Environmental safety case models supporting geological disposal of the UK’s radioactive waste

Presentation for US Nuclear Waste Technical Review Board

November 2021

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Introducing Sarah…

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Post Closure & Environmental Safety Manager

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- Sarah has over 20 years experience working on the scientific underpinning for geological disposal of radioactive waste and the long-term safety case
- She is a Chartered Engineer and a Fellow of the Institute of Materials, Minerals and Mining and her PhD was on pitting corrosion of stainless steel.
- Sarah manages the Environmental Safety Case team at RWM
- Sarah's early career roles were in the printing industry and the Research councils

Presentation overview

- Update on siting in the UK
- Our Focus for the Environmental Safety Case (Aims and objectives)
- Scope of the Environmental Safety Case
- The 2016 generic Disposal System Safety Case
- Current work

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Siting Process in the UK

Three working groups now established

Geological Disposal in the UK

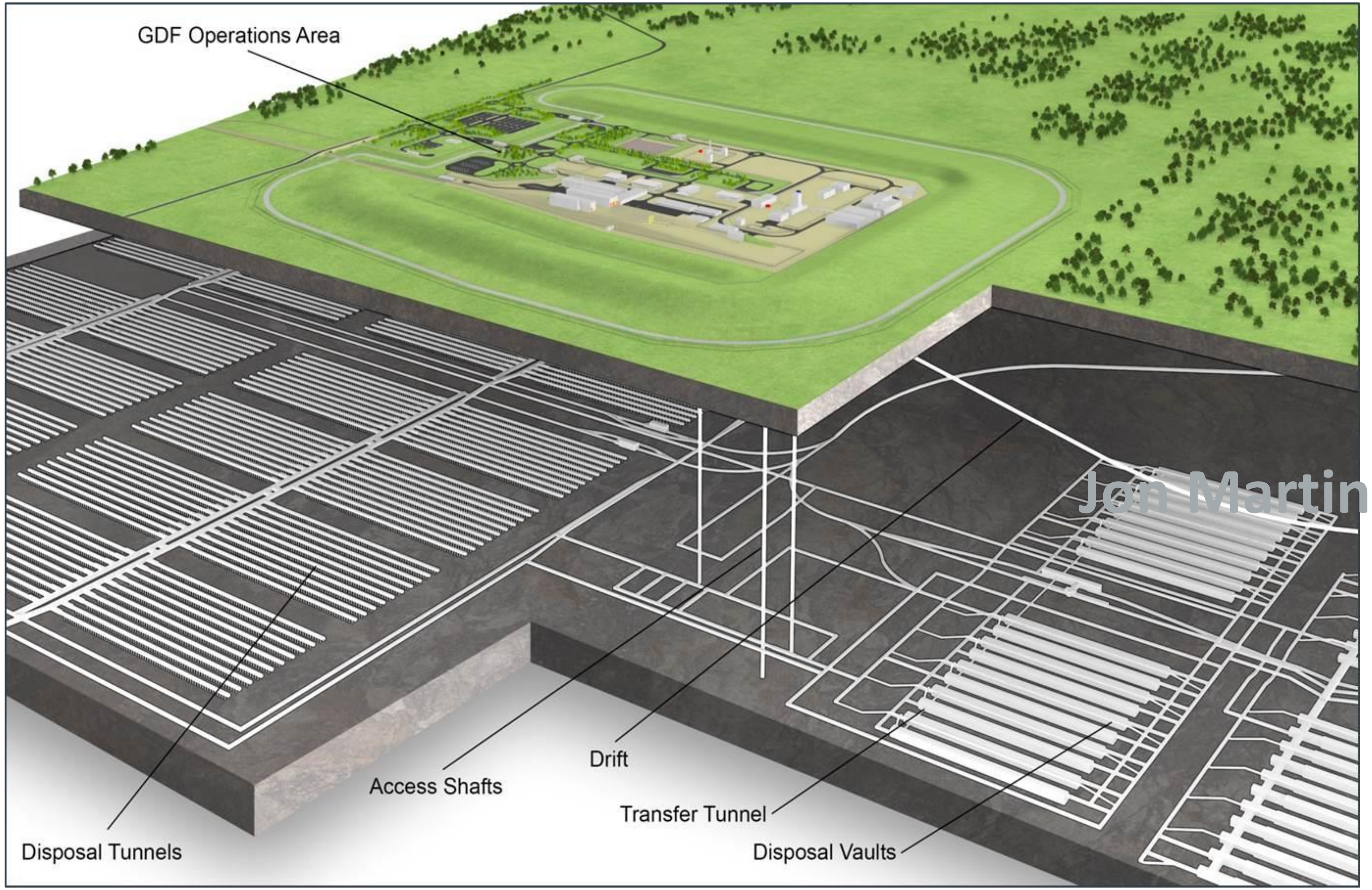
Key principles:

ISOLATE radioactivity from the surface

CONTAIN until most of the hazard has decayed

PASSIVE safety, not requiring human action

Internationally accepted as best solution for long-term management of these wastes



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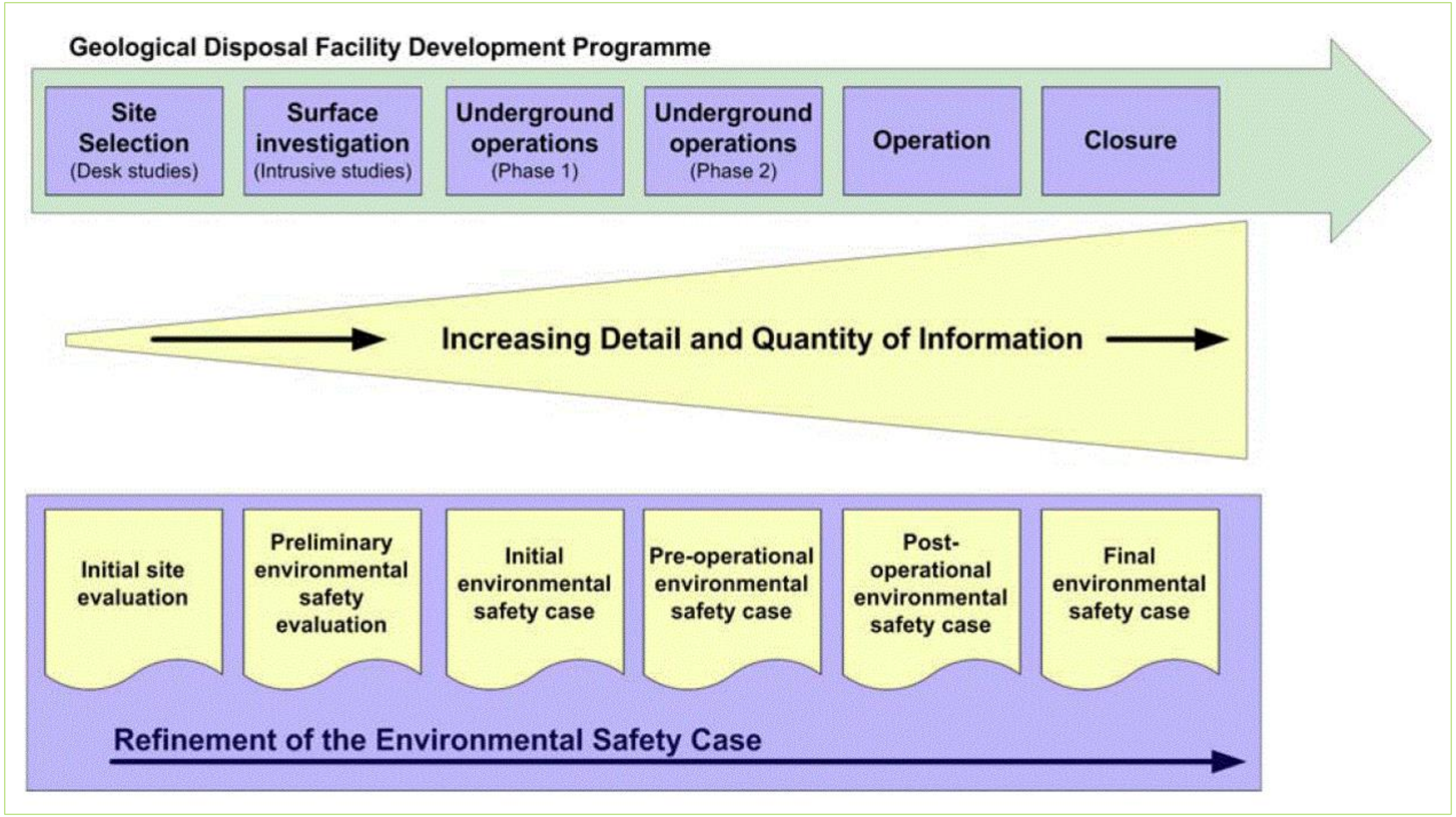
Our Focus (Objectives and strategy)

- To demonstrate that it is **feasible to make an environmental safety case** for the UK's higher activity radioactive waste.
- To support Site Evaluation – to ensure that that the relevant safety requirements are met.
- To support Waste Packaging – to ensure packaged waste is suitable with disposal.
- Capability development.

Staged approach



Geological Disposal Facility Development Programme

Site Selection (Desk studies)

Surface investigation (Intrusive studies)

Underground operations (Phase 1)

Underground operations (Phase 2)

Operation

Closure

Increasing Detail and Quantity of Information

Initial site evaluation

Preliminary environmental safety evaluation

Initial environmental safety case

Pre-operational environmental safety case

Post-operational environmental safety case

Final environmental safety case

Refinement of the Environmental Safety Case

Environmental Safety case - scope

Includes:

- Claims, arguments and evidence
- Post Closure Safety Assessment
- Operational Environmental Safety Assessment

Numerical safety assessment is just one part of the safety case

Drawing on:

- Waste package evolution
- Engineered barrier evolution
- Geosphere evolution
- Groundwater
- Gas generation and migration
- Criticality safety
- Radionuclide behaviour
- Biosphere
- Analogues

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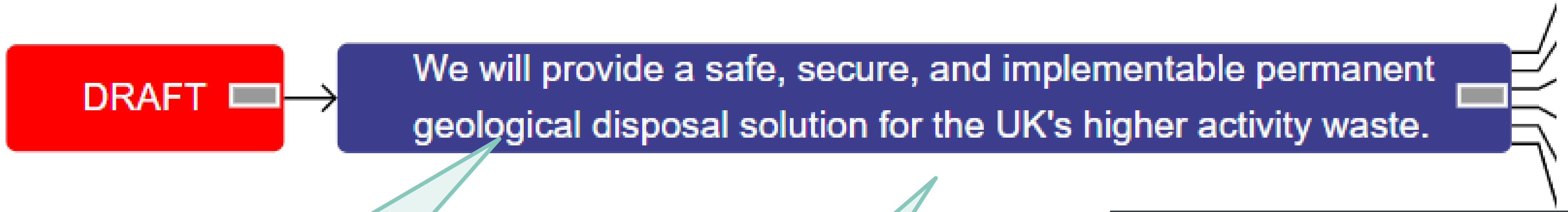
Claims, Arguments and Evidence

> *"An environmental safety case is a set of claims concerning the environmental safety of disposals of solid radioactive waste, substantiated by a structured collection of arguments and evidence."*
>
> Environment Agency – Guidance on Requirements for Authorisation

> *"A safety case is a logical and hierarchical set of documents." "The safety case clearly sets out the trail from safety claims through arguments to evidence."*
>
> Office for Nuclear Regulation – Safety Assessment Principles for Nuclear Facilities

- RWM is looking to emphasise this logical, structured format in its safety cases and is currently developing a generic claims, arguments, evidence (CAE) diagram which illustrates the safety case in an explicit CAE structure.

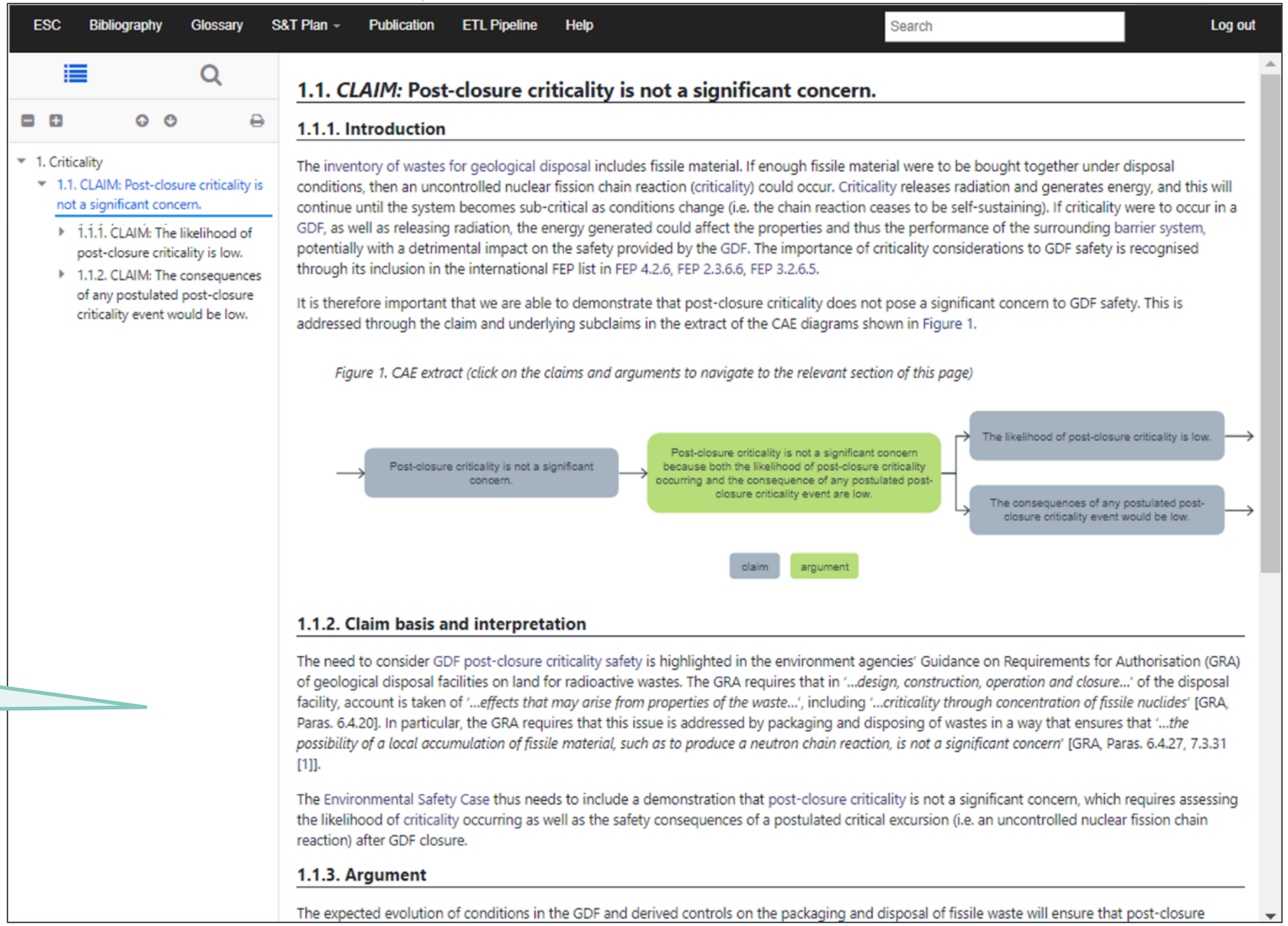
Safety case diagram collection (ViSI)



All claims trace back to the root node.

Users can access underpinning information by clicking nodes in the diagram.

References to other sections are rendered as hyperlinks.



- 1. Criticality
  - 1.1. CLAIM: Post-closure criticality is not a significant concern.
    - 1.1.1. CLAIM: The likelihood of post-closure criticality is low.
    - 1.1.2. CLAIM: The consequences of any postulated post-closure criticality event would be low.

1.1. *CLAIM:* Post-closure criticality is not a significant concern.

1.1.1. Introduction

The inventory of wastes for geological disposal includes fissile material. If enough fissile material were to be bought together under disposal conditions, then an uncontrolled nuclear fission chain reaction (criticality) could occur. Criticality releases radiation and generates energy, and this will continue until the system becomes sub-critical as conditions change (i.e. the chain reaction ceases to be self-sustaining). If criticality were to occur in a GDF, as well as releasing radiation, the energy generated could affect the properties and thus the performance of the surrounding barrier system, potentially with a detrimental impact on the safety provided by the GDF. The importance of criticality considerations to GDF safety is recognised through its inclusion in the international FEP list in FEP 4.2.6, FEP 2.3.6.6, FEP 3.2.6.5.

It is therefore important that we are able to demonstrate that post-closure criticality does not pose a significant concern to GDF safety. This is addressed through the claim and underlying subclaims in the extract of the CAE diagrams shown in Figure 1.

Figure 1. CAE extract (click on the claims and arguments to navigate to the relevant section of this page)

1.1.2. Claim basis and interpretation

The need to consider GDF post-closure criticality safety is highlighted in the environment agencies' Guidance on Requirements for Authorisation (GRA) of geological disposal facilities on land for radioactive wastes. The GRA requires that in '*...design, construction, operation and closure...*' of the disposal facility, account is taken of '*...effects that may arise from properties of the waste...*', including '*...criticality through concentration of fissile nuclides*' [GRA, Paras. 6.4.20]. In particular, the GRA requires that this issue is addressed by packaging and disposing of wastes in a way that ensures that '*...the possibility of a local accumulation of fissile material, such as to produce a neutron chain reaction, is not a significant concern*' [GRA, Paras. 6.4.27, 7.3.31 [1]].

The Environmental Safety Case thus needs to include a demonstration that post-closure criticality is not a significant concern, which requires assessing the likelihood of criticality occurring as well as the safety consequences of a postulated critical excursion (i.e. an uncontrolled nuclear fission chain reaction) after GDF closure.

1.1.3. Argument

The expected evolution of conditions in the GDF and derived controls on the packaging and disposal of fissile waste will ensure that post-closure

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PCSA methodologies and models

- Methodologies and models for assessing:
  - Groundwater pathway
  - Gas generation and migration
  - Non-radiological contaminants as well as radionuclide behaviour
  - Human intrusion
  - Impact to people and in the environment (non-human biota)
  - Post closure consequences of criticality
- Treatment of uncertainty important

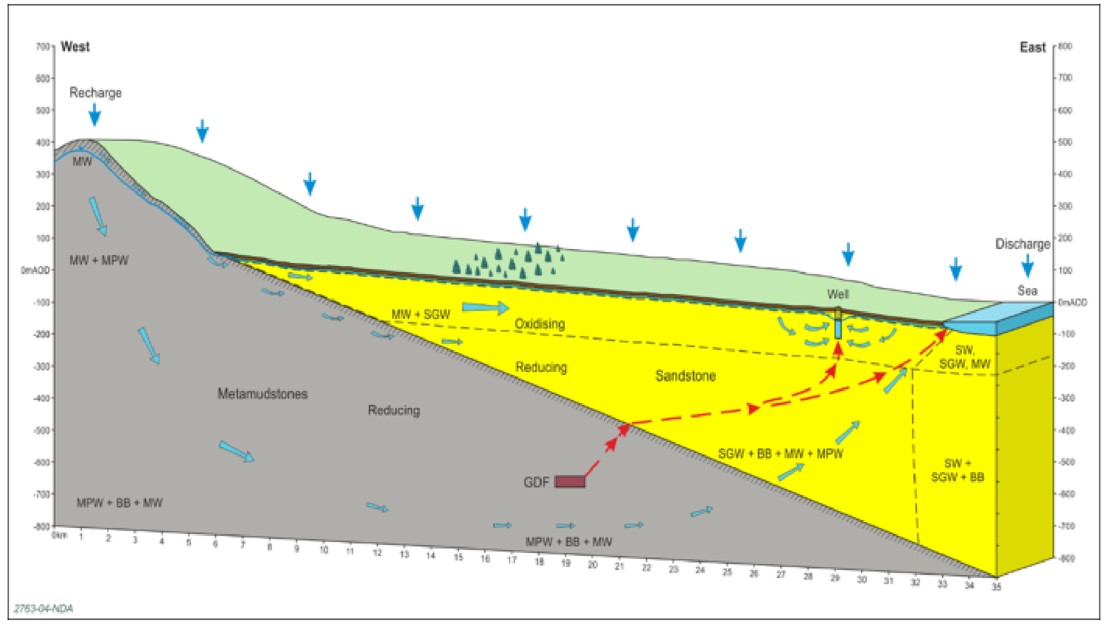
Operational Environmental Safety

- An environmental assessment covering the “period of authorisation”
- 2016 assessment focused on the gas pathway, with qualitative discussion of solid and liquid discharges
- Development draws on research tasks including
  - Non-rads project
  - Biosphere model development
  - Gas generation project

Detailed assessment not expected as part of the Initial Site Evaluation, but need to develop competency and approaches.

Generic Disposal System Safety Case - 2016

- Feasibility study based on
  - Inventory for Geological Disposal
  - Illustrative disposal concepts studied internationally
  - Illustrative geological and hydrogeological environments
  - Wide knowledge base – UK and International



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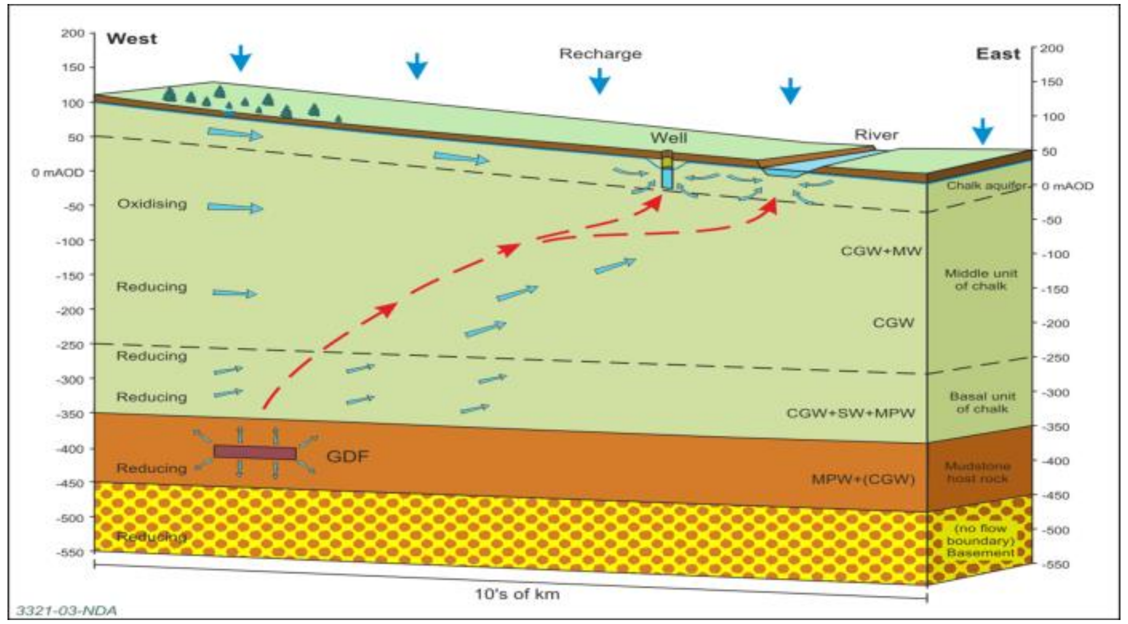

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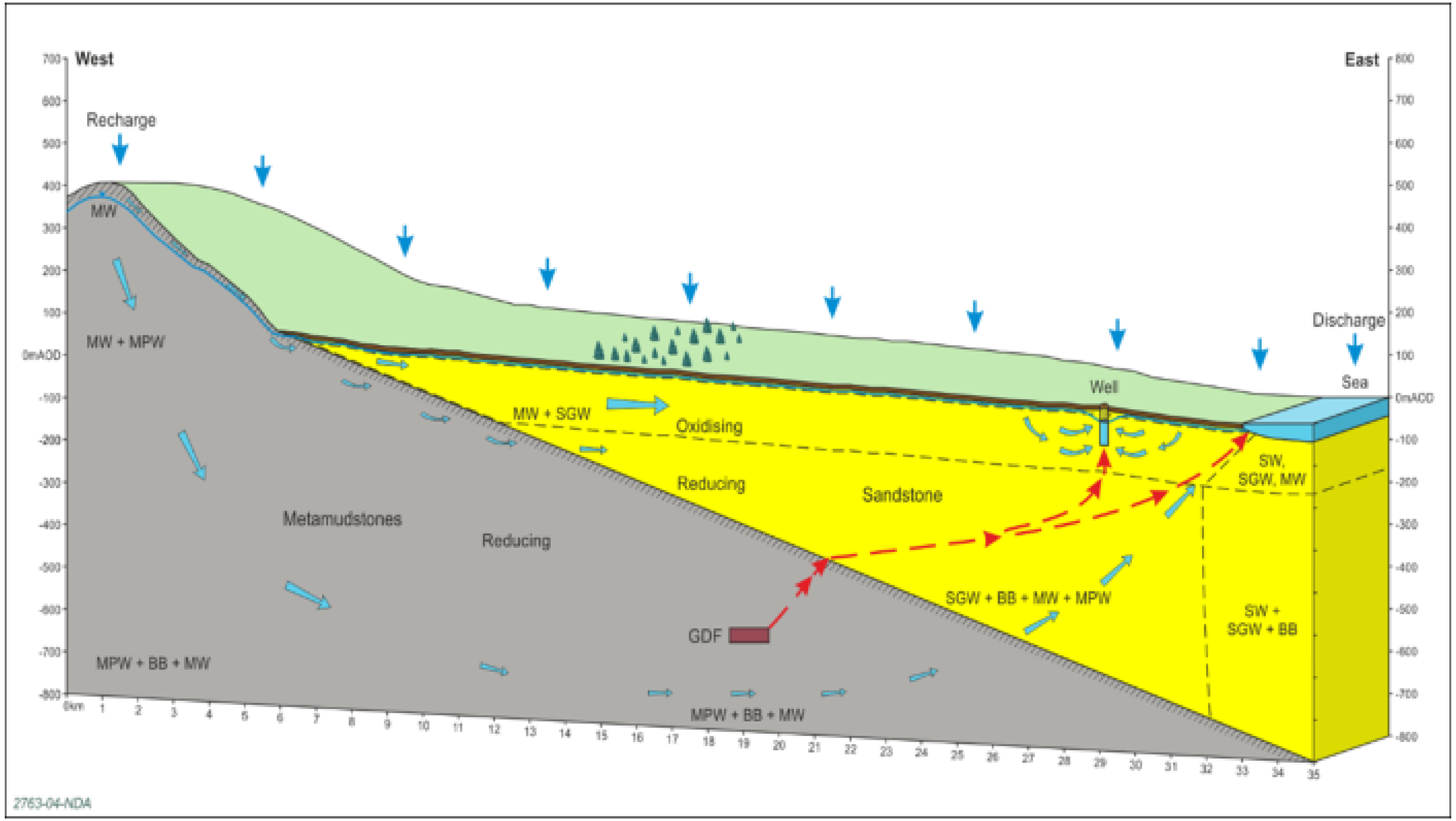
Illustrative Disposal Concepts in the 2016 gDSSC

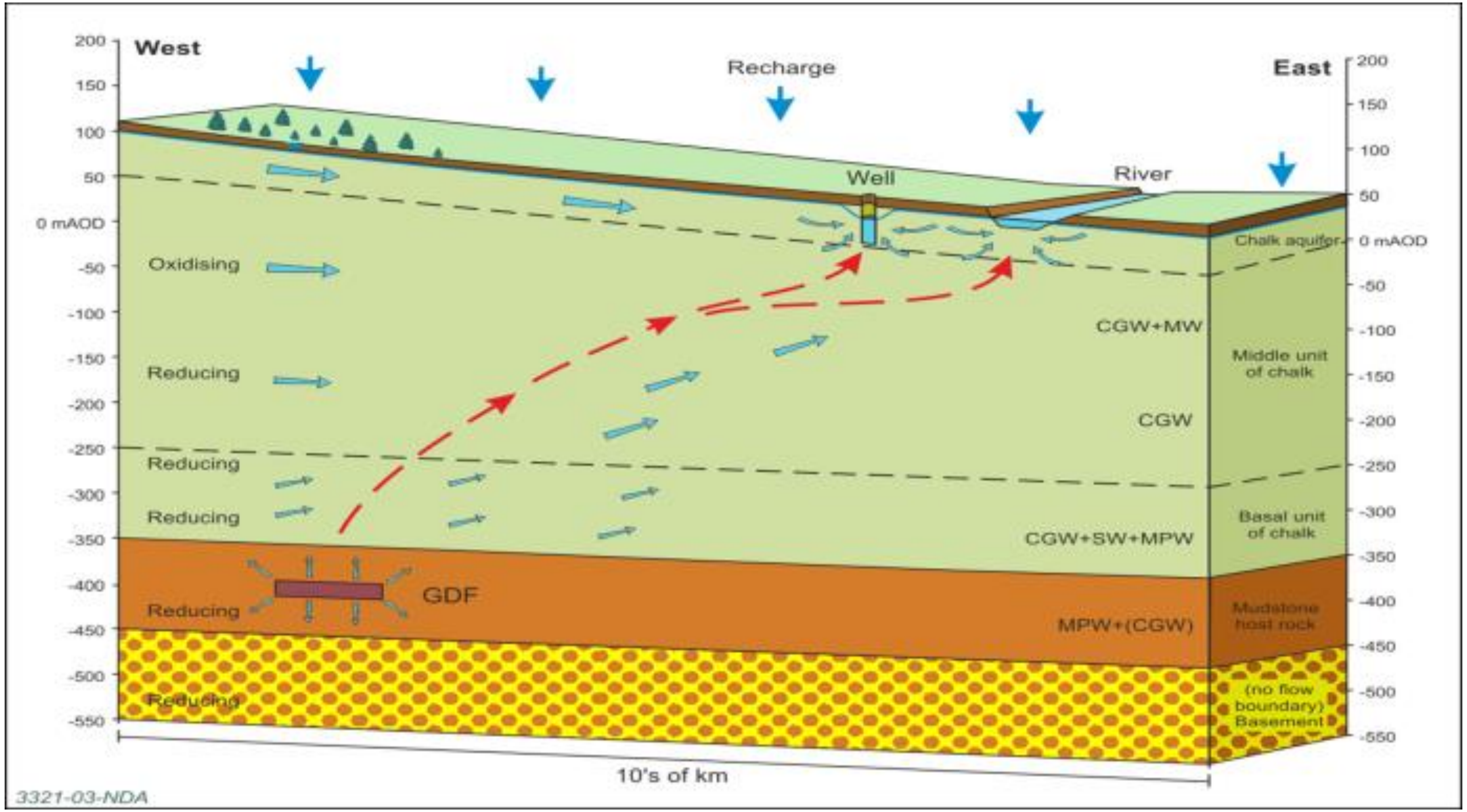
Host Rock	**Disposal Concept (Developer, Country)**	
	LHGW	HHGW
Higher strength rock	UK Concept (RWM, UK)	KBS-3V Concept (SKB, Sweden)
Lower strength sedimentary rock	Opalinus Clay Concept (Nagra, Switzerland)	Opalinus Clay Concept (Nagra, Switzerland)
Evaporite rock	WIPP Bedded Salt Concept (US DOE, USA)	Gorleben Salt Dome Concept (DBE Technology, Germany)

Model draws on understanding, data and approaches relating to these concepts

Illustrative higher strength rock – metamudstone overlain with sandstone



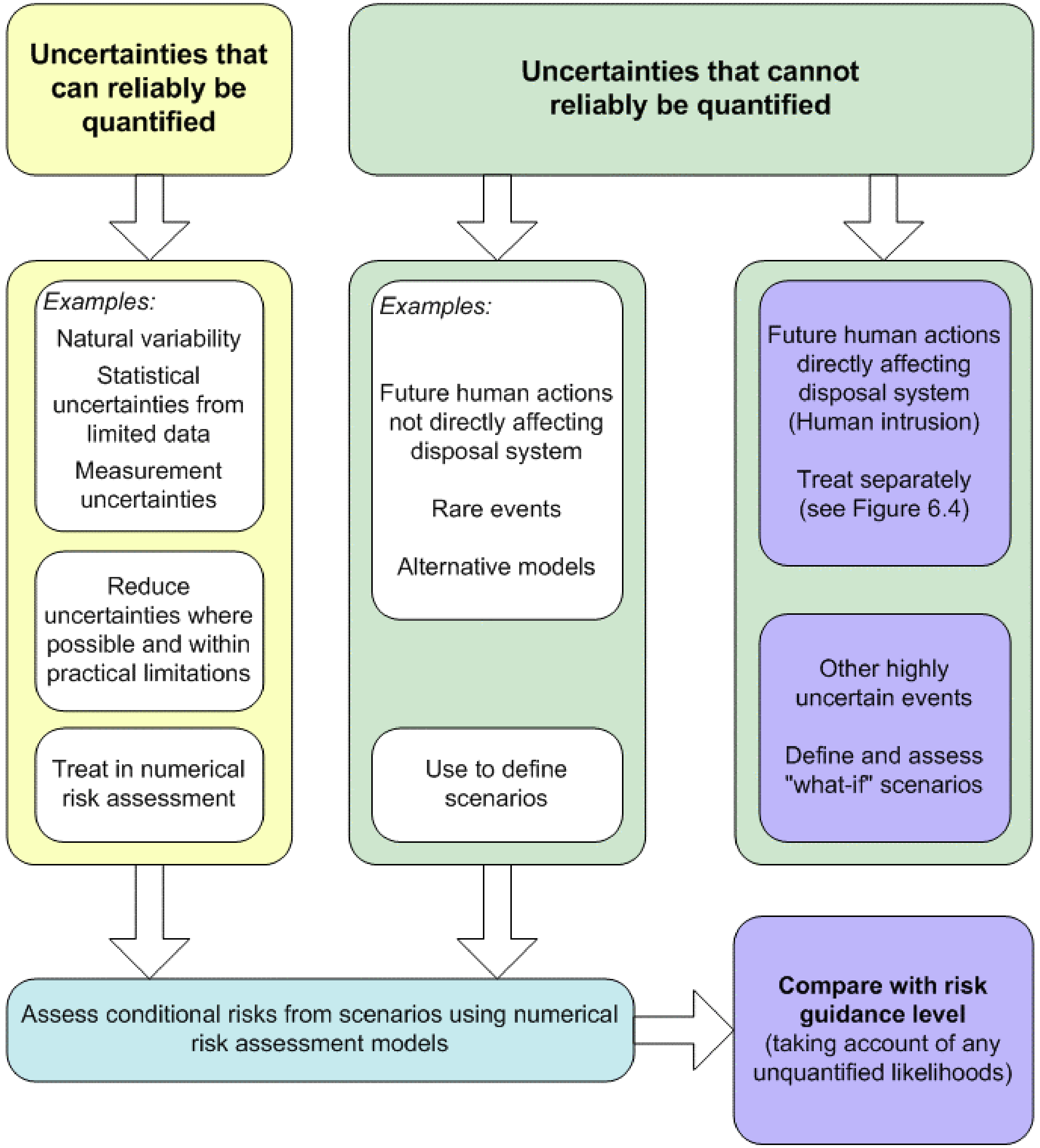
Illustrative lower strength rock – mudstone overlain with chalk



UK regulatory guidance - uncertainty

UK regulatory guidance requires uncertainties to be quantified, and implies probabilistic calculations of risk will form at least part of a post-closure performance assessment

Source: Environment Agency and Northern Ireland Environment Agency, *Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation*, February 2009.



Uncertainties that can reliably be quantified

Examples:
Natural variability
Statistical uncertainties from limited data
Measurement uncertainties

Reduce uncertainties where possible and within practical limitations

Treat in numerical risk assessment

Uncertainties that cannot reliably be quantified

Examples:
Future human actions not directly affecting disposal system
Rare events
Alternative models

Use to define scenarios

Future human actions directly affecting disposal system (Human intrusion)
Treat separately (see Figure 6.4)

Other highly uncertain events
Define and assess "what-if" scenarios

Assess conditional risks from scenarios using numerical risk assessment models

Compare with risk guidance level
(taking account of any unquantified likelihoods)

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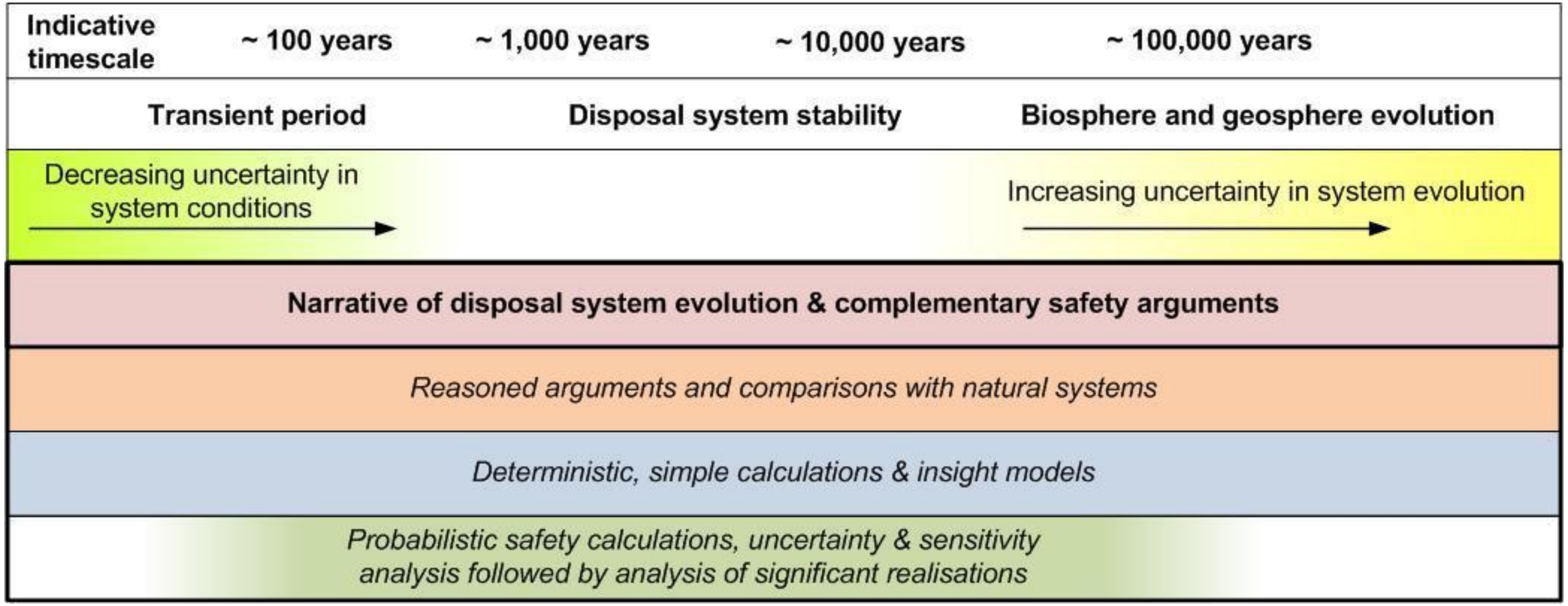
Geological timescales that require consideration



Indicative timescale — **~ 100 years** — **~ 1,000 years** — **~ 10,000 years** — **~ 100,000 years**

Transient period — **Disposal system stability** — **Biosphere and geosphere evolution**

Decreasing uncertainty in system conditions →

Increasing uncertainty in system evolution →

Narrative of disposal system evolution & complementary safety arguments

Reasoned arguments and comparisons with natural systems

Deterministic, simple calculations & insight models

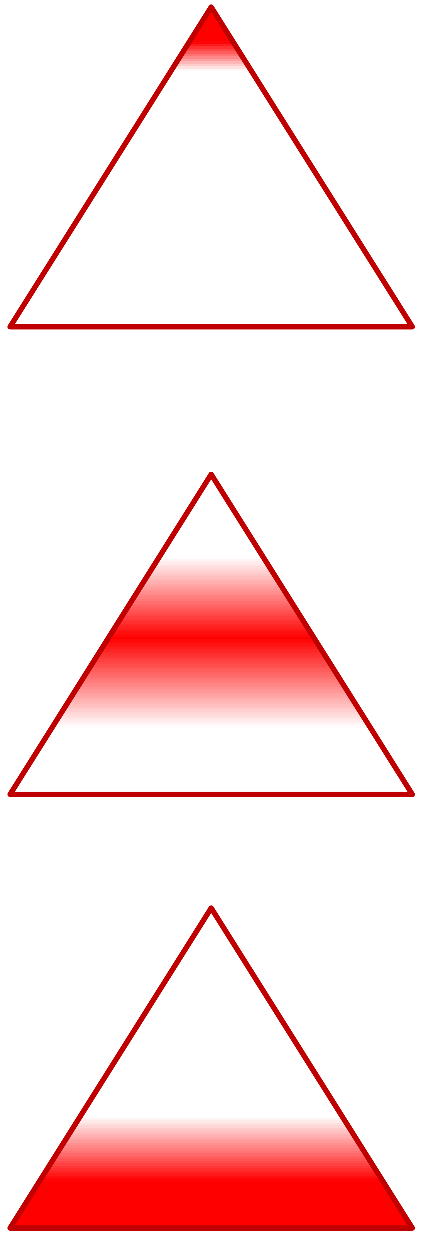
Probabilistic safety calculations, uncertainty & sensitivity analysis followed by analysis of significant realisations

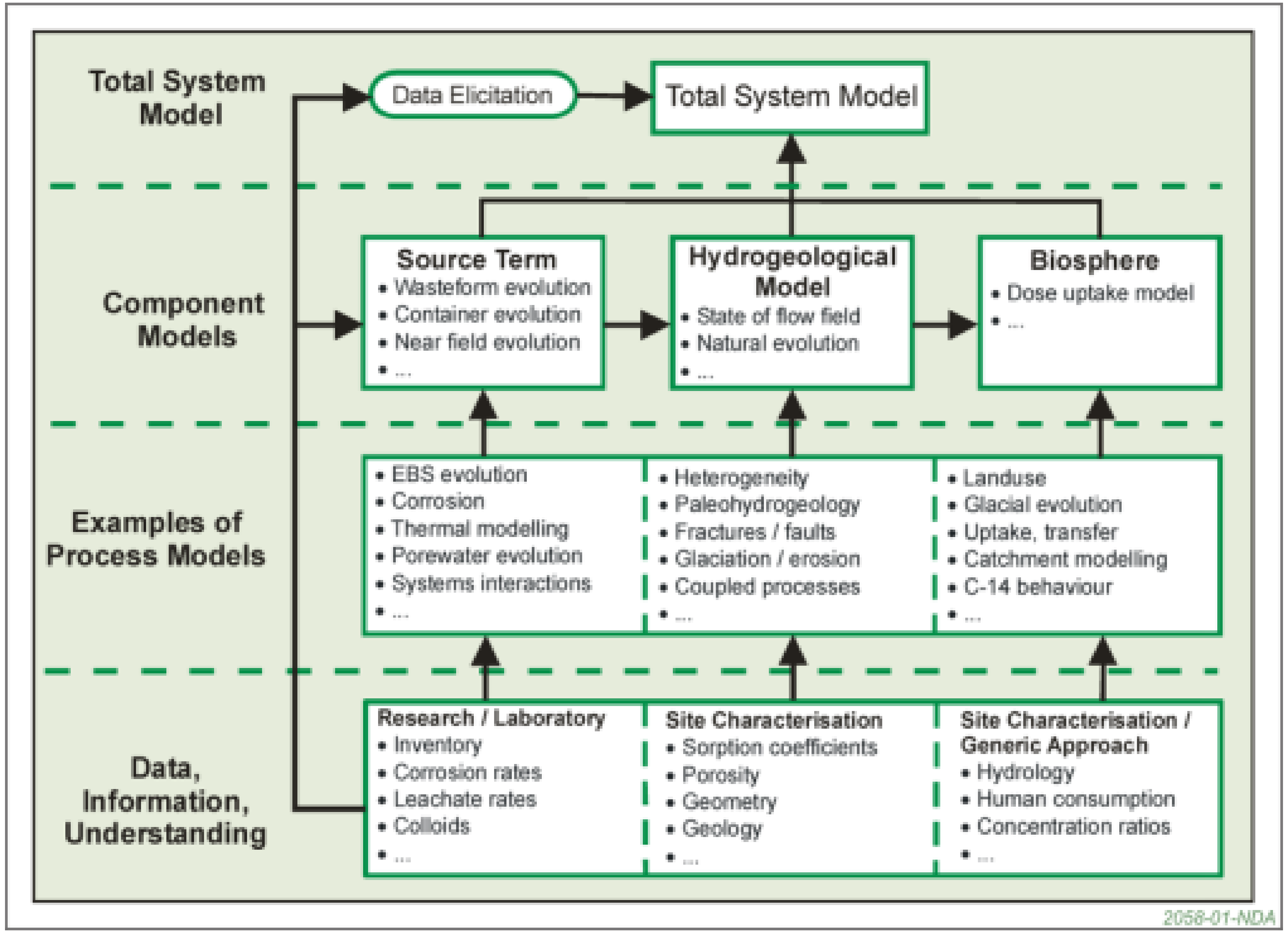
Model Hierarchy

Coarse, abstracted

Moderate detail, range of processes

Detailed





Total System Model

Data Elicitation

Total System Model

Component Models

Source Term
- Wasteform evolution
- Container evolution
- Near field evolution
- ...

Hydrogeological Model
- State of flow field
- Natural evolution
- ...

Biosphere
- Dose uptake model
- ...

Examples of Process Models

- EBS evolution
- Corrosion
- Thermal modelling
- Porewater evolution
- Systems interactions
- ...

- Heterogeneity
- Paleohydrogeology
- Fractures / faults
- Glaciation / erosion
- Coupled processes
- ...

- Landuse
- Glacial evolution
- Uptake, transfer
- Catchment modelling
- C-14 behaviour
- ...

Data, Information, Understanding

Research / Laboratory
- Inventory
- Corrosion rates
- Leachate rates
- Colloids
- ...

Site Characterisation
- Sorption coefficients
- Porosity
- Geometry
- Geology
- ...

Site Characterisation / Generic Approach
- Hydrology
- Human consumption
- Concentration ratios
- ...

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We need to consider uncertainties in the post-closure safety case

- Assessing post-closure risk is an example of modelling a complex system, with a range of processes, with high uncertainty.
- A total system model, including uncertainty, provides key understanding.
- Then we can establish an iterative loop of data gathering and performance assessment, so that the site-characterisation and research programmes are ‘needs driven’ i.e. focussed on reducing uncertainty in those things the model is showing that the performance measure (e.g. risk) is most sensitive to.

Strategies for managing uncertainty when assessing post-closure safety

- Strategies for managing uncertainty for any given scenario fall into the following five broad categories:
  - Demonstrating that the uncertainty is irrelevant i.e. uncertainty in a particular process is not important to safety because, for example, safety is controlled by other processes.
  - Addressing the uncertainty explicitly, using probabilistic techniques.
  - Bounding the uncertainty and showing that even the bounding case gives acceptable safety.
  - Ruling out the uncertain process or event, usually on the grounds of very low probability of occurrence.
  - Explicitly ignoring uncertainty or agreeing a stylised approach for handling an uncertainty – e.g. use of internationally agreed reference biosphere models.
- Usually modelling will show that output quantities are sensitive to only a small number of input parameters.

Approach to defining scenarios to model in a performance assessment

- Base scenario – the way the system is expected to evolve, likely to include
  - major time-dependent effects such as expected climate change
  - the migration of radionuclides via groundwater or gas pathways
- Variant scenarios – deviations from the base scenario caused by Features, Events and Processes (FEPs) that may or may not occur
  - but if a variant scenario has a ‘conditional peak risk’ which is less than the peak risk from the base scenario, it can be discounted, or considered ‘subsumed’ by the base scenario. Need to keep number of scenarios that need to be considered in a detailed assessment practicable.
  - could include human intrusion into the facility, disruptive events and criticality safety

Need for a structured approach to uncertainty quantification by expert judgement

- Quantifying uncertainty also requires a structured approach.
- Need:
  - expertise in the subject area relevant to the parameter;
  - analytical skill (e.g. elicitor, facilitator, modeller).
- Training, practice and feedback help experts to overcome biases and become well calibrated e.g. weather forecasters get continual feedback on their probabilistic forecasts and can become accurate at quantifying uncertainty in terms of probabilities.
- We have developed a methodology and tools to do this.

Assessment calculations – 2016 gDSSC

- Migration of radionuclides in groundwater
  - Conceptual model based on illustrative environment
  - Source term from UK Inventory for geological disposal
  - Probabilistic model, with distributions for key parameters
  - Biosphere factors convert flux to dose for e.g well or marine discharge
- Migration of radionuclides in gas
  - Deterministic model of gas generation
  - Reference to gas migration studies from elsewhere

- Human Intrusion (variant scenario)
  - Reference to IAEA HIDRA project
- Criticality Safety (variant scenario)
  - Post-Closure Criticality Consequences safety assessment based on 2010 safety case

Calculations are illustrative and aim to demonstrate the feasibility of making a safety case

Current work

- Integrated Design and Safety Case strategy using Systems Engineering approach to identifying requirements
- Claims, arguments and evidence development / population
- Model strategy – what is needed when, procurement and IT approach
- Identifying Site information needs / Research needs
- Increased focus on LSSR and halite environments, including variant scenarios
- Underpinning research
  - Gas migration & pressurisation
  - Non-radiological contaminants & groundwater protection
  - Marine biosphere & ecosystems
  - Backfill development

S&T Plan
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/931865/Science_and_Technology_Plan_2020.pdf

Non-Radiological contaminants work

- Used a Total System Model (TSM) approach based on the illustrative environments from the 2016 Post Closure Safety Assessment (PCSA)
- Considered 2016 PCSA geological and hydrogeological settings
  - Example Higher Strength Rock (HSR)
  - Example Lower Strength Sedimentary Rock (LSSR)
- Explicitly calculated concentrations along the groundwater pathway.
- Considered a small number of ‘example’ hazardous and non-hazardous pollutants
- Applied TSM to example pollutants for HSR and LSSR
  - base case and variants.

Results

The model outputs for the illustrative LSSR environment demonstrate that processes modelled within the host rock play an important role in reducing the concentration of pollutants. The modelled concentration of some pollutants was below the comparison value within a few metres of the facility. Of the pollutants modelled, only Be* was at concentrations above the comparison value at output points in the overlying chalk.

In the illustrative HSR environment, all modelled inorganic pollutants discharge from the host rock at concentrations above the comparison value, but are below the comparison value at output points in the overlying sandstone. These results are sensitive to the representation of groundwater flow and contaminant transport.

* Be is a non-hazardous pollutant

Integrated design and Safety Case Approach

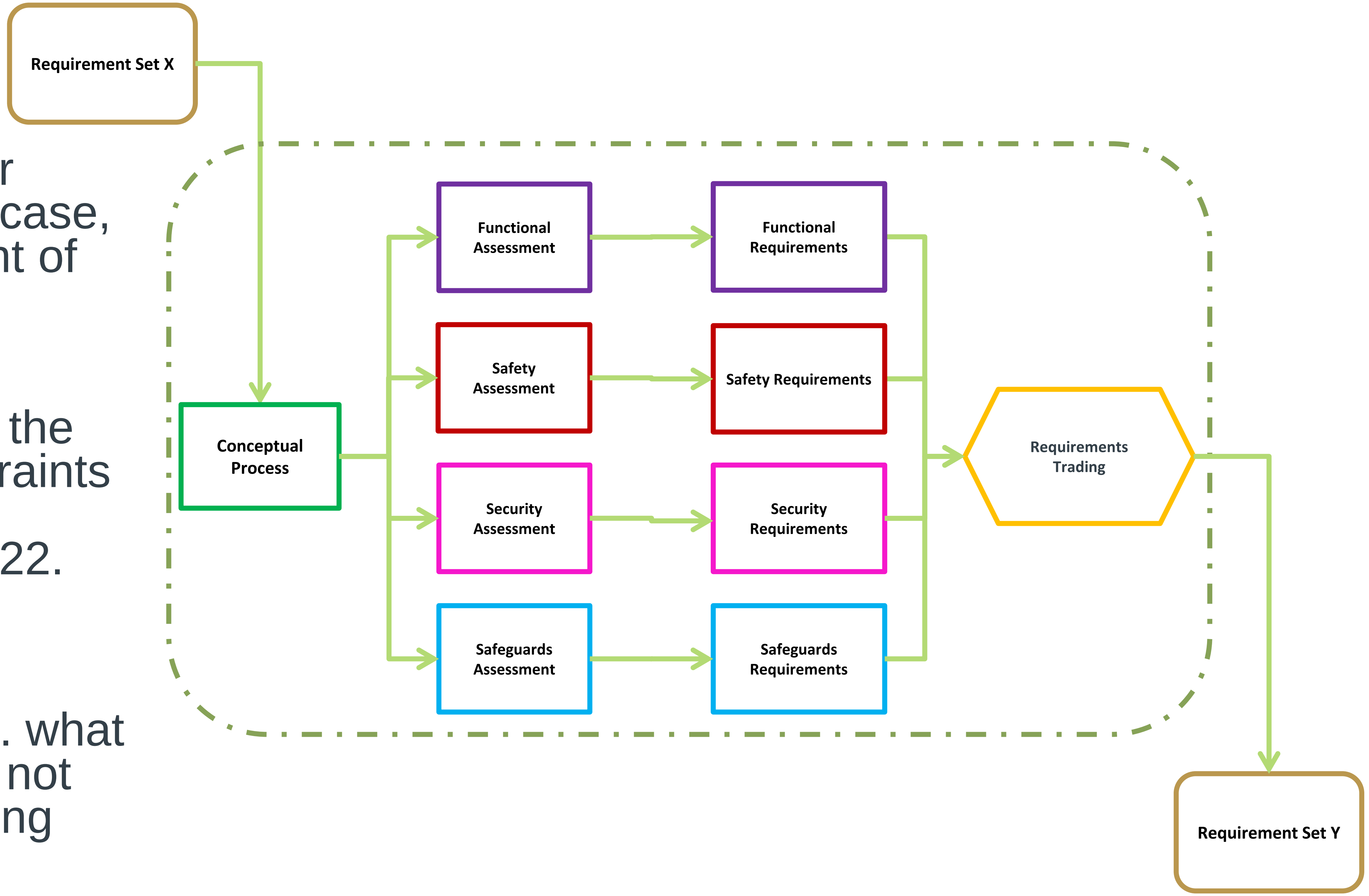
- An integrated design and safety case approach will:
  - Include optimisation processes that consider both operational and post-closure timescales and demonstrate radiological risks are as low as reasonably practicable / achievable.
  - Be carried out under appropriate management arrangements under control of the Design Authority
  - Identify requirements on the design that can be managed in an integrated way.
  - Site specific design will be developed with engineered and natural barriers working together to protect the waste.

Design and Safety Integration

- Systems Engineering is an approach for developing a holistic design and safety case, driven by identification and management of requirements

- Initial step (underway) is to deconstruct the sponsor (NDA) requirements and constraints (e.g. legal) to derive GDF functions & requirements. Corporate target for Mar 22.

- Establish a set of system requirements before detailed site characterisation, i.e. what does the system (the GDF) need to do, not how does it do it (which is the engineering solution and comes later)



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Summary

- Our 2016 generic disposal system safety case is a feasibility study based on illustrative geological environments which supports waste packaging and capability development and is underpinned by an extensive knowledge base.
- Moving forwards, site specific work will involve an integrated design and safety case approach, which will progress in a staged and iterative way.