Radiation Shielding Requirements for Magnets in Fusion Reactors

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Deuterium-Tritium fusion represents a nearly inexhaustible energy source.

Fuels: **Deuterium**: abundant in sea water

Tritium: Half-life~12 years…must be produced?

Reaction		Ignition Temperature		Output Energy
Fuel	Product	(millions of °C)	(keV)	(keV)
D + T	^4He + n	45	4	17,600

$^6Li + n$ --> $T + {}^4He + 4.8$ MeV + others

$T_{bred} / T_{burned} > 1$

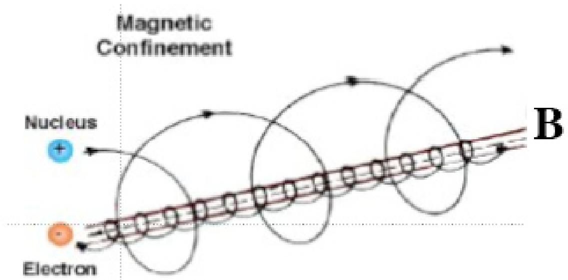
"Real" fusion fuel cycle:

$^6Li + D = 2\,{}^4He + 22.4$ MeV

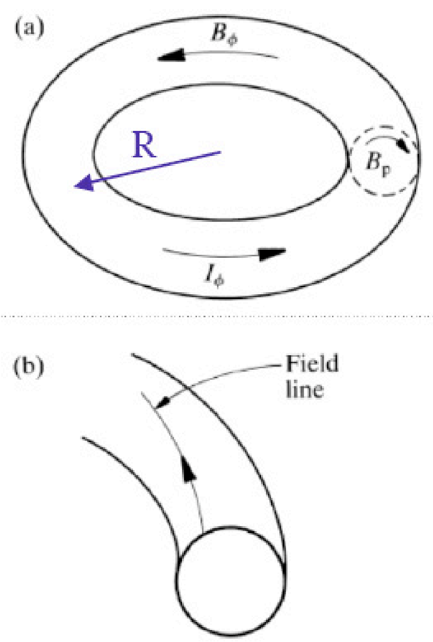
30 Million years of world energy demand in oceans

Fusion reactors require using superconducting magnets for plasma confinement

- Fusion energy balance:
  - ➢ 4/5 in neutron leaves → energy
  - ➢ 1/5 in He^{++} confined by B to heat & sustains plasma.



The toroidal "tokamak" is the most prevalent magnetic confinement configuration



- Self-closing helical magnetic fields.
- Stabilizing **toroidal** field produced by external coils.
  - ➢ $B_\phi \propto 1 / R$
- Plasma current provides confining **poloidal** field against ∇-B drifts.

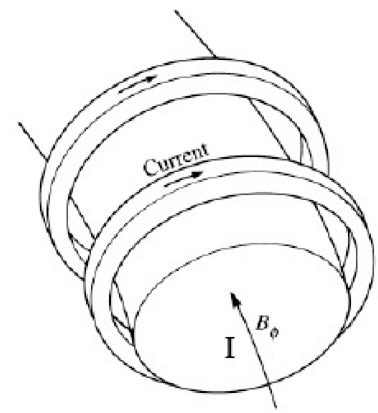
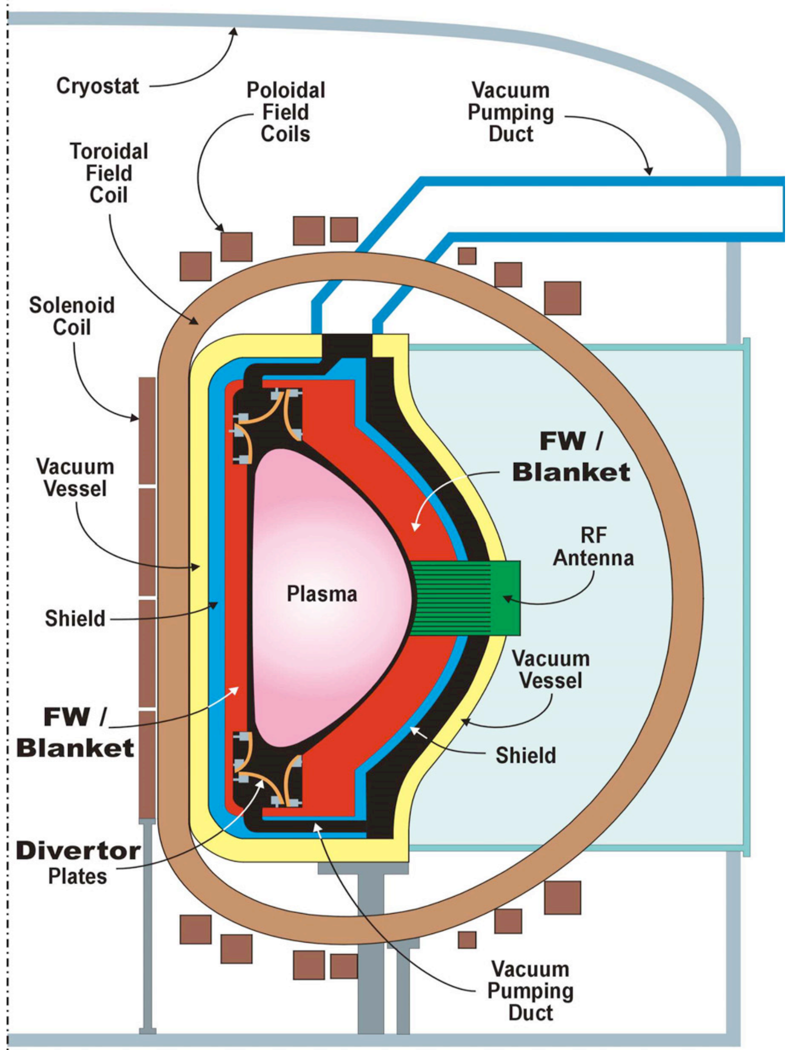


Fig. 1.6.2 The toroidal magnetic field is produced by current in external coils.

Tokamaks employ large D-shaped toroidal field (TF) coils that have to be shielded from high energy neutrons emanating for plasma

- Neutrons are attenuated and slowed down by components placed between plasma and TF coils
  - blanket that recovers thermal power and breeds tritium
  - vacuum vessel
  - radiation shield
- Neutron interactions result also in gamma production
- Performance of magnets influenced by both neutron and gamma radiation levels
- Various materials (steel, borated steel, tungsten, tungsten carbide, and boron carbide) can be used in shield with varying shielding performance
- Radiation limits for magnets determine required shield thickness and directly influence cost
- Minimum total radial build between plasma and coils is typically >1 m depending on material used, magnet radiation limits and neutron wall loading

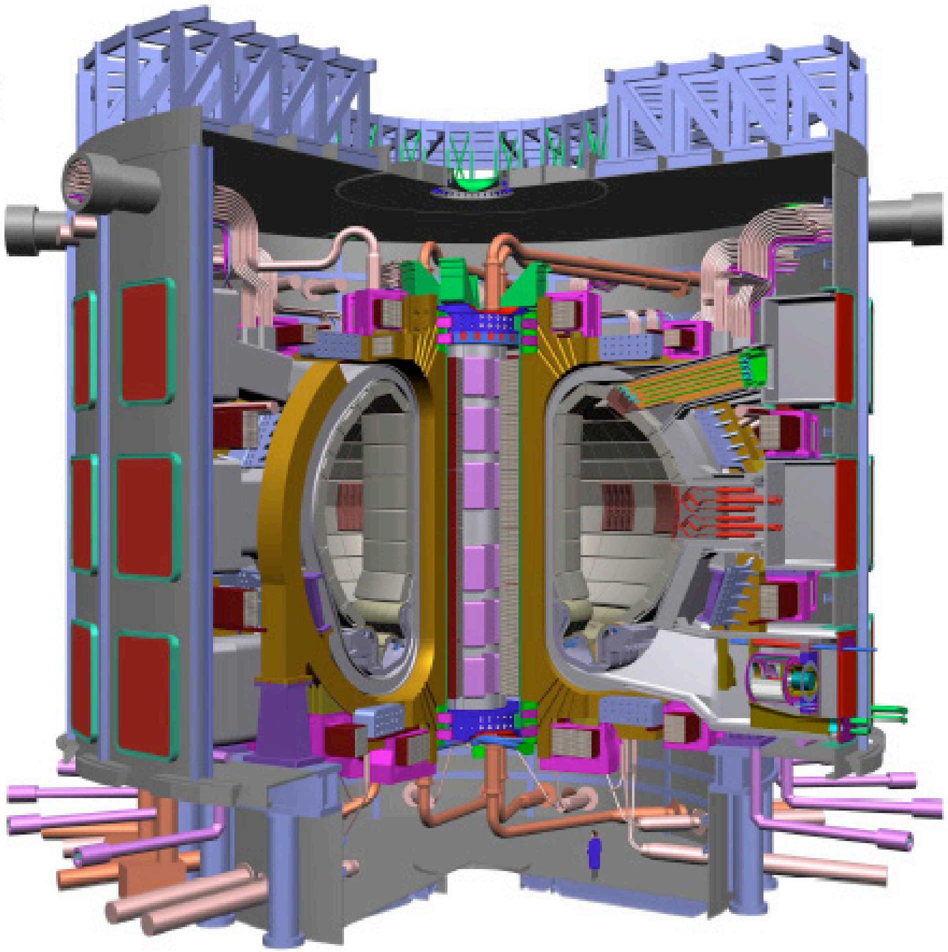


ITER

- Mission:
  - "Burning plasma" Q > 5 control
  - Current drive.

- Reactor level fusion power
  - P_{fusion} ~ 400 MW for 500 s
  - 20% duty cycle

- R~6 m + B~6 T = $5B
  - 1000 m^3 plasma
  - 1000 m^2 plasma-facing wall



Radiation Effects in Superconducting Magnet Components

- The superconducting magnet components most sensitive to radiation damage are the superconductor filaments, the stabilizer, and the insulator
- Nuclear heating affects the winding pack temperatures and the economic performance of the reactor through increased refrigeration costs
- Radiation effects on magnet components are related as they are determined by the same radiation levels at the magnet
- Previous magnet shielding calculations performed for conceptual fusion power reactors (e.g., ARIES) and near term burning plasma devices (e.g., ITER) reveals a rule-of-thumb relation for radiation effects that holds to within a factor of two
- A peak power density of 1 $kW/m^3 \Rightarrow 10^{22}$ n/m^2 fast neutron ($E>0.1$ MeV) fluence $\Rightarrow 10^7$ Gy insulator dose $\Rightarrow 10^{-3}$ dpa in Cu stabilizer after one FPY of operation
- Radiation limits should be considered simultaneously

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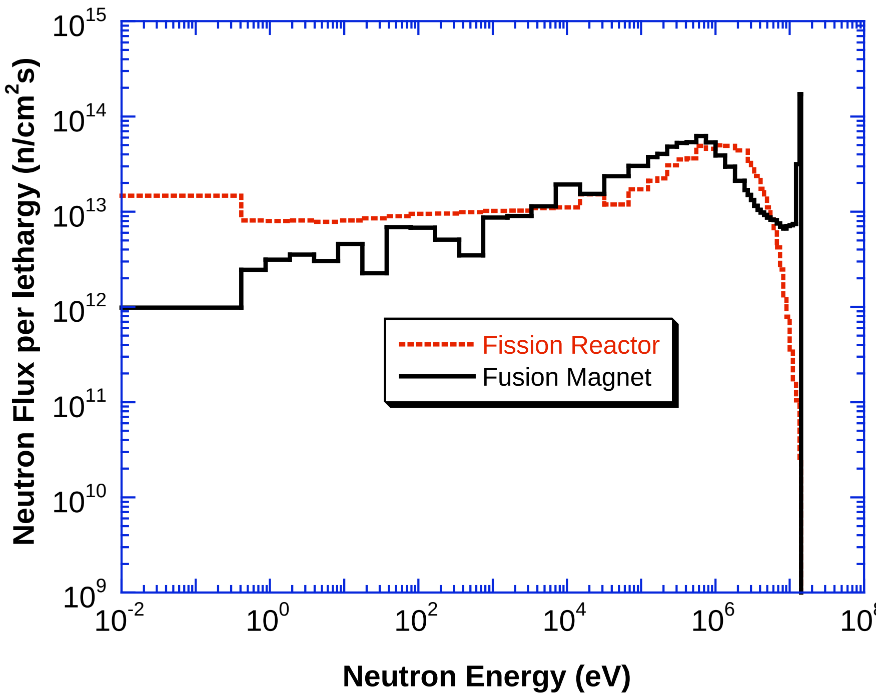
Radiation Damage to Superconductors

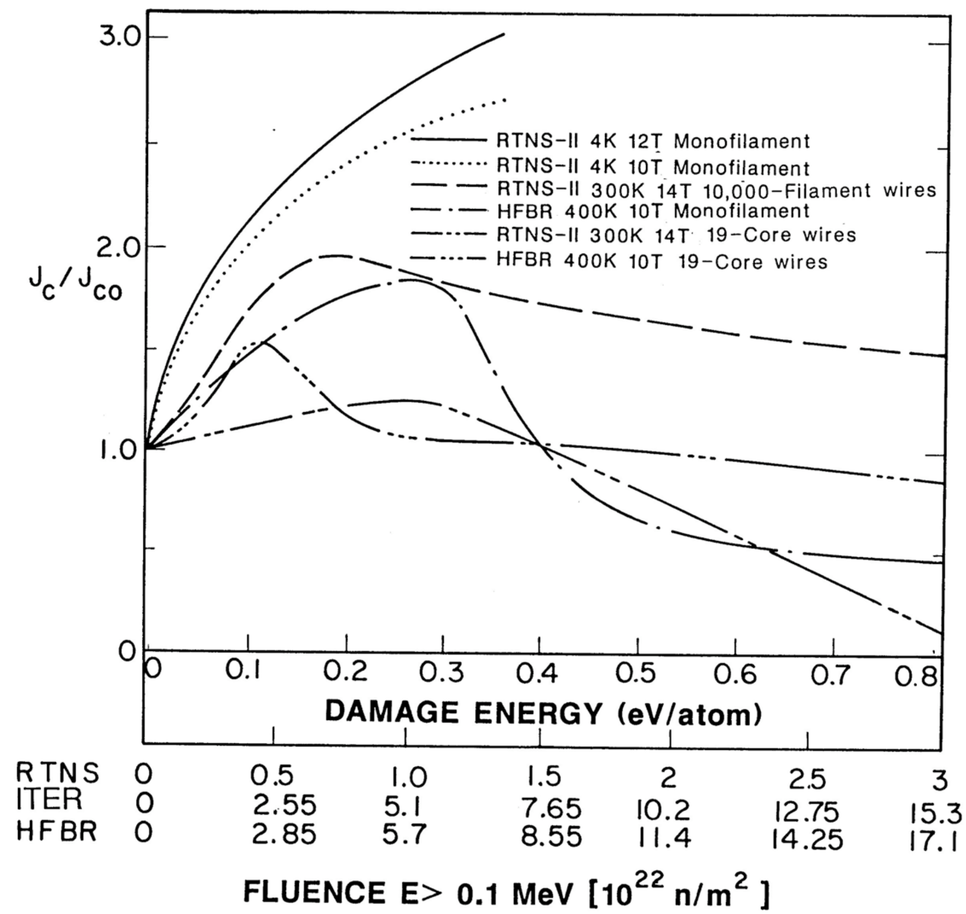
- Nb_3Sn is the prefered superconductor for fusion systems because of its relatively high critical temperature (T_c) of ~18 K and upper critical magnetic field (H_{c2}) of 25 T at 4.2 K
- Effect on critical properties related to damage produced by fast neutrons through production of defect cascades



- Due to steep variation of damage energy cross section with energy, knowledge of neutron spectrum used to produce experimental data is essential to relate data to neutron fluence in fusion reactor magnets

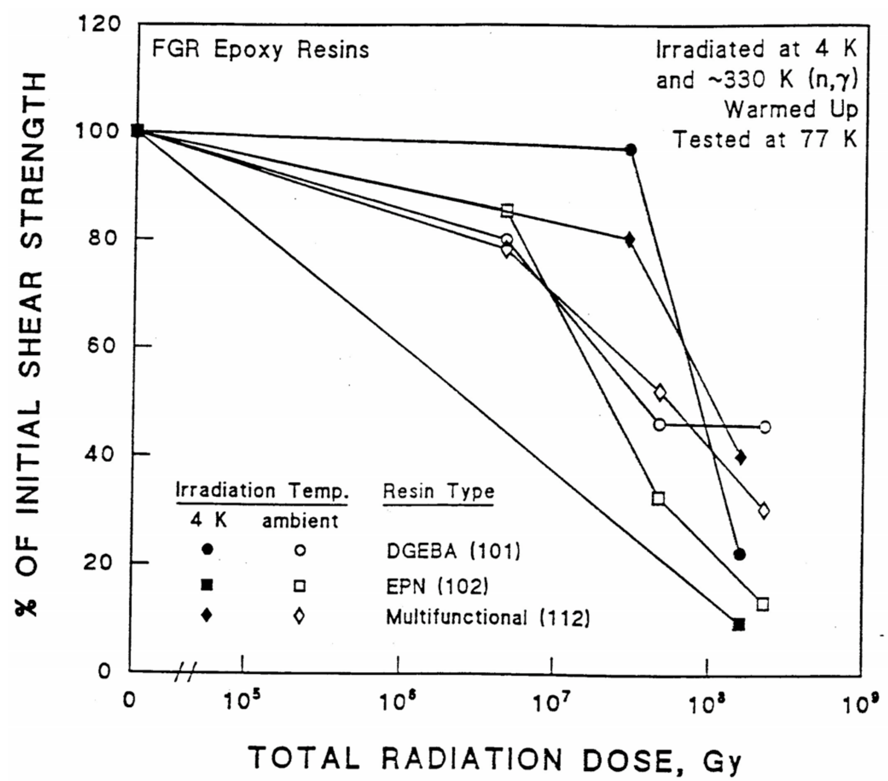
Degradation of S/C Properties with Neutron Fluence

- T_c is nearly constant up to ~10^{22} n/m^2 and drops by 20% at $2\text{x}10^{23}$ n/m^2
- J_c increases initially with fluence (due to increased H_{c2} with nearly constant T_c) with a subsequent drop at higher fluences
- High temperature irradiation results in larger J_c degradation compared to cryogenic irradiation due to defect mobility and subsequent cascade collapse resulting in lower flux pinning
- Using the high temperature irradiation data yields conservatively low fluence limits
- Based on available experimental data, a conservative fluence limit of 10^{23} n/m^2 can be used for Nb_3Sn



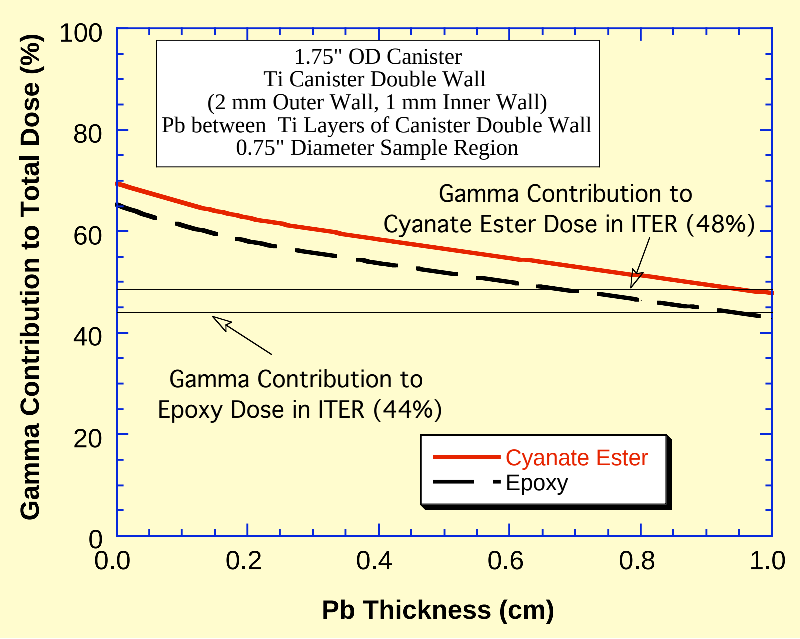
Organic Insulator Dose Limit

- Mechanical strength, dielectric strength and electric resistivity are the important properties
- Experimental data show that the mechanical properties degrade at lower dose than do the electrical ones
- Large data base exists on irradiation of glass reinforced epoxies and polyimides. However, most of the experiments employ mostly gamma irradiation and ambient temperature testing and/or irradiation
- Data on neutron vs. gamma damage show greater degradation with neutron irradiation compared to gamma irradiation at same dose
- Experimental data on effect of irradiation temperature, in general, indicate less degradation following 4K irradiation



Organic Insulator Dose Limit

- Commonly accepted dose limit for epoxies is 10^7 Gy which is used in ITER
- Polyimides and bismaleimides are more radiation resistant with experimental data showing only small degradation in strength at dose levels > 10^8 Gy
- Polyimides are difficult and expensive to process due to their high viscosity and requirement for high temperatures to fully cure
- Hybrids of epoxies, polyimides, bismaleimides, and cyanate esters are being developed to both improve ability to withstand high levels of radiation and to improve overall processibility
- We are irradiating insulator samples at the MIT reactor to dose levels close to those expected in fusion systems (up to ~5×10^8 Gy) with the proper neutron/gamma mix
- We performed calculations that indicated that ~1 cm thick lead shield is required around the sample to reproduce the correct neutron/gamma dose mix

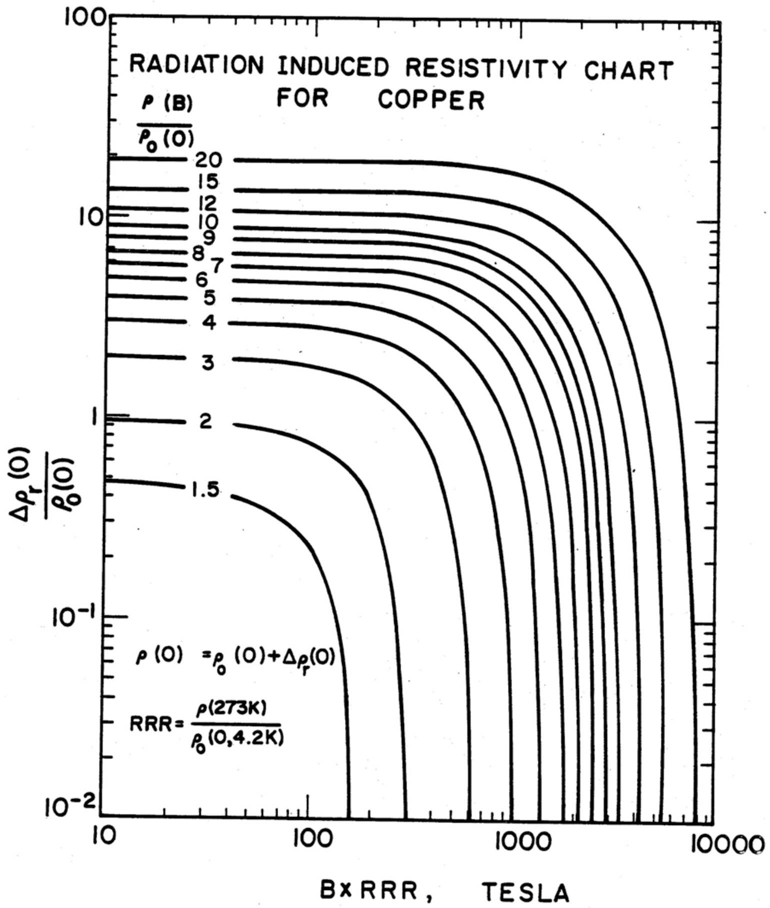


Damage to the Stabilizer

Neutron irradiation at cryogenic temperatures produces immobile point defects in the Cu stabilizer resulting in a radiation induced resistivity

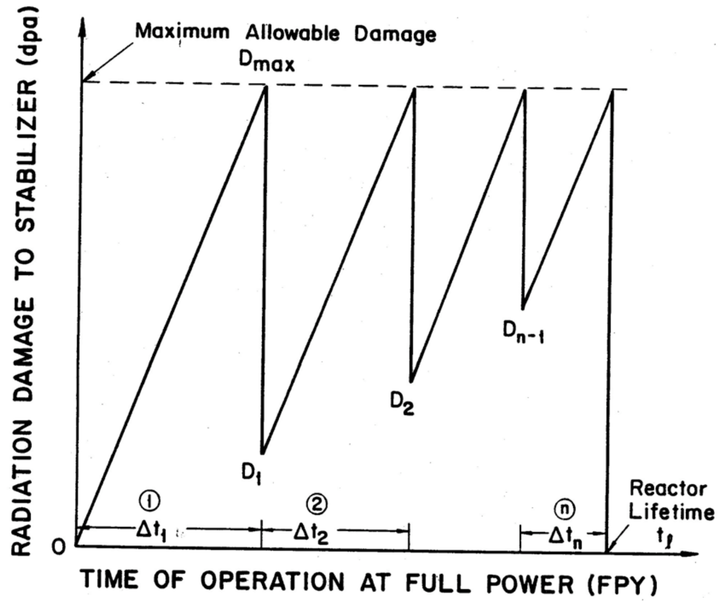
$$\Delta\rho_r = 3\,[1 - \exp(-240D)]\ \mathrm{n\Omega m}$$

- We generated charts to determine maximum allowable damage in Cu stabilizer based on Kohler's plot for Cu
- It accounts for
  - Cu purity (RRR value)
  - field B
  - maximum allowable total resistivity (determined by stability and protection requirements)



Damage to the Stabilizer

The maximum allowable damage rate can be determined by accounting for partial recovery (80-90%) of damage by annealing, and reactor availability limitation on minimum time between anneals



Application to ITER:

B = 12 T, Cu RRR = 100, T = 4.2 K

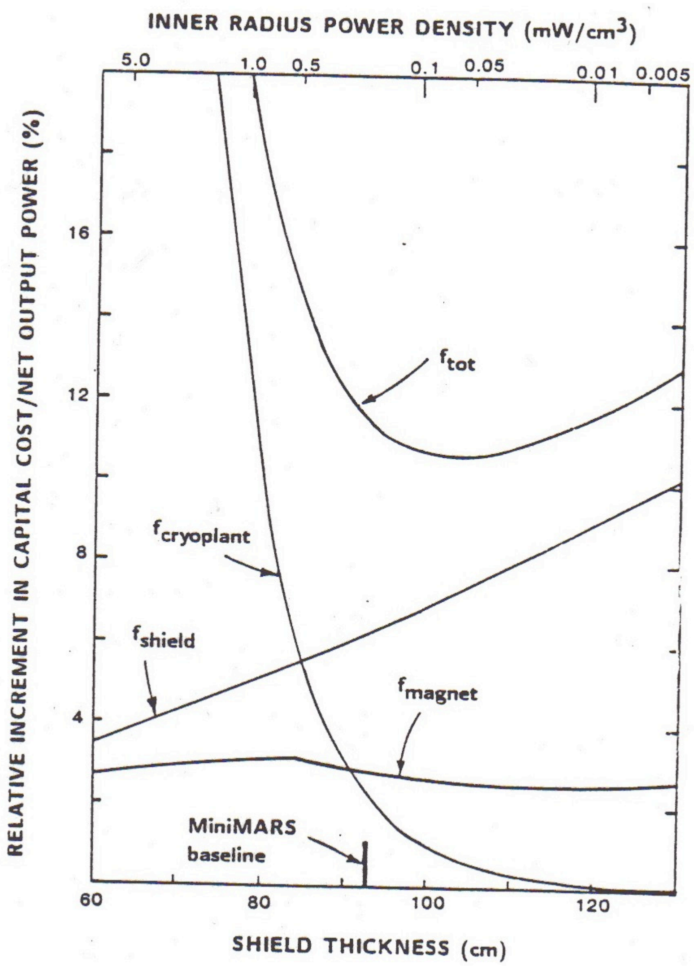
Total resistivity limit from stability and protection considerations = 3 nΩm

Chart ⇒ $\Delta\rho_{rmax}$ = 2.33 nΩm ⇒ $D_{max} = 6.3\text{x}10^{-3}$ dpa

For Δt_{min} = 0.2 FPY, lifetime = 3 FPY, r = 0.85 ⇒ dpa rate limit = 0.01 dpa/FPY

Nuclear Heating

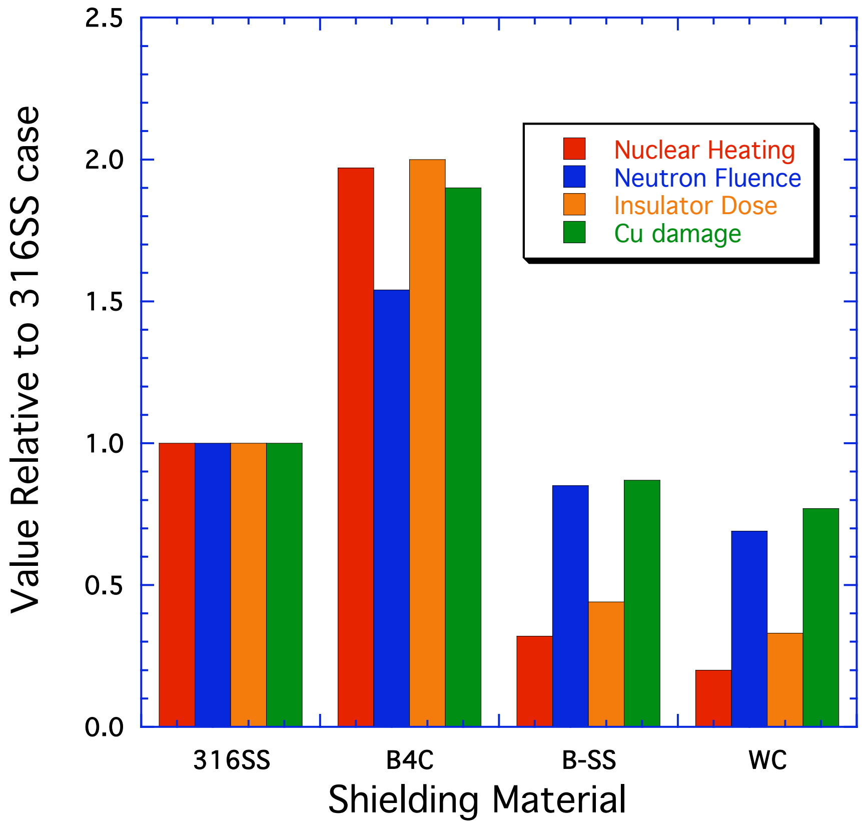
- Nuclear heating in practical designs causes negligible temperature difference between conductor and coolant compared to ohmic heating from a normal zone
- Major design impacts are economics, cryogenic system performance, and changes in superconductor parameters as a result of temperature changes
- Cost trade-offs should be performed to determine optimum nuclear heating level
- Total cost of all items affected by shield thickness is minimized under the constraints that magnet radiation effects do not exceed limits set by technical considerations
- The total nuclear heating in the 18 TF coils of ITER is limited to 17 kW corresponding to a peak local winding pack power density of 0.1 kW/m^3



Impact of Shielding Material on Magnet Radiation Effects

- 1 m thick inboard region (35 cm VV + 65 cm FW/B/S) in ITER
- Water-cooled double wall 316SS vacuum vessel with single-size (62% packing fraction) steel balls
- Shielding impact of replacing the steel balls in the VV by borated steel, boron carbide, or tungsten carbide balls is assessed

- Using B_4C balls in VV results in higher magnet damage
- Using B-SS balls in VV reduces magnet heating and insulator dose by a factor of 2-3 and neutron fluence and Cu damage by ~15%
- Largest shielding improvement results from using WC balls. Magnet heating and insulator dose reduce by a factor of 3-5 and neutron fluence and Cu damage by ~30%



Summary and Conclusions

- Knowledge of neutron spectrum, gamma/neutron mix, and temperatures used in irradiation experiments is essential to relate data to conditions in fusion reactor magnets
- Available irradiation data indicate that fast neutron fluences up to ~10^{23} n/m^2 and insulator doses up to ~10^8 Gy will not result in significant degradation in superconductor critical properties or insulator mechanical properties
- ~1 cm thick lead shield is required around insulator samples irradiated in fission reactors to reproduce the correct neutron/gamma dose mix
- Charts developed to determine maximum allowable damage in Cu stabilizer
- Cost trade-offs should be performed to determine optimum nuclear heating level
- The minimum total radial build between plasma and TF coils is typically >1 m depending on material used, magnet radiation limits and the neutron wall loading

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