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ADVISORY COMMITTEE FOR REACTOR SAFEGUARDS
U. S. NUCLEAR REGULATORY COMMISSION
WASHINGTON DC 20555

March 8, 2001

MEMORANDUM

To: ACRS Members and Staff

From: Robert E. Uhrig

Subject: Pebble Bed Modular Reactor (PBMR)

On June 4-5, 2001, the ACRS Thermal-Hydraulics Subcommittee, that also has the responsibility for Advanced Reactors, will hold a meeting to discuss what is generally called "Generation 4" nuclear plants. This discussion will include the South African Pebble Bed Modular Reactor (PBMR) that is sometimes called a "Generation 3 ½" plant because it is expected to be operational within ten years. The PBMR design is currently being considered by Exelon Nuclear Company for construction and operation within the United States. Exelon recently held a meeting with the NRC to discuss the issues that might arise if a PBMR were submitted for licensing in the U.S. The Commission recently issued a Staff Requirements Memorandum (COMJSM-00-0003) regarding the "NRC Staff readiness to review applications for new nuclear plants and specifically cited the pebble bed modular reactor as an example."

Since I visited Eskom, Ltd.[1], the national utility of South Africa, and discussed the PBMR design extensively about a year ago and have closely followed its progress since that time, I have undertaken, with the encouragement of the T/H subcommittee chairman, to put together a series (three or four) papers describing the PBMR and its operating characteristics and behavior for the information of ACRS members and staff in preparation for the June 4-5 subcommittee meeting. This is the first paper to be completed. Clearly, parts of it have a c lose relationship to the Trip Report I prepared on my meetings with Eskom that was subsequently distributed to the Commission members and elsewhere in the NRC. The source of all the information in this paper, as well as my South African trip report, is Eskom. They also provided me with the colored figures used in both reports. Subsequent reports will attempt to cover the safety issues identified by Eskom in their safety report to the National Nuclear Regulator (NNR), the nuclear regulatory agency of South Africa.

Since this paper contains only information publicly available from other sources, I have not used the designation "Predecisional." There is no information here that is not already in the public domain, but hopefully, it is organized in a logical and helpful way. Hence, there should be no restrictions on handling this paper. I welcome your comments on this paper with a view to improving my next papers on PBMR.

[1] As the PBMR investigation developed into a project, Eskom Ltd. created PBMR Ltd. as a subsidiary that was jointly owned by Eskom, Ltd. and the Republic of South Africa. Subsequent investments in PBMR, Ltd. resulted in the current ownership: Eskom 40%, Republic of South Africa 25%, British Nuclear Fuels 22.5%, and Exelon Nuclear 12.5%

THE PEBBLE BED MODULAR REACTOR

OVERVIEW

Eskom Ltd., the national utility of South Africa currently has about 34,000Mwe of generating capacity, primarily coal plants with some hydro power and two nuclear plants located in southwest South Africa near Cape Town

Additional generating capacity was needed in the Cape Town area.

The growth in their load was about 2½ % per year, comparable to the U.S.

Eskom's overall cost of generation was about 1.0 cent per KwHr, and their goal for new generation was set at 1.5 cents per KwHr

Eskom selected the PBMR from a variety of alternatives.

They rejected light water reactors like their Koeberg PWRs supplied by Framatome as being too expensive

There were no locations available in the region for water power.

The primary alternative was coal plants, but coal mines were located only in the northern part of the country where very economical coal plants are built adjacent to coal mines.

They selected the German pebble bed technology as providing an ultra-safe system so that they could concentrate on the economics of the system.

Modular plants of a modest size were selected to take advantage of the economies of building many identical systems that could be built as needed to meet the South African electrical needs as well as the needs of neighboring countries of Namibia, Botswana, and Mozambique.

Eskom and its partners envision the PBMR as a plant that could be exported and built on a world-wide bases because of its safety features and attractive economics.

Eskon has invested $30 million in development costs and estimates that an additional $90 million will be needed for development as well as $110 million for the construction of the first module at the Koeberg site.

GENERAL CHARACTERISTICS OF THE PBMR DESIGN

The PBMR concept is based on German high temperature helium cooled pebble bed reactor technology demonstrated in the AVR and THTR reactors.

The PBMR is a modular, graphite moderated, helium cooled, pebble bed type reactor that uses a Brayton direct gas turbine cycle to convert the heat into electrical energy by means of a helium turbo-generator.

A regenerative heat exchanger, called a recuperator, is used to improve the thermodynamic efficiency.

The thermal power output is limited to about 270 MWt per module.that can generate about 110 MW of electricity

The PBMR plant specifications developed by Eskom are given below:

PBMR PLANT SPECIFICATIONS

Max. sent out power	100-115 MW
Continuous stable power range	0-100%
Ramp rate (0-100%)	10%/min
Step change	10% of current power Load Rejection w/o trip
Anticipated Cost (n-th module)	$1000/KWe
Construction Schedule	24 months
General Overhauls	30 days per 6 years
Outage rate	2% planned & 3% forced
O&M and Fuel costs	$4-5/MWh
Emergency Planning Zone	<400 meters
Plant Operating Life Time	40 years

PBMR PLANT DESIGN

The initial PBMR plant will be a single 110 Mwe module for demonstrate purposes.

Standard plant configuration will be ten modules with a total generating capacity of about 1100 Mwe and operated by a crew of three supervisory operators, and twenty modules with six supervisory operators.

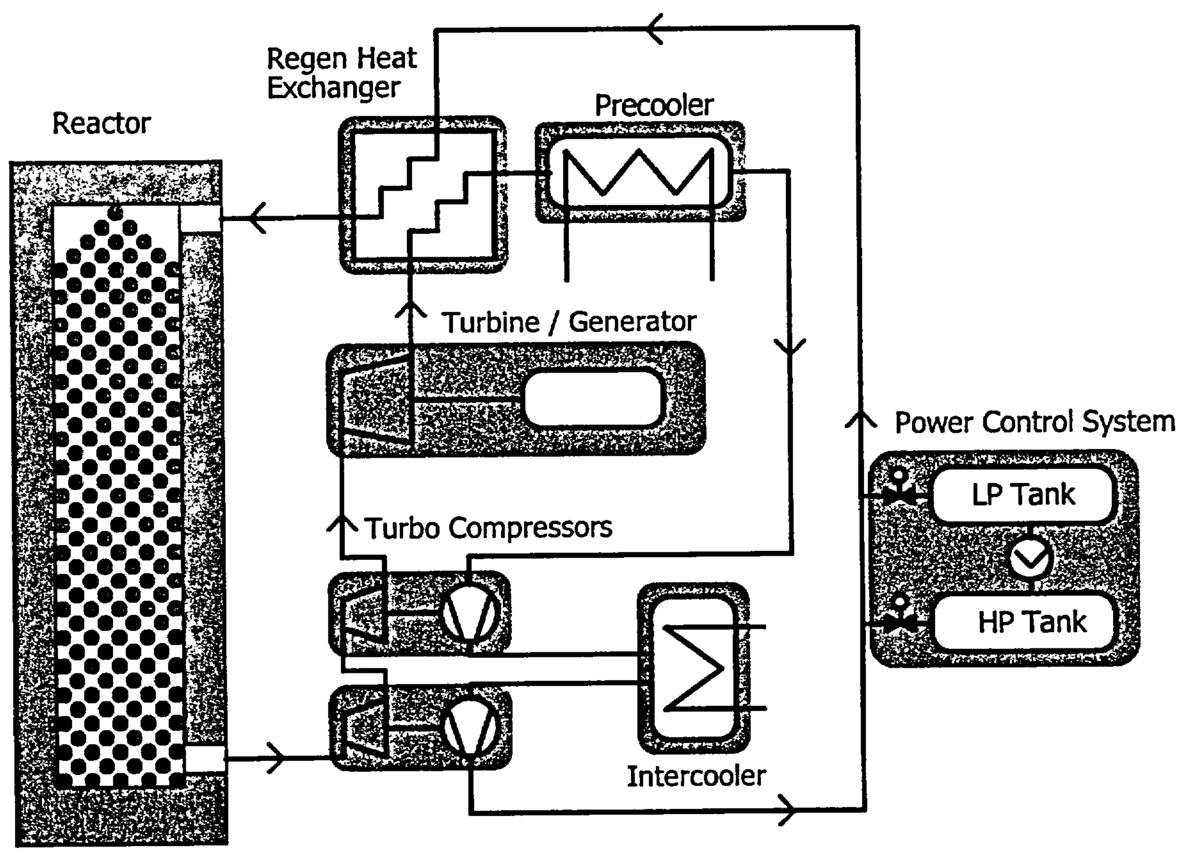
The total personnel for plants of one, ten and twenty modules would be 52, 80, 126.

Operation of each module will be entirely automated with control of ten modules from a central control room with three plant supervisors

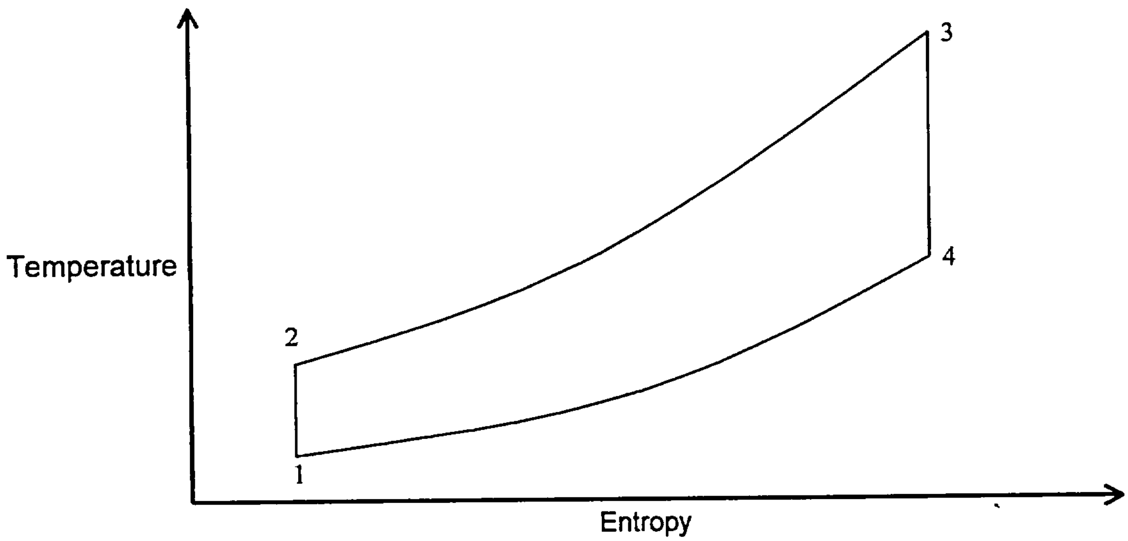
The PBMR has a large core with a low power density.

The helium coolant remains in a gaseous phase and is inert.

The plant layout is that of a traditional closed cycle gas turbine system using a recuperator to improve the thermodynamic efficiency. It is shown below:



THE IDEAL BRAYTON POWER CYCLE



The ideal Brayton cycle consists of two isentropic (no heat loss) and two isobaric (constant pressure) processes as shown in the above temperature-entrophy diagram.

Starting at state (1), gas at a low pressure and temperature is compressed in an isentropic process to a higher pressure and temperature (2) that requires added energy.

From states (2) to (3), the gas is heated in an isobaric process to the maximum cycle temperature, that required the addition of heat.

From states (3) to (4), the hot high pressure gas is expanded isentropically in a turbine to a lower pressure and temperature, while delivering energy to the turbine.

The cycle is completed from states (4) to (1) by cooling the gas at constant pressure, that requires the removal of heat.

The efficiency of the cycle is the ratio of the area enclosed by the cycle (1-2-3-4) in the above figure to the area under the (2-3) process all the way down to absolute zero temp.

Increases in efficiency are gained by raising the temperature of the (2-3) process and lowering the temperture of the (4-1) process.

In practice, there are heat losses during compression and expansion of the gas as well as pressure losses during heating and cooling. Both decrease the efficiency.

If state (1) remains constant, then state (2) moves to the right, state (3) moves down, and state (4) moves to the right.

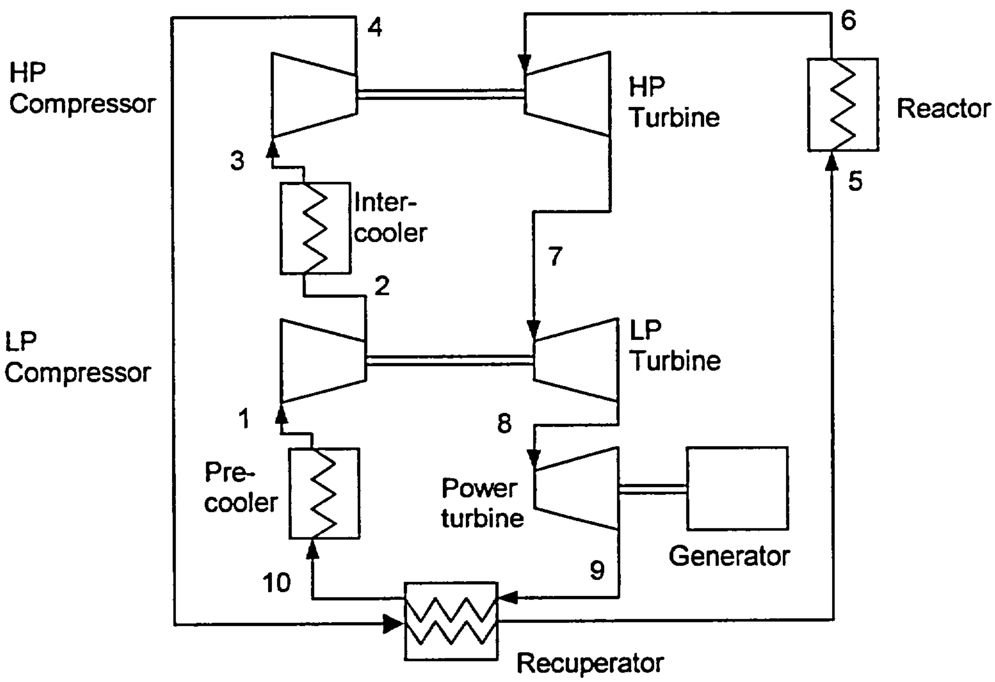
THE RECUPERATIVE PBMR BRAYTON POWER CYCLE

The efficiency of the ideal Brayton cycle can be improved by using a portion of the heat rejected during the cooling process (4-1) of the ideal cycle to preheat the gas before it enters the reactor core.

Another method of improving the efficiency is to use multistage compression with intercooling between the stages as well as precooling before compression.

The PBMR utilizes both these mechanism, and the modified cycle on which the PBMR is based is referred to as the recuperative Brayton cycle.

A schematic layout of the equipment for the recuperative cycle is shown below while the temperature-entropy diagram of the recuperative cycle is shown on the next page.

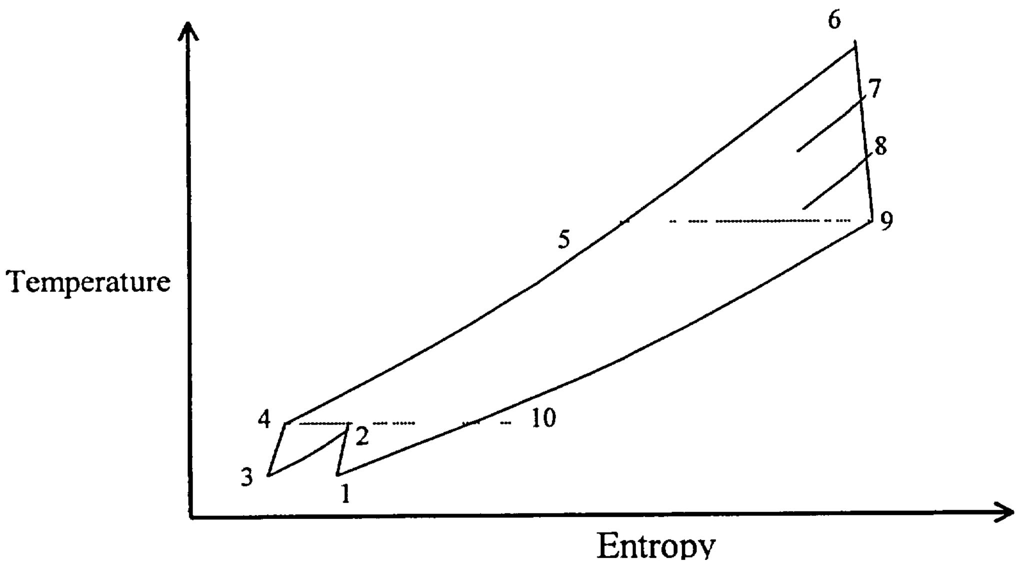


Lay-out of the PBMR Recuperative Brayton cycle.

Comparison of Ideal and recuperative cycles

	Ideal Cycle	Recuperative Cycle
Compression	(1-2)	(1-2) and (3-4)
Heat Addition	(2-3)	(4-5) and (5-6)
Gas Expansion	(3-4)	(6-7), (7-8) and (8-9)
Heat Removal	(4-1)	(9-10), (10-1) and (2-3)

THE PBMR RECUPERATIVE BRAYTON POWER CYCLE



This figure is the temperature-entropy diagram of the PBMR Recuperative Brayton cycle.. The inclined lines of processes (1-2), (3-4), and (6-9) indicate real processes which have heat losses.

Starting at (1), helium at a relatively low pressure and temperature is compressed by a low pressure (LP) compressor to an intermediate pressure (2) after which it is cooled in an intercooler to state (3).

A high pressure (HP) compressor then compresses the helium to state (4).

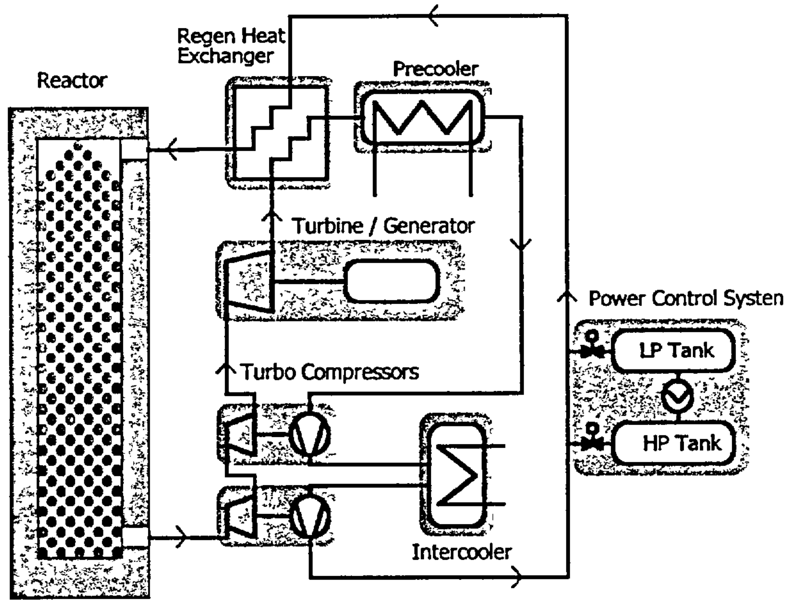
From (4 to 5) the helium is preheated in the recuperator before entering the reactor which heats the helium to state (6). Note: $T_5 \leq T_9$

After the reactor the hot high pressure helium is expanded in a high pressure (HP) turbine (driving the HP compressor) from states (6) to (7) after which it is further expanded in a low pressure (LP) turbine (driving the LP comprssor) from (7) to(8).

After the LP turbine the helium is further expanded in the power turbine to pressure (9) which is approximately the same as the pressure at (10) and (1).

From states (9) to (10), the still hot helium is cooled in the recuperator after which it is further cooled in the pre-cooler to state (1). Note: $T_{10} \geq T_4$

This completes the cycle. The heat rejected from (9) to 10 in the recuperator is equal to the heat transferred to the helium from (4) to (5).



FLOW DIAGRAM FOR PEBBLE BED NUCLEAR POWER PLANT[2]

Helium enters top of the pebble bed core reactor at 501°C and 1037 psi

At bottom of the pebble bed reactor, the helium has been heated from 501°C to 900°C and the pressure has drops from 1037 psi to 1017 psi

Helium enters HP Turbine (driving the HP compressor) where the temperature decreases from 900°C to 809°C and the pressure drops from 1017 psi to 855 psi

HP Turbine utilizes 45.5 MW heat energy at 90.6 % efficiency.

Helium then enters LP Turbine (driving LP compressor) where the temperature decreases from 809°C to 691°C and the pressure drops from 855 psi to 648 psi

LP Turbine utilizes 68.6 MW heat energy at 91.3 % efficiency

Helium then enters the Power Turbine where the temperature decreases from 691°C to 513°C and the pressure drops from 648 psi to 388 psi

The Power Turbine absorbs 125.9 MW heat energy at 91.9 % efficiency to deliver a net of 115.7 MW thermal energy to the generator
The generator produces 112.2 MWe (50 Hz) of electricity at 97% efficiency
Hence, with a house load is 3.2 Mwe, the Net Generation is 109 Mwe

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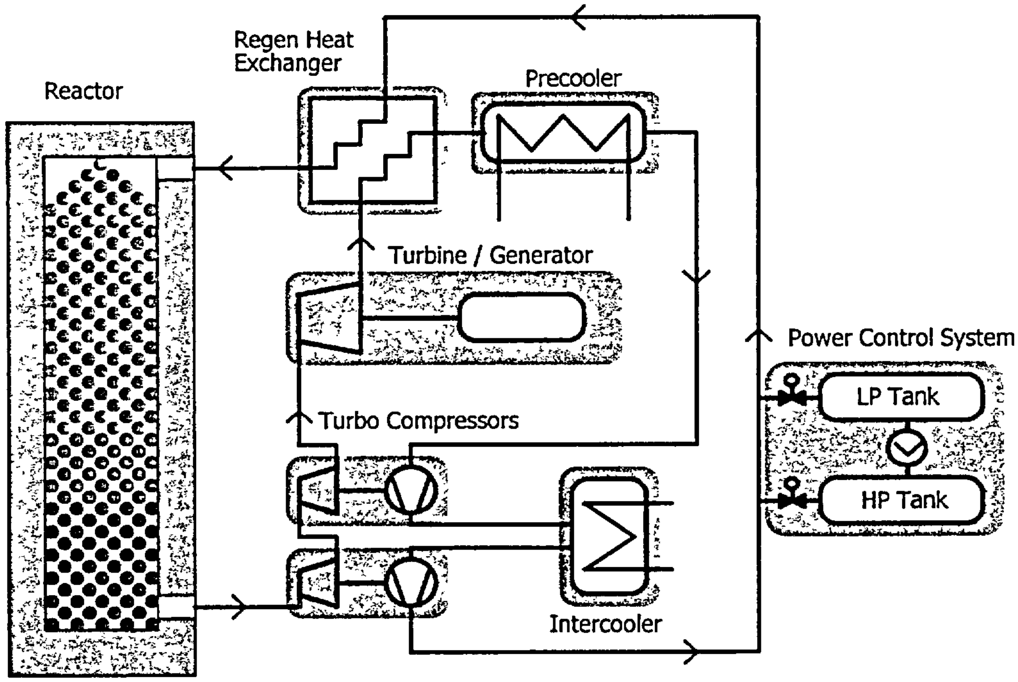
[2] For purposes of this example, pressure and temperature changes in pipes are ignored.



Helium then enters the heat Recuperator where the temperature drops from 513°C to 138°C and the pressure drops from 388 psi to 384 psi

Recuperator transfers 274 MW of heat energy at 97.25% efficiency

Helium then enters a water-cooled Precooler where the temperature drops from 138°C to 23°C and the pressure drops from 384 psi to 382 psi

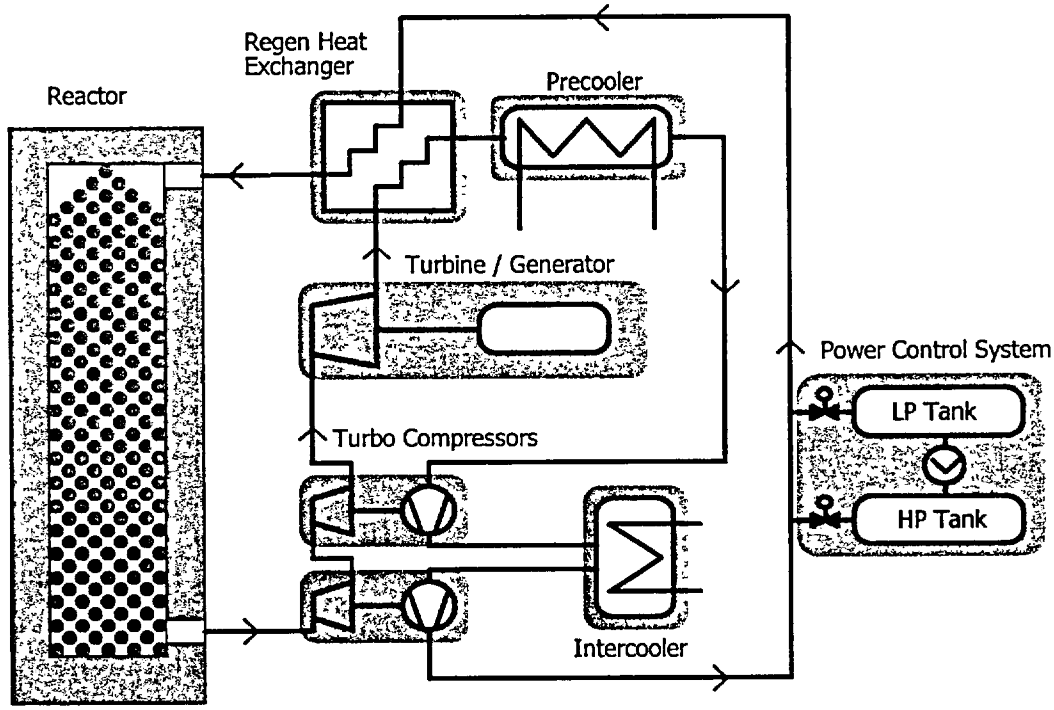
Precooler removes 84 MW of heat energy at 98.2 % efficiency

Helium then enters the LP Compressor where the temperature increases from 23°C to 116°C and the pressure increases from.382 psi to 694 psi

The LP Compressor utilizes 67.9 MW of heat at 89.5 % efficiency

Helium then enters the water-cooled Intercooler where the temperature decreases from 116°C to 25°C and the pressure decreases from 694 psi to 691 psi

The Intercooler removes 64 MW of heat energy at 95.7 % efficiency



The helium then enters the HP Turbine where the temperature increases from 25°C to 88°C and the pressure increases from 694 psi to 1043 psi

The HP Compressor utilizes 44.5 MW of heat energy at 90.6% efficiency

The helium then enters the Recuperator where the temperature increases from 88°C to 501°C and the pressure drops from 1041 psi to 1039 psi

The Recuperator transfers 274 MW of heat from one side of the recuperator to the other side with 92.2% efficiency

The helium then returns to the top of the pebble bed reactor

It can be shown that the power level is directly proportional to the system pressure.

To increase power, helium from the HP tank is bled into the coolant loop.

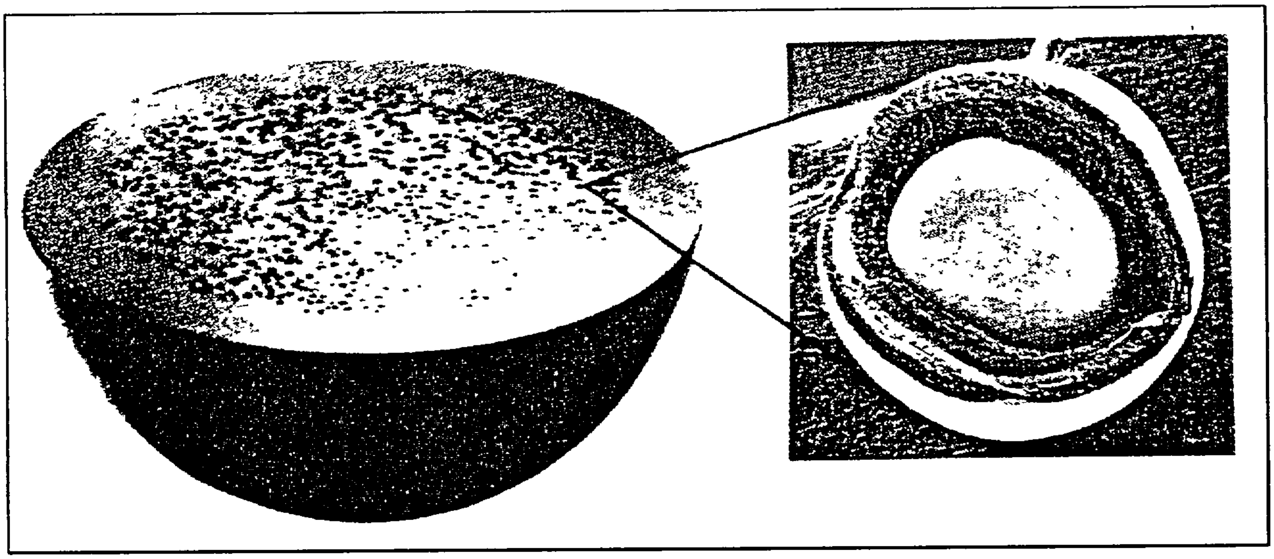
To decrease power, helium from the coolant loop is bled into the LP tank.

A compressor compresses gas from the LP tank and stores it in the HP tank

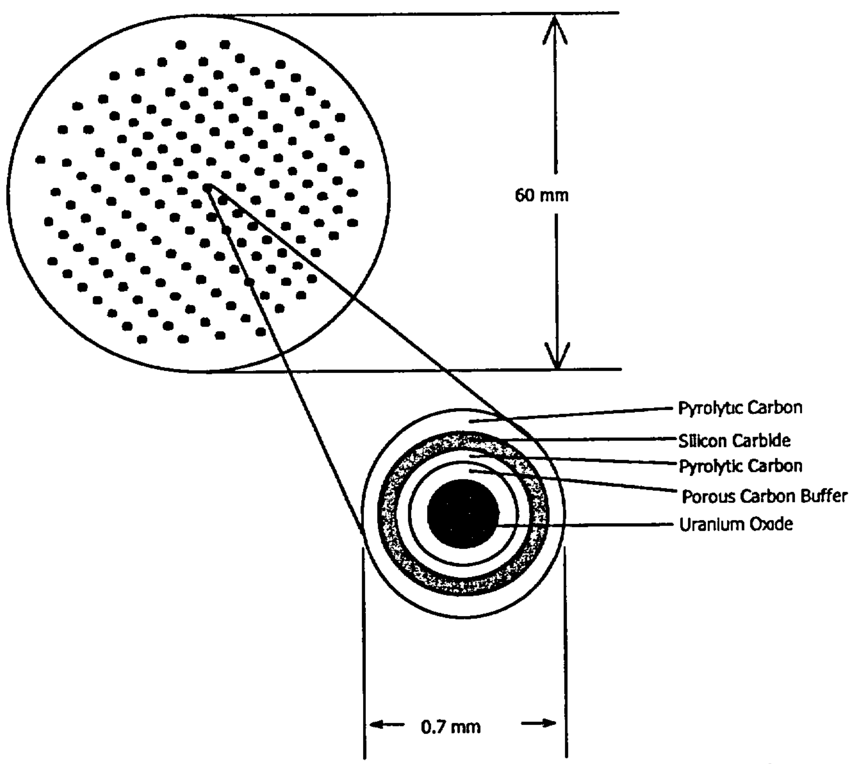
PEBBLE BED REACTOR FUEL DESIGN

The PBMR uses spherical pebbles 60 mm in diameter, each impregnated with about 15,000 enriched (8% U-235) uranium particles coated using the three-layer TRISO particles shown schematically in the following figures.

HTR Pebble Cross-section **Cut-away Coated Particle**

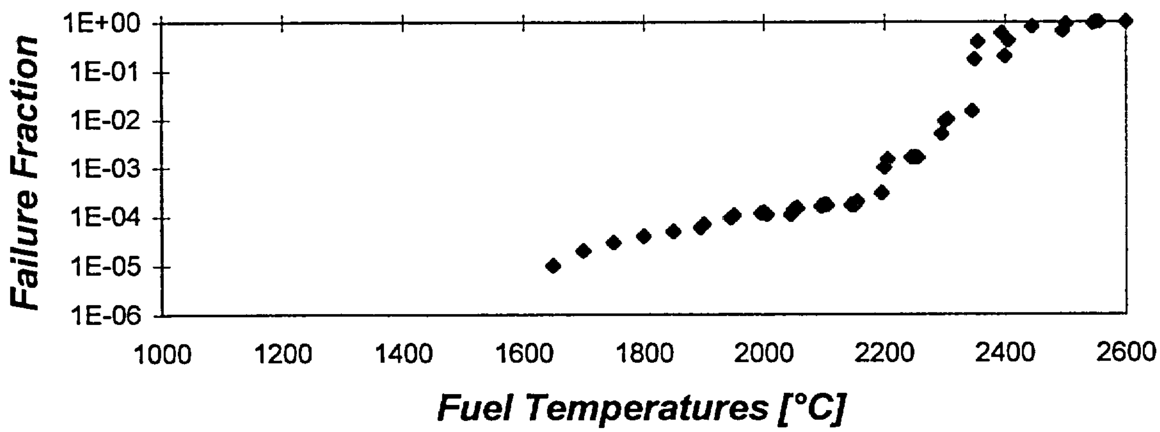


Graphite Pebble impregnated with TRISO Fuel Particles as used in the PBMR



Details of Pebble with TRISO Fuel Particles (8% Enrichment) Used in PBMR

RESULTS OF FUEL TESTS



The above figure shows data from a German test facility indicating that these fuel particles can withstand a temperature of about 1700 degrees C with no significant damage and up to 2200 degrees C with damage limited to about 0.01% of the fuel.[1]

These test results are based on the release of the fission product Krypton–85 during annealing for 100 hours as an indication of fuel damage.

The maximum operating fuel temperature under normal conditions is about 1100 degrees C with an average fuel temperature of about 1000 degrees C.

These temperatures will provide helium with an average temperature of about 900 degrees C at the outlet of the pebble bed core.

These operating temperatures give about 600 degrees C margin before fuel damage.

The outer 5-mm of each pebble is graphite without fuel particles so that minor damage to the pebble's surface due to handling and recirculation does not release fuel particles into the system.

Fuel utilizing TRISO particles has been used extensively in the German AVR and THTR reactors and to a certain extent in the United States.

[1] Not withstanding these test results, some fuel experts believe that 1900 degrees C is a practical upper limit for the temperature in silicon carbide coated fuel, even during the shout time of accident conditions.

PEBBLE BED REACTOR CORE DESIGN

The core is 3.5 m (about 11.5 feet) in diameter and 8.5 m (about 28 feet) high.

It operates at a pressure of about 7 MegaPascals (approximately 1040 psi).

The inlet and outlet temperatures of the helium in the core are approximately 500 and 900 degrees C respectively.

The average power density of the core is about 3.27 MW per cubic meter or about 0.8 KW per pebble, significantly less than the limiting experience of 3.9 KW per pebble.

The two region core has a cylindrical inner region where the pebbles contain only graphite and an annular outer region where the pebbles contain TRISO fuel particles.

This arrangement flattens the neutron flux and limits the maximum fuel temperature in the core under both operating conditions and accident conditions.

It also has the advantage that decay heat under accident conditions has a shorter distance to travel through reflector and pressure vessel to the outside.

The power peaking factor is 2.0 with the two region core design.

The core contains approximately 110,000 moderating balls and 336,000 fuel balls.

About 5000 pebbles are removed from the core each day and separated into moderator and fuel categories by a gamma ray monitor.

Moderator pebbles are recirculated to the center region of the core and fuel pebbles are assayed neutronicly to determine if the amount of fuel remaining to warrants recirculation to the fuel region.

On average, each fuel pebble is recirculated ten times before its fuel content reaches the point that it is sent to a spent fuel storage facility that is large enough to store all spent fuel pebbles used in 40 years of operation.

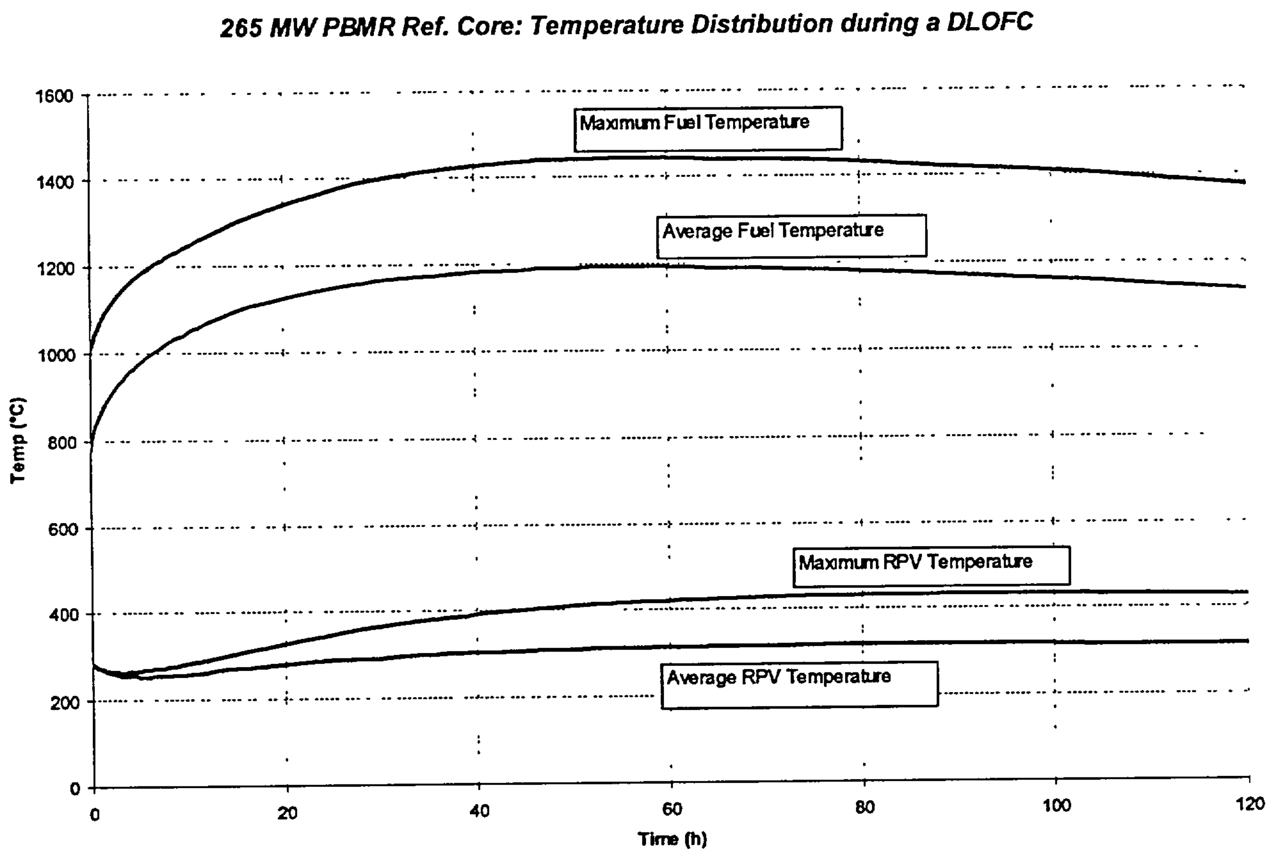
The reactivity control and shutdown system is located in the graphite reflector region outside the core.

ACCIDENT TRANSIENTS

The most severe accident envisioned by ESKOM is a "depressurized loss of forced circulation" (DLOFC). The transient associated with a DLOFC accident shown in the figure below indicates that the maximum fuel temperature would not exceed 1450 degrees C.

Even if the control rods were being withdrwn simultaneously with a DLOFC accident, the maximum fuel temperature is not expected to exceed 1600degrees C.

This is at least 100 degrees C lower that the temperature at which no significant damage occurred in tests conducted for 100 hours



Depressurized Loss of Forced Circulation (DLOFC) Transient in the PBMR

INSTRUMENTATION, CONTROL, AND SAFETY SYSTEMS

The instrumentation and safety systems will be assembled from traditional commercial-off-the-shelf components used in nuclear power plants around the world.

The reactor will be fitted with separate and diverse control and shutdown systems for purposes of defense in depth, to bring the reactor to a subcritical state.

The reactivity control and shutdown systems are designed to individually make the reactor subcritical at normal operating temperatures and keep it there indefinitely.

The reactor protection system (RPS) has three modes: 1) Partial Scram where only some of the control rods are inserted, 2) Full Scram where all the control rods are inserted simultaneously, and 3) the insertion of Small Absorber Spheres (SAS).

> It appears that the SAS is an emergency backup system (similar to the gadolinium backup safety system in the CANDU) that is manually tripped only in emergencies

RPS functions of partial and full scrams are normally initiated automatically based on predetermined conditions, but a partial scram can be initiated manually..

The SAS must be initiated manually by the operators. It is not used except for emergency situations when it is needed to avoid transients that depend upon negative temperature coefficients to limit transient temperatures.

Shutdown panels are located in both at the individual PBMR and at the Unit Control Room where up to ten PBMRs are monitored and controlled by three operators.

Since power level is controlled by adjusting the helium pressure, the primary need for external reactivity changes is to compensate for xenon changes for which control rods are used.

Reactivity losses due to burnup and removal of fuel pebbles are compensated for by the addition of newer fuel pebbles at the top of the core to maintain minimal excess reactivity.

The control system adjusting the helium pressure is expected to incorporate a simulation model of the thermal-hydraulics of the plant (the same model currently being used in the design of the plant) in order to attain the desired rate of change of power.

POWER CONTROL SYSTEM

The power level is changed by adjusting the pressure of the primary coolant system

To increase the power level, high pressure helium from the high pressure control tank is bled into the main coolant loop, increasing its pressure.

> This increases the pressure and mass flow rate without changing the temperatures and pressure ratios.
>
> The increased pressure and subsequent increased mass flow increase the heat transfer, thus increasing the power.

To decrease the power level, helium from the main coolant loop is bled into the lower pressure control tank and is subsequently pumped into the high pressure tank for reuse.

> This decreases the pressure and mass flow rate resulting in a decrease in heat transfer. Thus decreasing the power.

A bypass valve from the main coolant loop to the low pressure control tank is used to rapidly dump large quantities of helium if there is a need to decrease power rapidly.

PLANT CONFIGURATION AND STAFFING

The initial PBMR plant will be a single 110 MWe module for demonstration and testing.

The standard plant configuration will be ten modules with a total generating capacity of about 1100 MWe operated by a crew of three supervisory operators supported by administrative and maintenance personnel.

Operation of each individual modular plant will be entirely automated.

A "two unit" plant would consist of two arrays of ten modules with an augmented administrative and maintenance staff.

The total staff on site for the one, ten and twenty module configurations would be 52, 80, and 126 total staff members respectively.

PBMR LTD. DESIGN PHILOSOPHY

The design of the PBMR is driven by two factors: safety and economics.

PBMR Ltd. has chosen what they consider to be an ultra-safe nuclear power generating technology.

They maintains that once inherent safety is assured with high quality, high temperature fuel having a strong negative temperature coefficient, all other design decisions are driven by economics.

They maintain that there is a very substantial margin in the Triso fuel over the maximum temperature that could be reached under the worst accident conditions.

They point out that in the PBMR, the fuel is the last thing that would be damaged in an accident whereas in the LWR technology, the fuel is the first thing that is damaged (e.g., as at TMI-2).

The PBMR design provides a large core with low power density (about 3.3 MWt per cubic meter) and lots of surface area to dissipate heat.

They maintain that there is an inverse relation between plant thermal output and safety and have chosen a small modular plant.

Although a probabilistic risk assessment (PRA) has not been carried out for the PBMR, risk considerations are important to its designers.

PRAs carried out for the high temperature gas-cooled reactor (HTGR) designs of the early 1980s, even for those with steam cycles that involved the two-phase behavior of pressurized water in plant accident scenarios, gave core damage frequencies (CDFs) at least an order of magnitude smaller than for the LWRs of that era.

Given the improvements of the PBMR design over the HTGR plants and the use of a single phase coolant, the CDF of the PBMR should be even lower.

PBMR Ltd. maintains that risk associated with the PBMR is reduced by the use of high integrity Triso fuel particles, the large negative temperature coefficient, the inert single-phase coolant, the high heat capacity and low power density of the large core, and the long thermal time-constants associated with the pebble design.

Each of these factors individually contributes to reducing the probability of a core-damaging accident, and the synergistic interactions of these factors reduce the risk further.

It is the contention of the PBMR designers that the resultant risk is so low that accident mitigating systems such as engineered safeguard features or a conventional containment structure, would contribute little to reducing the risk associated with the operation of the PBMR and would certainly not be cost-effective.

Having achieved what they consider to be assured safety, all other PBMR Ltd. decisions are driven by economics.

The have competitive bids on major components such as gas turbo-generator, recuperator and circulators.

The German fuel fabrication plant will be duplicated in South Africa with considerable assistance from experienced German fuel fabricators.

They see no need for plant containment in the traditional sense; only a civil structural "confinement" is used.

Putting in additional safety systems that are not justified on technical grounds is viewed as being out of the question.

Indeed, they indicate that the whole PBMR project will be canceled if costs are driven up by what they consider to be unjustified additional requirements.

Never previously in history has a nuclear power plant design been pursued with such a focus on economics.

Their goal is 1.5 cents per KWHr so that this "Generation 4"("Generation 3 ½ "?) nuclear power plant will be competitive with new coal plants in South Africa.

Right now, they calculate that the cost of electricity for a 10 module plant with 80 plant staff members constructed in 24 months at a cost of $100 million per module (with 25% owners cost) will be 1.6 cents per KWHr using a load factor of 93%, a discount rate of 6%, and a 30 year amortization period.

If such a cost level is achieved in South Africa, it is virtually guaranteed that the PBMR plant will be economically competitive anywhere in the world

PBMR APPROACH TO LICENSING AND GENERAL DESIGN CRITERIA

Historically, the approach to licensing non-LWR plants has been to adapt LWR licensing procedures (i.e., those currently documented in the licensing agency's standard review plan) to reflect the different technology involved.

Sometimes, this leads to reasonable results where the difference in technology is not large (e.g., a heavy water moderated and cooled plant that uses the Rankine steam cycle has many characteristics similar to a LWR plant).

Since the NNR, the South African nuclear licensing authority has no previous experience with gas cooled nuclear power plants, PBMR Ltd. developed a philosophical basis, called the Safety Case Development Framework, for licensing a gas cooled reactor from which a set of General Design Criteria (GDCs) could be established.

Basic Tenants of the Safety Case Development Framework.

The PBMR is a nuclear reactor system designed to derive maximum safety benefits from its natural characteristics.

This gives significantly advantageous safety performance compared to LWR designs that must rely on engineered safety systems to achieve an acceptable level of safety.

The most important characteristics of the PBMR design are

1) the proven ceramic fuel elements that assure containment of fission products in billions of tiny fuel elements up to temperatures significantly greater than the maximum temperature associated with the worst accident sequence, a depressurized loss of forced circulation with simultaneous control rod withdrawal,

2) the negative temperature coefficients of reactivity associated with increasing fuel temperatures,

3) the low power density associated with a large core geometry that has a large heat capacity,

4) use of an inert single-phase coolant, and

5) low excess reactivity.

This means that natural shutdown can be achieved without engineered safety systems because no credible faults can lead to the loss of fuel integrity, thus assuring containment of the fission products.

No operator action is required for several hours following a faulted condition.

The fundamental safety design philosophy is based on the premise that the fuel adequately retains its integrity, and hence, contains radioactive fission products under normal and accident conditions and thereby assures radiological safety.

This is achieved by relying on fuel, whose performance has been demonstrated under simulated normal and accident conditions and whose integrity is therefore not challenged even under any accident conditions.

To ensure this fuel integrity is maintained, the plant design for normal and accident conditions

1) includes sufficient heat removal capability such that the maximum fuel temperatures remain in the proven safe region,

2) limits chemical and other physical attack on the fuel, and

3) provides adequate measures to ensure the shut down of the reactor and to control reactivity indefinitely under all conditions.

FUNDAMENTAL SAFETY DESIGN PHILOSOPHY

PBMR Ltd. contends that an appropriate analysis demonstrates that the Fundamental Safety Design Philosophy has been met with adequate margins.

The design has been systematically analyzed to ensure that all potential accident and operating conditions have been identified and evaluated.

This analysis will be updated with any changes to the design during the plant's life and reviewed periodically.

The design is such that any single failure of an element of the safety case does not invalidate the Fundamental Safety Design Philosophy through the use of "defense in depth."

The design ensures for all pathways that any dose received by the operators and public and radioactive releases to the environment in normal operations, as well as risks from accident conditions, not only meet all NNR regulatory limits and constraints but are also are "as low as reasonably achievable."

The PBMR design minimizes the generation of radioactive waste throughout its life cycle (including decommissioning) and includes appropriate processing, conditioning, handling and storage systems.

An extensive test and commissioning program will be used to demonstrate the performance of all systems, structures, components and materials important to safety.

This program ensures that any physical phenomena that have a unique application to the safety of the PBMR design are adequately demonstrated on the first module. To support the safety of the plant, the PBMR operates inside a series of defined programs throughout its operating life.

These include 1) operations, 2) radiation protection, 3) maintenance, and 4) inspection and testing.

The plant design facilitates and makes provision for these programs.
Over its entire life cycle, the PBMR will be supported by a quality management system

KEY TECHNICAL FEATURES AND CHARACTERISTICS OF SAFETY

The PBMR uses passive safety design features and inherent characteristics to contain fission products at the source of their generation—within ceramic coated fuel particles—for the full range of licensing basis events.

Aspects of PBMR technology that allow reliance on passive features and inherent characteristics are:

High Heat Capacity/Low Power Density . The high heat capacity of the graphite moderated core, in concert with its large size and relatively low power density of the core, results in a very slow response to imbalances in heat generation and removal during both operating and accident conditions.

The large heat capacity of the PBMR core and the large margin between the maximum fuel temperature under accident conditions and the fuel failure temperature are primary factors in the ability of the PBMR to withstand an indefinite loss of coolant circulation.

High Temperature Capability.

The graphite structural elements of the core maintain strength (which actually increases at high temperatures) to temperatures far in excess of those reached in conceivable accident conditions.

This assures that the core remains in a stable configuration. Low probability accident analysis is greatly simplified and uncertainties reduced by eliminating the potential for reconfiguration of core materials, i.e., a severe core disarray accident.

Inert, Single Phase Coolant.

Because the helium coolant is chemically and neutronicly inert and is not required for decay heat removal, whole classes of accident events are reduced or eliminated.

Since there is no phase change of the coolant under accident conditions, the complex semi-empirical relationships for flow and heat transfer characteristics of water as a function of geometry, pressure, boiling regime, etc. are avoided.

Reactor Cavity Cooling System (RCCS). The RCCS removes heat from the reactor cavity by circulating water through arrays of cooling vessels.

The thermal capacity of these vessels filled with water is sufficiently large that heat can be transported away by boiling for a long period even without active circulation.

The RCCS maintains acceptable reactor cavity concrete temperatures under normal operating conditions and, in conjunction with the features discussed above, limits the reactor internals and reactor vessel to acceptable temperatures under accident conditions.

Civil Structures.

The reactor building is a low-pressure confinement and is designed to support and protect the reactor and equipment.
Parts of the civil structures important to safety provide protection from

1) environmental factors (seismic events, flooding, etc.),

2) external events (including aircraft crash),

3) internal blowdown forces, and

4) internally generated missiles.

CLASSIFICATION OF SYSTEMS, STRUCTURES AND COMPONENTS (SSCs)

The classification of SSCs is a necessary input into the design rules because it determines the quality assurance requirements and the importance of the particular SSC in meeting the PBMR Fundamental Safety Design Philosophy Statement.

The standard used is ANSI 51.1 which divides SSCs into four groups, Safety Classes 1 to 3 and Non Safety related.

The primary boundary is Safety Class 1.

The systems engineered to directly support the cooling of the fuel in case of a loss of coolant and emergency reactivity control are Safety Class 2.

Those systems that provide support to Safety Class 2 SSCs are Safety Class 3.

In application to the PMBR, the barrier for containment of fission products is the coatings on the fuel particles, and hence they are considered Class 1.

The function of heat removal following a loss of cooling event is achieved by conduction, convection, and radiation heat transfer through the core structure, core barrel and reactor pressure vessel to the structures in the reactor cavity. These are therefore Safety Class 2 components.

In the same way as the ultimate heat sink on an LWR, the reactor cavity cooling system (RCCS) and related civil structures are classified as Safety Class 3.

Due to the inherent characteristics of the PBMR, there are no conditions where external emergency addition of negative reactivity is required to limit fuel temperature; hence, there is no specific system needed for this function.

PHILOSOPHY FOR DERIVATION OF GENERAL DESIGN CRITERIA (GDCs)

As indicated earlier, many criteria and analyses designed for LWRs are often not applicable to gas cooled reactors.

However, there are general criteria, e.g., quality assurance and external events, which are universal and can be used for any nuclear reactor design.

Furthermore, the PBMR Fundamental Safety Design Philosophy discussed above together with the PBMR Basic Licensing Criteria LG-1037 issued by the South African NNR provide a basis for deriving General Design Criteria for the PBMR.

A specific example will help illustrate the process.

Event trees can be used to identify challenges to the fuel integrity.

One such challenge can come from reactivity control.

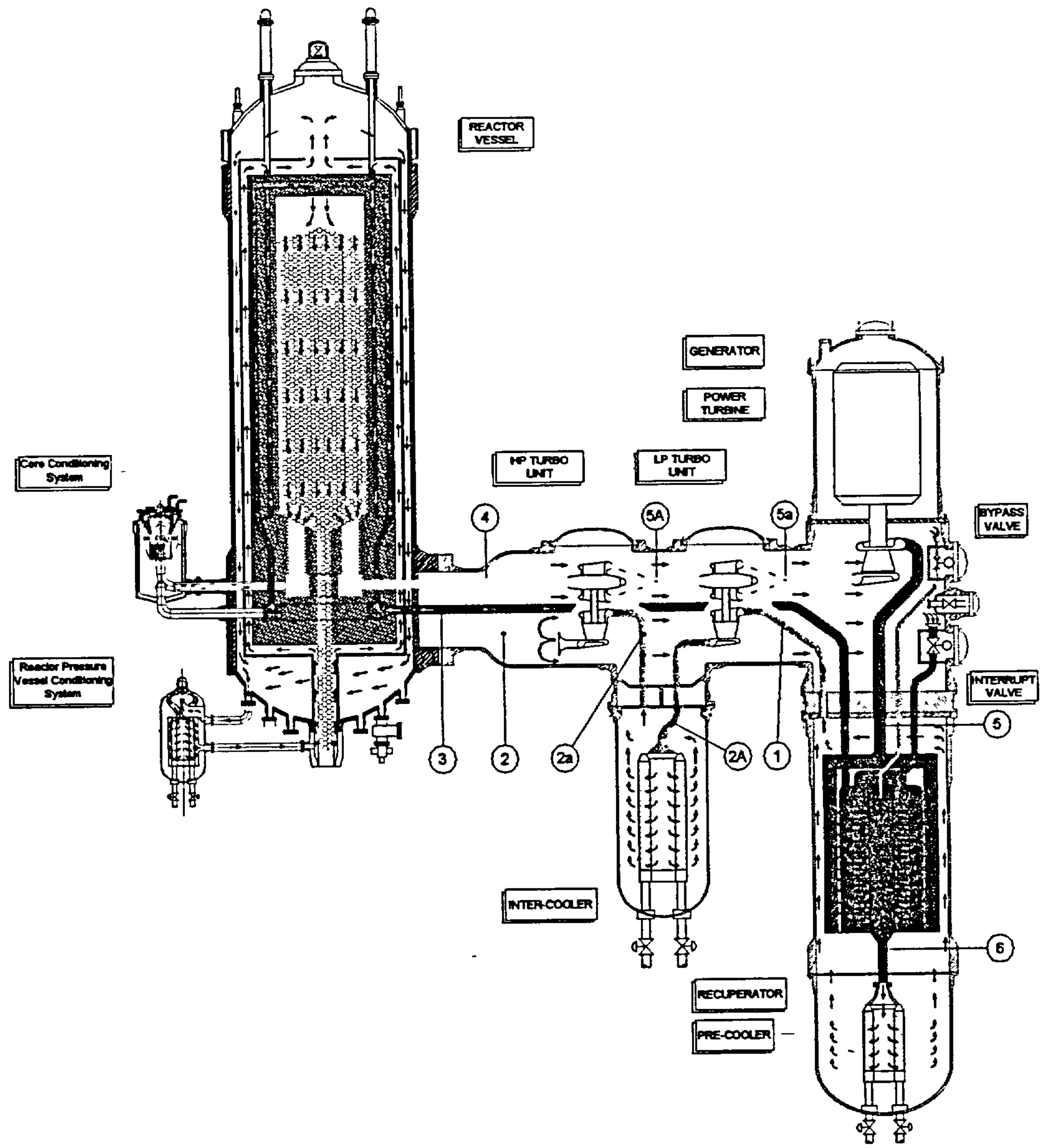
The appropriate General Design Criterion specifies that the coefficient of reactivity of the core must be negative with increasing temperature of the fuel under all possible circumstances.

A complete set of safety relevant GDCs can be generated using the following steps:

1) For each of the Fundamental Safety Design Philosophy Statements challenges are identified, or the implications of the statement are detailed in order to formulate GDCs.

2) After an internal review of these steps, the resultant GDCs are formulated for the PBMR to negate these challenges.

PBMR -- PEBBLE BED MODULAR REACTOR



Note: The design of the pipes connecting the pressure vessel with the power turbine and recuperator has been changed since this drawing was prepared.