THE PBMR CONTAINMENT SYSTEM

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ABSTRACT: The Pebble Bed Modular Reactor (PBMR) is a high-temperature gas-cooled reactor using fuel spheres (pebbles) that circulate through the reactor core. The fuel is of a proven design, able to resist very high temperatures without damage. The plant design requirement is that there be no conceivable situation in which the fuel sustains such damage that a concern for the safety of the public at the boundary of the exclusion zone can be postulated. Under these circumstances a building having the functionality of a conventional Light Water Reactor (LWR) type containment is inappropriate and can be counterproductive in terms of safety. Instead, a containment system (or confinement) is envisaged whereby the overpressure resulting from a pipe break is vented to the environment and the vent system is closed after the pressure pulse has passed. This enables filtered ventilation to be re-established within a short time after a depressurization event and prevents the build-up of pressure that could conceivably act as a driving force to disperse delayed releases into the environment.

KEYWORDS: HTR, PBMR, containment

0. INTRODUCTION

Modular HTR designs are not new, and many of the safety aspects particular to this form of power generation have been investigated in the past. In particular, the philosophy that a leak-tight containment is not needed has been stated in both the HTR-Modul and MHTGR preliminary safety analysis reports. This point of view was accepted by the German regulator, but the Nuclear Regulatory Commission - USA (NRC) expressed concerns and declared that more analysis was needed before such a concept could be approved in the USA [1]. However, the issue has not disappeared from view and an effort is being made in the USA by the NRC to formulate a position on the matter. This also in view of the proposed hydrogen producing High Temperature Reactor (HTR) planned for the USA and the fact that several utilities making early site applications have included a modular HTR in their proposals.

What was valid for the earlier applications is also true for the PBMR, and the PBMR design has from day one assumed that a high-pressure, leak-tight containment is not needed nor advisable.

1. SOURCE TERMS

The design of engineered defences to protect the public from postulated accidents in a nuclear system must establish the potential threat a failure of the defence can pose. Thus, much effort has gone into determining expected and maximum fission product releases to the environment due to the immediate release of circulating gases and the possible late releases resulting from a core heat-up. The behaviour of the TRISO fuel under normal and accident conditions is well described in [3]. Many experiments were performed on fuel pebbles in the course of the German projects and as part of the AVR operating history. These experiments and the results thereof give reasonable confidence that predictions of fuel failure during upset conditions give credible or justifiable and often conservative results, particularly when an increased rate of fuel failure is assumed immediately on reaching above normal operating temperatures.

During the evolution of the PBMR core configuration, many preliminary calculations for normal releases of fission products into the circulating gas, as well as expected releases during core heat-up accident, were performed. These calculations used conservative assumptions to avoid the possibility of underestimating the effects of accident conditions.

The results show that in common with other modular HTR designs, the potential accidents can be divided into two phases:

- An immediate release of all circulating gases including entrained fission and activation products. Depending on leak size, a fraction of the deposited graphite dust that is contaminated with adsorbed fission products can also be re-suspended, and is assumed to escape the containment system together with the coolant gas.
- After depressurization, the core and reflector will heat up and enhanced fission products are released from already damaged fuel and fuel damaged due to increased fuel temperature. This additional release from the fuel to the core starts between four and six hours after depressurization, and continues until the maximum transient temperature is reached, usually between 36 and 48 hours after the accident.

Results indicate that the delayed release is orders of magnitude higher than the release due to activity circulating with the gas. With the exclusion zone set at 400 m, the initial dose due to this release is well below the As Low As Reasonably Achievable (ALARA) target, which itself is 10% of the regulatory limit for design basis accidents. The contribution of delayed releases to potential dose is discussed in paragraph 0, following a description of the various scenarios of releases from the core and the containment system.

2. CONTAINMENT PHILOSOPHY

Although conventional containments have an important function during normal operation in delaying release of activity resulting from daily leaks, the main emphasis has been on its role in preventing release following a serious accident involving core damage. Three Mile Island was the only accident in which the containment function was both needed and very beneficial, despite some containment bypass release. However, it is recognized that after a core damage accident there can be a very large amount of radioactivity bottled up within the containment, and a containment building failure in the first few days after the accident could lead to serious public exposure. As a result, some countries have required the installation of a filtered containment venting system to prevent just such a scenario. Whilst the immediate releases can be very high in an LWR core damage scenario, and thus the containment should not be allowed to fail in this early phase, the situation for an HTR is very different.

Core damage in the LWR sense cannot occur, and delayed fuel damage is limited. The PBMR emphasis is thus shifted towards preserving the capability of the containment system to control the delayed releases during the period following the initial release.

A conventional containment with a filtered venting system will obviously allow that to be done, but it may depend on operator intervention, and is contrary to the PBMR requirement that operator intervention is not required for the first 24 hours following the initial event. The initial release is entirely predictable, being a known quantity. It consists of the activity in the circulating gas (which is monitored) and the desorption of plated out fission products. Thus the potential dose due to the early release can be predicted, and operating rules can ensure they cannot be exceeded. As already mentioned, such a release gives a dose well below the ALARA limit, and is therefore of no great concern. Thus from a dose viewpoint there is no need for a high-pressure containment building. As the containment system is required to survive the initial pressure pulse, the question remains whether the late releases should be contained, filtered before release, or not contained at all. Obviously the last choice is not compatible with good safety practice, and the choice lies between the first two alternatives, or a combination of both.

At PBMR the decision has been to allow the pressure pulse to dissipate through the Pressure Relief System (PRS), and thereafter to seal the PRS to ensure that any later releases are kept within the containment system until a filtration system can be activated to filter out the main biologically active isotopes. The building containment, together with the PRS and filtration system, is called the Containment System.

The new initiative of the NRC to look into such systems for advanced reactors seems to favour calling it a confinement, a phrase also used by the International Atomic Energy Agency (IAEA). The practical application of this principle is described in the next paragraph.

3. THE CONTAINMENT SYSTEM

FIGURE 1 shows a cross section of the PBMR building, including the generator hall and structures outside the containment.

FIGURE 2 shows a cross section of the PBMR layout in which the primary pressure boundary is included within the citadel of the module building. The citadel is designed to resist pressures up to 300 kPa and to maintain leak tightness after the venting of the initial pulse. Some volumes, in particular the reactor cavity, can take significantly higher pressures due to the thickness of the surrounding concrete structures that is mandated by shielding requirements. Each compartment containing high-pressure components is connected via rupture discs to the PRS depressurization route. The rupture discs are designed to open to the depressurization shaft before the design pressure of the cavity is reached. The layout is configured such that the pressure relief to this shaft occurs at the lowest point in the building. The PRS exit to the environment is capped by a dust filter located at the highest building elevation.

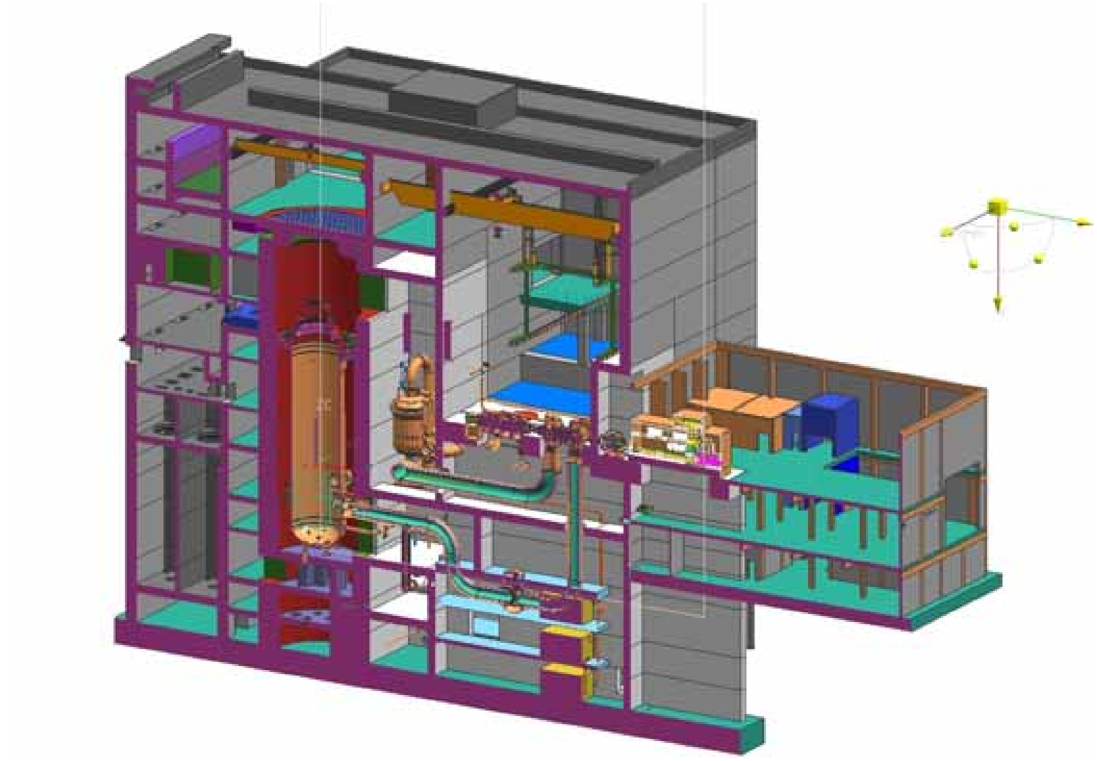

FIGURE 1: Cross-sectional view of PBMR building.

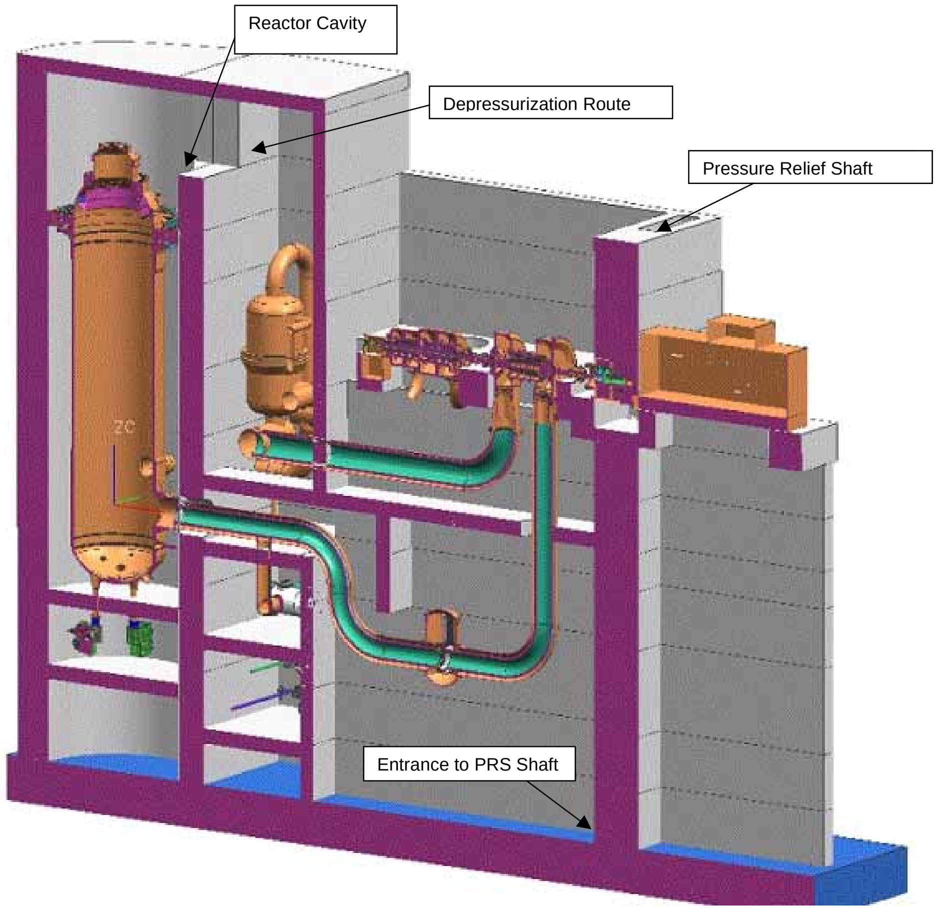

FIGURE 2. Cross-sectional view of main power system in building, showing depressurization path.

After the pressure pulse has been vented, a gravity driven mechanism closes the shaft with sufficient air tightness that the normal Heating, Ventilation and Air-conditioning (HVAC) system can re-assume its function of providing a negative pressure as soon as internal conditions allow. The HVAC itself is protected from damage by blast dampers as well as temperature-operated dampers. The blast dampers are passive, needing neither sensors nor mechanical moving components. Manually operated seals that can be inserted from outside the containment cavity provide a back-up to the automatic closure of the PRS.

Analysis shows that the internal temperature following a depressurization drops sufficiently after about six hours to allow normal HVAC operation to resume. On resumption, the carbon filters are switched into the exhaust path to remove the most important isotopes released in the heat-up phase. Whether or not such filtered venting is to take place will depend on the need to enter the affected areas for repair to the gas pressure boundary, and the possible dose to the public from unfiltered components (noble gases).

A design requirement is that penetrations through the containment building and above the lower part of the core should be limited in number to essential services only, and be leak tight. All HVAC to the containment must be supplied from below the reactor vessel elevation. This ensures that provided the HVAC is pressure protected or placed in a shaft, any depressurization from the top of the vessel is directed downwards to below core height, and any late leakage from the core through an opening above the vessel will not automatically leak out of the top of the building, but will potentially create a helium bubble in the top cavity. These design features help to delay any activity leak from the core to the environment, giving time for decay to take place, and for mitigating actions to be taken. In addition, the ingress of air through the containment system and core by means of convection is restricted.

4. ACCIDENT SCENARIOS

The containment system safety functions are defined as follows:

- Protect safety systems from external events and internal missiles.
- Provide, for all postulated design basis events, a stable structure that allows unimpeded operation of systems required for safety.
- Allow, as far as is reasonable, the possibility of early (within 24 to 48 hours) operator intervention to mitigate the effects of the accident.

For external events, the most severe predicted earthquake and other natural phenomena are included in the design requirements. The outer shell of the building provides the primary barrier and is designed to absorb the impact of all design basis externally generated missiles, e.g. a small aircraft and tornado-borne missiles.

For beyond design basis missiles, e.g. the impact generated by a large commercial airliner, the inner containment structure is designed to survive with minimal damage, whilst the outer building acts as an energy-absorbing zone which breaks up the aircraft. Minimal damage means that all necessary safety actions and features will continue, and that fires from fuel ingress will not affect the areas housing safety-related plant.

For internal accidents, the safety functions include resistance to missiles, drop loads and high-energy pipe breaks. The following classes of leaks and breaks have been identified:

- Small leaks and breaks in which the effective diameter of the break is < 10 mm. These are typically sampling lines, and the depressurization time, if not isolated, is in the order of 20 hours. During depressurization, the HVAC will continue to operate and the carbon filter will be switched into the exhaust path. Any dust released will be caught by the HEPA filters.
- Medium breaks are classified in the range between 10 mm and 230 mm effective break diameter and include the largest diameter pipe that connects to the top of the RPV dome. For these breaks it is assumed that the pressure build-up is too fast for the HVAC to respond, and the ventilation path is closed to protect the filters from high pressure and temperature. Conservatively, breaks are considered to be unisolated, and they include the tubes of the coolers and the fuelling pipes. The PRS will open all or part of the rupture panels, and closure of the PRS is possible after an hour (assuming a depressurization time for a heat exchanger tube to take that long).
- Large breaks comprise those breaks having pipe diameters above 230 mm. They are considered to be beyond design basis events, as all the large vessels and piping are manufactured according to the requirements for Leak before Break principles. The PRS is able to limit the overpressure except if very short depressurization times are presumed. For such an extreme case the containment system will sustain damage that includes cracking of walls and penetrations failure. It is not expected to impair the structural stability of the reactor cavity such that its fundamental safety functions can no longer be performed.

5. SAFETY EVALUATION

In paragraph 0 it was mentioned that there are two distinctly separate stages for potential public exposure. The first occurs during the initial release of the high-pressure gas contaminated with fission and activation products, and the second when active core cooling fails or is impossible, and the fuel temperatures increase, resulting in additional releases from the coated particles. The circulating activity is known, and there will be limiting conditions of operation to ensure that any release of the total content will not result in a public dose exceeding the ALARA targets. Thus, for this phase, it is a requirement that the containment system retains its integrity. Reducing the containment pressure by designed in passive venting of the gas will not endanger the public, but will ensure that the building can quickly be restored to a normal filtered, ventilated condition. By the time this is achieved, the fuel will only be heated to approximately 100 ºC above normal operating temperature with minimal release to the core. In the course of the next 30 to 40 hours, fission products consisting mainly of iodine, caesium, silver and noble gases will be released from the coated particles. Ignoring any hold-up in the graphite matrix, these products will enter the core. It can be assumed that the primary pressure boundary is depressurized, and that the helium in the core increases in temperature and is partly expelled through the breach in the system.

Over the course of time and until the core starts to cool, it is calculated that about 10% of the helium escapes to the containment volume and carries with it 10% of the released fission product with 90% remaining in the core. Without any filtration, part or all of this will eventually be released to the environment. According to [3], it can be assumed that the deposition rate in the containment system of iodine is 10% per hour and 30% per hour for caesium. Thus even if the deposition rate is slower, as long as the containment system does not leak at a rate exceeding the design air exchange rate, almost none of the mentioned dominant fission products will enter the outside environment. When deposition is not credited, the dose due to release of the total fraction entering the containment system will not cause a dose at the boundary exceeding the ALARA target.

A more demanding scenario is when it is presumed that the hole is on top of the reactor and connected to the core. This would be a fuelling line and, to a lesser extent, a control rod housing break. In such a scenario, the heavier air can displace all the helium in the core, though this happens at a very slow rate. Once all the helium is displaced, the air inside the core and outside differs only in temperature, and analysis shows that exchange through a single 65 mm hole is almost non-existent. Nonetheless, for purposes of estimating the worst possible conditions, it is assumed that all delayed fission products resulting from such an accident will enter the building. Again, if the deposition rate is as described in [3], the release to the environment is minimal. With no deposition and no containment decay or mitigating actions such as switching to filtered exhaust, the potential dose to the public is presently estimated to be approximately 40% of the regulatory limit, which in South Africa is 50 mSv for a design basis accident.

Air ingress is a concern for reactors containing large quantities of graphite at elevated temperatures. In theory, a leak-tight containment would limit the amount of air that could enter the core, and thus limit the amount of corrosion that can occur. However, analysis shows that air ingress proceeds at a very slow rate, and by the time it is assumed that operator intervention is achieved and the leak temporarily closed, very little actual corrosion will have taken place. This is illustrated in FIGURE 3 where a simultaneous break of a 500 mm defuelling chute and a 65 mm fuelling pipe is analysed. As can be seen from FIGURE 3, the air, which has quickly replaced the helium, will enter and leave the core at a rate of about 14 g/s. Assuming total conversion of the oxygen to carbon monoxide, the estimated carbon corroded away in a period of 48 hours would be ~375 kg. The corroded carbon will come partly from the core structures and partly from fuel spheres. Even though the core needs to be defuelled and inspected for damage after such a severe accident, this is not seen as a convincing argument to demand a closed containment.

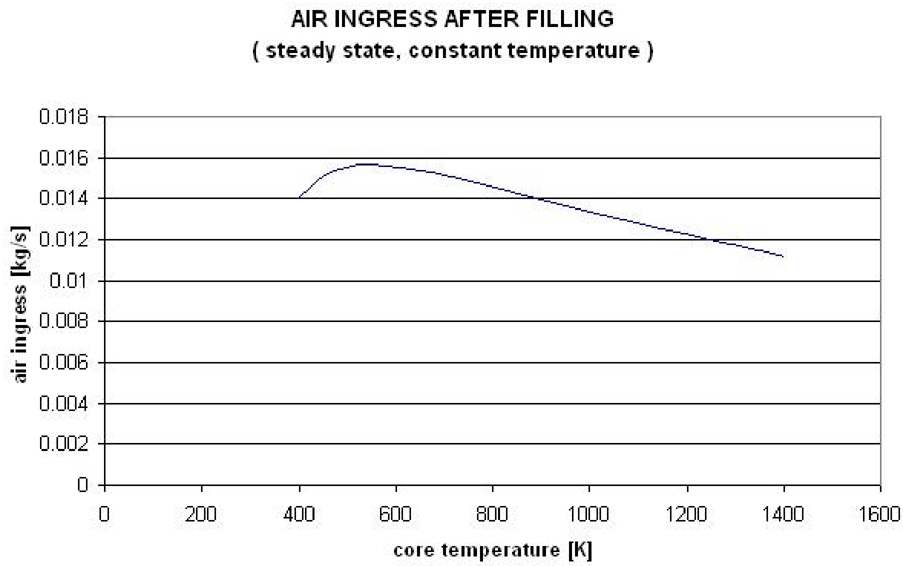

FIGURE 3. Air exchange bottom to top for double break as a function of core temperature.

6. CONCLUSION

The type of containment chosen for the PBMR is similar to those proposed for the HTR-Modul and MHTGR as well as the GT-MHR. Safety analyses performed on the PBMR containment, conservatively assuming that all mitigating systems fail or are unavailable due to lack of power, etc. show that the dose to the public will not exceed the regulatory limits. The analysis is dependent on the assumption of good fuel quality and predictable heat removal, both of which can be tested during normal operation. By removing the helium pressure, there is no driving force that could cause delayed release fission products to be driven from the containment system, and the probability that mitigating action and natural deposition will reduce a potential dose to very low values is high. Further work will include a probabilistic risk assessment to assess the probability of worst-scenario accidents and possible containment bypass failures. From a basic safety perspective, the design philosophy is based on the following requirements:

- removal of high-pressure gas immediately after the break whilst the FP concentration is low;
- venting the depressurization gases from the lowest point in the containment;
- minimization of leaks through penetrations and openings above the base of the core;
- ability to seal the PRS and the containment system after an event and so control the release of FP to the environment;
- ability to perform operator intervention after an event;
- ability to filter releases to the environment after an event.

On the basis of the design requirements and safety analysis, it is considered unnecessary to have the equivalent of an LWR containment. A building containing an inner core capable of surviving both external and internal worst-case events and having a capability for sufficient hold-up of fission products will be shown to meet the ALARA targets set for public exposure in South Africa.

REFERENCES

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AUTHOR INTRODUCTION

Albert Koster is a senior nuclear safety specialist with PBMR (Pty) Ltd and has been involved in various aspects of HTR technology since 1988. He has worked in the fields of reactor physics and nuclear safety since 1963, mainly at the South African Atomic Energy Corporation.

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