NDA

Sellafield Ltd

Nuclear Decommissioning Authority

Department for Business, Energy & Industrial Strategy

Scottish Government
Riaghaltas na h-Alba
gov.scot

Llywodraeth Cymru
Welsh Government

Policy

Nuclear Decommissioning Authority (NDA)

Strategy
$160bn over 120 years
Annual spend ~$4bn

Sellafield Ltd

LLWR Ltd

Magnox

Dounreay

Radioactive Waste Management

Direct Rail Services
safe secure reliable

INS
INTERNATIONAL NUCLEAR SERVICES

Delivery

Dry Storage of Spent Fuels

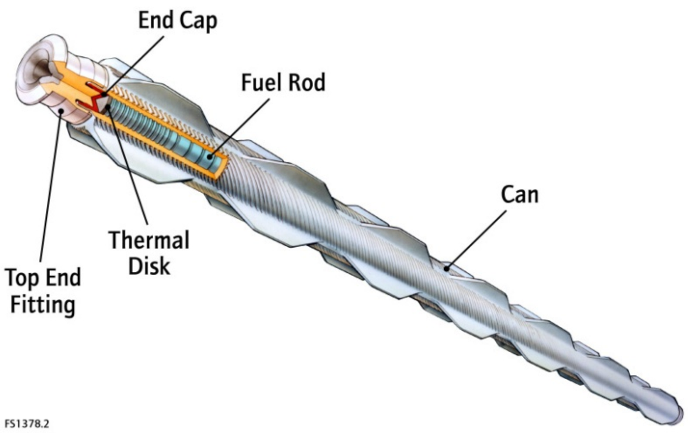
Supporting R&D

14 November 2019

Contents

Magnox Nuclear Power Plants (NPPs) – UK 1st Generation

- Carbon dioxide (CO_2) Gas Cooled
- Graphite Moderator
- All reactors now defueled

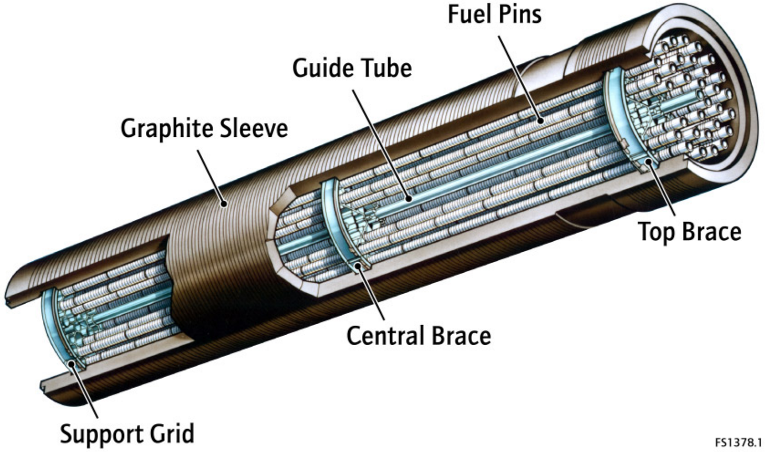


- Uranium Metal Fuel
- Magnesium Alloy Clad (Mg-0.8%Al)

Advanced Gas Reactor (AGR) – UK 2nd Generation

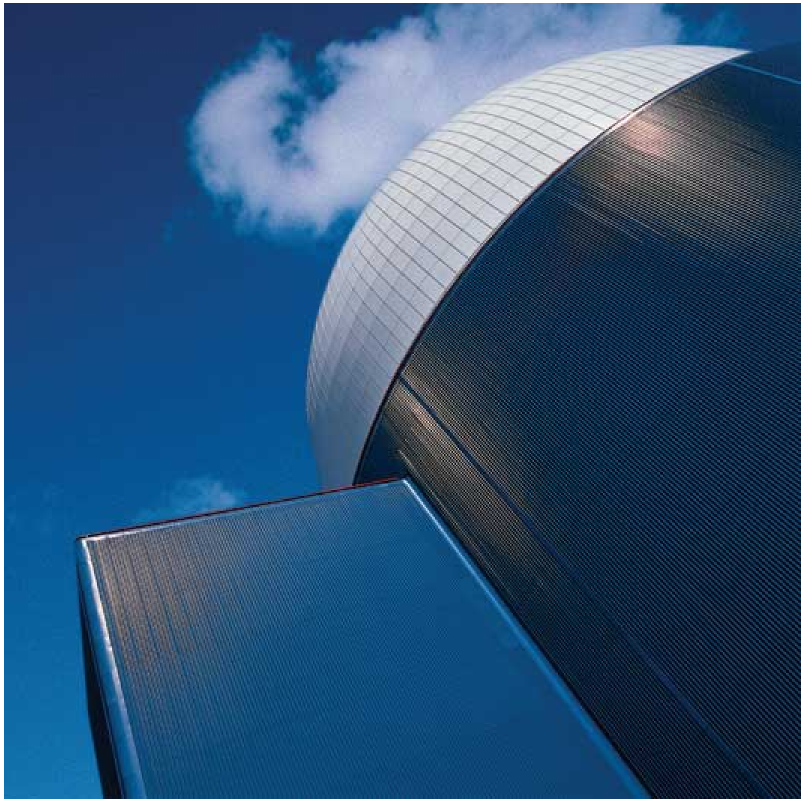
Hunterston B
Picture courtesy of EDFE

- CO_2 Gas Cooled
- Graphite Moderator
- 7 Operational Stations



- UO_2 fuel
- Stainless Steel Clad

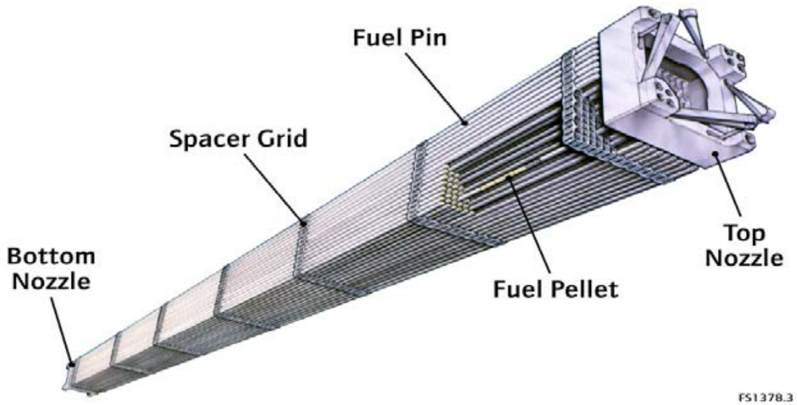
Pressurised Water Reactor (PWR)- UK 3rd Generation



Sizewell B

Picture courtesy of EDFE

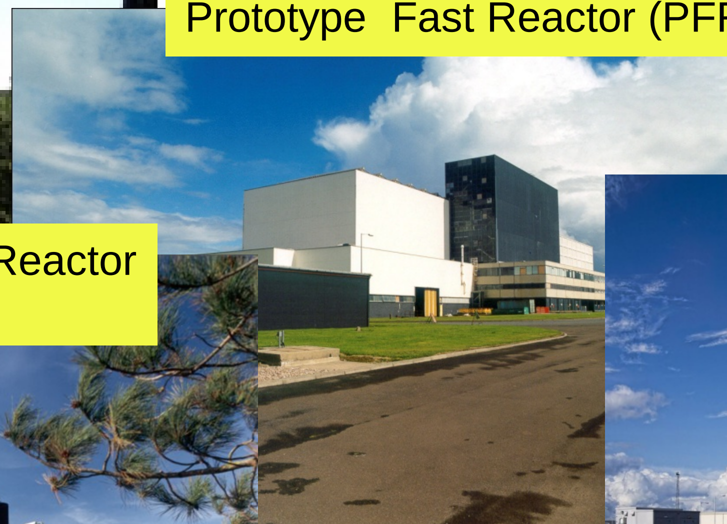
- Light Water Cooled and Moderator
- 1 Operating Station



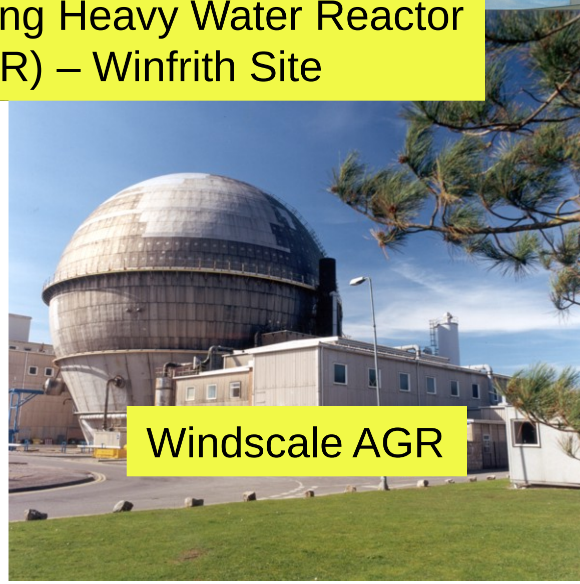
- Zircaloy Clad
- Fuel managed by Electricity de France Energy (EDFE) at Sizewell B

Experimental Spent fuel from the UK Power Development Programmes (‘Exotic Fuels’)

Steam Generating Heavy Water Reactor (SGHWR) – Winfrith Site



Prototype Fast Reactor (PFR)



Windscale AGR

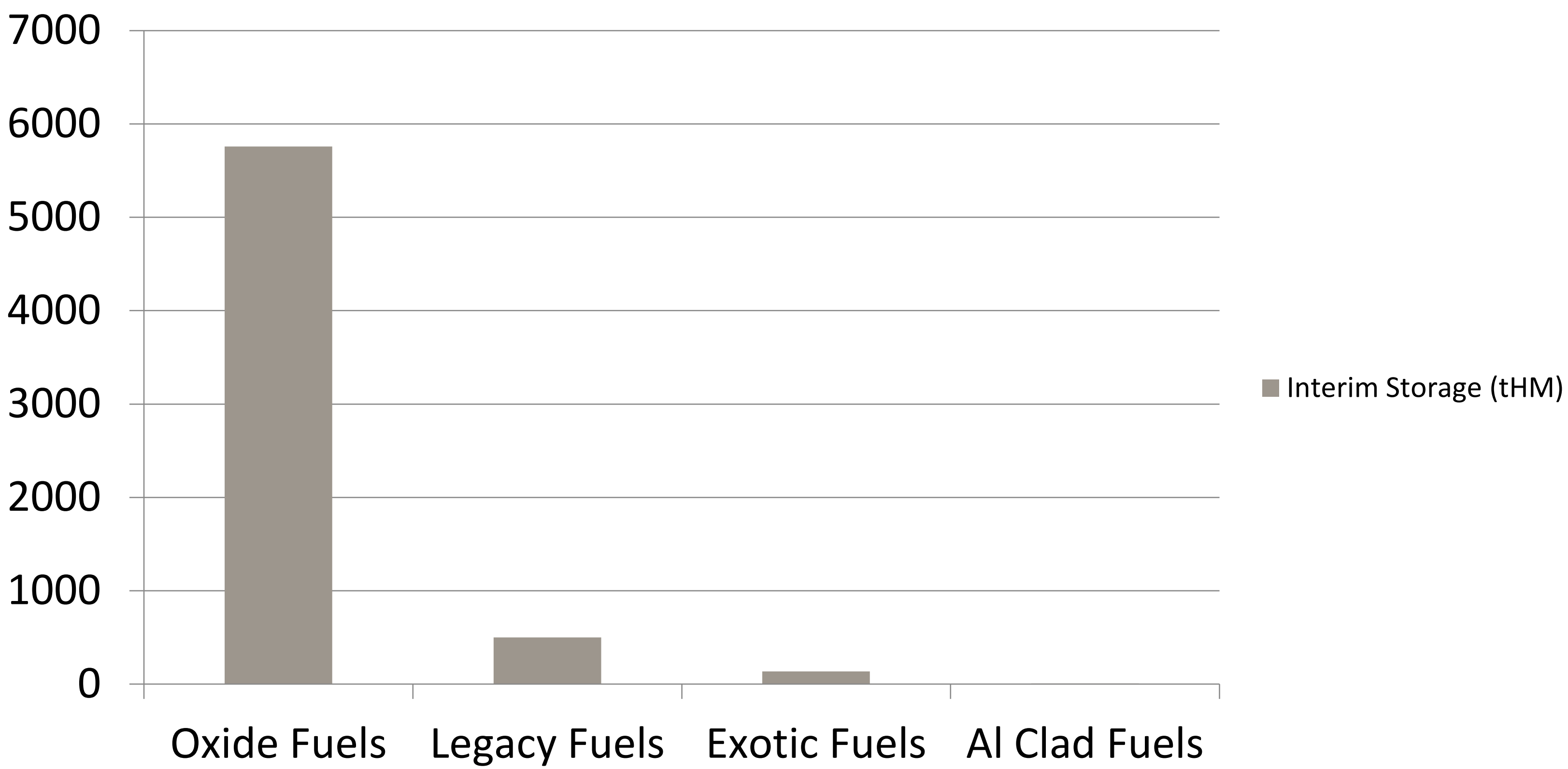
Dounreay Fast Reactor (DFR)

Aluminium Clad Fuels

All aluminium (Al) clad fuels stored at Sellafield are from reactors which have been shut-down and have either been decommissioned or are in the process of being decommissioned

Reactor	Fuel Type	Storage Regime	Status
BEPO (British Experimental Pile zero energy)	Al-Clad, Uranium Metal fuel (U Metal)	1. Demineralised Water 2. Sodium hydroxide (pH 11.4)	1. Fair condition 2. Degraded
Windscale Piles	Al-Clad, U Metal fuel	1. Demineralised Water 2. Sodium hydroxide (pH 11.4)	1. Fair condition 2. Degraded
Jason/Consort	Al-Clad, Al-U fuel	Demineralised Water	Good condition

Al-clad fuels in the context of the total quantity of spent fuel to be interim stored at Sellafield



UK Dry Storage Experience

Location	Fuel Type	Fuel Status	Water Carry-over Assumption	Remark
Wylfa NPP	Magnox	Intact	Trace in CO_2	Ops 1972, Now defueled
Wylfa NPP	Magnox	Intact	Moisture in air	Ops since 1978, Now defueled
Sizewell B NPP	PWR	Intact	(0.12L)	Operational, modified Holtec system

UK Dry Storage Projects/R&D

Location	Fuel Type	Fuel Status	Water Carry-over Assumption	Remark
Torness NPP	Advanced Gas Reactor (AGR)	Intact	Target <50 VPM (15 000 VPM)	R&D in support of modular vault dry store (MVDS) Project (Cancelled)
Sellafield	Magnox	Intact, Degraded	0.73-2.6L	Contingency
Sellafield	Legacy Fuels (Mostly Magnox, Includes Al-Clad)	Intact, Degraded	60L	Project delivery phase
Sellafield	AGR	Intact	VPM	R&D in support of Contingency
Sellafield	Al-Clad, AL-U	Intact	Bound water	Study
Sellafield	Fast Reactor	Intact/Failed	Trace	Study

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Magnox Contingency

- Contingency option to mitigate the risk of failure of Magnox reprocessing at Sellafield
  - Magnox reprocessing plant is now in its 55th year of operation
- Requirement
  - Safe Storage of Fuel (intact and degraded)
- Concept
  - Existing Magnox dry storage technologies have been discounted as they are based on processing intact dry fuel
  - Contingency builds on the Hanford multi-canister overpack (MCO) concept for metallic fuel
    - Fuel vacuum dried in a canister which is capable of being pressurised
- Development
  - To a point to enable deployment as soon as practical

Canister Development – Material Selection

- Design Criteria Material Selection
  - Corrosion performance
    - Attack from the inside - nitric acid/fuel corrosion product if the fuel is not dry
    - Attack from the outside - storage in a marine environment for up to 150 years
  - Strength
    - Canister to meet pressure code PD 5500
      - Fault scenario incomplete drying
- Material Selected
  - Duplex Stainless Steel grade 2205
    - Provides improved corrosion resistance and strength over 300 series stainless steel
      - Consideration of temperature of application

Canister Development – Technical Issues

- Efficiency of drying wetted Magnox fuel
    - Free Water
    - Physically adsorbed water
    - Chemically adsorbed water (tightly bound to magnesium hydroxide $Mg(OH)_2$)
- Canister chemistry evolution (sealed system)
  - A canister chemical model has been developed
  - The model was used to establish if the canister design would be challenged (pressure and corrosion) and to inform the safety case
  - The model is pessimistic (bounding)
    - The assumptions and further information is provided in International Atomic Energy Agency document number IAEA-TECDOC-1771
    - The model looked at the behaviour of intact and degraded fuel

Canister Development - Fuel Drying Trials

- Full-scale drying trials and simulants
- Process based on using re-circulated warm argon in combination with vacuum drying (to speed up drying cycle)
- Drying trials have been conducted
  - 24 intact elements
  - Elements coated with 200μm layer of magnesium zirconate with 50% porosity
  - Degraded fuel
  - Water trapped behind the fuel clad

SFM Sellafield Ltd – Examples of R&D

- Hanford MCO developed for degraded zirconium clad uranium metal fuel

- Development of a Magnox fuel canister
  - 26 intact fuel elements

- Resolution of Technical Issues
  - Drying of wetted Magnox fuel
    - Free Water
    - Physically adsorbed water
    - Chemically adsorbed water (tightly bound to $Mg(OH)_2$)
  - Canister Chemistry Evolution

Cold Vacuum Drying

- Fuel weighed before and after
  - Dipped in a thermostatically controlled bath and held for a set time allowed to drip dry for 10 seconds before weighing

- Conclusions
  - Capable of removing all free water, but did not remove any chemically bound water
  - Drying times varied depending on the fuel design and water carryover, but were typically in the range 2-4 hours
  - Increasing the heat input to the vessel reduced the drying time

Canister Chemistry - Principle Reactions Modelled

- Magnox Corrosion

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2$$

Magnox – Magnesium non oxidizing fuel cladding

In comparison, Aluminium Clad fuel readily forms protective a Aluminium oxide (Al_2O_3) film which inhibits the formation of the hydroxide

At elevated temperature in the presence of moisture the following reaction can occur

$$2Al + 4H_2O \rightarrow 2Al_2O_3 . H_2O + 3H_2$$

Canister Chemistry - Principle Reactions Modelled

- Uranium Metal Corrosion (degraded fuel)

$$U + [(2 + x)/2]O_2 \rightarrow UO_{2+x}$$

Where x= $0.006 < x < 0.1$

$$U + (2 + x)H_2O \rightarrow UO_{2+x} + (2 + x)H_2$$

Where x= $0.13 < x < 0.20$

$$2U + 3H_2 \rightarrow 2UH_3$$

Canister Chemistry - Principle Reactions Modelled

- Uranium Hydride (exposed uranium metal, degraded fuel)

$$UH_3 + 2H_2O \rightarrow 2UO_2 + H_2O$$

$$UH_3 + O_2 \rightarrow 2UO_2 + H_2$$

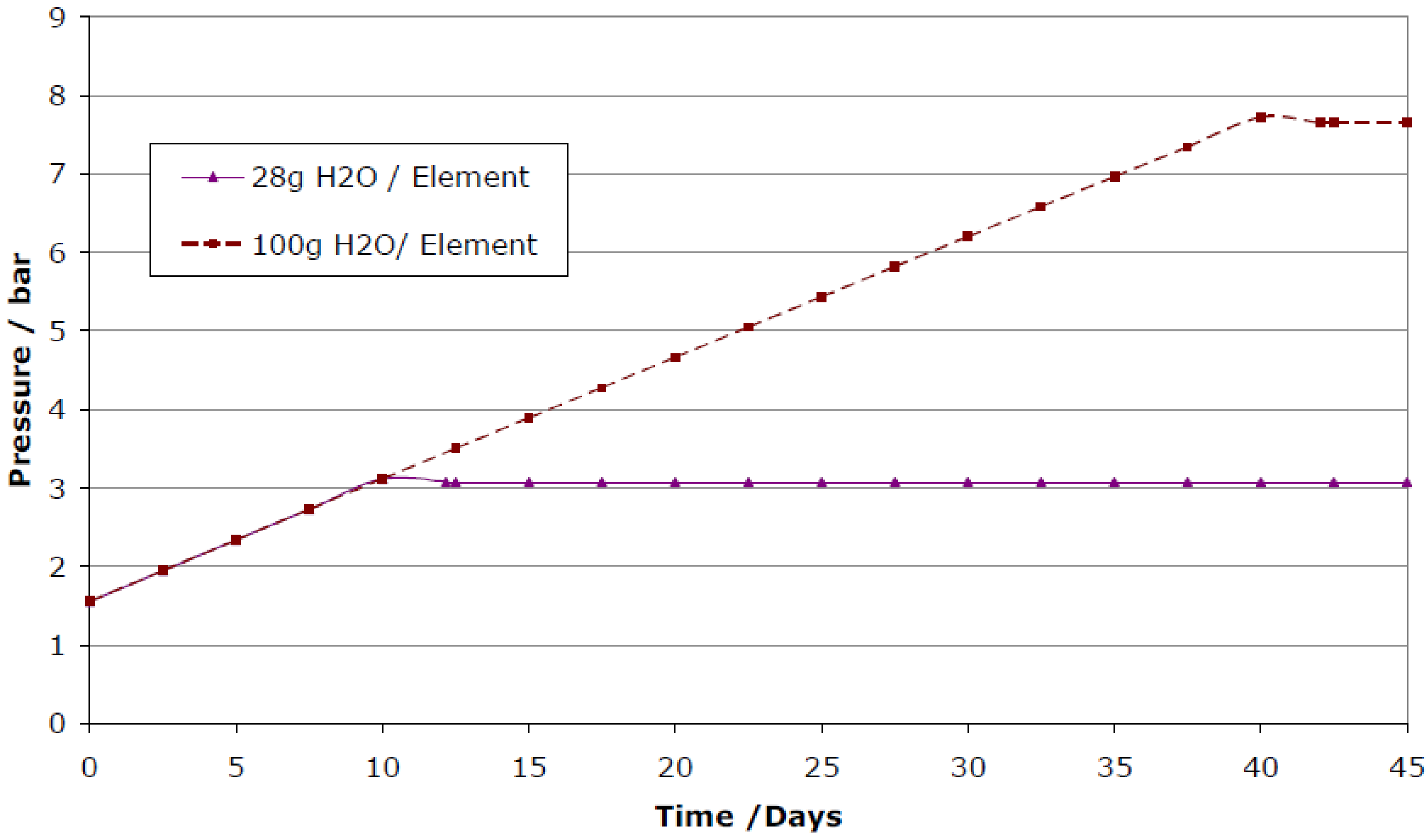
- Radiolysis

$$H_2O + \gamma \rightarrow \rightarrow H_2, O_2$$

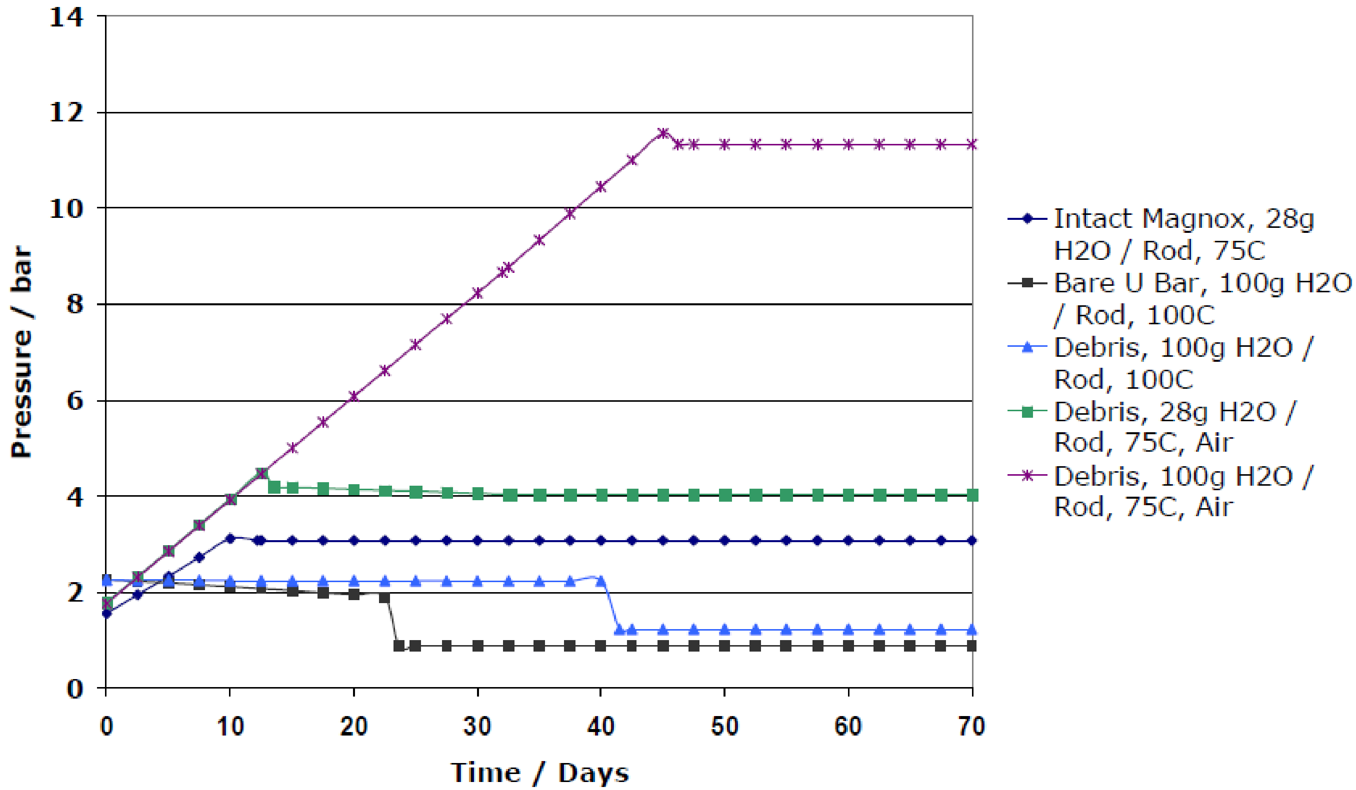
(N.B. a series of radical reactions)

Results – Pressure: Effect of Water Carryover

Effect of water carryover (0.73-2.6L) on canister internal pressure (intact fuel, 75 ºC)

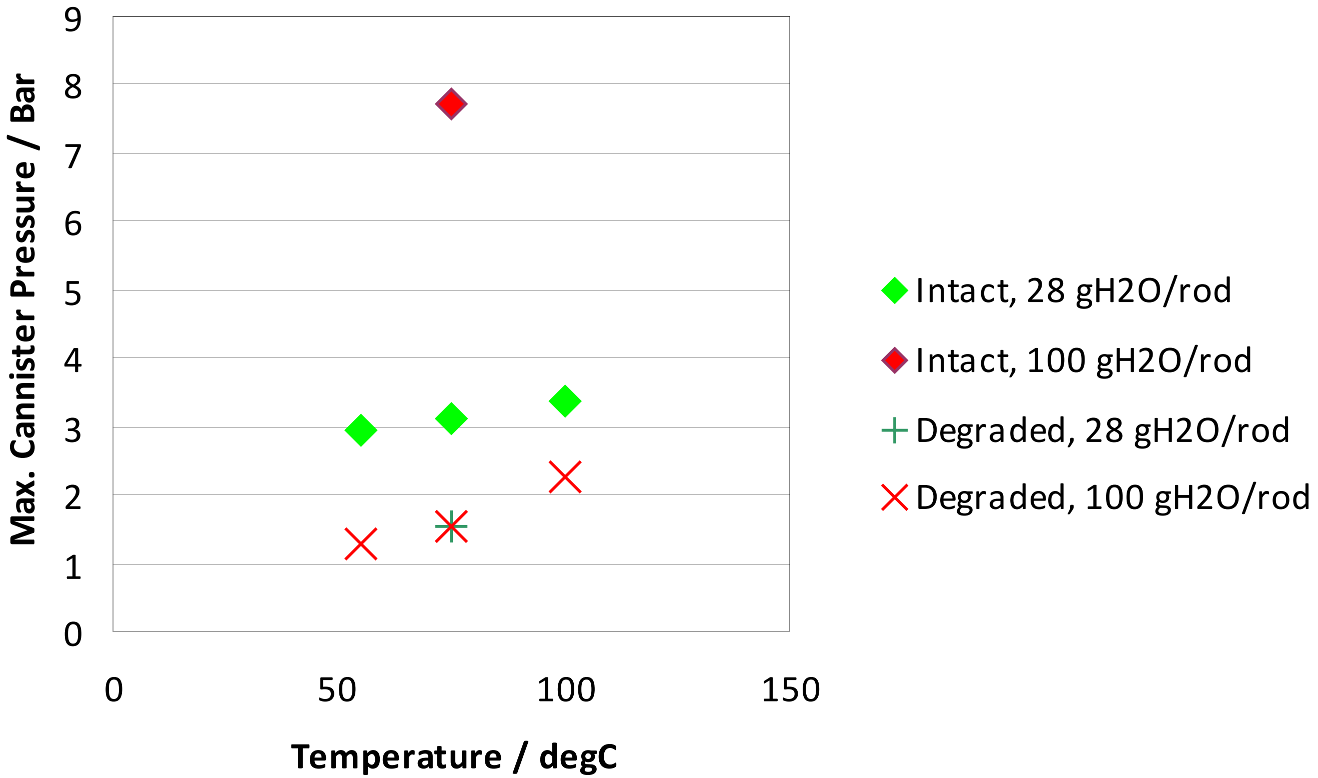


Results – Pressure: Variation with Time



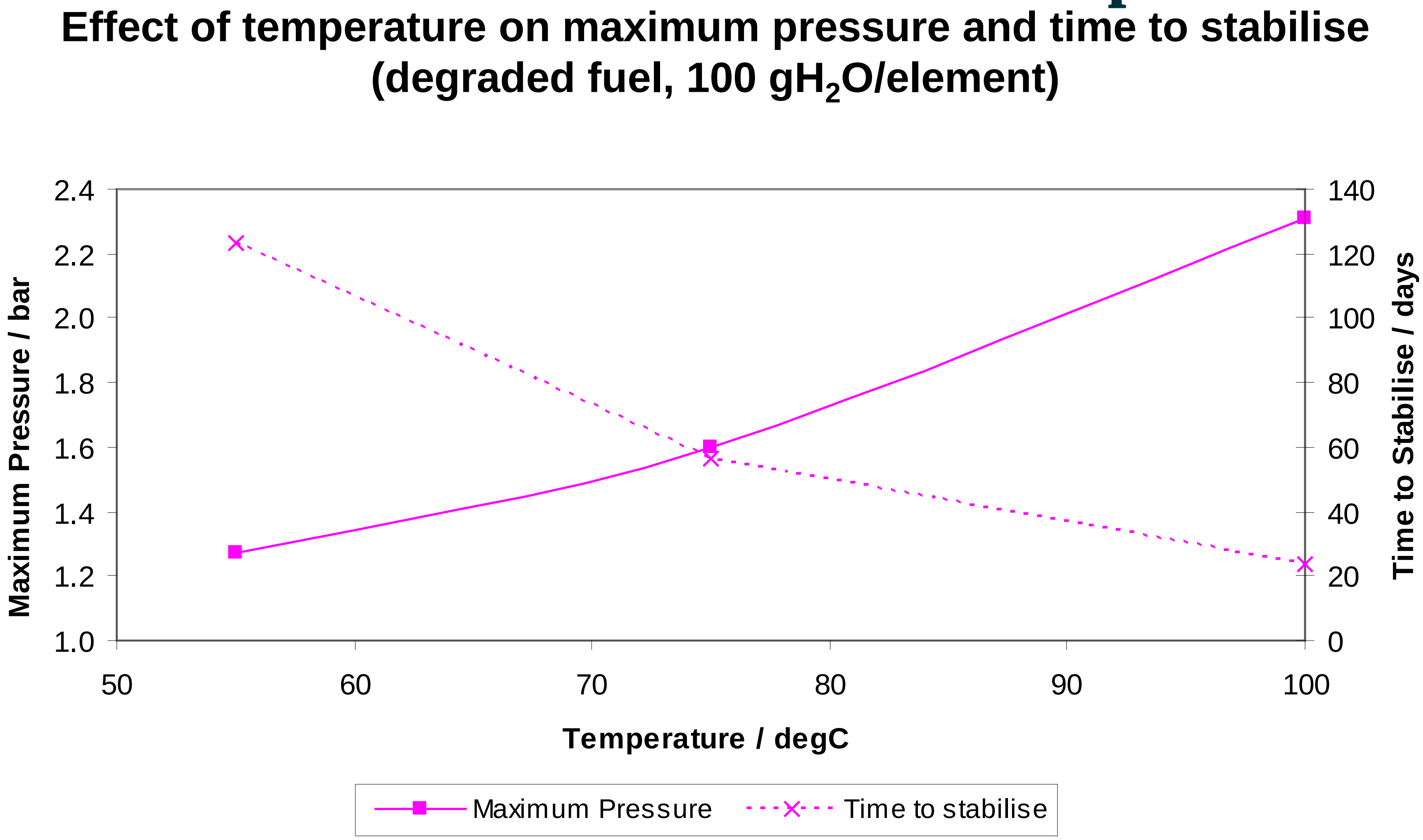
Canister design basis: Nominal Pressure = 30 bar
Maximum Pressure = 100 bar

Results – Comparison of resultant internal canister pressure



NB. The calculated pressures for degraded fuel (exposed uranium metal) demonstrate the effect of the uranium reaction with hydrogen reaction in lower the internal canister pressure

Results – Pressure: Effect of Temperature



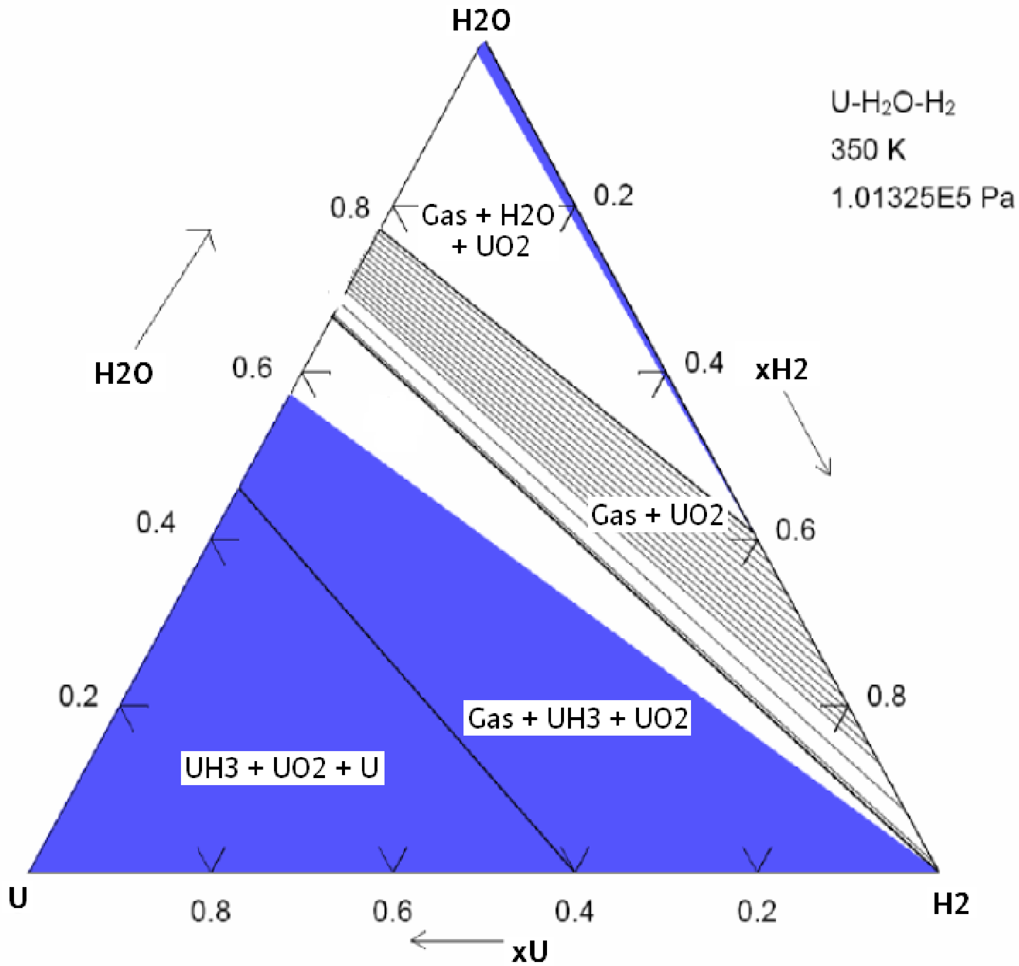
Results – Pressure: Other Effects

1) **Radiolysis:**
   Minimal impact on canister pressure as
   a) Radiolytic gas generation small with respect to corrosion
   b) Insufficient radiolytic O_2 to inhibit U/H_2 reaction

2) **Fission product gas release:**
   - Some volatile fission products released (iodine (I-129) & krypton (Kr-85))
   - Insufficient quantities to affect canister pressure
   - helium production by alpha decay negligible

3) **H_2 migration through canister wall:**
   Negligible effect on pressure (0.1 bar decrease over 150 yrs)

Results – Potential for UH_3 Formation



- UH_3 stable except at high water or H_2 mole fractions, i.e. formation expected in canister where U exposed

- Stoichiometric estimates quantity of UH_3 formed in range
6.5 – 23.2 kg per canister

- Amount of UH_3 formed directly related to water carry over

Conclusions

- A provisional safety case was developed
- Fault scenario for degraded fuel leads to uranium hydride formation (safety issue)
- <u>Option retained as a contingency for intact fuel only</u>

- Project Issues
  - high cost to implement
  - Need to address the potential for large amounts of uranium hydride to be formed
    - Consideration given to a vented canister approach

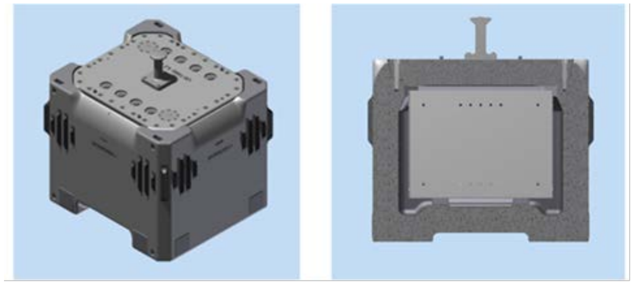
Latest Developments

Management of legacy wastes and fuels

14 November 2019

Self Shielded Box – Management of Legacy Waste

- Self Shielded Box (SSB)
  - System was developed for the removal and interim storage of spent ion exchange skips
    - Ion exchange skips are a modified standard Magnox fuel storage skips
  - The SSB is based on a Magnox Transport Flask
    - Lighter construction
    - Vented
    - Minimises handling
  - Technical issue/Critical technology element
    - Avoiding the build-up of flammable gas from radiolysis
    - Airborne aerosols
  - Critical technology element
    - Filter design



Self Shielded Box – Application for the interim storage of legacy fuels

- Basis of use is hazard reduction
  - Fuel skips washed and simply drained with minimal sorting prior to loading to box
    - As fuel warms up it dries out
      - Internal temperature is a function fuel burnup, store temperature and plateaus out with time

- Technical Issues which need to be evaluated
  - Internal corrosion of the skip/box
  - Potential for filters to block
  - Potential for thermal excursion
  - Radiolysis
  - Uranium hydride formation (link to number of operable filter to avoid)
  - Airborne aerosols
- A number of models have been developed to model each of the issues
  - Base case is degraded Magnox fuel (self draining)

Self Shielded Box – Technical Issues

- Internal corrosion of the skip/box
  - Impacts shielding, filter performance and skip retrievability
- Potential for filters to block from material dry out
  - Modelling has shown that only one filter needs to be operable to maintain oxic conditions
- Potential for thermal excursion
  - There is potential for a thermal excursion from the oxic corrosion of fuel
    - Influenced by fuel packing within the skip
    - Potential to volatilise caesium and mobilize particulates
  - Radiolysis
  - Uranium hydride formation (link to number of operable filter to avoid)
    - Under normal conditions exposed U metal will react with the oxygen in air entering the SSB
    - Passive sintered metal filter which allows air ingress to maintain oxic conditions
    - Rate of reaction is slow
  - Airborne aerosols

Al-Clad, U Metal Fuel (Legacy Fuel)

- Dry storage Position
  - Fuel originally assessed against the Magnox contingency
    - Similar issues to the management of degraded Magnox fuel in terms of the potential to form uranium hydride
  - SSB option
    - A gap analysis has been undertaken to compare to reference case of self draining fuel
    - Apart from differences in material types and packing densities
      - Some additional modelling would be required
      - Overall conclusion is that legacy Al-Clad U-Metal fuels are bounded by the assessments for self draining fuel

Al-Clad, Al-U Fuel

- Management options have included:
  - Reprocessing
  - Dry storage
    - Continued wet storage is not an option as wet storage facilities going forward will be sodium hydroxide dosed
- Dry storage Position
  - Spent fuel evaluated against the Magnox Contingency Canister work
    - Only an option if taken forward for other fuels due to the cost
  - Proposal to evaluate against other dry storage options such as Self shielded box

Summary

- An overview of dry storage and supporting R&D in the UK has been provided
- Also provided information on:
  - The Magnox dry storage contingency and underpinning R&D
  - Current developments for the management of legacy fuels
  - Options for managing Al-Clad fuels have been out-lined