Location in London

Imperial College
A few facts about Imperial

- **14,600 students** (8,600 UG, 6000 PG)

- **3300 academic** and research staff
Our history

1851–1890 Constituent Colleges formed, Prince Albert and the Great Exhibition

1907 Imperial College founded by merger of:
  • City and Guilds College
  • Royal College of Science
  • Royal School of Mines

1988-2000 Mergers with:
  • St Mary’s Hospital Medical School
  • National Heart & Lung Institute
  • Charing Cross/Westminster and Royal Postgraduate Medical Schools
  • Kennedy Institute

2007 Left the University of London to become an independent university
An international institution

Students from **126** countries

Top international countries:
- China
- Greece
- Malaysia
- Italy
- France
- Cyprus
- Singapore
- India
- Germany
- Thailand

50% Full time international students (non UK)
36% International staff
Faculty of Engineering

- Largest Engineering Faculty in UK
- 9 academic departments
- Over 1,000 staff
- 4,800 students: 3,300 UG & 1,500 PG
- £100M pa turnover
Department of Materials – Thematic Areas

- Advanced Alloys
- Functional Materials
- Biomaterials and Tissue Engineering
- Nanotechnology and Nanoscale Characterisation
- Theory and Simulation of Materials
- Ceramics and Glasses

35 Academic Staff
51 Research Associates
135 Research Students
6 Research Officers
8 Technical Staff
• Research Groups in Materials Department:
  – Advanced Alloys
  – **Ceramics and Glasses**
  – Nanotechnology
    • Materials Theory and Simulation
    • Nanoscale Characterisation
  – Functional Materials including Thin Films & Coatings
  – Biomaterials

• Major materials areas include:
  – Energy (esp. nuclear and SOFCs)
  – Biomaterials, Tissue Eng. & Regenerative Medicine
  – Transport (aerospace, land vehicles)
  – Novel Electronic Devices (thin films, sensors, photonic crystals)
  – Environment (clean up, pollution control & prevention)

• Multi-departmental and multi-disciplinary research groups enabling world-leading research including:
  – **UK Centre for Advanced Structural Ceramics (CASC)**
  – Centre for Nuclear Engineering (CNE)
  – London Centre for Nanotechnology (LCN)
  – Institute for Biomedical Engineering (IBE)
  – Thomas Young Centre for Materials Theory
  – Energy Futures Lab/UKERC.
UK Centre for Advanced Structural Ceramics (CASC).

- Funded by EPSRC between Depts. Materials and Mech Eng. at Imperial.
- Strong links to energy (including nuclear), aerospace and defence, transport and healthcare industries.
- Director Eduardo Saiz, Deputy Director Luc Vandeperre. Technical Manager Fraser Wigley.
- £30M research contracts.
- Supports research visits.
- Supports host national/international conferences (IWAC 5, UHTC 2).
- See www.imperial.ac.uk/CASC
Imperial College Centre for Nuclear Engineering

Management Team
Co-Directors (Grimes and Lee)
Strategy (Waterman)
PA (Warriss)

Undergraduate Nuclear Engineering
Mechanical and Nuclear Engineering
Chemical and Nuclear Engineering
Materials and Nuclear Engineering

MSc in Nuclear Engineering

Repository Science & Engineering
- Hooper
- Cosgrove
- Zimmerman
- Goddard, Pain
- Parry, Jarvis
- Bommer
- Bell, Butler

Spent Fuel & Waste Management
- Lee
- Streat
- Vandeperre
- Grimes
- Parry
- Ryan
- Cheeseman
- Buenfield

Fuel Design & performance
- Wenman
- Grimes
- Dye
- Hewitt
- Walker
- Lee
- Eaton

Reactor Operation Design & Monitor
- Hewitt
- Walker
- Goddard
- Nikbin
- Cawley
- Pain
- Bluck
- Lowe
Imperial College
London

Nuclear Research Capabilities

Key Research Groups & Themes:

- Non-destructive evaluation
- Radiation transport & reactor physics
- Thermal hydraulics (CFD)
- Structural Integrity
- Metallic structural materials
- Welding
- Fuel and ceramic materials fabrication
- Materials degradation
- Fuel and waste performance
- Radiochemistry
- Near-surface processes & hydrology
- Geomechanics for repository
- Seismic hazard assessment

A whole engineering approach to Nuclear Power
Bill Lee Research Group: Ceramics and Glasses for Extreme Environments

- Dr. Osama Farid: Nuclear Ceramics and Glasses.
- Chin Heng Phuah: Corrosion of Spent AGR Nuclear Fuel (with Mary Ryan).
- John O’Neill: Durability of Spent MOX Nuclear Fuel (with Mary Ryan).
- Edoardo Giorgi: Modelling and Processing of ZrC (with Robin Grimes).
- Nor Ezzaty Ahmad: Durability of Radwaste Glasses (with Julian Jones).
- Dr. D Daniel and Dr. S Wong: Processing, Characterisation & Oxidation of Ultra High Temperature Ceramics.
- Tayyab Subhani: Carbon Nanotube Reinforced Silica & Borosilicate Glass (with Milo Shafer and Aldo Boccaccini).
- Omar Cedillos: Development of TaC-HfC Ternary Carbides.
- Amanda Quadling: Thermal Shock and Corrosion of Refractories (with Luc Vandeperre).
- Jennifer Alex: Effect of Impurities on Solid-liquid Interactions in Calcium Aluminate Refractories (with Luc Vandeperre).
- Janke Ye (at Sheffield University with Shaowei Zhang): Molten Salt Synthesis of Non-oxides.
- Szymon Kubal (at Swansea University with Tata Steel): Development of BOF Tuyere and Surrounding Refractory Materials.
Background on Ceramic Processing.

Ceramic Processing I: Bulk Ceramics From Powders

- Holistic approach.
- Many steps, each of which can influence properties of final product.
- Highly pure powders with small particle size (often nano) and even size distribution.
- Provides high driving force for densification on sintering.
- Large and controlled shrinkage on sintering.
Calcination.

• Endothermic decomposition reactions in which an oxysalt decomposes to oxide solid and gas.

• E.g. $\text{Al(OH)}_3 \rightarrow \text{Al}_2\text{O}_3 + \text{H}_2\text{O}$.

• E.g. $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$.

• Product is usually reactive and sinterable powder.
Milling.

- E.g. ball milling.
- Reduce particle size in controlled manner.
- Fracture of powder particles.
- Contamination from wear of media so match to product.
Granulation.

- Forming agglomerates from powder by addition of binding agent and a processing step such as spray drying.
- Granules (or granulates) usually made spherical to improve powder flow and packing behaviour.
Purpose of Shape Forming.

• To get as close to final shape (not size) as possible – since machining ceramics is difficult as they are hard and it introduces surface flaws.

• To get maximum particle packing and uniformity so get minimum porosity during densification.
Shape Forming Techniques.

- After shape forming but before firing body is said to be green.
- Different rheology mixtures used for various shape forming operations e.g. “dry” powders, slurries, pastes and plastic bodies.

Fig. 1.26 Techniques used to form shapes from ceramic powders: (a) uniaxial pressing, (b) isostatic pressing, (c) slip casting, (d) tape casting, (e) jolleying, (f) jiggering, (g) extrusion and (h) injection moulding.
Ceramic Densification Processes.

- **SSS Solid State Sintering:** Only solid involved in mass transport.
- **LPS Liquid Phase Sintering:** Less than 15vol% of ceramic becomes liquid.
- **VGS Viscous Glass Sintering:** All ceramic becomes liquid. Viscous flow.
- **VCS Viscous Composite Sintering:** > 15vol% but < 60vol% of ceramic becomes liquid. Common in clay-derived ceramics.
Sintering.

- Removal of pores between starting particles accompanied by shrinkage of the component combined with growth together and formation of strong bonds between adjacent particles.
- Driving force is reduction of surface area obtained by replacing a loose powder having many high energy solid-vapour interfaces with a bonded solid having fewer lower energy solid solid interfaces.
- Therefore, desire fine starting powders (submicron size particles).
- Solid State Sintering (SSS) and Liquid Phase Sintering (LPS), <15% liquid.
- Usually aim in structural ceramics for as high a density as possible.
Relation Between Ceramic Microstructure and Densification Process.

- **Solid State Sintered.** Typically single phase, clean grain boundaries.

- **Liquid Phase Sintered.** Second phase at grain boundaries, often glassy.

- **Vitreous or Viscous Composite Sintered.** Multiphase grain and bond system.
Relation Between Ceramic Type and Densification Process.

SSS Solid State Sintering
LPS Liquid Phase Sintering
VGS Viscous Glass Sintering
VCS Viscous Composite Sintering

- Glasses, Glass Ceramics, Glazes, Enamels
- Structural Ceramics
- Electroceramics
- Bioceramics
- Refractories
- Whitewares, Structural Clay Products
Aims of Ceramic Processing Where Desire High Strength.

- To minimise the number and size of weakening flaws (e.g. pores and agglomerates).
Approaches to Ceramic Matrix Composite (CMC) Manufacture.

• Fabricate composites with low volume (15-30%) of particles, whiskers, platelets or short random fibres. Processing often similar to that of bulk ceramics from powders.

• Fabricate composites with high volume (40-50%) of continuous fibres.
Ceramic Processing II: Composites.

• Ceramic Matrix Composites (CMCs) combine synergistically the properties of a ceramic matrix and ceramic reinforcement phase.

• With careful processing improved strength and toughness compared to unreinforced ceramics is obtained.

• CMC performance depends on physico-chemical relationship of matrix, reinforcement and interface between them (want weak so avoid brittle fracture).

• Several types of reinforcements e.g. particulates, fibres, whiskers and platelets.
Continuous Fibre CMCs.

- May be 1D, 2D or 3D.
- Properties 1D extremely anisotropic while 2D and 3D attempt to reduce anisotropy.
- In 2D fibres are 0/90 or 45/45 where fibres are stacked in bundles // or ⊥ to each other (0/90) or at 45° to each other.

**Fig. 1.8** Schematic diagram of (a) 0/90 and (b) 45/45 fibres in a CMC. The fibre direction is indicated by the arrow and the numbers indicate the layers in which fibres at the orientation indicated occur.
Fabrication Continuous Fibre CMCs.

- Additional complication of reinforcing phase with high aspect ratio sintered with the matrix powder.
- Means densification mechanisms usual for unreinforced ceramics insufficient as reinforcement forms a skeletal network which resists further deformation and mass transport during sintering.
- During processing need to maintain integrity of reinforcement.
- Reinforcement degradation can arise from:
  - Mechanical abrasion on mixing (so protect with size, polymer coating)
  - Grain growth
  - Chemical reaction with matrix.
Continuous Fibre CMC Processing.

- Hot pressing is most common densification process.
- Alternatives are liquid infiltration methods e.g. sol-gel or DIMOX or Chemical Vapour Infiltration (CVI).

Fig. 9.1 Schematic of continuous fibre CMC processing route (after Hyde, 1988).
CMC Microstructures

SiC fibre-reinforced alumina, 0,90 layup.

Zirconia Toughened Alumina – particulate reinforced.
Ceramic Processing III: Coatings.

- Deposited to improve corrosion and oxidation resistance and protect against high temperature.
- Often via liquids (e.g. sol gel) or vapours (e.g. PVD, CVD).
Coatings from Vapour: PVD.

- Physical Vapour Deposition uses physical mechanisms to obtain source atoms e.g.
  - Evaporation, by heating.
  - Sputtering, by impact of gaseous ions.

- Then controlled transfer of atoms to substrate where film formation and growth occurs.

- Solid deposit and gas phase have SAME composition.

- Use for metals and ceramics.

- Heating modes: resistance, inductance, laser, plasma...

- Under vacuum or reduced pressure.
Coatings from Vapour: CVD.

- In Chemical Vapour Deposition source material is vaporised or reacted with other species to produce non-volatile reaction product which deposits on a (usually heated) substrate.
- Deposit and gas phase have DIFFERENT composition.
- Mostly for ceramics for wear enhancement e.g. SiC, TiC, ZrO₂, Al₂O₃…
- Various heating modes e.g. plasma assisted.
Advanced Ceramics and Composites in the Nuclear Sector.

Bill Lee

Centre for Nuclear Engineering (CNE) and Dept. of Materials.
Outline

• **World Nuclear Scene**
  – Fission and Fusion

• **Current Nuclear Applications of Ceramics**
  – Fuels and Wasteforms

• **Future Nuclear Applications of Ceramics: Near Term**
  – Inert Matrix Fuels;
  – Advanced cement, glass composite and ceramic wasteforms

• **Future Nuclear Applications of Ceramics: Longer Term**
  – Advanced fuel cycles
    • Wasteforms
    • Proliferation resistant, transmutation and composite fuels
  – Fusion
    • Tritium breeding
    • Structural.
Rising Expectation.

- Benefits of nuclear power recognised
  - Fossil fuel price rise & carbon tax
  - Security of supply
  - Environment: low CO$_2$, Gulf of Mexico
  - Confidence from decades of stable, safe and reliable operation.

- More than 50 countries have expressed interest in nuclear power and are in various stages of considering/planning their first NPP.

- 12 countries at advanced stage of planning including UAE, Saudi Arabia and Vietnam.

- BUT accidents such as Chernobyl and Fukushima.
Waste and Contamination Concerns.

• While progress is being made there are still waste disposal issues.

• Radionuclides escaped into the biosphere at Fukushima (Japan), Hanford (USA), Chernobyl (Ukraine) & Dounreay (UK) are a concern & many sites needing clean up.

• Yucca Mountain impasse.

• No operating repository for HLW/SNF.
Global Vision.

• Increased globalisation and international schemes
  – Innovative Nuclear Reactors and Fuel Cycles (Gen IV)
  – International Thermonuclear Experimental Reactor (ITER).

• Sharing and open access to expensive infrastructure such as research reactors, hot cells
  – Advanced Test Reactor National Scientific User Facility INL USA
  – EC Joint Research Centre: ITU, Ispra, Petten etc.
Other Developments.

- Technical innovations to reduce proliferation risk and increase security e.g. International Framework for Nuclear Energy Cooperation (IFNEC), advanced fuel cycles, use and fuel return reactors, fuel for life reactors.

- Future small reactors
  - Extend nuclear adoption to developing states with limited grid capacity
  - Will include greater safety conditions, extreme proliferation-resistance through lifetime cores and high $^{238}$Pu production
  - E.g. IRIS, Hyperion, Atoms For Peace Reactor.

- Mars rover driven by Pu nuclear reactor.

- Increasing acceptance of need for fast reactors.
Fusion

Two techniques:

- **Steady state** magnetic confinement of plasma (Tokamak e.g., ITER France)

- **Pulsed** power laser fusion (National Ignition Facility USA and Laser Megajoule France).

Massive intl. R&D effort.
Outline

• World Nuclear Scene
  – Fission and Fusion

• Current Nuclear Applications of Ceramics
  – Fuels and Wasteforms

• Future Nuclear Applications of Ceramics: Near Term
  – Inert Matrix Fuels
  – Advanced cement, glass composite and ceramic wasteforms

• Future Nuclear Applications of Ceramics: Longer Term
  – Advanced fuel cycles
    • Wasteforms
    • Proliferation resistant, transmutation and composite fuels
  – Fusion
    • Tritium breeding
    • Structural.
Fuels
Current Ceramic Applications in Fission Fuel Cycle: UO$_2$ Fuel Manufacture

- Uranium ore converted into UF$_6$
- $^{235}$U content of UF$_6$ increased before converting to UO$_2$ powder by Integrated Dry Route (IDR) using steam and hydrogen in rotary Inconel kiln.
- Granules pressed into pellets then sintered to ~97%TD in H$_2$. 
**UO₂ Pellet Sintering**

- > 5h ~1750 °C under H₂ (prevents oxidation) - UO₂ melts at 2850 °C
- Sintering determines density and grain size
  - key in-reactor performance parameter
- Evenly distributed, rounded porosity ~ 3%
- Thermal conductivity key property – need to get heat from reactor core and use to generate electricity.
UO$_2$ Fuel Microstructure
Post-irradiation

- Pellet had 30 GWd/tU burn up.
- Radiation damage and transmutation reactions degrade microstructure.
- Cracking leads to concerns over retention of radionuclides in spent fuel during storage and disposal.
Gives fundamental understanding of mechanisms that accompany radiation damage: shown here, displacement damage caused by ballistic resolution of a fission product (Xe) into UO$_2$ fuel.

Current Ceramic Applications in Fission Fuel Cycle: MOX Fuel

- Mixed OXide Fuel – UO₂/PuO₂ used in PWR’s.

- 1.5-30wt% PuO₂ as *heterogeneous* discrete phase (France) or in *homogeneous* solid solution (UK).

- Manufactured by SBR or MIMAS processes.

**SBR - Short Binderless Route Process**
- Powders attrition milled
- Pressed into green bodies
- Sintered in a reducing atmosphere (4% H₂ in Ar) at 1750°C for 24 hours

**MIMAS - Micronised MASter blend**
- PuO₂ and UO₂ co-attrition milled to create primary blend
- UO₂ added to primary blend to reduce PuO₂ content
- Pressed and Sintered
- PuO₂ is less likely to accumulate in hot spots and be more dispersed across the pellet.
Heterogeneous MOX Fuel – As processed microstructure

- SEM reveals porous structure and alpha radiograph the uneven PuO₂ distribution.
Irradiated MOX Fuel

Post Irradiation Examination of BNFL SBR MOX after high burn-up reveals cracks and columnar grains around central hole.

- Limited number reprocessing cycles due to Pu radionuclide make up.
- Interface issues (common to all fuels).
Fuel/Clad Contact Region in SBR MOX

Hydride Stringers in Zircaloy Clad

ZrO₂ Layer due to O migration from fuel

Fuel Bonding Layer where links to clad

Void

Pu Rich Region

Heat is generated within fuel and must be transported across different interfaces before it can be taken away by the coolant
Wastes
# UK wastes destined for Geological Disposal

<table>
<thead>
<tr>
<th>Waste Type</th>
<th>Waste Volume (cubic metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RWMD 2010 Baseline + NB SF</strong></td>
<td></td>
</tr>
<tr>
<td>LLW</td>
<td>13,800</td>
</tr>
<tr>
<td>ILW</td>
<td>490,000</td>
</tr>
<tr>
<td>HLW</td>
<td>6,910</td>
</tr>
<tr>
<td>AGR spent fuel</td>
<td>4,800</td>
</tr>
<tr>
<td>existing PWR SF</td>
<td>1,640</td>
</tr>
<tr>
<td>new PWR SF (16GWe scenario)</td>
<td>34,400</td>
</tr>
<tr>
<td>Plutonium*</td>
<td>7,820</td>
</tr>
<tr>
<td>Uranium*</td>
<td>106,090</td>
</tr>
<tr>
<td>All (total volume)</td>
<td>665,460</td>
</tr>
</tbody>
</table>

*Not declared as wastes.

500,000m³ is ~ St. Paul’s cathedral.

See CoRWM doc. 2997, Note on Inventories for Geological Disposal, Jan 2012.
High Level Wastes: Glass

- Calcined product of reprocessing chemically immobilised in alkali borosilicate glass, ~25wt% waste, heat generating.
- 6910m³ inventory
- >5100 stainless steel canisters stored at Sellafield
HLW Vitrification Process

- Dissolve spent fuel in nitric acid
- Recover U/Pu from Highly Active Liquor and calcine remaining raffinate to granular solid.
- Maximum calcination temp. ~500°C.
- Discharge granular calcine to Inconel melter + borosilicate glass frit.
- Melt several hours at 1050°C + air sparge.
- Pour into SS canisters and allow to cool.
Durable Glass for Thousands of Years.

- Mostly borosilicate and phosphate glasses.
- Active species can go into the glass network or other sites. E.g alkalis ($^{137}$Cs, $^{90}$Sr) into Na site.
- Open and random structure can accommodate most of the Periodic Table.

# HLW Glass Formulations

<table>
<thead>
<tr>
<th>Oxide, wt.%</th>
<th>SiO₂</th>
<th>P₂O₅</th>
<th>B₂O₃</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>Na₂O</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>R7/T7, France</td>
<td>47.2</td>
<td>-</td>
<td>14.9</td>
<td>4.4</td>
<td>4.1</td>
<td>-</td>
<td>10.6</td>
<td>18.8</td>
</tr>
<tr>
<td>DWPF, USA</td>
<td>49.8</td>
<td>-</td>
<td>8.0</td>
<td>4.0</td>
<td>1.0</td>
<td>1.4</td>
<td>8.7</td>
<td>27.1</td>
</tr>
<tr>
<td>Magnox Waste, UK</td>
<td>47.2</td>
<td>-</td>
<td>16.9</td>
<td>4.8</td>
<td>-</td>
<td>5.3</td>
<td>8.4</td>
<td>17.4</td>
</tr>
<tr>
<td>PAMELA Germany-Belgium</td>
<td>52.7</td>
<td>-</td>
<td>13.2</td>
<td>2.7</td>
<td>4.6</td>
<td>2.2</td>
<td>5.9</td>
<td>18.7</td>
</tr>
<tr>
<td>HLW, Russia</td>
<td>-</td>
<td>52.0</td>
<td>-</td>
<td>19.0</td>
<td>-</td>
<td>-</td>
<td>21.2</td>
<td>7.8</td>
</tr>
<tr>
<td>K-26 Commercial LILW, Russia</td>
<td>48.2</td>
<td>-</td>
<td>7.5</td>
<td>2.5</td>
<td>15.5</td>
<td>-</td>
<td>16.1</td>
<td>10.2</td>
</tr>
<tr>
<td>P0798, Japan</td>
<td>46.6</td>
<td>-</td>
<td>14.2</td>
<td>5.0</td>
<td>3.0</td>
<td>-</td>
<td>10.0</td>
<td>20.2</td>
</tr>
<tr>
<td>GC-12/9B, China</td>
<td>46.2</td>
<td>-</td>
<td>13.4</td>
<td>4.2</td>
<td>2.5</td>
<td>1.5</td>
<td>9.1</td>
<td>23.1</td>
</tr>
</tbody>
</table>
Benefits of Glasses for HLW Immobilisation.

- Simple melting process, powder batch becomes liquid and flows.
- Easy to process in large volumes.
- Accommodate large part of Periodic Table using low melting temperatures (1100-1150°C).
- Glasses retain many radionuclides in their structures.

An 80 year lifetime use of electricity for 1 person generates a small puck of vitrified HLW.
Difficulties.

- Some elements difficult (I, Cl, Ru, Mo, Pu) or need high melting temperatures (e.g. ZrO$_2$, Al$_2$O$_3$-rich wastes).
- Processing problems e.g. heel at bottom of melter in French AVH process (UK), products of refractory erosion/corrosion in Joule melters (USA). Need to immobilise these.
- Presence of unwanted crystals or crystallisation over time.
- Durability of UK Magnox or Blend glasses not well characterised.
Vitrification Processes

• One Stage Process (Joule Heated Ceramic Melter)
  – Glass forming additives mixed with concentrated liquid wastes.
  – Batch fed to melter where further water evaporation occurs, calcination & glass melting occur directly in melter.
  – E.g. Savannah River & West Valley USA.

• Two Stage Process (Induction Heated)
  – Waste concentrate fed into separate calciner.
  – After calcination glass frit & calcine product fed into melter.
  – E.g. Sellafield UK & La Hague France.
Difficult Species for Glass Immobilisation.

- Decreasing solubility leads to bubbles or crystals in glass matrix.

<table>
<thead>
<tr>
<th>Element</th>
<th>Solubility limit, wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al, Si, P, Pb</td>
<td>25</td>
</tr>
<tr>
<td>Li, B, Na, Mg, K, Ca, Fe, Zn, Rb, Sr, Cs, Ba, Fr, Ra, U</td>
<td>15 - 25</td>
</tr>
<tr>
<td>Ti, Cu, F, La, Ce, Pr, Nd, Gd, Th, Bi, Zr</td>
<td>5 - 15</td>
</tr>
<tr>
<td>Mn, Cr, Co, Ni, Mo</td>
<td>3 - 5</td>
</tr>
<tr>
<td>C, S, Cl, As, Se, Te, Sn, Sb, Te</td>
<td>1 - 3</td>
</tr>
<tr>
<td>H, He, N, Ne, Ar, Br, Kr, Ru, Rh, Pd, Ag, I, Xe, Pt, Au, Hg, Rn</td>
<td>Less than 0.1</td>
</tr>
</tbody>
</table>

Relatively homogeneous glass

Waste particles encapsulated

Leads to Glass Composite Materials.
Intermediate Level Waste: Cemented Packages and Other Options.

- E.g. Magnox swarf, graphite, legacy wastes (sludges, degrading fuels, MBGW).
- Physically encapsulate in OPC/PFA/BFS composite cement.
- Possibly some placed directly in large metal containers (yellow boxes).
- Thermal treatment (e.g. Joule heated in-can vitrification) for some legacy wastes.
- Total packaged volume for GDF will be ~500,000m³.
- To date about 25,000 m³ packaged = 46,000 packages i.e. <10% total.
**Composite Cements for Encapsulation ILW**

- Inexpensive, easy to make in large volumes, absorb radionuclides, predictable durability.

- Currently use *Composite cements*: ordinary Portland cement (OPC) + **waste materials** including:
  1. **Pozzolanic**: e.g. pulverised fuel ash (PFA).
  2. **Latently Hydraulic**: e.g. ground granulated blast furnace slag (BFS).

- *Composite* systems are less costly than pure OPC with lower heats of hydration and potentially superior long-term durability.

Angular grains of BFS and unhydrated OPC embedded in a calcia-silicate-hydrate, C-S-H gel matrix. Typically, 9:1 BFS:OPC.

![Image of composite cements](image-url)
Sellafield Magnox Encapsulation Plant (MEP) Process
ILW Temporary Storage at Sellafield.

- 46000 containers ILW currently stored on surface at Sellafield
- 2m, 3m, 4m boxes and 500l drums.

- 6440 m³ AGR and PWR (Sizewell B) spent fuel.
- 7820 m³ plutonium. Likely reuse in mixed oxide (MOX) fuel.
- Contaminated Pu. Immobilised in ceramics being developed.
- 106,090 m³ uranium. Likely reuse.
- 34,400 m³ high burn up PWR spent fuel (at 16 GWe new build).
- Spent MOX (from new build).

Single-phase Pu-containing zirconia, zirconolite or pyrochlore.
Overpack Containers: UK Spent Nuclear Fuel (SNF) & HLW.

Options being examined include Multi Purpose Containers (MPC) for SNF suitable for storage, transport & disposal.
Glass/Ceramic/Cement Wasteforms

Ceramics
- Solid State or Liquid Phase Sintered
  - Pressureless Sintered or Hot Pressed.
  - Single phase e.g. Zircon or multiphase e.g. Synroc.

Cements
- Room Temp. Hydration
  - OPC-based Composites or Alternates e.g. CSA.
  - Multiphase.

Glass Composite Materials
- Vitrified or Viscous Composite Sintered
  - Glass Ceramics.
  - Melted Wasteforms (cold or hot crucible).
  - Crystal Waste Encapsulated in Glass Matrix.

Glasses
- Vitrified
  - R7T7.
  - Magnox
  - RBMK.

Summary

• Imperial College London.
• Ceramic Processing: Monoliths, Composites and Coatings.
• World Nuclear Scene: Fission and Fusion
• Current Nuclear Applications of Ceramics: UO$_2$ and MOX Fuels, and HLW Glass and ILW Cement Wasteforms.