PEBBLE BED MODULAR REACTOR

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Contents

Summary:

Gas cooled nuclear reactors have a good track record and have the potential to reach high temperatures as there are no phase changes in the coolant possible. The HTR line of reactors use fuel in the form of small (0.5 mm) coated particles that individually act to retain fission products within the coating. These so-called TRISO particles can withstand very high temperatures enabling the use of gas turbines in a high efficiency closed cycle electricity generating system. These reactors can also be used to produce hydrogen via a variety of chemical reactions at high temperature, giving better yields than electrolysis. The PBMR is a Generation IV design whereby the possibility of a core melt and accidents with serious consequences for the public is basically excluded. The design and use of the TRISO fuel builds on many years of experience in both the USA and in particular Germany.

1. General Description

The Pebble Bed Modular Reactor (PBMR) being developed by the South African utility Eskom together with international partners is a 400 MWt nuclear reactor that uses the TRISO (refer to Section 1.2) fuel embedded in 6 cm diameter graphite spheres (pebbles) with a projected electricity output of 165 MWe. The term modular stems from the design intent that identical modules can be placed in a block of 4 to 8 reactors to make up a large power station. The small size and modularity allow short (24 months) construction times and give flexibility to the utility to match generation capability more closely to demand than single large plants allow. The small size is dictated by the design requirement that neither fuel nor major plant systems may be damaged to the extent that there could exist a danger to the public at the exclusion zone of 400 m, following a total cessation of active systems. This is achieved by the following design principles.

1.1. Passive Heat Removal

The major reason why nuclear reactors present a potential danger is because the reactor continues to produce heat even though the fission reaction was terminated by inserting the control rods. This so-called decay heat emanates from the multitude of radioactive isotopes that result from the fissioning of the original uranium. These isotopes continue to decay by emission of various types of radiation. This radiation is converted to thermal energy which, if not removed by some means, can lead to unallowable heating of the fuel and its container until the cladding melts and the contained radioactive products are released to the core and ultimately to the environment.

Thus in present designs, active cooling of the core is at all times needed to prevent a core melt and multiple core cooling systems combine to make the probability of that happening very small.

The small modular approach, pioneered in Germany and adopted by several other groups, is to ensure passive heat removal by radiating the heat to a heat sink from where it can be dissipated to the environment.

To prevent overheating of the fuel, the design calls for a long slender reactor vessel to provide a large surface area for heat radiation. Additionally the heat path from the fuel to the reactor vessel requires guaranteed heat conduction and radiation properties to achieve the stated goal. The PBMR design is sketched in Section 2.

1.2. The Fuel

The present generation of planned and operating High Temperature Gas-cooled Reactors all uses the so-called TRISO fuel particles, which in turn are an enhancement of the BISO particles developed as part of the Euratom Dragon Reactor Experiment that operated from 1964 to 1973 in Winfrith, UK.

The BISO particle consisted of a UO_2 kernel coated with a porous Pyrocarbon layer and two layers of dense Pyrocarbon. These coatings provided a good barrier against the release of fission products from the fuel kernel.

This fuel was used in the AVR and THTR reactors in Germany, and in the Peach Bottom and Fort St Vrain reactors in the USA. The TRISO particle includes an extra silicon carbide layer in between the two dense pyrocarbon layers which significantly increases the fission product retention capabilities of the fuel.

It is the ability of these coated fuel particles to withstand temperatures beyond 1600 ºC that allows the high coolant operating temperatures of the PBMR. This TRISO fuel for Low Enriched Uranium (LEU) was used extensively in the AVR and its characteristics were confirmed up to high burnup values of up to 400 GWd tonne^{-1}.

The composition of a typical fuel sphere as planned for use in the PBMR is shown in Figure 1. Each fuel sphere contains 15 000 individual coated fuel particles with each kernel being only 0.5 mm in diameter.

The coatings of the particles form the effective barriers against release and the failure of a single particle due to manufacturing defects will have negligible effect on the contamination of the coolant gas. Of the 6 billion particles in the reactor on average about 120 000 are expected to have defects that may lead to fission product releases when the fuel is heated to high temperatures.

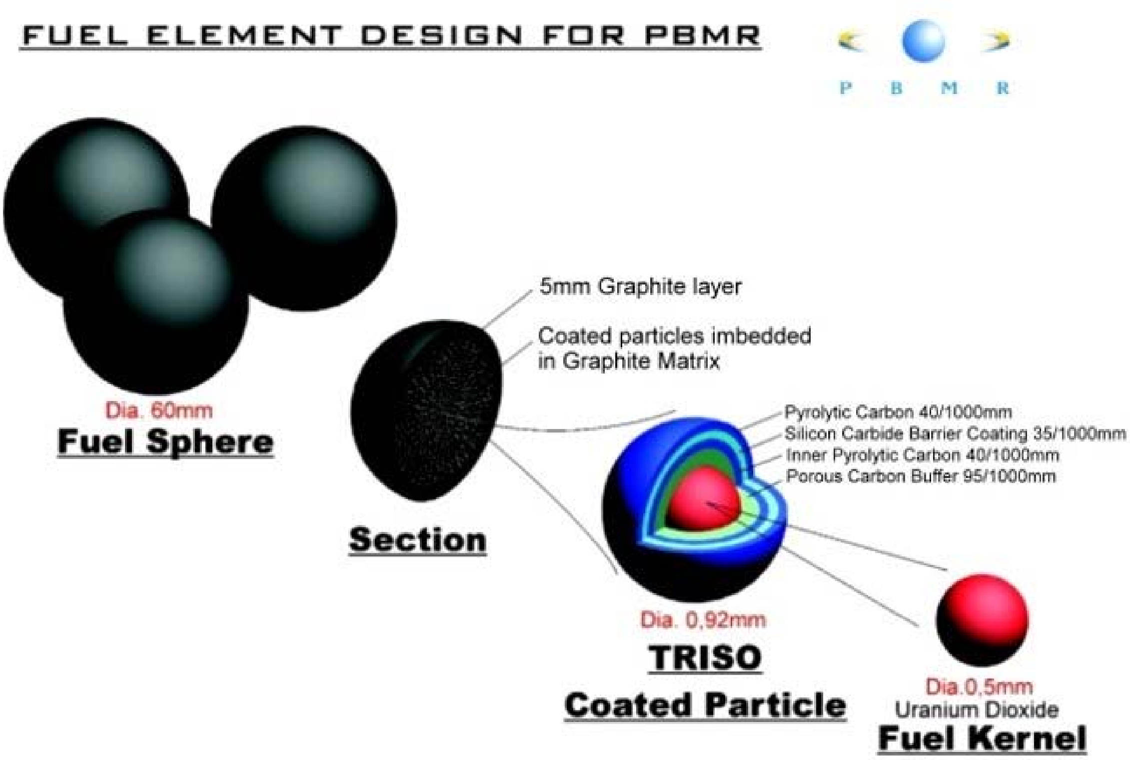

Figure 1: Coated particles in a typical fuel pebble.

The achievable burnup is a function of original enrichment and limitations due to cumulative radiation damage caused by fast neutrons. At present, for the type of fuel to be used in the demonstration reactor, a burnup of at least 100 GWd tonne^{-1} is proven technology. There is great confidence that this can be extended to 200 GWd tonne^{-1} for which an enrichment of just under 20% is required. This is still within the generally accepted international norm for low enriched fuel unsuitable for making nuclear explosives. The PBMR intends to use fuel enriched to 12.9% for a burnup of about 120 GWd tonne^{-1}, but this will have to wait until a fuel qualification program has proven such fuel burnup still maintains the accepted and verified high retention of radionuclides. The demonstration PBMR reactor will initially use an enrichment of 9.6%.

1.3. On-line Fueling

One of the attractive features of the PBMR is the on-power fueling capability. This has been a design element of all pebble bed reactors and is one of the main reasons why a high availability is predicted for commercial plants. Fuel pebbles are extracted from the bottom of the core, checked for burn-up and integrity, and either recirculated or discarded to the spent fuel storage if the burnup exceeds the set limit. The AVR and THTR used multiple fueling points and a single defueling chute. Fuel was recirculated within the pressure boundary. As a result of optimization and maintainability studies, the PBMR designers opted for a system whereby the fuel spheres are transported outside the main pressure boundary to the top of the reactor where the measurement and discrimination systems are housed. From there the spheres are fed by gravity back to the core or to the spent fuel storage tanks. Three loading positions are used as the small width of the annulus (see design of reactor core in Section 2.2) makes more fueling positions unnecessary. The annulus also requires three defueling chutes, each with its own defueling machine at the bottom. The result is a fuel handling system in triplicate, each line complete with its own diverters and measurement systems. A more complete description is given in Section 3.

For 400 MWth operation the fuel spheres are recycled on average 6 times before the end of life burnup is reached. Around 3000 spheres are circulated every day at a rate of 500 spheres per hour, allowing sufficient time for maintenance in the off periods. Of the order of 460 spheres are discarded every day and replaced with fresh spheres supplied through three fueling locks placed near the fresh fuel store.

The main safety advantage of on-line fueling is that the fuel content can be adjusted to require only a small amount of excess reactivity for load following operation. This means that there is a limitation on the amount of reactivity that can be added even if all the control rods were erroneously withdrawn. Even if this were to happen, the reactor power would reach a new limit that does not damage the fuel or result in unacceptable conditions prior to a loss of cooling.

1.4. The Direct Cycle

A major decision made early in the project was the choice of a direct gas cycle system rather than a steam cycle system. This was considered feasible in the light of advances in gas turbine technology over the past two decades. From an economic viewpoint the direct cycle has the advantage of promising higher cycle efficiencies once all the systems have been optimized. There is also an advantage of less potential operating disruption due to water leaks caused by corrosion and other factors inherent in water-cooled technology. As a side benefit, there is the exclusion of the possibility of significant water ingress into the reactor core, a possible event that places limitations on the fuel composition in steam system designs. For the demonstration reactor an effective thermal efficiency of 42.5% is at present predicted. Further improvements in the design of the turbine compressors and other systems are expected to add another 2% with further improvements for follow up reactors. However, the PBMR reactor can equally well be coupled to a steam generator to produce super critical steam for a high efficiency steam cycle. However, the advantage of the direct cycle is the high outlet temperature of the coolant which can also be used in industrial applications, including hydrogen production.

2. Technical Description

Figure 2 shows the general layout of the reactor in the building. It shows the Reactor Pressure Vessel (RPV) in its own enclosure, connected to the Power Conversion Unit (PCU) consisting of the High Pressure Turbine (HPT) and Low Pressure Turbine (LPT), the high and low pressure compressors, the recuperator, a gearbox and the generator. All the coolant carrying parts are in the PCU cavity which forms part of the low pressure containment. Below the PCU are the Helium Inventory Control System (HICS) tanks that hold the helium used to regulate the power level (refer to Section 2.4). The Fuel

Handling and Storage System (FHSS) is both below and above the RPV in separate compartments with the spent fuel tanks on the side and below grade. Each is described separately below.

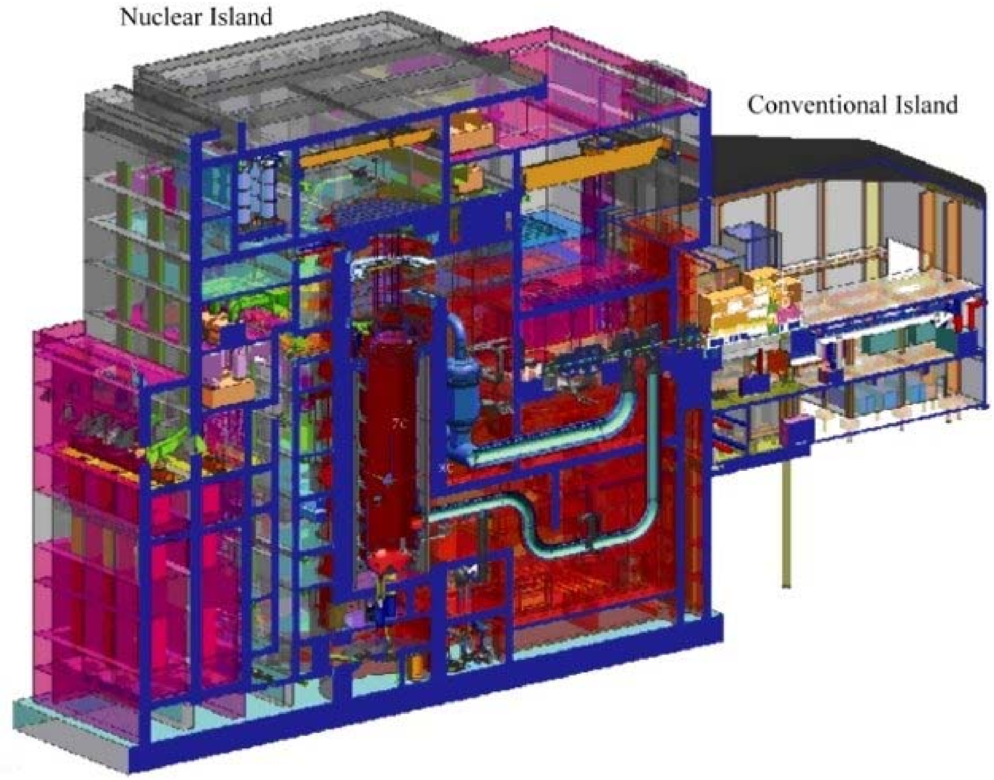

Figure 2: General layout of reactor and auxiliaries in PBMR building

As can be seen, the reactor unit is nearly at the centre of the building. The reactor cavity walls are 2.2 m thick and, together with the outer walls of the building, provide a high integrity resistance against external events. The design basis aircraft impact is a 5.7 tonne light passenger plane, but analysis has shown that the reactor safety and the heat removal systems will remain intact and functioning as designed after the impact of an aircraft like the Boeing 747 or 767. As the spent fuel is housed below grade, it will not be affected by any external event.

2.1. Principles of the Direct Cycle

2.1.1. Brayton Cycle Description

The PBMR Main Power System (MPS) utilizes a recuperative Brayton cycle with helium as the working fluid. A schematic layout of the cycle is shown in Figure 3, while the temperature-entropy diagram of the cycle is shown in Figure 4.

With reference to Figure 3, starting at state 4, helium at a relatively low pressure and temperature, state 4, is compressed by a Low Pressure Compressor (LPC) to an intermediate pressure, state 5, after which it is cooled in an intercooler to state 6. The intercooling between the two multistage compressors improves the overall cycle efficiency. The High Pressure Compressor (HPC) then compresses the helium to state 7. From states 7 to 8, the helium is preheated in the recuperator before entering the reactor that heats the helium to state 1. After the reactor, the hot high-pressure helium is expanded in the Power Turbine (PT), directly driving the LPC and HPC, to state 2. From states 2 to 3, the still hot helium is cooled in the recuperator, after which it is further cooled in the pre-cooler to state 4. This completes the cycle. The heat rejected from states 2 to 3 is equal to the heat transferred to the helium from states 7 to 8. The recuperator uses heat from the cooling process that would otherwise be lost to the main heat sink to heat the gas before it enters the reactor, thereby reducing the heating demand on the reactor and increasing the overall plant efficiency.

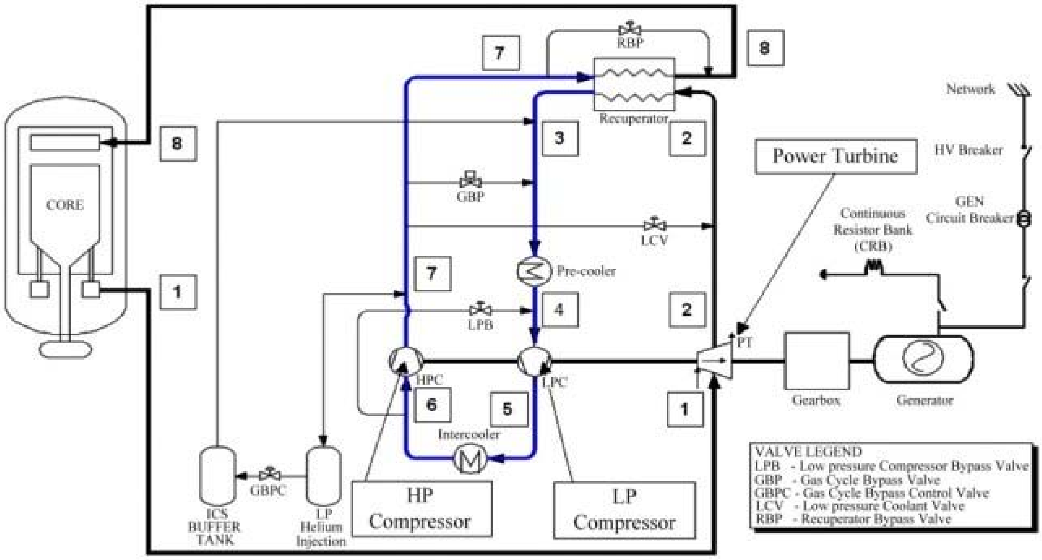

Figure 3: Layout of the PBMR recuperative Brayton cycle

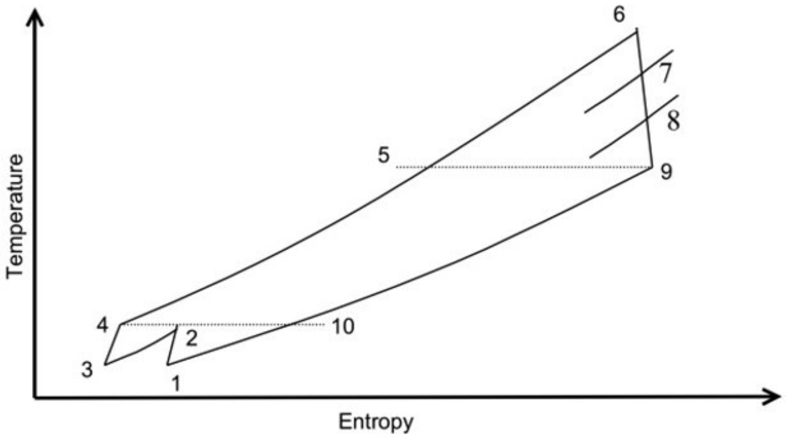

Figure 4: Temperature-entropy diagram of the PBMR recuperative Brayton cycle

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Biographical Sketch

Albert Koster was born in the Netherlands and immigrated to South Africa after finishing an apprenticeship as compositor in a printing works. He switched to science in 1959 and was engaged in geochronology from 1959 to 1963. After that he joined the newly formed Atomic Energy Board of South Africa as part of the reactor physics team. He worked for 2 years in Vienna at the IAEA doing nuclear data collection from 1969-1971 before returning to South Africa working mainly in the fields of reactor design and nuclear safety until 1990, ending as assistant manager of the department of nuclear engineering responsible for reactor physics. In the last two years there he was also project manager for HTR reactor studies in co-operation with the utility Eskom. After a stint in the business world he joined the PBMR project in 1998 working in different capacities involving nuclear safety. Presently he is senior nuclear safety engineer in the engineering division.