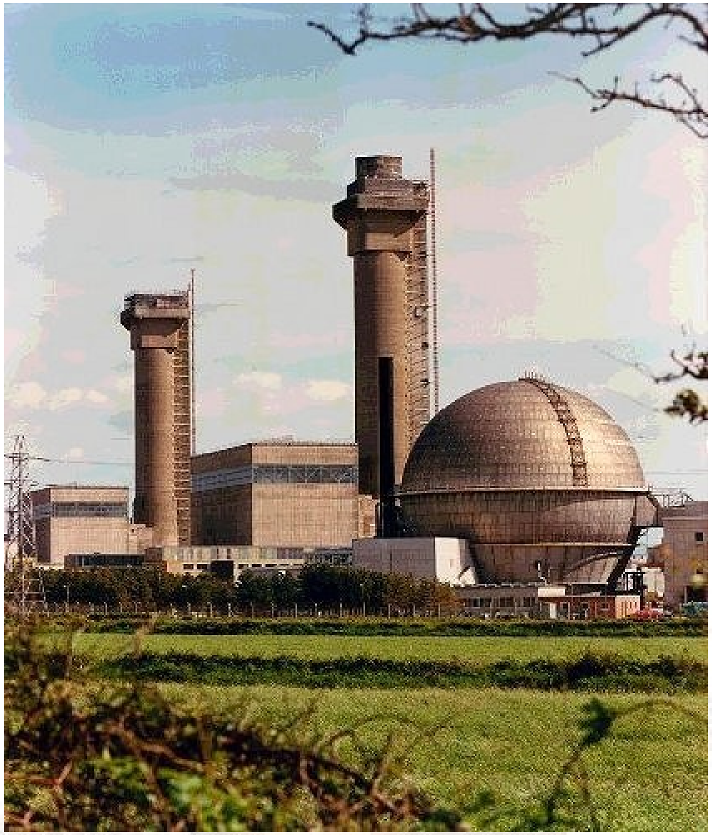
Windscale Piles Decommissioning Project

Presented by MT Cross, NUKEM Ltd, UK at the Brookhaven Graphite Research Reactor Workshop, 9 -10 May, 2007

Introduction



- The Piles and their History
- Structure and present condition
- Uncertainties for present state/decommissioning
- Safety related issues
- Waste management of graphite
- Conclusions

Background

- Non-conventional large decommissioning project (accident-damaged reactor with fire damaged core, not all fuel removed)
- 2 reactors in safestore since core fire in Pile1, 1957
- Increasing regulatory pressure (2007, 50th anniversary of fire)
- Characterisation issues dominate
  - some unique considerations
  - intrusive inspection of fire-damaged region to be carried out

The decommissioning problem is dominated by the lack of a detailed knowledge of the present state of the core

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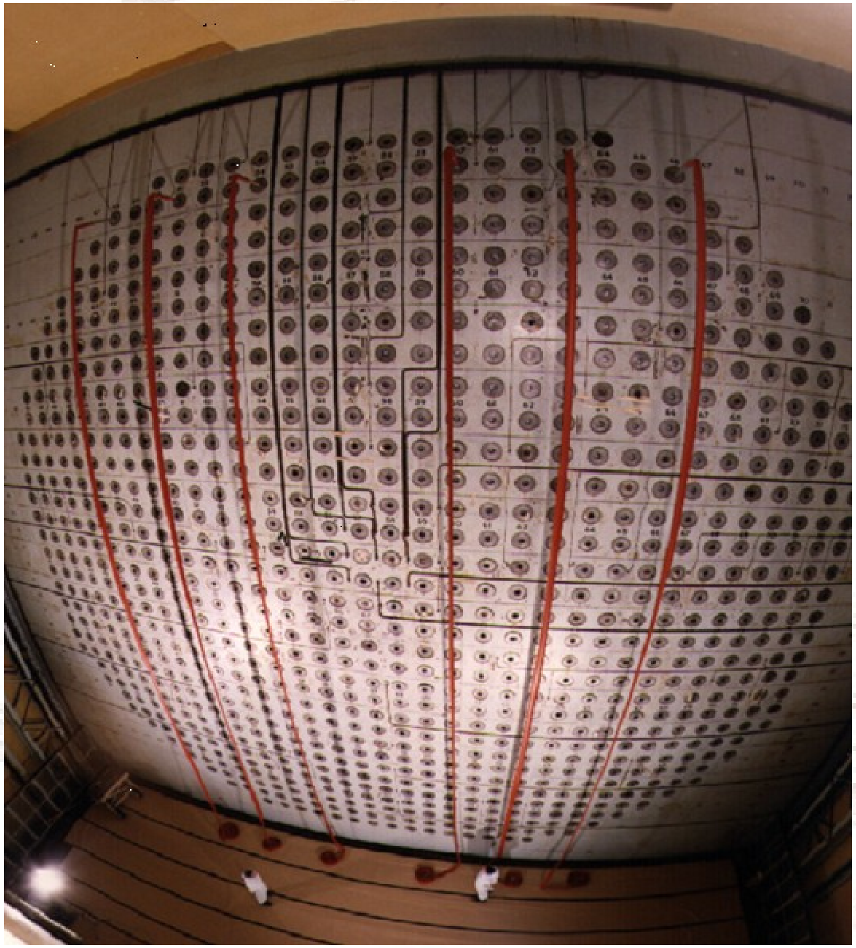
Pile parameters

- Graphite moderated, 2000 te
- 180 MW_t, air-cooled, once-thru, no PV, 200 ^oC outlet temp
- 3444 horizontal fuel channels
- 977 horizontal isotope channels
- Fuel:
  - natural uranium metal rods, 21 elements per channel
  - later used 0.92% U-235
  - clad in finned aluminium
  - 70, 000 elements, 180 te U full charge



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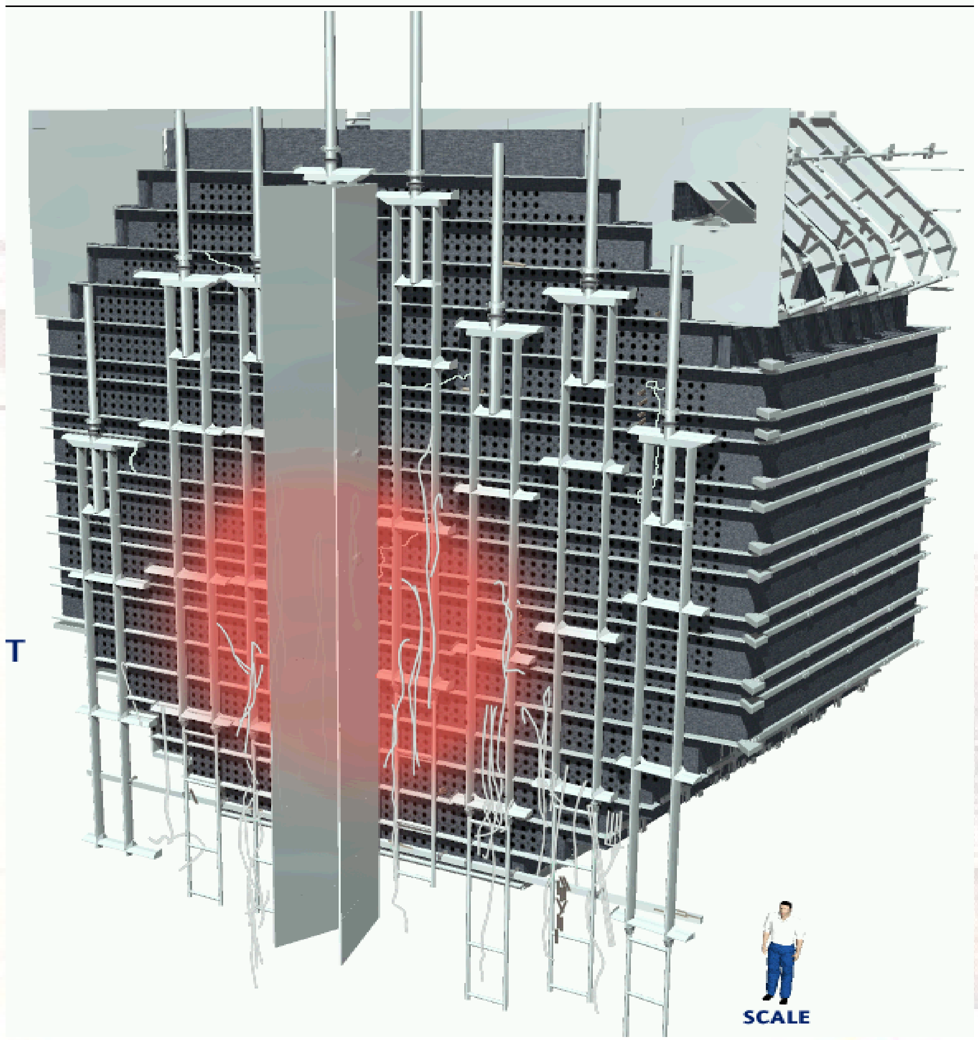
Fire-Affected Zone (FAZ) in Pile 1



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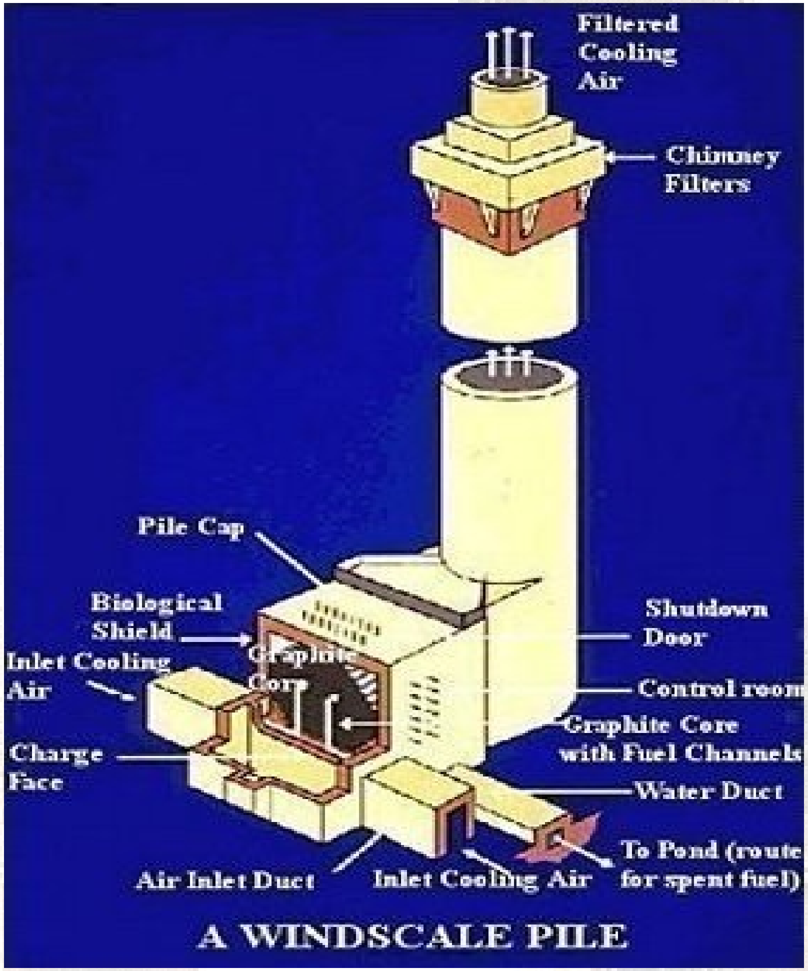
Schematic structure



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Lateral cross-section

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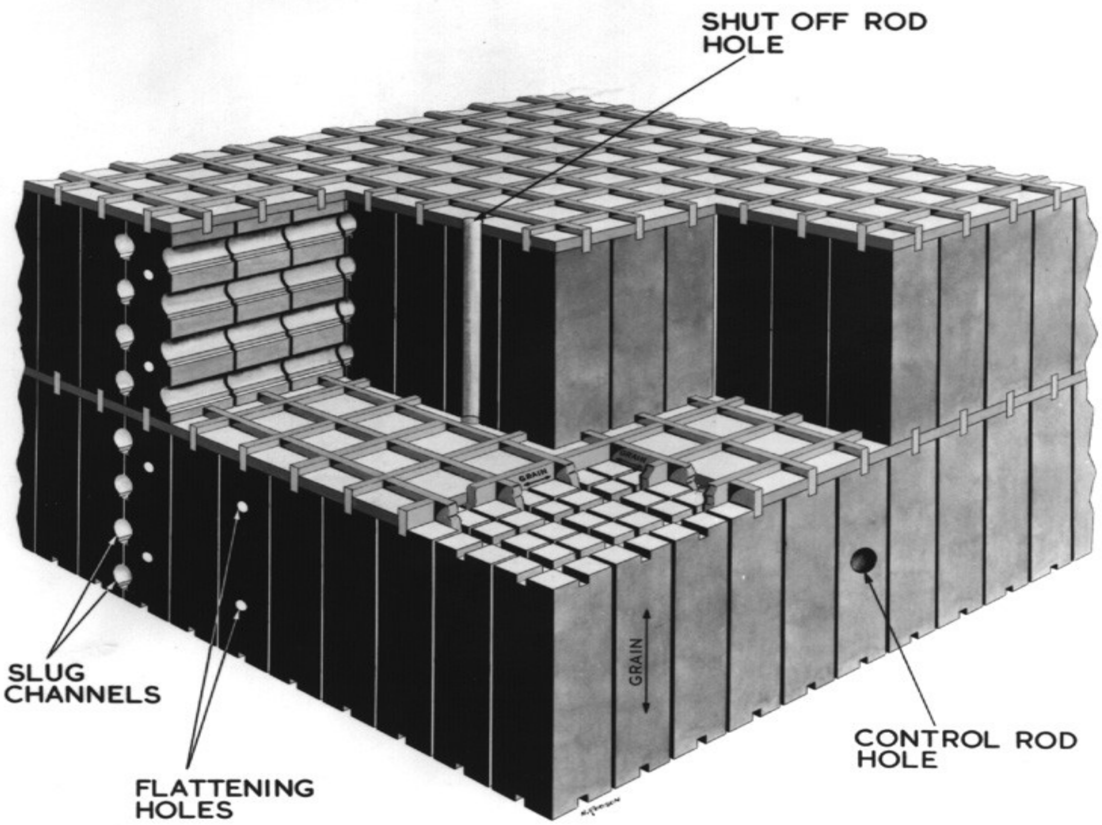
Piles' graphite core structure



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UK graphites/1

There are four main sources of UK Graphite:

- UKAEA, Windscale Piles, BEPO, GLEEP and various research reactors. Types AGXP, AGX, Welland etc. Grades A, B and C depending on the quality
  - manufactured from refining coke from Sarnia Canada obtained from Alberta oilfields
- Magnox, Pile Grade A (PGA) and Pile Grade B (PGB) found in various grades
- AGR Moderator Gilsocarbon and Reflector manufactured from various isotropic graphites
  - Gilsocarbon purity less than PGA, particular concerns with $^{59}Co \rightarrow ^{60}Co$
- Magnox and AGR Sleeves, PGA (Magnox) and various pitch coke graphites respectively

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UK Graphites/2

Piles, AGXP, PGA(Magnox) graphites:

- Petroleum coke, by-product of oil refining process.
- Needle-shaped coke particles.
- Extrusion process aligns coke particles.
- Crystallographic layer planes tend to lie parallel to extrusion axis.
- Graphite properties are anisotropic

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Early Decommissioning, Phase I - securing the safety of the facility

- Commenced early 1980's
  - Sealing of bioshield
  - Installation of ventilation and monitoring
  - Loose fuel removal from outside core
  - Drain-down of water duct
  - Core removal option studies
  - Completed June 1999

Air Duct Clearance

Water Duct Clearance - Before

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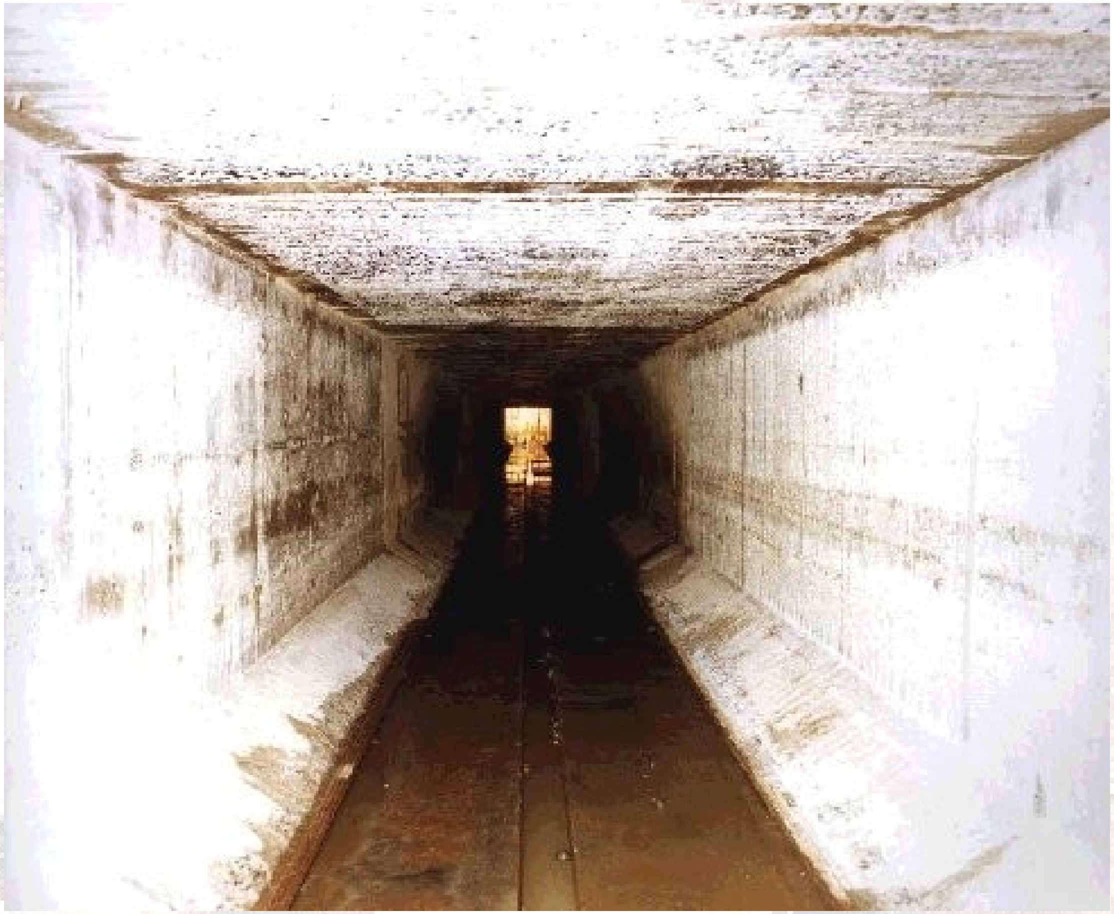
Water Duct Clearance - After



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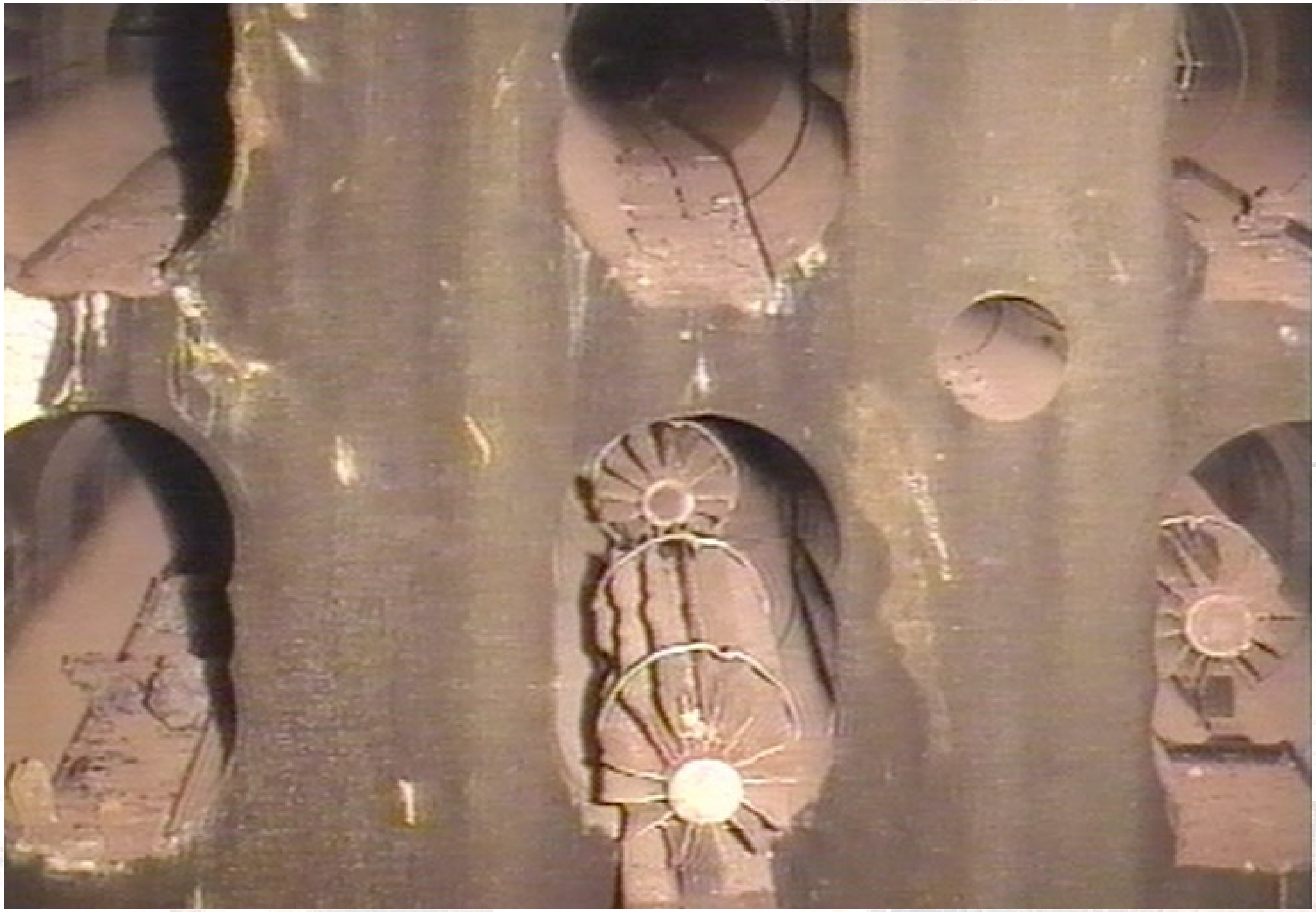
Present condition of Pile 1

Apparently Pristine Fuel



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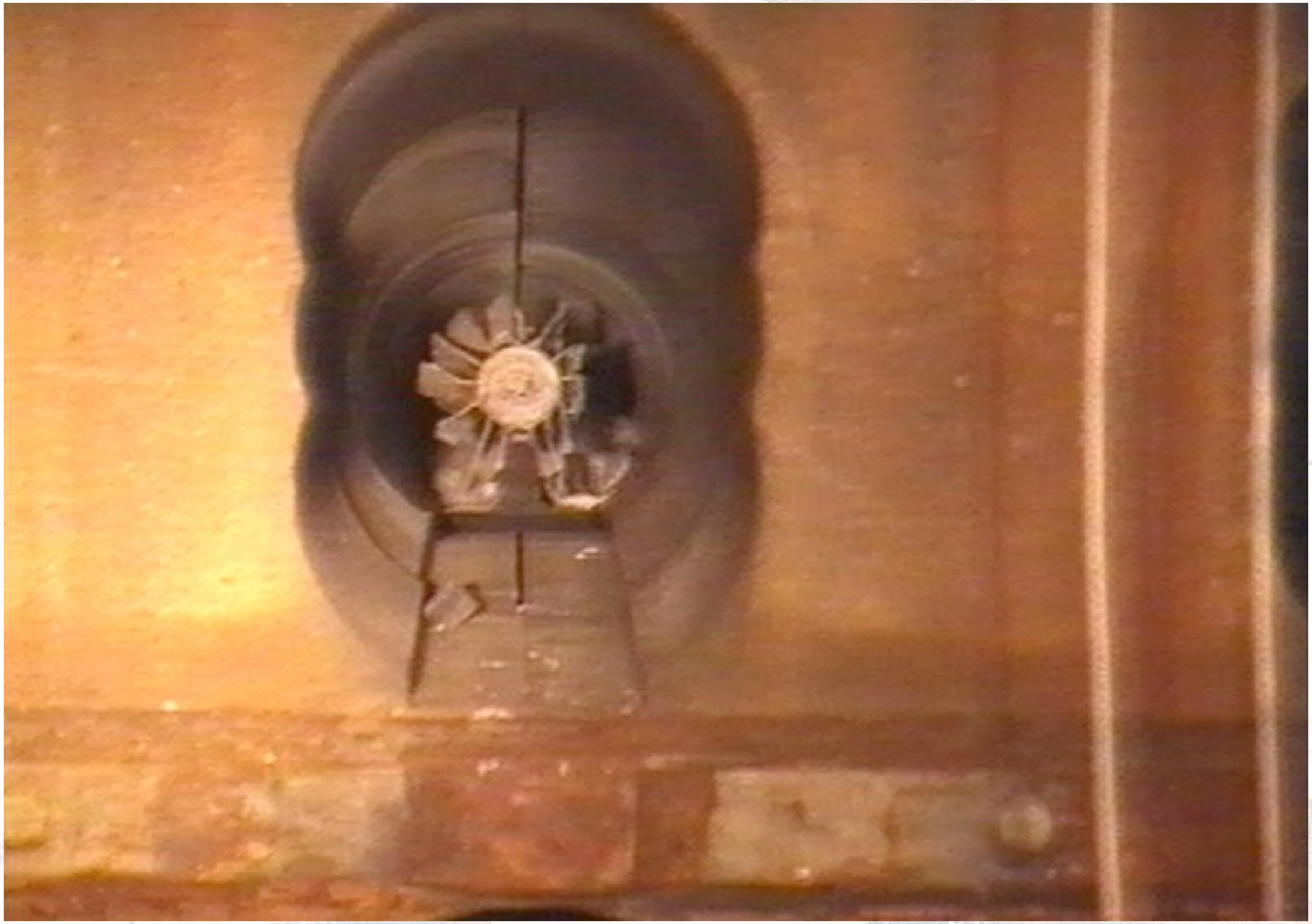
Slightly Damaged Fuel



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Destroyed Fuel - 23.54

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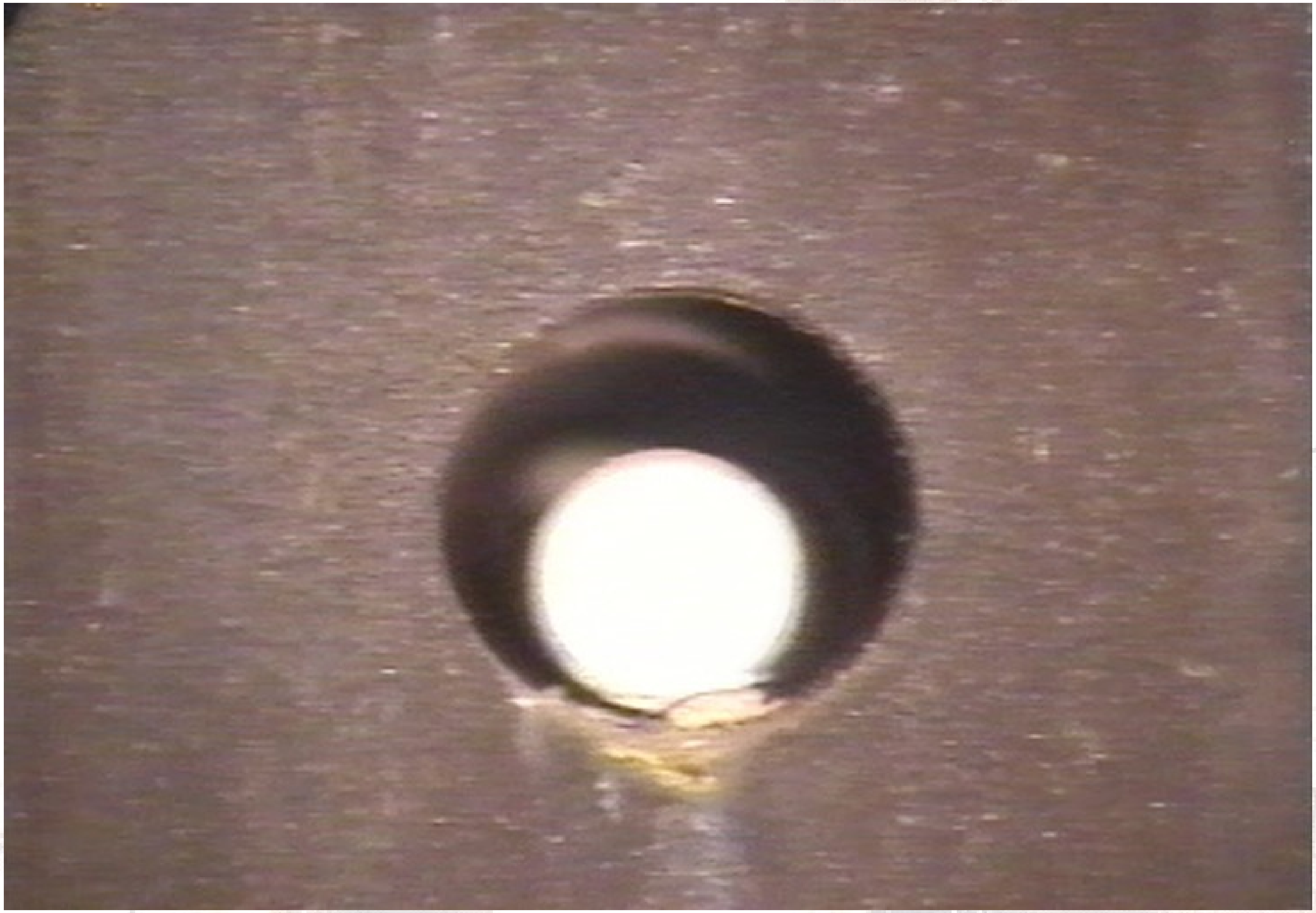
Intact Isotope Cartridge



Damaged Isotope Cartridge

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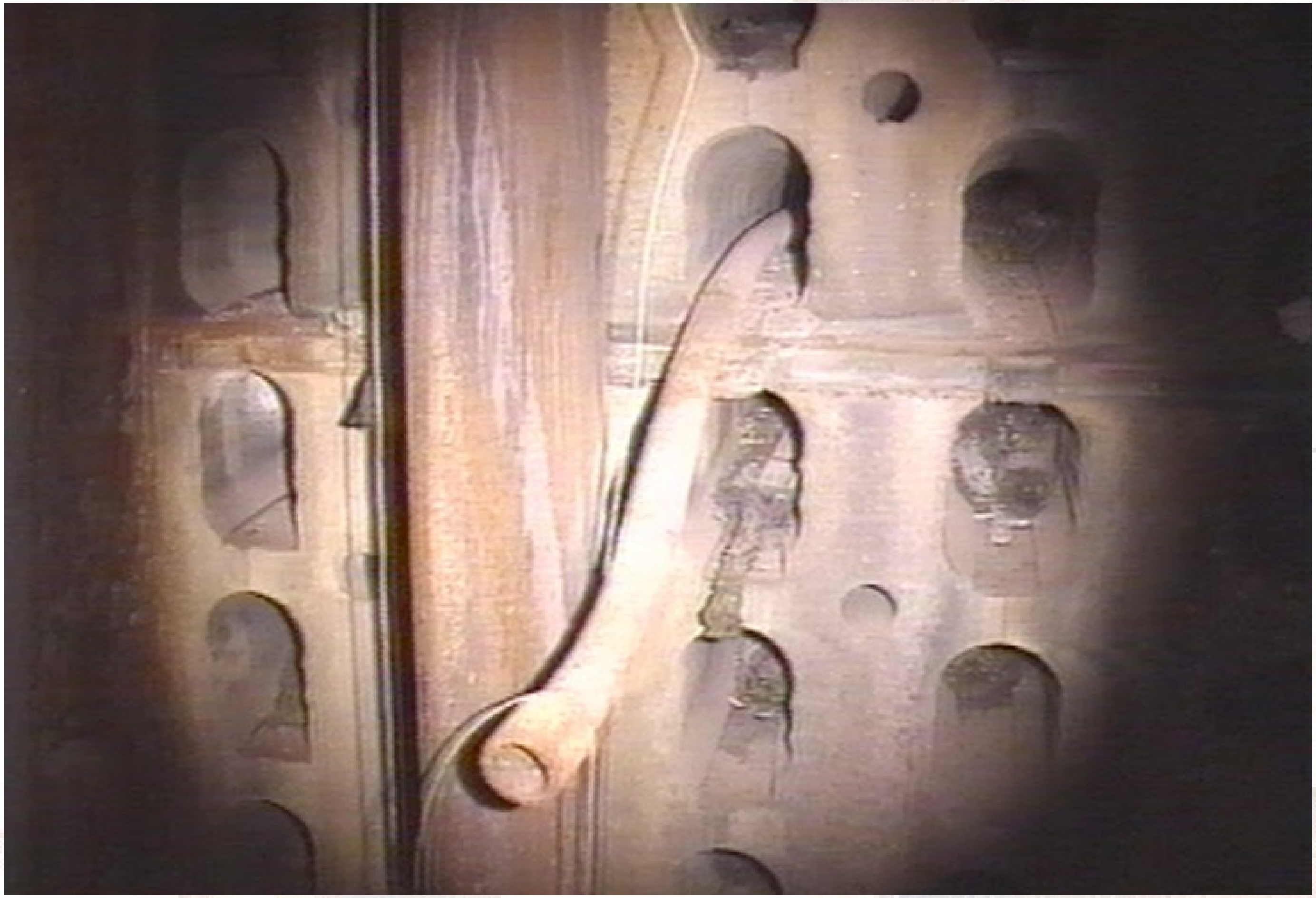
Metal Pipe - channel 21.55



Hazards and decommissioning issues

Pile 1 safety issues for decommissioning

- ~15 te fuel still present
- Possible core voidage post ‘57 fire - seismic collapse is Design Basis Accident under C&M
- Characterisation issues:
  - Wigner energy in graphite
  - ‘hydride event’ (pyrophoric material present?)
  - graphite dust explosion?
  - Criticality?

Characterisation issues dominate - no intrusive FAZ survey at present. Physical characterisation dominates.

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Hazards - Wigner energy

- Pile was left partially unannealed in '57
- Extent of anneal is unknown
- WE will be greatest nearer cooler charge face and core edges in high flux regions
- WE is principally issue for waste disposal
- Pile 1 accumulated ~3 times more neutron dose than Pile 2 (4.1 x 10^4MWd cf Pile 2, 1.5 x 10^4MWd)

Only route forward for WE determination is physical sampling!

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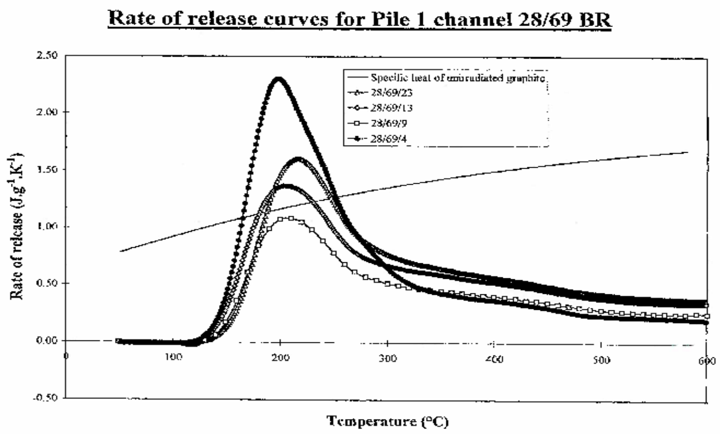
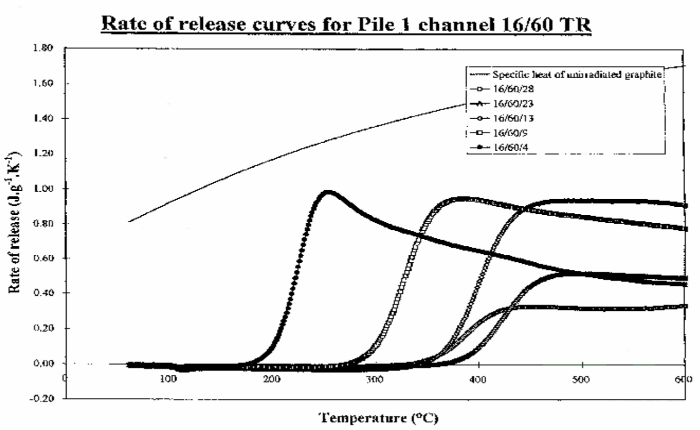
Rate of release curves for Pile 1 graphite samples



← **<0.4 x 10^{20}n/cm^2;T_{irr}<50°C**

- Ch 28/69 BRH shows 'classic' WE pk at 200°C . Nr Pile edge, low temp
- Total WE 400-500 J/g
- *3 plots above C_p*



← **>0.4 x 10^{20}n/cm^2; T_{irr}> 50°C**

- Ch 16/60 above FAZ; loss of 200°C peak
- Total WE >1000 J/g
- *No plots above C_p*

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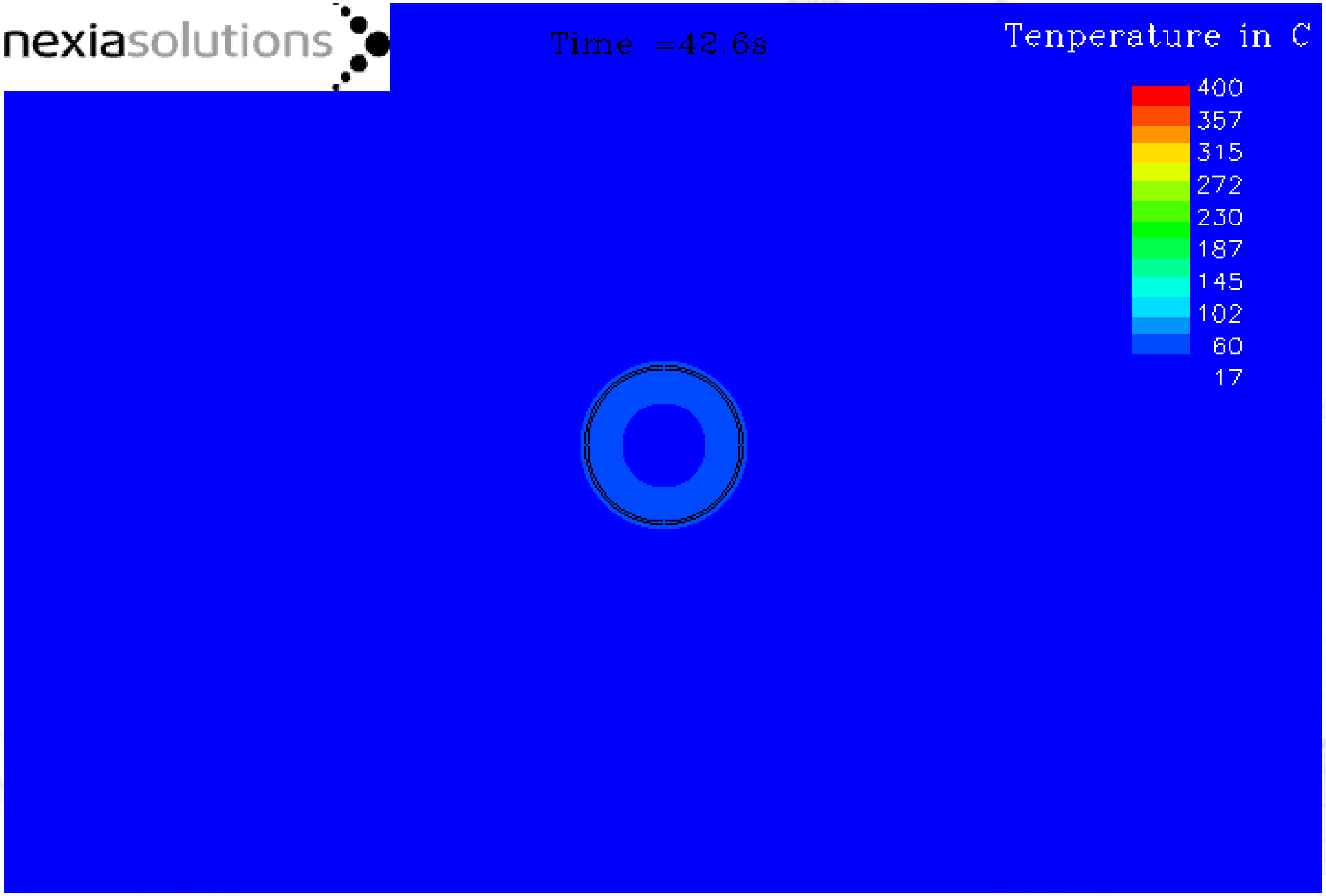
Modelling sequence for Wigner energy release in Pile graphite (courtesy of Nexia solutions)



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Results of trepanned graphite samples from Pile 1

Pile 1 had ~3 time the dose of Pile 2 (4.15×10^4 MWd)

- *Density*; 3% wt. loss (1.58 cf 1.63g/cm^3); radiolytic oxidation
- *Wigner energy*; up to 1220 J/g
- *Thermal conductivity*; min 2.1 W. m^{-1}.K^{-1} cf 100 - 200 W. m-^{1}.K^{-1} ⊥ and ‖ to extrusion direction
- *Thermal oxidation rate* at 637 K – high variability; 30-700 µg.g^{-1}.h^{-1}, mean 760 µg.g^{-1}.h^{-1}; isolated results to 7405 µg.g^{-1}.h^{-1} Catalytic effects probably Pb.

Results of trepanned graphite samples from Pile 2

- *Density*; 3% wt. loss (1.58 cf 1.63g/cm^3); radiolytic oxidation
- *Wigner energy*; up to 1060 J/g
- *Thermal conductivity*; min 2.3 W. m^{-1}.K^{-1}
- *Thermal oxidation rate* at 637 K – high variability; 30-700 µg.g^{-1}.h^{-1} isolated results to 10767 µg.g^{-1}.h^{-1}. Catalytic effects.

Strategy for graphite waste management

Key Points:

- Disposal as ILW in standard Nirex 4m box
- Not annealing graphite
- Not encapsulating graphite in cement for interim storage
- Intent to demonstrate safety during interim storage, transport and final disposal in National ILW repository

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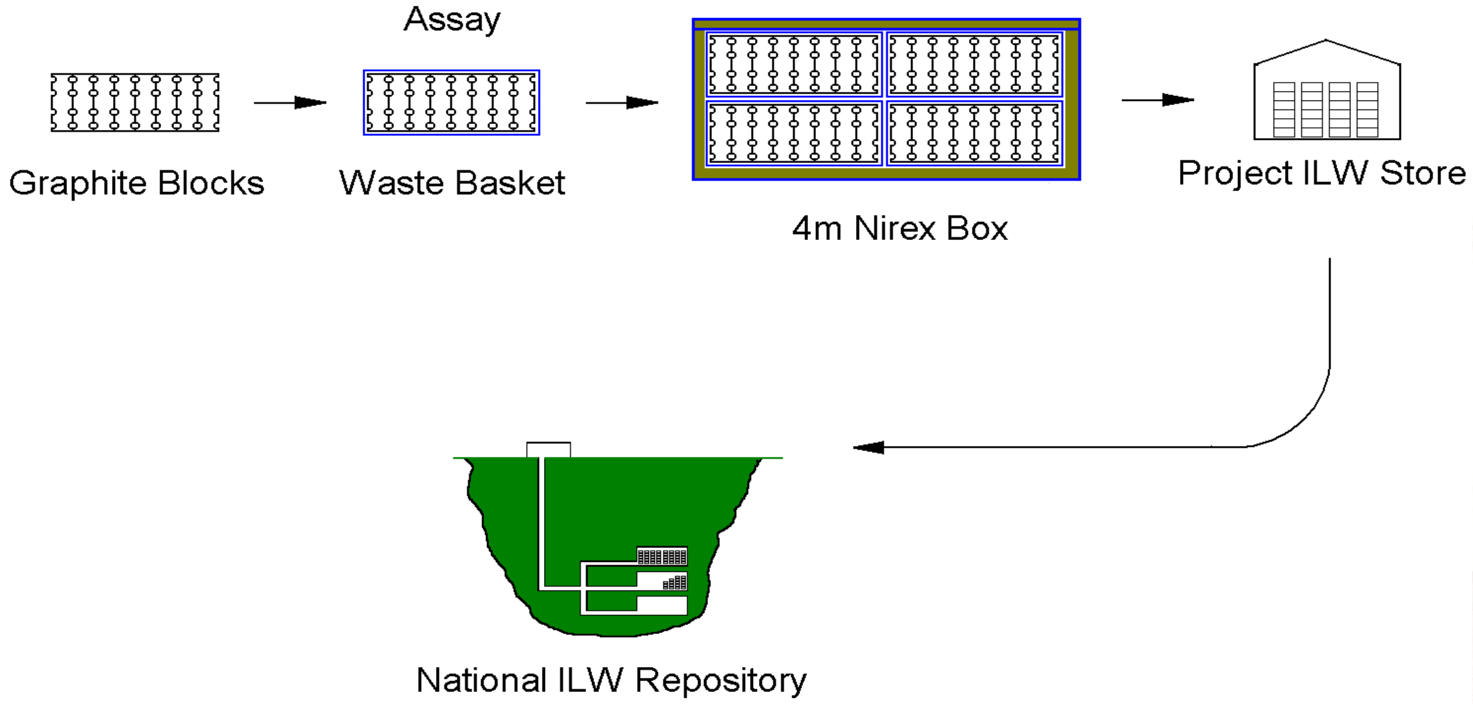
Piles Project Strategy for Graphite WM



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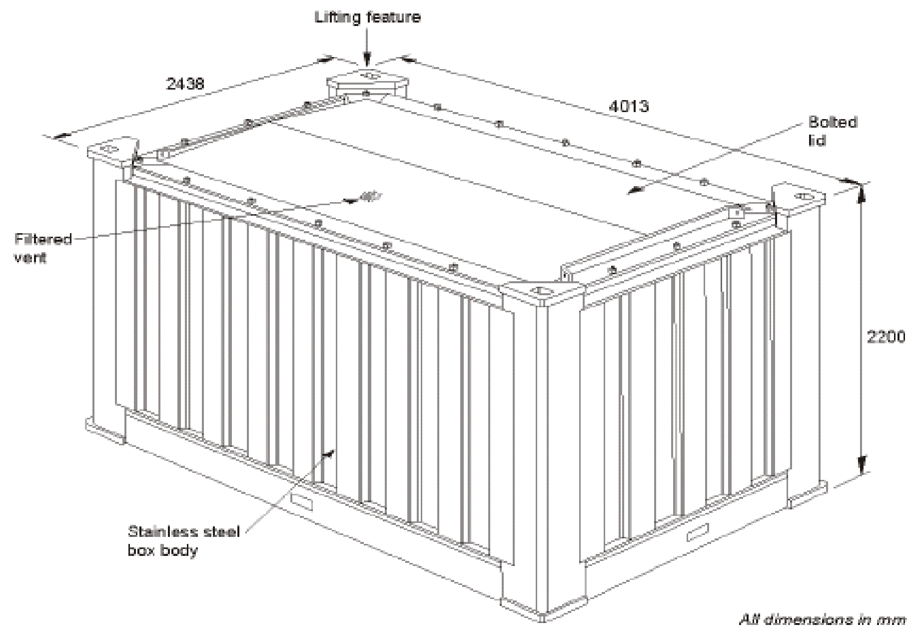
Nirex 4m Boxes



Key Issues for graphite waste packaging

- Dust (mainly oxidation products)
- Graphite flotation (if encapsulated later)
- Galvanic corrosion (acts as ‘noble’ metal, galvanic corrosion)
- Wigner energy

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Wigner Energy issues

Issue – stored energy could be released during grouting of the National ILW repository causing heat release which could damage the integrity of the wasteform and/or backfill.

Intent - To work with Nirex in modelling the behaviour of the repository and graphite boxes during grouting in order to :

- Understand the causes and effects
- Quantify the risks – impacts and probabilities
- Reduction of key risks e.g. exploring backfilling scenarios

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Hazards - pyrophoric materials

- Uranium hydride is the only pyrophoric material ***conjectured*** to be a hazard in the Pile (from thermodynamic considerations)
- Water used during '57 fire to extinguish and remove heat
- UH_3 unlikely to have formed but cannot be ruled out:
  - anaerobic pockets, 'crimped' fuel cans from rodding
  - for safety argument purposes some is assumed to exist
- Recent published work has improved our understanding of hydride oxidation kinetics. New approach being taken:
  - Use of CFD modelling
  - Combination of CFD with oxidation kinetics to produce a 'thermal model'
  - Simulation of probable Pile 1 scenarios

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Uranium Reactivity

- U metal reacts with oxygen in air → UO_{2+x}
- U metal reacts with water vapour → UH_3
- In Pile 1 conditions UH_3 would not form (air)
- In Pile 1 conditions UH_3 would not survive unless in microclimate situation – unlikely, but cannot ‘prove a negative’

Hence we have pessimistically assumed that the presence of some UH_3 cannot be ruled out for safety case purposes!

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Uranium Hydride Event Sequence

Conjectured event sequence:

→ Hydride Formed → Hydride Survives → Hydride Oxidation → Uranium Oxidation → Graphite + Isotope Oxidation

↑ (into Hydride Survives)

Mechanical disturbance

Seismic event

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Fuel element condition - gross corrosion, Channel 21, 58

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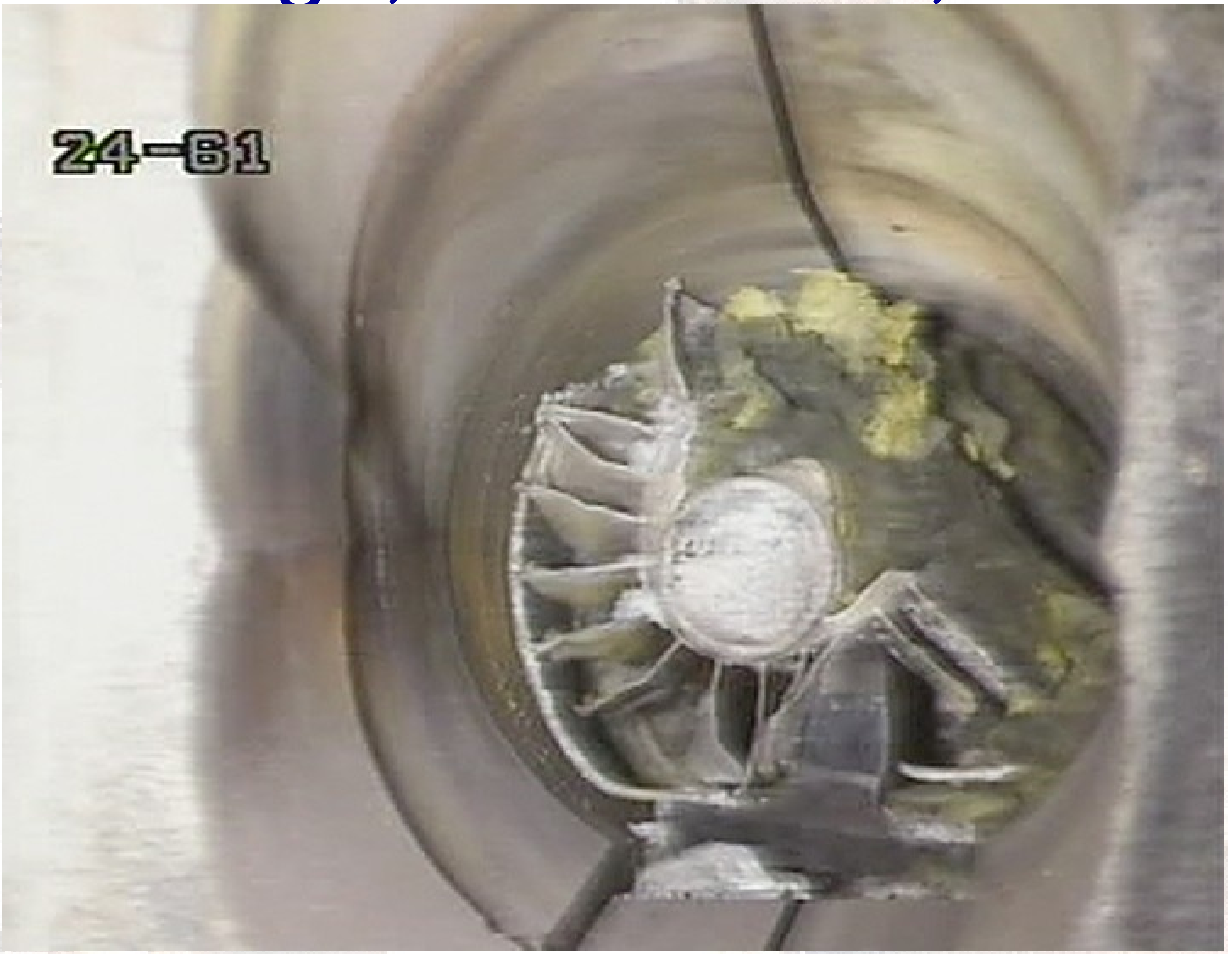
Fuel element condition - severe fuel damage, Channel 24, 61



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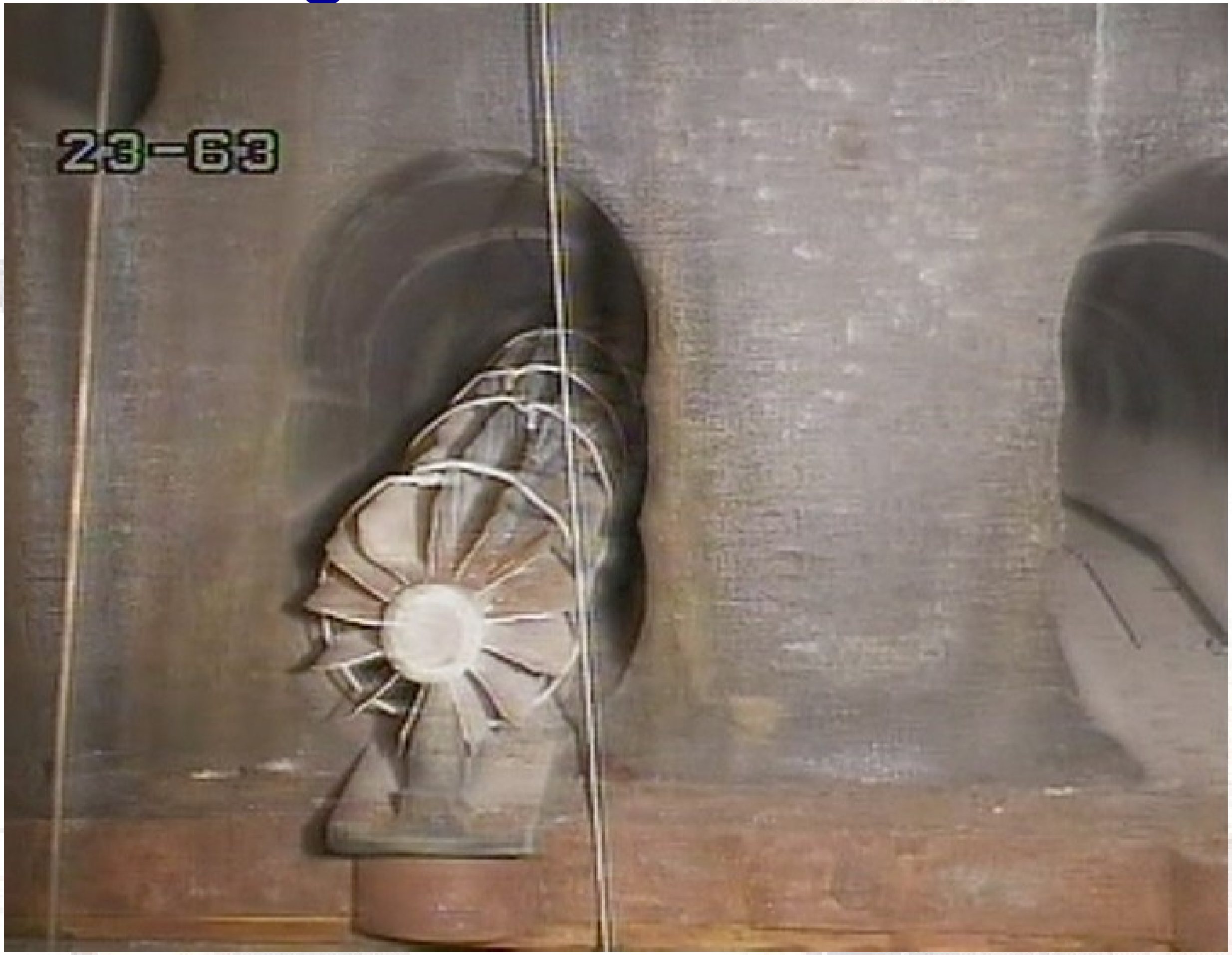
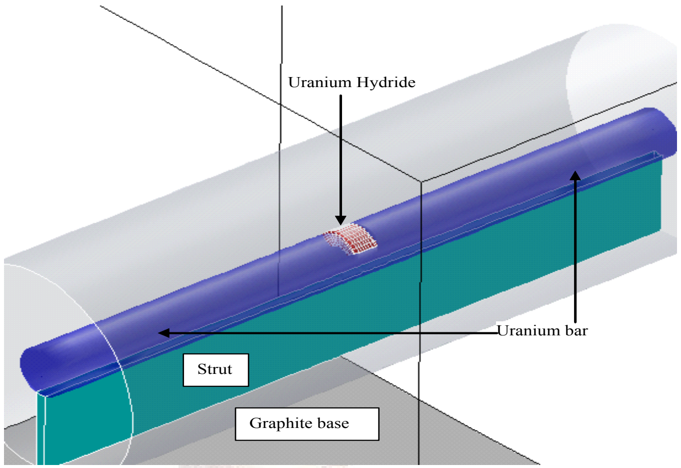
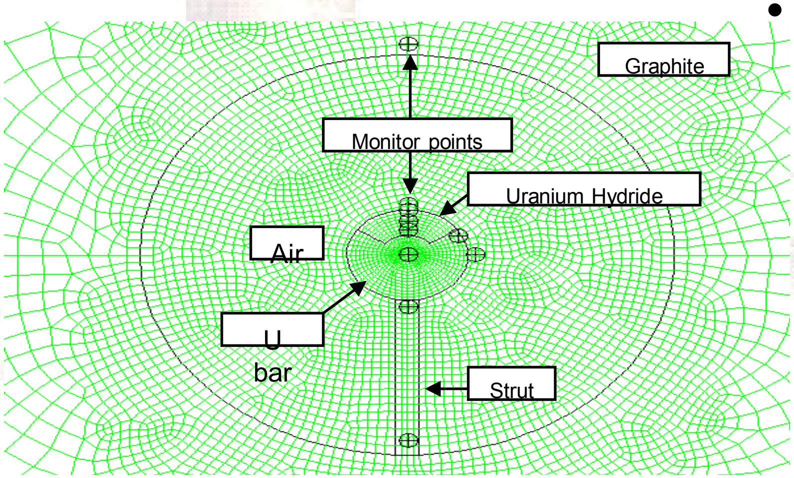
Fuel element condition - minor fuel damage, Channel 23, 63



3D-geometry model of a Pile 1 channel with a hydride patch located in the centre of the uranium bar





- Microclimate hypothesis - small-scale localised corrosion
- Not pure hydride - hydride surface-oxidised
- Assume mechanical disturbance removes clad closure
- Assume air now has unrestricted access to corrosion product

Hydride oxidises with heat generation

Self-heating depends on heat transfer

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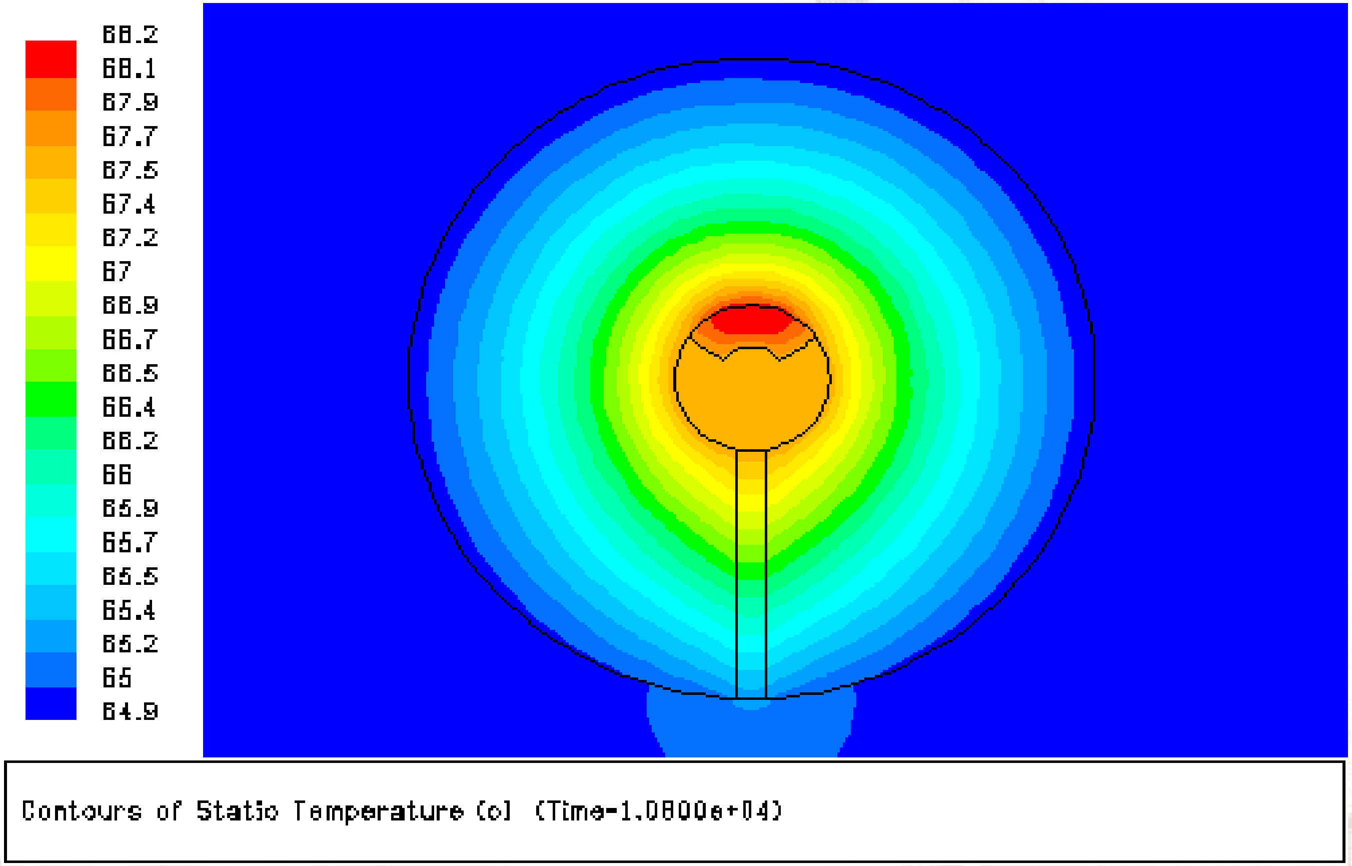
Example temperature contour plot for hydride patch oxidising in contact with uranium



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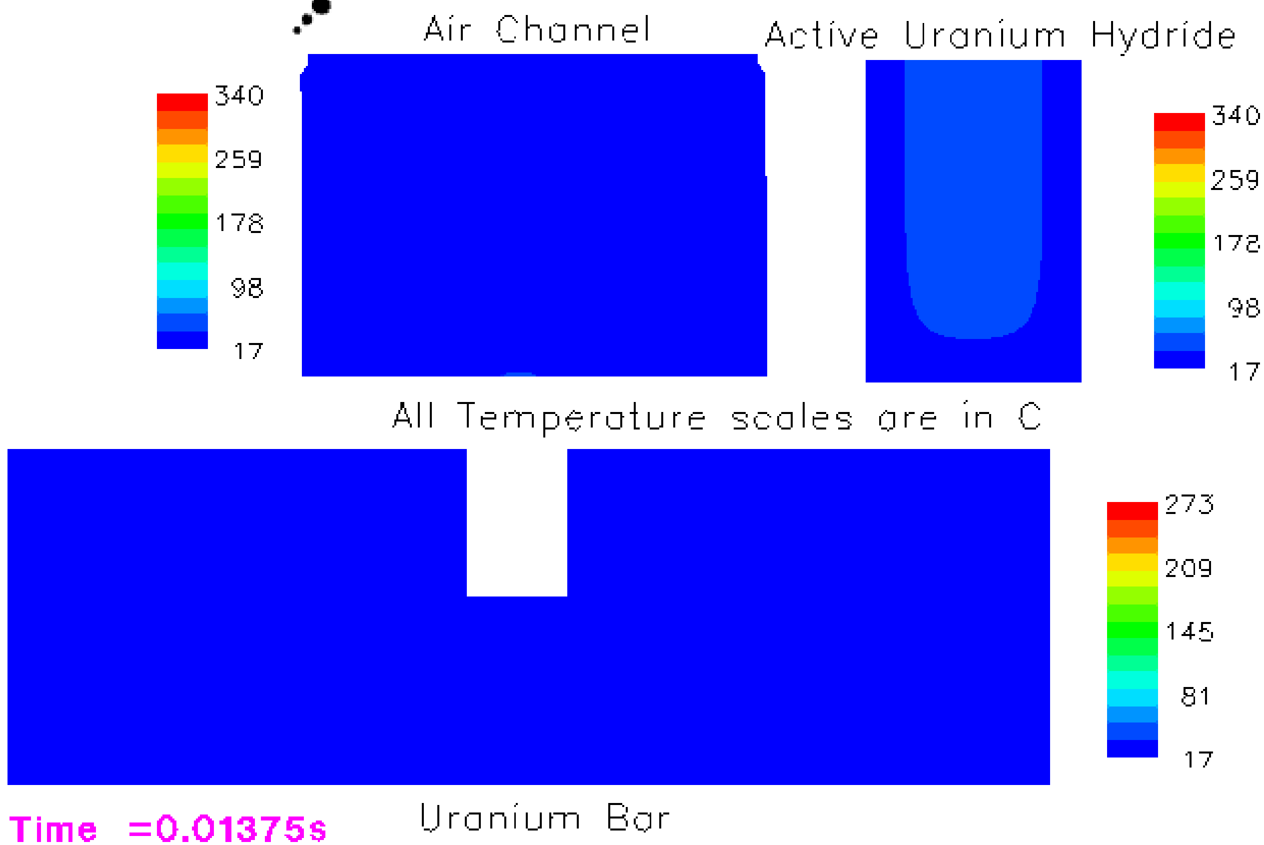
Modelling sequence for UH_3 oxidation in Pile graphite (courtesy of Nexia solutions)

nexiasolutions



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Lessons learned for Pile 1

Conjectured surviving hydride will not self-heat to give a propagating thermal excursion if exposed to air:

- Bulk U metal will not be heated enough to oxidise significantly
- Temp. rise so small - no WE release in neighbouring graphite
- Isotope cartridges remain unaffected; no cross-channel effects
- Effects of hydrogen liberation are insignificant

Argon cover will not be required during dismantling

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Hazards - graphite dust explosibility

- Controversy has existed over the potential for a graphite dust explosion during decommissioning (UK, France, Italy, Japan)
- Graphite dust when levitated in sufficient concentration, with appropriate particle size and high energy input is weakly explosible
- Lead (Pb) is known to enhance graphite oxidation markedly – lead cartridges in Piles
- For safety case purposes some quantitative data was required – research programmes have now been conducted
  -

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Graphite dust 'explosions' - general principles

To have a dust explosion, you must simultaneously have:

- A combustible dust
- An ignition source of sufficient energy
- An atmosphere capable of supporting combustion
- Suspended dust (turbulence or disturbance of deposits);
- A concentration within the 'explosible range'
- A particle-size distribution which permits flame propagation.

For a disruptive incident to occur you must also have:

- Confinement

Important Parameters

- Maximum rate of rise in pressure *(measured as 'deflagration index' K_{st}) – delivers an impulsive load to the system*
- Maximum explosion pressure attained
- Minimum ignition energy
- Minimum explosible concentration
- Auto-ignition temperature for deposited dusts.

Nuclear grade graphite dust is now formally classified as "weakly explosible" [St_1]
(based upon the ISO test which uses a powerful chemical igniter)

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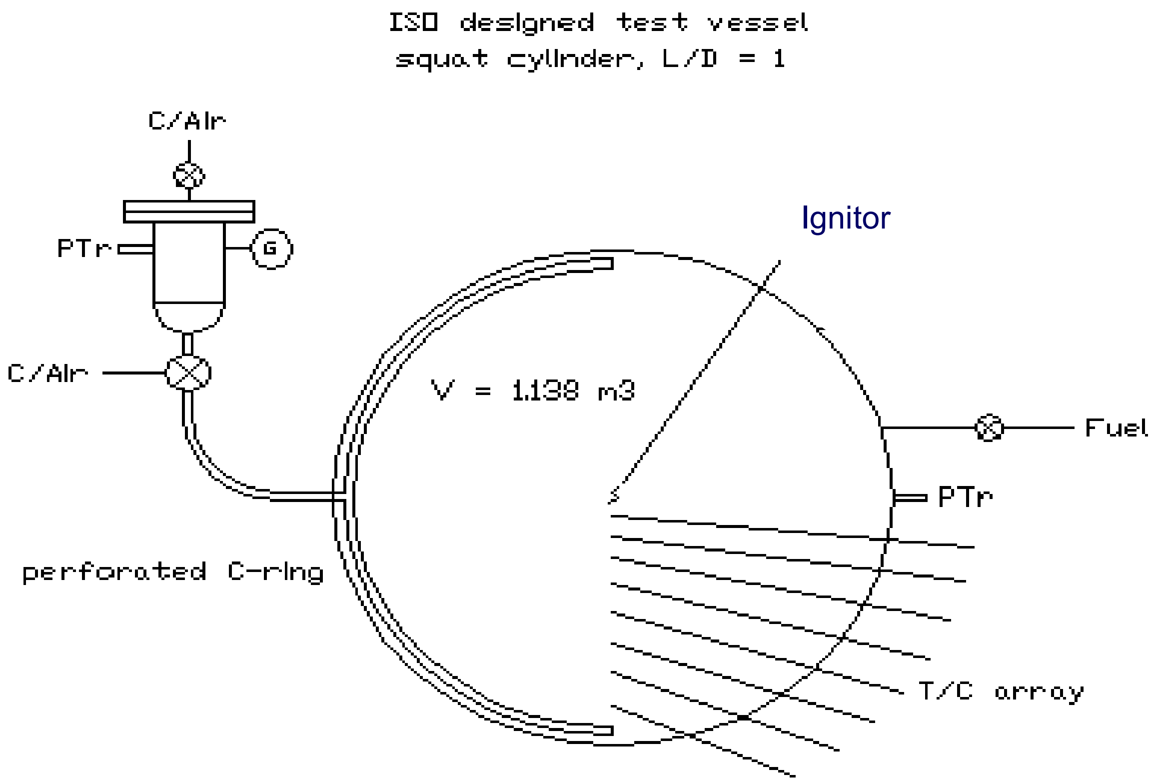
ISO Standard Apparatus



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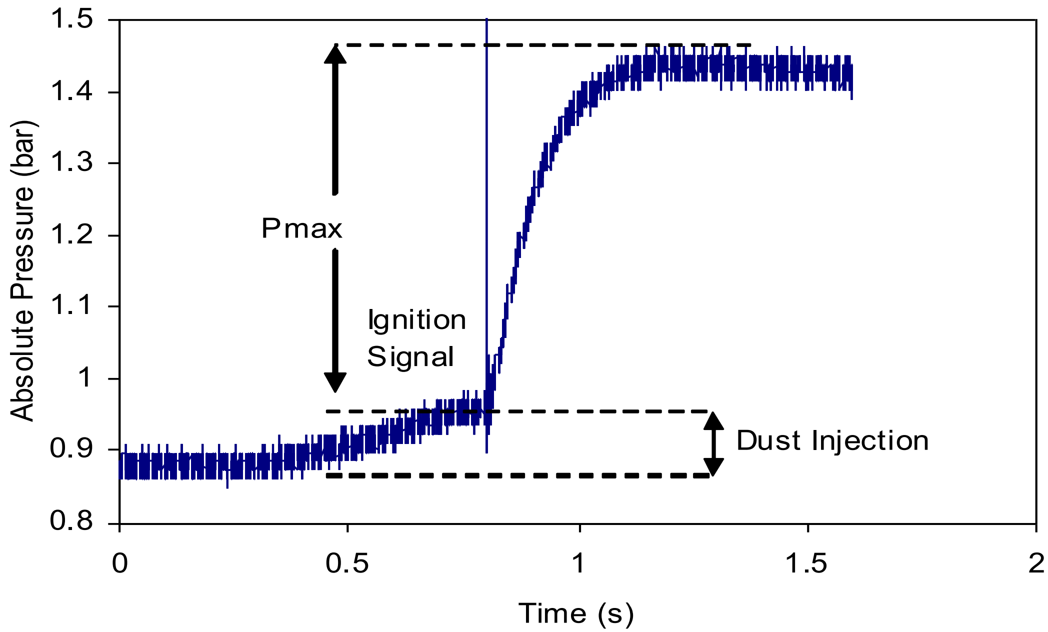
University of Leeds programme



Typical pressure v. time plot for a dust explosion

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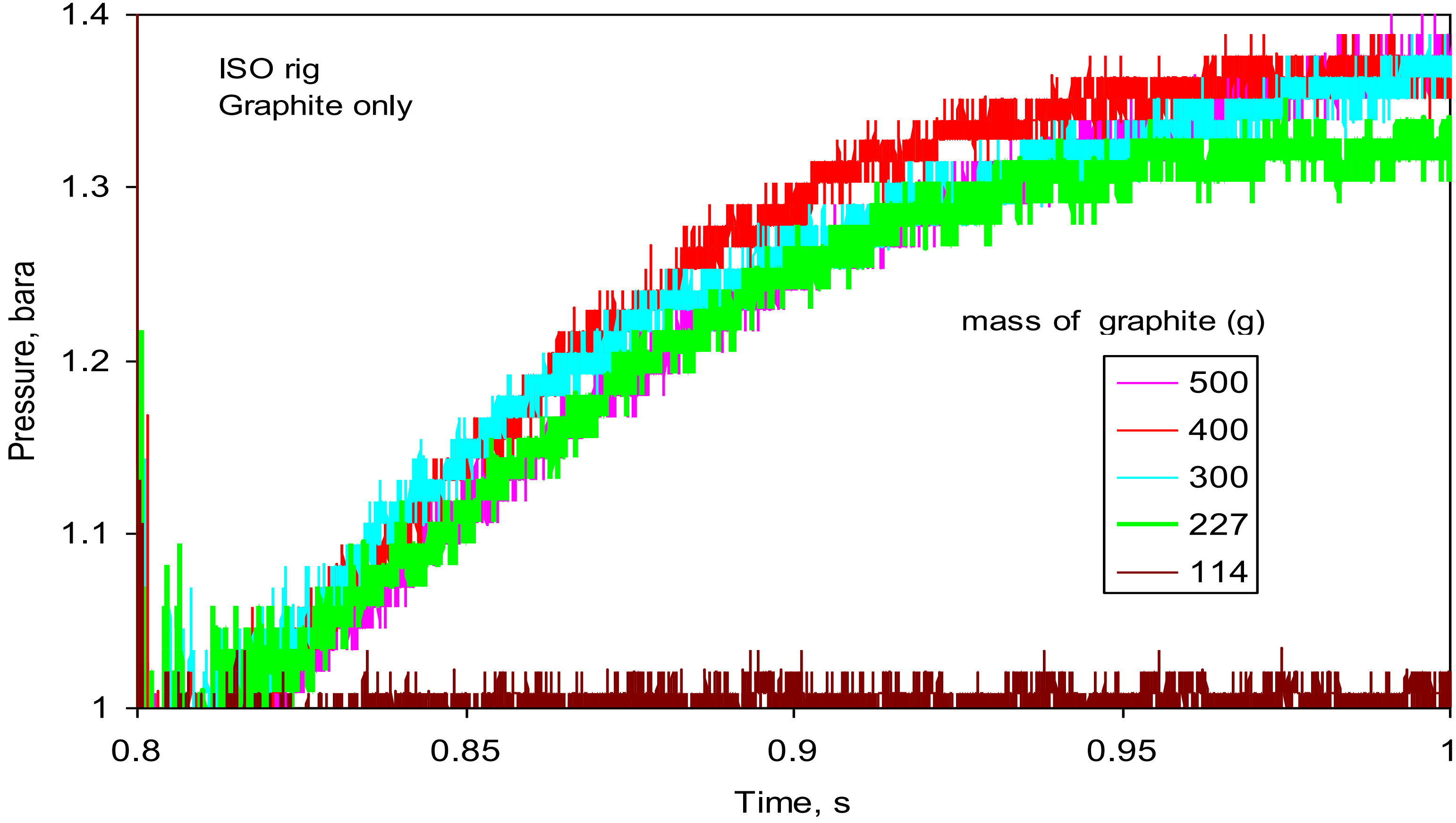
Overpressure due to Graphite alone



Conclusions/1

Studies for Pile 1 have shown graphite to be weakly explosible – but:

- it is unlikely that there will be sufficient graphite dust present or that it will be rendered airborne;
- it is likely that a significant fraction of the inventory of graphite particles will be in the explosible size range;
- the graphite dusts are likely to be mixed with a substantial amount of inert material;
- a sufficiently powerful and energetic ignition source is not available (2000 J required); and

- it can be eliminated completely by careful attention to operation practice *i.e.* by removing at least one of the necessary conditions for a deflagration.

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Conclusions/2

- WAGR graphite in UK successfully removed without any concerns from graphite dust, despite initial metal cutting operations above the open graphite channels: this reactor had operated with high-methane coolant and also contained reactive (non-graphitic) deposits associated with the graphite. Propane torches were used in adjacent areas…

…the safety case, which included analysis of the potential risk of starting a secondary dust explosion from an initial propane explosion in the reactor vessel, was accepted by UK safety authorities *(with obvious use of safety cut-off valves!)*

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Hazards – remaining fissile content of Pile 1

- Estimation of effective neutron multiplication factor, k_{eff} is required for criticality safety analysis:
  - to plan dismantling
  - under accident conditions (seismic)
  - Quantitative estimate of reactivity required since 15 te U is sufficient for a criticality (Li cartridges suppressing reactivity)
  - a combination of modelling codes (MONK, MCNP) and direct neutron flux measurements used

Pile 1 fissile content - results

- Direct neutron measurements showed improved criticality margin over value estimated by MONK calcs (6% less)
- Indication that less fuel present than previously thought
- Safety report demonstrated that criticality margin is preserved during DBA (seismic core collapse)

Conclusions on decommissioning issues

- Pile 1 presents some particularly difficult decommissioning problems with unique issues
- Situation will be improved by ability to remove samples from fire-damaged area
- Progress has been made on several fronts:
  - Visual inspection via CCTV
  - Better understanding of the Wigner energy levels in graphite
  - Uranium Hydride
    - pessimistic analysis shows oxidation transient will not propagate
    - can dismantle in air
  - Graphite dust explosions can be dismissed
  - Criticality - no problems during a seismic event providing neutron absorbing material remains
    - no additional N absorber needed
    - sequenced removal of material during dismantling

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