Control of Chemical Attack in the PBMR Presentation to USNRC In Support of PBMR Pre-application Activities

Supporting Document

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1. INTRODUCTION

The safety philosophy of the PBMR is based on the premise that the fuel adequately retains its integrity to contain radioactive fission products for all normal operating and design basis accident conditions, thereby allowing radiological safety to be assured. This is achieved by relying on fuel, whose performance has been demonstrated under simulated operating and accident conditions, and whose integrity is therefore not compromised even under accident conditions.

To ensure that this fuel integrity is maintained the plant design for all operating and design basis accident conditions

- includes sufficient heat removal capability such that fuel temperatures will remain in the proven safe region,
- provides adequate measures to control reactivity.
- limits chemical and other physical attack on the fuel,

By chemical attack is meant the effect of corrosion of the graphite matrix due to water or air ingress as these are the only chemical agents available in quantities large enough to impact on the materials. This presentation discusses the safety design approach to control chemical attack in terms of prevention and mitigation of off normal events with either water or air ingress.

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2. Historical background

The PBMR builds on the world-side experience of nuclear power plants, including the extensive operating experience of gas-cooled reactors. Off-normal events have occurred in graphite reactors that have involved oxidation by water and air. Examples of each and the applicability to the PBMR is discussed below

Water Ingress Experience

Two of the seven helium cooled reactors have experienced water ingress events. They were the AVR research reactor in Germany and the Fort St. Vrain power reactor in the U.S.

In the AVR reactor a leak in the steam generator allowed more than 25 m^3 water to enter the core, and flow to the bottom of the reactor pressure vessel and the defuelling installation. Altogether about 5000 fuel spheres spent some time under water. Examination of some 150 of these spheres showed no damage and no need to remove the remaining affected spheres. The event caused a lengthy outage.

In Fort St. Vrain water-lubricated bearings were used for the steam driven blowers to circulate the helium around the primary system. During transients the bearing seal system frequently allowed water into the helium, causing some corrosion of the core support structures that were manufactured from a higher impurity grade graphite. The problem was a major factor in the poor operating capacity factor and related economies of operation led to its early shutdown.

The following table highlights the differences between the PBMR and these earlier high temperature helium cooled reactors. The primary difference is that the high pressure water sources have been minimized in the PBMR; there are no steam generators or water-lubricated bearings.

Table 1: Comparison of AVR, Fort St. Vrain and PBMR water ingress resistance

	AVR	**Fort St. Vrain**	**PBMR**
Water Source	Steam generator	Water bearings of the helium blower	Direct cycle, magnetic bearings
Coolant	Helium	Helium	Helium
Fuel	Ceramic	Ceramic	Ceramic
Graphite Type	Nuclear grade	PGX core support	Nuclear grade

Air Ingress Experience

High temperature helium cooled reactors have not experienced any air-ingress incidents or events with oxidation consequences. However, two severe accidents have occurred in graphite moderated reactors that have involved catastrophic oxidation of the fuel and graphite of the reactor. The best known and most damaging of these were the fires in Windscale and Chernobyl.

The Windscale reactor was one of the first of the UK's power plants built as part of their nuclear weapons programme. Air was used as the coolant for the graphite moderated metallic fuel core. The simple, open cycle design operated with air from the environment directly cooling the core and then being discharged back to the environment. At the low operating temperatures and under neutron bombardment, graphite absorbed energy through the displacement of carbon atoms by neutron collisions. This stored energy was generally annealed out in a controlled fashion by lowering the coolant flow to allow the graphite to heat up.

On October 8, 1957 a technician was heating up the reactor to release this Wigner energy. However, because of the inadequacy of the temperature measuring instrumentation, the control room staff mistakenly thought the reactor was cooling down too much and needed an extra boost of heating. Thus temperatures were actually abnormally high when the control rods were withdrawn for a routine start to the reactor's chain reaction. A canister of lithium and magnesium, also in the reactor to create tritium, was believed to have burst and ignited. This coupled with igniting uranium and graphite sent temperatures to 1,300 degrees centigrade. The operators were unable to cool the core with the outside air without causing more core oxidation. An unlimited air supply and a large radionuclide release resulted with the direct path to the environment. Dousing the reactor with water finally quenched the fire.

The PBMR has little in common with Windscale as shown in the following table. First and foremost, the PBMR is cooled by inert Helium and has ceramic fuel. The PBMR operates above the temperatures that the Wigner Energy is formed. Core heat removal in the PBMR is not dependent on convection so that the fuel is kept at acceptable temperatures regardless of the helium pressure or the influence of air ingress.

Table 2: Comparison of Windscale and PBMR air ingress resistance.

	Windscale	PBMR
Initiating Event	Wigner energy	Not applicable
Coolant	Air	Helium
Fuel	metal	Ceramic
Air Supply	Unlimited	Limited by design

The Chernobyl reactor was a power production reactor with water cooled metallic fuel and graphite moderation. The water was carried in pressure tubes inside the graphite structure. A design flaw was that if the control rods were extracted to the limit they could add reactivity on insertion before reducing the power level. This was not supposed to ever happen, but at very low power operation for an experiment the rods were completely withdrawn and later inserted when the experiment was finished. The added reactivity, coupled to very low water flow, caused the water to turn to steam inside the core adding more reactivity and resulting in a steam explosion that blew off the roof of the reactor. With no decay heat removal possible, the core heated up until the fuel started to melt and burn. After some 20 hours the graphite started to burn as well due to the high temperatures and the availability of air from the opening in the roof.

Table 2 displays the major differences in the Chernobyl and PBMR designs relative to air ingress. There is not counterpart to the positive reactivity initiating event. Once again the PBMR selection of helium cooled ceramic core provides resistance to air ingress.

Table 3: Comparison of Chernobyl and PBMR air ingress resistance

	Chernobyl	**PBMR**
Initiating Event	Positive reactivity on control rod insertion	Not applicable
Coolant	Water	Helium
Fuel	Metallic	Ceramic
Air Supply	Unlimited through the roof	Limited by design

3. PBMR Safety Design Approach

Limitation of water ingress

During normal operation, secondary system water is at a lower pressure than the helium coolant. The main water cooling circuit provides water to the pre- and inter coolers that together remove about 55% of the heat generated in the reactor. Operating procedures as well as interlocks ensure that the water circuits are not activated until the gas pressure exceeds the water pressure by a suitable margin. This ensures that any leak in the gas/water boundary will cause gas to leak out and prevents in-leakage of water. The helium leaking out of the system carries small quantities of radionuclides along with it, sufficient to enable even very small leaks to be detected. The size of the leak will determine the actions to be taken in the short and long term, but water cooling will cease long before the primary pressure has dropped to water pressure levels. Thus, at worst, even if a complete tube rupture is postulated, no more water than that contained in the one leg of the tube can enter the gas side after pressures have equalised and it will collect in the cooler housing. As there will be no circulation of helium once the coolant pressure drops, this water cannot be transported to the core and will be removed from the system after repairs and before a restart is allowed.

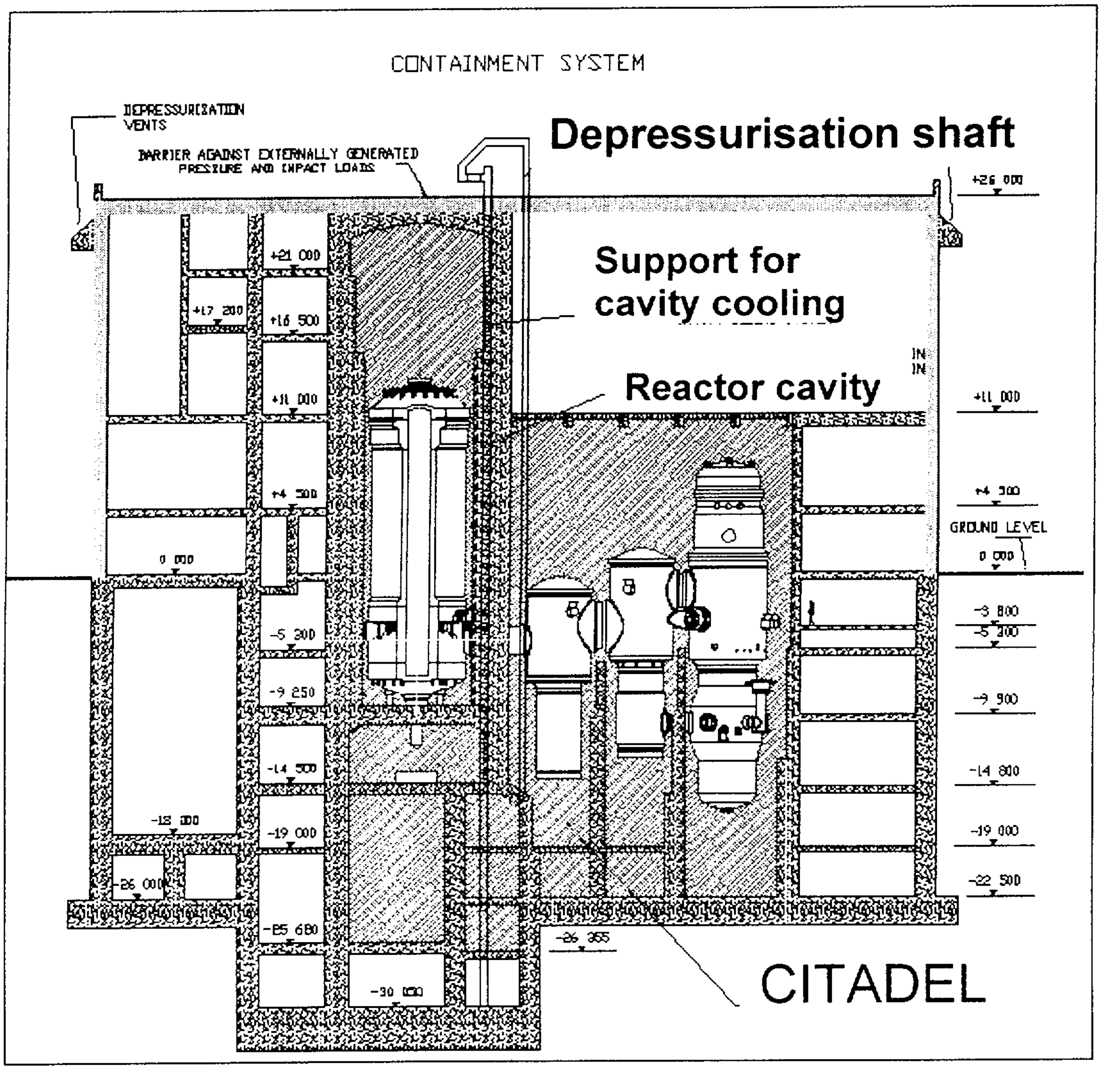
The only exception to the principle that the water pressure must be lower than the gas pressure is during maintenance decay heat removal, when the pressure needs to be reduced to atmospheric in order to allow maintenance on the Power Conversion Unit (PCU). In these conditions the cooling is performed by the Reactor Unit Conditioning System (RUCS) that circulates helium through the core only and cools it by means of a recuperator and an intermediate heat exchanger with limited water volume. In operation the core is cooled down at medium gas pressure until the required shutdown temperature has been reached. Thereafter the pressure is reduced and remains below the water pressure until the maintenance activities are completed. The planned outage time per six-year interval is one month. Even with longer down times the total outage time when the cooling will be by RUCS at low pressure will amount to less then 5% of the total operating time of the plant. If in this time there should be a water leak, the water will enter the RUCS housing and as long as the core is cool, the water will not evaporate and enter the core. On detection of a leak the water circuit will be isolated and the RUCS will close down. In such a case the core will heat up and be removed radially by conduction and radiation to the reactor vessel and the reactor cavity cooling system. With the RUCS switched off there is no circulation of hot gas through the RUCS that can evaporate the water and transport it to the core.

Limitation of Air ingress

Air ingress events are infrequent, that is, they are not expected in the plant lifetime. During normal operation the pressure boundary is closed and the helium is under high pressure. All parts of the Main Power System (besides pipes with < 65 mm diameter) are designed and manufactured to the ASME III code, thus making large failures improbable. The citadel around the helium pressure boundary provides protection from external events. This same citadel limits the amount of air ingress available for ingress.

The air ingress design basis (not expected in the lifetimes of a fleet of PBMR plants with 10 reactors each) is piping breaks up to 65mm in diameter. These include instrument lines (<10mm), the Fuel Handling and Storage System (FHSS) lines (<65mm), and the Helium Inventory and Control System (HICS) lines (<65mm). The isolation of the helium pressure boundary is possible depending on the break location. Within the FHSS or HICS, it is automatic or remote manual isolation; within the PCU helium pressure boundary, it is remote manual isolation.

The pipe connections to the Reactor Pressure Vessel are all below the core level, making helium egress from the top unlikely and thus "bottling up" the helium, thereby not allowing air ingress. The following figure shows the relative elevations of the vessels and the citadel and building layout.



Small breaks

Small breaks are breaks of pipes like instrument lines and are defined as being less than 10 mm diameter pipe breaks, or 78.5 mm^2 area. Leaks of that size present a long depressurisation time, allow cooling of the core in the depressurisation phase and beyond and will offer great resistance to air inflow. Any heating up of the fuel will push more helium out of the core thereby preventing air entering. In the event that a crack of that size developed above core level, helium would leak out but in the process inhibits air coming in through the same fissure. Even if after some days the entire content of the RPV were to be filled by air, there will be no circulation, as the nitrogen in the air as well as the products of graphite oxidation will prevent any further air entry. At maximum a fraction of .00005 of the graphite content of the RPV can be corroded.

Medium size breaks

These are breaks of < 65 mm diameter or 3300 mm^2 area. A break of that size will cause the failure of rupture panels in the relief shaft designed to protect the containment system against beyond design overpressures. The vents are designed to automatically close after the event and include a second manually operated closure. The HVAC is protected by explosion as well as temperature driven dampers that will reopen as soon as normal conditions are re-established. The design makes provision for isolation of the fuel handling as well as the helium inventory control system, thus only a break in an area outside these systems can possibly be the cause of air ingress. If the break is below the core, then air will not be able to enter for several days during the core heat up phase. If it is above the core, it can enter while helium is flowing out, but as was argued before, the corrosion products (CO and CO_2) will quickly fill the volume and limit the amount of corrosion possible. If it is still argued that air can continue to enter, then under the extreme assumption that all the air in the citadel passes through the core, and all the oxygen is consumed, a maximum fraction of < .002 of the graphite will be consumed.

Larger Breaks Beyond the Design Basis

For events beyond the design basis, that is, not expected within the lifetimes of a fleet of PBMR plants of 10 reactors each, the large breaks are designed to vent through blow out panels in the top of the citadel. These will open at a higher pressure than the rupture discs for the smaller breaks. A series of trellised vents are situated in the sidewall of the upper floor and will allow blow off of the released coolant gas. They are not made to close automatically although at least partial closure is expected.

Depending on the location of the large break, two-way flow is conceivable and air transport to and through the reactor core is possible. Assuming that the total inventory of air in the building passes through the reactor, a fraction of <0.01 of the graphite will be oxidized.

Mitigating Strategies

For small leaks that cannot be isolated it is intended to keep the core cooled while the coolant with its radioactive content is filtered and exhausted through the stack. Filtering will remove the biologically most important isotopes and entry into the areas where the leaks might be will not be problematic.

For medium size leaks the vents will be closed and the HVAC restarted thus allowing cleaning of the remaining air in the building. Some surface contamination will obviously exist after the event, but entry into affected areas with the proper protective clothing is regarded as standard procedure. Even in the case where air cleanup is not effective or possible, calculations show that the external dose due to the air/helium mixture that remains in the citadel will lead to an external dose of below 100 μSv/hr and entry and activity is still well within planned maintenance exposure levels for special operations.

For large breaks the mitigation strategies are similar. Assuming that core isolation was unsuccessful, the actions of the operators will be to close the opening with a suitable material, which will be available in the module building or nearby, and/or to add inert gas to the building, citadel, and/or core.

4. Summary

The PBMR design has taken full cognisance of the potential problem of water or air ingress and the design features enumerated above lead to the conclusions listed below:

- Water ingress is very unlikely and in any case limited to quantities that will not cause any permanent damage to core internals or fuel spheres;
- The most likely Helium pressure boundary break is < 10 mm and this size creates enough resistance to air flow that air ingress is negligible;
- A 65 mm opening will only allow air to enter after the helium heatup phase is finished (approx 48 hrs) and then only a small air flow is expected; There is a high probability that the core can be isolated from the outside by means of isolation valves so allowing continued core cooling and stopping all possibility of air ingress;
- Large breaks beyond the design basis are extremely unlikely and have acceptable risk due to limitations on air flow through the core, the low susceptibility of the coated particle to corrosion at the expected prevailing temperatures and the very high achievability of beak closure by manual means.