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RESOLVING THE TECHNICAL UNCERTAINTIES IN THE DECOMMISSIONING OF AN ACCIDENT DAMAGED REACTOR – WINDSCALE PILE 1

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ABSTRACT

Windscale Pile 1 was a plutonium producing, graphite moderated, air-cooled ‘pile’ built in the NW of UK and operating in the 1950’s. In October 1957 the reactor core caught fire releasing radioactive contamination into the environment – a major nuclear accident for the developing UK nuclear industry. Pile 1 was promptly closed down (together with its sister plant, Pile 2). Attempts to defuel Pile 1 were only partially successful and approximately 15 tonnes of uranium metal fuel is estimated to remain within the reactor core. Since that time the pile has remained in a quiescent state under a regime of surveillance and maintenance. Work is now gathering apace to decommission the reactor but the present state of the core internals remains unknown. This lack of adequate characterisation has limited the forward programme for decommissioning. Hence the initial step prior to dismantling is to understand better the present status of the pile in order to develop the safety arguments. Intrusive inspection into the Fire Affected Zone (FAZ) of the pile has not yet been possible until safety related issues have been resolved – these issues present a number of technical uncertainties that must be addressed to enable a safe and cost effective option to be selected for decommissioning. This paper details the approaches taken that have now resolved the various technical uncertainties and provided a firm basis for the future dismantling of the pile.

INTRODUCTION

A sectional view of Pile 1 is shown in Figure 1. The reactor core consists of a 2000 te graphite moderator/reflector comprising about 50,000 blocks of graphite keyed together using a system of graphite slats and tiles (Figure 2) generating an interlocking structure of approx. 15x15m in section and 7.5m deep. The core is penetrated by 3444 horizontal fuel channels of 100mm diameter and 977 isotope channels of 44mm diameter. Each fuel channel contained a stringer of 21 solid uranium metal fuel rods clad in finned aluminium, each resting on individual, linked graphite ‘boats’ for loading and discharge purposes. The fresh fuel was loaded from the charge face from an ascending platform. Fuel discharge was effected by pushing out the irradiated fuel by the incoming train of fresh fuel until it fell under gravity from the pile discharge face into a transfer skip contained in a water-filled duct (see Figure 1). Transfer skips were then towed remotely into a cooling pond prior to subsequent reprocessing of the irradiated fuel. The pile was designed to operate at up to 180 MW_t power (no electricity was produced) and cooled from a bank of blowers that forced air through the pile into a collection plenum and then exhausted to atmosphere via filters through a vertical stack of ~130 m. The graphite core is surrounded by steel thermal shield plates, a core restraint girder system - all encased in a reinforced concrete bioshield.

Fig. 1. Cross-section through Pile 1 structure[a].

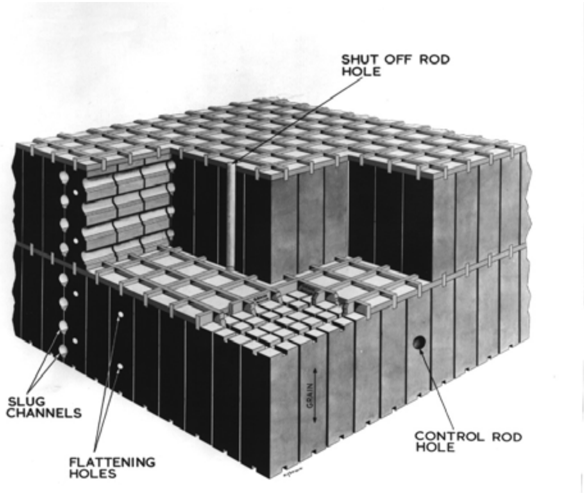

Fig. 2. Graphite block arrangement in Pile 1[b]

PILE OPERATIONS

Design work on the piles started in the late 1940s. Pile 1 started to operate in 1950 as the principal provider of strategic defence materials for the UK nuclear deterrent. Subsequently, the second pile, Pile 2, was completed and started to operate in 1951.

The nuclear properties of the various materials used to construct the piles were not fully understood at the time of design and in particular the need to accommodate the growth in the graphite caused by neutron irradiation (Wigner growth) at the low irradiation temperatures encountered (20 to 153 ^{o}C mean graphite temp). Accordingly, the graphite core was designed with small gaps between the core blocks, back-to-front and side-to-side whose size varied according to core position. The ‘Wigner effect’ not only caused anisotropic growth in the graphite blocks but also manifested itself as ‘stored energy’ within the graphite crystal structure. Hence one of the operational tasks was to limit both the growth and the stored energy by using nuclear heating to anneal the core. During the working life of both piles, nuclear heating with reduced air cooling was used to elevate the core temperature to a point where temperature excursions occurred caused by the release of stored Wigner energy. It was during one such incident during October 1957 that an uncontrollable temperature rise was experienced which led to a fire in the reactor core. The fire was eventually extinguished by a combination of water pumped into the core and by closing down the cooling air flow. The precise cause of the fire is still a source of conjecture. The sequence leading up to the fire, its ultimate control and post fire recovery, has been widely documented [1]. It serves little purpose in this paper to describe events in more detail save to say that, post the accident, not all the remaining fuel could be ejected from the core (either by conventional or more energetic means) and up to 15 tonnes may still remain. The use of water during the accident sequence has consequences both for the pile in its current quiescent state and for ultimate decommissioning. These consequences and the approaches taken to determine their safety implications are developed in the rest of this paper.

TECHNICAL CHALLENGES

The current work programme has centred on research activities to support a safety submission for Pile 1 in its present quiescent state. The Design Basis Accident (DBA) [2] under these circumstances is a seismic disturbance. The technical challenges to be addressed are detailed below. Further, to enable a safe and cost effective option to be selected for decommissioning [3], these safety issues must be addressed also and developed in future studies:

- The remaining fuel mass and moderator is sufficient to present a potential criticality hazard;
- The graphite moderator was left in a partially annealed state following shutdown – the quantity of Wigner energy within the graphite cannot be easily determined;
- The physical and chemical state of the fuel is presently unknown and, due to the injection of water in 1957, the presence of pyrophoric uranium hydride cannot be easily discounted. This material could be present in sealed ‘pockets’ which on exposure to air would oxidise exothermically. Hence, disturbance of the core either by a seismic event or during dismantling is considered to be a hazard, potentially leading to a thermal transient resulting in a release of Wigner energy and runaway oxidation of core materials;
- Damaged fuel, the accumulation of dusts and larger debris has been observed in the discharge exits to the horizontal fuel channels by CCTV survey (Figures 3, 4). It is postulated that the levitation of graphite dust during a seismic disturbance could constitute an explosion hazard if ignited by a pyrophoric material, with potential pressurisation of the reactor containment and release of activity.

Fig. 3. Fuel element debris within FAZ fuel channel

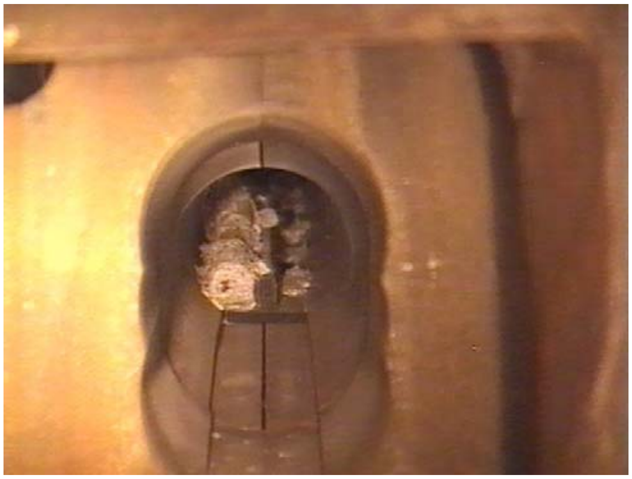

Fig. 4. Fire damaged fuel element displaced from its graphite boat

Criticality

The inventories of fuel and moderator in the FAZ exceed the minimum values required for criticality in an idealised maximum reactivity lattice. Past theoretical criticality assessments of Pile 1 have been unrealistically pessimistic, and have consequently indicated the sub-criticality margin to be small. The theoretical modelling work has been compromised by a lack of detailed knowledge of the remaining core contents and configuration. From analysis of the core reactivity measurements by direct measurements [4], it has been concluded that there is likely to be a substantial sub-criticality margin. Recent modelling of credible seismic disturbance scenarios for moderator, fuel and neutron absorbers has shown conclusively that the measured margin of sub-criticality would not be significantly changed. This has been supported by a sensitivity analysis of the effects of the numerous variables involved.

When considering the possible disturbance of fuel, isotope cartridges and moderator, it is assumed that due to graphite oxidation during the 1957 fire, the channels of the inner regions of the FAZ may have increased in diameter reducing the overall strength of the FAZ structure. Consequently, a likely outcome of a seismic shock could be fracture of the reduced graphite sections, with graphite fragments settling downwards, carrying fuel and isotope cartridges, (as original or oxidised material), into a reduced vertical pitch array. It is pessimistically assumed that an increase in moderation could also occur due to the possible filling of cavities surrounding the fuel with graphite debris. The exact distribution and condition of the fuel and neutron absorbing materials is unknown, but the as-designed fuel array pitch and channel dimensions were very close to optimum for maximum reactivity. The analysis therefore assumes pessimistically that the horizontal pitch of the fuel remains unchanged.

The criticality safety assessment and the associated sensitivity studies, have demonstrated that Pile 1 will remain sub-critical during current quiescent conditions and a seismic disturbance of the FAZ cannot be expected to cause a criticality.

Uranium hydride issues

During the 1957 fire, water was injected into Pile 1 in order to extinguish the fire and remove heat. The possibility that uranium hydride may have been formed as a consequence and could present a pyrophoricity hazard on exposure to air has been identified. Although the formation and survival of UH_3 in Pile 1 is considered to be extremely unlikely, its presence cannot be ruled out definitively in regions that may have been sealed since the post-accident clean-up phase. It has therefore been considered for many years that fuel removal should only be undertaken with an inert gas cover. A detailed assessment of the practicability of this strategy revealed the impracticality of its implementation, prompting a re-appraisal.

‘Historically’ it was considered that hydride in the core could be enclosed and protected from contact with air, and would exothermically oxidise if the enclosing material was mechanically disturbed. It was further pessimistically assumed that the inventory of hydride was sufficient to heat and ignite uranium in contact with it. Further contribution of heat was considered to arise from the release of Wigner energy and the ignition of isotope cartridges, leading eventually to self-sustaining graphite oxidation and potential for release of activity to the environment.

As part of this research, the formation and survival of uranium hydride in Pile 1 has been reassessed in detail. A principal argument used in the safety analysis is that the open conditions in Pile 1 with an air atmosphere were never conducive to formation of uranium hydride even during water injection. If hydride did form in local transiently anaerobic conditions in 1957, it is unlikely that it will have survived the subsequent period of aerobic (oxidising) conditions. However, it has been assumed for the purpose of the safety argument that some hydride is currently present locally in Pile 1. A thermal model has been developed using the Fluent CFD code [5], tested and applied to conceptualised arrangements of fuel in a Pile 1 environment. The thermal model itself has several in-built pessimisms, and a sensitivity analysis has been carried out.

Under ideal conditions for propagation of a uranium hydride oxidation transient, with improbable hydride exposure and an impossibly concentrated inventory of hydride, it has been demonstrated that:

- Bulk uranium metal will not get heated enough to ignite or oxidise at a significant rate;
- The temperature increase at the graphite fuel channel wall will be so slight that neither graphite oxidation nor release of Wigner energy will be initiated;
- Isotope cartridges will not get heated enough to release radiological inventory beyond that which would arise from physical damage in a seismic event;
- There is no significant thermal interaction between neighbouring fuel channels;
- Hydrogen generated from oxidation of uranium hydride cannot contribute to a thermal excursion promoting release of activity.

The overall conclusion is that even if uranium hydride is assumed to be present, improbably protected in anaerobic conditions, and its oxidation is stimulated by seismic disturbance, a thermal excursion causing a significant activity release will not develop. Any additional uranium oxides generated by oxidation of hydride alone will contribute an insignificant fraction to that already present and potentially rendered airborne.

The formation and survival of reactive compounds in addition to uranium hydride have also been considered, and it is concluded that other reactive materials will be in a form and or quantity that renders them insignificant.

Graphite dust explosibility

It has been noted, that since around 1890, no dust explosions in the graphite industry have been recorded. However, recent work carried out as part of this research with pure nuclear grade graphite dust, has demonstrated that under ideal laboratory conditions it can be weakly explosible. In the safety analysis it is argued that for Pile 1 conditions a graphite dust explosion is highly improbable and can be dismissed. The experimental work on graphite dust explosibility was carried out using pure nuclear grade graphite. In reality the dusts observed to be present in the channels of Pile 1 will be a heterogeneous mixture, probably dominated by metallic oxides. It is generically established that inert components of any dust have the effect of suppressing its explosibility and the use of pure graphite therefore represents a worst case. Lead oxide[c], which is assumed pessimistically to be present has an established catalytic effect, increasing graphite oxidation rate. Indicative tests however have not shown any observable effect, e.g. rendering the graphite dust more sensitive to ignition during an explosion scenario.

‘Ignition’ of airborne graphite dust suspensions requires a high energy and power source. Uranium hydride oxidation has been suggested as a possible ignition source, but even assuming sufficient hydride in a highly reactive form was present, the reaction cannot provide the level of ignition energy and power input required. Electrostatic charge build up in a ‘graphite environment’ will be minimal as graphite is an electrical conductor. An energy pulse from a criticality could in theory contribute to dust ignition, but the criticality event has been dismissed. No credible dust explosion ignition source has therefore been identified.

It has been established that only the very smallest particles contribute to a graphite dust explosion, (less than 10 μm). Larger particles have the effect of a heat sink, quenching the reaction, and inert additional material, e.g. metallic oxides within the FAZ, act as suppressants. Even in laboratory conditions it has proved extremely difficult to produce the small particle size required, and there has been a persistent tendency for the fine graphite dusts to rapidly ‘age’, forming spherical agglomerations, giving an apparent reduction in reactivity. In view of this experience it is likely that an insufficient fraction of the dusts present in the core will be within the explosible size range.

A high concentration of airborne dust is required for an explosion to occur. The quantity of very fine graphite dust, free from inert material, required to produce an explosible airborne concentration in the fuel channels, and enclosed voids within the pile structure would be considerable. It is argued that the graphite damage needed to produce the necessary concentration of fines could not credibly occur.

Additional radiological hazards

From recent CCTV surveys of the pile discharge face, dusts and loose debris are known to be close to the exit of several fuel and isotope channels of the FAZ (Figures 3, 4), and are also lodged on the Burst Slug Scanning Gear (BSSGs). In a seismic event some of this material is assumed to fall to the water duct floor. Fuel oxide dusts of a respirable size range (<10micron) entrained by the ventilation air flow, and discharged via the vent stack would be the principal hazard.

Engineering substantiation work on the seismic performance of the bio-shield, has concluded that it is vulnerable to damage and the retention of the present level of containment unlikely. Dust raised by seismic disturbance may therefore be released via adventitious leak paths. However, the bio-shield comprises multiple barriers and as its total collapse is improbable, it is argued that its post-seismic decontamination factor (DF) will be sufficient to maintain on-site and off-site consequences within region 0 of the DBA criteria.

Assessment of the seismic withstand of the ventilation system has shown it to be limited due to its location on the level of the pile cap which produces an amplification effect. The HEPA filters may be displaced and therefore wholly or partially by-passed. Similarly, the retention of airborne activity and dusts within the ducting could be potentially reduced.

IMPLICATIONS FOR THE SAFETY ANALYSIS AND DECOMMISSIONING PROJECT DIRECTION

It has been shown in the safety analysis that in the current quiescent conditions the perceived hazards of criticality, dust explosion, self sustaining oxidation and Wigner energy release transient will not be initiated by seismic disturbance of the core. No additional hazard management strategies are therefore required against a seismic disturbance for the core in its present state. As dismantling will be under controlled conditions it will not routinely incur the level of uncertain disturbance inherent in a seismic event. However, core dismantling, (or fuel and isotope removal), must comply with procedures which keep control of the core configuration and properties within acceptable limits. Activity releases and waste handling risks must be ALARA, and control of the waste form maintained.

It is argued that in the event of a seismic disturbance of the core, in particular in the FAZ:

- existing dusts within the core cavities will be levitated and due to bio-shield cracking will result in an airborne release of activity;
- an oxidation transient leading to significant thermally stimulated releases of activity will not occur;
- the core will not go critical, an adequate margin of sub criticality will be retained;
- conditions necessary for a graphite dust explosion are highly improbable and the event dismissed.

CONCLUSIONS

The criticality assessment has examined the effect of accidental (seismic) relocation of material in the FAZ. From this work it can be deduced that provided sufficient neutron absorbing isotope cartridges are retained in the FAZ, the movement of fuel, graphite moderator, control rods or shut down rods during dismantling will not cause a criticality.

No additional neutron absorber, or criticality shut down systems will therefore be required during core dismantling.

Procedures for the orderly removal of material from the FAZ must be assessed and provide the control to ensure that criticality risks remain ALARA.

The formation of uranium hydride and its subsequent survival over 48 years in aerobic conditions is highly improbable. Analysis based on an impossibly high uranium hydride inventory, shows that at ambient conditions the oxidation thermal transient caused by disturbance and exposure to air will not propagate to adjacent material.

Dismantling in an air environment will therefore be possible.

ALARA considerations will require that techniques for core dismantling, fuel and isotope removal should minimise energy input and limit temperature rise.

Although the risk of a graphite dust explosion can be dismissed, techniques which minimise the generation of any type of dust are recommended. This will ease the problem of dust handling, minimise the potential airborne activity release and reduce the challenge to the core ventilation treatment system.

There is a need to satisfy ALARA requirements and control the basic radiological hazards of external radiation and airborne activity, (e.g. avoid the intentional cutting of fuel and isotope cartridges).

The completion of this technical programme has been a major milestone for the Pile 1 decommissioning project. The work described has reduced the uncertainties for the forward decommissioning programme enabling momentum on this major UK decommissioning project to be maintained.

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[a] Figure 1 represents a section through Pile 1 following care and maintenance activities carried out during the late 1980s

[b] Slug channels are fuel channels and flattening holes are isotope channels

[c] Considerable quantities of lead were used in the core during operations to weight cartridges in order to prevent ejection by the cooling air flow