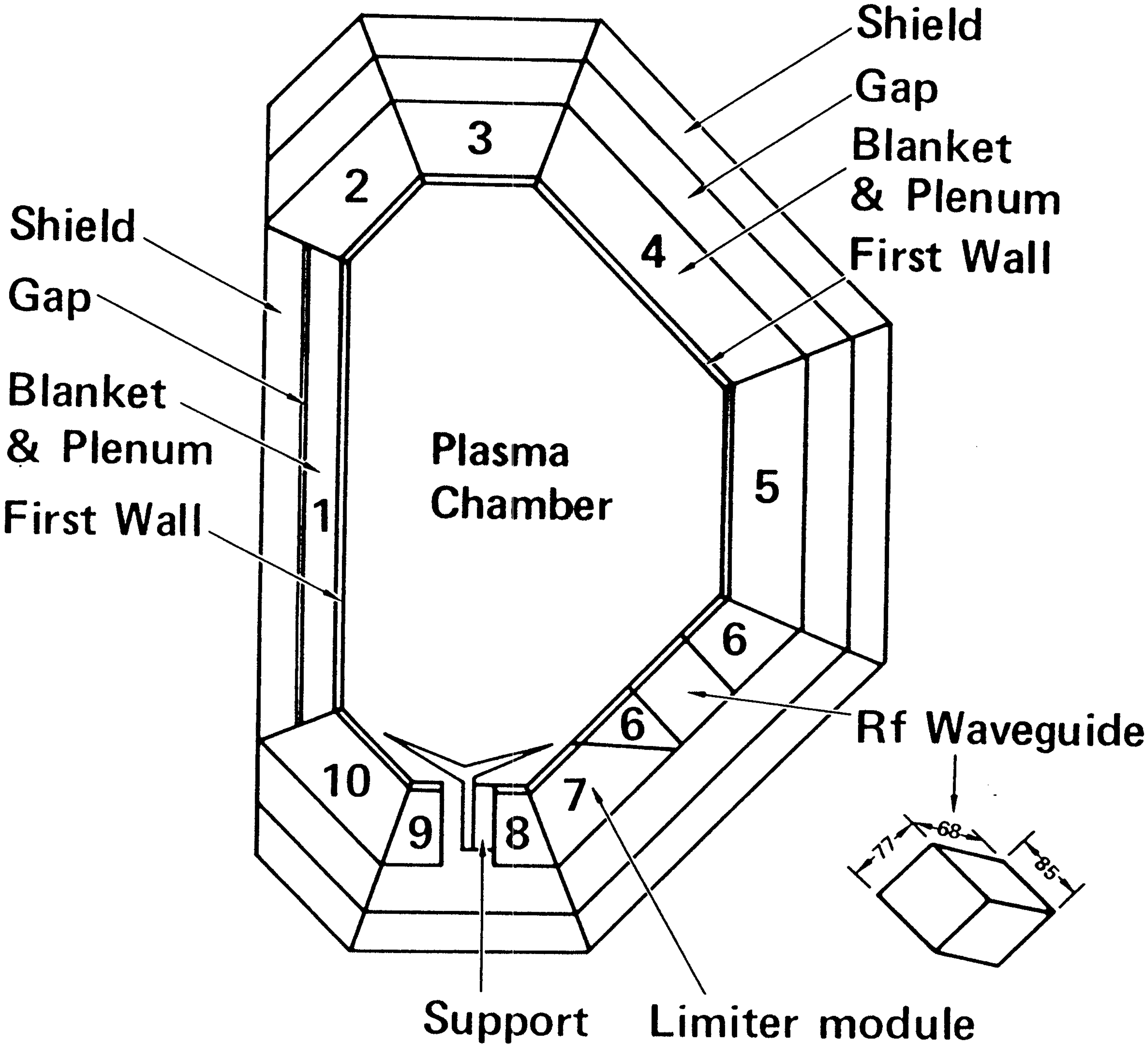
- First Wall/Blanket Definition
    - Configuration details, structure, coolant, manifolds, form and porosity of solid breeders, thermophysical property variations, etc.

- Reactor Definition
    - Technology choices (type of rf vs. neutral beams, limiter vs. divertor, etc.)
    - Requirements and specifications for specific technology choices (e.g., size and configuration of penetrations for limiter, material choices for limiter)
    - Presence of yet undefined components (e.g., penetrations for diagnostics and fueling, I&C)
    - Possible need for components to satisfy yet undefined requirements (e.g., passive copper coils in the blanket for plasma stabilization, sector to sector electrical joints, etc.)

Δ_p = UNCERTAINTIES ASSOCIATED WITH PREDICTING TBR FOR A GIVEN SYSTEM

- Approximations in Geometrical Modeling (Δ_m)
  - Approximating engineering 3D surfaces and volumes by traditional mathematically convenient shapes (intersection of cones, cylinders, spheres, cubes, etc.)
  - Approximating discrete by continuous geometric zones
  - Approximating the details of heterogenity
- Nuclear Data (Δ_d)
  - Uncertainties in basic nuclear data
  - Approximations in data processing
  - Approximations in final data libraries (number of energy groups, weighting functions, etc.)
- Calculational Methods (Δ_c)
  - Inherent in methods and codes
  - Introduced by analyst (e.g., order of S_n, P_n, etc.)

Vertical Cross Section of Reference Tokamak Reactor



UNCERTAINTIES IN ACHIEVABLE BREEDING RATIO DUE TO UNCERTAINTIES IN SYSTEM DEFINITION

Type of Change	Change in TBR (%)
No inboard blanket	14
Limiter:	
Non-breeding limiter module	6
Doubling limiter duct width	2
Strong absorber coating	4
Divertor replaces limiter	7
Other penetrations:	
Auxiliary heating	1
Fueling, diagnostics, etc.	1
Other materials in blanket (e.g., passive copper coils)	3
Blanket first wall specification details (configuration, structure, coolant, manifolds)	2

Δ_d, ESTIMATE OF UNCERTAINTY IN TBR DUE TO UNCERTAINTIES IN NUCLEAR DATA

Blanket Concept	Δ_d (%)
Li/Li/HT9	5.5
LiPb/LiPb/V	4.4
Li/Li/V	6
Li_2O/He/HT9	4.9
$LiAlO_2/H_2O$/HT9/Be	2.1

ACHIEVABLE AND REQUIRED TRITIUM BREEDING RATIOS AND UNCERTAINTIES FOR LEADING BLANKETS IN TOKAMAKS

Concept	Achievable Λ_a		Required Λ_r		
	Δ_c	Δ_a	$1 + G_o$	Δ_g	$\varepsilon = \Lambda_a - \Lambda_r$
$LiAlO_2$/DS/HT9/Be	1.24	0.22	1.077	0.143	-0.20
LiPb/LiPb/V	1.30	0.24	1.072	0.142	-0.15
Li/Li/V	1.28	0.24	1.072	0.142	-0.17
Li_2O/He/HT9	1.11	0.21	1.077	0.143	-1.32
$LiAlO_2$/He/HT9/Be	1.04	0.19	1.077	0.143	-0.37
Li/He/HT9	1.16	0.22	1.072	0.142	-0.27
$LiAlO_2$/H_2O/HT9/Be	1.16	0.21	1.077	0.143	-0.27

Table 25.
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 26.
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.