Nuclear Decommissioning Authority

# Criticality Safety Research for a UK Geological Disposal Facility

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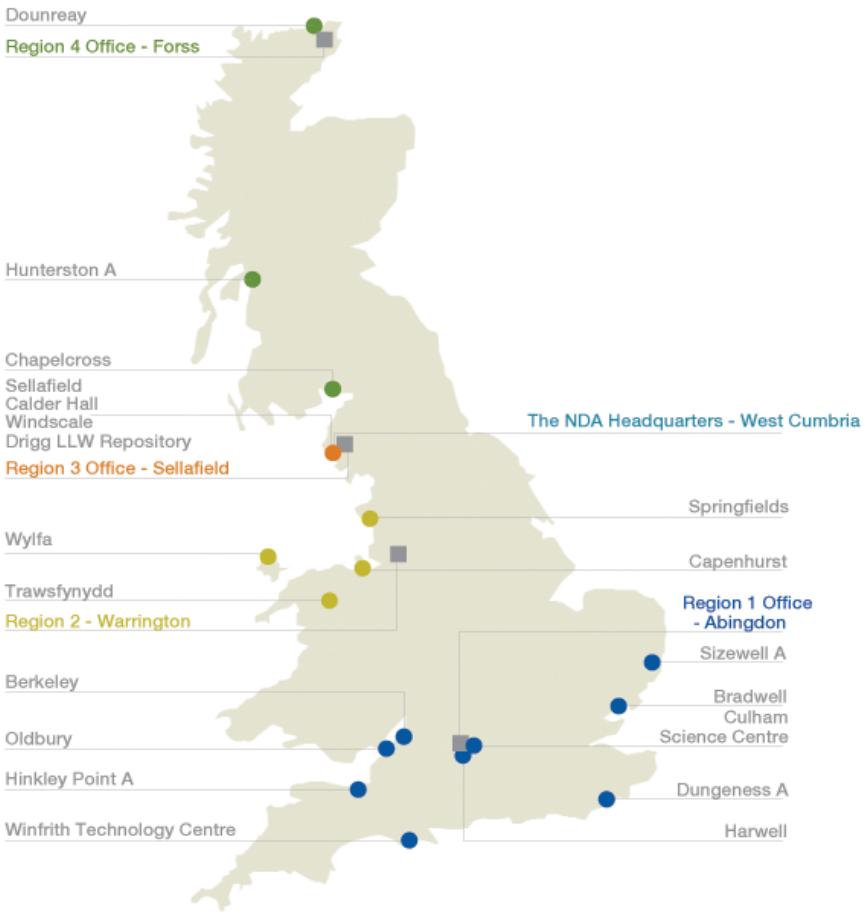
# The NDA

- Non-Departmental Public Body since April 2005
- Remit to clean up the civil public sector nuclear legacy
- Sites and facilities built from 1940's onwards
- Responsible for 20 former UKAEA and BNFL sites & integrated waste strategy
  - Safe and secure storage of radioactive waste
- Planning and implementing geological disposal

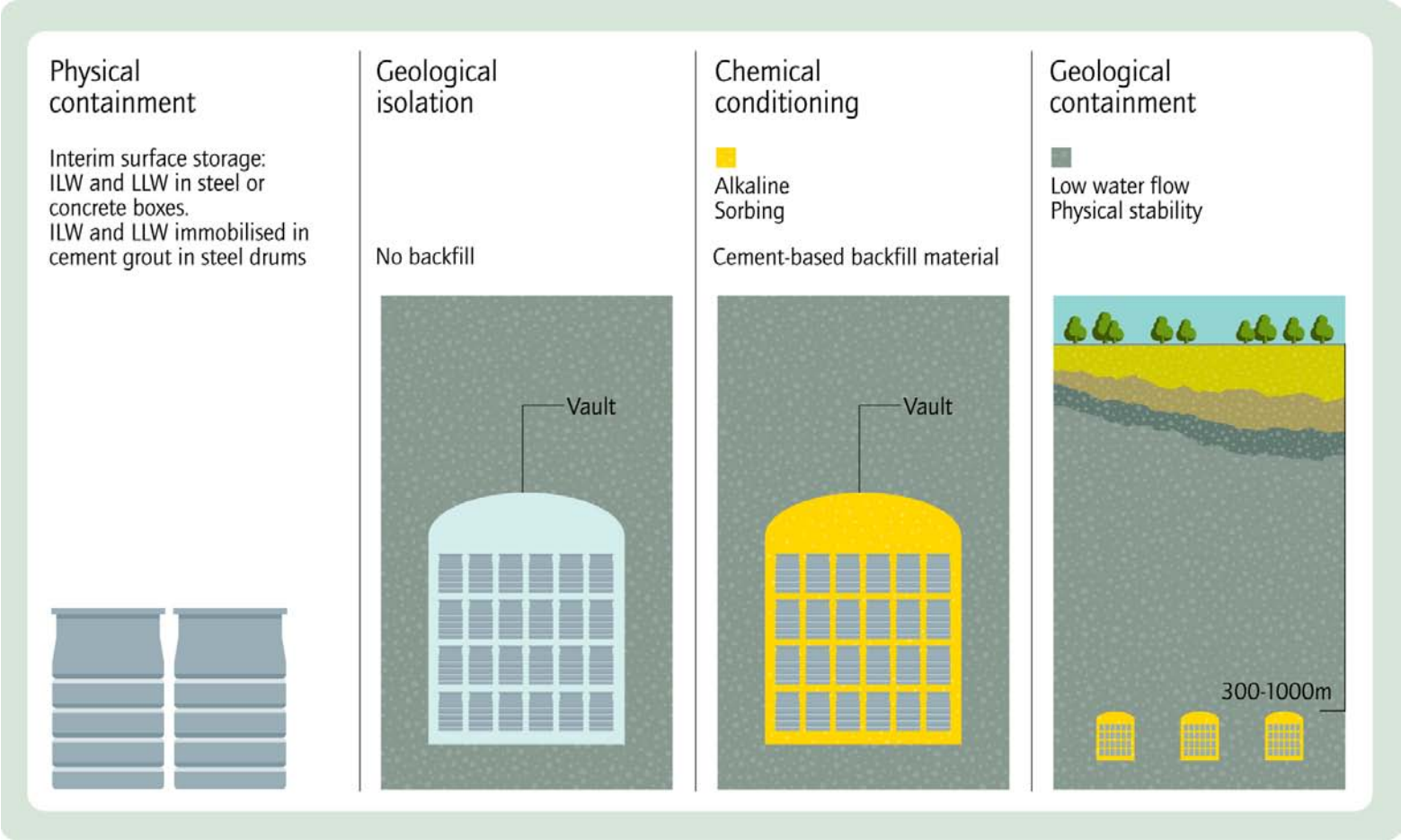


# Inventory of radioactivity

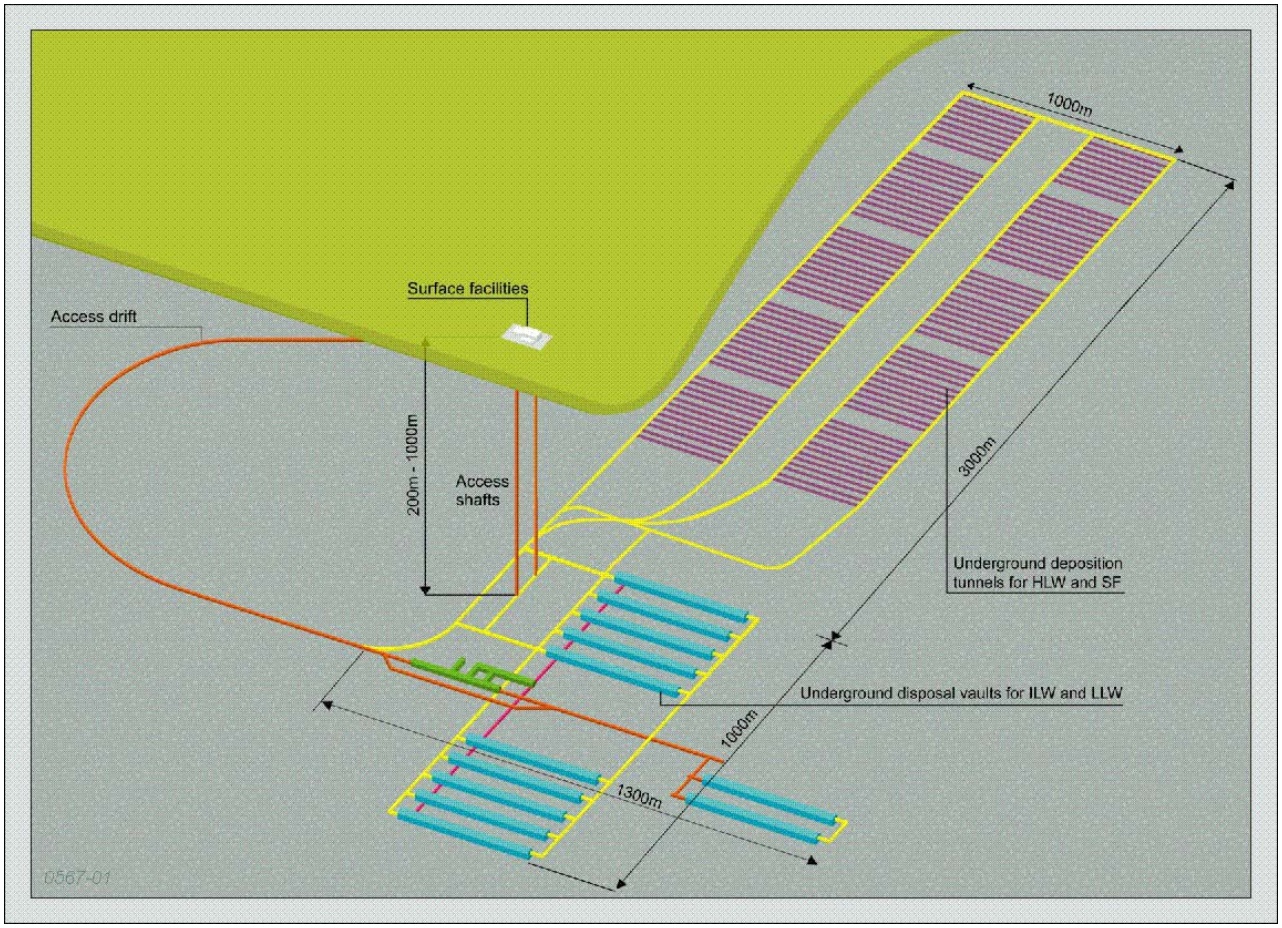
| Material | Terabequerels | % |
|---|---|---|
| HLW | 36,000,000 | 41.3 |
| ILW | 2,200,000 | 2.5 |
| Spent Fuel | 45,000,000 | 51.6 |
| Pu | 4,000,000 | 4.6 |
| U | 3,000 | 0.0 |
| Total | 87,200,000 | 100 |

# Intermediate Level Waste (ILW)

# Geological disposal concept for Intermediate Level Waste



# Geological disposal facility



# Criticality Safety Requirements

- Transport:
  - prevent criticality
- Operations:
  - risk is ALARP
- Post-closure:
  - demonstrate that the possibility of a local accumulation of fissile material to produce a neutron chain reaction is not a significant concern

# Criticality safety arguments - wastes

- detailed knowledge of the inventory of wastes and materials
- in ILW, the fissile material is mostly mixed with a large excess uranium-238
- small amounts of ILW will contain separated plutonium and High Enriched Uranium (HEU); however, they are mixed with other waste materials.
- For pure materials such as plutonium and uranium we can design a wasteform that is subcritical
- Most spent fuel is removed from nuclear reactors because a large proportion of the fissile content has been used up

# Criticality safety arguments - packages

- specify and ensure control of all waste package contents
- For spent fuel, the design is already fixed so we would design a package to be sub-critical; this might include using materials that absorb neutrons to prevent criticality
- In all cases we aim to design packages that are robust to operational faults.

# Criticality safety arguments - system

We consider a criticality post-closure to be a low probability event.

- For ILW, the packages may be well spread out; the fissile content totals 15 tonne, but this is present at a low average concentration within 1,000,000 tonne of waste, packaging and backfill materials.
- We encapsulate much ILW in cement, and we have designed a cement backfill that will maintain physical and chemical barriers to relocation of waste materials.
- For pure materials, we would design a wasteform that is stable for long times and would only slowly release fissile material
- For spent fuel we would use a package and emplacement design to maintain sub-critical conditions over long timescales.

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# Understanding Criticality under Repository Conditions (UCuRC)

- Background
- Approach
- Example results
- Reporting
- Independent peer review

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# Background (1)

Relationship to assessment work

- Programme developed from work on post-closure criticality safety of Nirex disposal concept in 1990s – concluded we needed a better understanding and models to calculate effects
- Approach has been informed by assessment work, e.g. scenarios considered for concentration of critical mass
- But not considering probabilities of criticalities here – range of test cases up to very large critical masses

# Background (2)

What we knew at the beginning of the programme (2001)

- General understanding of criticality
- Results of previous point static calculations for (absolute) minimum critical concentrations and masses for repository materials
- Most critical systems would have negative feedback
- But some plutonium systems would have positive feedback and evidence in literature of heterogeneous uranium systems with positive feedback
- Plutonium systems with positive feedback in backfill at repository pressures would not turn over just from radiolytic gas or steam production

# Approach

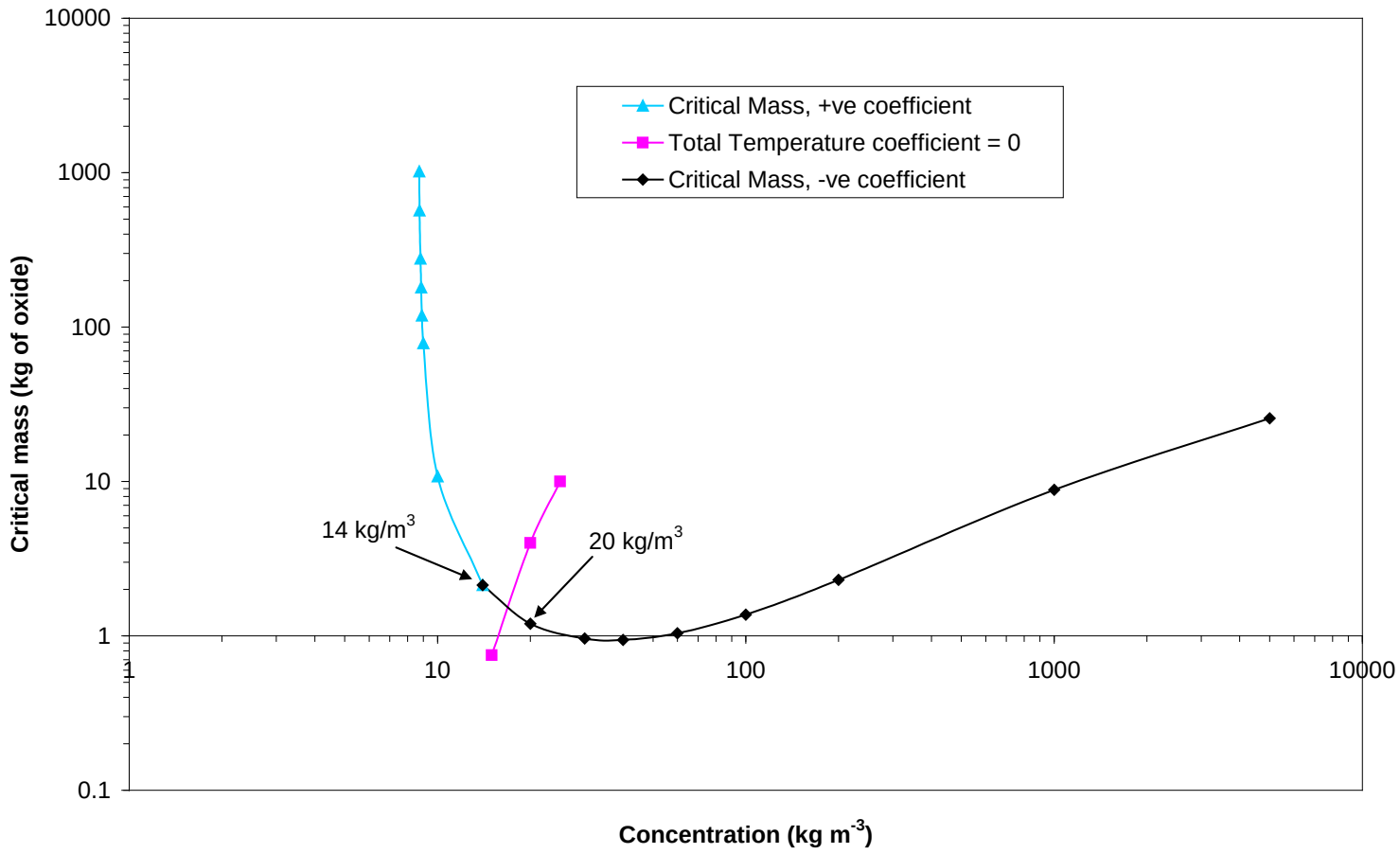
- Developed a flow chart on evolution of a criticality covering systems with positive and negative feedback
- Based model development on flow chart and scenarios for accumulation of a critical mass
- Static calculations to provide understanding for assessment

# Approach – Statics calculations

Static calculations

- Large suite of calculations to identify critical systems
- Also calculated initial feedback characteristics
- Criticality ‘maps’
- Wide range of parameters varied

# Statics criticality map: Pu-239 in backfill



# Approach – QSS model

Quasi-steady-state (QSS) criticalities

- Most systems would lead to QSS criticalities
- QSS criticalities would take a long time to initiate and evolve – burn-up and radioactive decay important
- Developed QSS Model:
  - Relatively simple point kinetics model
  - Wide range of cases can be calculated

- Investigated uranium systems with positive feedback at boiling with QSS Model and FETCH in combination

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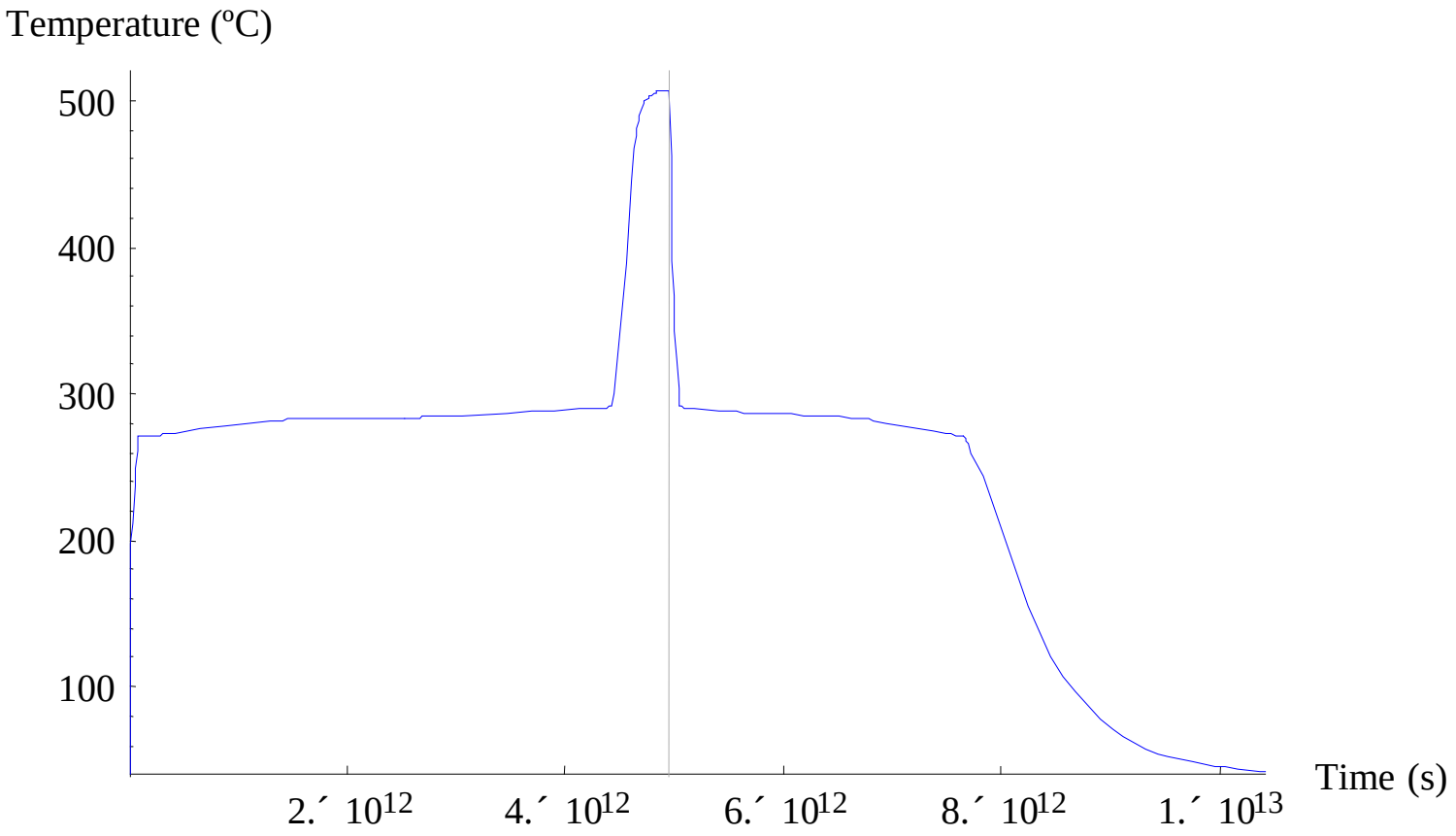
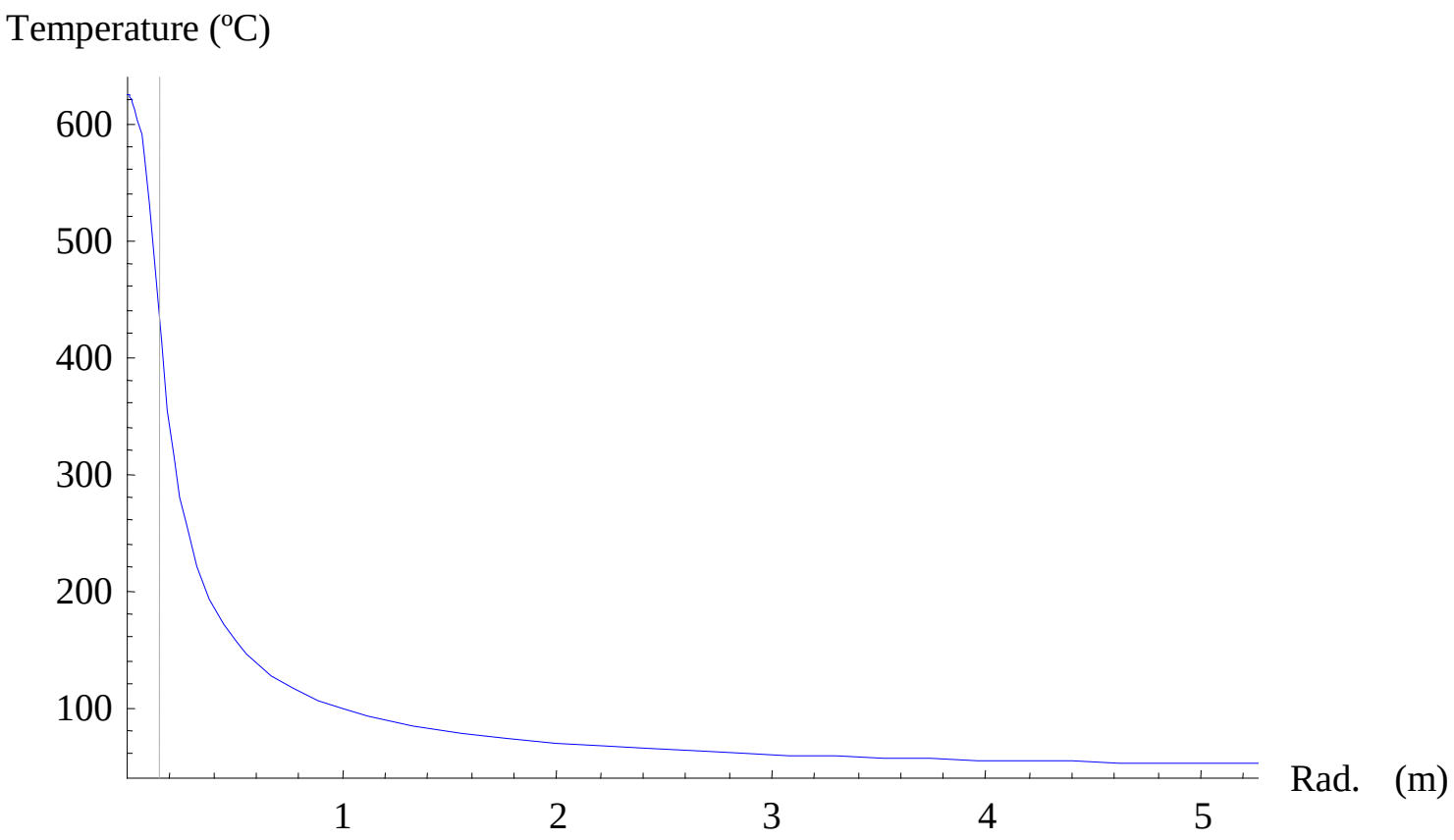
# QSS: $^{239}PuO_2$, $10^{-9}$ kgm$^{-3}$s$^{-1}$, backfill sphere radius 0.15 m



# QSS: $^{239}PuO_2$, $10^{-9}$ $kgm^{-3}s^{-1}$, backfill sphere radius 0.15 m

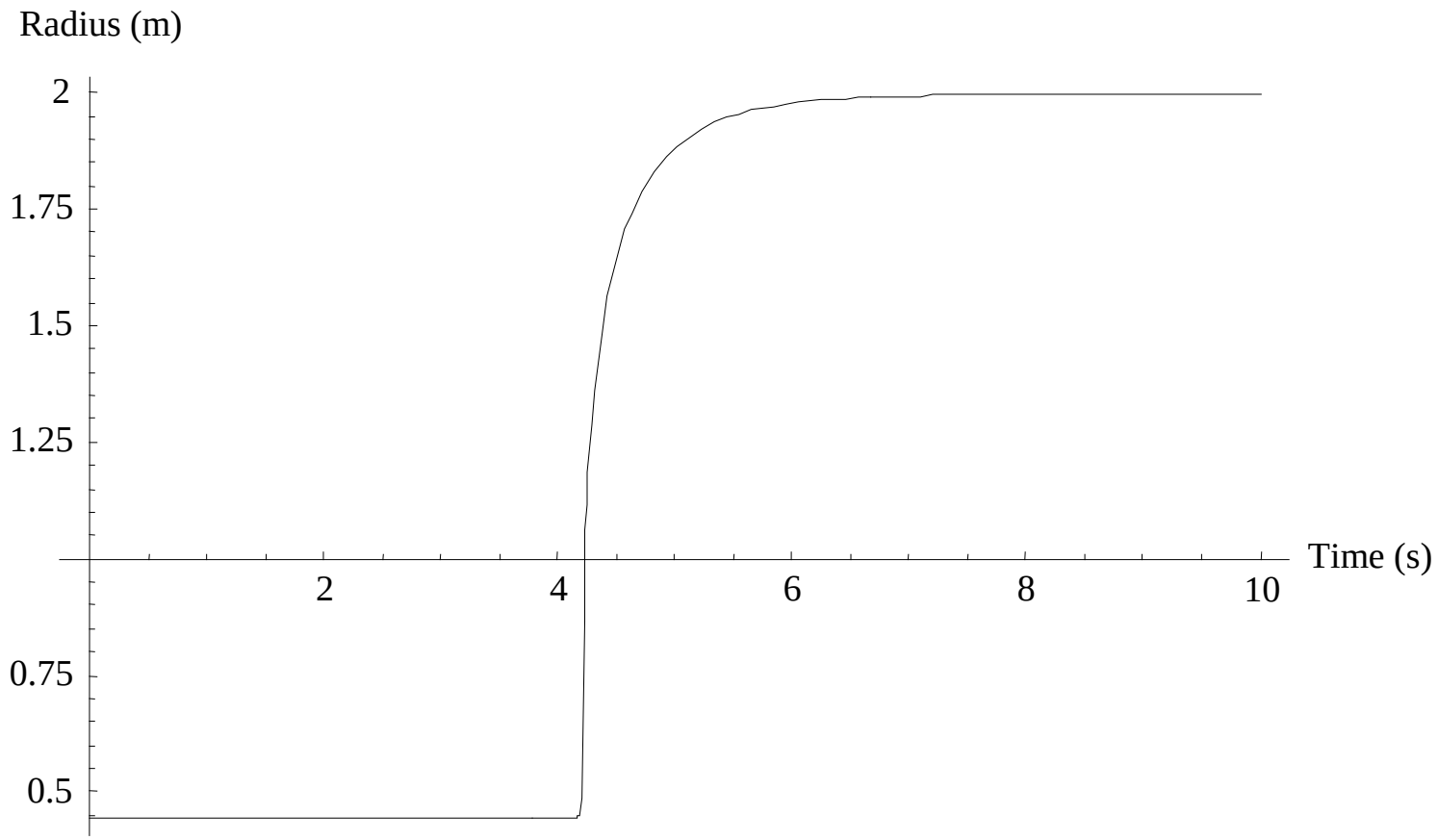


# Approach – Rapid Transient models

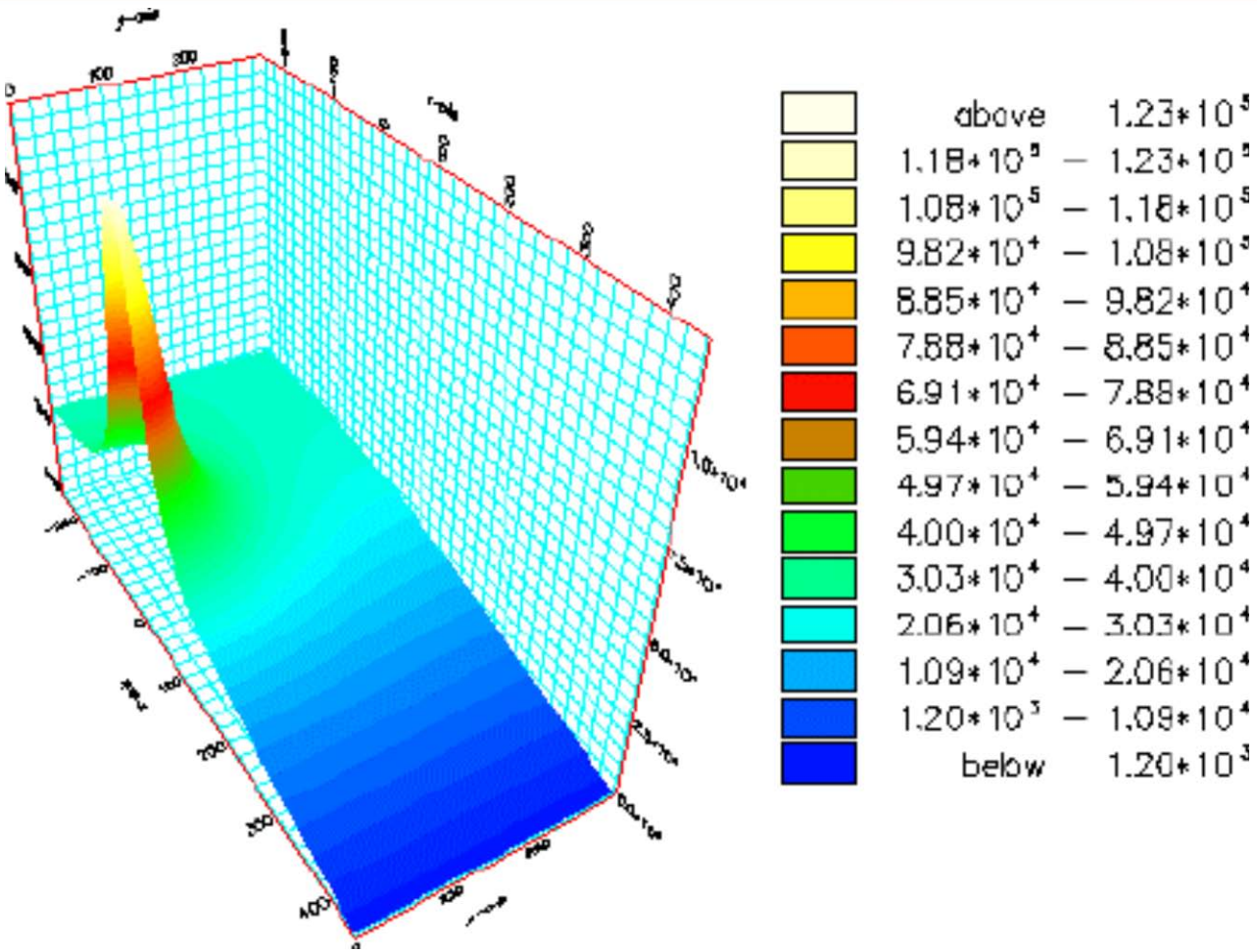
Rapid transients

- Showed early on with FETCH that increase in permeability insufficient to turn over positive feedback events
- Twin-track approach:
  - RTM, new relatively simple point kinetics model based on known phenomenology of underground nuclear and chemical explosives
  - Develop FETCH to model necessary phase changes, fracturing and movement of materials

# RTM: 3.9 kg $^{239}PuO_2$, 10 kgm$^{-3}$, backfill sphere radius 0.44 m



# FETCH: 4.5 kg $^{239}PuO_2$, 10 kg.m$^{-3}$, backfill cylinder 0.416 m, pressure (Pa)



# Main reports

- Research reports (2006) subjected to Independent Peer Review
- Verification, Validation, Benchmarking, Uncertainty and Sensitivity (2008)
- Criticality Safety Synthesis Report (2009)
- NDA Bibliography: http://www.nda.gov.uk/documents/biblio/

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# Independent peer review

- Undertaken by independent experts in criticality and rock mechanics, from US and UK.
- The extensive and careful nature of the work was noted by the reviewers.
- The difficulty in obtaining data for direct benchmarking was recognised, but further benchmarking against any existing data was considered important.
- Therefore the approach of developing two separate models for energetic transients was thought sensible, and the reasonable agreement between them was thought to give added confidence to the overall results.
- It was thought important to understand the significance of fracturing in real materials, which might already be fractured.
- The need for further benchmarking and building confidence in the material response models is recognised and is part of the ongoing programme.

# Research Needs

- Validation requirements – comparison of prediction with measurement
- Benchmarking opportunities – comparison of prediction with prediction
- Further evidence – comparison with observation, e.g. Oklo.

# Fit for purpose models

| | Desired end-state | UK models | International |
|---|---|---|---|
| Verified | Y | Y | |
| Validated | Partial / full | As far as currently possible | |
| Benchmarked | Y | ? | ? |
| Uncertainty | Y | Partial | ? |
| Sensitivity | Y | Y | ? |

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# Post-closure Performance Assessment: Consequence of criticality assessment

- To carry out an initial assessment of post-closure criticality safety for the Phased Geological Repository Concept (PGRC).
- Building on the UCuRC work and NDA post-closure performance studies and methodologies, this will involve performing calculations and assembling the arguments for safety to progress the NDA understanding of the consequences of repository criticality on post-closure indicators such as calculated near-field and far-field fluxes, and dose and risk to man.
- This project (now in its second year) forms an input to the DSSC, initially to the Generic DSSC

# Summary of first year activities of project

1. Determined factors controlling repository performance
2. Determined how these factors are affected by a criticality
3. Determined magnitudes of the direct effects of a criticality
4. Calculated changes to factors controlling repository performance
5. Calculated effects of changes on repository performance
6. Determined range of criticalities that could affect repository performance

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# Direct effects of a criticality

- Increase in temperature
- Increase in pressure and changes to rock properties
- Change to inventory
- Radiolysis

# Conclusions from first year of project

- Very large amounts of fissile material would have to accumulate to adversely impact on repository performance

- When coupled with probabilistic analysis showing probability (of any) criticality low, would meet regulatory requirement, namely to demonstrate that criticality is not a significant concern

# Aims of second year of project

- Work to date has focussed on ILW; project now considering implications of criticality in a single Geological Disposal facility (GDF) hosting range of higher activity wastes
- Further examining probability of a criticality / multiple criticalities in a GDF (to couple with first year of *Consequences* project)
- Examining criticalities in context of GDF hosted in a range of host rocks (hard crystalline rock has been main focus to date)
- Output from project, together with Criticality Safety Synthesis Report, will form basis of input to Generic DSSC

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