Possible Future Applications of Ceramics in the Nuclear Sector.

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Summer School on Inorganic Materials for Energy Conversion and Storage, UCSB, USA, August 27-28, 2012

Outline

- 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.
- Geological Disposal of Radioactive Waste: UK Case Study.

Advanced Fuels: IMFs.

- **Inert Matrix Fuels (IMFs) designed to burn excess Pu in current reactors**
  - ***Heterogeneous particle composite* fuels when Pu is embedded in inert matrix. Mix oxide fuel with particles of neutron inactive, chemically-inert phases e.g. ZrO_2, CeO_{2-x}, Y_2O_3, spinels.**
  - ***Homogeneous solid solution* fuels where Pu forms a SS with inert matrix e.g. $(Zr,Y,Pu)O_2$, (Pu,Zr)N and $(Th,Zr,U,Pu)O_2$.**
- **Actinide production and radiotoxicity of spent IMFs significantly less than UO_2 or MOX.**
- **Mechanically stable after high burn up.**
- **Can be directly disposed of after burning U/Pu in reactor.**

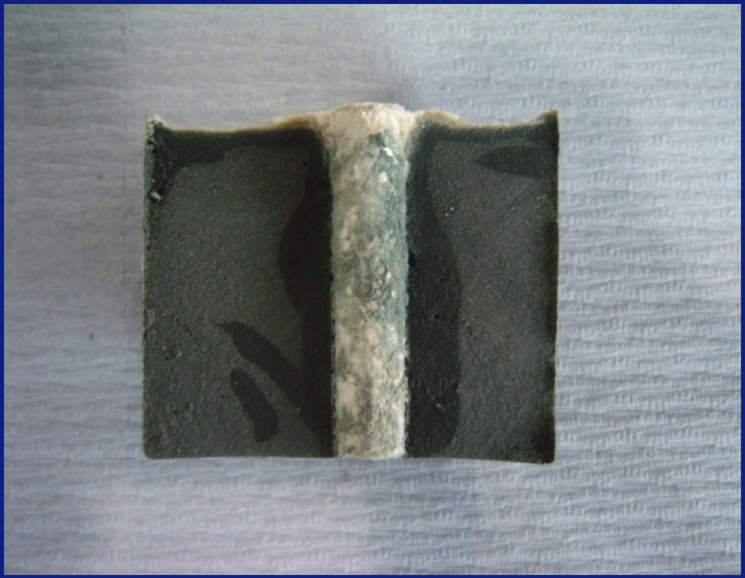
Pu-IMF pellet:
$(Zr,Y,Pu,U)O_{2-x} + MgAl_2O_4$

Schram, van der Laan *et al*., *J. Nucl. Mater.* 2003, *319*

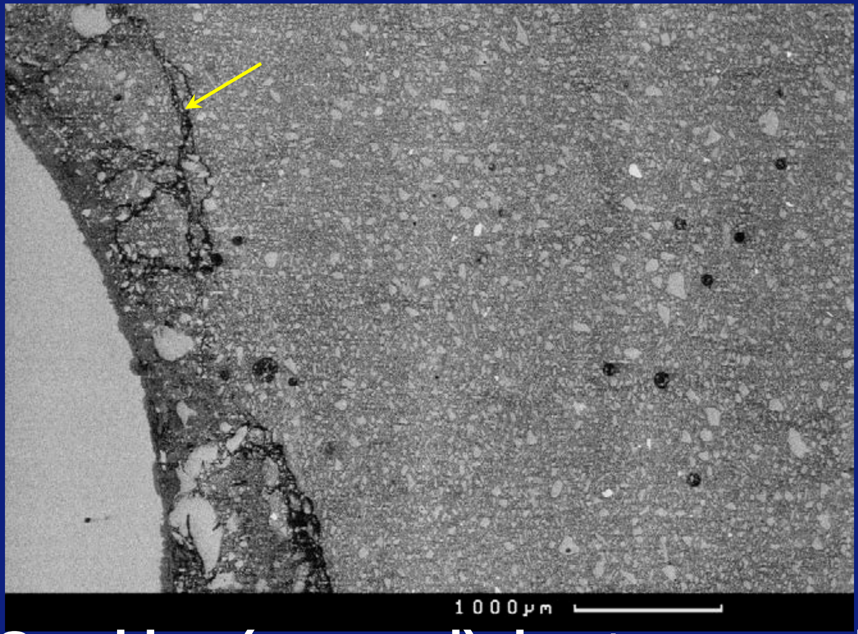
Advanced Wasteforms: Need for Toolbox of Cements for ILW

- Some wastes incompatible with alkali cements.
- E.g. Al and Mg is present in UK Magnox fuel clad.
- pH of internal pore solution of OPC composites typically above 12.

$$Al + OH^- + H_2O \rightarrow [Al(OH)_3]^- + H_2$$
$$Mg + H_2O \rightarrow Mg(OH)_2 + H_2$$



Al in 9:1 BFS:OPC w/s = 0.33
90 days 20^{o}C



Cracking (arrowed) due to expansile formation of $Al(OH)_3$.

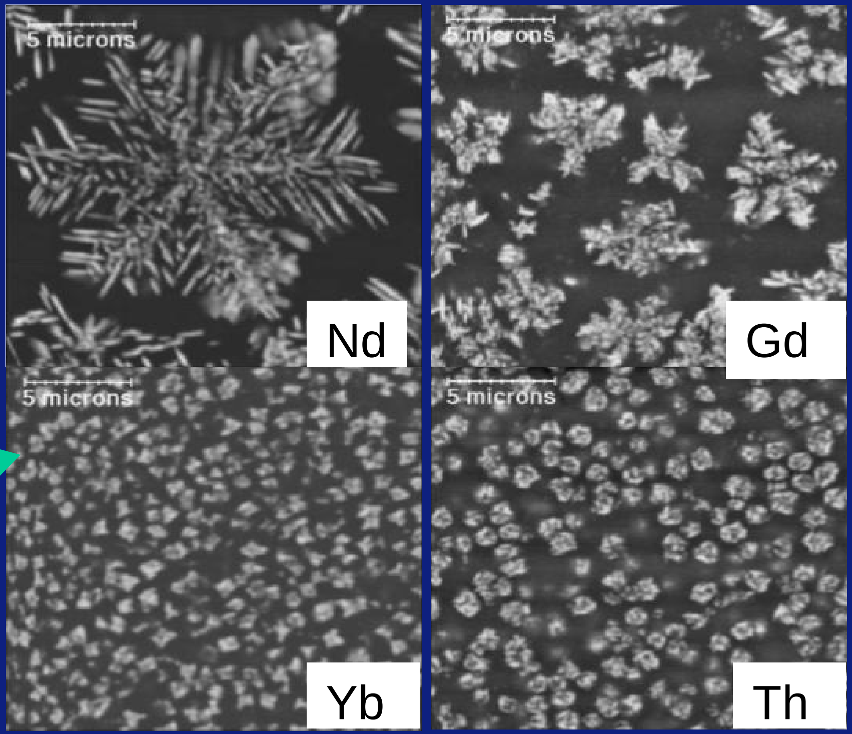
Calcium Sulphoaluminate (CSA) Cements

- Used extensively in China for 30 years.
- Clinker contains $4CaO.3Al_2O_3.SO_3$
- Activated with $CaSO_4$ to give ettringite, $3CaO.Al_2O_3.3CaSO_4.32H_2O$, as main binder along with $Al_2O_3.nH_2O$.

- Aluminium metal in a CSA cement (left) and a BFS/OPC cement (right) after 135 days cure at 20^{o}C.
- Visual observation indicates Al corrosion significantly reduced in CSA.
- Other systems under development including e.g. geopolymers.

Advanced Wasteforms: Glass Composite Materials (GCMs)

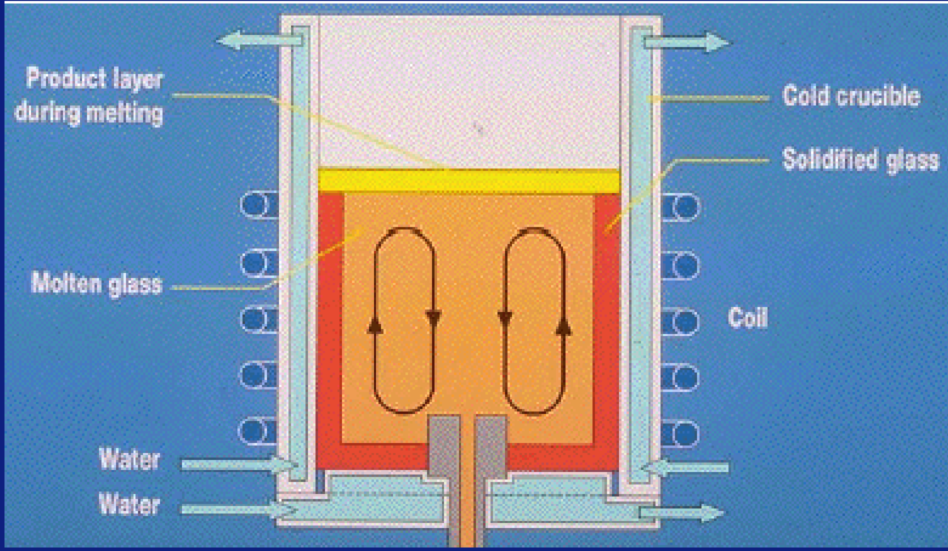
1. **Glassy wasteforms in which crystals form on processing in CCM.**
2. **Glass ceramics, glass crystallised on cooling or in separate heat treatment step e.g. zirconolite-based for separated long-lived actinides.**

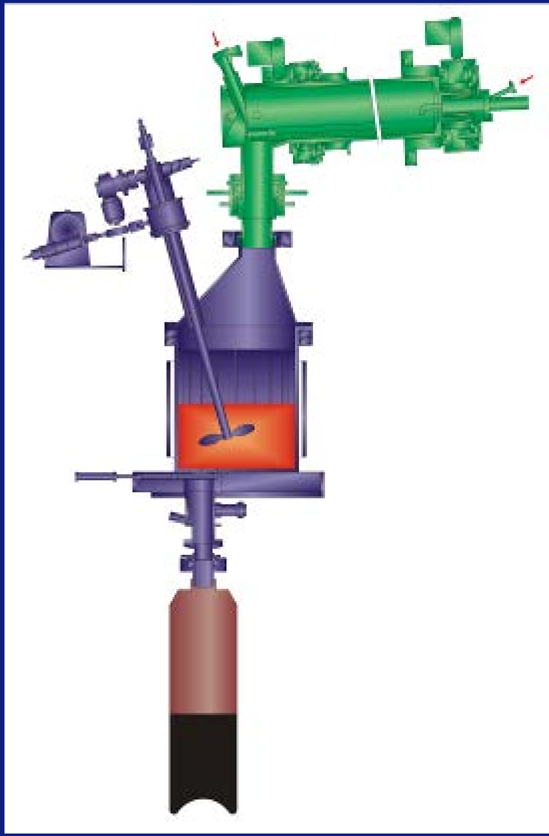


D Caurant *et al.* Glasses, Glass-Ceramics and Ceramics for Immobilization of Highly Radioactive Nuclear Wastes (Nova Science, 2009)

Cold Crucible Melter

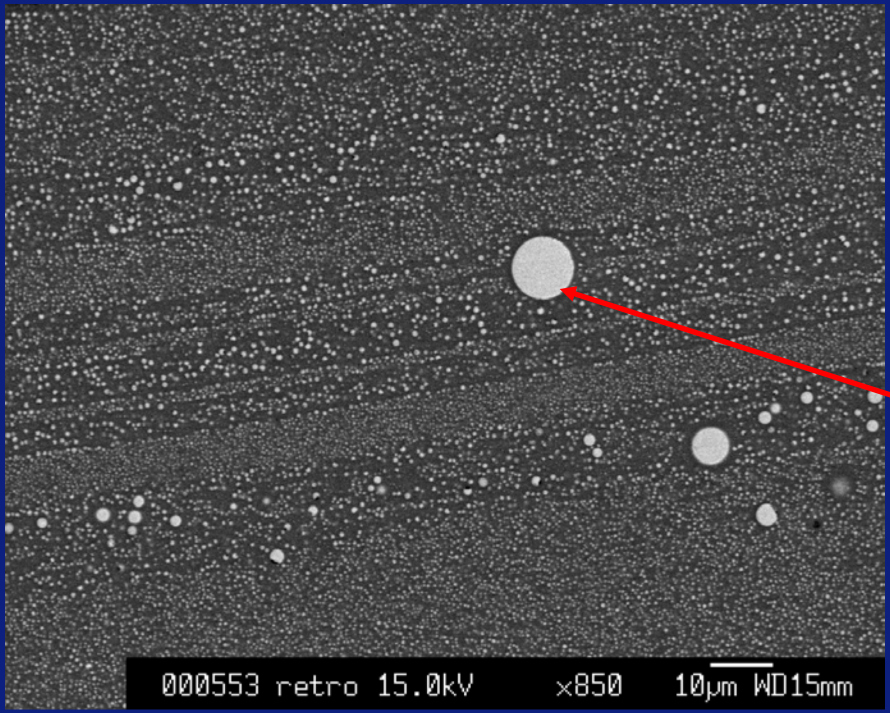
- CCM's: no refractory and can go to higher temps than normal melters.
- U/Mo/P-rich waste from French gas cooled reactors.
- High Mo/P melt is corrosive & requires high temperature (1250ºC) glass formulation to incorporate enough Mo (12wt%) so cannot use two stage hot crucible.
- Developed CCM in which waste and CaO-ZrO_2 enriched alumino-borosilicate glass additives melted by direct high frequency induction.
- CCM installed at La Hague, France early 2010 in existing vitrification hot cell.





Two-step CCM process

U/Mo Wasteform Microstructure



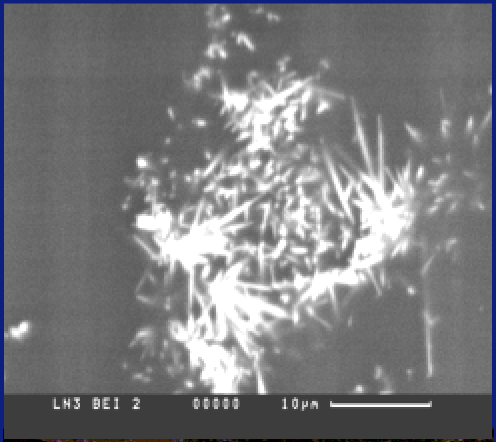
microspheres enriched in Mo, P, Ca.

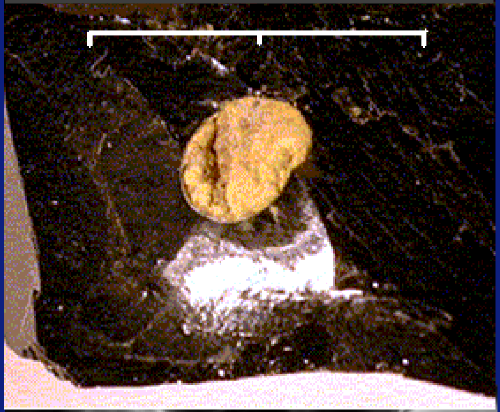
- Liquid-liquid phase separation leads to crystallisation of water soluble molybdate microspheres isolated in R7T7 type glass matrix.

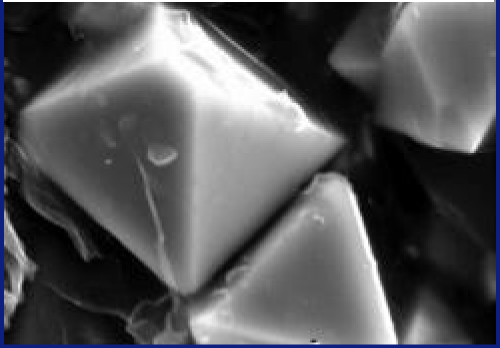
Courtesy T. Advocat, CEA Marcoule, France.

Trend to High Crystallinity.

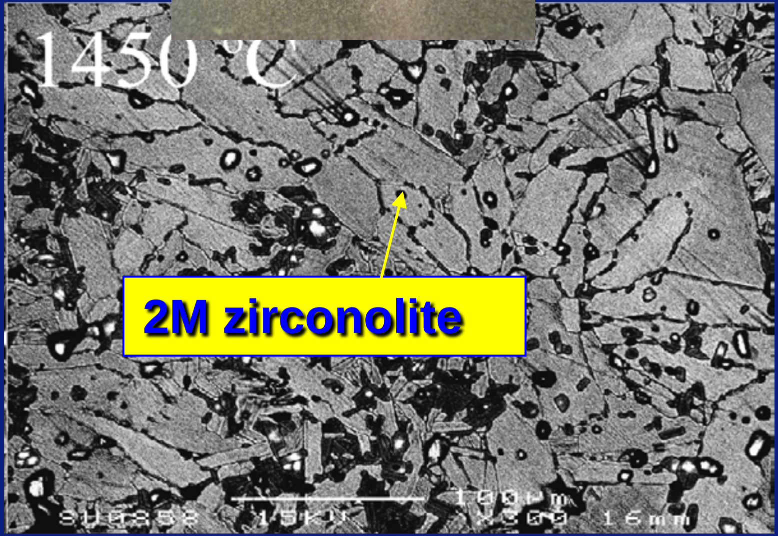
- Crystals in glass used to be unacceptable but now realised presence of crystals may not compromise durability.
- GCM’s now accepted as potential wasteforms.
- Crystal-tolerant glasses (with higher waste loading) being developed.







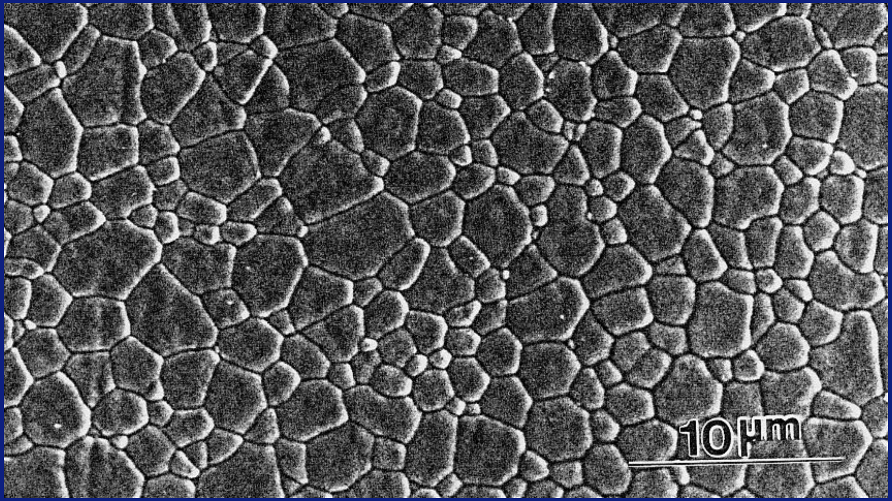
Plutonium.

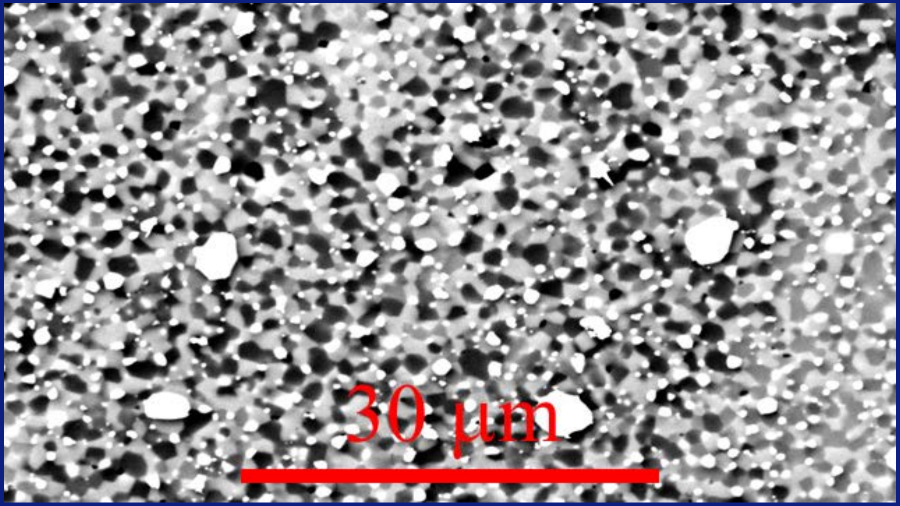


- Many hundreds of tonnes of Pu worldwide mostly oxide powder.
- Sensible to recycle by mixing with UO_2 to make Mixed Oxide (MOX) fuel which can be burned in PWR reactors.
- Some Pu is contaminated (Cl from PVC) and unsuitable for use in MOX and must be immobilised.
- Limited solubility of Pu in borosilicate glasses so ceramic wasteforms (e.g. Synroc, zirconolites, pyrochlores) being developed.

Advanced Wasteforms: Ceramics for Pu.

- **Desire durable, high-density, solid solution ceramics made by firing pressed powders and powdered waste.**



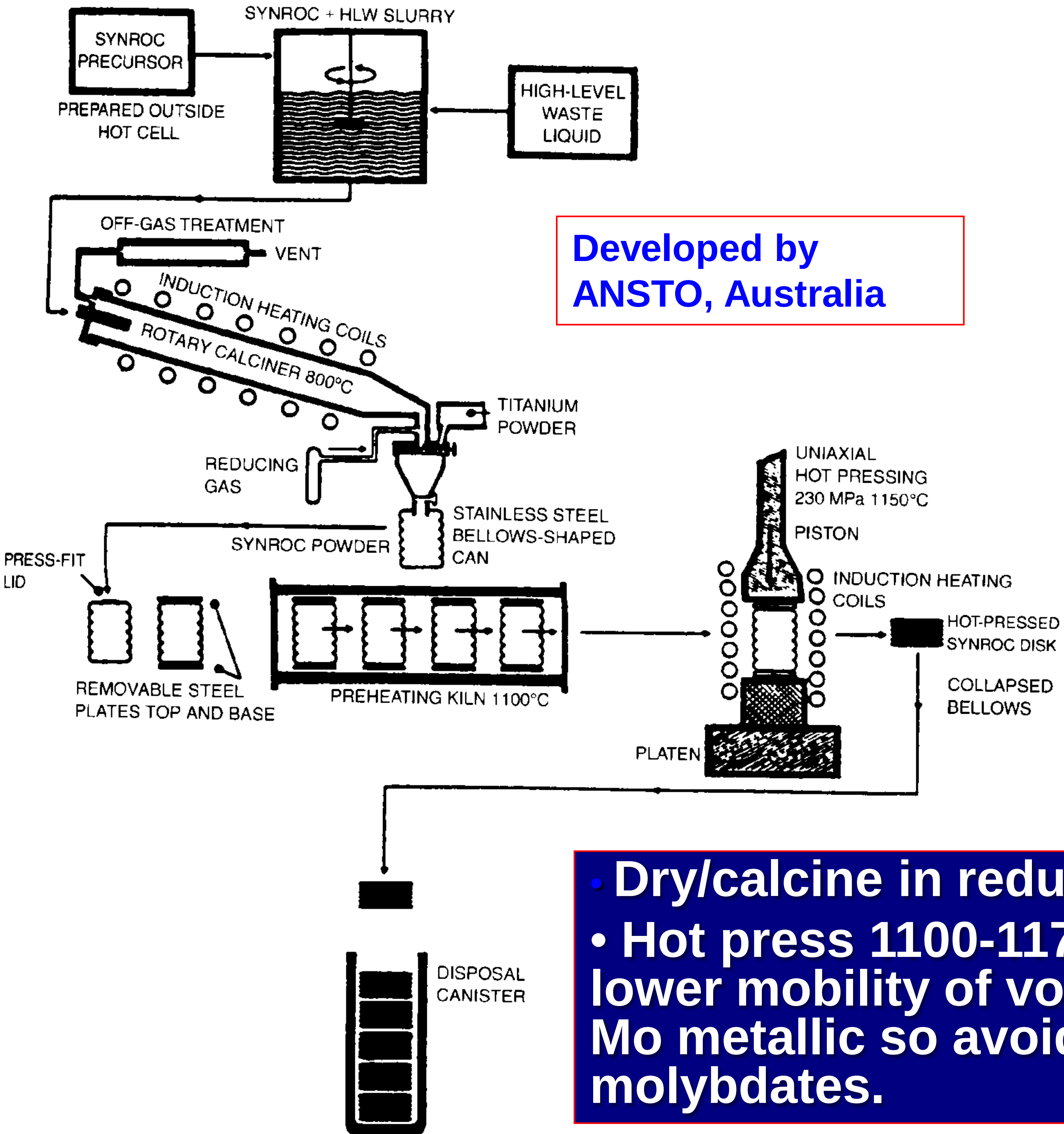


Single-phase **zirconia (Zr,Gd,An)O_2 zirconolite or pyrochlore.**

Actinides: An = (U, Pu, Np, Am and Cm)

Multi-phase **ceramics such as hot pressed titanate/zirconates like Synroc better for immobilising multi-valent actinides.**

Synroc Process.

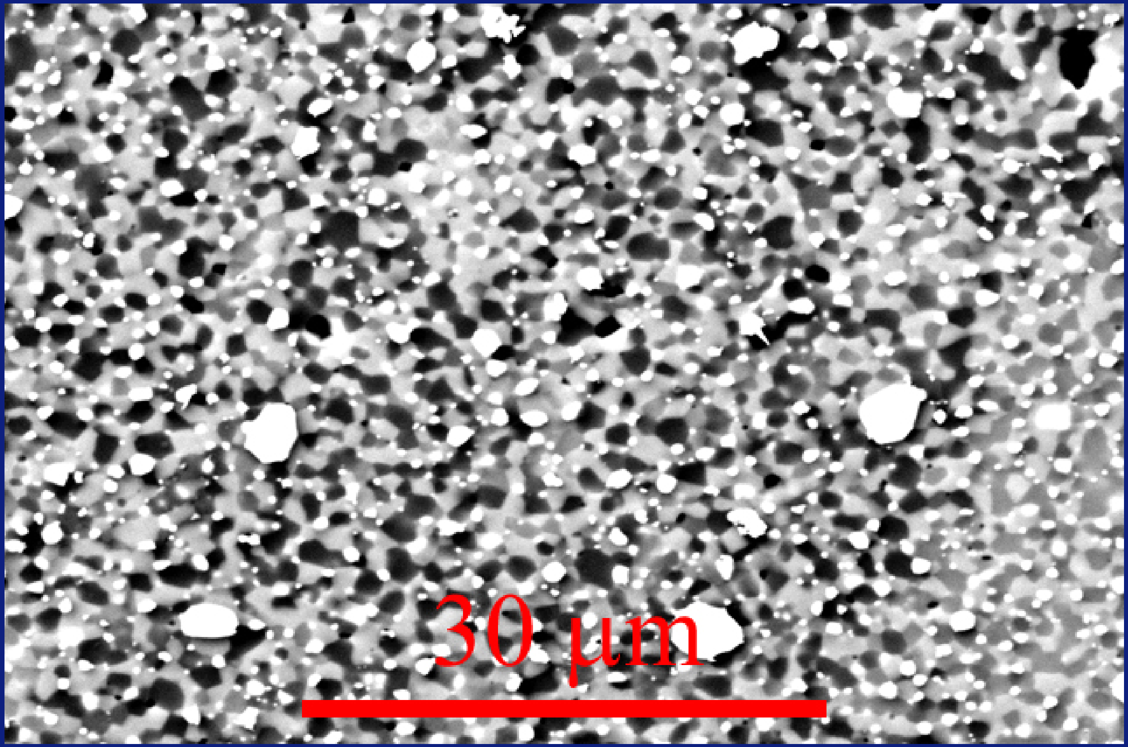


Developed by ANSTO, Australia

- **Relatively simple chemical route involving Ti and Zr alkoxide hydrolysis in presence of NaOH**

- **Dry/calcine in reducing conditions.**
- **Hot press 1100-1170ºC + 2 wt% Ti to lower mobility of volatiles and keep Mo metallic so avoid water soluble molybdates.**

Multiphase Ceramics.



- Typically consist of fine grains of up to 6 phase types: fluorite derivatives (zirconolite, $CaZrTi_2O_7$), perovskites ($CaTiO_3$), rutile (TiO_2), hollandites ($BaAl_2Ti_6O_{16}$), magnetoplumbite($Sr_{0.6}Fe_2O_3$), β-alumina types and alloys.

Synroc Formulations.

- Different radionuclides in each phase e.g. Pu in zirconolite, Cs in hollandite.
- Various formulations designed to accommodate wastes containing many different radionuclides via different proportions of these phases.
- E.g. Synroc C with 20% waste is 30% zirconolite, 30% hollandite, 20% perovskite, 10% rutile, <5% magnetoplumbite and <5% alloy.

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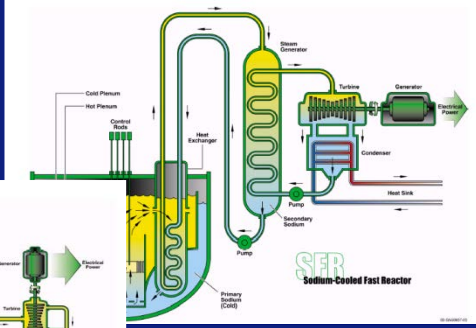
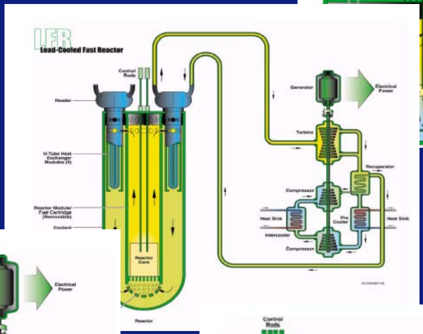
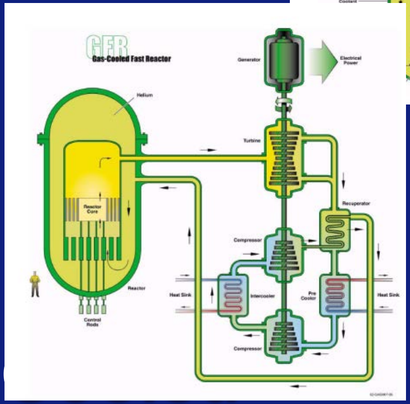
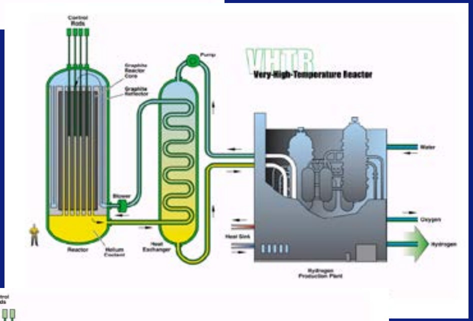
Generation IV Reactors.

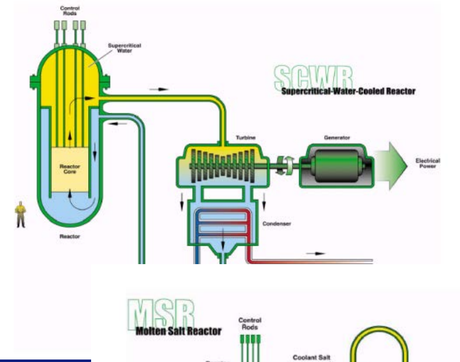
- Projected for use in 30 years.
- Large international programme.
- 6 reactor types:
  - Sodium Cooled Fast
  - Lead Alloy Cooled
  - Gas Cooled Fast
  - Very High Temp. Gas
  - Supercritical Water
  - Molten Salt.

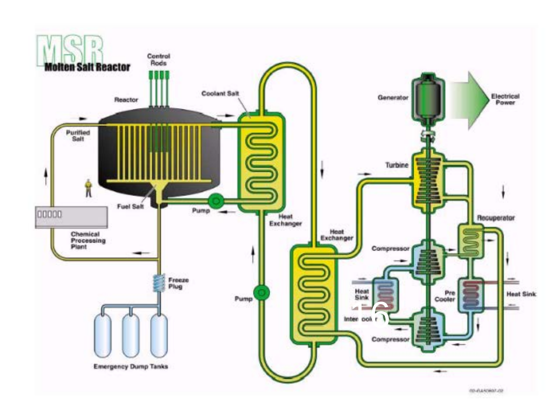








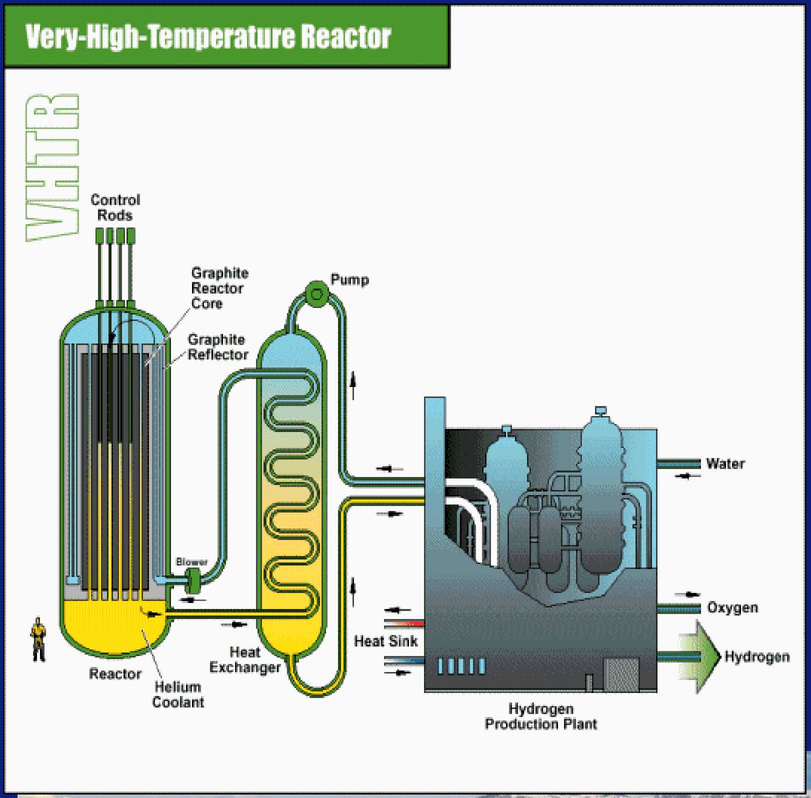


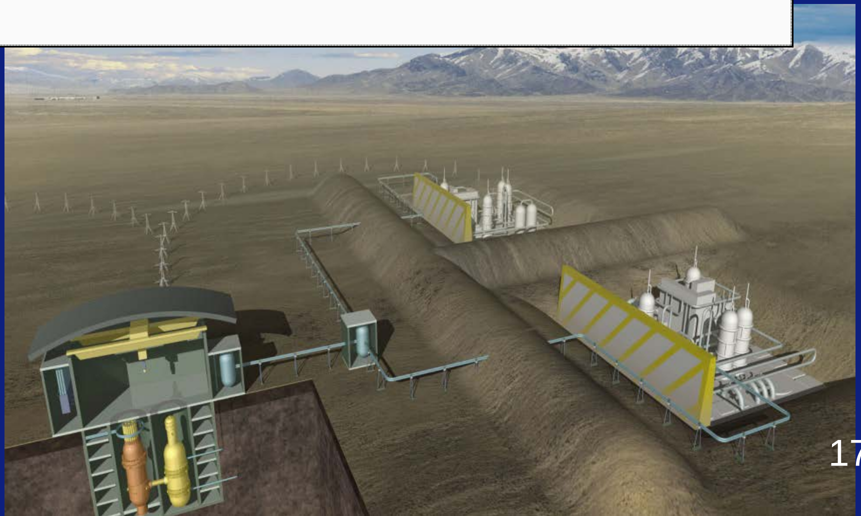


- Much ceramics R&D needed for all of these.

Very High Temperature Reactor

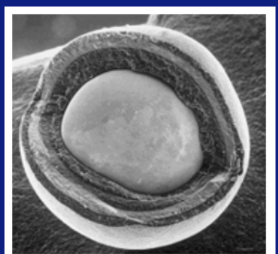
- Gas-cooled reactor capable of producing electricity and/or H_2.
  - Passively Safe
  - Designed with graphitic structural components e.g. C/C and SiC/SiC control rods.
- Current R&D Focus:
  - High temperature fuels and materials irradiation performance
  - Design and safety methods development and validation
  - Advanced energy conversion and high-temperature H_2 production



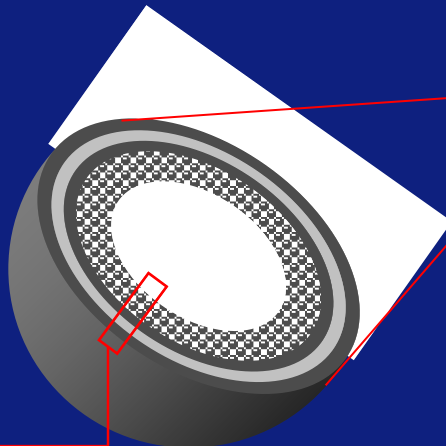


ZrC in Advanced Nuclear Fuels

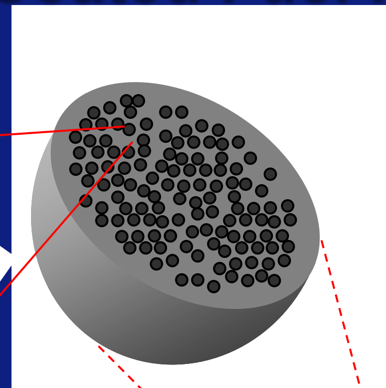
Tri-Structural Isotropic Coated Fuel Particle



0.9 mm

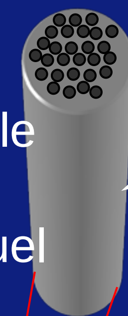


700 – 900 μm



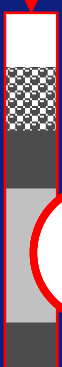
60 mm

Pebble
or
rod fuel



12 – 25 mm

Composite fuel retains fission products for all foreseeable conditions

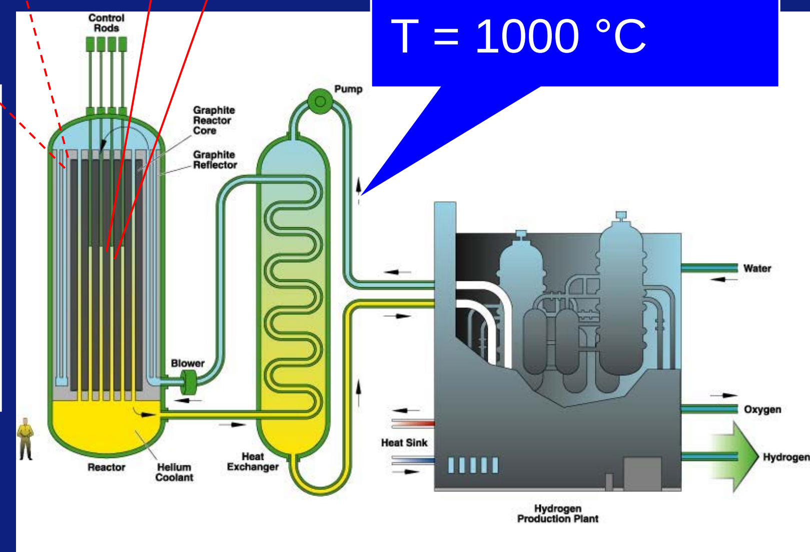


- Fuel Kernel e.g. UO_2 (300 – 500 μm)
- Porous Carbon Buffer (~100 μm)
- Inner Pyrocarbon (35 – 40 μm)
- Silicon Carbide (35 – 40 μm)
  - Dense barrier to fission product diffusion
  - Pressure vessel containing fission
- Outer Pyrocarbon (40 μm)

ZrC of interest: excellent high-temperature performance

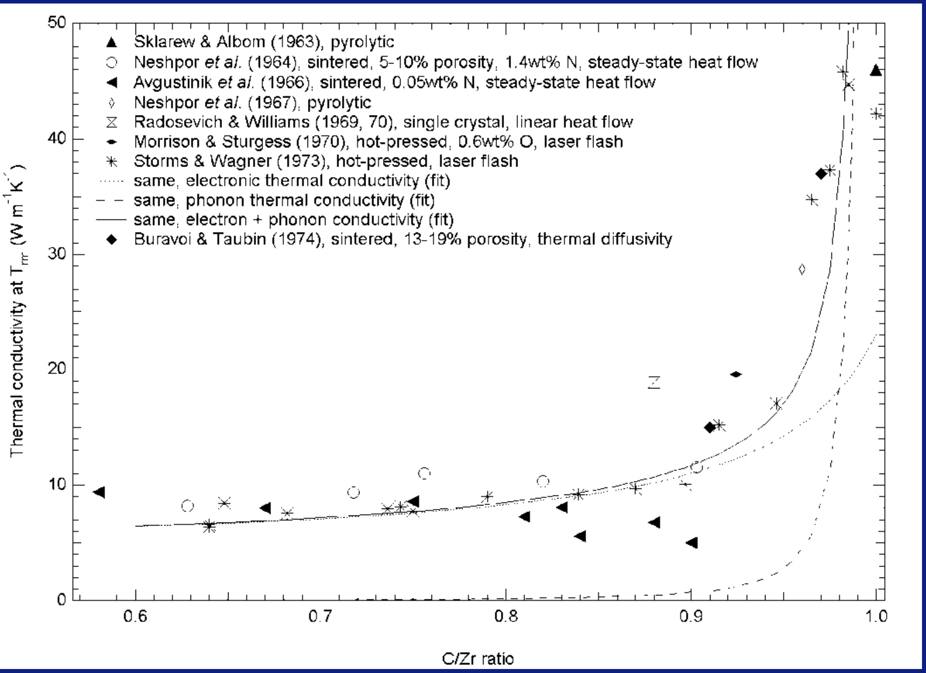
Fuel T > 1250°C;

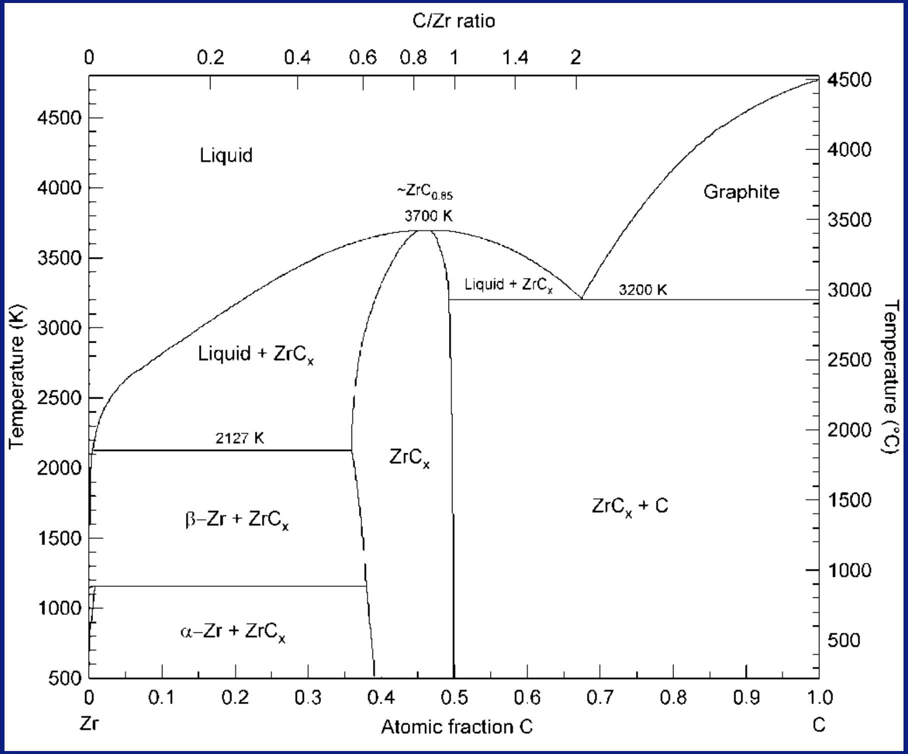
Coolant outlet T = 1000 °C



Very High Temperature Gas-Cooled Reactor

ZrC_{1-x} Non-Stoichiometry

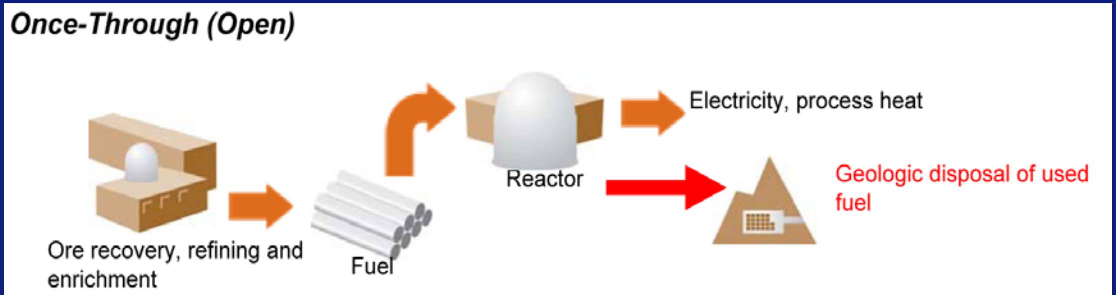




- Steep drop off in thermal conductivity with off-stoichiometry
- Care with ceramic processing to maintain C/Zr ~1.

Jackson and Lee, ZrC, chapter 23 in Comprehensive Nuclear Materials, edited by R Konings (Elsevier 2011).

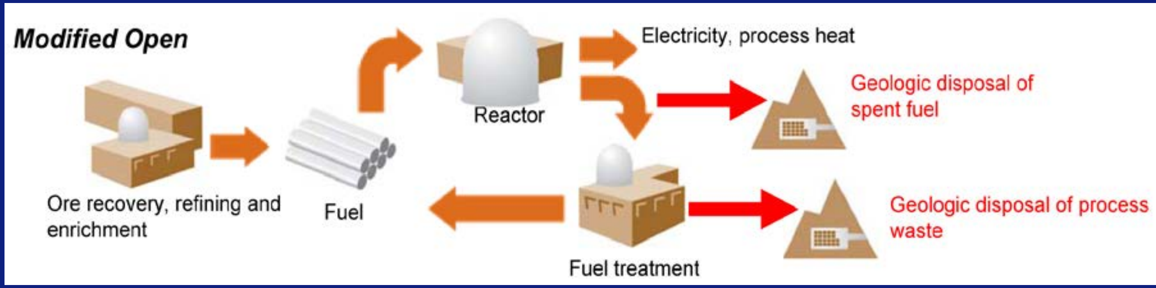
Alternative Nuclear Fuel Cycles



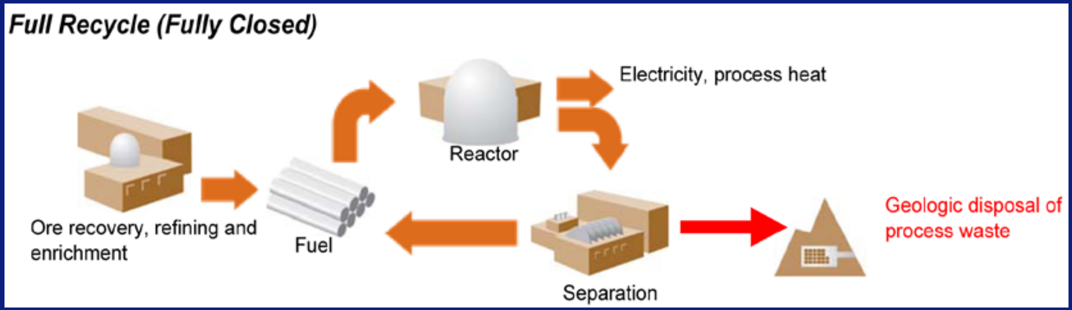
A schematic of an open fuel cycle, as currently used in the US.

Fuel is used only once in a reactor and then discarded.

Part separation of actinides and fuel reprocessing. Waste contains actinides and fission products.



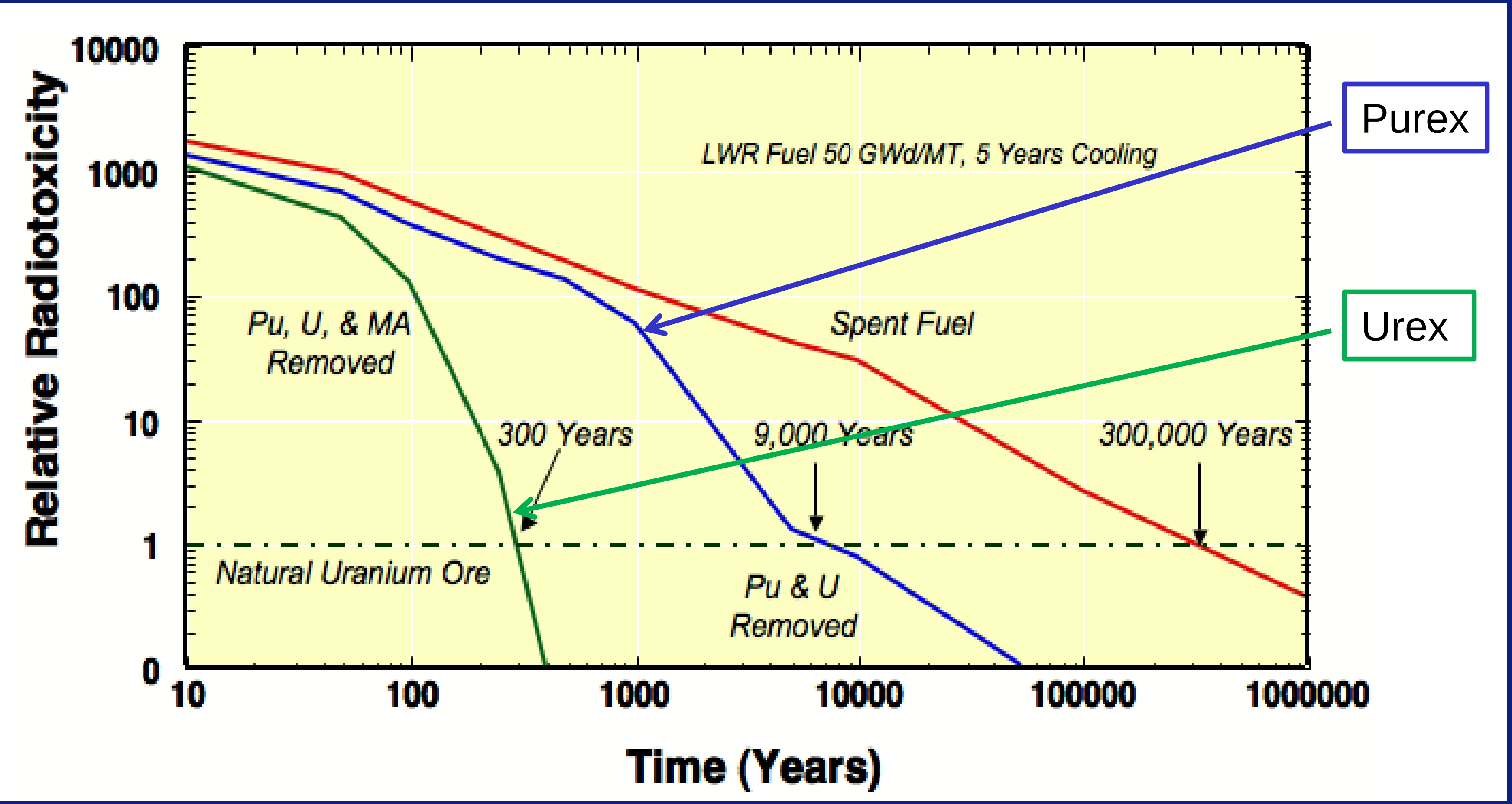
A schematic of a modified-open fuel cycle, as envisioned by the U.S. Dept. of Energy.



A schematic of a full recycle closed fuel cycle, as envisioned by the U.S. Dept. of Energy.

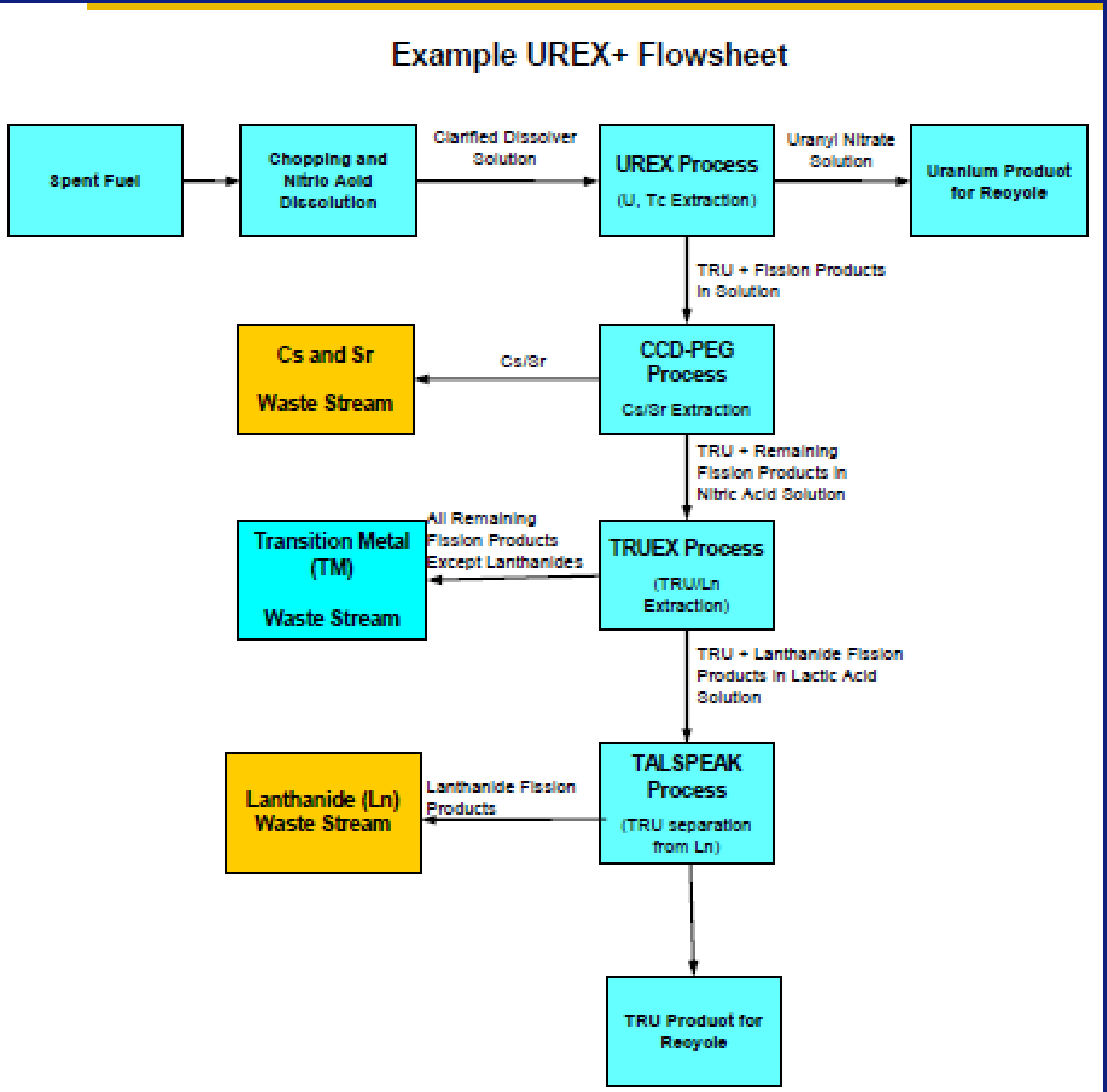
All actinides are separated from the used fuel and burnt in appropriate reactors. Waste contains only fission products.

Disposal Consequence of Fuel Cycle Choice



- Without reprocessing (Once Through) time to ore activity is 300,000 yrs.
- If Pu and U are removed from the waste this time is reduced to ~9,000 yrs (Modified Open).
- Removing Pu, U and Minor Actinides (MA) leaves waste that is no more hazardous than un-mined uranium after about 300 yrs (Full Recycle).

Advanced Fuel Cycle: Separating Waste Streams.



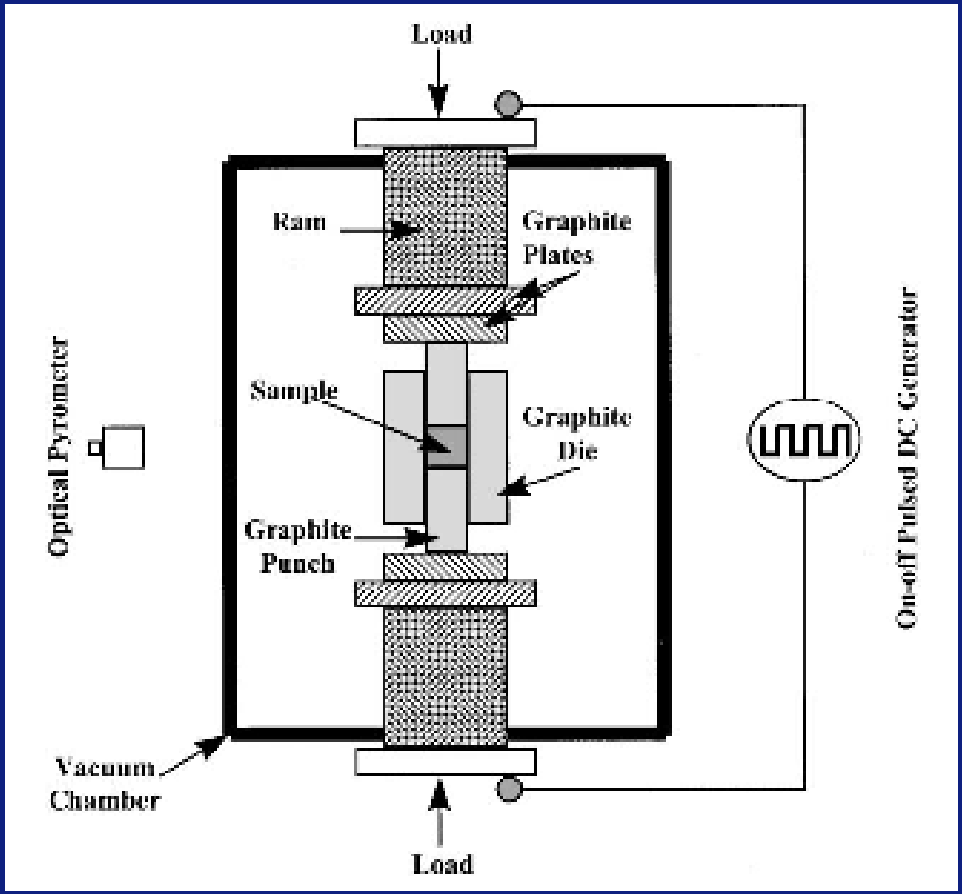
- Multiphase Synroc-type ceramic wasteforms being developed to host e.g. separated Cs/Sr (short lived and hot) and Ln wastestreams.

Advanced Fuel Cycles: Ceramic Wasteforms

- DoE Office of Nuclear Energy's fuel cycle programme (SRNL and LANL).
- Evaluating wasteforms for combined previously separated waste streams e.g. Cs/Sr, Lanthanide and Transition Metal FP streams.
- Process wasteforms by:
  - Melting and crystallising (CCM), 1h at 1500^{o}C
  - Cold press and sinter, 25h at 1200^{o}C
  - Spark Plasma Sintering.
- Formulations: CsSr/LN Waste, Al_2O_3 and TiO_2.
- Target phases: $(Ba,Cs,Rb)Al_2Ti_5O_{14}$ "hollandite", $LnAlO_3$ "Ln-Al perovskite" and $SrTiO_3$ "Sr perovskite".

A Billings, K Brinkman, K Fox, J Marra, M Tang and K Sickafus, "Development of Ceramic Waste Forms for an Advanced Nuclear Fuel Cycle," Presentation at MS&T Conf., Houston, Texas USA Oct 2010 .

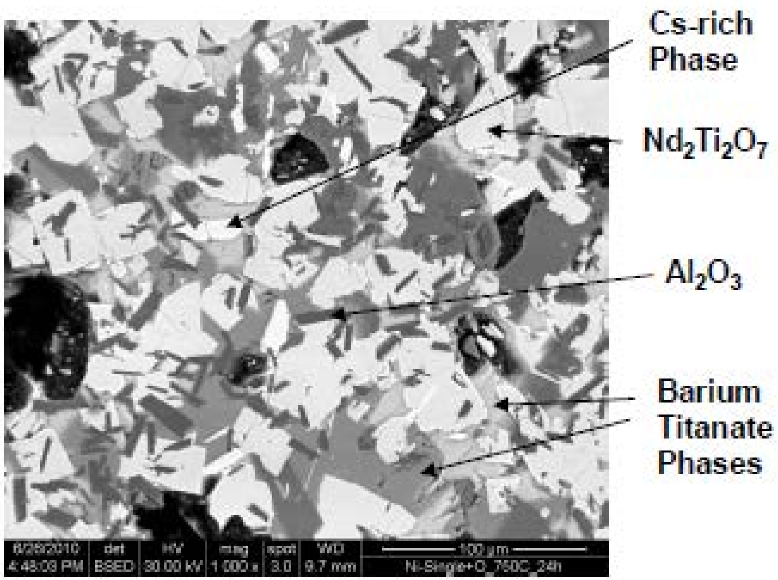
Spark Plasma Sintering

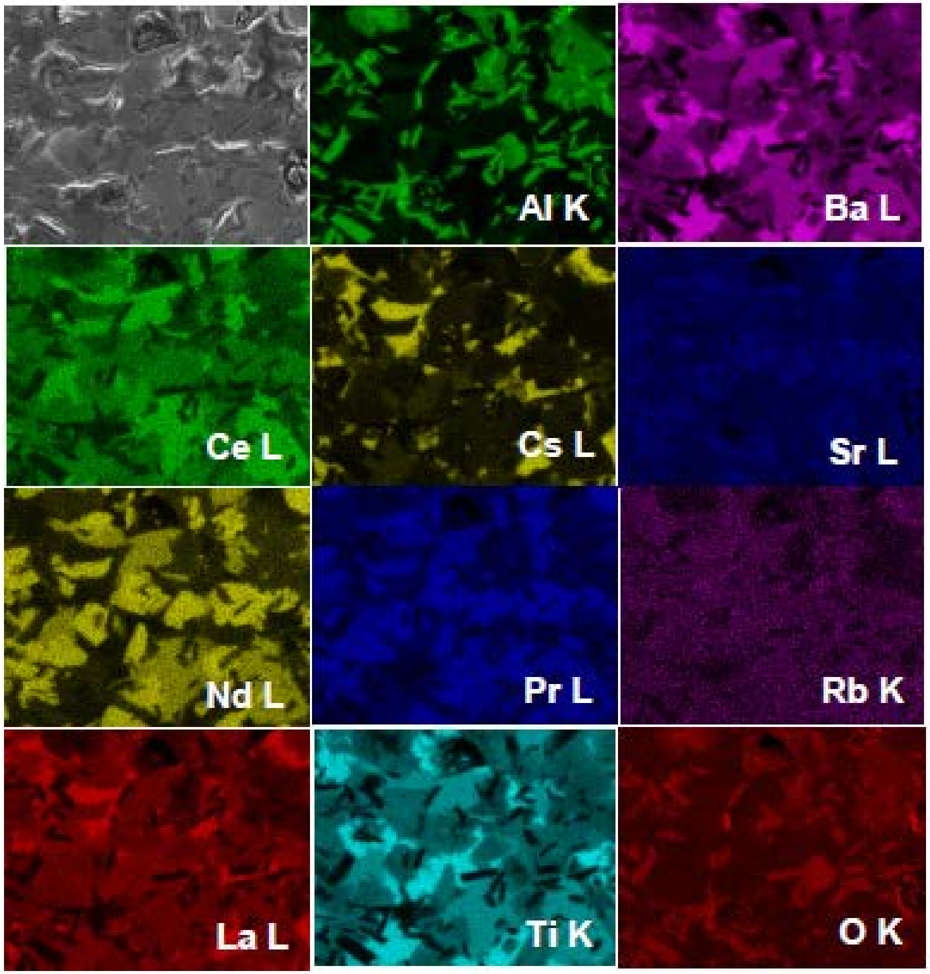


Courtesy Prof Mike Reece, Nanoforce Ltd, Queen Mary London

SEM/EDS of Mixed Cs/Sr+LN Melt & Crystallised Wasteform.

- Unreacted Al_2O_3 evident
- Cs appeared to partition into distinct phase (Cs,Ti,Al,O)
- Identifiable "barium titanate" and "pyrochlore" phases





- Compositions identified that could be made using achievable processing temperatures, 50-60wt% waste loadings with simple additives (Al_2O_3 and TiO_2).
- Cold press & sinter generally formed desired hollandite, pyrochlore & perovskite phases.
- Melt & crystallise generally formed hollandite, pyrochlore & other titanates.

Ceramic Fuel Development: Composite Fuels.

- **Range of CERamic-CERamic (CERCER) composite systems examined to:**
  - **Transmute species like I^{129}, Pu & MA**
  - **Control temperature distribution across core in high burnup fuels**
  - **Control changing thermal conductivity of fuel during use.**
- **Proliferation resistant fuels with minor actinide (MA e.g. Np, Cm, Am) additions, keeping MA mingled with Pu reduces its potential for use in weapons. E.g.**
  - **MOX + MA**
  - **(U,Pu)C + MA.**

$Pu_{0.5}Am_{0.5}O_{2-x}$ + 80 vol.% MgO

MOX and MA-MOX, φ~5 mm

Partitioning and Transmutation (P&T).

- Is a suggested option for reducing the inventory of Long Lived Waste.
- Aim to partition (chemically separate) some RN from the other materials in waste and then to transmute them, change one nuclide into another via a nuclear reaction to produce shorter lived or more stable nuclides.
- Transmutation (or burning) achieved by bombardment with neutrons from fission reactors or particle accelerators or in future, from fusion reactors.
- Currently at research stage.

P&T

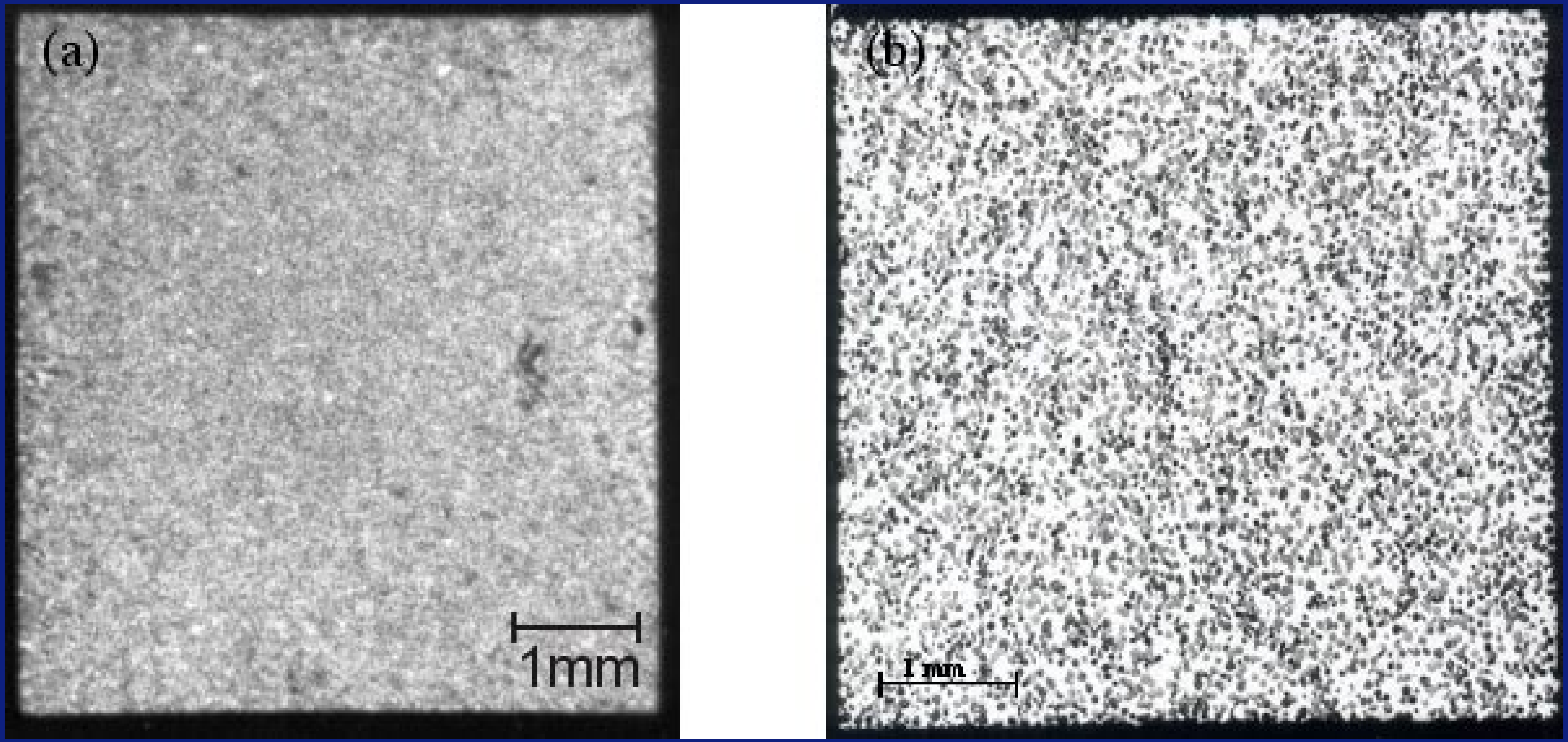
- Has potential to reduce inventory of some long-lived wastes but is not applicable to all.
- Each step of the process would produce secondary wastes that need to be managed; some RN could not be transmuted over a feasible timescale; and worker safety is an issue because of the doses created when handling wastes from potentially higher burn-ups.
- Cannot be applied to existing wastes because RN are either dispersed through too large a volume or are already in vitreous wasteforms from which they cannot easily be accessed.
- May be useful in the long term for future fuel cycles.

Transmutation Fuels and Targets.

- **Ceramic targets containing separated wastes (e.g. MA) bombarded with neutrons in reactor or accelerator to induce transmutation and remove difficult radionuclides.**
- **Similar to IMF's**
  - ***Homogeneous* actinide-containing solid solutions e.g. (Y,Zr,Cm)O_{2-x}, (Am,Y)N made by sol gel routes.**
  - ***Heterogeneous* composites of sol-gel infiltrated actinide-containing particles e.g. (Y,Zr,Cm)O_{2-x} , (Pu,MA,Zr)O_2, (Pu,MA,Zr)N mixed with inert matrix phases e.g. MgO, $MgAl_2O_4$, TiN, ZrN then pressed and sintered.**

(Pu,Zr)O_2 beads

Transmutation Fuels and Targets.



a) Homogeneous $Pu_{0.045}Y_{0.163}Zr_{0.792}O_{2-x}$ and b) Heterogeneous MgO + $Pu_{0.241}Y_{0.128}Zr_{0.631}O_{2-x}$

- **Heterogeneous fuels minimise radiation-induced property changes by localising fission heavy ion damage in isolated regions containing MA.**

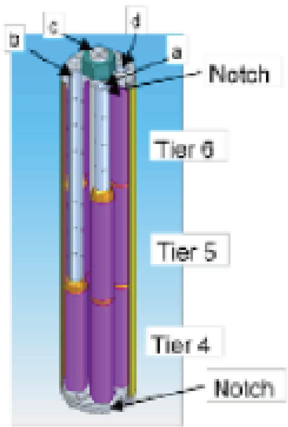
Advanced Fuel Cycles: Nonoxide and Composite Fuel Systems.

- Much research into composite fuel systems utilising e.g. dispersion of fuel particles in inert matrices.
- Advanced non-oxide (carbide, nitride) ceramics are potential fuels for next generation reactors.

- F-BRIDGE EC Project: Basic Research for Innovative Fuel Design for GEN IV systems.
- Examining ternary systems e.g. (U,Pu) oxycarbides, UO_2/UC_2 mixtures

- SiC/SiC is a potential composite fuel cladding material for high burn up PWR & higher temperature (e.g. GFR) fuels.

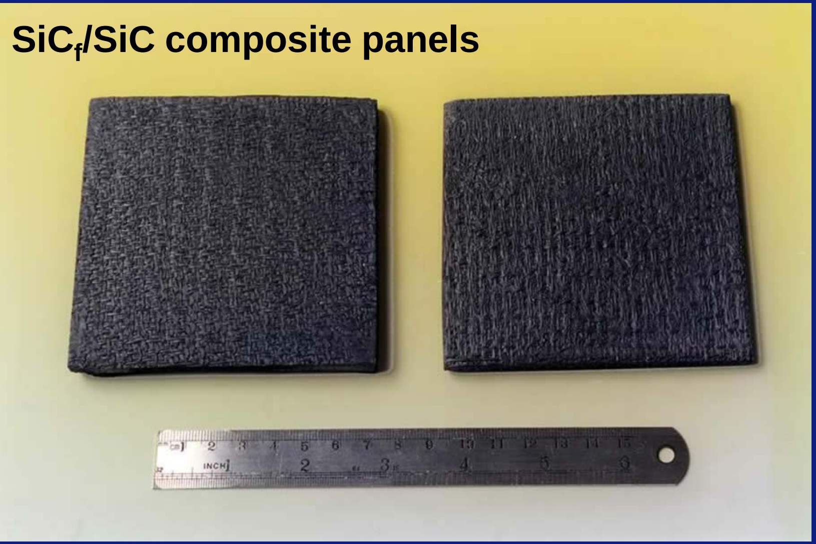
Irradiation Behavior of Triplex SiC/SiC Tubing Under PWR Conditions



Round 7 Tube Capsule

SiC-fibre Reinforced Composites

- Thermal conductivity lower than monolithic SiC.
- Neutron irradiation degrades mechanical properties causing e.g. interface debonding due to crystallisation of partly amorphous SiC fibres.
- Both improved by development of high purity, crystalline, β-SiC fibres (e.g. Hi-Nicalon Type S and Dow Sylramic).
- Triplex SiC/SiC:
  - Inner SiC monolith for fission gas retention.
  - Chemical Vapour Reaction of Si into C preform gives composite able to withstand internal fission gas pressure, retain solid fuel material and prevent its dispersal in any accident.
  - Dense outer monolithic SiC layer for corrosion resistance.



K. Yueh, D. Carpenter, H. Feinroth, Nuclear Engineering International, 2010.

Carbide and Nitride Fuels

- Rock-salt structured (U,Pu)C and (U,Pu)N studied extensively in 1960/70's but interest reinvigorated with Gen IV reactors.
- Suitable for fast reactors as work at high temp.
- High thermal conductivity results in lower temperatures and temperature gradients compared to oxide fuel reducing migration of fuel constituents and fission products.
- Problems:
  - Fabrication requires protective atmospheres as susceptible to oxidation, hydrolysis and pyrophoric in powder form.
  - Need to control stoichiometry.
  - Decreased thermal conductivity due to radiation damage.
  - Need to reprocess using pyrochemical methods such as molten salt electrorefining due to poor dissolution in aqueous systems.

ZrB_2 coated nuclear fuel pellet

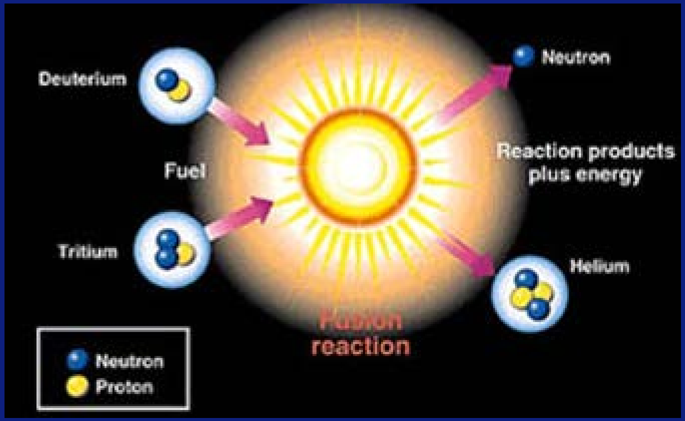
Middleburgh, Grimes *et al*. J Am. Ceram. Soc. In press 2011.

Outline

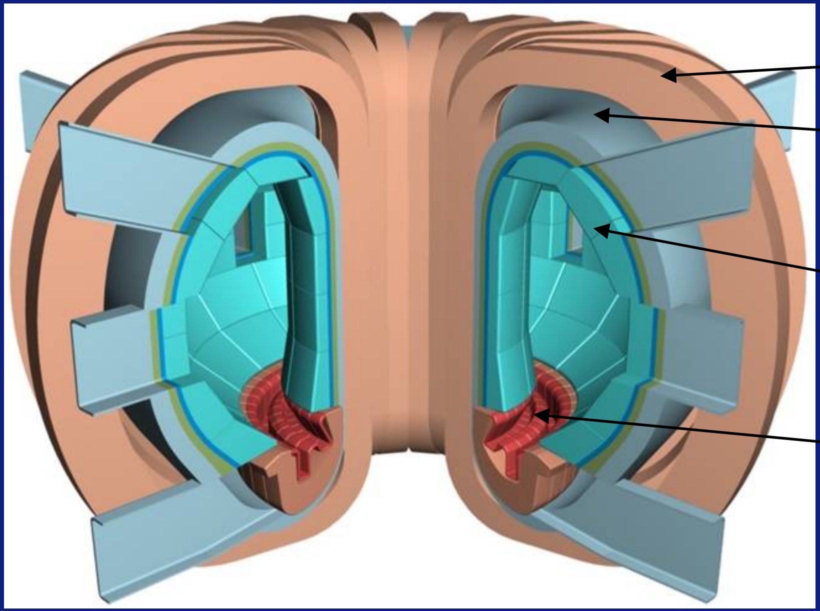
- Future Nuclear Applications of Ceramics: Near Term
  - Inert Matrix Fuels;
  - Advanced cement, glass composite and ceramic wasteforms

- Future Nuclear Applications of Ceramics: Longer Term
  - Advanced fuel cycles
    - Wasteforms
    - Proliferation resistant, transmutation and composite fuels
  - Fusion
    - Tritium breeding
    - Structural.
- Geological Disposal of Radioactive Waste: UK Case Study.

Fusion



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



Magnets

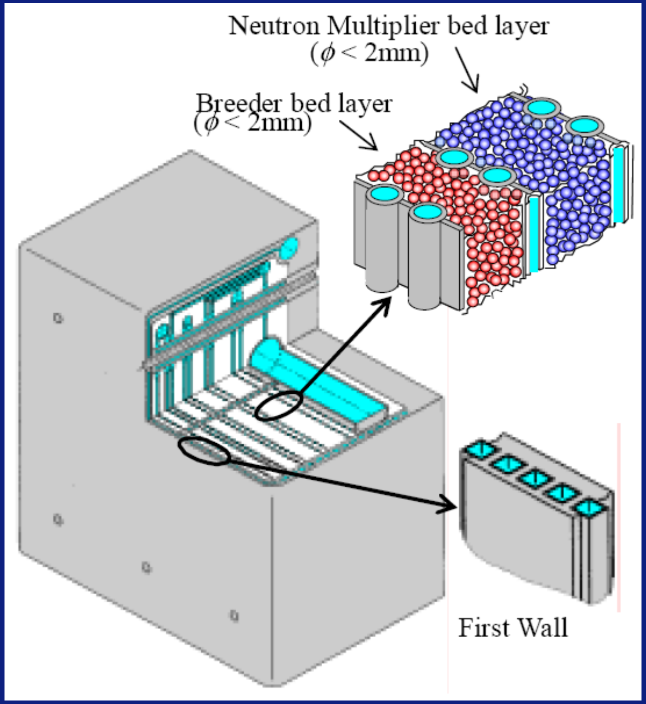
Vacuum vessel

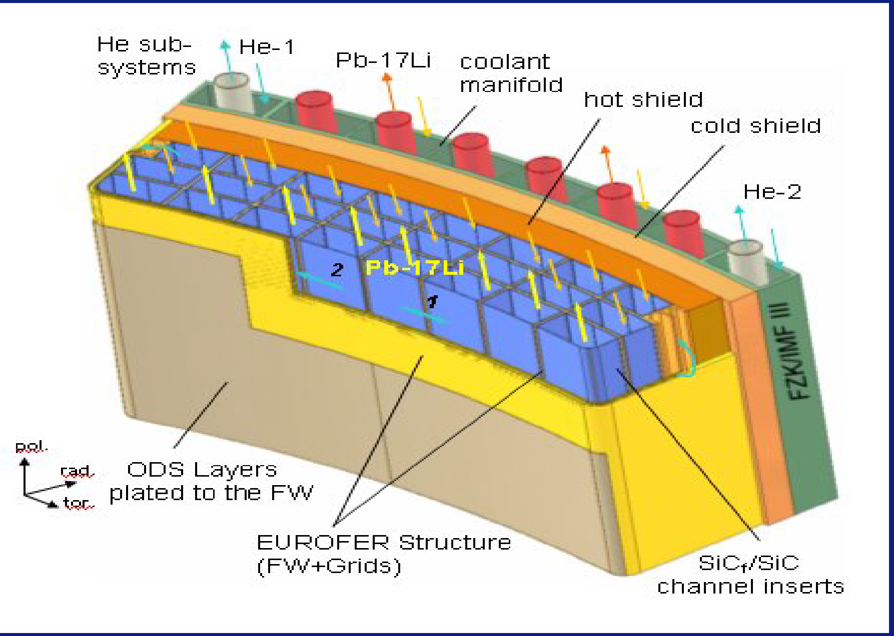
Blanket

Divertor

Fusion First Walls and Blankets

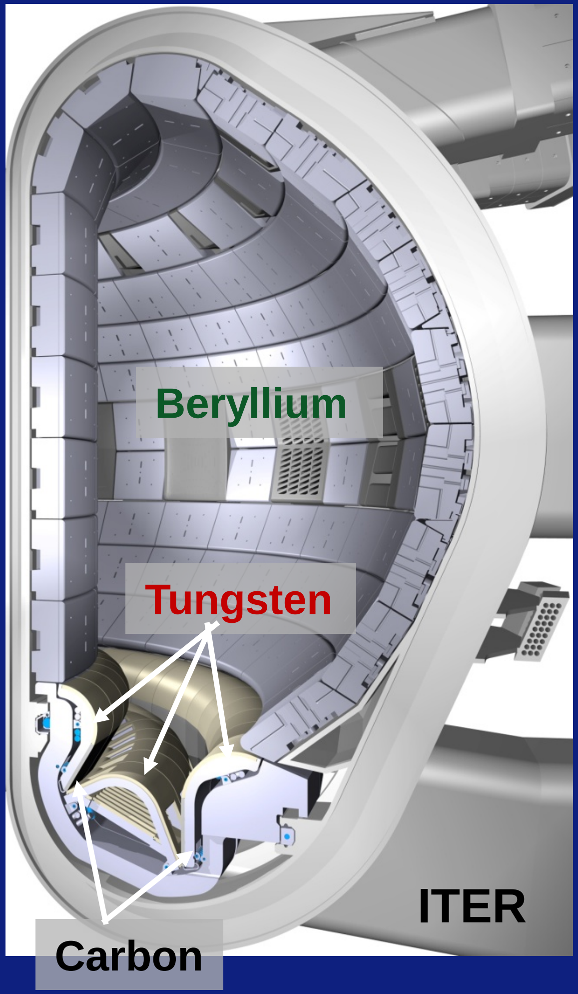
- **Potential uses for ceramics:**
  - **Tritium breeding in Li-containing blankets by transmuting Li to tritium.**
  - **Structural components in first wall and divertor e.g. C_f/C, C_f/SiC, SiC_f/SiC**





Ceramics Needs in Fusion Systems

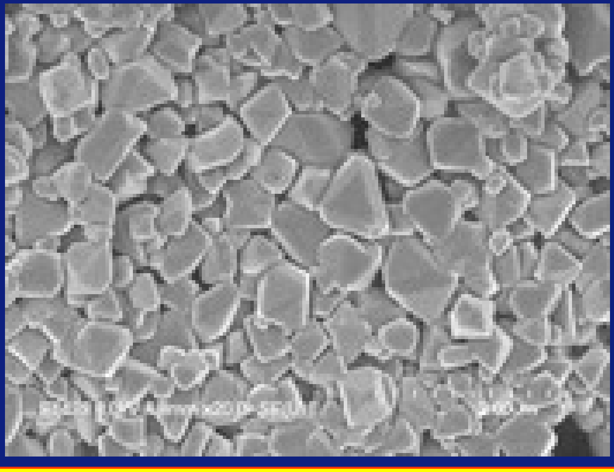
- Resistance to sputtering and chemical erosion from high heat & particle flux to
  - Keep plasma pure
  - Extend component lifetime
- High stability under neutron irradiation, radiation damage & He production.
- Minimal retention of tritium and activation.
- Large scale manufacturability (e.g. Li ceramics, C/C, SiC/SiC).
- Materials joining & compatibility in this environment.



Plasma Diverter System

R&D Issues for Tritium Breeder Blankets

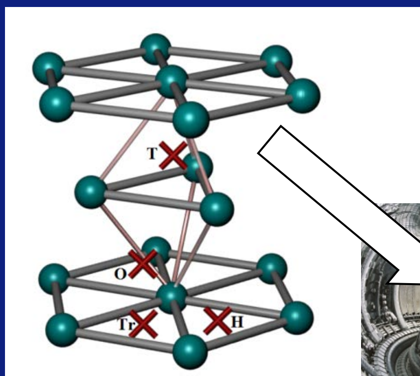
- Lithium ceramics (e.g. Li_2O, Li_2TiO_3, Li_4SiO_4, Li_2ZrO_3, γ-$LiAlO_2$) potential candidates because of general:
  - Ease of tritium recovery
  - Excellent thermal performance
  - Good irradiation behaviour.

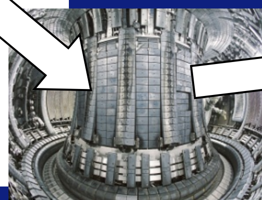


Lithium Titanate, L. Kavan *et al.,* J. Electrochem. Soc., *150*, 2003.

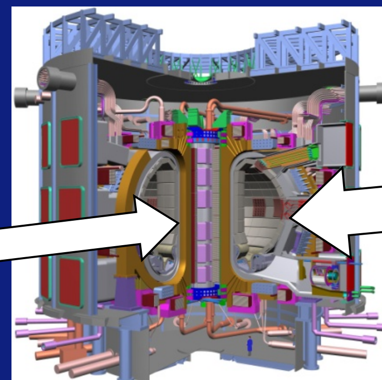
- But none ideal, all have problems e.g.
  - Mechanical integrity, activation, tritium retention.
  - Compositional changes leading to formation of secondary phases and effects on properties, e.g. melting point, tritium diffusivity, thermochemical performance.

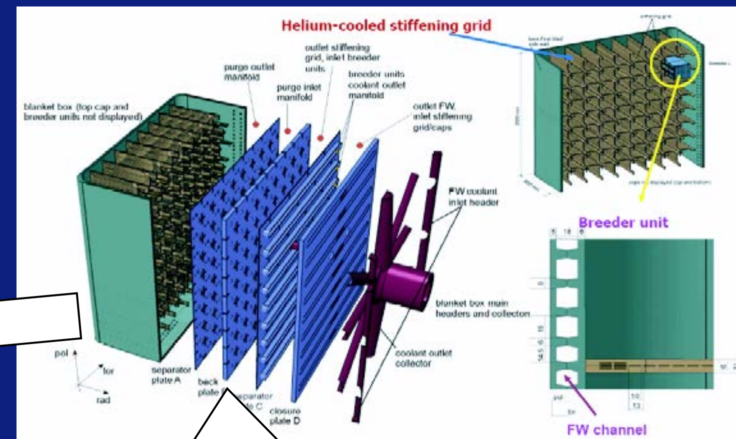
Modelling Opportunities in Fusion



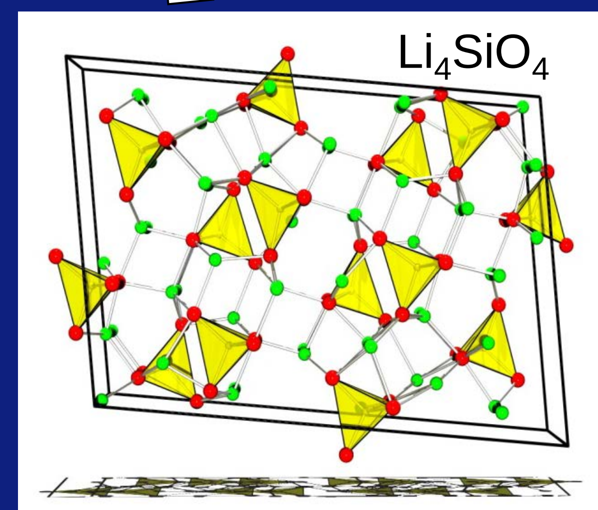


First wall material





Breeder blanket material



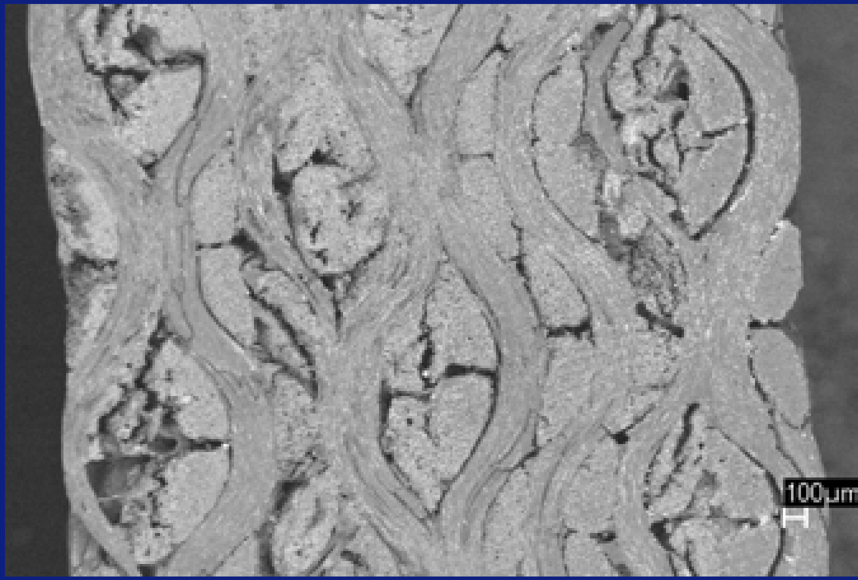
- Many questions about possible ceramic breeder materials such as such as how to recover the tritium from the material, which is controlled by atomic scale defect processes.
- Radiation damage mechanisms and radiation effects on properties must be modelled.
- Use of atomistic computer simulation to identify the defect processes that mediate damage and diffusion and must be understood to inform and interpret experiment.

Fusion: Structural C_f/C, C_f/SiC and SiC_f/SiC Composites

- Candidate material for first wall and blanket structural materials.

- Low activation materials and do not poison plasma.

- Current R&D:
  - Alternative matrix densification techniques e.g.
    - Electrophoretic Deposition and Polymer Infiltration Pyrolysis,
    - Nano-Infiltration and Transient Eutectoid (NITE) phase.
  - Joining to metals e.g. by NITE, SiC to SiC by Ti-Si-C or glass ceramic interphases.
  - Compatibility SiC with Li aluminate breeder ceramics.

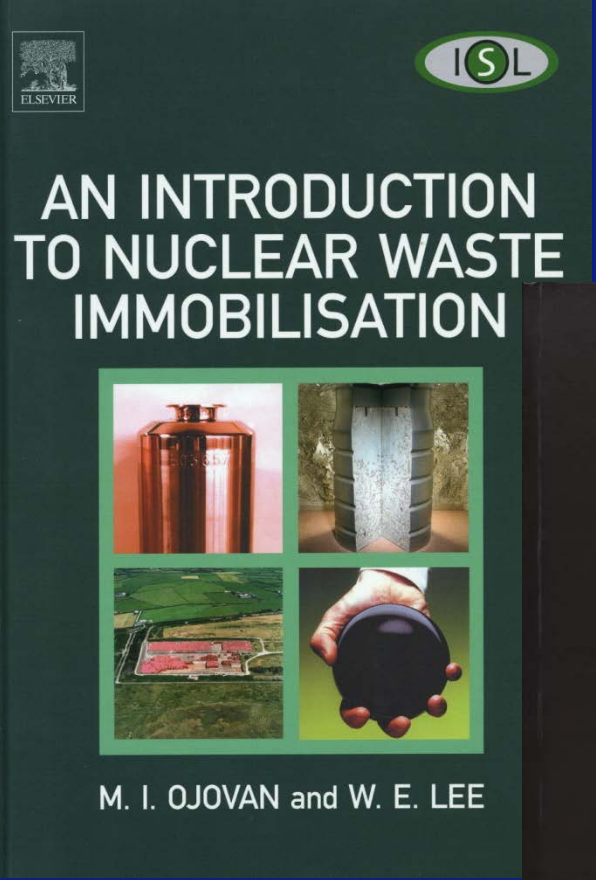


SiC_f/SiC, M. Florian *et al.* 17th CBECIMat, 2006.

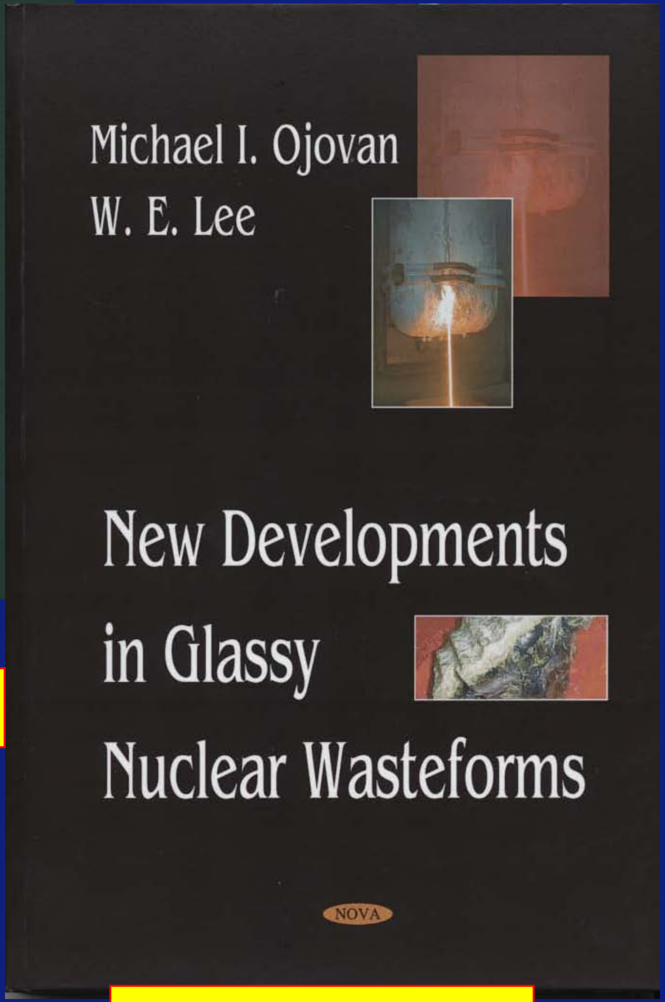
Summary

- Ceramics used throughout nuclear fuel cycles
  - From fuel to waste immobilisation
- Ceramics, cements and glasses crucial materials for ‘closing the fuel cycle’
  - Ceramic- and glass- based wasteforms are durable and can be produced economically
- Next-generation nuclear (fission and fusion) will require new high-performing ceramics.
- Ceramic processing will be crucial. Working with radioactive materials is difficult but:
  - Global sharing of facilities
  - Use of inactive simulants
  - Ion irradiation experiments
- In all cases, ceramic performance is limited by radiation damage and interface controlled processes.
- To understand these need a combined modeling and experimental approach.

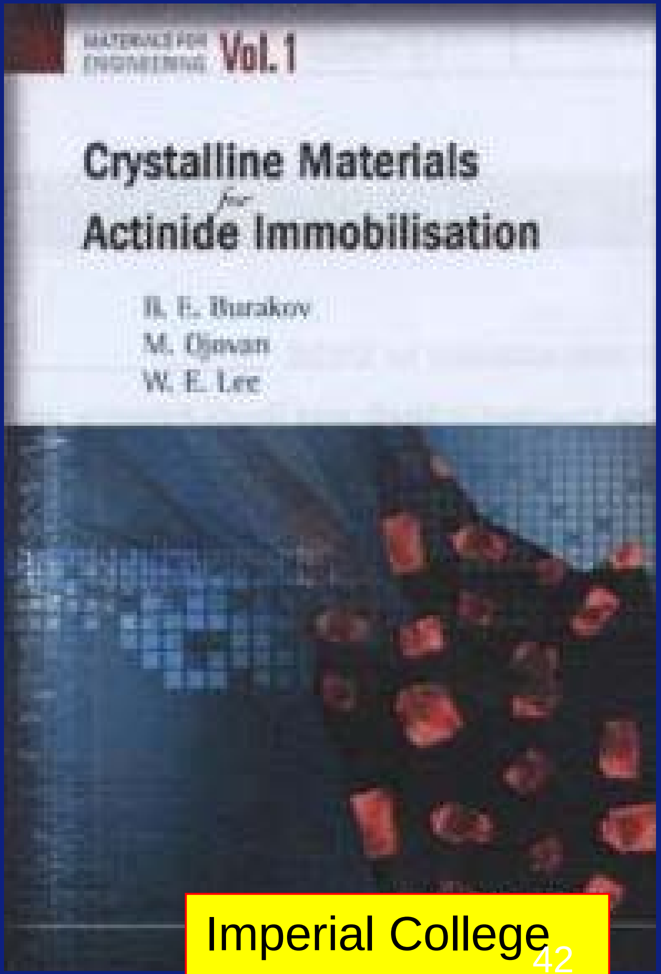
- **For more information see these books!**



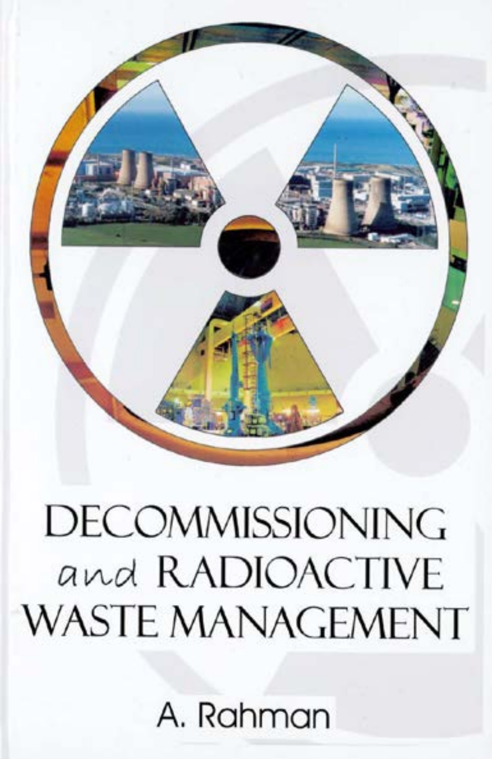
Elsevier 2005

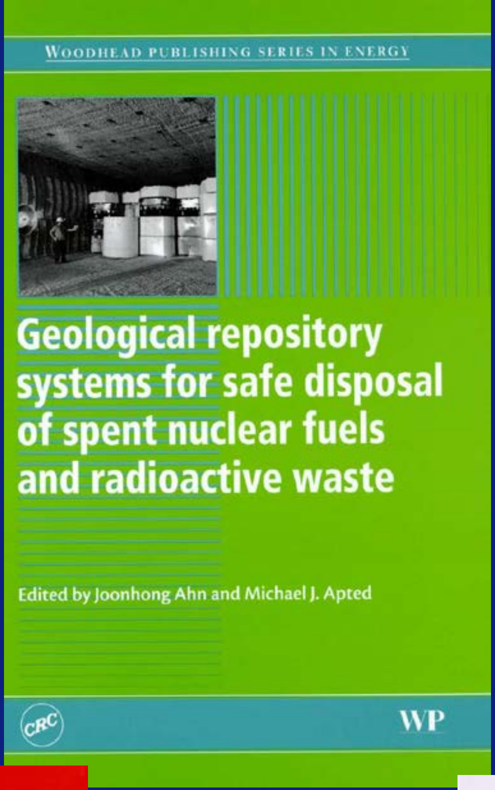


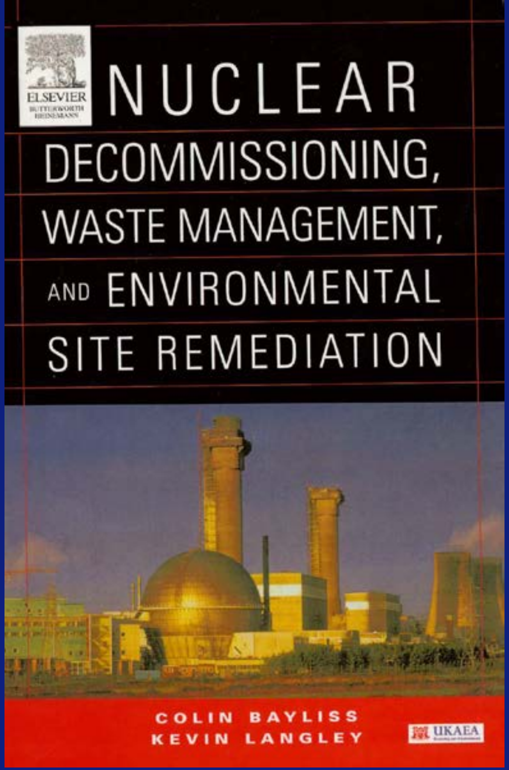
Nova Science Publishers 2007

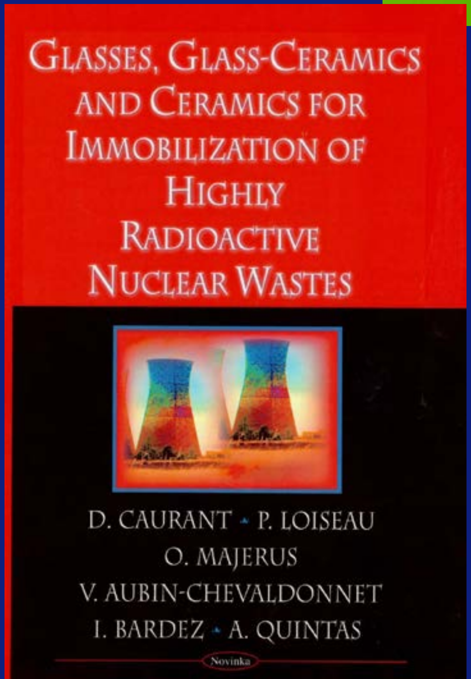


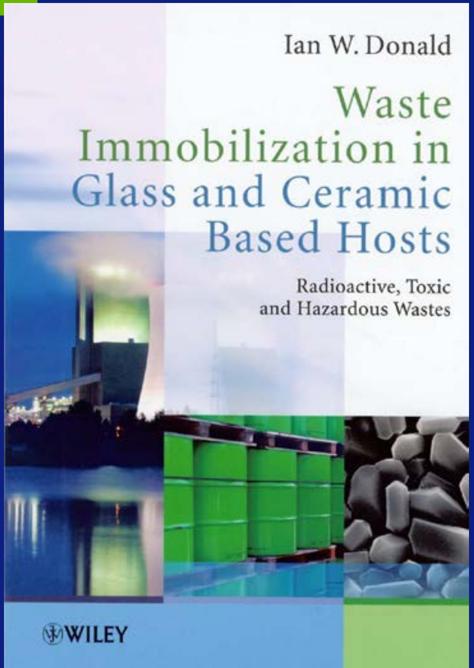
Imperial College Press 2010


DECOMMISSIONING
and RADIOACTIVE
WASTE MANAGEMENT
A. Rahman


WOODHEAD PUBLISHING SERIES IN ENERGY
Geological repository systems for safe disposal of spent nuclear fuels and radioactive waste
Edited by Joonhong Ahn and Michael J. Apted
CRC
WP


ELSEVIER
NUCLEAR
DECOMMISSIONING,
WASTE MANAGEMENT,
AND ENVIRONMENTAL
SITE REMEDIATION
COLIN BAYLISS
KEVIN LANGLEY
UKAEA


GLASSES, GLASS-CERAMICS
AND CERAMICS FOR
IMMOBILIZATION OF
HIGHLY
RADIOACTIVE
NUCLEAR WASTES
D. CAURANT · P. LOISEAU
O. MAJERUS
V. AUBIN-CHEVALDONNET
I. BARDEZ · A. QUINTAS
Novinka


Ian W. Donald
Waste
Immobilization in
Glass and Ceramic
Based Hosts
Radioactive, Toxic
and Hazardous Wastes
WILEY

Outline

- **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.**
- **Geological Disposal of Radioactive Waste: UK Case Study.**

Progress in Geological Disposal of Radioactive Waste: UK Case Study.

- UK's Managing Radioactive Waste Safely (MRWS) programme: background and developments.
- UK progress towards deep geological disposal.
- Selected technical issues:
  - Sellafield Legacy Ponds and Silos (LP&S) wastes.
  - Options for UK's Pu stockpile.

Background to UK Waste Management.

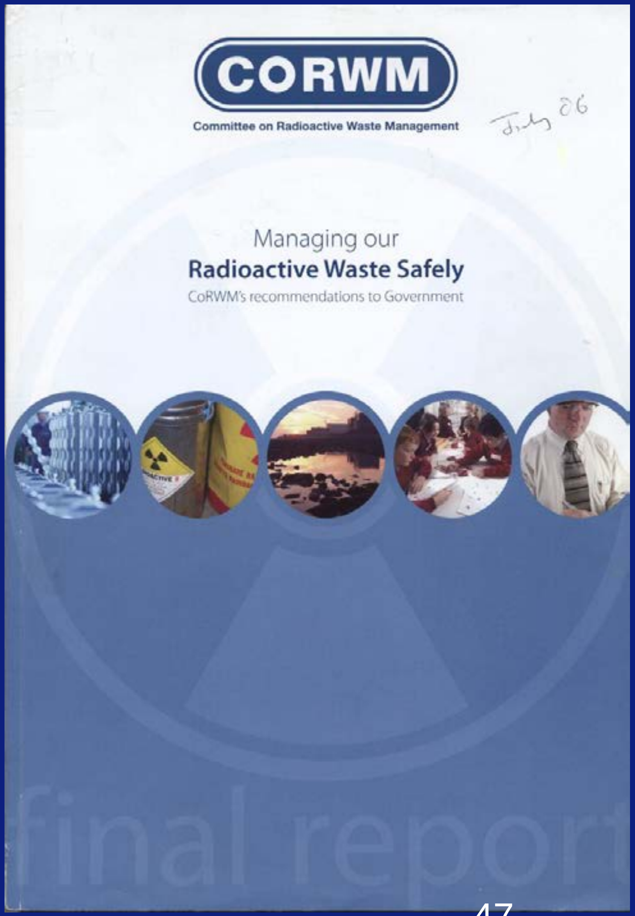
- History of inaction in the UK culminating in a Govt. decision in 1997 not to pursue a planned examination of the suitability of the geology nearby Sellafield for a Rock Characterisation Facility.

- In 2004 Government set up independent Committee on Radioactive Waste Management (CoRWM) reporting directly to Ministers.

- In April 2005 set up Nuclear Decommissioning Authority (NDA) with responsibility for UKs radwaste-contaminated site clean up with £80B budget.

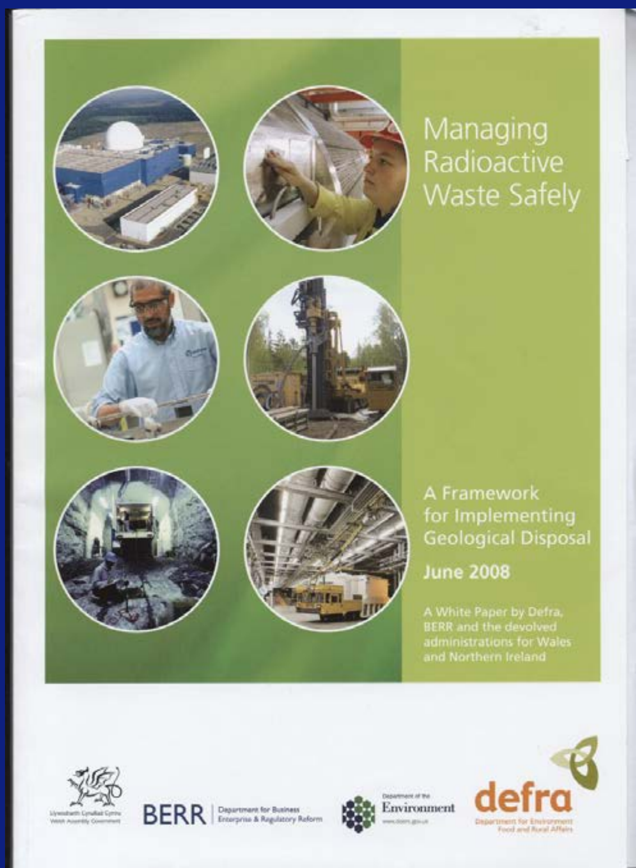
Committee on Radioactive Waste Management (CoRWM) 2004-06.

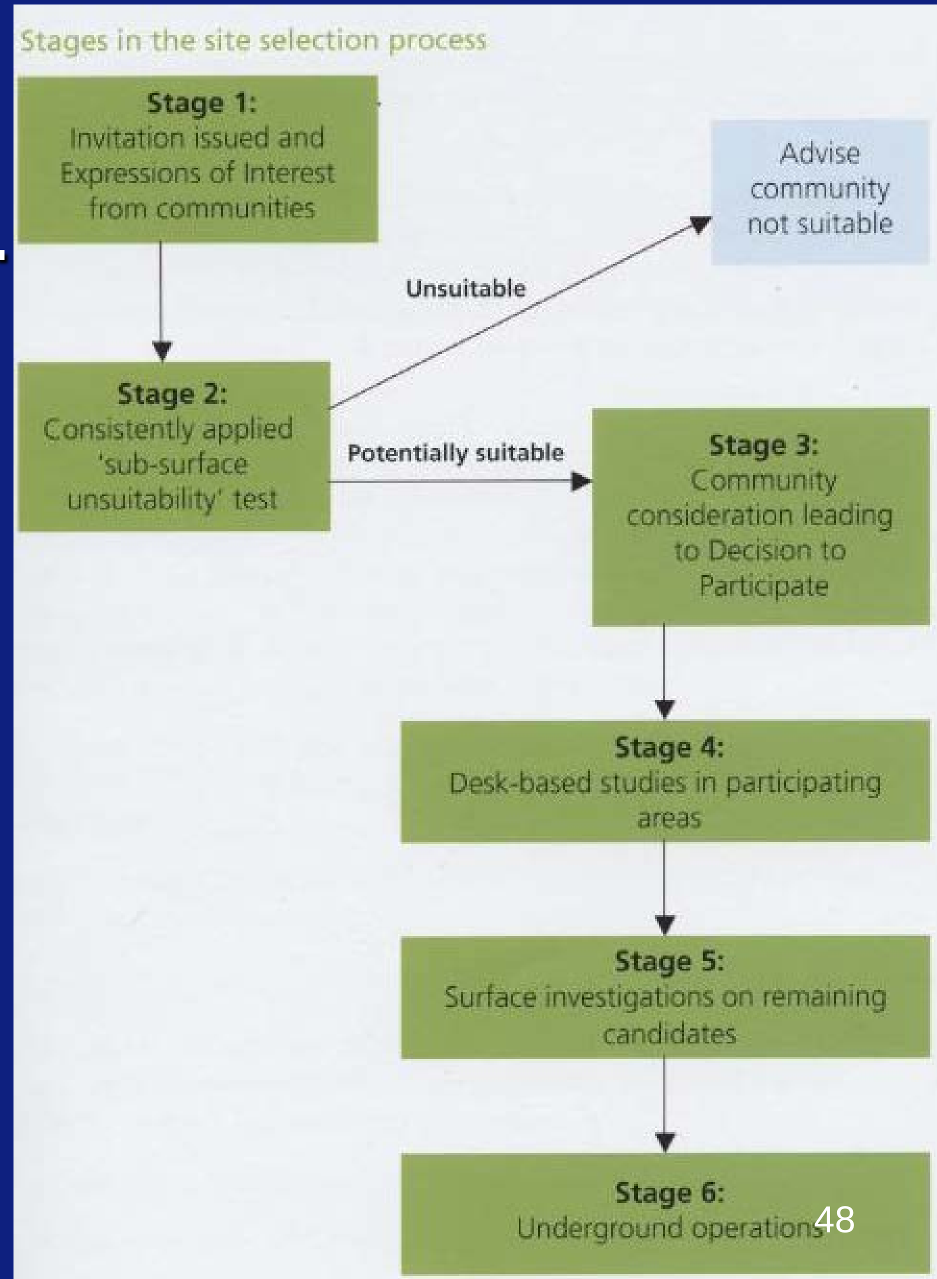
- CoRWM set up to review options for managing UK's radwaste and recommend solutions to Govt.
- CoRWM reported to Govt. July 2006 and recommended:
  - Geological disposal as end point for long-term management of radioactive wastes.
  - Robust storage in interim period with provision against delay or failure in reaching end point.
  - Expanded R&D programme.
  - Need for a staged process with flexibility in decision making and partnership with communities willing to participate in siting process (volunteerism).



Managing Radioactive Waste Safely (MRWS) Programme

Government White Paper outlining process and stages.



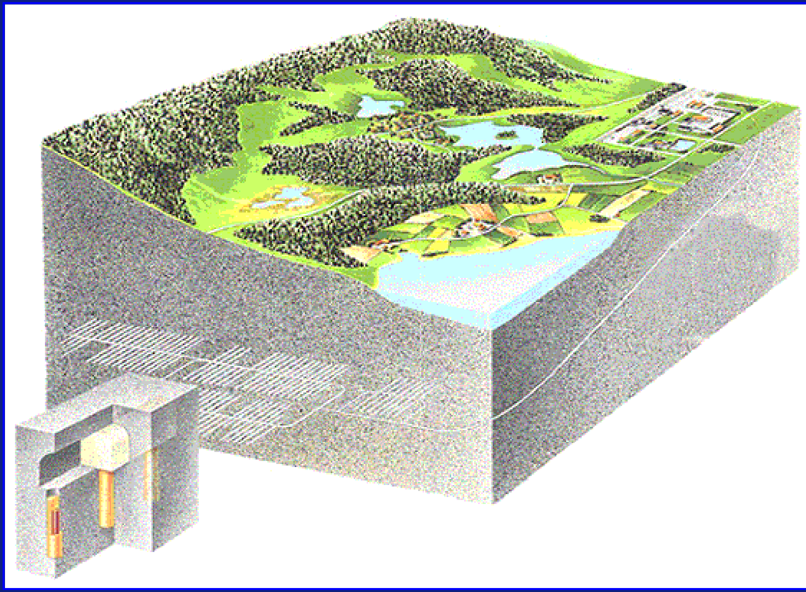


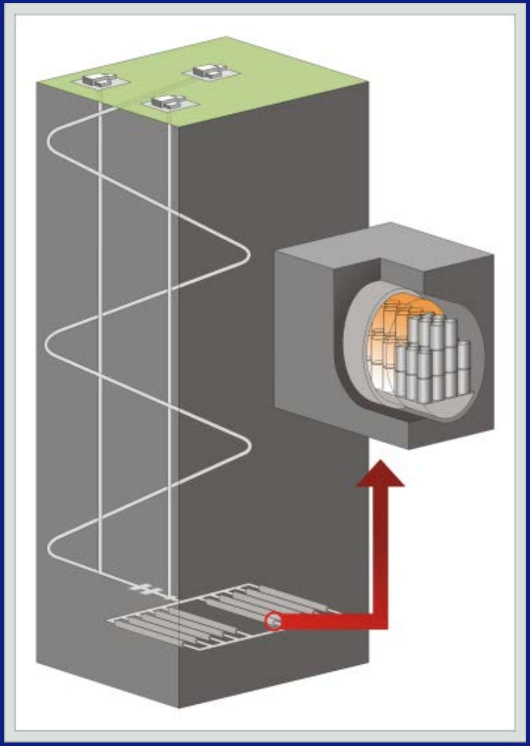
Nuclear Decommissioning Authority (NDA).

- Established April 2005 to ensure 20 civil public sector nuclear sites are decommissioned and cleaned up, safely, securely, cost effectively in ways that protect the environment for this and future generations.
- Oct 2006 - Govt. announced NDA would take extended role as single UK body responsible for implementing geological disposal of higher activity radioactive waste.
- 2007 - Radioactive Waste Management Directorate (RWMD) set up by NDA and Nirex incorporated into it.

Radioactive Waste Management Directorate (RWMD).

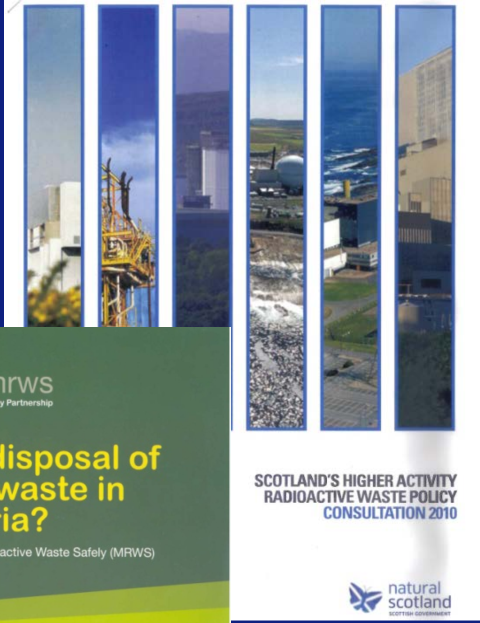
- **Being developed by NDA into delivery organisation to implement geological disposal i.e. to construct the geological disposal facility (GDF or GDFs).**
- **Will become wholly-owned subsidiary of NDA and, at later stage of GDF siting, will become a Site Licence Company.**

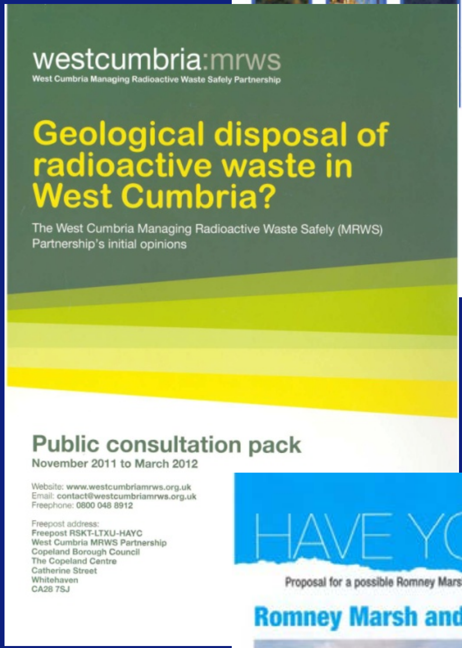




Current UK Situation: Volunteerism Process.

- **Scottish Government opted out of MRWS process, policy is *near surface near site* storage and disposal of Scottish waste will not be deep geological disposal.**
- **Copeland & Allerdale Borough Councils & Cumbria County Council (all near Sellafield) set up W Cumbria MRWS Partnership (WCP) and expressed interest in hosting GDF.**
- **WCP consulting community & a decision will be made on whether to participate in autumn 2012.**
- **Favourable MORI opinion poll May 2012.**
- **Shepway District Council examining possibility of expressing interest (May 2012).**





Current UK Situation.

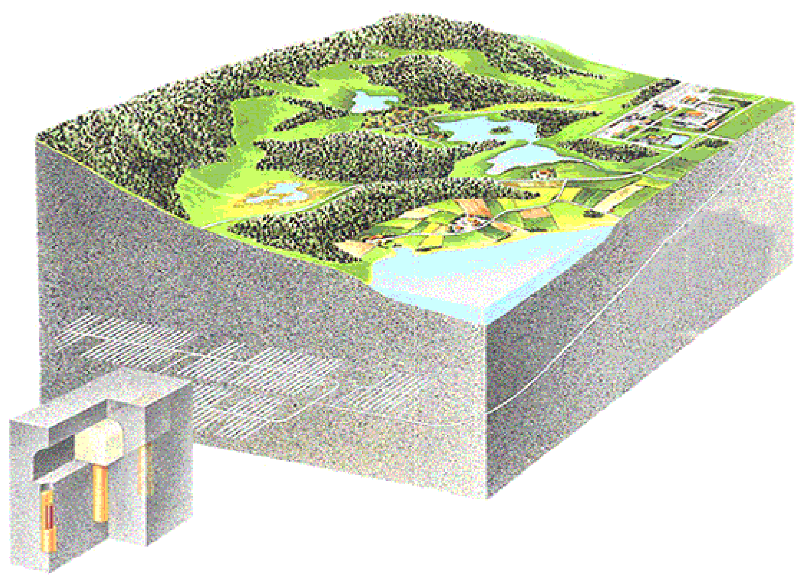
- Nuclear infrastructure being reinvigorated:
  - Universities and R&D (EPSRC, NERC)
  - National Nuclear Laboratory (Battelle, Man Univ, Serco)
  - National Skills Academy for Nuclear
  - National Centre for Nuclear Manufacturing (Sheffield)
  - House of Lords Science and Technology Committee enquiry into R&D capability (Nov 2011).
- Nuclear National Policy Statement (July 2011) stated that effective arrangements exist, or will exist, to manage and dispose of new build waste.
- Is it possible to accelerate implementation of geological disposal?
- Development of generic Disposal System Safety Case (DSSC).

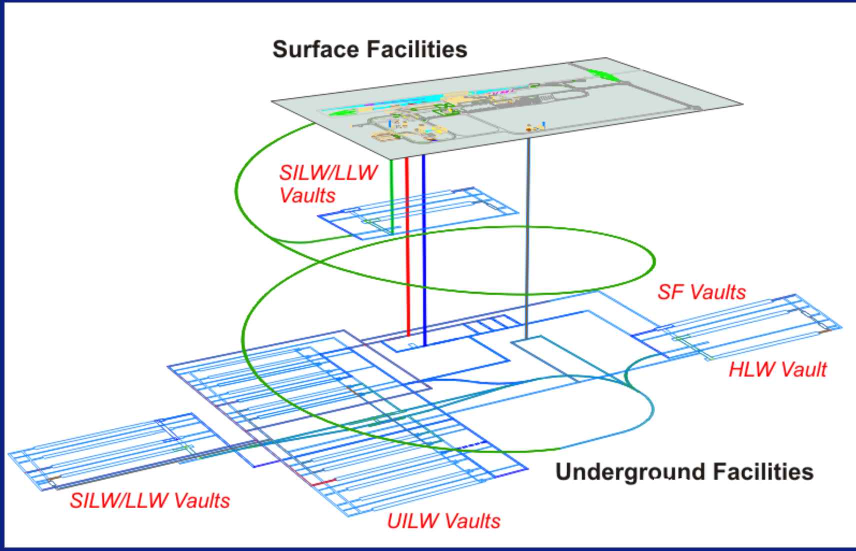
CoRWM View of Acceleration Options

CORWM

Committee on Radioactive Waste Management

- Government asked NDA to examine options for accelerating implementation of geological disposal to perhaps 2029 for 1st waste emplacement.
- 3 scenarios were examined with changes to e.g. packaging assumptions for HLW and SF, phased site investigation for different waste types and alternative disposal methods e.g. for short-lived ILW.
- Not practicable or desirable to bring forward current planning date of 2040 for 1st waste emplacement in GDF (should not rush communities & R&D e.g. URL).
- Advantages in bringing forward 2075 planning date for 1st emplacement of HLW and legacy SF.

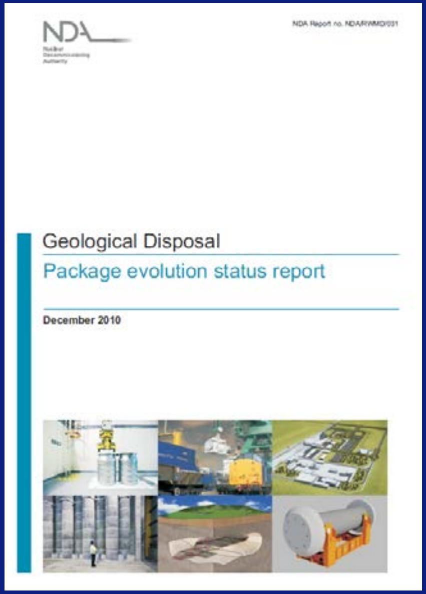


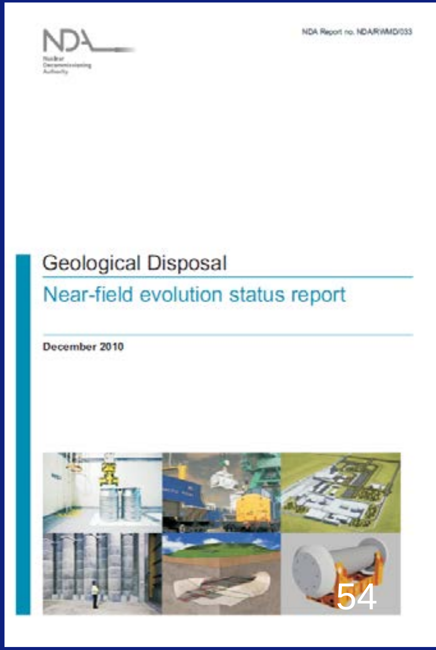


CORWM 8th Annual Report June 2012. CoRWM doc. 3026.

RWMD Disposal System Safety Case (DSSC).

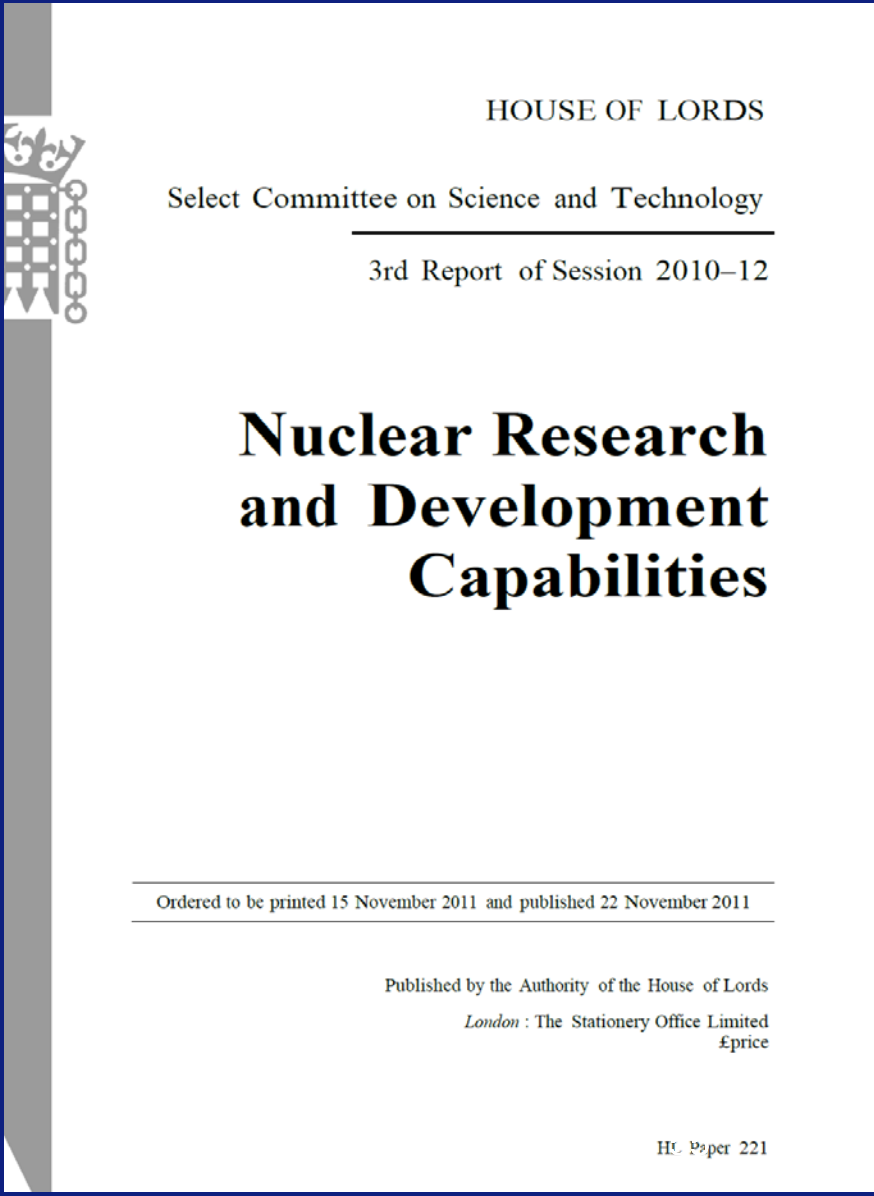
- The safety of a Geological Disposal Facility is crucial.
- Closely regulated.
- Process is long and complex and has already started, even before have a UK site.
- A Generic DSSC exists. It considers
  - Safety of radwaste transportation to a GDF
  - Safety of the construction and operation of the GDF
  - Safety of the GDF in the very long term after it has been sealed and closed.
- Also underpinning documents e.g. research status reports.





House of Lords Inquiry into Nuclear Research and Development Capabilities.

- **Main Points relevant to Waste Issues:**
  - **Spend more on nuclear R&D**
  - **National strategic Nuclear R&D Board**
  - **Nuclear R&D Roadmap**
  - **Improved facilities to work on active materials**
- **Government responded Feb 2012:**
  - **set up *Ad Hoc* Nuclear R&D Advisory Board to write R&D roadmap to 2050 and report on addressing infrastructure issues by end 2012.**


HOUSE OF LORDS

Select Committee on Science and Technology

3rd Report of Session 2010–12

Nuclear Research and Development Capabilities

Ordered to be printed 15 November 2011 and published 22 November 2011

Published by the Authority of the House of Lords

London : The Stationery Office Limited
£price

HL Paper 221

Some of the UKs Difficult Wastes.

- Poorly characterised and heterogeneous ILW (Sellafield LP&S).

- ~100 tonnes of Pu mostly in form of oxide powder.

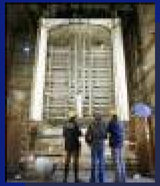
Sellafield Legacy Ponds and Silos: High Hazard Programmes.

Pile Fuel Storage Pond

First Generation Magnox Fuel Pond

Magnox Swarf Storage Silos

Pile Fuel Cladding Silo



HAL (Highly-Active Liquor) Workstream

Legacy Ponds & Silos

- 22% of all site programmes
- 35% of total site costs during next 4 years
- 77% of major project costs during next 4 years
- >90% of nuclear hazard potential on Sellafield site

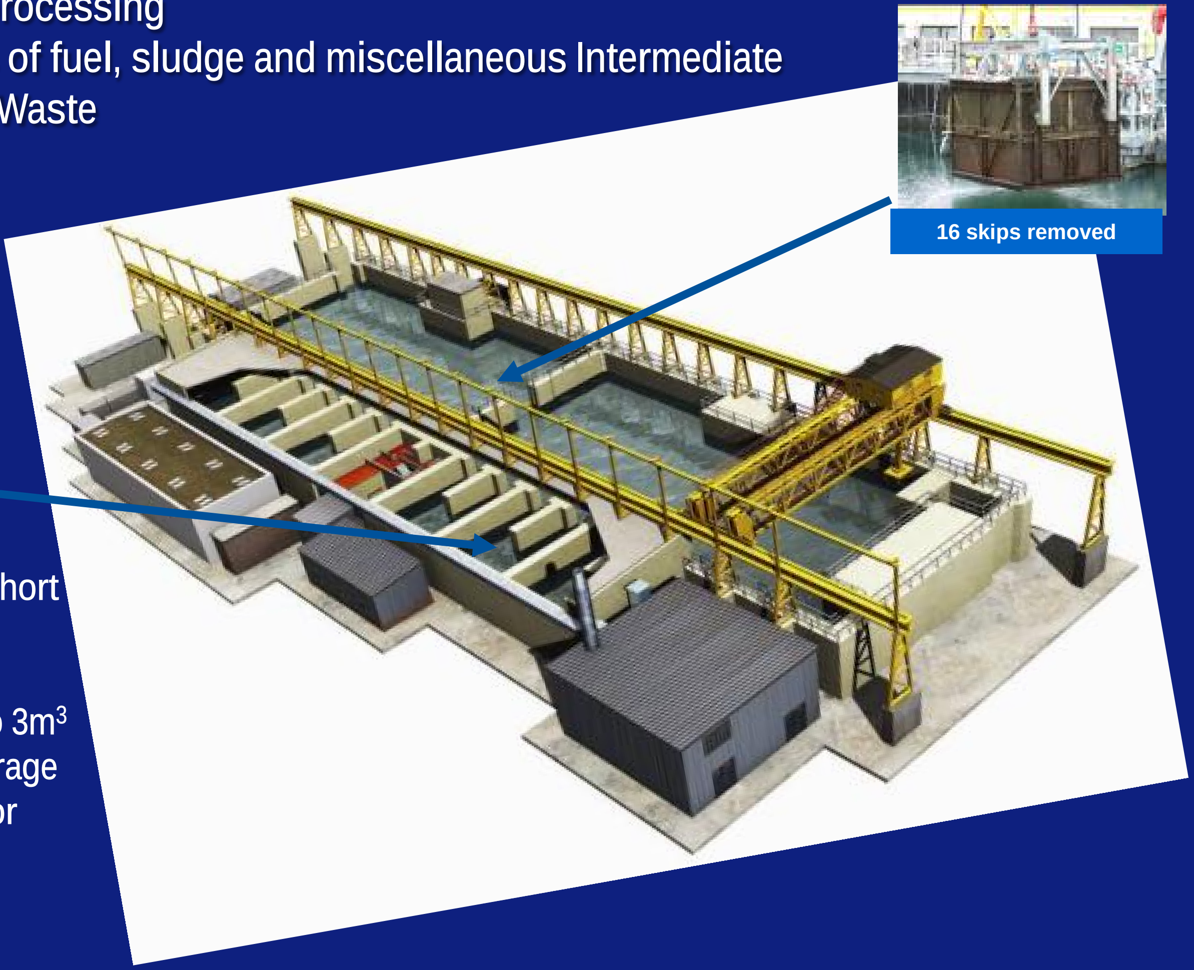
LP&S Strategy Objectives

- Acceleration of High Hazard/High Risk Reduction
- Restore and maintain the basic condition of the assets and facilities.
- Reduce or mitigate the impact of the risk of a loss of containment of Nuclear Materials.
- Prepare the facilities for retrieval operations
- Retrieve the waste (hazards)
- Immobilise the waste (hazards), e.g. research into novel thermal methods.

Pile Fuel Storage Pond

Legacy

- Constructed 1948 – 1952 to store, cool and prepare Windscale Pile fuel for reprocessing
- Waste consists of fuel, sludge and miscellaneous Intermediate and Low Level Waste



Baseline Plan

- Sludge retrievals to an in-pond corral
- Local Sludge Treatment Plant* (LSTP) for short term storage of sludge
- Local Sludge Treatment Plant Process & Export* (LSTP P&E) to package sludge into $3m^3$ boxes and export for long term interim storage
- Oxide fuel to Oxide Fuels Storage Ponds for reprocessing
- Metal fuel to Fuel Handling Plant (FHP) for interim storage
- Remaining solid ILW inventory to pond solids conditioning facility, and packaged into $3m^3$ boxes for long term interim storage

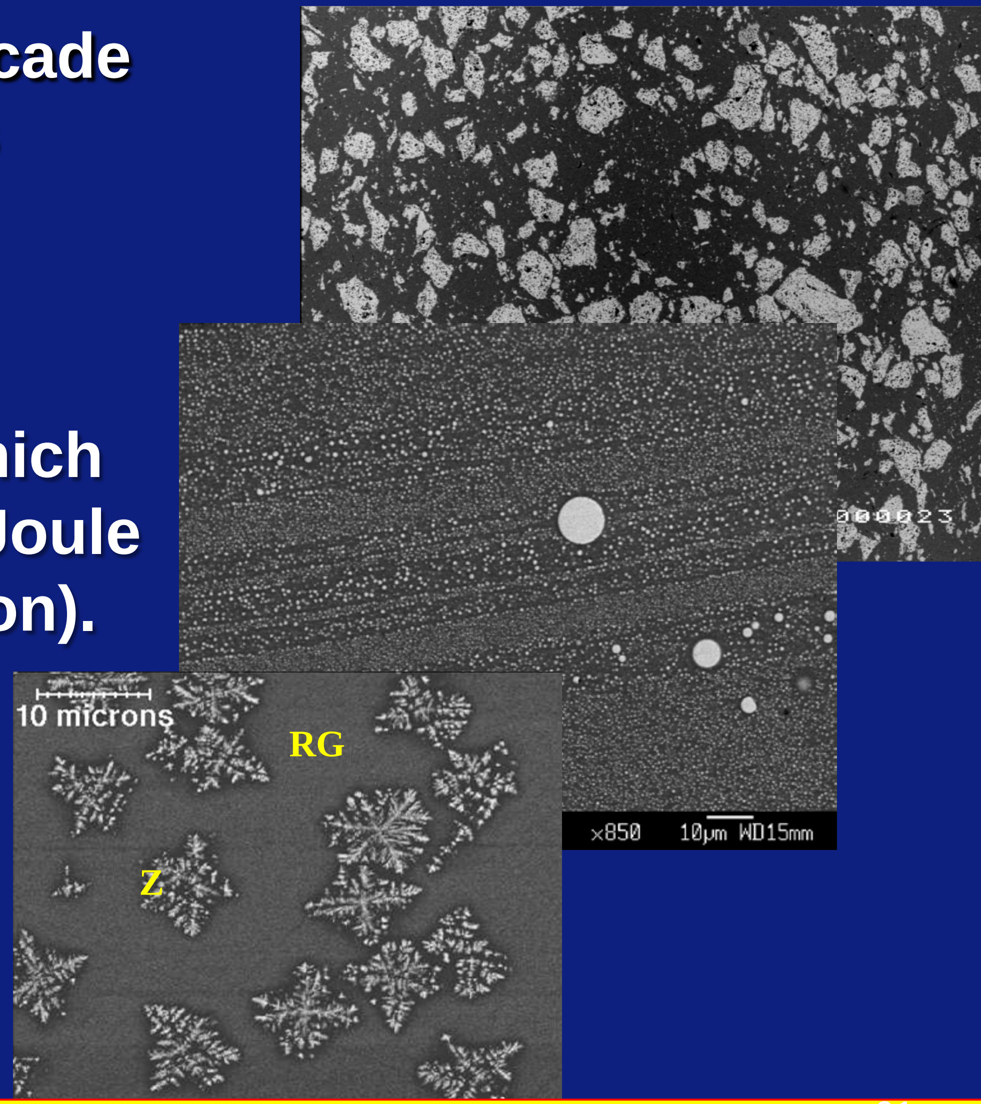
Pile Fuel Storage Pond

- **Operating Plan targets 2011/12:**
  - Pile Fuel Storage Pond Hazard Reduction
  - Retrieval and Export of 20te Contaminated Items
  - LSTP Storage, Commissioning Tests
  - Initiate Project Delivery Gate for sludge process and export project
  - Wash 80 skips to support retrieval of pond solids and fuel
  - Commit Sludge to LSTP Storage Tanks
  - Start canned fuel export
- **Operating Plan targets 2012/13:**
  - Retrieve and Export x tonnes of contaminated item
  - Rate of Export of canned fuel
  - Milestone 1 - Sludge - produce recommendation for disposal of Pond Sludge
  - Milestone 2 - Sludge - Actively demonstrate the route
- **Operating Plan targets 2013/14+:**
  - Last canned fuel exported

Clearing Sludge from Pond sections.
Completing storage facility construction.
Removing redundant skips.

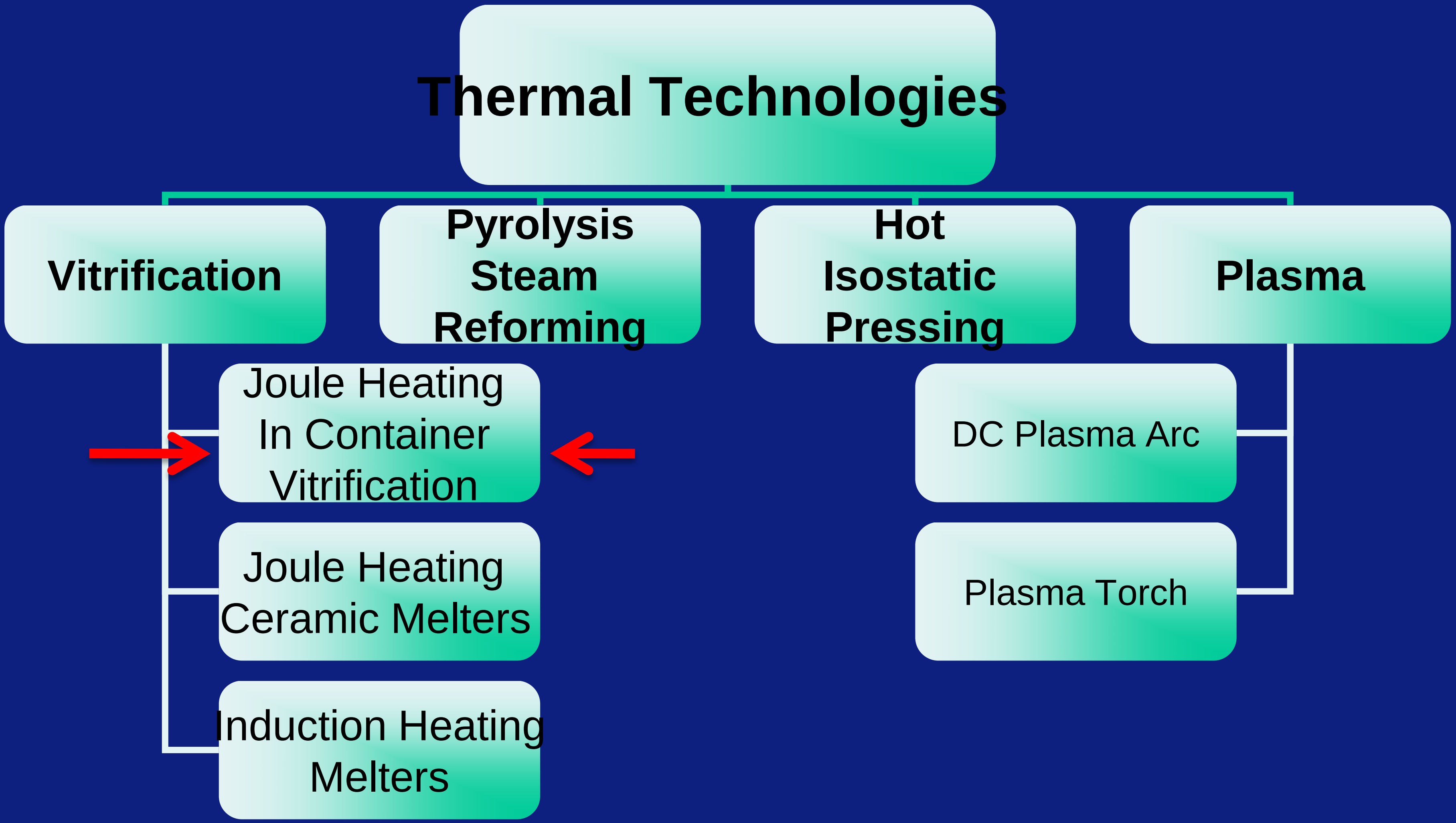
Novel Wasteforms: Glass Composite Materials (GCMs) from Thermal Technologies

- **Realisation over last decade that mixed crystal-glass wasteforms can be as durable as pure glass.**
- **E.g. crystalline waste encapsulated in melt which solidifies to glass (e.g. Joule Heater In-Can Vitrification).**
- **Applicable for some LP&S wastes.**



WE Lee, MI Ojovan, MC Stennett and NC Hyatt, "Immobilisation of Radioactive Wastes in Glasses, Glass Composite Materials and Ceramics," Adv. Applied Ceramics 105 [1] 3-12 (2006).

Wasteforms from Novel Thermal Processes



Range of available technologies with differing Technology Readiness Levels.

Proof of Concept Trials using Surrogates

- **Demonstrated potential of thermal treatment options to treat several LP&S wastes and they**
  - **can handle Sellafield LP&S wastes**
  - **are deployable at Sellafield**
  - **produce a durable product**
  - **offer cost benefits**

- **E.g. Joule Heater In-Can Vitrification – Mixed solids & sludge waste**

Before

During

After

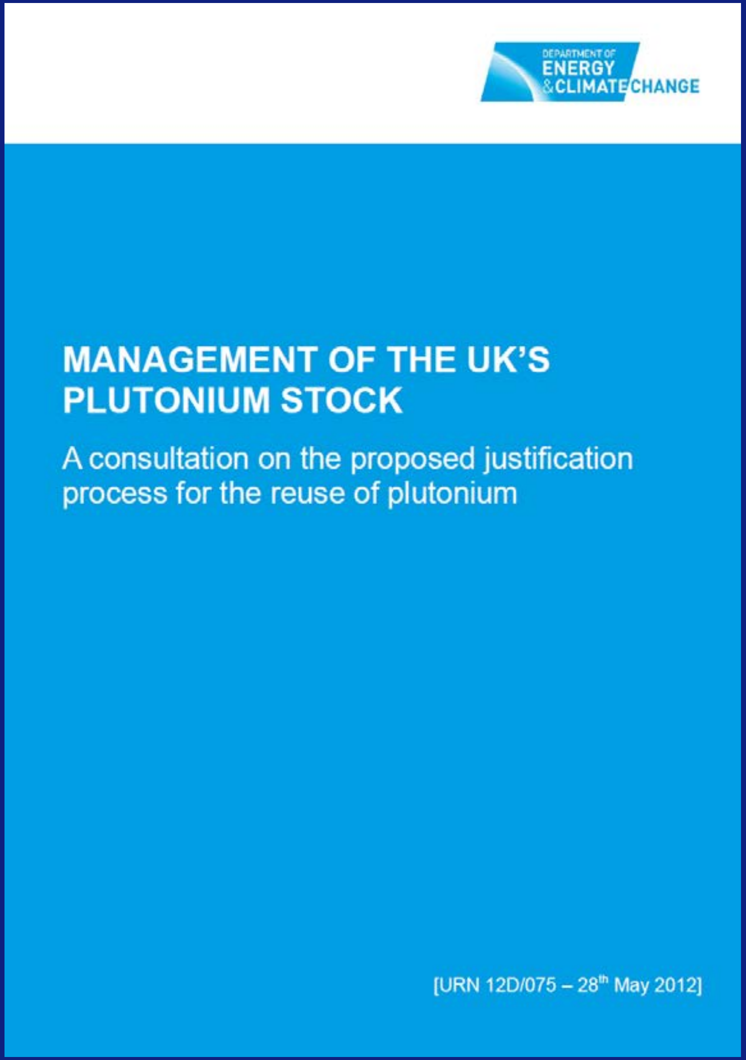
Key Issues of Thermal Processes.

- **Convert reactive material (e.g. metals, sludges & organics) to more stable forms. But the following need addressing:**
  - **Variable nature of wastes make control of process and product difficult.**
  - **Difficult to characterise heterogeneous waste and product.**
  - **Durability testing of product.**

- **Nonetheless, the reduction in hazard is enormous and we need to be pragmatic.**

Options for Plutonium.

- **Government favoured option to recycle PuO_2 by mixing with UO_2 to make Mixed Oxide (MOX) fuel which can be burned in PWR reactors.**
- **Will need new MOX plant at high capital cost.**
- **Govt is open to other options e.g. burning in fast reactors e.g. PRISM.**
- **Am intergrowth with time is contaminating Pu and will require processing to remove.**

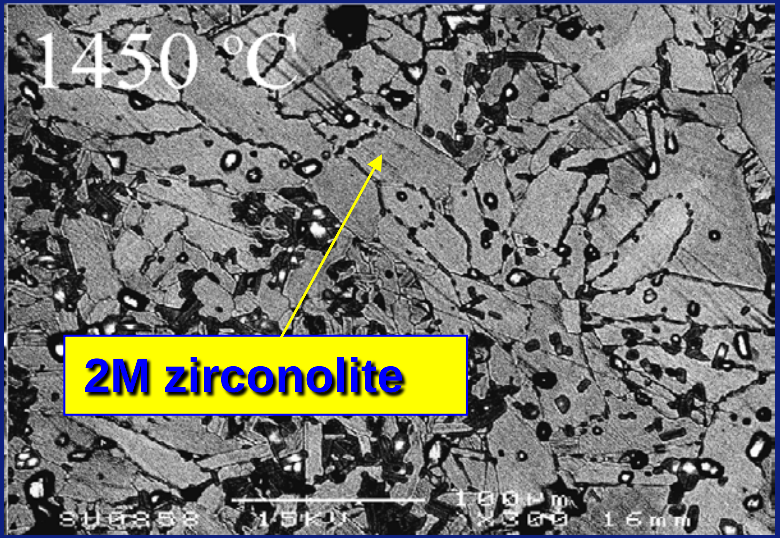

DEPARTMENT OF ENERGY & CLIMATE CHANGE

MANAGEMENT OF THE UK'S PLUTONIUM STOCK

A consultation on the proposed justification process for the reuse of plutonium

[URN 12D/075 – 28th May 2012]

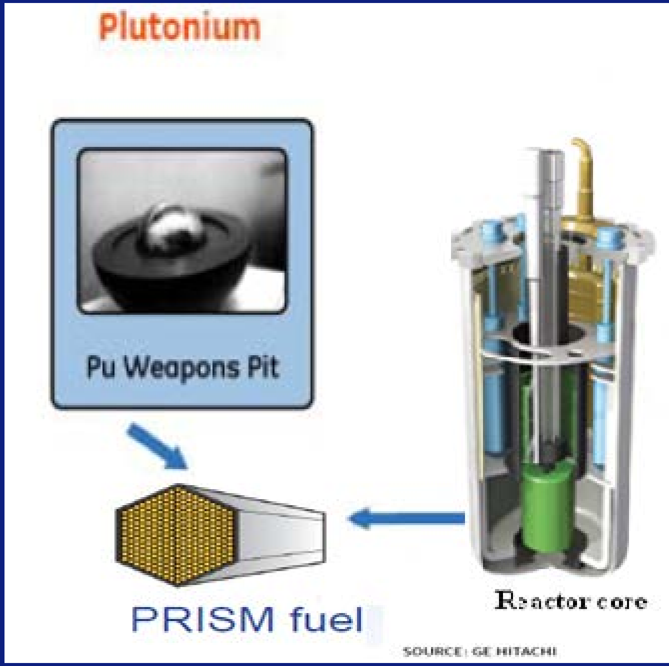
Options for Plutonium.



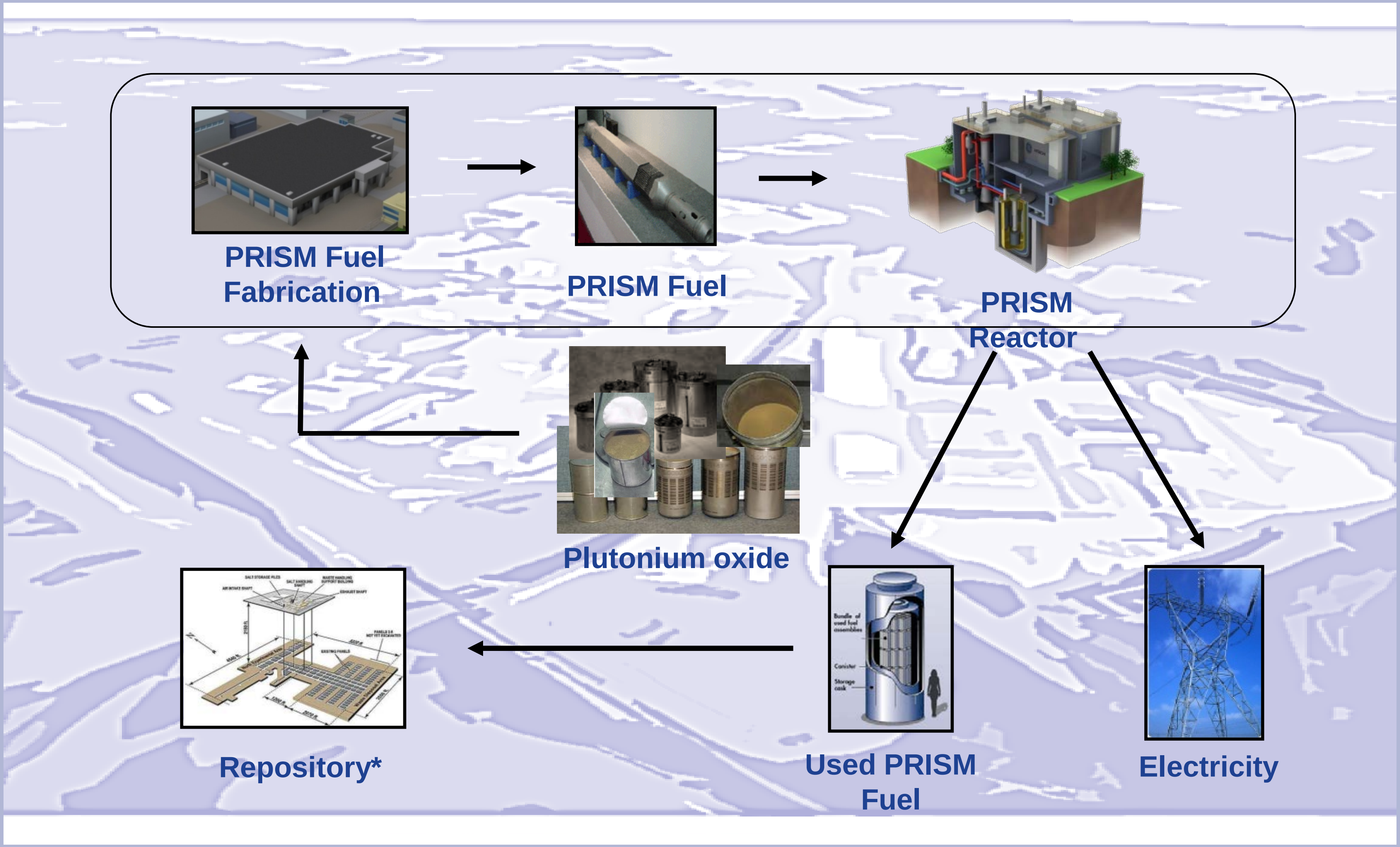
- Some Pu is contaminated and unsuitable for use in MOX and must be decontaminated or immobilised.
- Limited solubility of Pu in borosilicate glasses so ceramic wasteforms (e.g. Synroc, zirconolites, pyrochlores) being developed.
- Hot Isostatic Pressing being examined as ceramic processing route.

Power Reactor Innovative Small Module (PRISM)

- GE Hitachi fast reactor with liquid sodium coolant.
- Operates at high temperature - over 500°C.
- Uses metallic Pu fuel + Depleted U rod inside zircalloy cladding with Na metal heat transfer medium.

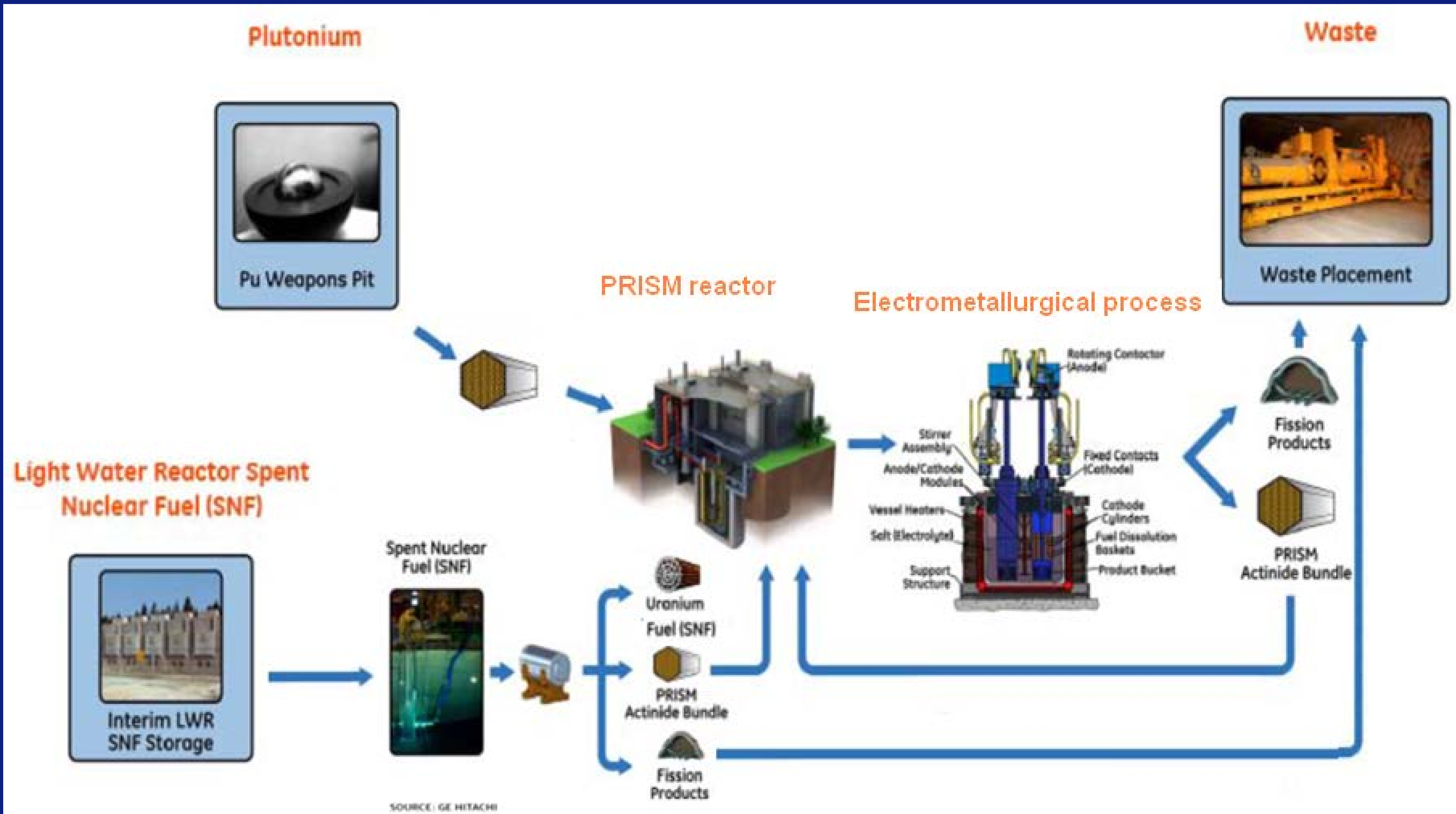


Plutonium burning in PRISM Reactor.



- Figure implies direct disposal of spent PRISM fuel.

PuO_2 - PRISM Fuel - Waste Cycle



- **Figure implies reprocessing of spent PRISM fuel and disposal of vitrified short-lived FPs.**

PRISM Waste Issues.

- Generate secondary Pu-contaminated molten salt waste during Pu + DU metal fuel fabrication from Pu oxide; currently no clear disposal route for such salt wastes.
- Not clear whether will directly dispose spent PRISM fuel or reprocess.
- If reprocess need to build reprocessing plant, generate secondary wastes and still have FPs to immobilise in glass.

CoRWM Comments on Government Pu Policy.

CORWM
Committee on Radioactive Waste Management

- Need disposability assessments for spent MOX fuel, and R&D on interim storage and geological disposal of spent MOX to provide input to these assessments.
- Need R&D on disposability of immobilised waste Pu (ceramics).
- Include spent MOX in inventories of wastes for geological disposal.
- Optimisation of the management of MOX fuel, from arising through to and including geological disposal.
- Consider waste aspects when judging the credibility of new options for reuse of Pu.

CORWM 8th Annual Report June 2012. CoRWM doc. 3026.

Conclusions

- Good progress on clean-up, storage and disposal aspects of UK MRWS programme.
- Sellafield LP&S is the most challenging site.
- Need both volunteer community and suitable geology for successful geological disposal.