Insulation and the effect of radiation

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“Conventional” magnet insulation

- A composite material containing:
  - A fibre, e.g. S-glass
  - A thermosetting polymer, e.g. epoxy

- The polymer is the “weakest link” in terms of radiation damage
- Fibres must be boron-free for use in a neutron radiation environment

Model coil section showing glass fibre and epoxy

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Thermoset polymers

- A thermoset is formed by the reaction of liquid chemicals (monomers) to form a solid
- Examples: Epoxy, Cyanate Ester, BMI, PI
- This might be a reaction of a monomer with itself, catalysed and/or with heat
- Or, more commonly, a reaction of a “resin” and a “hardener”
- There are only a few epoxy resins to choose from, but many hardeners

Specification for vacuum impregnation materials

- **Vacuum impregnation** is the process of choice for large composite structures
  - Compatible with “React and Wind” technology
- A useful vacuum impregnation resin should have:
  - Low viscosity (max. 300 mPa.s)
  - Long pot life (min. 12 hours)
  - Safe to use
  - Modest cure temperature (max. 170°C to avoid melting solder)
  - Easily available in relatively small quantity
  - Affordable cost

What radiation problems does the LHC upgrade present?

- **Many times the radiation load of LHC**
- Radiation load ~150 MGy, damaging to organic materials
  - Insulation is the life-limiting component in a magnet
  - Replacement might be impossible or have significant impact
  - Compares to few MGy lifetime for “conventional” epoxies
- Increased heat load: quench stability
  - Electrically insulating composites are also thermally good insulators
- Residual dose rates for maintenance

Interaction of Radiation with Resin

High energy particles lose energy and transfer it to polymer by:

Ionisation
  - breaking chemical bonds
- Excitation
  - Separation of orbital electrons
- Nuclear Displacement Reactions
  - mainly fast neutrons - leads also to ionisation
- Scattering and Emission
  - Absorbed energy is degraded and appears as heat

Radiation Type

Several types of high energy radiation:

- Fast neutrons – no charge
  - deposit energy mainly by collisions
- Slow neutrons – no charge
  - capture and nuclear transformation
- Gamma photon - electromagnetic
  - Ionisation and excitation
- Electrons and Protons – charged particles
  - Ionisation - results also in charge separation
- Alpha particles – short range (neutron capture)

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Fast Neutrons

- Deposit Energy by collisions
- $Et = \frac{4 \times M}{(M+1)^2}$

Nucleus	Mass	Energy Transfer (%)
Hydrogen	1	100
Carbon	12	28
Nitrogen	14	25
Oxygen	16	22

Fast Neutrons are intensely damaging

- Major result is production of fast protons
- Energy transfer to other atoms may break chemical bonds
- Re-coiled neutron may still have sufficient energy to break more bonds

Slow Neutrons

- Most elements have larger capture x - section for slow neutrons than for fast - result is nuclear transformation reactions:

- After capture nucleus may be unstable:

H(1) (n,γ)D(2)	N(14) (n,p) C(14)
2.2 MeV γ	0.66 MeV proton

B(10) (n,α) Li(7)

Boron gains 1 amu and loses 4 (a high energy alpha particle)- a net loss 3 amu

Gamma Photons

Three significant damage mechanisms:

- Photo-electric effect
  - photon collides with and ejects electron - photon is annihilated. (low energy photons)
- Compton Scattering
  - photon - electron collision & ejection - photon survives but is deflected (Intermediate energy photons)
- Electron - Positron Pair Production
  - Photon is annihilated & electron-positron pair result. Photon energy greater than 1 MeV is required

Charged Particles

- 1.0 MeV Electrons e^-~ 5-7 mm in unit density materials (LET 0.24 eV/nm)

- 1.0 MeV Protons H^+~ 1mm in unit density materials (LET 43eV/nm)

- 1.0 MeV Alpha He^{2+} (LET 130ev/nm)

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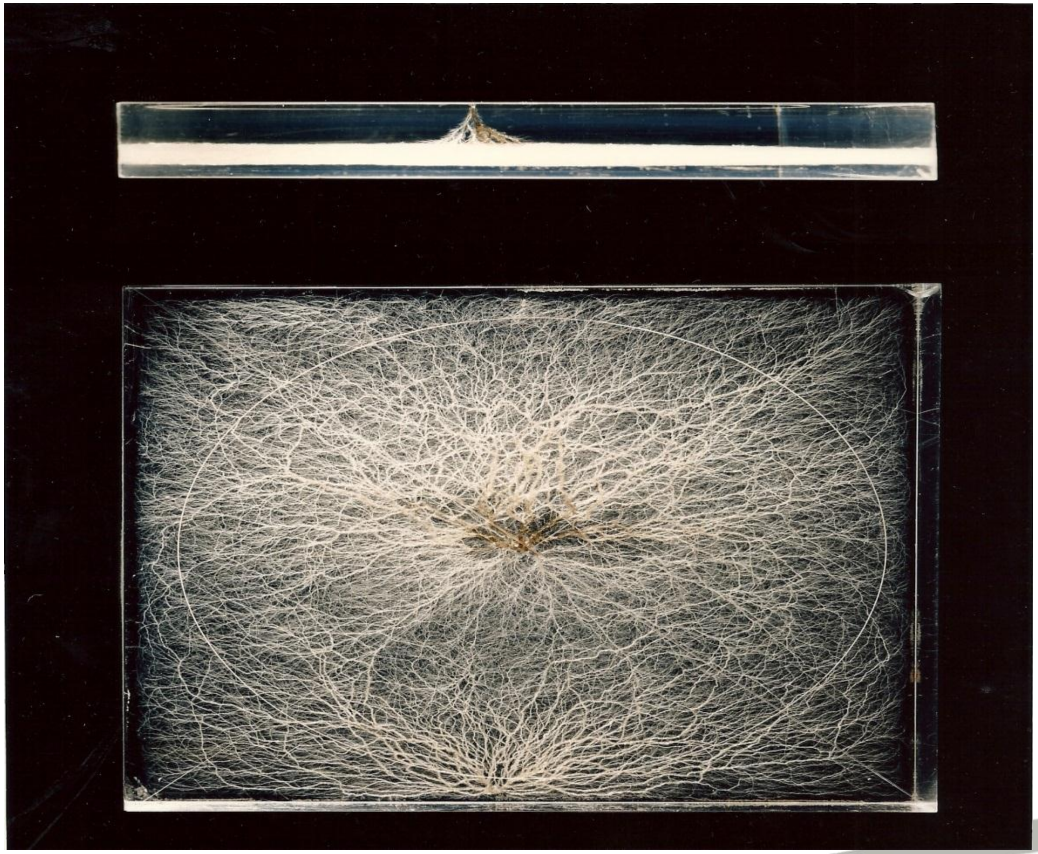
Electrons in acrylic

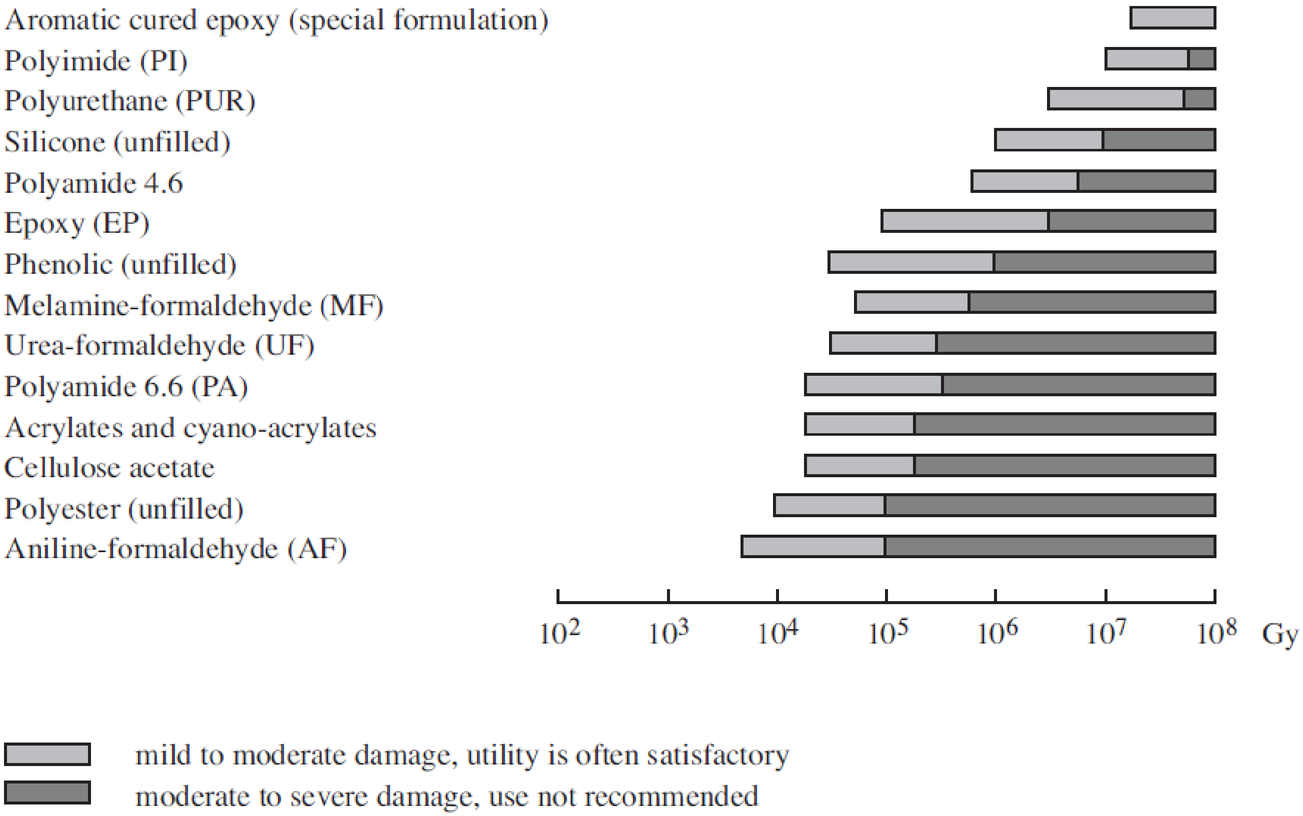


Radiation Effects in Resins

- Changes in electrical properties
  - Carbon tracks
- Changes in Mechanical properties
  - Particularly matrix dependent properties such as flexural strength and shear strength
- Classification of “Damage”
  - IEC544 “radiation index”, RI
  - Defined as Log of dose required (Grays) to reduce the most radiation sensitive property by a defined amount (usually 50%)
  - E.g. Shear strength drops by 50% at 1 MGy, RI=6
- Gas evolution
  - Not related to mechanical damage effects

- CERN 2001-006, Compilation of radiation damage test data Part IV: Adhesives for use in radiation areas

Table 2: Classification of adhesives according to their radiation resistance



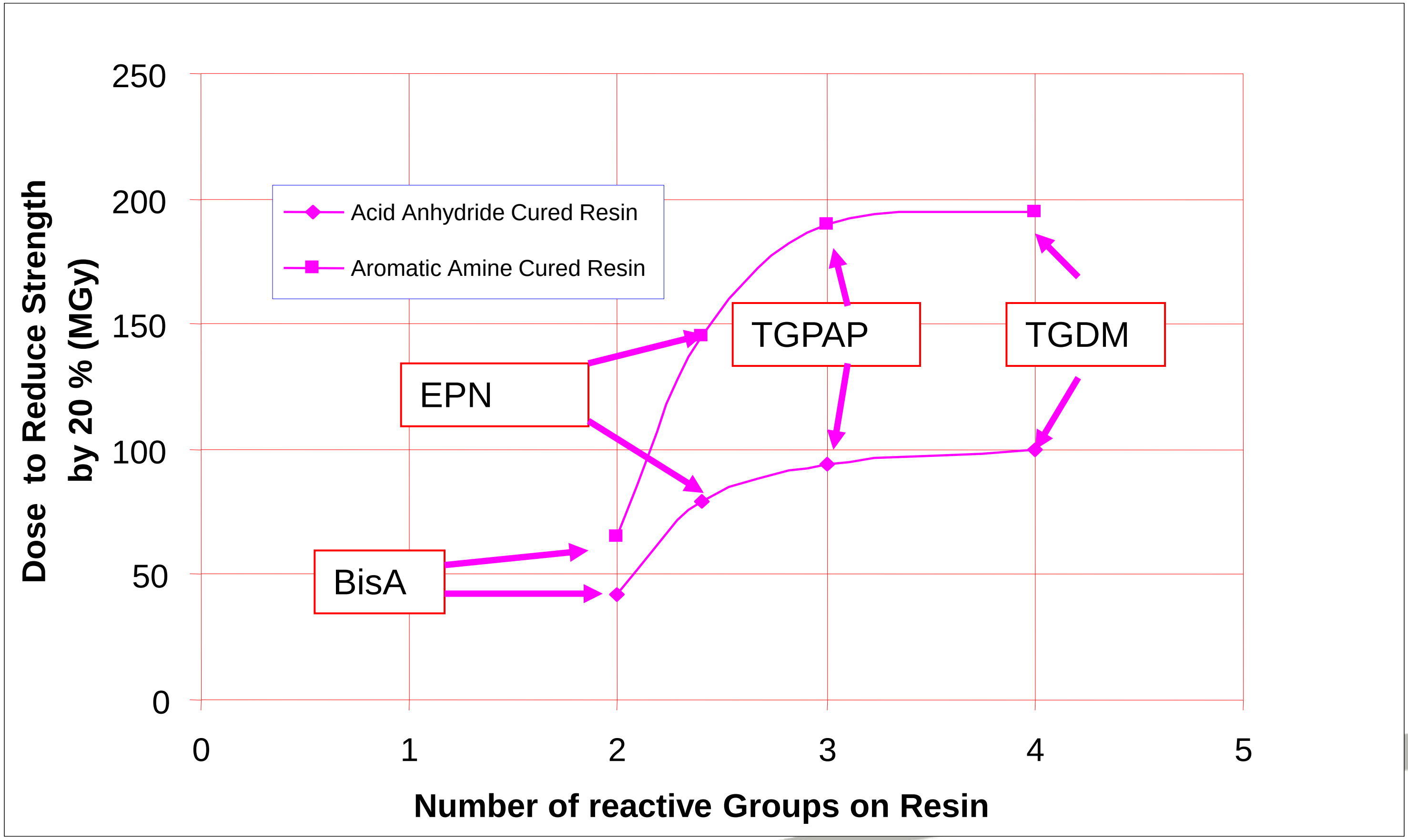
Structure-property relationship

- Molecular structure affects all properties including radiation stability
- Increased performance:
  - Aromatic (ring) structures
  - High functionality (crosslink density)
- Reduced performance:
  - Aliphatic (linear) structures
  - Low functionality

BUT these same structures reduce toughness and increase shrinkage on cure (leading to high cure strain)

So pure resin volumes must be engineered out

An example of how structure affects radiation stability



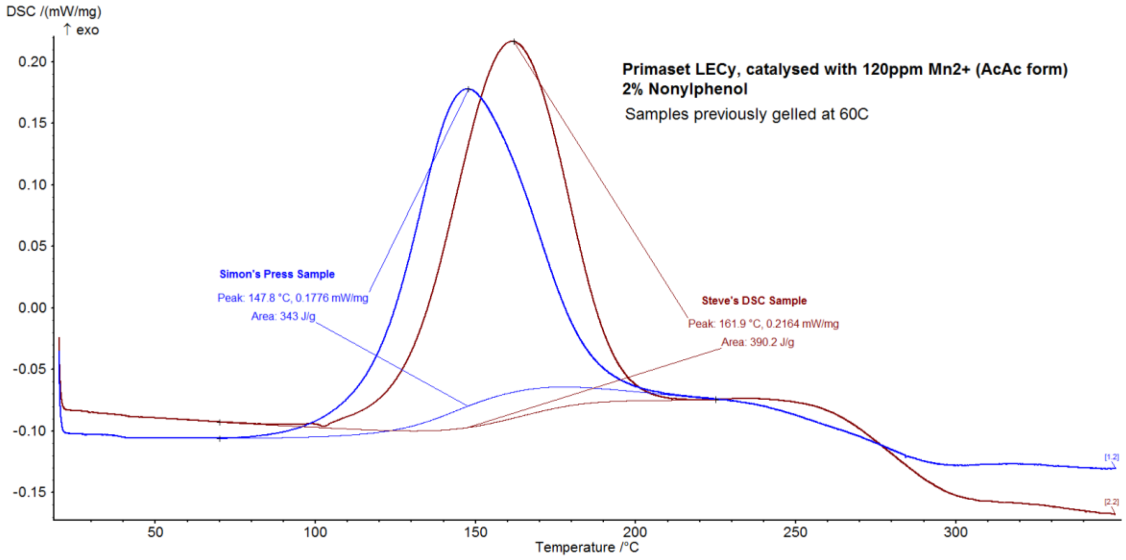
More crosslinking

Testing aspects

- Electrical breakdown testing relevant for magnet insulation
- Does not always correlate with mechanical effects
- Activation of specimens
- Ensure fibre does not mask changes in resin properties- esp. tensile testing
- Thermal analysis and FTIR techniques also useful
- No single technique that can be used to qualify a material, tests should be tailored to the application

CE formulation trials at RAL

- Catalyst choice and concentration
  - Mn, Co
- DSC trials on small amounts (add a curve)
- Scale-up to larger quantities, relevant for real magnets



Cure Exotherm

- Some epoxies and CE materials have a reputation for unmanageable exothermic behaviour - but it can be easily managed
- The monomers have low molecular weight and high functionality
- This means many more reactions per unit mass of resin compared to common epoxies
- So more heat is produced: take steps to deal with this:
  - **Tooling with high thermal mass, long and slow gel+cure times**
  - **This is compatible with magnet production**

Examples of rad-hard polymers suitable for vacuum impregnation

- TGPAP trifunctional epoxy
- Aromatic epoxy hardeners such as DETDA
- Liquid cyanate-ester
- Cyanate ester-epoxy blends

Any questions

Thank you for your attention

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References

- Schonbacher, Tavlet et al CERN reports (catalogues of polymer radiation testing)
- Handbook of radiation effects, 2nd ed., A Holmes-Siedle and L Adams
- Chemistry and Technology of cyanate esters, Hammerton

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