Radiation damage issues for superconducting magnet insulation materials

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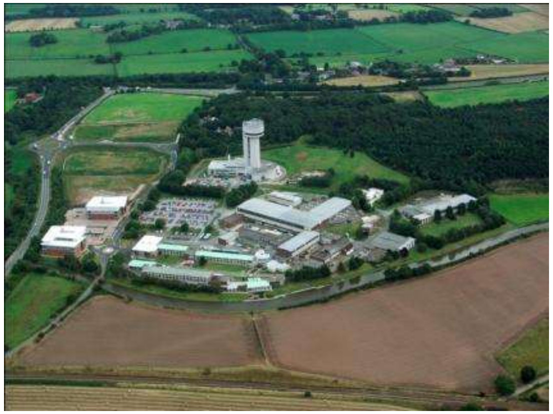
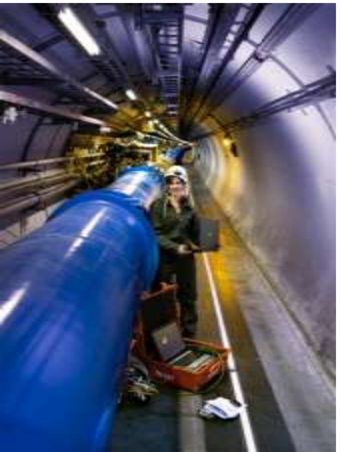




Science & Technology Facilities Council

Superconducting magnet heritage at RAL

Detector magnets: Delphi, H1, ATLAS End Caps

Accelerator dipole magnet projects:

- Next European Dipole (EU FP6),
- CERN EuCARD High Field Magnets (EU FP7)

CERN High Field Magnet programme

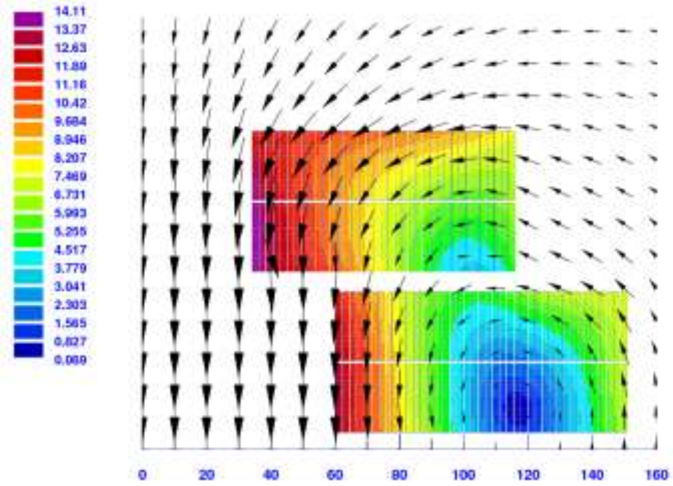
To develop technology for LHC upgrade scenarios

Aims to build a **13T**, 100mm dipole "FRESCA 2" for the FRESCA test facility at CERN

(compared to **8T** in LHC NbTi dipoles)

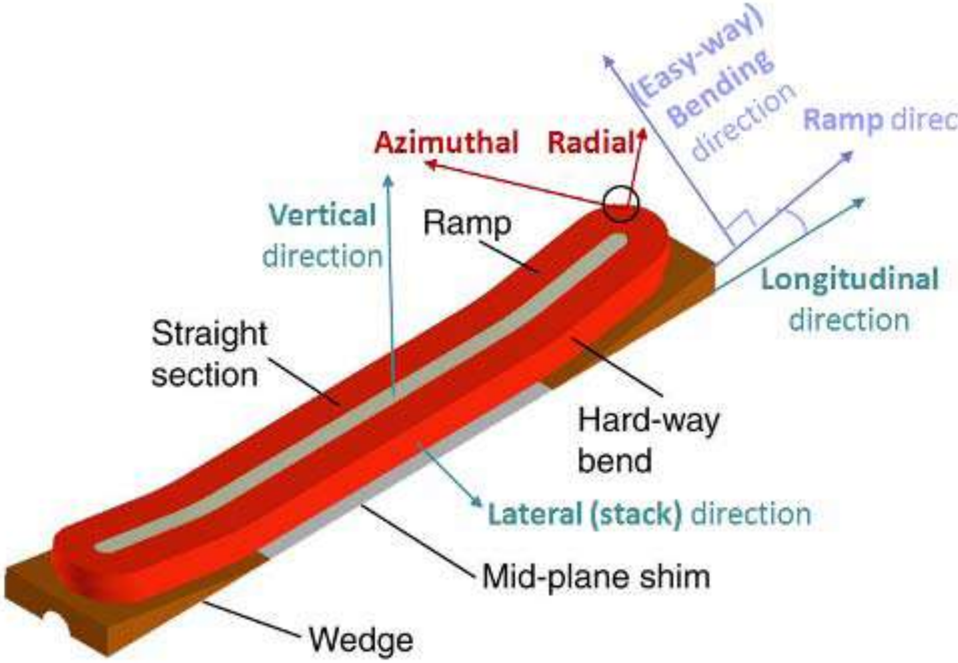
Block coil design, Nb3Sn

VHFM insert, +6T in High Temp Superconductor



Baseline block cross section (a quarter shown).
The field in the coil is computed for a 13 T bore field.

CERN HFM Nb3Sn magnet design borrows concepts from the American LARP “HD2”



Magnet "Insulation" Materials

Electrical insulation between turns and to ground

But just as important,

- "Insulation" forms a monolithic, mechanically stable structure
  - Form a coil pack for assembly into magnet structure
  - To resist and transmit Lorentz forces during operation, high compressive strength (300MPa) and shear strength (100MPa)

Polymer Composites

- Advantages of thermoset composites:
  - suitable for low volume production runs, using vacuum impregnation to form high quality composites
  - easily available
  - relatively cheap
  - Chemistry can be varied to give a very wide range of properties including relatively high radiation resistance (cf other polymers)
    - E.g. Formulations for ATLAS End Cap Toroids and "RAL 71A", developed at RAL
- What are the disadvantages?
  - Can have low radiation hardness **so polymer dictates magnet lifetime**

Known radiation dose limits for polymers

Many factors influence rad-hardness, including:

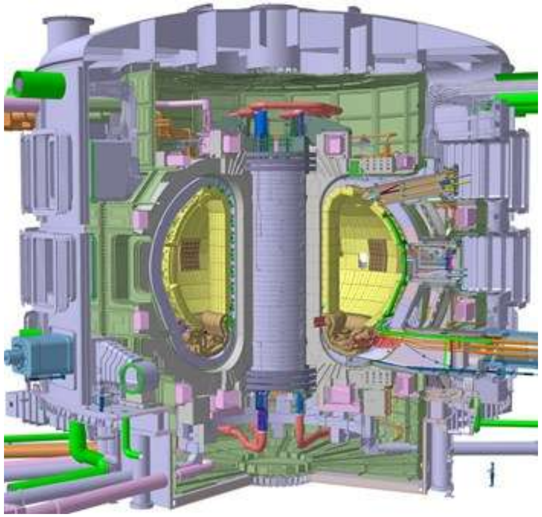
Material: Epoxy resin structure, curing agent structure, cure schedule...

Radiation: environment, temperature, dose, dose rate, particle type, particle energy, synergistic effects...

Testing: test type, temperature, rate, environment since irradiation...

But in general, in the environments tested to date, we know: tens of MGy for linear chain epoxies, up to 200MGy and beyond for aromatic structures (CERN Yellow reports, Tavlet et al)

ITER TF coils



Dose 10MGy, neutron flux 10^{22}N/m^2

Interest in cyanate ester/epoxy blends for ITER TF coil insulation

Tests to date (fission reactor irradiation) are encouraging

How do they compare with best epoxies?

How does existing test data relate to high energy physics applications?

Effect of particle type

Neutrons – highly penetrating, lead to knock-on protons

Protons- charged, so *not* highly penetrating but highly damaging

Gamma- interaction with orbital electrons, forming ions and radicals

Ideally we should consider more than just dose...

Radiation types do have different effects on polymers:

-Egusa 1991, reported glass/epoxy up to ***2.6 times more*** *sensitive to neutrons than gamma*

-Abe 1987 reported 14MeV neutrons are ***eight times more*** *damaging than Co-60 gamma to polyimide (Kapton DuPont (R))*

What properties to test?

Classical **mechanical** properties can be useful, esp. Short beam shear as it tests the glass/polymer interface.

Electrical testing is more sensitive than mechanical testing to radiation damage

FTIR and thermal methods in use at RAL (e.g. DMA, DSC, TGA) useful and use minimal material. They provide information on radiation-induced **chemical** change.

Ideally we would test materials beyond the expected lifetime dose using expected conditions but this is often impossible

Opportunities

Many projects are undertaking irradiation programmes, opportunity for synergies

Take advantage of the long term nature of NF/MC to launch irradiation testing

Radical new approaches and inorganic materials?

Conclusions

Some polymers have been shown to be useful up to hundreds of MGy dose

Polymers usually dictate the lifetime of a magnet in a radiation environment

There is a lack of data at high doses owing to the long irradiation times required

There could be a need for inorganic materials, but bear in mind the processing advantages of current (organic) materials

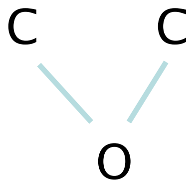
Extra slides

Effect of epoxy chemistry on radiation hardness

High functionality epoxies with aromatic hardeners are more radiation-stable compared to “standard” epoxies (Evans)

In HFM we plan to test cyanate esters, trifunctional epoxy

What are epoxy resins?



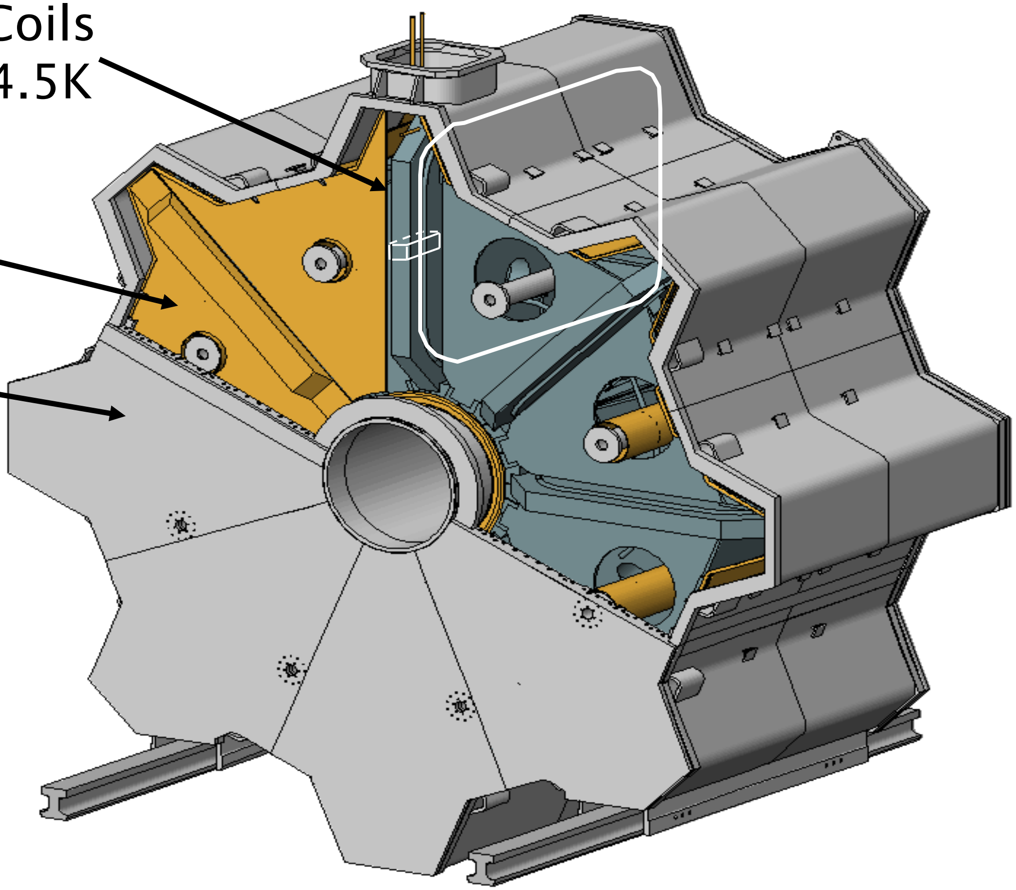
A family of materials characterised by the epoxide ring structure.

Useful epoxy materials have more than one epoxy ring that reacts to produce a thermoset material of high molecular weight.

The chemical structure of the epoxy resin, and curing agent, is varied to produce a wide variation of thermal and mechanical properties.

Therefore it is vital to specify both the resin and curing agent when referring to "epoxies"

Case Study:
Atlas End Cap Toroid Magnets



Superconducting Magnet Coils
Cold Mass 160 Tonnes @ 4.5K

Thermal Radiation Shield

Vacuum Vessel

Diameter 11m
Length 5m
Stored Energy 200MJ
Operating Current 20kA
Peak Magnetic Field 4.7T
Overall Mass 239 Tonnes

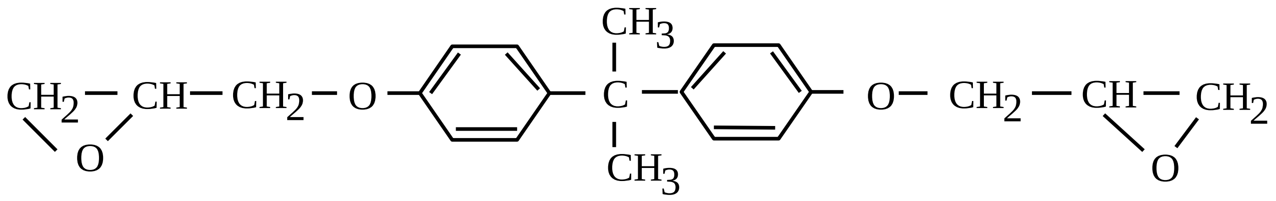
Case Study: Requirements

REQUIRED: A resin system with low viscosity and long working time, together with high modulus, tensile strength and work of fracture at low temperature.

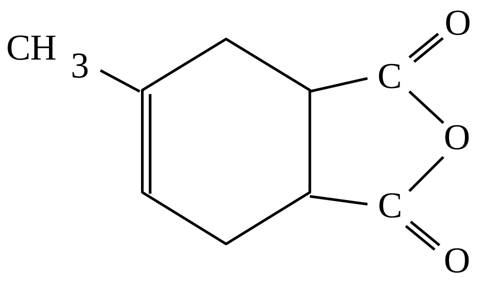
EXISTING SYSTEMS:

System	Advantages	Disadvantages
DGEBA/MTHPA	Low viscosity	Low work of fracture
	High modulus/UTS	
	Long working time	
DGEBA/POPDA	Low viscosity	Short working time
	High modulus.UTS	
	High work of fracture	

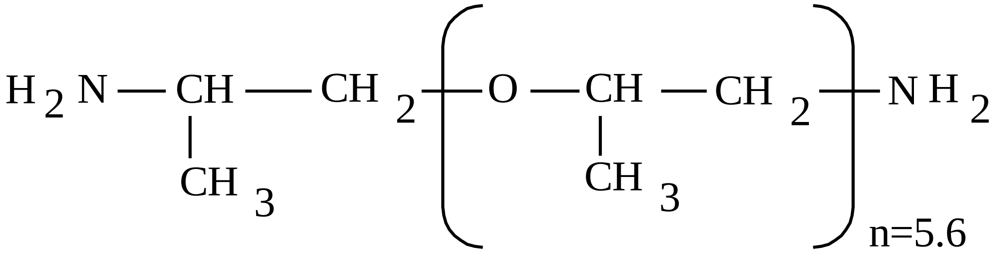
Case Study: The Molecules



resin



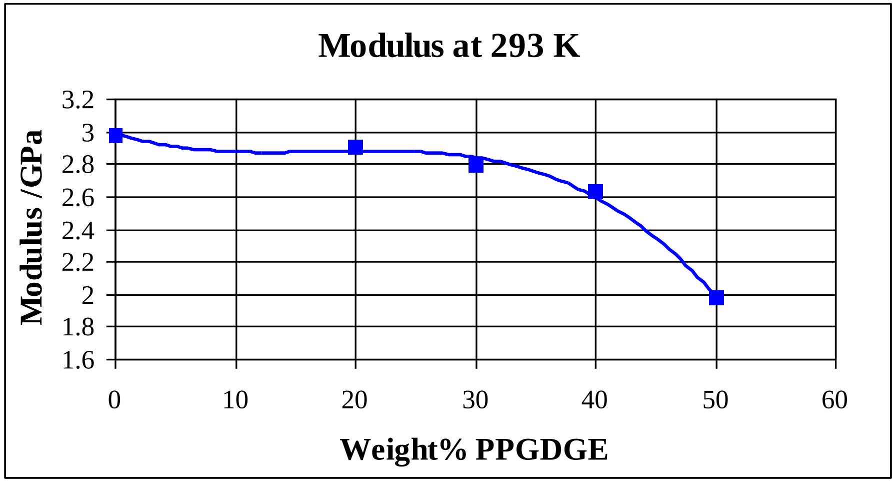
MTHPA
hardener:
stiff



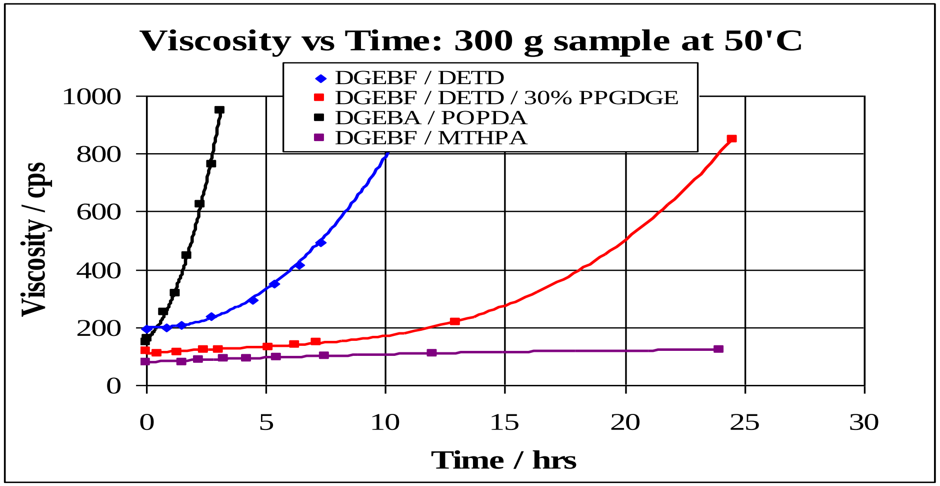
$$H_2N-\underset{CH_3}{CH}-CH_2\left(O-\underset{CH_3}{CH}-CH_2\right)_{n=5.6}NH_2$$

POPDA:
flexible

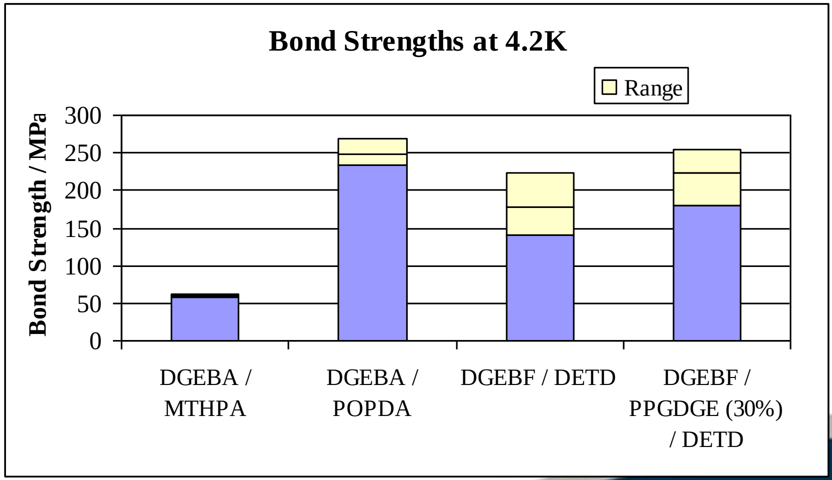
Case Study: Characterising



Modulus at 293 K

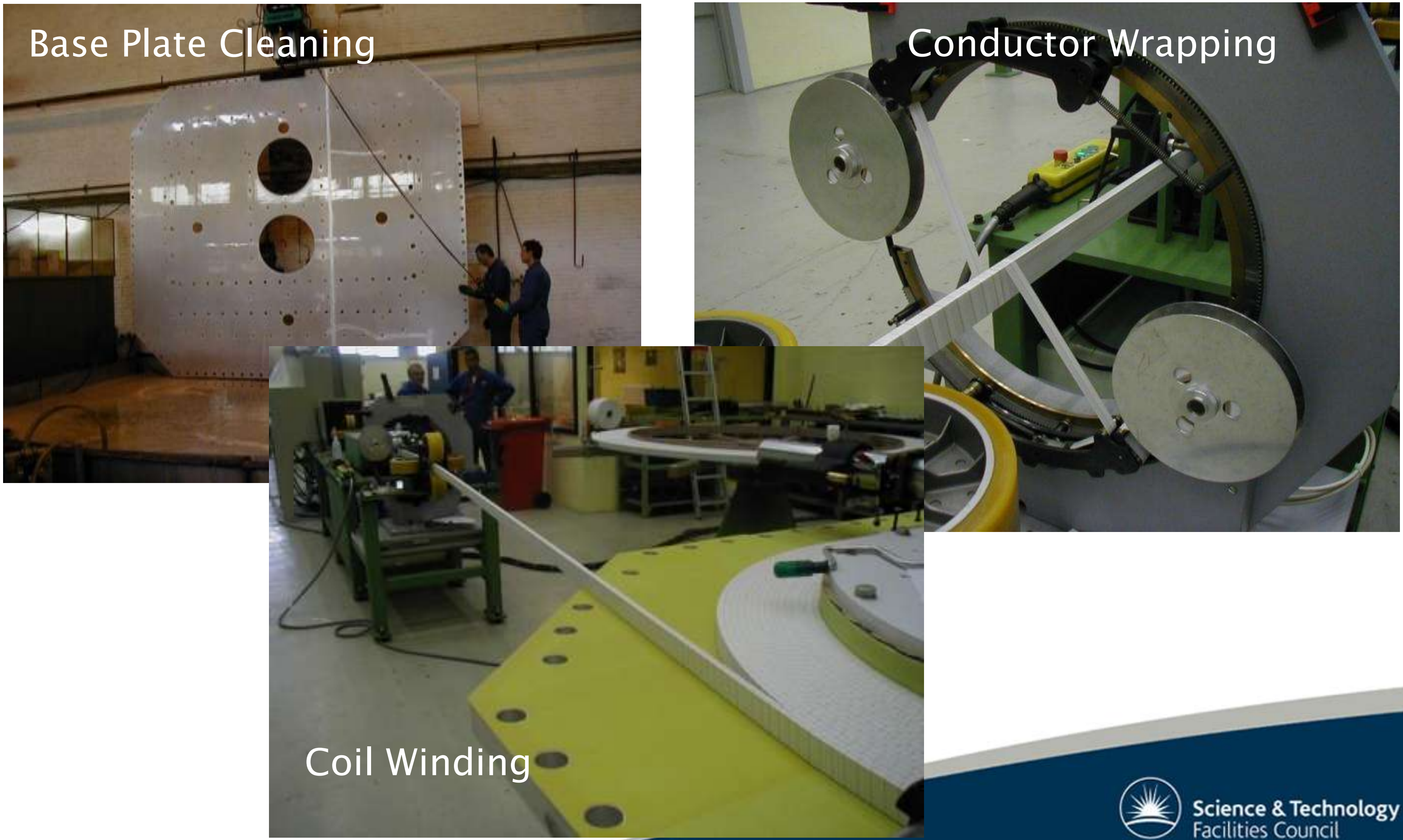


Viscosity vs Time: 300 g sample at 50'C



Bond Strengths at 4.2K

Atlas Manufacture 1



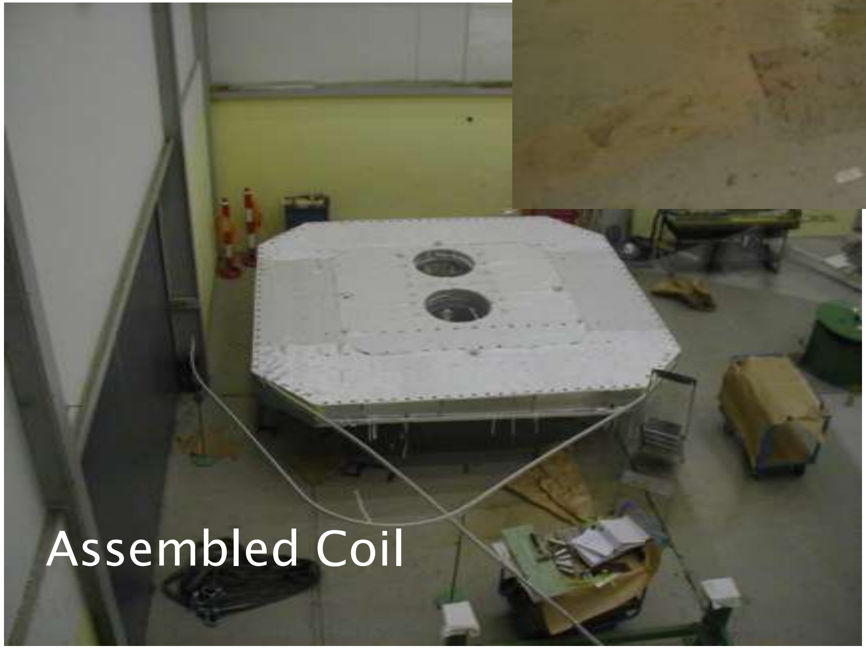
Base Plate Cleaning

Conductor Wrapping

Coil Winding

Atlas Manufacture 2


Vacuum Impregnation


Assembled Coil


Impregnated Coil

Atlas Manufacture 3

Coil Breakout

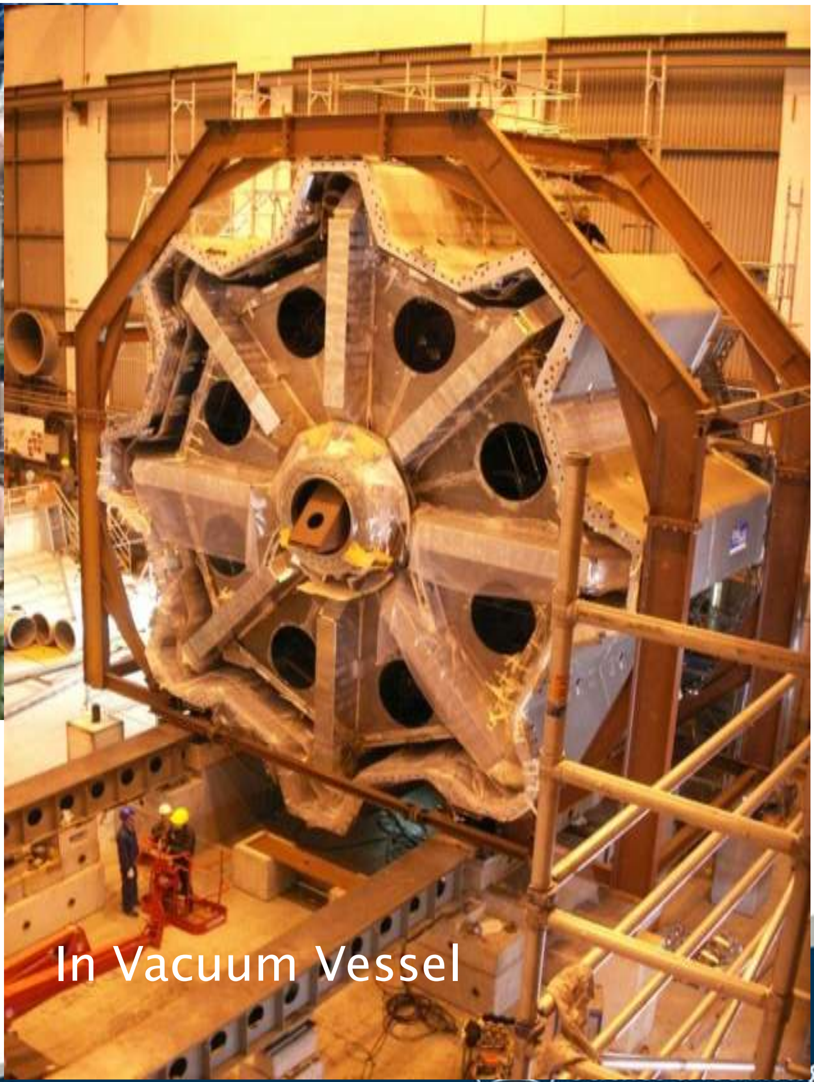
Assembly

Completed “Cold Mass”

Atlas Manufacture 4

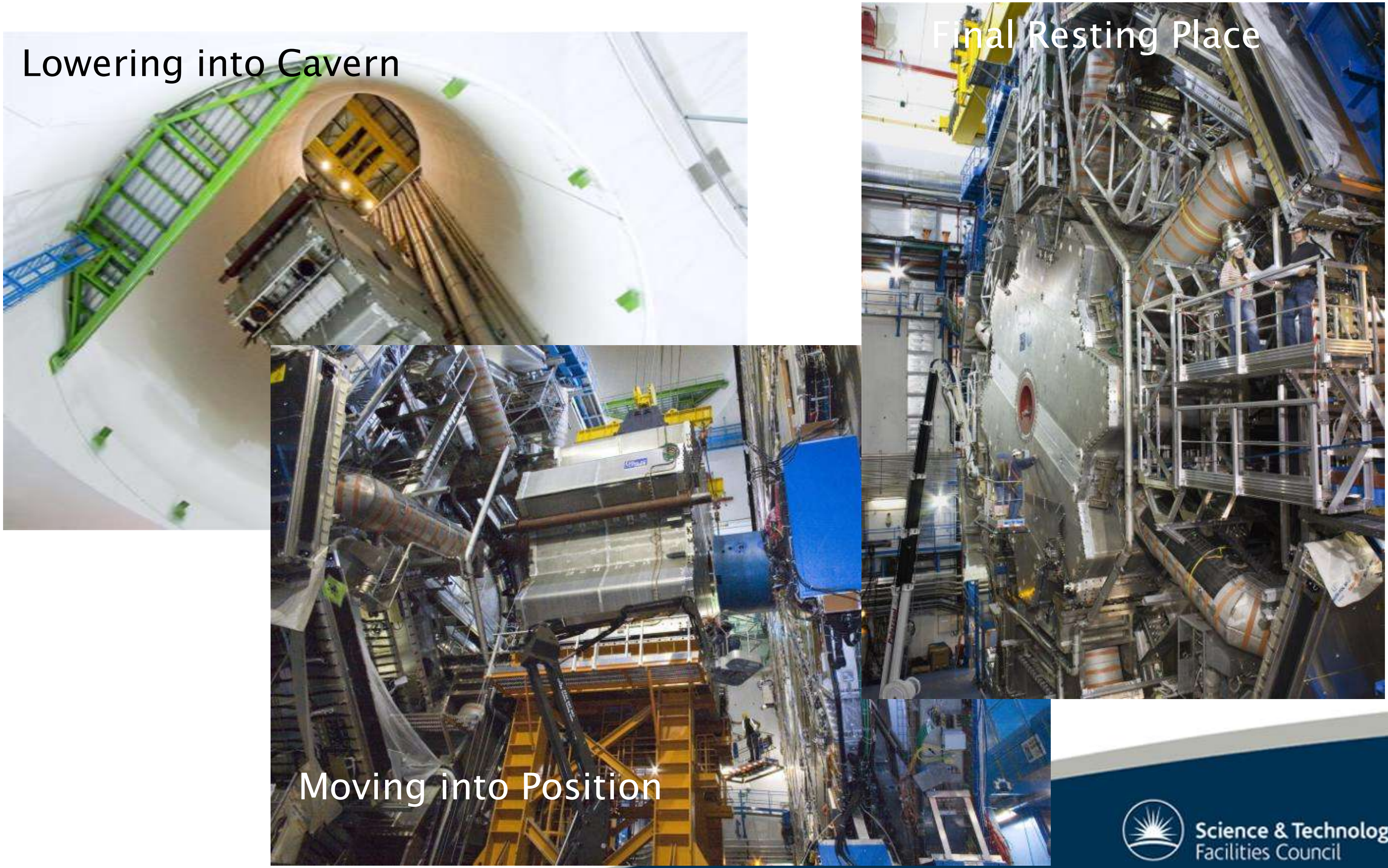
Barrel Magnet

Finished Magnet



In Vacuum Vessel

Atlas Manufacture 5



Lowering into Cavern

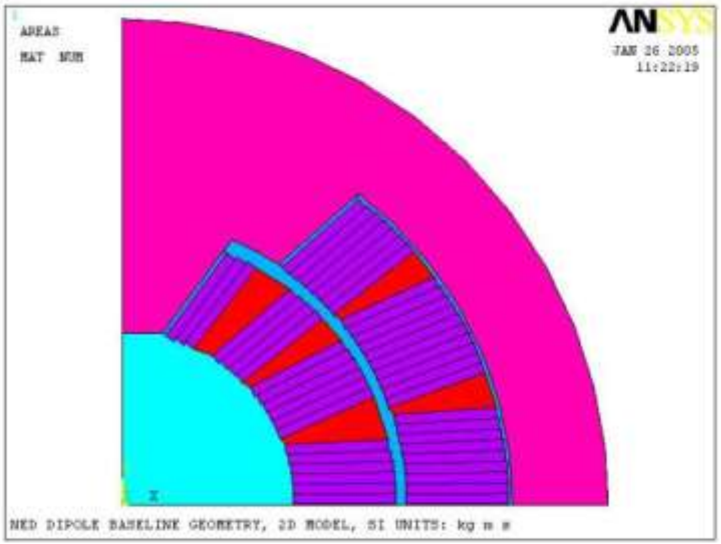
Moving into Position

Final Resting Place

Magnets for Accelerators

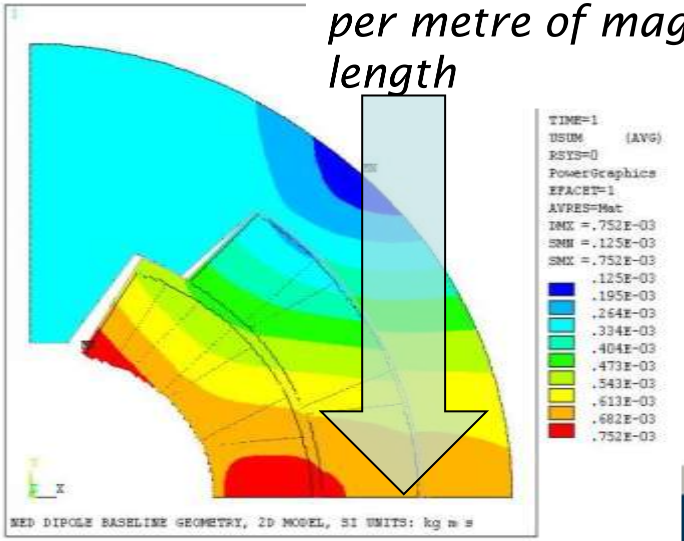
-synchrotrons need powerful magnets to bend the particle beam
-State of the art today is 8 Tesla
-The next step for the LHC will need double the field of todays magnets:
15 Tesla or 300 000x earth's magnetic field

-Only one superconductor material is feasible today: niobium-tin
-The whole magnet needs heat treating in vacuum at 700°C
-How do we insulate between the magnet windings?



¼ Symmetry model geometry

Forces of 100 tonnes per metre of magnet length



Deflection due to magnetic loads only

The first heat treated coil

A testbed for a record-holding European superconductor