Safety and Dose Management During Decommissioning of a Fire Damaged Nuclear Reactor

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INTRODUCTION

In 1946, it was recognised that Britain, which still had considerable world-wide defence responsibilities and commitments, needed an independent deterrent and work began in the UK to produce plutonium in atomic reactors. Within 6 years, plants had been produced to treat uranium ores, produce uranium metal and fabricate nuclear fuel elements. A pair of reactors (called Pile 1 and Pile 2) had been built to produce plutonium, and chemical plants were available to process irradiated fuel elements and extract and purify the plutonium produced.

Construction work began on the Piles at Windscale in Cumbria UK in 1947. Pile 1 went critical in October 1950 and Pile 2 in June 1951. The first plutonium was produced by mid 1952.

Wigner growth in the graphite moderator was known of at the time and taken account of at the design stage (1). However, the phenomenon of stored Wigner energy (an increase in potential energy due to displacement of atoms in the lattice when bombarded with neutrons) was not. This stored energy in the graphite moderator can be released by annealing, but if this is not carried out a spontaneous and potentially dangerous release of heat can occur.

Such a release was first seen in Pile 2 in May 1952 when an unexpected temperature rise was seen in the core. This rise was not understood and a similar event occurred soon after in Pile 1 while the reactor was shut down. The phenomenon of Wigner energy was finally recognised and deliberate annealing to reduce the stored energy was carried out on both Piles periodically from this time until October 1957.

In October 1957, the period between anneals on Pile 1 had been extended from 30000 to 40000 megawatt.days and it is likely that small packets of graphite had failed to release energy during the previous anneals where the irradiation level may have reached 80000 megawatt.days (1). An anneal was begun on Pile 1 on 7 October 1957, but a fire started in the heart of the core which was not extinguished until 11 October 1957. Both Piles have been shut down since the accident.

Initial decommissioning on Pile 1 has been carried out (see below) on behalf of the owners, the United Kingdom Atomic Energy Authority (UKAEA). A second phase of decommissioning, which will dismantle the fire damaged reactor core and treat and store the resulting radioactive waste, is now being carried out by a consortium of BNFL, Rolls Royce and NUKEM (the Consortium).

WINDSCALE PILE 1

Windscale Pile 1 (figures 1 and 2) was a graphite moderated, air cooled reactor with horizontal channels fuelled with uranium metal rods clad in finned aluminium cans. The biological shield consists of reinforced concrete walls nominally 2.7 m thick, the roof being 2.6 m thick. The inner face of the biological shield is protected with a mild steel thermal shield, the plates of which vary in thickness from 25 – 150mm.

Fuel was introduced into the fuel channels via holes in the "charge face" which is 1.2 m thick reinforced concrete. Plugs in the charge face are removable and each gives access to 4 fuel channels and a central isotope channel. Twenty one fuel cartridges filled a single channel. Fuel discharged from the reactor fell into bogies in the water duct which were transferred into a cooling pond and then to decanning and processing facilities.

The graphite moderator is an approximate cylinder of diameter 15.3 m and length 7.4 m laid with its axis horizontal. It consists of over 4800 blocks of graphite each keyed to its neighbours with graphite slats. There are 3444 fuel channels and 909 isotope channels. The moderator is supported and constrained with a steel and aluminium structure.

Reactor power was controlled with 24 horizontal boron steel control rods, 12 from each side of the Pile. Sixteen safety shut off rods operated vertically through the top of the Pile. Both control and shut off rods were fully inserted after the fire; operating mechanisms were removed and penetrations capped. None of these rods passes through the fire affected zone (FAZ).

The isotope cartridges loaded into the pile contained, inter alia, cobalt, aluminium nitride, lead, lithium – magnesium alloy, bismuth oxide, potassium chloride, thulium, thallium, thorium and antimony.

Following the fire, as many isotope cartridges and fuel rods as possible were removed from the core. However, it is estimated that up to 15Te of the fuel could remain. It is likely that a large proportion of this fuel is located in the FAZ. An estimate of the remaining inventory in the core is shown in table 1.

The condition of the remaining fuel and of the graphite moderator, particularly in the FAZ, is not known. It is postulated that the moderator could contain voids, greatly reduced density graphite and fused materials in a disordered matrix.

Use of water to extinguish the fire in 1957, together with the possibility that the solidification of molten materials or other local sealing mechanisms could have excluded air, means that the risks associated with pyrophoric materials such as uranium hydrides and carbides (which are most likely to exist within damaged fuel or isotope cartridges) must be considered. In addition, some residual Wigner energy still exists in the moderator.

CURRENT STATE OF PILE 1

Current operations include routine monitoring and surveillance to determine the state of the core and surrounding structure. A ventilation system ensures air flow through the core at all times and provides a means of estimating changes in radiological activity and core temperature. The radiological state is monitored via the ventilation air flow using activity in air monitors, filter gamma monitors and infra red gas analysis. There is an installed fire fighting system.

PREVIOUS DECOMMISSIONING

Phase 1 decommissioning has already been carried out on Pile 1. This decommissioning included:-

- Sealing of the outlet air ducts connecting the core space to the chimney.
- Provision of ventilation plant to provide containment via depression
- Removal of the fuel cartridges from the air outlet and outlet ducts.
- Isolation of the water duct from the cooling pond.
- Clean out, draining and sealing of the water duct.
- Core surveys to collect data for Phase II

GENERAL PRINCIPLES OF DISMANTLING

The UKAEA carried out optioneering studies and examined a number of commercial proposals to decide how best to carry out the work involving the dismantling of the core. These proposals included carrying out the work in air, under water and in an argon atmosphere. The final decision was based on a deterministic requirement that there should be no fire in the core during dismantling and an argon inerting solution (as proposed by the Consortium) was adopted.

At the time of writing, preparation work is being carried out to allow core dismantling. The core dismantling operations themselves can be divided into three distinct categories:-

- Material and structures peripheral to the core
  Since it is intended to export waste from the core using both the inlet air and water ducts, these must be cleared of obstructions such as the burst cartridge detection gear (BCDG), air inlet vanes (which directed air flow from the air inlet ducts through the core), baffles and core support structures. It is known from previous surveys that there is loose fuel lodged between the BCDG and the discharge face of the core.
- Undamaged graphite blocks and fuel from the core.
- Fire damaged zone, potentially fused and disordered.
  Due to the possibility of water reactive and pyrophoric materials being present in the core the whole of the biological shield containment will be filled with argon to ensure that the entire core is in an inert state prior to core dismantling operations. This argon will be injected into the shield at a low temperature (-20^{0}C). In addition to ensuring inerting of the core, the chilling of the core will provide a heat sink for the suppression of both Wigner energy releases and chemical reaction rates. The injection at low temperature will also cause thermal stratification of the argon within the shield and therefore ensure that the oxygen concentration in the FAZ remains below the target 2% required to eliminate the risk of fire in that area. Emergency (fire fighting) supplies of argon, which will flood the shield if necessary, will also be available.

As noted above, it is intended to dismantle the core from both the inlet air and water duct. A transfer tunnel is being constructed to allow the waste to be moved from the water duct to the inlet air duct. Once in the air duct the waste, together with that produced in the inlet air duct will be transferred to the Waste Processing Facility (WPF), see figure 3. Here the waste will be treated, placed in containers suitable for deep disposal, grouted and placed in the purpose built store. The inlet air duct, water duct, transfer tunnel, waste transfer route to the WPF and waste processing cell will all be inerted with argon.

The radiation and contamination levels (as well as the presence of argon) within the shield, waste transfer route and processing cell in the WPF are such that it will be necessary for all operations to be carried out remotely with CCTV feed back.

The use of manipulators deployed on vertical masts in the inlet air and water ducts to dismantle the core was closely examined but finally rejected on operability and ALARA grounds.

The preferred option is now to deploy remotely operated vehicles (ROVs) in the inlet and air water ducts on vertically movable platforms. Using a variety of tools these ROVs will dismantle the core from the top down, placing the waste produced in skips for transfer to the WPF.

PREDICTED WASTES ARISINGS

All materials within the core (with the exception of undamaged fuel cartridges, which are reprocessible) are considered to be waste. Predicted arisings are as follows:-

- Graphite 2 x 10^6 kg
- Isotope cartridges 2 x 10^3 kg
- Uranium 15 x 10^3 kg
- Mild steel 140 x 10^3 kg
- Stainless steel 11 x 10^3 kg
- Aluminium 7 x 10^3 kg
- Cadmium 0.6 x 10^3 kg
- Cast iron 4 x 10^4 kg

All these wastes will be appropriately conditioned and placed in the purpose built store.

In addition to the above, there will be some wastes produced from the preparatory phase eg concrete wastes from the demolition of part of the inlet air duct to allow the construction of the extension waste transfer route to the WPF (figure 3). This waste will be disposed of to a nearby low level waste facility.

Aerial discharges from the dismantling process will remain within current authorisations and best practicable means will be used to minimise them. Liquid waste arisings will be small and will mainly arise from coring operations to produce penetrations in the biological shield.

CRITICALITY

The current degree of sub-criticality of the core is not known and therefore reactivity measurements will be carried out to determine if any neutron poisons need to be injected into the core prior to the start of core dismantling operations. There is, of course, the possibility that voids within the FAZ will cause a core collapse during dismantling. This possibility will be taken account of during reactivity testing.

SAFETY MANAGEMENT SYSTEMS

The work described above will be carried out on the UKAEA Windscale Nuclear Licensed site and will be directed and controlled by the UKAEA Authority to Operate (ATO) holder leading a dedicated UKAEA Safety Management and Control (SMAC) team. The SMAC team is supported by a joint UKAEA/Consortium project safety management team. The work will be carried out by a joint UKAEA/Consortium project team.

All work carried out during the decommissioning will be done in accordance with:

- All relevant current legislation and Site Licence conditions
- UKAEA Safety and Environmental Procedures (from Corporate to project level)
- Approved (by UKAEA) safety documentation, method statements and Instructions.

In addition to the above, Permits to Work will be issued prior to any work which might affect safety being carried out. The ATO holder has the authority to stop operations when he believes safety is being compromised.

The ATO holder will ensure that safety and quality audits are carried out based on UKAEA manuals and procedures. To ensure day to day control, the ATO holder, or any other member of the SMAC team, has the right of access to any relevant activities of the Consortium which must provide the UKAEA with any information which the ATO holder believes may affect safety.

The client (UKAEA) and the Consortium have recently gone through a partnering exercise and the integrated environmental, health and safety plan (which also incorporates the quality plan) ensures that every activity carried out during the work is considered from a quality, safety, health and environmental viewpoint. It is based on HS(G) 65 (2).

SAFETY CASES

A hierarchy of safety cases will be put into place covering all aspects of the work to be carried out during decommissioning. These will be categorised on potential accident impact in line with UKAEA requirements. The Regulator in the United Kingdom, the Nuclear Installation Inspectorate (NII), has “called in” the decommissioning project for examination which means that they will regulate the project through the issue of Licence Instruments without which work may not proceed.

In order to facilitate the production of safety cases satisfactory to the NII, the safety case authors and UKAEA liase with the NII assessors during the preparation stage. This ensures that the requirements of the NII are addressed in a manner satisfactory to them and that no unsatisfactory proposals are made.

In addition, the safety case authors are working closely with UKAEA specialists during the case preparation stage to facilitate the passage of the safety case through the UKAEA safety case approval system.

DOSE MANAGEMENT

The UKAEA applies the following Dose Restriction Levels:

- 20 mSv in a calendar year, and
- 75 mSv in any five consecutive calendar years

Before any work with ionising radiation is undertaken, UKAEA require predictions of collective dose and maximum individual dose that employees, contractors and others affected by the work are likely to receive. When predicted individual doses are greater than 2 mSv in a calendar year, Dose Restraint Objectives are required to be set for the maximum radiation dose to be received by their employees and contractors. In addition, the doses received must be shown to be ALARA. In order to ensure this, an ALARA procedure will be followed throughout the project. This consists of:-

Stage 1

The requirement to ensure that doses are ALARA was taken account of at the optioneering stage of the project.

Stage 2

As design work progresses the requirement for ALARA is considered in more detail. In practice, this is done by ensuring that a Radiation Protection Advisor (RPA) is present at all appropriate hazard and operability (HAZOP) studies.

Stage 3

During final design at task level, formal ALARA meetings are being held to ensure that individual tasks are being carried out in accordance with the ALARA principle. It is a requirement that the UKAEA RPA or his nominated representative is present at all these meetings. The output from these meetings form an input to the method statement for the task to be performed. At this stage a dose budget is produced for the task. Risk assessments, including both radiological and non radiological risks are being carried out on all tasks as required by UK legislation (3). These too form an input to the method statement.

Stage 4

If radiological conditions change as the work is being carried out, or if the dose budget is not being adhered to, a stage 3 ALARA study is carried out again to ensure that all reasonable steps have been taken to minimise dose. The method statement will be changed as appropriate. In order to facilitate this process electronic personal dosemeters (EPDs) are issued on a task specific bases thereby ensuring that the dose received as the task proceeds can be readily compared with the dose budgets.

In addition, these EPDs facilitate dose control on a daily basis and the audible dose rate signal gives real time warning of changes in external dose rate. There is, of course, co-operation at all times between the UKAEA RPA and those of the Consortium and sub contractors.

INSTALLED INSTRUMENTATION

The currently installed instrumentation for activity in air detection is appropriate for a care and maintenance regime with a relatively small number of locally alarmed monitors (including stack discharge monitors) connected to a central environmental monitoring system (EMS). Preparatory work now being carried out uses stand alone alarming monitors at the work face, where appropriate, to warn of changing local conditions within the workface containment.

Prior to decommissioning an appropriately sophisticated network of activity in air monitors will be installed and connected to the EMS. Great care has been taken with the siting of these monitors to ensure appropriate coverage of both the reactor building and WPF.

Appropriately placed gamma dose rate monitors will also be installed prior to core dismantling and bulk waste movement.

The introduction of argon into the biological shield, waste transfer route and WPF processing cell also introduces a conventional safety hazard. Work is being carried out at the time of writing to seal the biological shield to preclude leakage and, in line with best radiological practice, the volume containing the argon will be maintained at a depression to ensure any leakage is inwards.

Nethertheless, a sophisticated system of oxygen level monitors will be installed throughout appropriate areas and individuals will wear personal oxygen detection equipment. Confined space working will be very tightly regulated.

CONCLUSIONS

The methodology outlined above will be used to ensure that the core of a fire damaged reactor will be decommissioned safely with doses incurred below the regulatory limits, in line with UKAEA requirements and ALARA. Conventional risks to the workforce will be kept to the lowest reasonably practicable and best practicable means will be used to limit discharges to the environment.

At the end of decommissioning the total risk associated with Windscale site will be greatly reduced with wastes stored in a safe, stable and secure form awaiting final disposal.

REFERENCES

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2. Successful Health and Safety Management, Health and Safety Executive, HSE Books HS(G) 65, 1991. ISBN 0-7176 0425X
3. The Management of Health and safety at Work Regulations 1992

ACKNOWLEDGEMENT

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Table 1: INVENTORY OF PILE 1 CORE

Nuclide	Fuel (TBq)	Graphite (TBq)	Isotope Cartridges (TBq)	Total (TBq)
H 3	2.43 E-1	9.2E1	1.47E3	1.47E3
C 14	-------	4E0	-----	4E0
Fe 55	-------	5E-2	-----	5E-2
Co 60	-------	2E0	2.2E0	4.2E0
Ni 63	------	9.3E-1	-----	9.3E-1
Se 79	1.76E-3	-----	-----	1.76E-3
Kr 85	4.56E0	-----	-----	4.56E0
Sr 90	1.89E2	-----	-----	1.89E2
Y 90	1.89E2	-----	-----	1.89E2
Zr 93	1.09E-2	-----	-----	1.09E-2
Tc 99	7.71E-2	-----	-----	7.71E-2
Ag 108m	3E-3	2E-4	-----	3.2E-3
Sn 126	2.27E-3	-----	-----	2.27E-3
Sb 125	1.17E-3	-----	-----	1.17E-3
Te 125m	2.72E-4	-----	-----	2.72E-4
I 129	1.06E-4	-----	-----	1.06E-4
Cs 134	2.30E-5	-----	-----	2.30E-5
Cs 135	5.34E-3	-----	-----	5.34E-3
Cs 137	2.13E2	-----	-----	2.13E2
Pm 147	5.30E-2	-----	-----	5.3E-2
Sm 151	6.93E0	-----	-----	6.93E0
Eu 152	8.84E-3	4.4E-4	-----	9.29E-3
Eu 154	2.57E-2	-----	-----	2.57E-2
Eu 155	6.14E-2	-----	-----	6.14E-2
Th 228	8.24E-7	-----	-----	8.24E-7
Th 230	7.02E-5	-----	-----	7.02E-5
Th 234	1.85E-1	-----	-----	1.85E-1
Pa 233	3.84E-4	-----	-----	3.48E-4
U 232	8.01E-7	-----	-----	8.01E-7
U 234	1.88E-1	-----	-----	1.88E-1
U 235	8.12E-3	-----	-----	8.12E-3
U 236	1.82E-3	-----	-----	1.82E-3
U 237	2.79E-5	-----	-----	2.79E-5
U 238	1.85E-1	-----	-----	1.85E-1
Np 237	3.48E-4	-----	-----	3.48E-4
Np 239	2.22E-7	-----	-----	2.22E-7
Pu 238	5.48E-7	-----	-----	5.48E-7
Pu 239	9.12E0	-----	-----	9.12E0
Pu 240	7.28E-1	-----	-----	7.28E-1
Pu 241	1.14E0	-----	-----	1.14E0
Pu 242	2.51E-6	-----	-----	2.51E-6
Am 241	2.16E-1	-----	-----	2.16E-1
Am 242m	8.67E-6	-----	-----	8.67E-6
Am 242	8.43E-6	-----	-----	8.43E-6
Am 243	2.22E-7	-----	-----	2.22E-7
Cm 242	6.98E-6	-----	-----	6.98E-6
Cm 243	4.26E-8	-----	-----	4.26E-8
Cm 244	5.58E-8	-----	-----	5.58E-8
Cm 245	3.15E-13	-----	-----	3.15E-13
Cm 246	1.43E-15	-----	-----	1.43E-15

Figure 1

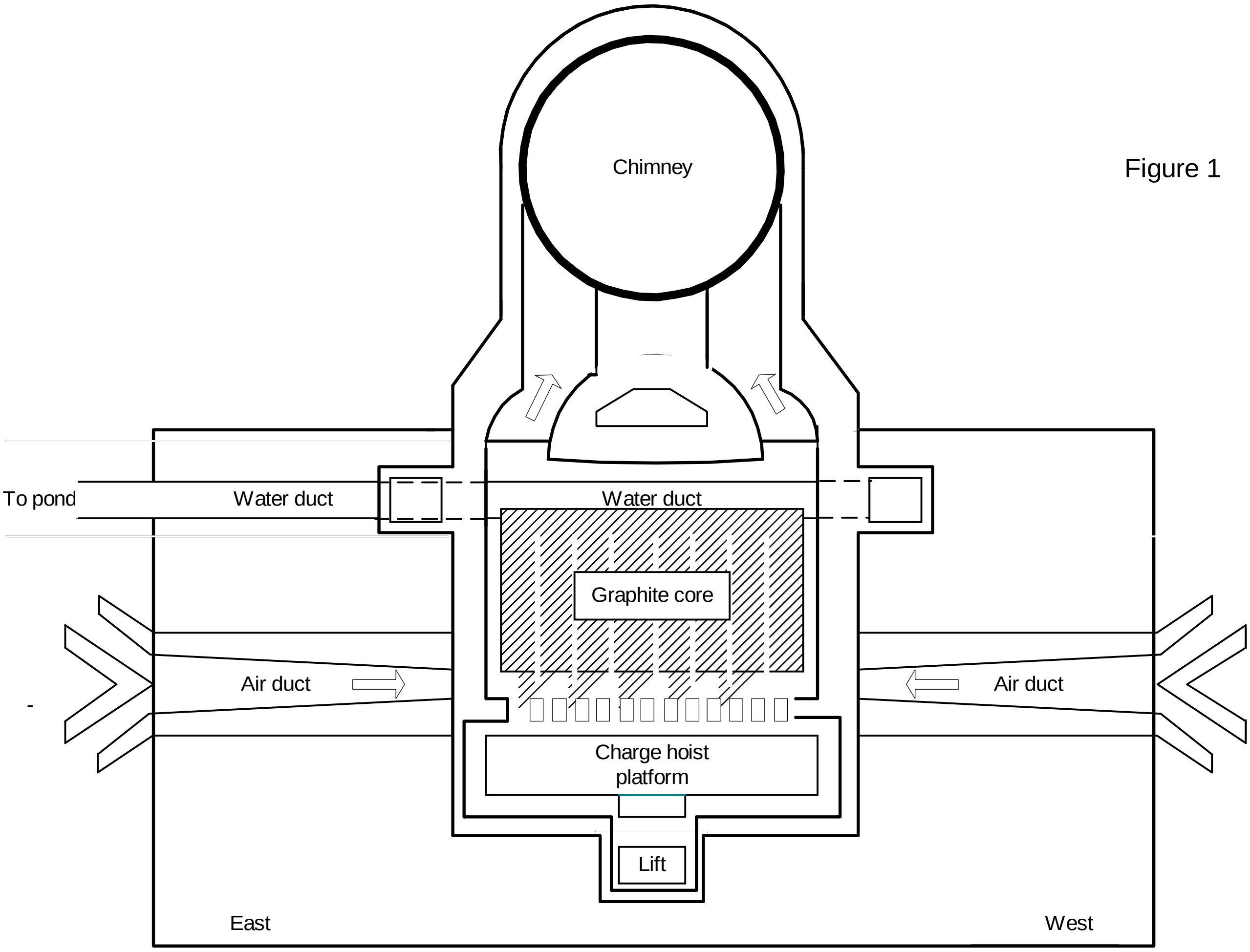
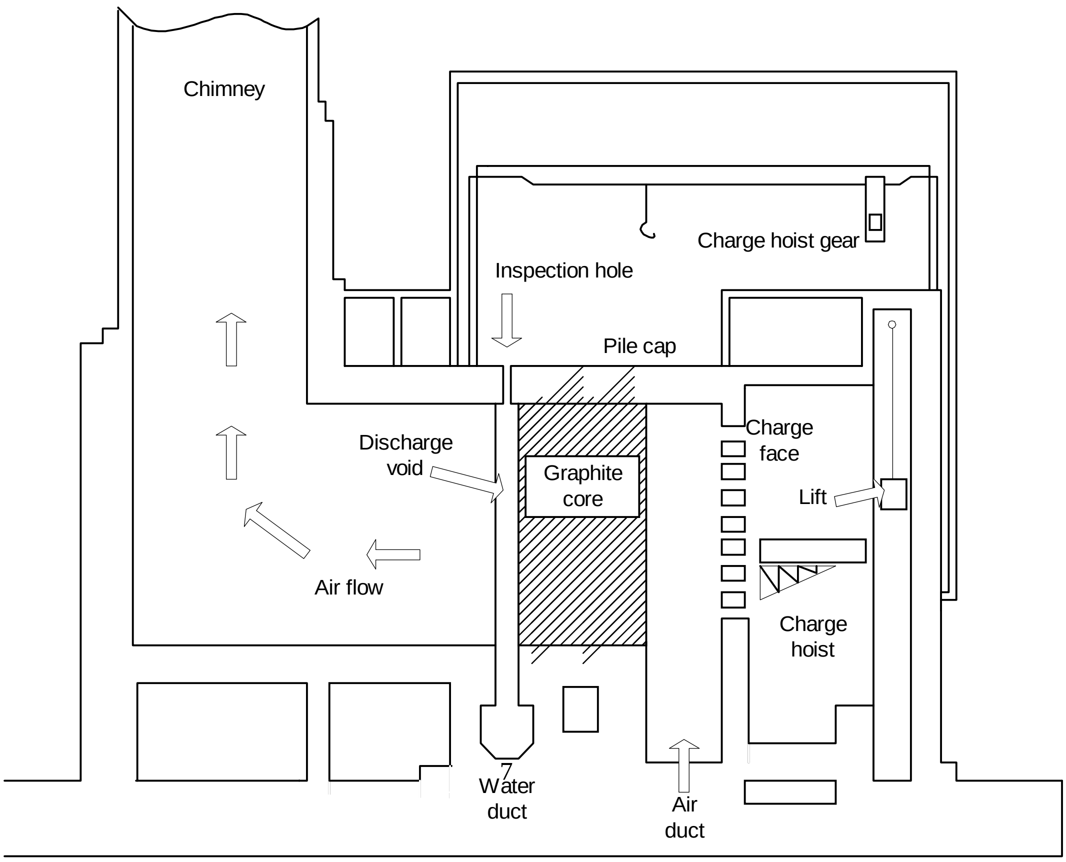


Figure 2



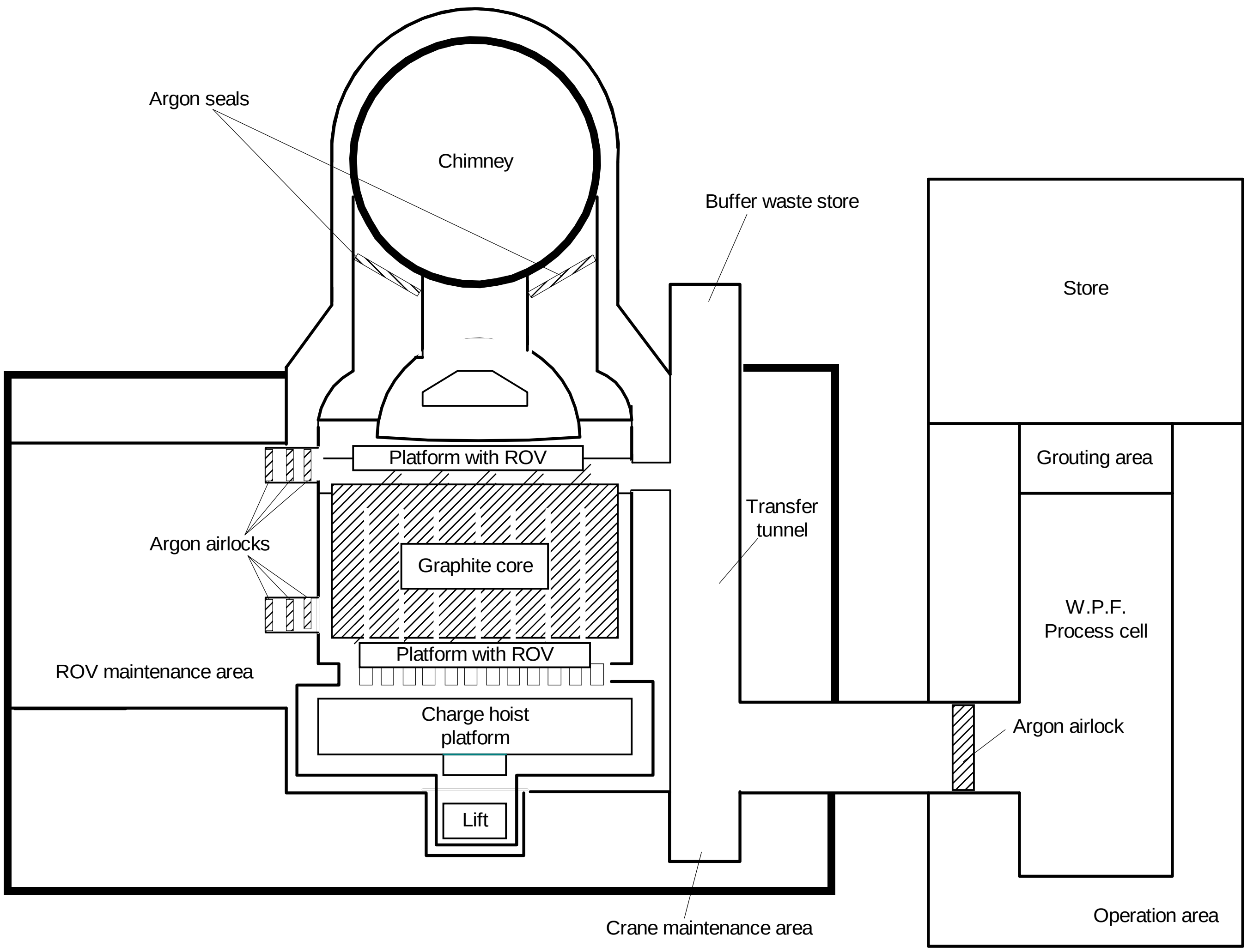

Argon seals
Chimney
Buffer waste store
Store
Platform with ROV
Grouting area
Transfer
tunnel
Argon airlocks
Graphite core
W.P.F.
Process cell
Platform with ROV
ROV maintenance area
Charge hoist
platform
Argon airlock
Lift
Operation area
Crane maintenance area

Figure 3