Review and Identification of Typical HTR Tribology Conditions of Components

NNC Contribution

by

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Summary

This report covers a review and identification of typical tribological conditions of components in an HTR. The report contributes to deliverable D38 of the HTR-E Project. As requested the report focuses on the PBMR type reactor design.

The published information on this reactor design is very limited. No documents were located discussing the tribological conditions for this type of reactor. NNC has used its experience in gas cooled reactors to make an initial assessment. The conclusions reached should therefore only be taken as an indicator of areas where future investigation may be needed

Introduction

This report covers a review and identification of typical tribological conditions of components in an HTR. The report contributes to deliverable D38 of the HTR-E Project. As requested the report focuses on the PBMR type reactor design.

The purpose is to provide where possible available information on environmental conditions and tribological conditions (type of contact, contact conditions, loading conditions) for the components.

The published information on this reactor design is very limited. There are few details available on components (Ref. 1 provides perhaps the main source of information) and no information on loading and tribology.

To provide some guidance on possible problem areas, a preliminary assessment has been made based on the few references located and using NNC's experience in gas reactor operation and on the Dragon reactor. The conclusions reached should therefore only be taken as an indicator on where possible future investigation may be needed.

This document contains the results of work at NNC on Deliverable D38 of the HTR-E Project.

PBMR type Reactor

Description

The PBMR type reactor is being developed in South Africa as the first of a new generation of cost-effective and inherently safe power plants that uses a modular approach. It consists of a helium cooled graphite moderated reactor core coupled to a power conversion unit that uses a gas turbine driven by the reactor coolant gas. The reactor system is based on an annular pebble bed core design and uses a central column of graphite spheres. Fuel spheres are loaded from positions on the periphery, through the top reflector to form an annulus, which enables the required power output to be achieved within the fuel safety margin. The process cycle used is the Brayton cycle with a closed circuit water-cooled inter-cooler and pre-cooler.

Separate turbo-compressors and power turbine are used in the power conversion unit (PCU) with magnetic type bearings to avoid contaminants in the helium circuit and limit maintenance.

The high efficiency power system is achieved from a 900^{o}C reactor gas outlet temperature combined with a high efficiency recuperator. Helium leaves the pebble bed reactor and flows through the high and low pressure turbines and these drive the associated compressors. Power control is achieved by adding or removing helium to the volume inside the main circuit, which increases primary circuit pressure and mass flow rate without changing temperatures and pressure ratios. The reactor systems are placed inside a Reactor Pressure Vessel with the PCU components located separately. The whole plant is housed in a single building. Figure 1 shows a schematic cross section through the reactor and PCU components.

Main systems & components

A schematic of the power conversion system is shown in Fig. 2. The hot helium gas leaves the reactor at 900^{o}C, and pressure of around 70 bars and flows through high and low pressure turbines and through to the power turbine which drives the generator. The gas continues through to the recuperator and gives up much of its heat to the helium just about to re-enter the reactor. The lower-energy helium gas passes continues to pass through a water cooled pre-inter-cooler and inter-cooler and low and high pressure compressors before returning to the reactor core at 540^{o}C degrees.

The reactor vessel is approximately 6.2 m in diameter and 20.5 m high, manufactured from reactor grade forged steel with a wall thickness varying between 160 and 260 mm. It has an internal steel core barrel that supports the graphite reflector. The reactor core is nominally divided into two distinct regions, a central reflector of graphite spheres (60mm diameter pebbles) and an annulus containing the fuel spheres. When fully loaded the core is expected to contain over 360,000 fuel and 170,000 graphite spheres. The combined radial thickness of the two graphite side reflector blocks is 0.9m. The system uses nine control rods for reactivity control during load changes and nine control rods to shut down the reactor.

The PCU uses three separate shafts for the different compressor/turbine and turbine generator pairs. A high pressure turbine drives the high pressure compressor and a low pressure turbine drives the low pressure compressor. Adjustable stator blades are used for short term control. Magnetic bearings are used in the cycle to avoid contaminants in the helium circuit and to limit maintenance.

The output of the plant can be controlled by changing the helium inventory of the system or by opening and closing of the bypass valve (Fig. 2). Changing of the helium inventory is a relatively slow process and used for load following, while the faster bypass valve can be used for load rejection.

Tribological considerations and terms

Excessive friction

Failures from high frictional resistive forces are often referred to as seizures. Excessive friction can give unacceptable stresses in neighbouring components or allow self-jamming of complex mechanisms that would normally be expected to function under lubricated conditions. Lack of lubrication in reactor applications can lead to high friction coefficients with many material combinations. Most structural materials in helium have high friction coefficients (>1.0). In many applications friction is an overriding consideration especially where there is rubbing and where reliable and efficient operation is demanded in an emergency (e.g. safety shut down rods).

Adhesion

With moderate or long-term contact under load at high temperature substantial adhesion can develop. Metal surfaces in static contact at elevated temperature in helium tend to adhere and resist being parted or separated. Adhesion is important because forces resisting motion can become significantly higher than expected. The degree of adhesion during contact can vary from a relatively small but significant increase in the force required to initiate sliding after some minutes to one where parting is no longer possible.

The tendency to develop adhesion comes from the general inability of surfaces to form oxide layers and also to a lesser extent the absence of organic contaminants.

Static adhesion can lead to difficulties in plant maintenance, particularly where this has to be carried out by remote handling techniques and high separation forces. Additionally static adhesion can lead to unacceptable stresses causing for example creasing or tearing in the case of thin metallic foil insulation.

Galling

Galling is used to describe the generation of severely roughened surfaces due to sliding in inert environments or between certain like materials in oxidising environments, e.g. nickel alloys. Experiments in high vacuum have shown surfaces undergo sever adhesion when there is little or no protection by absorbed oxide films. There is surface disruption, transfer of material back and forth between surfaces and little production of loose debris. Since many mechanisms demand accurate location through closely fitted clearances galling can lead to seizure with unacceptable consequences in many instances. Materials and coatings therefore have to be chosen to take account of galling characteristics. For bearings the moisture level of the gas is critical for good running performance (> 20 vpm) or use of good lubricants is required.

Fretting

The use of high velocity fluids can result in turbulent buffeting and eddy shedding and possibly lead to the vibration of reactor components. Where such components are restrained or held by neighbouring assemblies (e.g. tube and grid supports of heat exchangers) fretting wear can result from the high frequency, small amplitude movements generated. It is important that such a mechanism does not lead to fretting scars that can act as stress raisers and lead to fatigue failure or to bearing strength reduction. Penetration of thin walled tubing or sections separating high pressure helium and water in heat exchangers for example must be avoided.

Wear

Wear in an inert gas such as helium is strongly adhesive in character. Information on wear rates between contacting moving surfaces is therefore important to integrity. Reliable operation may be affected by wear or ultimate life limited by wear. Wear scars can act as stress raisers, leading to reduced strength or fatigue life and loss of integrity or malfunction through inaccurate running or location or lead to jamming of mechanisms.

Types of motion

Wear rates and coefficients of friction may also be influenced by whether the relative motion is unidirectional or reciprocating and if the latter, the magnitude of the stroke. There is evidence for increasing coefficients of friction and changes in surface roughness with decreasing stroke.

Results of the Review

The information gained from a search of published documents on PBMR proved to be very limited. No published data was available on component tribology conditions or potential locations for tribological problems. Also very little information was available on component details of the PBMR.

To provide a starting point for assessment purposes NNC has made a preliminary review of potential tribological areas using its experience and knowledge from other gas reactors (inc. AGR and Dragon). The IAEA International Working Group on Gas Cooled Reactors (IWG-GCR) which provides a valuable forum for the exchange of information, has edited and published a document on the current status and future development of HTR's (Ref. 1) and this, perhaps, provides the most comprehensive published information on PBMR details available to date. Much of the component information for the review of PBMR tribological issues has been taken from this document.

For the review of PBMR tribology areas the following approach was adopted:

- From the list of available documents establish list of key components where tribological problems might be possible.

- Identify mating surfaces where relative movement between surfaces was possible during reactor commissioning / operation / maintenance

- Identify mating pairs of materials and relevant reactor parameters (where available)

- Make assessment of potential problems (either noted or estimated from NNC experience).

Since the formal information on PBMR was very limited the conclusions reached were considered preliminary and only to be taken as an indicator to possible locations where future investigation may be needed.

Reactor Areas

The review has considered the reactor system and the power conversion unit within the primary pressure boundary plus some of the main supporting systems. The components and areas considered are listed in table 1.

The reactor system

This includes the core, and surrounding structure plus the control and fuel system.

For the core the main tribological concerns are expected to come from the contacts between the graphite pebbles, blocks and location keys and between the graphite and the surrounding steel and structural supports. The steel structures include the core barrel and bottom structure, support flange at the lower section, stiffening ring at the top, pipes and components of the fuel system, fuel tube and lower discharge tube (Fig, 3)

Wear and powdering caused by graphite to graphite contact and rubbing due to relative movement between spheres and bricks under the action of the gas flow and temperature changes needs to be at an acceptable level to mimimise dust and provide a smooth action of pebbles through the system. Other graphite to graphite contact areas include the bricks and keys under the action of temperature and temperature gradients (i.e. a relative sliding / rubbing action during transients) which may result in wear (or even cracking) and loosening of components.

The metallic parts of the core are expected to expand further under temperature than the graphite. Graphite material properties are affected by irradiation, the most important ones from a core design point of view being strength, Young's modulus and Coefficient of Thermal Expansion (CTE). For example the strength and Young's modulus of the graphite can be increased by irradiation, whereas although CTE also initially increases, it subsequently falls, reducing to around half the unirradiated value over the dose range of interest. The result is relative movement between graphite bricks and steel causing wear of the graphite. Main areas to be reviewed include the core to core barrel contact points and the graphite to bottom support plate contact.

For the control and fuel system the main areas of tribological concern are those for static adhesion, wear and leakage. The control units within the Reactivity Control and Shutdown System (RCSS) are required to operate when called upon after periods of inactivity and in the helium atmosphere this can lead to sticking and failure of the component to operate. A multi-pass fuel handling scheme is used capable of supplying 370 new fuel spheres per day fed largely by pressurised reactor helium. The main part of the system is in a shielded area below the reactor.

Cooling systems

The several cooling systems within the PBMR design are shown in table 3. These systems are designed for investment protection rather than to perform a nuclear safety function (Ref. 1).

The reactor core conditioning system, which acts to provide helium flow through the core for heat up purposes and can be used to remove core decay heat if required, contains valves, blowers, heat exchangers (both water cooled and gas to gas (recuperator)) and pipe connections to allow inlet/ outlet gas mixing. There are two systems each delivering a capacity of 50% and installed in separate vessels coupled to the primary pressure boundary. For the heat exchangers the areas of tribological concern are from fretting, adhesive wear and rubbing mainly due to the relative movement between the heat exchanger tubing and its supports caused by differences in thermal expansion and vibration. Coatings and bearing materials need to be investigated to minimise these effects. For the blowers fretting wear can reduce efficiency of operation. Areas of concern would be the seals and bearings and effects of vibration. At the valves static adhesion in the helium atmosphere may be an issue although at lower temperatures ~450^{o}C Dragon experience suggests this may not be a problem (Ref. 12).

The reactor vessel conditioning system maintains the RPV at a homogenous temperature (280-300^{o}C). It consists of a blower, water cooler, valves and pipe connections. Two 100% systems are to be used again in separate pressure vessels connected to the primary pressure boundary. Again fretting wear, rubbing and stiction (high friction on first movement) are the main issues.

The Power Conversion Unit

This covers the equipment necessary to convert the high temperature helium leaving the reactor towards a generator for electricity. The system includes high (HPT) and low (LPT) pressure turbo units, Power turbine (PT) with generator (G), recuperator, intercooler and pre-cooler plus valves and pipes. The LPT and HPT run at 14,200 and 15200 rev/min respectively and the PTG rotor at 3000 rev/min. All three shafts are supported by electro-magnetic bearings. For the turbo-units and power turbine the bearings constitute the main areas of tribological concern with the risk of fretting wear, adhesion and rubbing or galling. Other issues include erosion of the blades and potential for effects of vibration should out of balance occur.

There are two water-cooled heat exchangers within the closed loop Brayton cycle having similar heat loads. Finned tubes are incorporated and fretting, adhesive wear and rubbing due to the relative movement between the tubing and supports from differential thermal expansion and vibration are again important. Coatings will play an important role here in reducing these effects. For the recuperator, which returns the helium temperature back up to reactor inlet levels the plate supports present the most likely area of relative surface motion.

Startup of the Brayton cycle is achieved through the Start-up Blower System which uses two large electrical blowers and a number of shutdown by pass valves. As with the reactor core conditioning function the main concerns are fretting wear, rubbing and adhesion.

Helium services

This includes the helium inventory control system and the helium purification system. Components within these two systems mainly affected by tribological factors include the compressors and the valves. The former with respect to wear and leakage and the latter concerning static adhesion. The helium inventory control system controls the power output during load following. Two positive displacement compressors are used to reduce the helium inventory in the system. In the helium purification system chemical and particle contaminants are removed from the primary coolant. Assurance against wear, leakage and stiction in these components is therefore extremely important to the reliable operation of the plant.

Plant Maintenance

Plant maintenance of most of the major equipment is expected to take place every six years. Access ports are incorporated in the design to allow for removal and replacement of components following inspections. Static adhesion is the main difficulty, particularly where remote handling techniques are required and / or where separation of surfaces in contact with helium is needed for components that have been in contact for some time.

Conclusions & recommendations

This document contains the results of work at NNC on Deliverable D38 of the HTR-E Project and reviews the potential tribological problem areas in the Pebble Bed Modular Reactor.

The main findings from the review are summarised in Table 1

The published information on this reactor design is very limited. There are little or no details available on components (Ref. 1 provides perhaps the main source of information) and no information on loading and tribology.

This review is a preliminary assessment based on the few references located and using NNC's experience in gas reactor operation and on the Dragon reactor. The conclusions reached should therefore only be taken as an indicator on where possible future investigation may be needed

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Table 1 Reactor Areas Considered

1.	Core (including supports and restraints)
2.	Reactivity control system (inc. control rods)
3.	Reserve shutdown system
4.	Reactor pressure vessel & conditioning system
5.	Low and high pressure turbo units (inc. supports, shafts)
6.	Power turbine & generator (inc. supports, shafts)
7.	Heat exchangers (inc. recuperator, pre-cooler & intercooler)
8.	Core conditioning system
9.	Helium inventory & control system plus bypass valves
10.	Start-up blower system

Table 2 Potential Problems

Component	Area	Temperature	Type of Motion	Possible Materials	Potential Problems
Helium Inventory Control System	valves compressors				static adhesion wear and leakage
Heat Exchangers	pre-cooler inter-cooler	<150°C	thermal movement vibration	carbon steel	fretting adhesive wear rubbing
Power Turbine	magnetic bearings braking system	700°C			
Recuperator	plate supports	500- 700°C		austenitic steel (type 347)	
Turbo Units (LP & HP)	bearings (electromagnetic. axial, capture)		sliding		high speed, long life fretting erosion due to dust
Reserve Shut Down System	storage container valve		sliding		static adhesion wear and leakage
Reactivity Control System (Control Rod)	drive mechanism	450 - 900°C	sliding motion	alloy 800 or similar	wear gear wear chain drive wear contact adhesion
Core	pebbles blocks bricks keys supports steel barrel	450 - 900°C	thermal movement sliding	graphite type 316 stainless steel	brick restraint brick movements thermal cycle wear cracking from keyed slots
Core Conditioning System	valves blowers service hatch heat exchanger	~150°C	sliding		static adhesion wear and leakage

Table 3 PBMR Cooling Systems Matrix

System	Sub-system	Active (Seawater) Heat Sink	Passive (Air)	Support Cooling Tower (Air)
Main Power System (MPS)	Pre-Intercooler	♦		
	Inter-Intercooler	♦		
	Generator	♦		
	Components	♦		
Reactor Pressure Vessel Conditioning System (RPVCS)		♦		♠
Core Conditioning System (CCS)		♦		♠
Fuel System	Fuel Handling (FH)	♦		
	Spent Fuel (SF)		♥	
Reactor Cavity			♥ ♥ ♥	
Helium Inventory Control System (HICS)		♦		
Air Compressors		♦		♠
Heating, Ventilation & Air Conditioning (HVAC)		♦		♠
Initial Cleanup System		♦		♠

Figure 1 Schematic of PBMR Power System

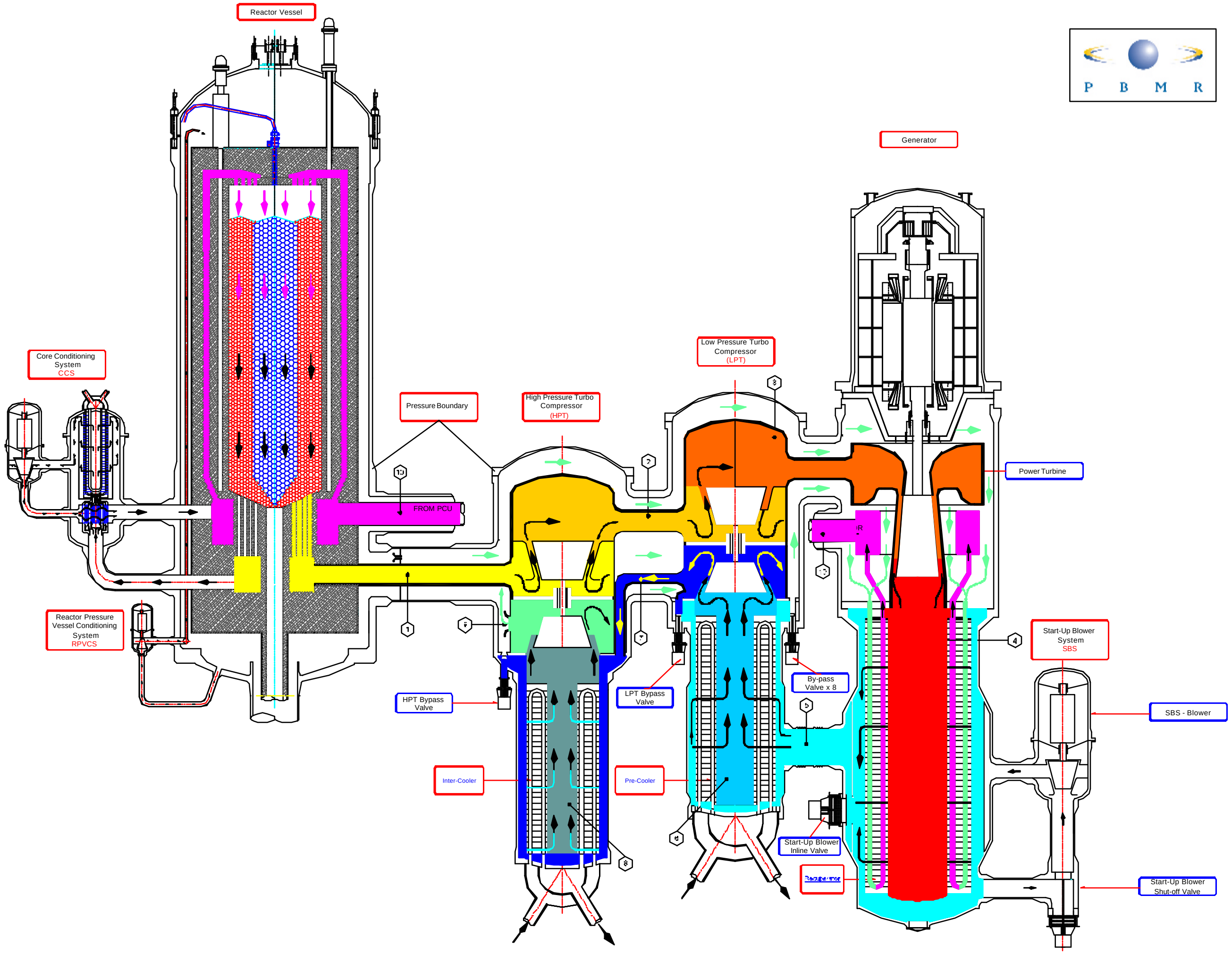

Figure 2 PBMR helium flow path schematic (Brayton cycle) (Ref. 15)

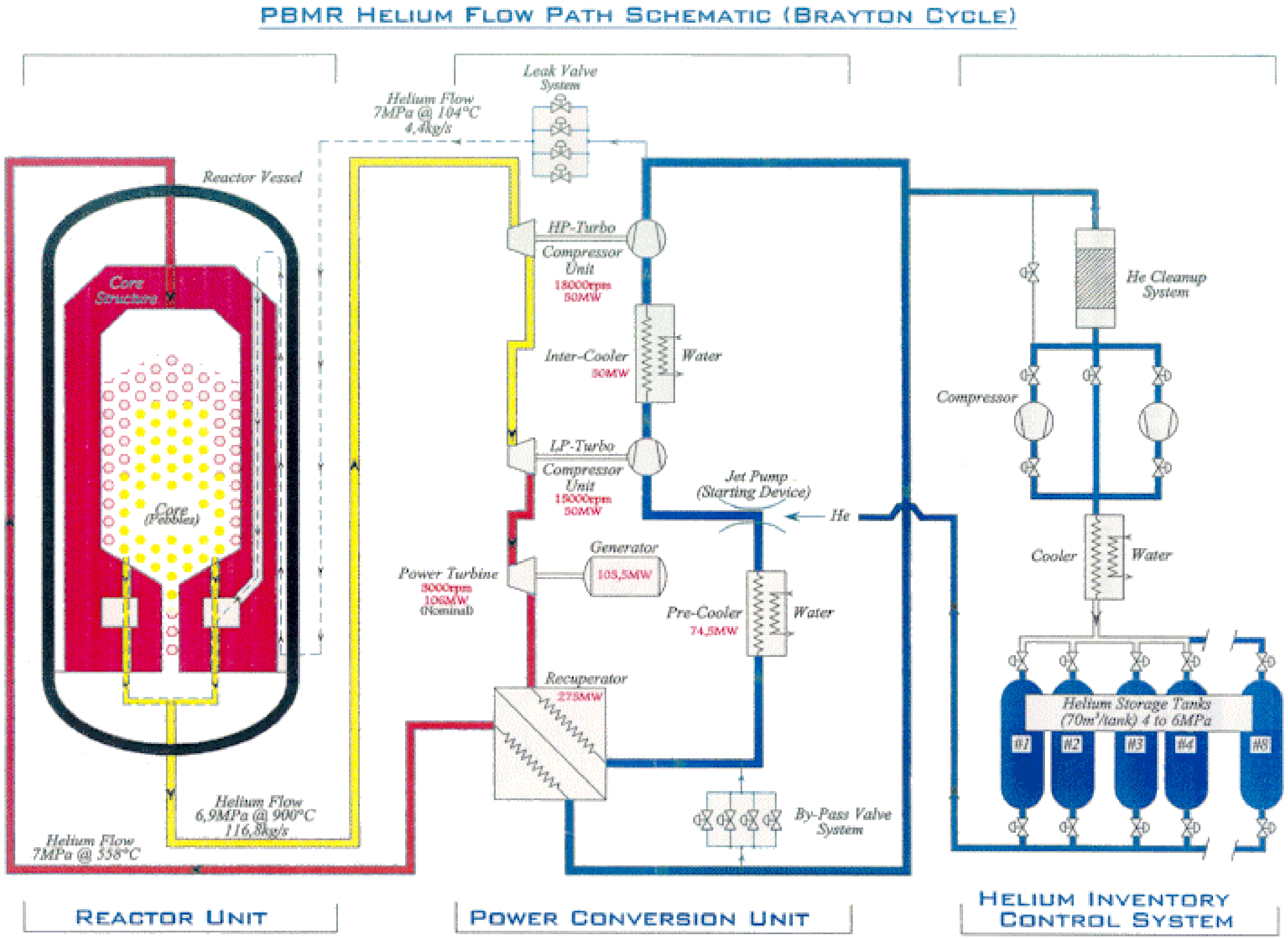

Figure 3 Reactor Layout (Ref. 1)

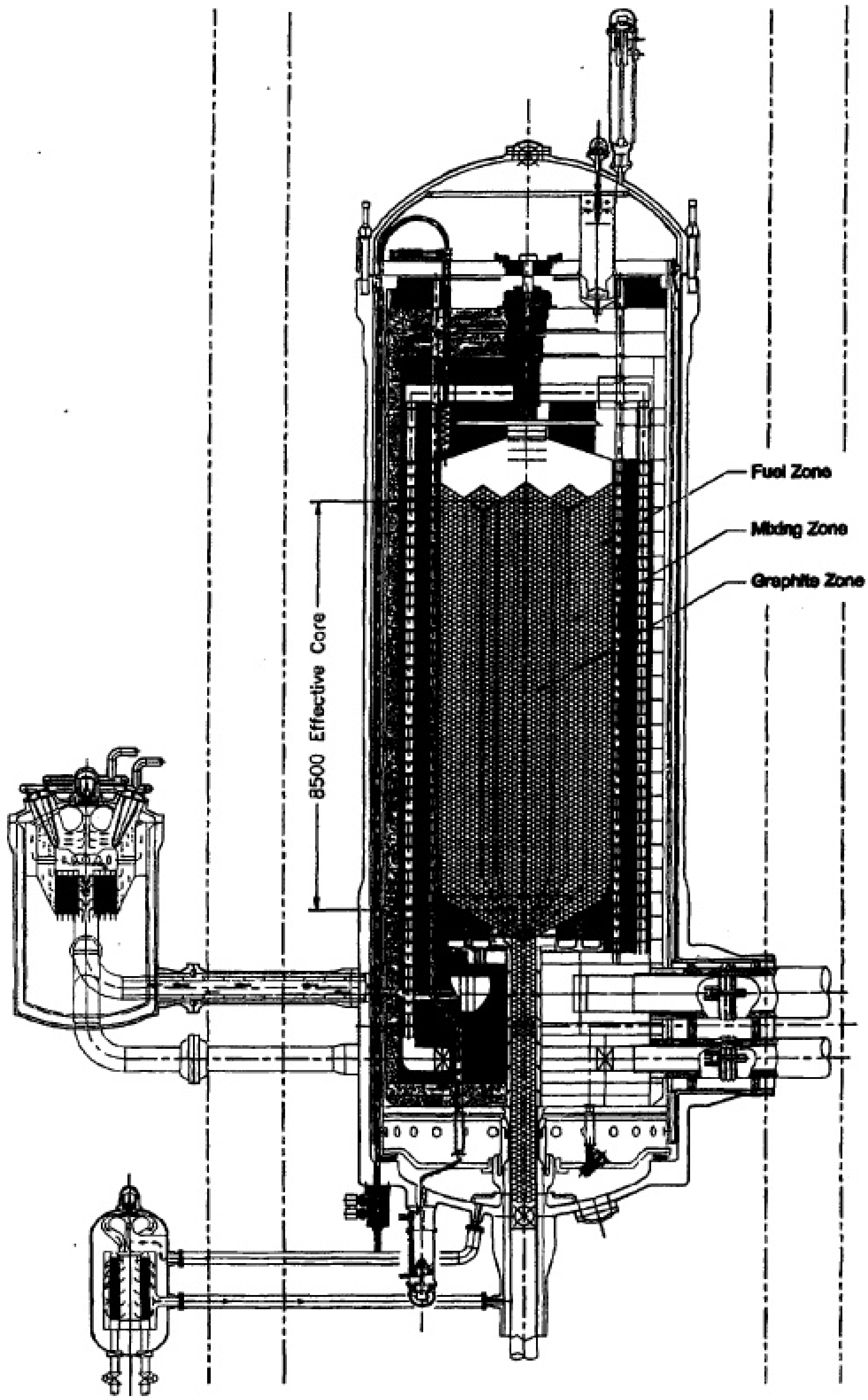

Figure 4 PBMR Reactor Arrangement (Ref. 14)

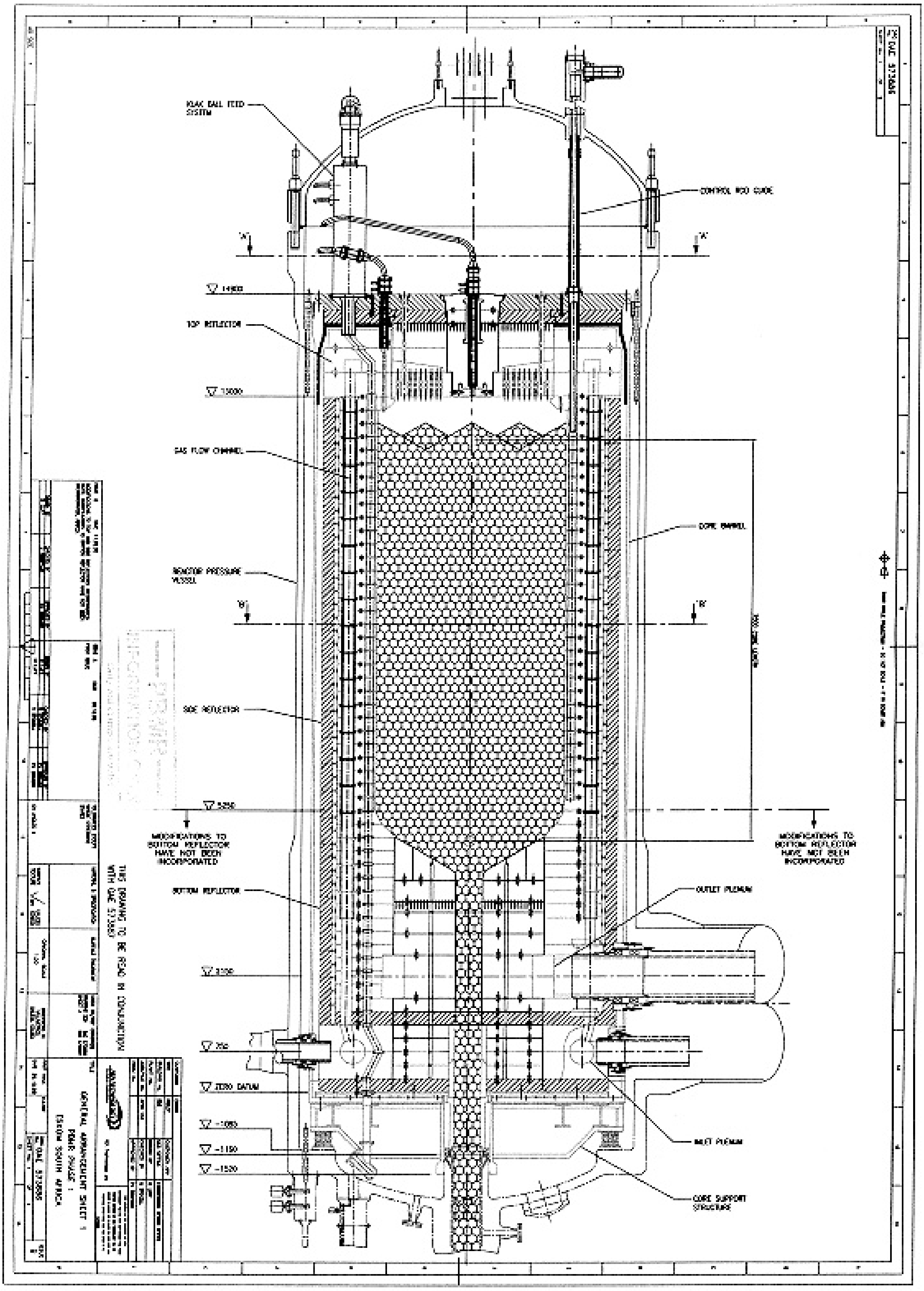

Figure 5 PCU Arrangement (Ref. 1)