AN OVERVIEW OF THE MANAGEMENT OF EXOTIC FUELS IN THE UNITED KINGDOM

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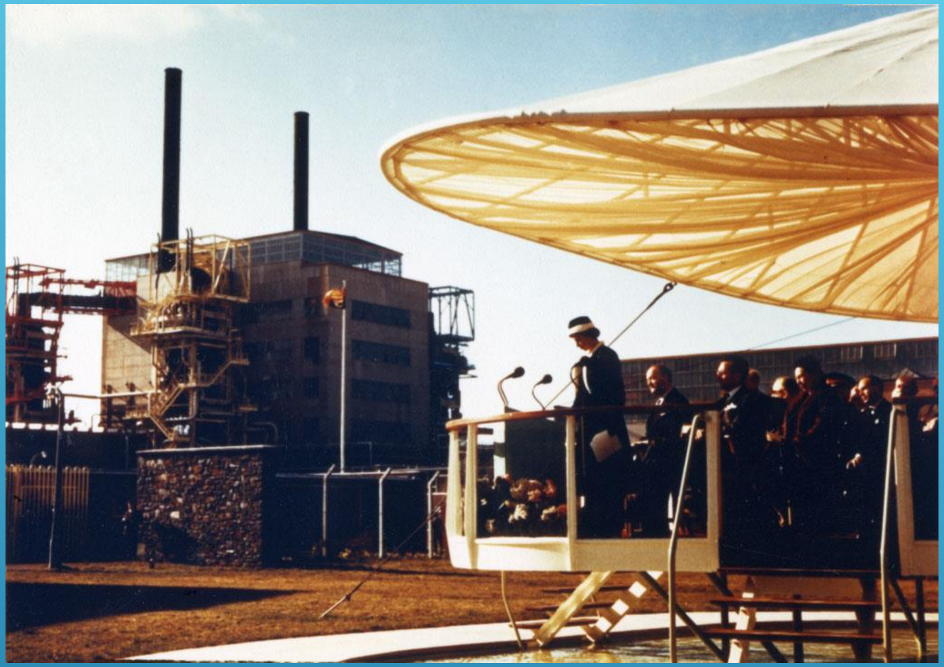
- The following presentation will:
  - Define Exotics and the strategy for managing them
  - Provide an overview of the fuels, how they are managed and relevant lessons learned
  - Generic lessons learned

INTRODUCTION

EXOTIC FUELS – SCOPE AND STRATEGY

- Nuclear Decommissioning Authority owns and manages spent Magnox, Advanced Gas Reactor, legacy and residual fuels from reprocessing activities in the UK
- Amongst this inventory is a group of fuels referred to as 'Exotic'
  - Exotics fuels covers non-standard, research reactor and prototype reactors
- The NDA's strategy for managing exotic fuels:
  - "..is to consolidate all our exotic fuels at Sellafield and to store them safely and securely either alongside oxide or Magnox fuels or develop bespoke solutions for some fuel pending a decision whether to classify them as waste for disposal in a geological disposal facility"

PROTOTYPE REACTORS AND SPENT FUEL MANAGEMENT



- Construction started in 1953
  - Calder Hall (4 reactors built)
  - Further prototypes were built at Chapelcross (4 reactors)
- Graphite moderated, carbon dioxide cooled, 20MW(e)
- Fuelled with natural uranium clad in Magnox
- Most Magnox fuel from these reactors was processed
  - Reprocessing was the preferred management option
  - Contingency options were looked at from mid-2000s
  - Exceptions are any degraded fuel and Magrox

FIRST GENERATION MAGNOX PROTOTYPE REACTORS

MAGROX

- Magrox was a proposed replacement for Magnox fuel
  - Mechanism for extending Magnox station lives
  - Based on low enriched standard AGR pins in a skeleton designed to fit into a Magnox fuel channel
- Only one trial batch of fuel was made
  - Irradiated at Calder Hall
- All fuel was manually dismantled in the Active Handling Facility (Sellafield)
  - Some of the fuel was subject to destructive post irradiation examination
  - Cut pins and pieces were packed into welded thin-walled capsules
  - Both intact pins and capsules are wet stored in slotted pond storage cans
- Storage regime and behaviour is the same as commercial AGR
  - Only difference is the residual enrichment is slightly higher

- A parallel development programme on fast reactor was initiated in Scotland with the construction of DFR in 1955
- DFR was a 15 MW(e), sodium-potassium cooled fast reactor system
  - Built as a proof of concept, it was later used as a test bed for prototype PFR fuel
- Core divided into zones from inner driver fuel (fissile) to breeder blanket material (fertile)
  - Driver fuel was 75% enriched U-7%Mo clad in Niobium (singe rod design)
  - Breeder material was stainless-steel clad natural uranium 'pucks'
- Spent fuel management was based on reprocessing
  - Most driver fuel has been reprocessed at Dounreay
  - Most blanket material has been reprocessed at Sellafield
- Residual driver fuel/breeder material
  - Driver fuel is stainless-steel clad prototype PFR fuel
  - Breeder material will be dry stored pending disposal

'FOURTH' GENERATION DOUNREAY FAST REACTOR (DFR)

- WAGR was a 36 MW(e), graphite moderated/reflected carbon dioxide cooled gas reactor
  - Increased thermal efficiency over the Magnox system was achieved through operating at a higher temperature
- Fuelled with low enriched UO_2 fuel clad in stainless-steel
- Apart from proving the reactor system and collecting vital safety data, it was used as a test bed for fuel development and performance
- Irradiation experiments included:
  - Changes in fuel enrichment (0.4-12.5% ^{235}U)
  - Fuel pellet development
  - Fuel clad development
  - Irradiated MOX and Carbide pins
- Fuel management was based on reprocessing
  - Over 30% has been reprocessed between 1969 to 1973 and in 2016

SECOND GENERATION WINDSCALE ADVANCED GAS REACTOR (WAGR)

WAGR FUEL

Example of welded can for cut pins/debris

Example of a slotted can for intact pins

- All the fuel was manually dismantled after irradiation
  - A large amount was subject to destructive PIE
  - Dismantled fuel was incorporated into a variety of stainless-steel pond storage cans
- Remaining fuel is wet stored
  - Performance in storage is like commercial AGR fuel (CAGR)
- Issues associated with storing the fuel (generally applicable to all legacy PIE material):
  - Reduced storage density (70% reduction) c.f. CAGR fuel
  - No standards for packing or welding
    - Early material in screw top cans
    - Wide range of can types
    - Materials accountancy data suggests some cans are under weight

LEGACY WAGR PIE

- Around 2010, some 40-year wet stored WAGR fuel, that had been stored in screw top cans, was repacked
- Findings:
  - All cans were flooded
  - Some cases a sludge had formed on the outside of cut pins/pieces
  - Unexpected metallic items found:
    - lead weights
    - aluminium sample cans
    - cave tools
    - pin stubs with gas pipe couplings used in stress-rupture tests attached

NEA (2021), View of Dragon Reactor. Photo: AEA Technology., OECD Publishing, Paris

DRAGON REACTOR

- Dragon, operated between 1966 and 1975, was a 20 MW(th), helium cooled high temperature gas reactor
  - Built at Winfrith, Dragon was a first of its kind OECD project
- Fuel is vastly different from other prototype power reactor fuels
  - Graphite fuel compacts (graphite support holding fuel kernels)
  - Fuel kernels
    - Highly enriched fuel particles coated with multiple protective layers of pyrocarbon and silicon carbide
    - Ratio of graphite to fuel is high
    - 25 different variants were tested of varying compositions including: UC_2 + C, (Th, U)C_2, (Zr, U)C
- Dragon fuel is an example where a decision has been made to classify it as waste and a bespoke storage solution has been developed
  - Fuel storage cans are being entombed in grout in a 500 L stainless steel waste drum
  - Conditioned drums are stored alongside other reprocessing waste
  - Challenges:
    - Treated differently to other stored waste (security and safeguards)
    - Specific spent fuel storage guidance doesn't specifically cover the conditioning of spent fuel into a wasteform

- SGHWR, operated between 1967 and 1990, was a 100 MW(e) light water-cooled heavy water moderated pressure tube type reactor
- Fuelled with low enriched UO_2 fuel clad in Zircalloy-2
- Most development studies related to proving the reactor system. Fuel development was relatively modest.
  - Changes in fuel enrichments, rod lengths and rods per cluster
    - Optimised design was a 57-rod cluster, earlier designs included 36 and 60 rods
  - Exception was the irradiation of a prototype 'FUGEN' MOX FA
- SGHWR fuel management was based on reprocessing
  - Spent fuel was routinely transported to Sellafield between 1972 and 1994
  - No issues with storing the fuel. Operational issues related to:
    - Fuel crud migration in transport/transfer to storage
    - Different FA lengths
    - Reactor damaged fuel
  - Some fuel was reprocessed in Thorp prior to its closure in 2018
  - Residual fuel is wet stored in MEBs pending disposal to a GDF

THIRD GENERATION
STEAM GENERATING HEAVY WATER REACTOR (SGHWR)

- PFR was a 250 MW(e) sodium cooled fast reactor, construction started in 1966, operational 1975-1994
  - Basis for the commercial fast reactors
- Like DFR fuelling is zoned from the inner to the outer
  - Fuelled with (22—28 w%, ^{235}U + Pu) UO_2–PuO_2 pellets clad in stainless-steel (PE16, M316 and FV548)
- Most fuel has been reprocessed at Dounreay
- Residual fuel is dry stored at Dounreay and comprises subassemblies, intact pins, and cut pins/fuel debris in stainless steel cans

FOURTH GENERATION PROTOTYPE FAST REACTOR (PFR)

CONSOLIDATION OF PFR FUEL AT SELLAFIELD

- PFR fuel is challenging in terms of transport and disposal
  - Security and Safety
    - For example, criticality safety in transport and under accident conditions has led to the requirements for moderator exclusion design of transport cask
  - Compared to thermal reactor fuels
    - higher enriched
    - higher burnup (peak of 200 MWd/tHM)
  - Inventory also includes mixed carbide fuel
    - Unlike Dragon fuel where the uranium carbide is in the form of particles that are protected by hard layers of carbon and silicon, fast reactor carbide fuels rely on clad integrity
    - Carbide is pyrophoric and readily reacts with water
      - Previous assessments have looked at converting to the oxide (practicality of doing this)
      - Drives storage solutions towards an inert dry environment

RESEARCH REACTOR FUEL

- Most research reactor fuel was reprocessed at Dounreay
- Research reactor fuel remaining in storage
  - Graphite Low Energy Experimental Pile (GLEEP)
  - CONSORT
  - Jason

Reactor	Type Reactor	Fuel	Fuel Management (original plan)
GLEEP	Pile	Nat U in aluminium cans	Disposal as ILW to a GDF Conditioned wasteform (epoxy coated and grouted into a 500L drum) (Store until reactor is decommissioned)
CONSORT	Pool	HEU U/Al Plate	Wet store pending disposal to a GDF (Reprocessing at Dounreay)
Jason	Argonaut	HEU U/Al Plate	Wet store pending a decision

RESIDUAL FUELS FROM REPROCESSING ACTIVITIES

RESIDUAL FUELS FROM REPROCESSING ACTIVITIES

Dounreay

- PFR reprocessing facility was designed to be able to reprocess a range of difficult fuel including MOX a and HEU
- Services were marketed in late 1980/early 1990s
- Facility was shutdown in 1994
- Overseas fuels remaining in storage after shutdown included:
  - Fast reactor MOX
  - Fast Reactor Carbide
  - Early LWR MOX
  - Irradiated HEU
- Like PFR they are challenging from a transport and disposal viewpoint and share the same issues

Sellafield - Thorp

- Thorp was shutdown in 2018. Residual overseas fuels included:
- Standard power reactor MOX
- Damaged power reactor oxide fuels
- UKAEA manufactured or owned fuels that had been irradiated overseas as part of collaboration programmes
  - For example, BR3 Vulcain core fuel (Up to 9% 235U UO2 stainless steel clad HWR fuel assemblies)
  - MOX fuel elements or assemblies
  - MOX PIE
- Residual fuels will be wet stored in MEBs pending the disposal to GDF.

LESSONS LEARNED GENERIC

- Fuel management was based upon the assumption that it could be reprocessed
  - Underpinning and the need for contingencies appear to have been secondary
- Records management beyond materials accountancy data is key
  - Materials accountancy information only provides part of the story
- Different lifecycle options have different needs
  - Reprocessing less robust packages prolonged storage more robust
  - Standard for PIE committed to storage
  - Fuel route/storage option would have been different