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

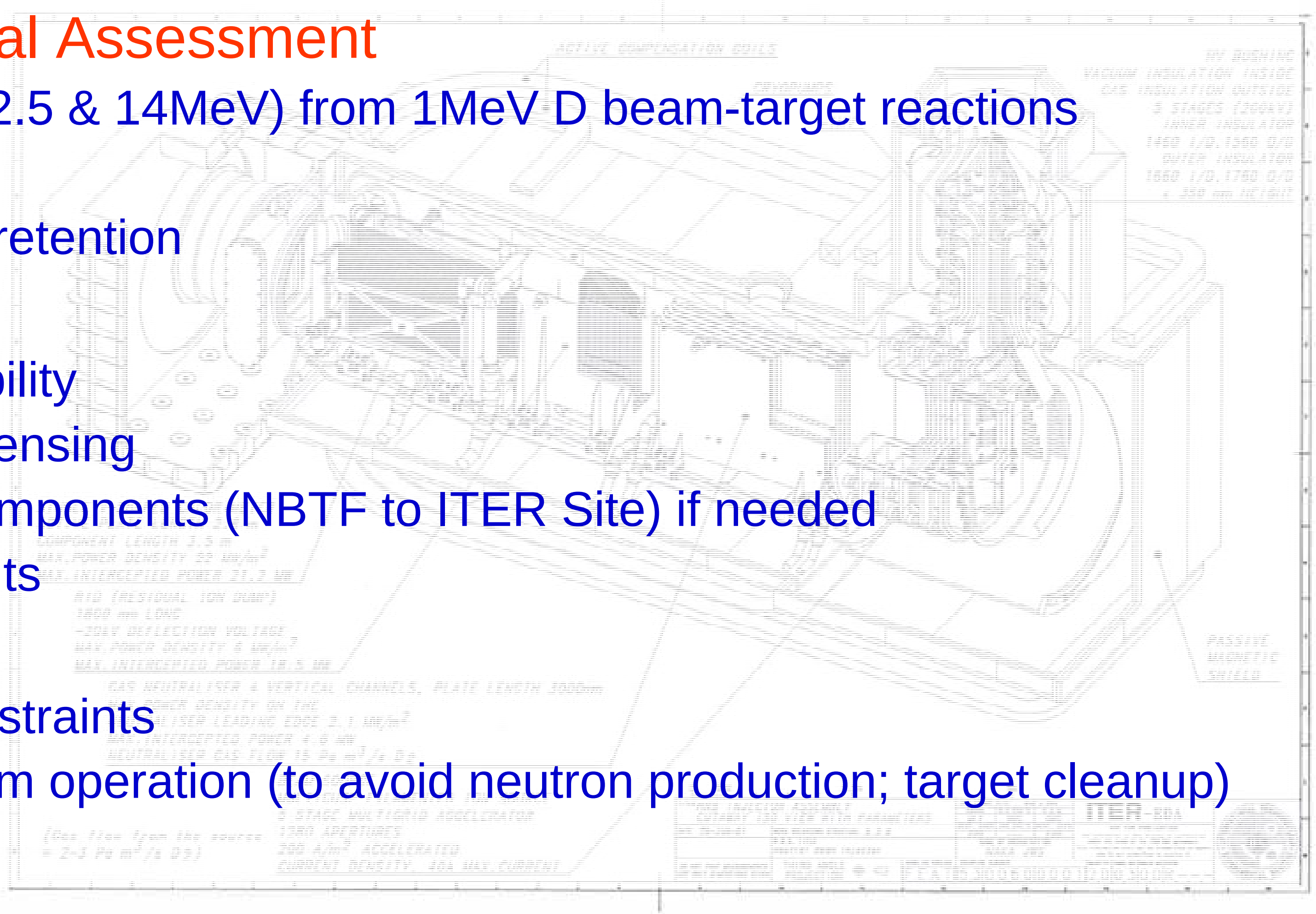
- Neutron production (2.5 & 14MeV) from 1MeV D beam-target reactions
- Neutron Activation
- Tritium production & retention

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

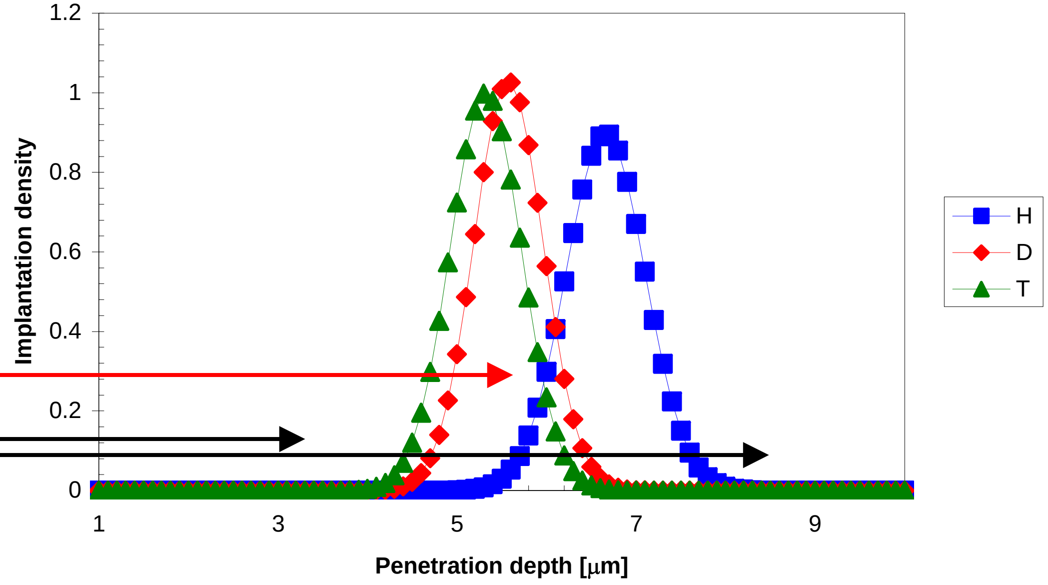
- Slowing-down of fast beam ions in the target material (Cu)
- Hydrogenic build-up and isotope exchange
- Fusion Reaction probability during slowing-down

e.g.

Relative Probability Distribution **P(x)** of implantation depths of 1MeV **H**, **D** & **T**

Fills to saturation quickly

Fills to saturation slowly



* Doyle, Wampler, Brice, Picraux, J Nucl Mat 93-94 (1980) 551-557

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 Φ_1, Φ_2

Rate of change of local densities given by:

$$\begin{cases} \dfrac{dn_1(x)}{dt} = P_1(x)\cdot\Phi_1 \\ \dfrac{dn_2(x)}{dt} = P_2(x)\cdot\Phi_2 \end{cases}$$

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

- In saturated regions an arriving particle displaces one already trapped

$$\begin{cases} \dfrac{dn_1(x)}{dt} = \dfrac{n_2(x)}{n_{sat}}\cdot P_1(x)\cdot\Phi_1 - \dfrac{n_1(x)}{n_{sat}}\cdot P_2(x)\cdot\Phi_2 \\ \dfrac{dn_2(x)}{dt} = -\dfrac{dn_1(x)}{dt} \end{cases}$$

(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}

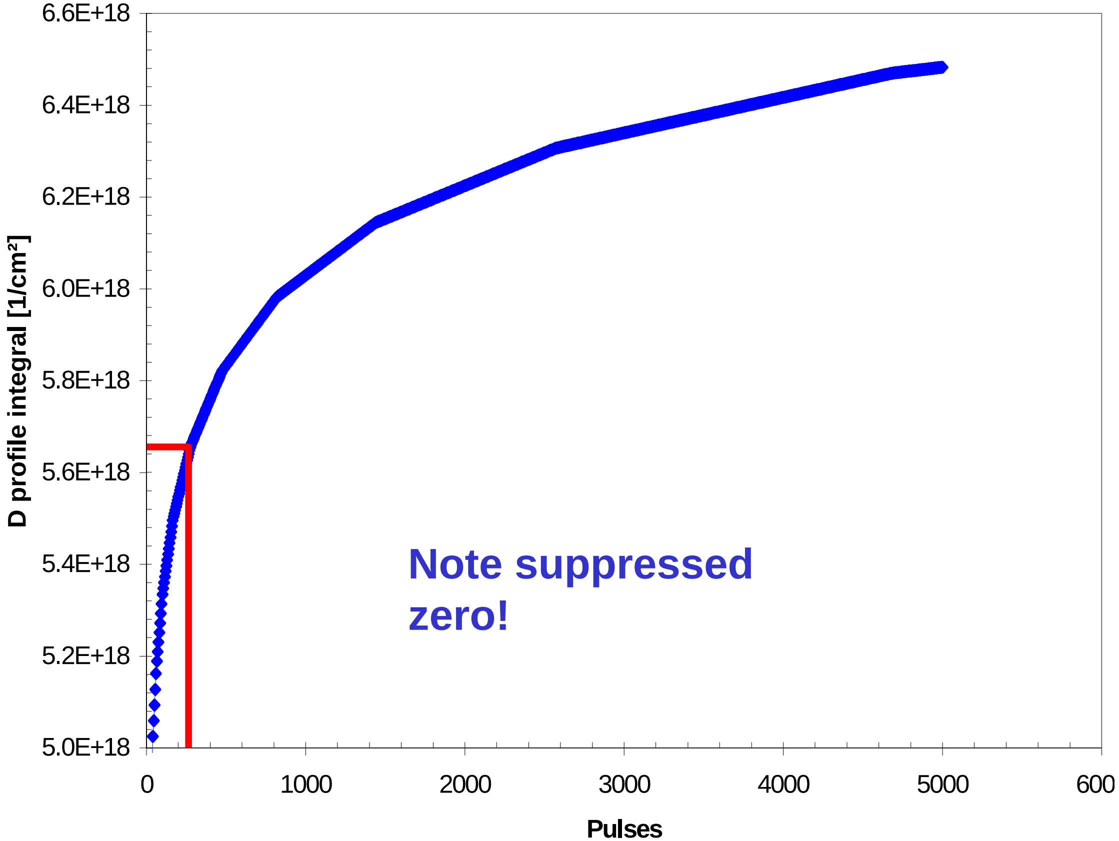
- i.e. a representative power density 10MWm^{-2} normal to surface of NBTF Dump/Calorimeter

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:

$N_{2.5} = 3.78 \times 10^{12}$ ***Coulomb^{-1}***

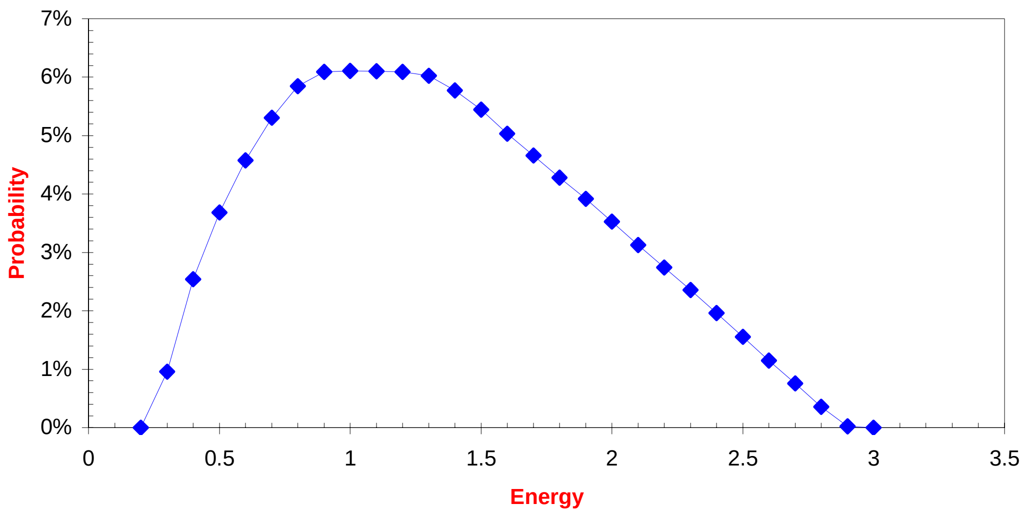


Treatment of Secondary DT Reactions in LMM (1)

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

$$\begin{cases} D + D \xrightarrow[50\%]{} \mathrm{He}^3 + \mathrm{n} & Q = 3.27\mathrm{MeV} \\ D + D \xrightarrow[50\%]{} \mathrm{T} + \mathrm{p} & Q = 4.03\mathrm{MeV} \end{cases}$$

- 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

$\Rightarrow$ Suggests treating T as ***component of incoming beam at 1MeV***

$\Rightarrow$ ***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 ($\approx$ 6μm)
- Secondary reaction rate contributions from D$\rightarrow$T and T $\rightarrow$D within Implantation Zone computed

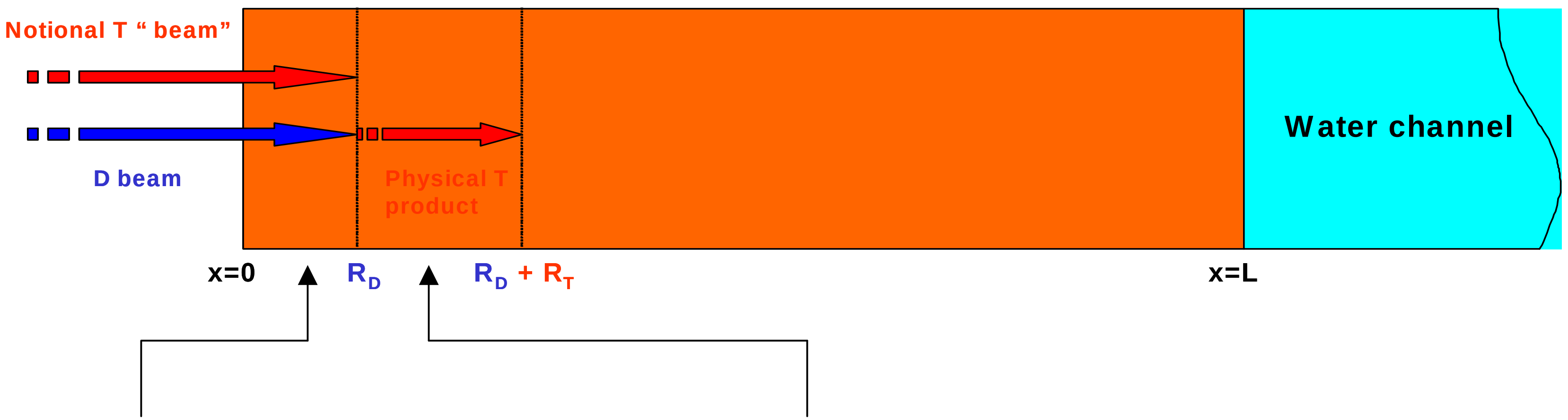
Pulses	Fluence D [C cm^{-2}]	Fluence T [C cm^{-2}]	DT neutr. [C^{-1} cm^{-2}]	TD neutr. [C^{-1} cm^{-2}]	Ret. T [cm^{-2}]
500	**$1.8{\cdot}10^{3}$**	**$1.09{\cdot}10^{-3}$**	**$1.2{\cdot}10^{5}$**	**$5.2{\cdot}10^{7}$**	**$1.0{\cdot}10^{10}$**
5000	**$1.8{\cdot}10^{4}$**	**$1.09{\cdot}10^{-2}$**	**$1.5{\cdot}10^{5}$**	**$5.2{\cdot}10^{7}$**	**$1.5{\cdot}10^{10}$**
50000	**$1.8{\cdot}10^{5}$**	**$1.09{\cdot}10^{-1}$**	**$1.9{\cdot}10^{5}$**	**$5.2{\cdot}10^{7}$**	**$2.2{\cdot}10^{10}$**

Characteristics of LMM predictions

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

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 $\boldsymbol{R_T}$
- 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)

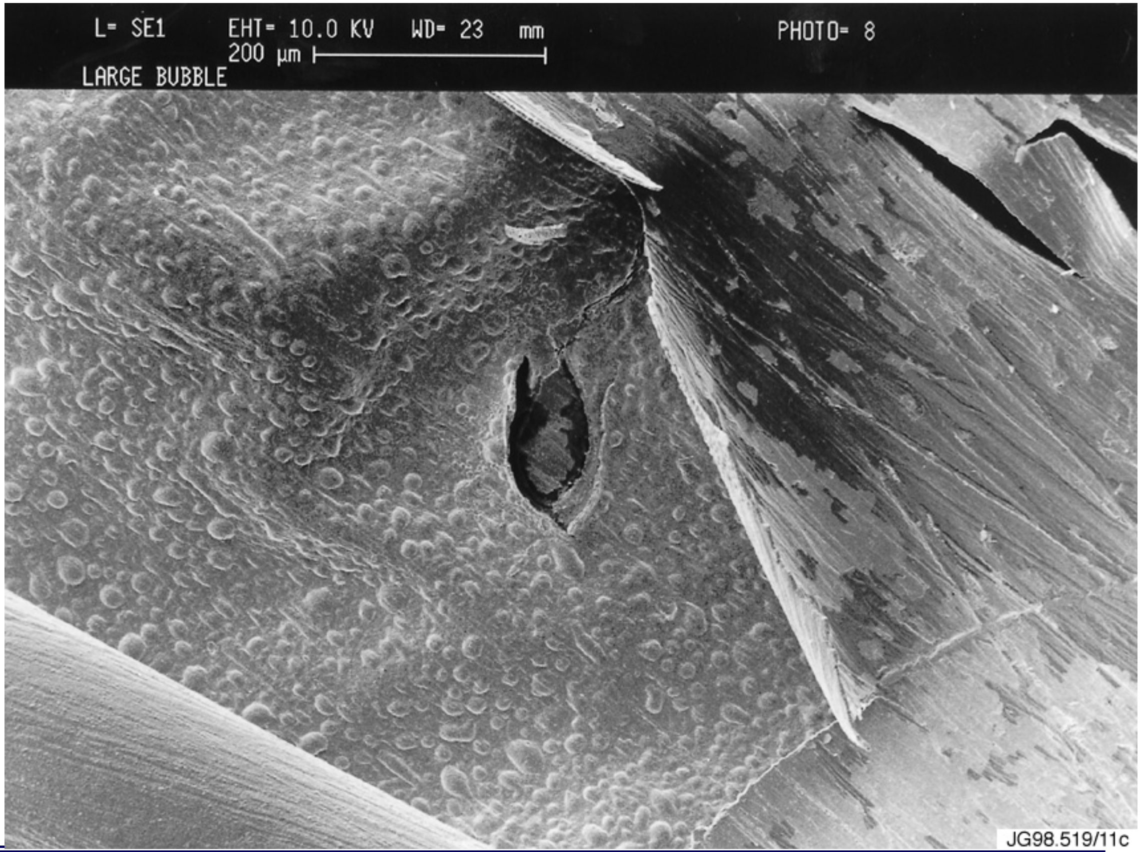
LMM well-validated* by measured neutron production in beam-target experiments in aged material where voids and microscopic bubbles exist ***within implantation layer***

* 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***

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

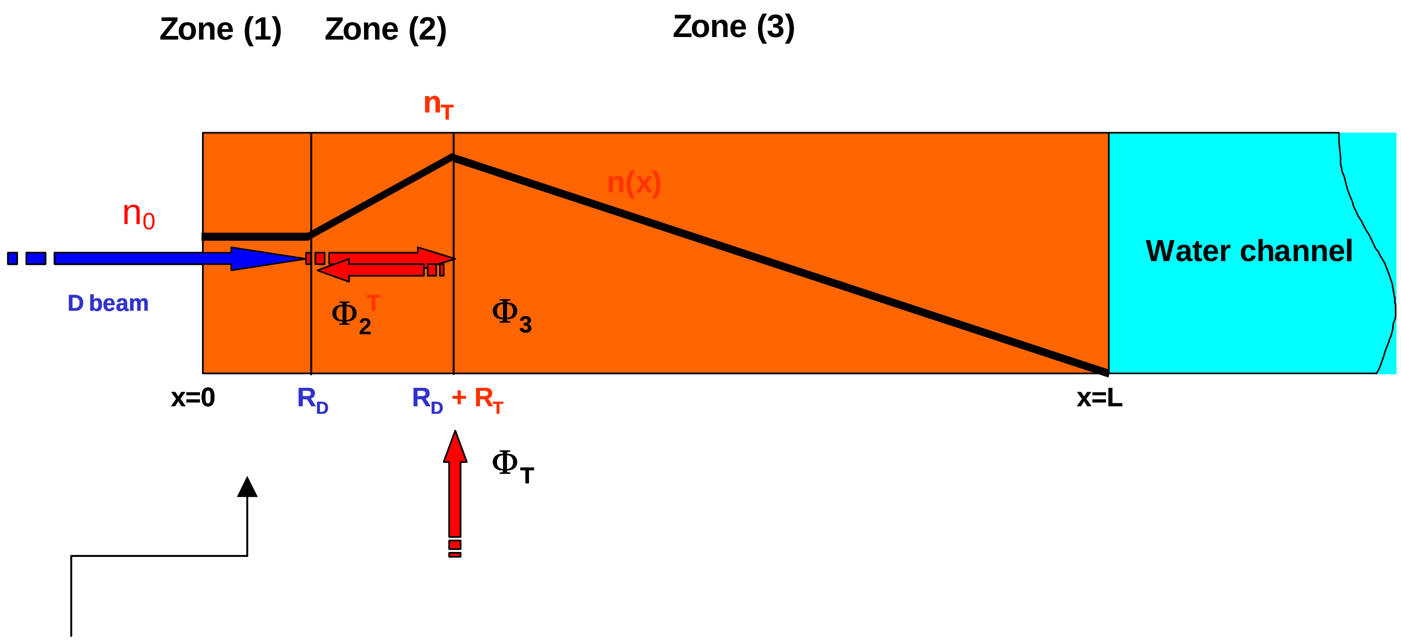
Temperature T (K)	Diffusion Constant *D*
473	$6.04 \cdot 10^{-6}$ cm$^2 \cdot$s^{-1}
293	$1.46 \cdot 10^{-8}$ cm$^2 \cdot$s^{-1}



Tritium Retention (2)

Combined LMM and Thermal Diffusion Model

- Worst-case assumption: entire T source Φ_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

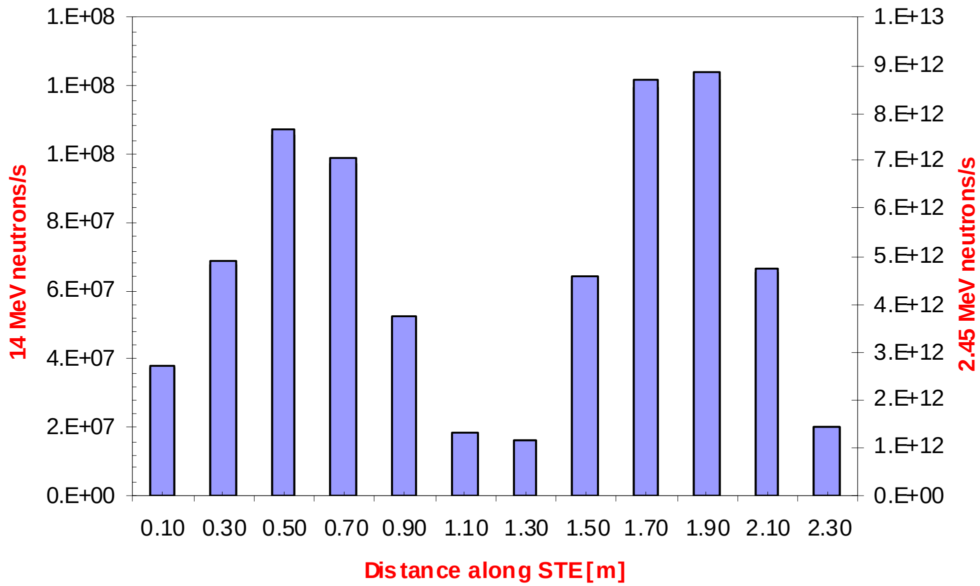
- Model is linear with D current density
- Therefore only need to consider total D fluence; assume **250 hrs at 1MeV, 40A**
- Assume thermal diffusion stops during beam-off periods (conservative)
- Assume 2mm distance to water cooling channel (Swirl-Tube design)

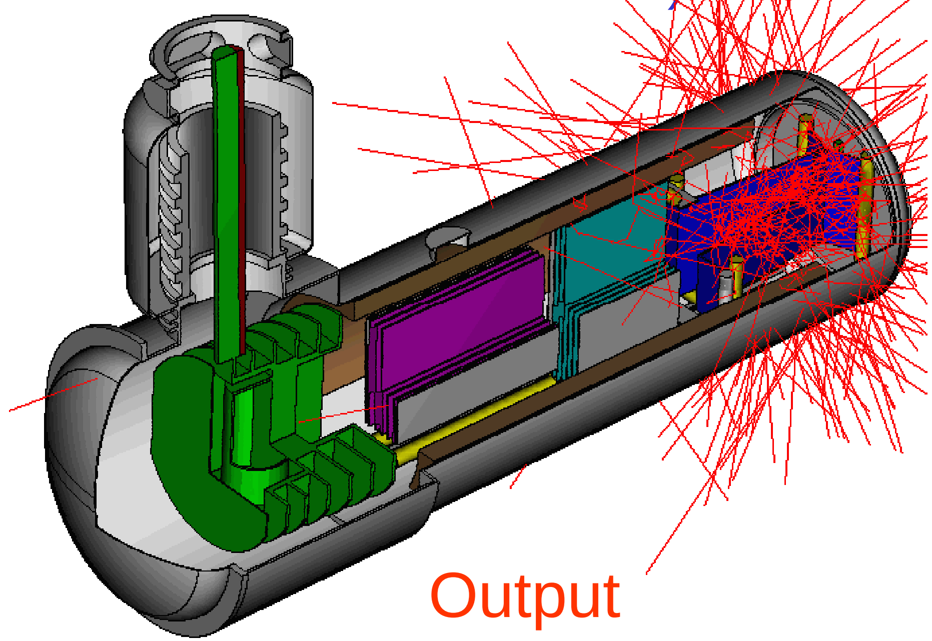
Total T production:	≈ **0.25TBq**
T released to cryopump	**0.20TBq**
T diffused to cooling water	**0.05TBq**
Retained in Dumps	**70MBq** c.f. IAEA Exempt Transport Package 1GBq
Max.areal density (for 2mAcm^{-2})	**3.5kBqcm^{-2}**

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 cellPassed 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)

Material	LLW after 1 year	Above Hands on limit after one year
Stainless Steel	Vessel around calorimeter	
	Horizontal lip of vessel at fast shutter end	
	End plate	
	Calorimeter- Support structure (2)	Calorimeter- Support structure
	RID Wall (2)	RID Wall (2)
"Water & steel"	Pipework around calorimeter (12)	Calorimeter lower pipework
	Pipework around RID	
	Cooling pipe (2)	
CuCrZr	none	none
Copper	none	none
Aluminium	none	none
Alumina	none	none

Note:

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

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

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”

Benchmark of LMM against Analytic Model (saturated target)

- Calculation of D$\rightarrow$D beam-target reaction rate (2.45MeV neutron production

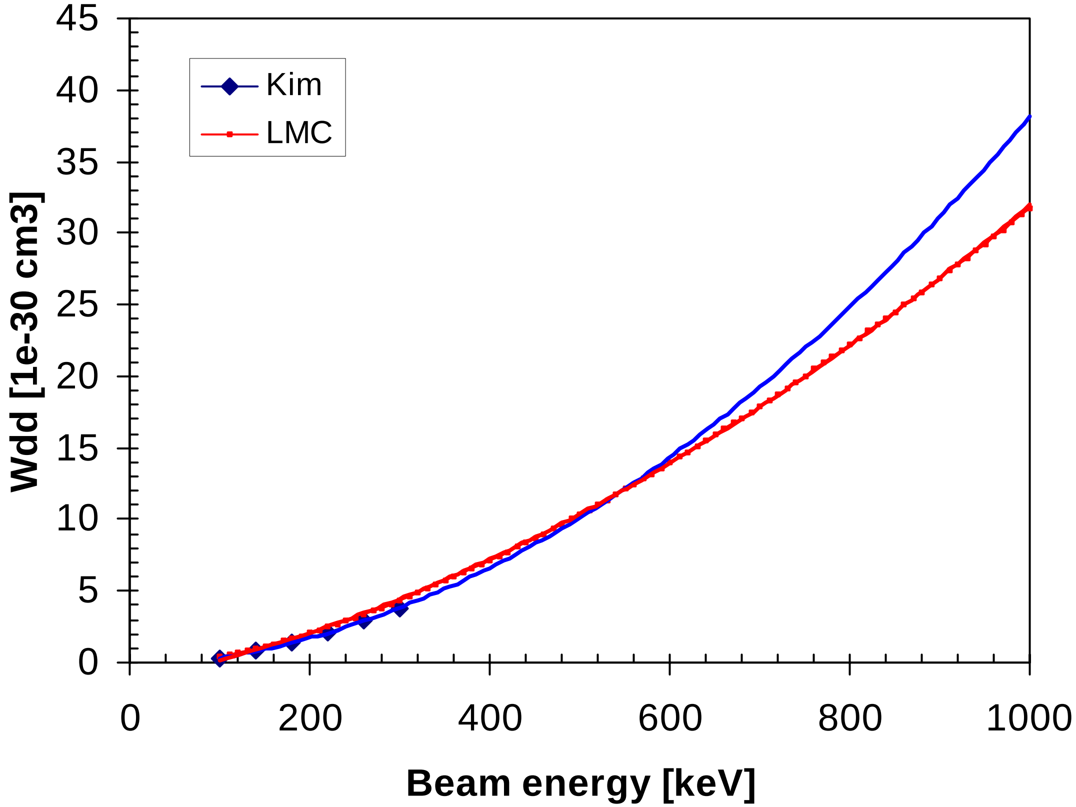
- Assume target is ***uniformly saturated with deuterium*** up to a depth $\approx$ 10μm which is beyond the mean implantation depth ($\approx$ 7μm)

- ***Local Mixing Code (LMC)*** *prediction* of 2.45 MeV neutron production from D$\rightarrow$D beam-target reactions expressed per Coulomb of incident D fluence:

  $\boldsymbol{3.78 \times 10^{12}\ C^{-1}}$

- This is within 7% of prediction of Kim formula[3] :

  $Y_N = I_{beam}(A).[D]_{solid}(cm^{-3}).W_{DD} / e$



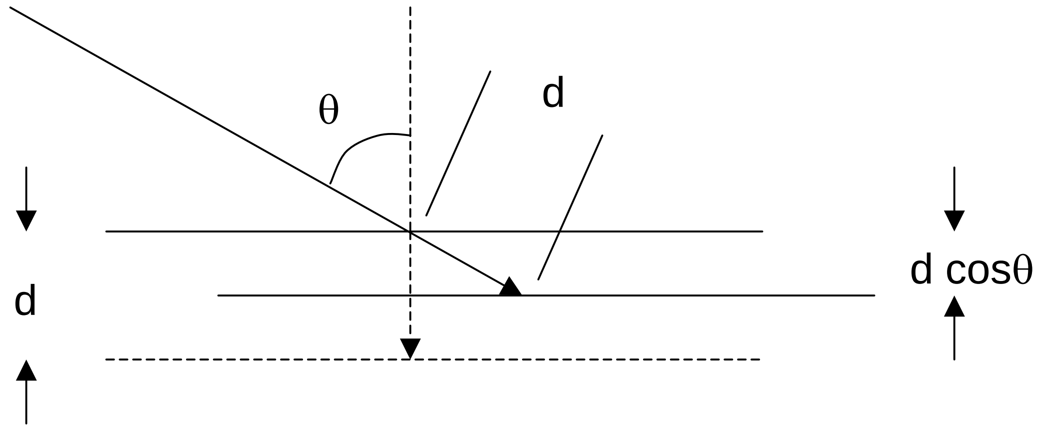
(3) J Kim, Nucl Tech 44 315 (1979)

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)

  ⇒ saturation is approached even faster than normal incidence case

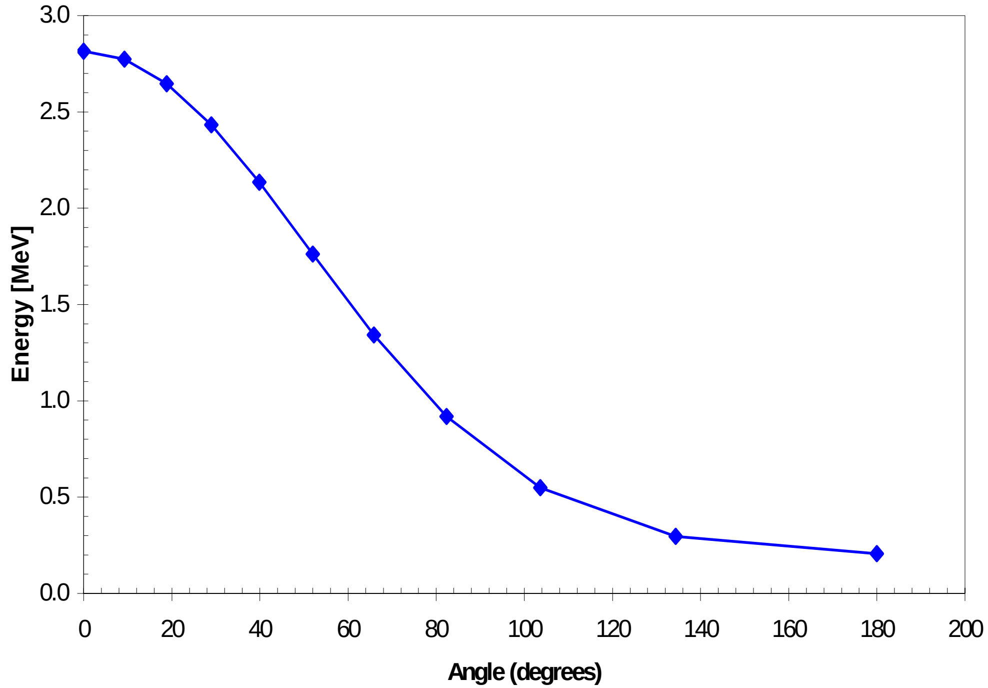
  ⇒ further justifies assumption of saturated target (though still pessimistic, i.e. contributes to safety margin)



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

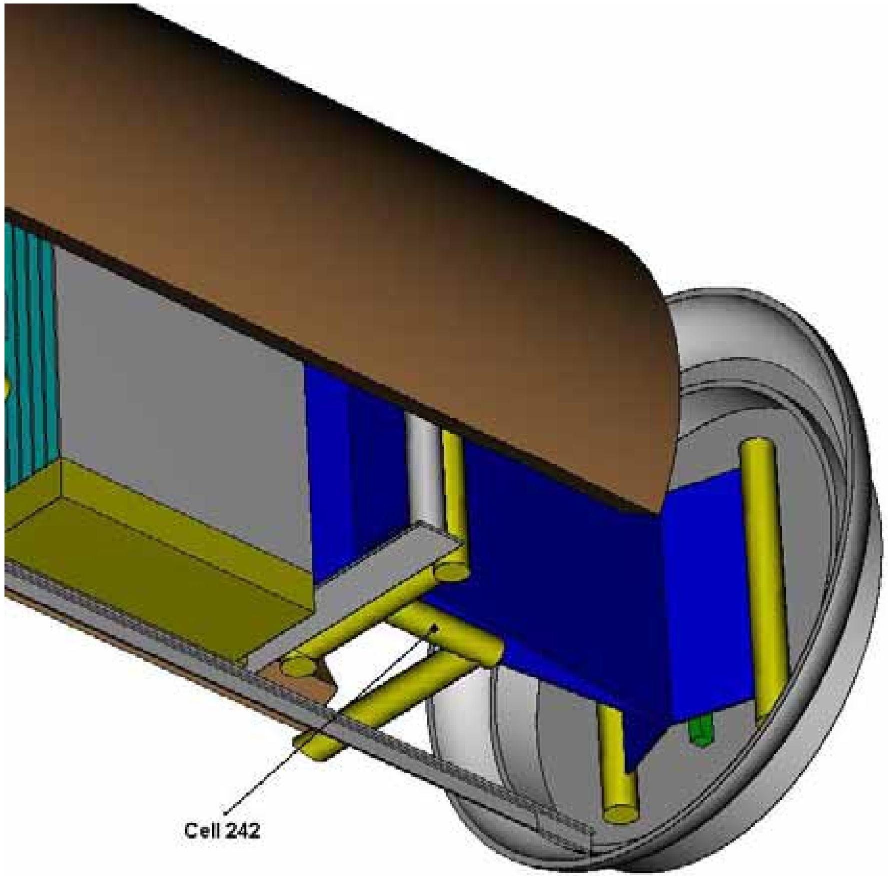
Radiological Limits

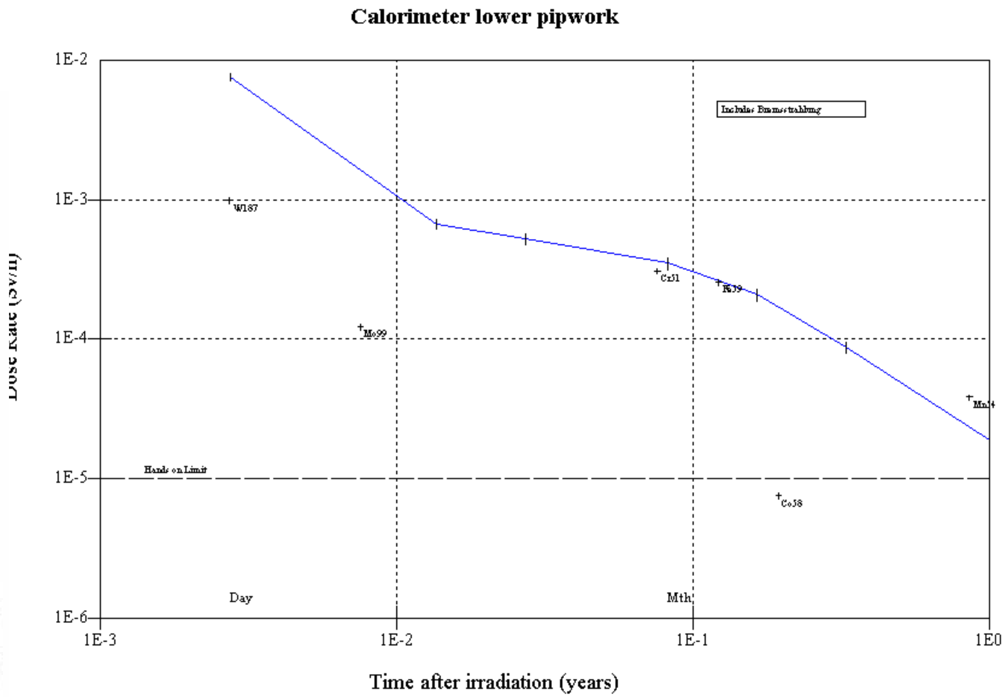
- **Activation - IAEA**
  - ILW at > 1.2×10^7 Bq/kg
  - LLW at > 7×10^4 Bq/kg
  - Considered “Non radioactive” below this

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

ILW = **I**ntermediate **L**evel **W**aste; **LLW** = **L**ow **L**evel **W**aste

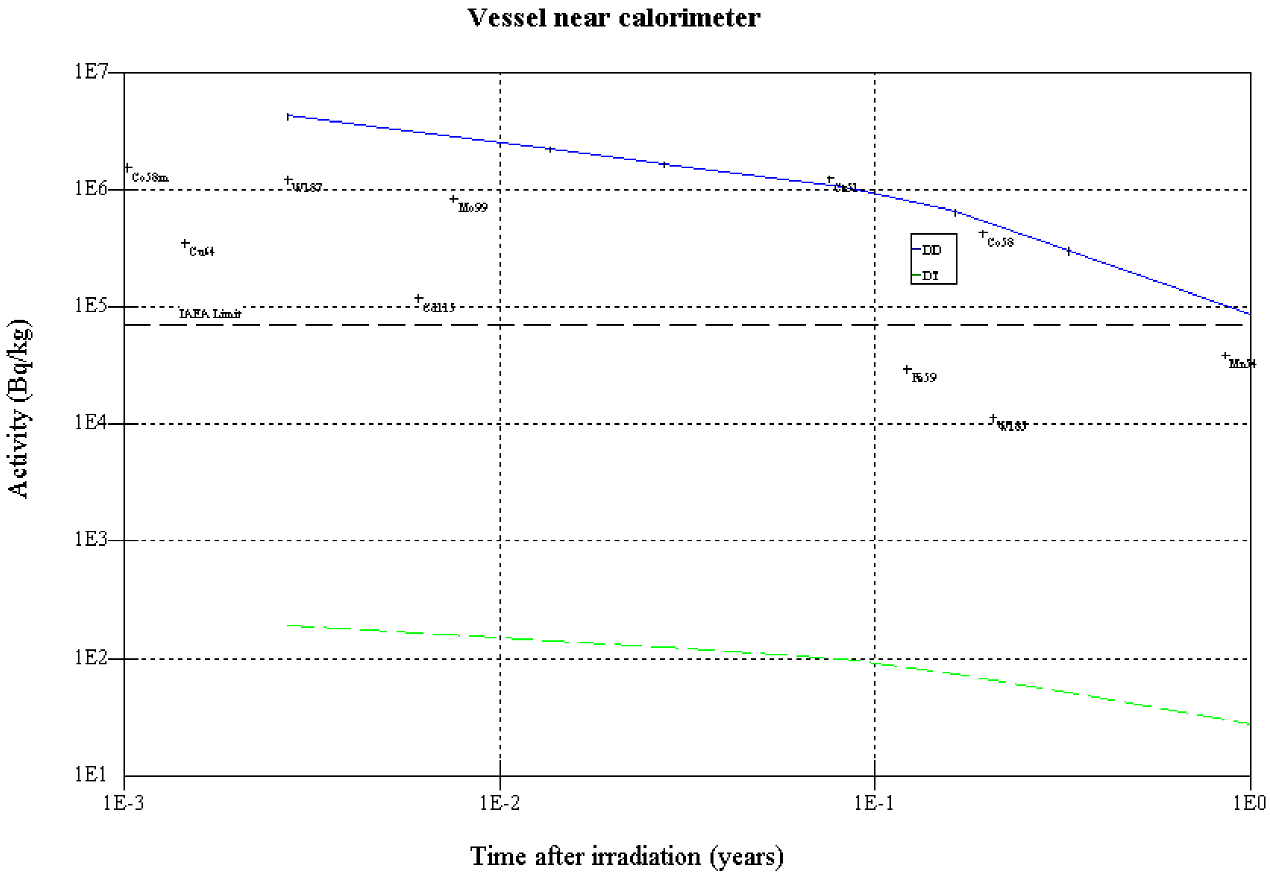
Dose Rate: Cell 242 (calorimeter water pipe)





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 × higher than for D→D neutrons, the DT reaction rate is more than 4 orders of magnitude lower than for D→D