OVERVIEW OF TRITIUM BREEDING
PROBLEMS AND EFFORTS

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\[ \Lambda_r = 1 + G_0 + \Delta_G \]

\( G_0 \) = doubling time margin for a reference conceptual design

\( \Delta_G \) = uncertainty associated with \( G \)

**Model**

- Model was formulated and used to evaluate dependence of \( \Lambda_r \) on reactor parameters.

- Methods for estimating \( \Delta_G \) are under development. Initial results are available.
TRITIUM BREEDING PROBLEM

- A part of DT fuel self-sufficiency issue

- Self-sufficiency condition:

  \[ \Lambda_r = \text{Required tritium breeding ratio} \]

  \[ \Lambda_a = \text{Achievable breeding ratio} \]

  \[ \Lambda_r > \Lambda_a \]

- Key question:

  Magnitude of uncertainties in \( \Lambda_r, \Lambda_a \)

  - Conventional types of uncertainties

  - Unconventional type
Schematic model of the fuel cycle for a DT fusion reactor used in the present work.

- Plasma Exhaust Processing $I_6, T_6$
- Limiter Coolant Processing $I_7, T_7$
- First Wall Coolant Processing $I_8, T_8$
- Breeder Processing $I_2, T_2$
- Water, Steam and Air Processing ($I_9, T_9$)

Flows and Processes:
- $\dot{N}^-/\beta$
- $\epsilon_6$
- $\lambda \epsilon_7$
- $\lambda \epsilon_8$
- $\lambda \epsilon_2$
- $\lambda \epsilon_4$
- $\lambda \epsilon_3$
- $i_9$
- $\Lambda \dot{N}^-$
- $f_F \dot{N}^-/\beta$
- $f_L \dot{N}^-/\beta$
- $1 - f_c$
- $f_c$
\[ \Lambda = \text{tritium breeding ratio} \]

\[ \dot{N}^- = \text{tritium burn rate in the plasma} \]

\[ I_i = \text{tritium inventory in compartment } i \]

\[ T_i = \text{tritium mean residence time in compartment } i \]

\[ \varepsilon_i = \text{nonradioactive loss of tritium in compartment } i \]

\[ \lambda = \text{tritium decay constant} \]

\[ \beta = \text{tritium fractional burnup in the plasma} \]

\[ f_i = \text{tritium fractional leakage in compartment } i \]

\[ I_0 = \text{constant flow rate of tritium recovered from waste, steam, and air processing units} \]
TRITIUM INVENTORY VARIATION WITH TIME
FOR THE BASE CASE PARAMETER VALUES
USING $\beta = 0.05$ and $t_d = 5$ YR

![Graph showing inventory variation with time for different units: Storage Unit, Plasma Recovery Unit, Blanket, Breeder Recovery Unit.](image-url)
Dependence of Required TBR on Plasma, Engineering Parameters

Reference Case ($X_{\text{ref}}$)

- $\beta = 5\%$
- $T_1 = 10d$
- $t_r = 2d$
- $t_d = 5y$
- $T_6 = 1d$
- $\epsilon_6 = 0.1\%$
REQUIRED TBR IS FOUND TO BE
STRONGLY DEPENDENT ON SIX KEY PARAMETERS

\[ \beta = \text{tritium fractional burnup in plasma} \]

\[ t_d = \text{doubling time} \]

\[ T_1 = \text{tritium mean residence time in blanket} \]

\[ T_6 = \text{tritium mean residence time in plasma exhaust processing} \]

\[ t_r = \text{number of days of tritium reserve} \]

\[ \epsilon_6 = \text{tritium extraction inefficiency in plasma exhaust processing} \]
Log-Normal Probability Distributions Used as Weighting Functions, Superimposed on the Variation of the Breeding Ratio with Doubling Time.
### REQUIRED BREEDING RATIO UNCERTAINTY
(95% CONFIDENCE LEVEL)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$x_g$</th>
<th>$\sigma_g$</th>
<th>$\Lambda_{ex,i}$</th>
<th>$\Delta_{Gi} (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doubling time</td>
<td>5 yr</td>
<td>2</td>
<td>1.120</td>
<td>4</td>
</tr>
<tr>
<td>Burn fraction</td>
<td>.05</td>
<td>2.5</td>
<td>1.18</td>
<td>9.6</td>
</tr>
<tr>
<td>Days of T reserve</td>
<td>2 d</td>
<td>2</td>
<td>1.108</td>
<td>3</td>
</tr>
<tr>
<td>Plasma recovery loss fraction</td>
<td>0.001</td>
<td>5</td>
<td>1.153</td>
<td>7</td>
</tr>
<tr>
<td>Plasma recovery time</td>
<td>1 d</td>
<td>2</td>
<td>1.092</td>
<td>1.4</td>
</tr>
<tr>
<td>Blanket inventory</td>
<td>5 kg</td>
<td>3</td>
<td>1.097</td>
<td>2</td>
</tr>
</tbody>
</table>
ACHIEVABLE TBR

- Problem - We cannot predict precisely $\Lambda_a$ 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

\[
\Lambda_a = \Lambda_c - \sqrt{\Delta_s^2 + \Delta_p^2}
\]
\( \Delta_C = \) TBR calculated (the best we know how today, 3D, etc.) for a specified blanket in a specified reactor

\( \Delta_S = \) 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)]

\( \Delta_p = \) Uncertainties in predicting TBR for a given system

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

\( \Delta_m = \) Uncertainties associated with geometric modeling

\( \Delta_d = \) Uncertainties associated with nuclear data

\( \Delta_c = \) Uncertainties associated with calculational methods
TYPES OF UNCERTAINTIES IN PREDICTING ACHIEVABLE TBR

Uncertainties Associated with System Definition ($\Delta_s$)

- 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.)
\[ \Delta_p = \text{UNCERTAINTIES ASSOCIATED WITH PREDICTING TBR FOR A GIVEN SYSTEM} \]

- Approximations in Geometrical Modeling ($\Delta_m$)
  - 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 heterogeneity

- Nuclear Data ($\Delta_d$)
  - Uncertainties in basic nuclear data
  - Approximations in data processing
  - Approximations in final data libraries (number of energy groups, weighting functions, etc.)

- Calculational Methods ($\Delta_c$)
  - Inherent in methods and codes
  - Introduced by analyst (e.g., order of $S_n$, $P_n$, etc.)
Vertical Cross Section of Reference Tokamak Reactor

- Shield
- Gap
- Blanket & Plenum
- First Wall
- Plasma Chamber
- Support
- Limiter module
- Rf Waveguide
UNCERTAINTIES IN ACHIEVABLE BREEDING RATIO DUE TO UNCERTAINTIES IN SYSTEM DEFINITION

<table>
<thead>
<tr>
<th>Type of Change</th>
<th>Change in TBR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No inboard blanket</td>
<td>14</td>
</tr>
<tr>
<td><strong>Limiter:</strong></td>
<td></td>
</tr>
<tr>
<td>Non-breeding limiter module</td>
<td>6</td>
</tr>
<tr>
<td>Doubling limiter duct width</td>
<td>2</td>
</tr>
<tr>
<td>Strong absorber coating</td>
<td>4</td>
</tr>
<tr>
<td>Divertor replaces limiter</td>
<td>7</td>
</tr>
<tr>
<td><strong>Other penetrations:</strong></td>
<td></td>
</tr>
<tr>
<td>Auxiliary heating</td>
<td>1</td>
</tr>
<tr>
<td>Fueling, diagnostics, etc.</td>
<td>1</td>
</tr>
<tr>
<td><strong>Other materials in blanket (e.g., passive copper coils)</strong></td>
<td>3</td>
</tr>
<tr>
<td><strong>Blanket first wall specification details (configuration, structure, coolant, manifolds)</strong></td>
<td>2</td>
</tr>
</tbody>
</table>
$\Delta_d$, ESTIMATE OF UNCERTAINTY IN TBR DUE TO UNCERTAINTIES IN NUCLEAR DATA

<table>
<thead>
<tr>
<th>Blanket Concept</th>
<th>$\Delta_d$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li/Li/HT9</td>
<td>5.5</td>
</tr>
<tr>
<td>LiPb/LiPb/V</td>
<td>4.4</td>
</tr>
<tr>
<td>Li/Li/V</td>
<td>6</td>
</tr>
<tr>
<td>Li$_2$O/He/HT9</td>
<td>4.9</td>
</tr>
<tr>
<td>LiAlO$_2$/H$_2$O/HT9/Be</td>
<td>2.1</td>
</tr>
<tr>
<td>Concept</td>
<td>Achievable $\Lambda_a$</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Li$_2$O/He/HT9</td>
<td>1.11</td>
</tr>
<tr>
<td>LiA1O$_2$/He/HT9/Be</td>
<td>1.04</td>
</tr>
<tr>
<td>Li/He/HT9</td>
<td>1.16</td>
</tr>
<tr>
<td>LiA1O$_2$/H$_2$O/HT9/Be</td>
<td>1.16</td>
</tr>
<tr>
<td>LiA1O$_2$/DS/HT9/Be</td>
<td>1.24</td>
</tr>
<tr>
<td>LiPb/LiPb/V</td>
<td>1.30</td>
</tr>
<tr>
<td>Li/Li/V</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Achievable and Required Tritium Breeding Ratios and Uncertainties for Leading Blankets in Tokamaks
Attaining DT Fuel Self Sufficiency
Requires Success in Both Physics and Engineering

\[ I_B = \text{Blanket Tritium Inventory} \]
\[ E = \text{Tritium Extraction Efficiency in Plasma Exhaust} \]
\[ R = \text{No. of days of tritium reserve} \]

\[ I_B = 20 \text{ kg} \]
\[ E = 99.5\% \]
\[ R = 4 \text{ d} \]

\[ I_B = 5 \text{ kg} \]
\[ E = 99.9\% \]
\[ R = 2 \text{ d} \]

Required Tritium Breeding Ratio

Tritium Fractional Burnup in plasma, %

Self Sufficiency \rightarrow Lower Risk

More Successful

Engineering
PRESENT EFFORT ON TRITIUM BREEDING

- Efforts to Reduce Uncertainties in:
  
  Required TBR
  
  Achievable TBR

- Efforts to Improve Predictability of Uncertainties
REDUCING UNCERTAINTIES IN REQUIRED TBR

- Models to predict required TBR as a function of reactor plasma and engineering parameters

- Identifying allowable range of parameter space to guide R&D
  - Plasma, plasma support systems
  - Blanket
  - Tritium processing system
  - Other components
  - Early stage of fusion commercialization (short doubling time)
REDUCING UNCERTAINTIES IN ACHIEVABLE TBR

- Design Definition
  - Narrow materials and design concepts
  - Greater engineering detail

- Calculations
  - Modest improvement in methods
  - More detailed geometrical modeling

- Nuclear Data
  - Measurements
  - Evaluation
  - Data representation and processing
IMPROVING PREDICTABILITY OF UNCERTAINTY IN TBR

- Uncertainty in **Required** TBR
  - Probability distributions for reactor parameters
  - Methods to evaluate $\Delta g$

- Uncertainty in **Achievable** TBR
  - Integral experiments with point neutron source
  - Sensitivity analysis
    Improve methods
    Perform sensitivity studies
  - Benchmark calculations
  - Identifying requirements for integral experiments in fusion testing devices
• **LOTUS**: Switzerland
  - Led by IGA, EPFL, EIR in Switzerland
  - Cooperation with US, India
  - Emphasis on fissile material and tritium production in hybrid modules

• **LBM**: Supported by EPRI
  - PPPL, GA
  - Li$_2$O module for insertion in TFTR
  - Delays in using tritium in TFTR
  - Other uses being explored

• **Others**
  - OKTAVIAN: Osaka University
    Focus on clean, single material sphere
  - Special Experiments
    e.g., Pulsed Beryllium Sphere, LLNL