Prediction of neutron source, tritium production and activation for long-pulse operation of the ITER Neutral Beam Test Facility

presented by T T C Jones

on behalf of

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Outline

Motivation
• Input to ITER NB Test Facility safety analysis: Neutron and Tritium sources

Local Mixing Model for Beam-Target interaction
• Brief description of LMM
• Hydrogenic build-up and isotope exchange
• Neutron Rates from DD and DT reactions

Tritium Retention
• Limitations LMM model
• Thermal Diffusion Model

Neutronics and Activation Calculations for NBTF
• Methodology
• Dose rate results

Conclusions
Motivation

Input to Radiological Assessment

- Neutron production (2.5 & 14MeV) from 1MeV D beam-target reactions
- Neutron Activation
- Tritium production & retention

For prediction of

- Hands-on maintainability
- Requirements for Licensing
- Transportability of components (NBTF to ITER Site) if needed
- Shielding requirements

Helping to define

- Operational Plan constraints
- e.g. periods of H beam operation (to avoid neutron production; target cleanup)
**Local Mixing Model code (LMM*) (1)**

Treats the basic processes of Beam-Target interactions
- Slowing-down of fast beam ions in the target material (Cu)
- Hydrogenic build-up and isotope exchange
- Fusion Reaction probability during slowing-down

**e.g.**

Relative Probability Distribution $P(x)$ of implantation depths of $1\text{MeV} \ H, \ D \ & \ T$

Fills to saturation quickly

Fills to saturation slowly

Local Mixing Model code (LMM) (2)

Local Isotopic Build-up and Exchange

- Unsaturated regions fill up according to where the fast particles come to rest:
  e.g. for 2 species (say D & T) with flux densities $\Phi_1$, $\Phi_2$

\[
\begin{align*}
\frac{dn_1(x)}{dt} &= P_1(x) \cdot \Phi_1 \\
\frac{dn_2(x)}{dt} &= P_2(x) \cdot \Phi_2 \\
\end{align*}
\]

(locally non saturated target: $n_1 + n_2 < n_{sat}$)

- In saturated regions an arriving particle displaces one already trapped

\[
\begin{align*}
\frac{dn_1(x)}{dt} &= \frac{n_2(x)}{n_{sat}} \cdot P_1(x) \cdot \Phi_1 - \frac{n_1(x)}{n_{sat}} \cdot P_2(x) \cdot \Phi_2 \\
\frac{dn_2(x)}{dt} &= -\frac{dn_1(x)}{dt} \\
\end{align*}
\]

(locally saturated target: $n_1 + n_2 = n_{sat}$)
Local Mixing Model code (LMM) (3)

Approach to saturation for 1MeV D beam at 1mAcm⁻²

- i.e. a representative power density 10MWm⁻² normal to surface of NBTF Dump/Calorimeter

250hr foreseen NBTF operation at full power

⇒ Assumption that target is always deuterium-saturated (20% Cu atom density) in implantation zone is reasonable but conservative

⇒ 2.5 MeV neutron production linear with D beam fluence:

\[ N_{2.5} = 3.78 \times 10^{12} \text{ Coulomb}^{-1} \]
Treatment of Secondary DT Reactions in LMM (1)

DD reactions produce Tritium (at same rate as 2.5MeV neutrons)

\[
\begin{align*}
D + D & \rightarrow^{50\%} \text{He}^3 + n \quad Q = 3.27\text{MeV} \\
D + D & \rightarrow^{50\%} \text{T} + p \quad Q = 4.03\text{MeV}
\end{align*}
\]

- In **Laboratory Frame** the T product energy depends on angle w.r.t. incoming D
- T energy distribution in LAB therefore linked to differential reaction cross-section

Most probable T birth energy

- = 1MeV in LAB frame

⇒ Suggests treating T as component of incoming beam at 1MeV

⇒ T source rate computed at \( t_n \)

added to “beam” at next iteration of code (\( t_{n+1} \))

Data provided by M Pillon, ENEA Fusion Division Technology Section
Secondary DT Reactions in LMM (2)

LMM computes T content within Implantation Zone

- Recall implantation depths approximately similar for D, T (≈ 6µm)
- Secondary reaction rate contributions from D→T and T→D within Implantation Zone computed

<table>
<thead>
<tr>
<th>Pulses</th>
<th>Fluence D [C cm⁻²]</th>
<th>Fluence T [C cm⁻²]</th>
<th>DT neutr. [C⁻¹ cm⁻²]</th>
<th>TD neutr. [C⁻¹ cm⁻²]</th>
<th>Ret. T [cm⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1.8·10³</td>
<td>1.09·10⁻³</td>
<td>1.2·10⁵</td>
<td>5.2·10⁷</td>
<td>1.0·10¹⁰</td>
</tr>
<tr>
<td>5000</td>
<td>1.8·10⁴</td>
<td>1.09·10⁻²</td>
<td>1.5·10⁵</td>
<td>5.2·10⁷</td>
<td>1.5·10¹⁰</td>
</tr>
<tr>
<td>50000</td>
<td>1.8·10⁵</td>
<td>1.09·10⁻¹</td>
<td>1.9·10⁵</td>
<td>5.2·10⁷</td>
<td>2.2·10¹⁰</td>
</tr>
</tbody>
</table>

Characteristics of LMM predictions

- T → D reactions dominate (>99%) **BUT only ≈ 10⁻⁵ DD rate**
- D → T reactions negligible; T constantly displaced by majority D in real beam
- Retained T (within Implantation Zone) increases asymptotically; \( n_T \approx 10^{-9} n_D \)
Limitations of LMM

- Incoming D gives up most of its energy in a narrow distance range and most T ions born around *most probable D penetration depth* $R_D$.
- From this location T can penetrate a further characteristic maximum distance $R_T$.
- D and T implantation zones do not therefore co-incide.
- $D \rightarrow T$ and $T \rightarrow D$ reaction rates therefore overestimated *(i.e. conservative)*.

- $T$ density overestimated.
- $T$ removal by incoming D overestimated by LMM.
- $T$ in this region not included described by LMM.
- No removal by incoming D possible.
Tritium Retention (1)

LMM well-validated* by measured neutron production in beam-target experiments in aged material where voids and microscopic bubbles exist within implantation layer

* Ciric, de Esch, Falter, Jones, Svensson Fus Technol 1 (1998) 481-484

• In undamaged Cu Thermal Diffusion can be described by a temperature-dependent diffusion coefficient

\[ D = D_0 \cdot \exp\left(-\frac{E_D}{kT}\right) \text{ [cm}^2\cdot\text{s}^{-1}] \]

<table>
<thead>
<tr>
<th>Temperature T (K)</th>
<th>Diffusion Constant ( D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>473</td>
<td>6.04\times10^{-6} \text{ cm}^2\cdot\text{s}^{-1}</td>
</tr>
<tr>
<td>293</td>
<td>1.46\times10^{-8} \text{ cm}^2\cdot\text{s}^{-1}</td>
</tr>
</tbody>
</table>
Tritium Retention (2)

Combined LMM and Thermal Diffusion Model

- Worst-case assumption: entire T source $\Phi_T$ at deepest physically possible location

- $T$ density $n_0$ overestimated by LMM
- Defines conservative boundary condition for Diffusion Model
- Solve diffusion equation for $n_T(x=R_D+R_T)$ assuming linear gradients for $\Phi_T = \Phi_2 + \Phi_3$ (in steady-state)
**Tritium Retention (3)**

**Results**

- Model is linear with D current density
- Therefore only need to consider total D fluence; assume 250 hrs at 1MeV, 40A
- Assume thermal diffusion stops during beam-off periods (conservative)
- Assume 2mm distance to water cooling channel (Swirl-Tube design)

Total T production: \( \approx 0.25 \text{TBq} \)

- T released to cryopump \( 0.20 \text{TBq} \)
- T diffused to cooling water \( 0.05 \text{TBq} \)

Retained in Dumps \( 70 \text{MBq} \) c.f. IAEA Exempt Transport Package 1GBq

Max. areal density (for 2mAcm\(^{-2}\)) \( 3.5k\text{Bqcm}^{-2} \)
Neutronics calculations for NBTF

Input

- Mass distribution of materials of beamline components
- Spatially distributed neutron source (allowing for beam ‘footprints’, easily scaled from LMM predicted source terms since these are all linear with D flux)

Output

- Neutron Transport (MCNP): neutron flux and spectrum in every material cell Passed as input to Activation calculations (FISPACT)
**Summary of results for dose rate from activation**

Assume operating history comprising 250 hrs full-power operation with time-dependent profile:
- 3 campaigns of 100 days with 100 pulses/day (20s duration)
- 1 campaign of 14 days with 6 pulses/day (3600s duration)

<table>
<thead>
<tr>
<th>Material</th>
<th>LLW after 1 year</th>
<th>Above Hands on limit after one year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>Vessel around calorimeter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal lip of vessel at fast shutter end</td>
<td></td>
</tr>
<tr>
<td></td>
<td>End plate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calorimeter- Support structure (2)</td>
<td>Calorimeter- Support structure</td>
</tr>
<tr>
<td></td>
<td>RID Wall (2)</td>
<td>RID Wall (2)</td>
</tr>
<tr>
<td>“Water &amp; steel”</td>
<td>Pipework around calorimeter (12)</td>
<td>Calorimeter lower pipework</td>
</tr>
<tr>
<td></td>
<td>Pipework around RID</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cooling pipe (2)</td>
<td></td>
</tr>
<tr>
<td>CuCrZr</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Copper</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Aluminium</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Alumina</td>
<td>none</td>
<td>none</td>
</tr>
</tbody>
</table>

Numbers in parentheses show number of components above the indicated limit, where this is >1

Note:
Activation from 2.5MeV neutrons dominates (by factor > $10^4$, due to lower 14MeV neutron source rate)
Conclusions

Applicability of LMM for DD and secondary DT reactions in NBTF

• Previously benchmarked against D→D beam-target experiments
• Convenient to treat T product ions to incoming beam due to similarity of energy
• Limitations inherent in this approach result in overestimated neutron sources *i.e. conservative for safety analysis*
• T retention predictions too optimistic since LMM only treats D implantation zone

T retention

• However, LMM can be used to set a conservative boundary condition for Thermal Diffusion model
• Predicted T retention in NBTF components appears to be easily manageable

Activation

• LMM predictions of 2.5MeV and 14MeV neutrons used as input source terms
• Components not excessively activated except for localised “hot spots”
Prediction of neutron source, tritium production and activation for long-pulse operation of the ITER Neutral Beam Test Facility
Benchmark of LMM against Analytic Model (saturated target)

- Calculation of D→D beam-target reaction rate (2.45MeV neutron production)

- Assume target is uniformly saturated with deuterium up to a depth ≈ 10µm which is beyond the mean implantation depth (≈ 7µm)

- **Local Mixing Code (LMC) prediction** of 2.45 MeV neutron production from D→D beam-target reactions expressed per Coulomb of incident D fluence:
  \[3.78 \times 10^{12} \text{ C}^{-1}\]

- This is within 7% of prediction of Kim formula\(^{(3)}\):
  \[Y_N = I_{\text{beam}}(A) \cdot [D]_{\text{solid}}(\text{cm}^{-3}) \cdot W_{DD} / e\]

\(^{(3)}\) J Kim, Nucl Tech 44 315 (1979)
Effect of non-normal beam incidence

- **Effect of non-normal incidence of beam on LMM**
  - in LMM normal incidence of beam upon target material has been assumed

- Consider effect of increasing the angle of incidence away from normal at constant power density at the surface

- **Consequences for LMM**
  - incoming D still slows down within saturated region
  - volume accessible is **reduced** by factor $1 / \cos \theta$ cf. normal incidence (ignoring effects of scattering)

  $\Rightarrow$ saturation is approached even faster than normal incidence case

  $\Rightarrow$ further justifies assumption of saturated target (though still pessimistic, i.e. contributes to safety margin)
Secondary DT Reactions in LMM

Physical validity of LMM treatment of Secondary Reactions

- Fast T **physically born in the material with a distribution of angles and velocities**
- Significant proportion of T therefore goes beyond range of incoming D
- D and T implantation zones do not therefore co-incide
- D \(\rightarrow\) T and T \(\rightarrow\) D reaction rates therefore overestimated **but represents a margin of conservatism** for the safety analysis
Radiological Limits

• Activation - IAEA
  - ILW at > $1.2 \times 10^7$ Bq/kg
  - LLW at > $7 \times 10^4$ Bq/kg
  - Considered “Non radioactive” below this

• Dose Rate
  - ‘Hands on Limit’ at 10µSv/h
  - based on surface contact dose for an infinite-slab model

ILW = Intermediate Level Waste;  LLW = Low Level Waste
Dose Rate: Cell 242 (calorimeter water pipe)

The only cooling pipe to have a dose level above the ‘hands-on’ limit after 1 yr
Results - DD vs DT neutron activation of vacuum vessel

- 2.5 MeV neutrons from D→D reactions dominate

- Although the specific activation per 14 MeV neutron from DT reactions is 3-4 \times higher than for D→D neutrons, the DT reaction rate is more than 4 orders of magnitude lower than for D→D reactions.