INTERIM DRY FUEL STORAGE FOR MAGNOX REACTORS

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1 HISTORICAL BACKGROUND

Out of the 20 U.K. supplied Magnox Gas Cooled Reactors (MGRs) Power Stations, 18 are located in the United Kingdom. At the time that the original National Nuclear Policy was established the overall scene encompassed chemical reprocessing to recover the plutonium produced in the MGRs as a fuel supply for future fast reactors. The high level waste from the reprocessing plant was to be temporarily stored as liquid in high integrity tanks pending the establishment of ultimate disposition in a repository in some suitable form yet to be determined.

This also was consistent with the uncertainties and unknown long term availability of world uranium ore supplies. Furthermore, the then predictions of chemical reprocessing costs appeared to be offset by the future worth ascribed to the value of recovered plutonium to be used in fast reactors. It was further considered that the ultimate treatment and disposal of the high level waste liquors would not significantly affect the prediction of power generation cost. At that time other countries assumed a similar position regarding chemical reprocessing, e.g. Italy and Japan where the other two MGR stations had been supplied.

At the same time Canada, which had committed itself to natural uranium fuel reactors, had followed the opposite route of not reprocessing, also coupled with the assumption that the ultimate disposal route for the irradiated fuel could be resolved later. In the meantime they could conveniently provide medium term buffer storage of the irradiated fuel in water ponds.

In the UK the practice of short term buffer storage in water ponds prior to chemical reprocessing had already been established on the early gas cooled reactors at Calder Hall. Thus the choice of water pond buffer storage for MGR stations logically followed the national policy decision to reprocess. The majority of the buffer storage period would take place at the reprocessing plant with only a nominal 100 days targeted at the station. Various inflexibilities in the transportation/reprocessing route caused this period to lengthen, and since Magnox clad fuel is not suitable for long term pond storage, alternative methods of storage on future stations was considered desirable.
The then operating experience of MGRs indicated that fuel not exposed to the highest temperatures or neutron fluxes was in a "pristine" condition even if it had been in the reactor for four years. In addition the experience with failed fuel, dry stored in CO₂ filled bottles which were stored in the ponds, gave additional confidence that storage in a dry CO₂ atmosphere would be such a suitable alternative.

Modification of the then new Oldbury contract was contemplated but following review of the implications it was concluded the changes were too extensive to contemplate. However, because of the perceived cost and technical advantages, the ultimate MGR (Wylfa) was specified as having a dry buffer store, Fig 1(b). The station is supplied with three cells each comprising a cluster of CO₂ filled fuel tubes, each tube containing 12 elements stacked vertically. The fuel tubes are cooled externally by natural draught induced atmospheric air flow across the tube bank, thus providing an entirely passive system. The excellent operating experience of this dry buffer store, coupled with the desirability of increasing the total MGR system dry storage capacity, led to the addition at Wylfa of two large vaults, Fig 1(c). These were air cooled by a recirculation system dissipating its heat to water coolers, ref (1). These latter stores have also performed excellently over the past 5 years since they were licensed and commissioned.

2 REAPPRAISAL UNDER 1983 CONDITIONS

Several countries have declared an interest in small to medium size nuclear power stations that are proven by experience, relatively unsophisticated, easy to license, and suitable for compliance with nuclear safeguard requirements. The natural uranium fuel MGR of Oldbury with its prestressed concrete pressure vessel containing the reactor and boiler units is a suitable candidate to meet this combination of requirements, and has been operating successfully for 15 years with a life load factor of 80%.

A major safeguard advantage of MGR is that the feed fuel does not need special NPT safeguard provisions. If, in addition, irradiated fuel is not being shipped from the site on a routine basis, then safeguards through containment and surveillance measures is markedly eased, i.e. indicating fuel storage rather than reprocessing is preferable.

In addition to safeguard considerations the economic picture of the fuel cycle is transformed by the following changes which all point to storage;

(a) The costs of chemical reprocessing have considerably escalated from the early estimates.

(b) Ample supplies of low cost uranium ore and surplus enrichment capacity both reduce the incentive to recover fissile material from the irradiated fuel.
(c) The development timescale of the fast breeder reactor is recognised as more protracted.

(d) Proven irradiation of MGR fuel has increased from 3000 to 6000 MWd/Te, thus reducing the quantity of fuel to be stored.

Today the purchase of an MGR Power Station with dry fuel storage and without commitment to reprocess would be a rational decision for a country initiating a nuclear power programme.

3 DRY STORE REQUIREMENTS

The selected interim storage period affects the store design concept. National policies on 'reprocessing versus conditioning' prior to disposal, and the state of the international economic market for irradiated fuel as an alternative feedstock to uranium ore, cannot be predicted with any degree of certainty. The likely uncertainty range has been suggested as 30 to 100 years, ref (2), this time range stretching from the power station operating life to the return to "greenfield" decommissioning of the power station site, respectively.

Storage concepts may be developed as derivations of existing U.K. dry buffer store experience, see Fig 1. This latter definition refers to a holding store prior to chemical reprocessing and thus ideally the storage positions are reuseable for further fuel assemblies. If reprocessing is intended, the storage and handling of bare uncontainerised fuel assemblies for transmission to the reprocessing system is desirable to avoid emptying and catering for the residual containers at the reprocessing plant. There is no fundamental reason why such a store concept cannot be extended to provide interim storage.

An alternative approach to the interim storage requirement is a concept in which the fuel assembly is sealed into its own high integrity dedicated container, the store being designed on the basis of 100 years of maintenance free storage. A detailed design of such a store for AGR fuel is nearing completion, ref (2).

The paper separately describes two such design approaches which could be used depending upon the prevailing conditions applicable to a specific Purchaser. In both cases fuel is discharged from the reactor refuelling machine into a preparation cell. Inside this cell, clusters of six elements in four layers high are assembled on a supporting rack for further handling as a combined fuel assembly unit. Since no specific provision is made for an initial decay period prior to interim storage, the environment for the fuel assemblies is CO2 to ensure that fuel/clad temperature limitations are conservatively met in the initial stages of fuel element heat decay.
Irradiated fuel is removed from the on load reactors using a fully shielded refuelling machine designed to operate at CO\(_2\) coolant pressure whilst coupled to the reactor. The refuelling machine transfers fuel to the Fuel Preparation Facility (FPF) for preparatory operations before storage. This facility is typically located centrally between the reactors of a twin reactor station to allow access with the refuelling machine, see Fig 6. Prepared fuel is removed from the FPF using a dry store charge machine and loaded direct into the storage vault. The refuelling machine and the charge machine are both gantry mounted, fully shielded and natural convection cooled machines, evolved from the extensive remote fuel handling experience derived from the British magnox reactor programme.

The FPF provides the following functions for each of the dry store designs described in this paper:

(a) Receives fuel from the refuelling machine into a dry CO\(_2\) environment.

(b) Loading of the support rack to form the circumferential array of six elements stacked four high whilst maintaining the CO\(_2\) environment.

(c) Transfer the loaded support rack to a location accessible by the dry store charge machine.

(d) Allow loading of empty (new) support racks prior to loading with fuel.

The alternative store design 'B' provides for the containerisation of the fuel and requires the additional functions:

(e) Loading the empty (new) storage container with enclosed support rack.

(f) Closure of the storage container; remote welding of the container closure after fuel loading; leak testing of the closure weld.

(g) Cutting of storage containers so that fuel can be removed from a container in the event of a fault in the closure welding process or for interim fuel inspection during storage.

Figures 2(a) and 2(b) illustrate FPF arrangements for the two store designs described in this paper both showing a CO\(_2\) filled reception cell and an adjoining air filled transfer corridor. The reception cell and transfer corridor are connected by a loading port having special features determined by the store design.
Whilst coupled to a reception cell access port, the refuelling machine is depressurised to atmospheric pressure, the cell closure plug removed, fuel loaded into the FPF and the loading cycle completed by replacing the plug and repressurising the machine.

The transfer corridor houses a transfer carriage that allows movements of an empty support rack to the loading port and after fuel loading, subsequent movement to the dry store charge machine loading station where the loaded support rack containing 24 fuel elements is removed to the store.

For the uncontainerised store design 'A' the transfer carriage provides the confinement boundary around the support rack that allows the retention of a local CO₂ environment during loading and transfer operations.

For the containerised store design 'B' the storage container is used for this purpose, but requires special purpose equipment at the loading port to allow remote welding and inspection of the container closure. The design of the loading/welding port for the container prevents contamination of the outer surfaces of the container during the loading, closure and welding operations. A container cutting machine is located in the floor of the reception cell and faulted containers are removed from the loading port position using an in-cell overhead crane.

The reception cell and transfer corridor equipment will achieve the design fuel handling rate (around one support rack per 24 hours) with a high degree of reliability achieved by a developed design and regular workshop maintenance of important items of equipment. This equipment will be replaced by identical "modules" allowing fuel handling to proceed whilst the spare module is maintained in adjacent workshops.

5 DRY STORE - DESIGN A

The accumulated experience of existing magnox storage facilities ref (3) is incorporated into the uncontainerised fuel dry vault design described and illustrated in Figure 3(a). The store may be located separately from the reactor building as a self contained unit using an on-site fuel transport flask to transfer fuel between the reactor and store. This alternative is used for the Fig 3(a) illustration showing two modules. Alternatively the store may be directly linked to the reactor building via the transfer corridor as illustrated in Fig 2(a) and Fig 6.

The concrete vault provides the air cooling ducts and the biological shielding for a vertical array of fuel storage tubes. Each storage tube is closed at its upper end by a removable fully shielding closure plug forming an engineered leaktight primary confinement boundary. The tube material is carbon steel with an external anti-corrosion protective treatment. The storage tubes (containers) are supported from the floor of the vault and penetrate the charge face created by the vault roof. When loaded, each storage tube contains one support rack of fuel.
Each storage tube is connected to a common manifold system composed of small bore pipework.

Decay heat from the spent fuel is indirectly rejected to the environment entirely by highly reliable passive heat transfer processes. Primary heat rejection from the spent fuel to the sealed containment envelope is by radiation and convection. Secondary heat rejection from the outside of the containment envelope to the environment is produced by a self regulating natural thermosyphon buoyancy driven cooling flow using ambient air flowing over the outside of the storage tubes. This cooling air flow is drawn by buoyancy forces from the outside of the vault, via ducting, and then across the tube bank before exiting to the atmosphere via the discharge ducts.

Because the fuel is indirectly cooled, there is no contact between the primary cooling air environment within the containment envelope and the secondary cooling air discharged to the atmosphere.

Cross-flow thermosyphon air cooling has been adopted in preference to axial flow cooling because of the benefits it bestows to this design, the chief being:

(a) This mode of air cooling has already been shown to be effective from the theoretical and actual operating data obtained from the operating vault stores that were built into the Wylfa nuclear power station, ref (1) and (4).

(b) There are no internal structures to delineate the air flow, thereby enabling cost reductions to be achieved. Long term corrosion of internal structures is avoided by their deletion.

(c) The volume of the storage vault is used more efficiently because a top plenum for the exit cooling air is not required.

(d) The warm exit air does not flow across the underside of the charge face, which can ease the thermal and structural problems in the charge face structure.

(e) The air resistance of the tube array is small for cross flow, enabling a greater flow and hence lower fuel temperatures, for a given heat load in the store.

For magnox fuel, storage in an inert environment is necessary until fuel temperatures have fallen to 150°C when storage in air is possible. This temperature is reached approximately 100 days after removal from the reactor. Thus, a short term operating mode is necessary for the store using CO₂ gas within the storage tube. In this mode, the tubes would be held at a slight positive pressure and the retention of this environment would be ensured by continuous monitoring via the manifold system. After the initial (100 days) cooling
period the storage tubes would be opened to a small absolute/ISI filter and exhauster system via the manifold pipework and the interior of the storage tubes reduced to a light negative pressure. In this mode, the storage environment is essentially air and this will be maintained for the remainder of the storage period. Storage of fuel in air avoids the risk of dilution or loss of the design environment during the storage period.

If leaks develop in the containment envelope formed by the storage tubes and their closures then air would flow inwards and then be discharged to the environment via the filter. Any increase in the volume of air flow through the exhaust system (that will be nominally zero in normal circumstances) can provide positive continuous monitoring of the leak-tightness of the containment envelope. There are, therefore, in addition to the fuel cladding, two engineered barriers against the possible release of radionuclides to the environment during the long term storage mode.

(a) The containment envelope formed by the storage tube and closure plug.

(b) The depression within the storage tube.

The diverse nature of these engineered barriers constitutes a high integrity confinement system with a high degree of protection against common mode failure. It should be pointed out that the radiological hazard contained within the storage tubes and outside of the fuel cladding is relatively mild comprising largely of the surface deposits arising from reactor operation. If temperature limits are reliably maintained, then significant release of radionuclides from the fuel element, even if cladding defects exist, can be avoided. The demands upon the containment system integrity are therefore largely dictated by the storage temperature of the fuel. The store containment and cooling system is illustrated schematically in Fig 3(b).

The storage tubes are individually removable from the vault for inspection or replacement by a simple vertical lift using the charge machine. The charge machine replaces a storage tube that has been removed by a temporary shield plug to reinstate the charge face shielding integrity. With the storage tubes removed, no permanent steelwork structures or monitoring pipework exists within the storage vault, that could be subject to long term degradation by corrosion.

The ability to monitor continuously and replace, if necessary, the complete primary containment boundary, allows the design to be applied to very long term storage applications.

The charge machine is capable of incorporating the necessary inspection and monitoring equipment so that the fuel assemblies in the tubes can be inspected when desired.
Remote viewing inspection equipment on the machine can visually examine any chosen assembly at any time, simply by visiting the chosen storage tube and hoisting the assembly into the machine. Gamma-ray spectroscopy can also be installed to gain some idea of radioactive inventory and hence irradiation history, burn-up etc. This facility can also provide individual characterisation for each fuel assembly.

**6 DRY STORE - DESIGN B**

This interim dry store was initially designed to the requirements of the UK Generating Board as a National Dry Store for their AGR reactors ref (2). The detailed design work has now been completed and manufacturing supply specifications drawn up. A preliminary safety report has already been reviewed by the UK Licensing Authority and the pre-construction safety report is planned for submission in Spring 1984. Design work has been carried out to show that the same store is equally applicable to storage of light water reactor fuel and high level waste storage ref (3).

This section of the paper describes how the same interim store modules may be used in conjunction with a magnox reactor power station to hold the total lifetime production of irradiated fuel. The principal features that have been built into the storage concept are:

(a) 100 year storage capability.
(b) Passive open cycle natural draught air cooling.
(c) Fuel in unpressurised, high integrity, welded containers.
(d) Uncontaminated store vaults.
(e) Low risk of activity release solid or gaseous.
(f) Containers retrievable on demand.
(g) Corrosion control.
(h) Safeguard provisions.
(i) Simple reinforced concrete structure.
(j) Handles hazards; wind, seismic, and aircraft.

An isometric of the vaults and container handling machine within the weatherproof secondary building is shown in Fig 5. Each vault is of a cuboid shape approximately 15 metres internal dimension. A reinforced concrete storage matrix is supported round three edges of the vault with one side partially integrated with the wall to act as a seismic fixture. The matrix is penetrated by steel lined cooling channels each holding two fuel containers, each fuelling channel having corresponding access.
holes in the vault roof. The roof shield plug is removed by the container handling machine when container transfer takes place. The natural draught air cooling flow enters the openings in the weatherproof building and the building acting as a large plenum chamber to smooth out external wind pressure variations. Air enters the storage vault through 16 inlet ducts, flows under the storage matrix, and then upwards over the containers within the channels. From the outlet plenum it passes through the shielding labyrinth up the stack. A portion of the air in the hot outlet plenum is entrained by the stack driven kinetic energy of the incoming cold air and recirculated through the venturi/ejectors to provide preheating to the inlet plenum chamber. This preheating ensures environmental control to eliminate corrosion and permits all the internal vault components, including the containers, to be manufactured from time proven carbon steel.

The physical design of the vault is very simple, the design know-how consisting primarily in having the knowledge to choose the correct geometry, and secondly the ability to predict the performance and specify the method of operation.

The design of the vault has many features similar to gas cooled reactors, but nevertheless the low forces available with natural draught have required extension of the areas of knowledge by further development testing ref (3). Development tests specific to the storage vaults have now been completed in four areas:

(a) Drop tests of the containers to show that the shock absorbing provisions are adequate.

(b) Tests of the venturi/ejector recirculation device to determine the geometry for maximum efficiency and uniform mixture temperature.

(c) Temperature and flow distributions in the upper plenum chamber.

(d) Stack detection and subsequent vault location of any leaking containers.

There are many examples of corrosion experience similar to those shown in Fig 4 which demonstrate both indefinite life of bare carbon steel under controlled conditions and premature failure in uncontrolled environments. For the required design life of 100 years without component replacement, (which would be protracted and costly), there are no materials or protective treatments which have proven evidence of durability for a 100 year life.

Using modern techniques, recent development work in support of gas cooled reactors has more precisely quantified the relatively earlier crude textbook experiments to relate corrosion rate, relative humidity, and surface contamination. In general it can be said that the most likely locations for power stations would require the relative humidity at the metal surface temperatures to be held below 32% if corrosion is to be negligible. The use of the venturi ejector ensures that sufficient outlet air is recirculated to meet this lifetime requirement.
The modular form of construction is shown in Fig 6 where an initial build of 2 x 300 MW reactor stations could have four vaults, suitable for the first 12 years operation. One vault could be added every 3 years throughout the rest of the plant operating life.

The containers are CO₂ filled to provide enhanced margin against internal corrosion/fuel clad defects in storage. In the event that one of these high integrity containers should develop a leak and that container should also contain a defective fuel clad element, any activity leakage rate is sufficiently slow to be detected by the stack monitor; the container location system used to locate the offending container; and for the offending container to be removed and returned to the containerising facility, thus terminating the incident.

The feature of maintaining the exterior surface of the containers free from radioactive contamination means that the container handling operations and the vault stores only require shielding and cooling provisions.

The facility takes into consideration the need for physical containment and surveillance measures that complement the IAEA NPT safeguards based upon materials accountancy procedures. The concrete enclosure of the long term fuel store provides a containment measure of very high integrity. Access penetrations to the facility have been reduced to the minimum necessary and arrangements have been made to preclude withdrawal of fuel containers from the store and their removal from the reactor site. The range of surveillance measures considered to supplement the inherent 'containment' feature of the spent fuel storage system are seals, radiation detectors and optical systems. Proposals for a comprehensive set of such measures are being actively formulated.

REFERENCES


TABLE A
TECHNICAL DATA FOR 2 x 300 MWe MGR STATION FUEL STORE

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<th>Fuel type</th>
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<tr>
<td>Element length</td>
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<td>mm 91</td>
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<tr>
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<td>Avg number support racks/wk</td>
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<table>
<thead>
<tr>
<th>Design 'A'</th>
<th>Design 'B'</th>
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<td>Max fuel temp (CO₂) °C</td>
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<td>Design air inlet temp °C</td>
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FIG 1
SOME U.K. DRY BUFFER STORES

(a) Pressurised/atmos. gas & water cooled
Hunterston 'B' & Hinkley Point 'B' AGRs
Operational 1975
Fuel UO$_2$/S.S.
Atmosphere Gas 600 psi CO$_2$/atmos. air

(b) Pressurised/atmos. gas & air cooled
Wylfa (cells 1-3)
Operational 1968
Fuel U/MMagnox
Atmosphere 2 psi CO$_2$

(c) Pressurised/atmos. air indirectly water cooled
Wylfa (cells 4-5) Windscale AGR
Operational 1978
Fuel U/MMagnox
Atmosphere Sub atmos. air 2 psi CO$_2$
CO
CO
co
RECEPTION CELL EXTENSION
TO CONTAINER CUTTING
MACHINE AND DECONTAMINATION
CELL

REACTOR REFUELLING MACHINE
NEW CONTAINER LOADING
ROOM
DRY STORE
CHARGE MACHINE
REACTOR CHARGE FACE
ACCESS PORT
RECEPTION
CELL CO₂
ATMOSPHERE
VIEWING
ROOM
TRANSFER
CARRIAGE
DRIVE ROOM
CONTAINERISATION
MACHINE
TRANSFER CORRIDOR
AIR ATMOSPHERE
CONTAINER JACKING
ROOM
CONTAINER ACCESS
MACHINE
FIG 2(b) FUEL PREPARATION
CELL - DESIGN 'B'
1) Spent Fuel or Vitrified Waste Receipt/Dispatch Building
2) Charge Hall
3) Charge Machine and Gantry
4) Storage Sub-Module fully equipped with Storage Tubes and loaded with Spent Fuel or Vitrified Waste
5) Storage Sub-Module prior to installation of Storage Tubes
6) Storage Sub-Module fully equipped with Storage Tubes and partially loaded with Spent Fuel or Vitrified Waste
7) Air filled Storage Tubes Primary Containment for Spent Fuel or Vitrified Waste
8) Thermosyphon Cooling Air Inlet Duct
9) Cooling Air Exit Duct
10) Offices
11) Transport Cask and Transporter

FIG 3(a) INTERIM DRY FUEL STORE - DESIGN 'A'
FIG 3(b) SCHEMATIC OF VAULT STORAGE SYSTEM, ILLUSTRATING THE SPENT FUEL CONTAINMENT SYSTEMS AND THE THERMOSYPHON COOLING FLOW - DESIGN 'A'

FIG 4 EXAMPLES OF CORROSION EXPERIENCE (CARBON STEEL)
(a) Uncontrolled external position 3 miles from coast for 30 years
(b) Controlled workshop conditions - hand made tool 1898, still in use
FIG 5 INTERIM DRY FUEL STORE - DESIGN 'B'
FIG 6  2 x 300 MWe MAGNOX STATION WITH VAULT FUEL STORAGE