THE PEBBLE BED MODULAR REACTOR (PBMR) AS A SOURCE OF HIGH QUALITY PROCESS HEAT FOR SUSTAINABLE OIL SANDS EXPANSION

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Abstract

Bitumen extraction, processing and upgrading consume large quantities of natural gas for production of steam, hot water and hydrogen. Massive expansion of bitumen production is planned in response to increasing energy demands, higher oil prices, and the desire for energy security. The Pebble Bed Modular Reactor ("PBMR") in its Process Heat configuration supports applications that are likely to compete in a cost effective and environmentally sustainable way with natural gas fired boilers for the production of steam for bitumen recovery. Technology development work to produce hydrogen using this nuclear technology is also underway. The PBMR has the benefit of size, passive nuclear safety characteristics (encompassing Generation IV safety principles), high reliability, high temperature process heat (750-950°C) in a modular design suited to the oil sands industry.

1. Introduction

Extraction of bitumen from the Oil Sands around the Athabasca River region in Alberta commenced in 1967 using surface mining techniques developed by Suncor, Syncrude, Petro-Canada and Shell amongst others. Processing surface mined bitumen requires low quality heat and power that can be supplied through conventional gas fired boiler and cogeneration units, to separate bitumen from the sandy substrate.

Surface mining techniques have been developed and refined to optimise the economics of the extraction process but the process is limited by the depth of the overburden that has to be removed to expose the bituminous sand layers and the deeper the deposit the more costly the resulting product.

Extraction of bitumen from the deeper deposits utilises the dominant Steam Assisted Gravity Drainage (SAGD) technique. This process injects high pressure steam into multiple wellheads, heating the underground oil sand reservoir and fluidising bitumen into horizontal collection pipes that have been drilled along the base of the reservoir. High pressure steam for the SAGD process is produced from natural gas fired boilers designed to work with recycled, chemically treated water from the oil separation process. Some high pressure steam is also produced by gas fired combustion turbine cogeneration units.

On a moderate growth expectation bitumen extraction is expected to increase to over 2 million barrels per day (bbl/day) by 2017[1], an almost threefold increase over 2000 production levels with proportional increases in gas consumption. Further increases in SAGD production are expected beyond the 2015 time frame, but these projects have yet to be announced.

Work carried out by Pebble Bed Modular Reactor (Pty) Ltd. (PBMRL), Shaw group and others has shown that deployment of some twenty $500MW_{(thermal)}$ PBMR reactors to support oil sands expansion would eliminate about 20m tonnes per year (TPY) of carbon dioxide (CO_2) emissions, supporting the Alberta targeted reduction in CO_2 emissions of 200m TPY by 2050. This work also shows that twenty $500MW_{(t)}$ PBMR reactors would thereby displace ~14 Quads[1] of natural gas over their anticipated 40-year operational life, greatly extending the remaining life of Canada's 58 Quads of natural gas reserves (as of 2006)[2].

PBMRL and Shaw Group have completed initial designs that adapt the existing PBMR configuration into a Process Heat Plant (PHP) as an "Advanced SAGD" nuclear steam supply system. This paper summarises that work.

2. Pebble Bed Modular Reactor

PBMRL is preparing to construct a Demonstration Power Plant (DPP) at the existing twin Light Water Reactor (LWR) site at Koeberg, South Africa, see Figure 1. A draft Safety Analysis Report has been submitted to the operator (Eskom) and they in turn have submitted a Revised Environmental Impact Assessment to the regulator. Critical test facilities have been constructed, full-scale tests of first-of-a-kind components are in progress and long lead items such as the Reactor Pressure Vessel (RPV) and graphite reactor internals are being fabricated.

Photo courtesy of Eskom

Figure 1, Koeberg Demonstration Power Plant Site

[1] Quadrillion British Thermal Units (Btu) roughly equivalent to One Trillion Cubic Feet (1Tcf)

The DPP is intended to demonstrate the linkage of the proven PBMR technology with a novel helium gas turbine being manufactured by Mitsubishi Heavy Industries (MHI) in a closed loop Brayton cycle, see Figure 2. The DPP is designed to generate 165MW$_{(electrical)}$ with load following capability and will represent a leap forward in safety, simplicity and modularity. The project is staffed by 700 full time employees supported by an international supply team consisting of some 1700 staff. Many first-of-fleet components have progressed to the detailed design phase and long lead equipment fabrication is underway.

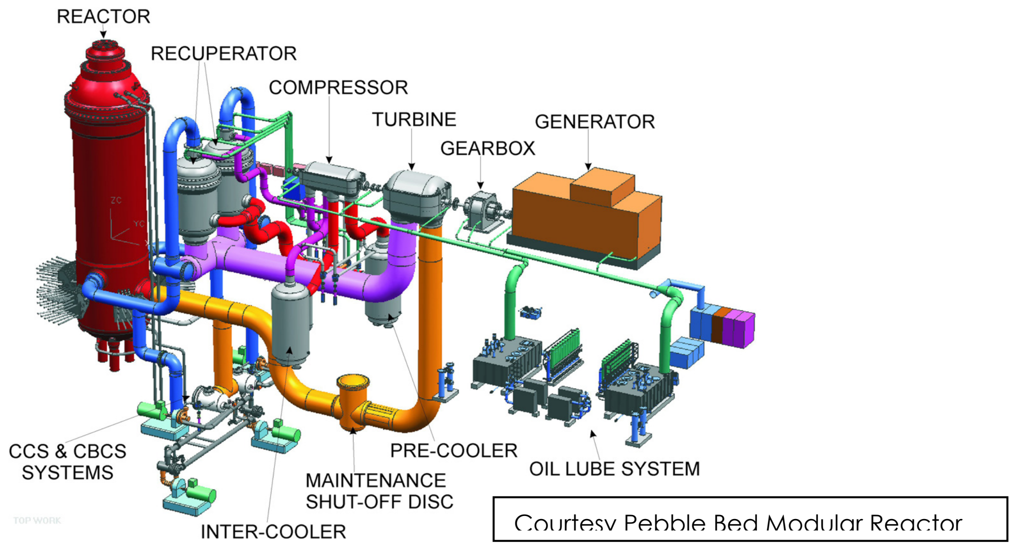
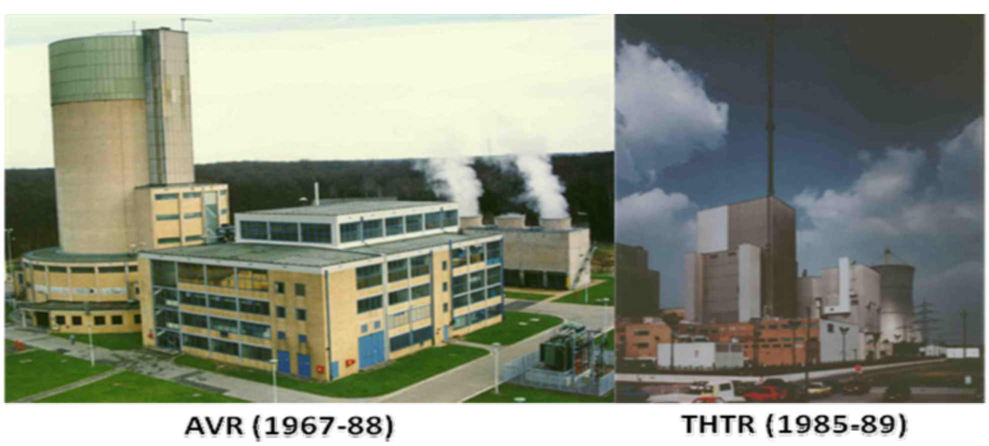


Figure 2, PBMR Full Scale Demonstration of the Brayton Cycle

The PBMR builds on three decades of German experience including a prototype and a full scale demonstration plant, see Figure 3. The operational and design experience gained from these plants have been embedded into the DPP reactor design such that the limiting nuclear licensing design basis events have no significant health or environmental impacts either on or off-site. The combination of reactor and fuel design means that water reactor type meltdown events are not possible.



AVR (1967-88) **THTR (1985-89)**

Figure 3, German Pebble Bed Reactors

3. SAGD Technical Requirements

Typical SAGD expansions are currently producing ~30k bbl/day of bitumen and the oil sands industry is looking towards increasing this incrementally as experience is gained with larger natural gas fired steam generators and gas turbine cogeneration. High pressure saturated steam in excess of 8MPa is required for distribution through steam manifolds to multiple wellheads. Each wellhead comprises a pair with the horizontal steam injection pipe above the bitumen collection pipe, see Figure 4

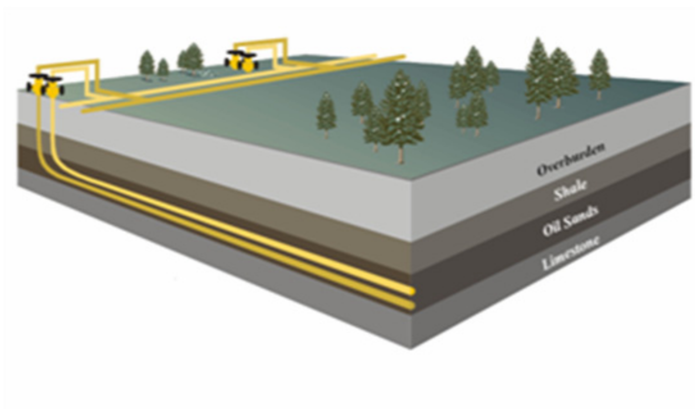


Figure 4, Steam Distribution Manifold and Well Pairs

The steam is controlled to meet the individual operational requirements of each well and is injected over 70m underground into a horizontal pipe where it fluidises the bitumen contained in the bituminous sand layer. The resulting water/oil mixture is collected in the return pipe before being pumped out for bitumen separation, water recovery and treatment.

A reliable steam supply is needed to optimize bitumen production, lifetime well performance, and economic utilization of upgrading and downstream refinery facilities.

Implementing a capital intensive nuclear steam supply option is likely to change how current SAGD systems are optimised to maximise overall investment value.

4. Standard Process Heat Plant

PBMRL is working to modify its existing 400 $MW_{(thermal)}$ 900°C reactor outlet design to a lower temperature (~750°C) $500MW_{(thermal)}$ rating for a simplified Process Heat Plant (PHP). The PHP design builds on the extensive engineering, safety analysis, and vendor equipment engineering work to minimise additional first-of-a-kind engineering needed for the "Advanced SAGD" steam supply system. While the South African DPP relies on "state-of-the-art" materials and new components, the lower temperature PHP design can use conventional materials and components with an operational track record.

An intermediate loop is included to isolate the boiler and associated equipment from the primary circuit facilitating conventional inspection and maintenance techniques. With a helium secondary heat transport system (SHTS) each "Advanced SAGD" reactor will supply 520MW$_{(thermal)}$ at ~720ºC to the steam generators. Figure 5 illustrates a possible arrangement for such a configuration.

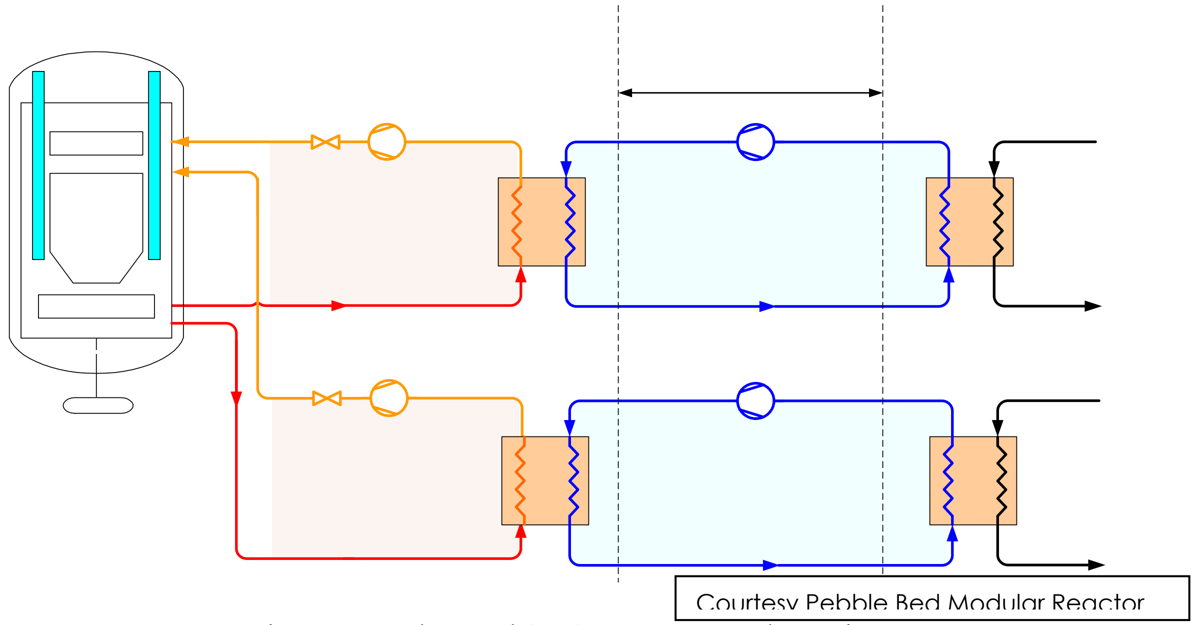


Figure 5, "Advanced SAGD" Process schematic

The steam generators are intended to utilize conventional heat exchanger designs in transportable modules, allowing reliable operation and minimum maintenance requirements, see Figure 6. Various steam generator configurations are being considered to facilitate maintenance opportunities in line with current boiler designs and operational best practice in the oil sands industry. The steam generators are located as close as practicable to the nuclear reactor to minimize high temperature/pressure piping, with plant laydown area provision for periodic inspection and maintenance.

REACTOR UNIT

Inlet

Core

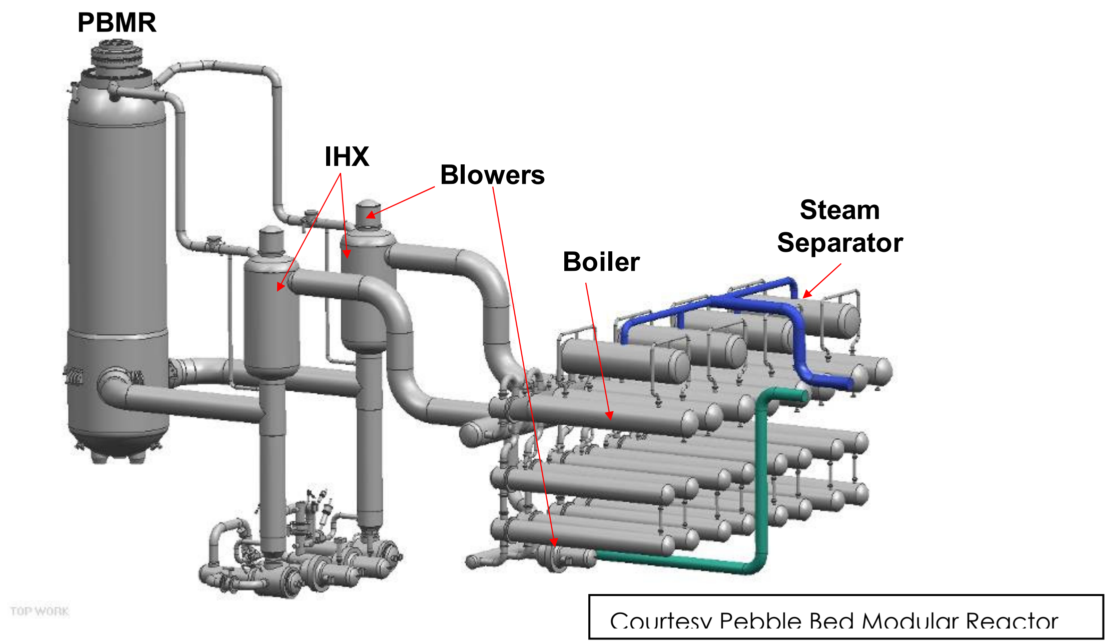


Figure 6, "Advanced SAGD" Plant arrangement

Recent examination of the requirements for surface mining steam supply and power needs suggest that a nuclear cogeneration configuration can produce approximately the power and lower quality steam needed for a major expansion, as shown in Figure 7. It is estimated that such a single unit 500MW$_{(thermal)}$ plant could support a 100k bbl/day surface mining production expansion or retrofit.

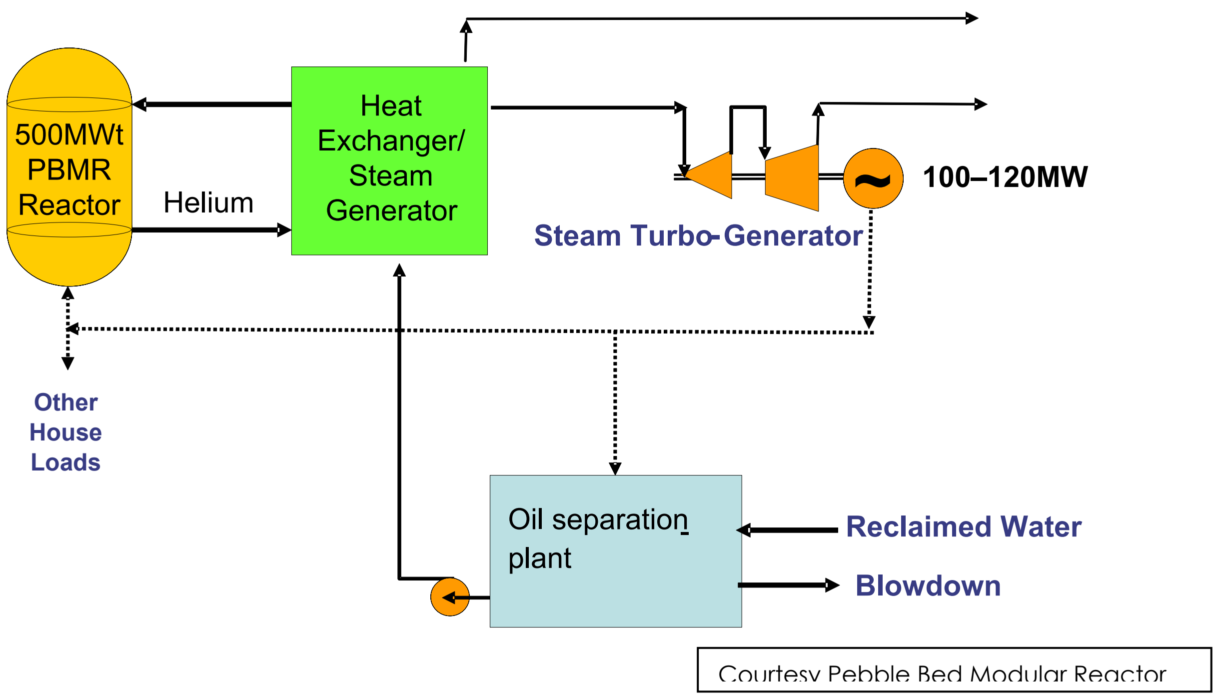


Figure 7, "Nuclear cogeneration" surface mining concept

5. "Advanced SAGD" plant performance

The "Advanced SAGD" unit is designed for 20 years operation with the option to extend life to 40 years upon completion of planned reactor internals replacement outage at approximately 25 years full power life.

Nominal steam production from a single "Advanced SAGD" unit at steady state full feed flow conditions with all steam generators in service will be ~260 kg/s of up to 11MPa saturated steam for delivery to the steam distribution system. The calendar day equivalent (CDE) steam production allowing for planned outages, boiler maintenance and unplanned outages will be 130k bbl/day.

The steam generator arrangement provides flexibility with a significant turndown ratio allowing matching of steam production to upgrader/refinery performance. The cooling and depressurisation time of the SHTS loops during maintenance has been included in the maintenance outages.

Current SAGD installations optimize water utilization by balancing water treatment costs against boiler operation and maintenance cycles. The steam generators and water treatment processes will be designed to maximise overall process performance and reliability.

The "Advanced SAGD" plant uses a continuous on-line nuclear refuelling process, therefore scheduled outages for fuel loading are not required and the plant can be expected to operate continuously for about six years between scheduled maintenance of the reactor systems. Such maintenance outages will be coordinated with the planned maintenance outages of the oil processing system to optimise overall plant availability. The duration of the planned maintenance outage is anticipated to be of the order of 20 days and would be staggered in a multi-unit version.

A two-unit version of the "Advanced SAGD" plant, see Figure 8 supports a larger scale steam production and provides substantial capital cost benefits from shared facilities. Two units should eliminate the need for other steam sources because the output from one of the two units should be sufficient to maintain well steam supply operational requirements during planned and unplanned outages.

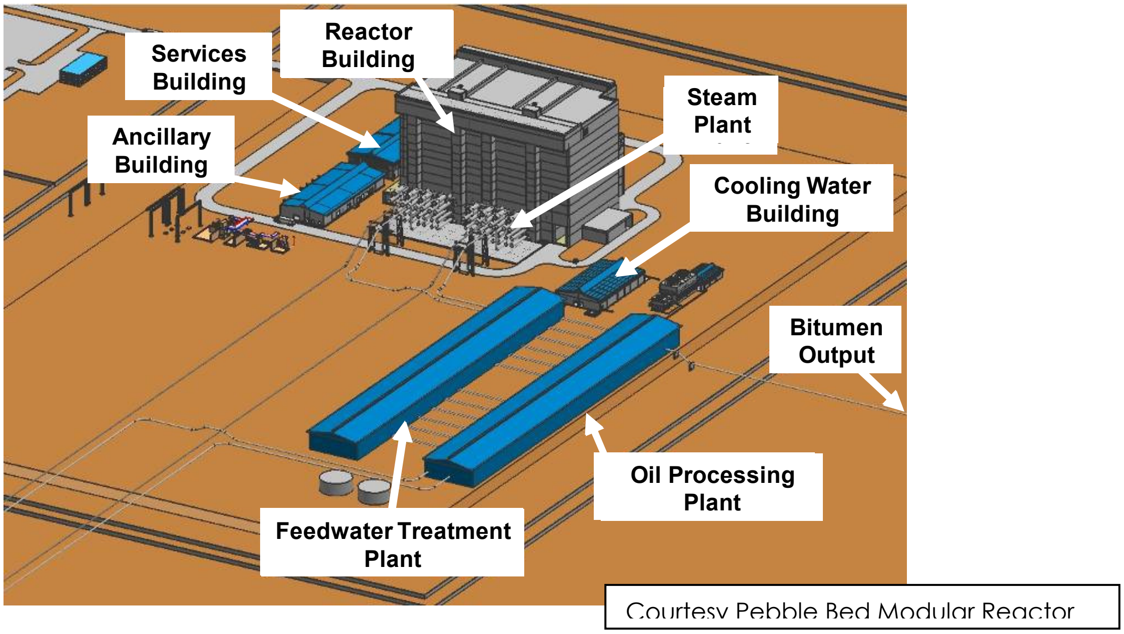


Figure 8, Twin-unit "Advanced SAGD" plant arrangement

6. "Advanced SAGD" Safety features

In most power reactors, safety objectives are achieved by means of custom-engineered, active safety systems. In contrast, the PBMR design has inherently safe features based primarily on the design of the fuel, the physics and geometry of the reactor design. This means that should the limiting nuclear licensing basis event occur no human intervention would be required in the short or medium term.

Post-event consequences of nuclear accidents are principally driven by the ability to shut down the nuclear chain reaction and thereafter by the residual power generated by the fuel after the chain reaction has stopped. This residual power (decay heat) is caused by radioactive decay of fission products. If this decay heat is not removed, it will heat up the nuclear fuel until its fission product retention capability is degraded and its radioactivity is released. In 'conventional' reactors, the heat removal is achieved by active cooling systems (e.g. pumps), which rely on the presence of the heat transfer fluid (e.g. water). Because of the potential for failure in these systems, they are often replicated to provide redundancy. Other systems, such as a containment building, are provided to mitigate the consequences of failure of such systems and to act as a further barrier to radioactive release.

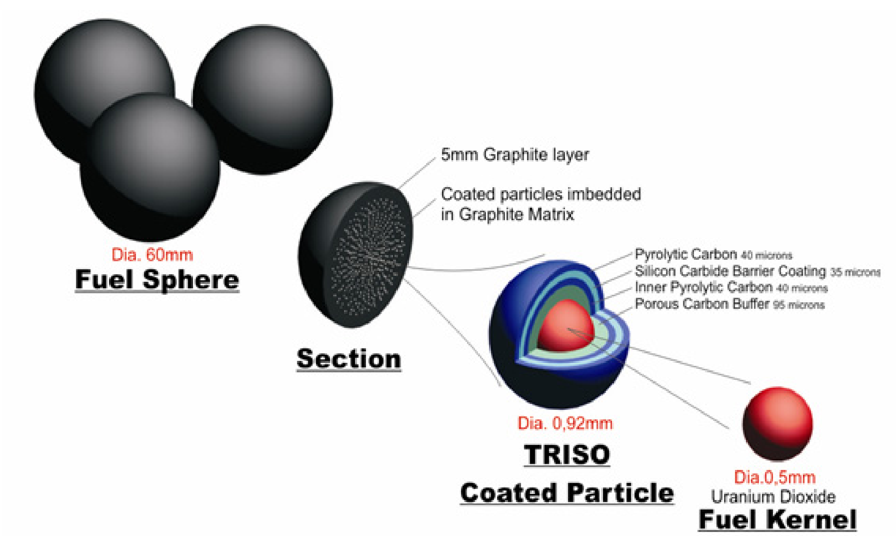
In the PBMR, the removal of the decay heat is independent of the reactor coolant conditions. The combination of the very low power density of the core (one-twentieth of the power density of a Pressurised Water Reactor), and the resistance to high temperature of fuel in billions of independent particles, underpins the superior safety characteristics of this type of reactor. The peak temperature that can be reached in the core of the reactor is below the temperature that may cause damage to the fuel. This is because the fission product radionuclides are contained by two layers of pyrocarbon and a layer of silicon carbide that are extremely tolerant of high temperatures.

Even if there is a failure of the active systems that are designed to shut down the nuclear reaction and remove core decay heat, the reactor will inherently shut down and eventually cool down naturally. Unlike the Chernobyl type of reactor, which during the accident produced more energy the hotter it became (known as ‘a positive temperature coefficient of reactivity’), the pebble bed reactor has a strong negative temperature coefficient of reactivity, which stops the nuclear reaction.

The size and form of the PBMR core ensure a high surface area to volume ratio. This means that the high heat capacity of the core and core structures, together with the heat loss characteristics of the core and the characteristics of the heat generated by the decay of fission products in the core, will limit the fuel temperature to below that value at which significant degradation of the activity retention capability can occur. Analysis shows that the progression of the fuel temperature as a function of time after a depressurized loss of forced cooling event is such that the maximum temperature will remain below that which will result in damage to the fuel. This inherently safe design of the PBMR renders obsolete the need for the typical safety backup systems and most aspects of the off-site emergency plans required for the more conventional water cooled nuclear reactors.

7. Nuclear Fuel

The intended PBMR fuel is based on a proven, high-quality German fuel design consisting of low enriched uranium triple-coated isotropic (LEU-TRISO) particles contained in a moulded graphite sphere, see Figure 9.



Courtesy Pebble Bed Modular Reactor

Figure 9, PBMR Fuel Element design

The spherical (60mm diameter) fuel sphere is cold pressed from matrix graphite, which is a mixture of natural graphite, electrographite, and a phenolic resin that acts as binder. It consists of an inner region that contains fuel in the form of spherical coated particles embedded in the matrix graphite. A shell of matrix graphite that does not contain any fuel surrounds the inner region.

A coated particle consists of a spherical uranium dioxide kernel surrounded by four concentric coating layers. The first layer surrounding the kernel is a porous pyrocarbon layer, known as the buffer layer. An inner high-density pyrocarbon layer, a silicon carbide layer, and an outer high-density pyrocarbon layer follow this layer. The layers are deposited sequentially by dissociation of gaseous chemical compounds in a continuous process in a fluidized bed.

The integrity of the fuel manufacturing process is of utmost importance to the PBMR design. The TRISO particles are the primary fission product barrier and the bases of all the safety cases. The fuel has a proven design and the operational parameters of the fuel need to be respected by the reactor under all conditions.

Analysis indicates that the $500MW_{(thermal)}$ “Advanced SAGD” concept does not exceed any of the critical proven fuel parameters intended for the $400MW_{(thermal)}$ DPP as follows:

- Discharge burn-up
- Fast-Fluence dose
- Power density

In addition, the selected operating temperature combined with the reactor thermal power results in a fuel temperature of below 1800°C (the PBMR Fuel Qualification Limit) for the depressurized loss of forced cooling event (limiting nuclear licensing basis event).

8. Economics

The economic viability of the “Advanced SAGD” plant will be determined by its costs of construction and operation relative to conventional methods. The present value of displaced gas and CO_2 for a $500MW_{(thermal)}$ heat source exceeds $1.5-2B[3] as gas prices increase subject to various economic assumptions. Current estimates indicate that a plant can be built and operated within this value proposition. Considerable work still needs to be done to complete the design of a fully modularized plant that requires minimum field construction costs, since recent construction projects in the oil sands business have seen considerable volatility and risk[4].

Economic analysis suggests that deployment of a series of $500MW_{(thermal)}$ “Advanced SAGD” nuclear steam supply systems may compete with conventional gas fired steam production based on US$7-8/million Btu (MMBtu) natural gas escalating at 2% per year[5]. The relative economics of cogeneration options will depend on the cost of power available from other sources.

9. Conclusions

Adaptation of proven pebble bed reactor, combined with the replication of an already qualified fuel design presents a low technical risk opportunity to apply this technology to displace natural gas consumption in the oil sands.

The down rating of the high temperature capability of the generic PBMR design concept for duty in the oils sands significantly simplifies the design and material considerations and enables a wealth of existing international operational and engineering experience[2] to be used in support of the necessary licensing and investment decisions.

The paramount concern in Alberta about potential bitumen resource contamination from a nuclear accident is not relevant to an "Advanced SAGD" type reactor with the passive heat removal and inherent reactor safety principles being proposed in the design.

The "Advanced SAGD" steam supply system has the key attributes of size, performance, safety and reliability that are well suited to SAGD new or incremental development and surface mining expansions. Ongoing work toward a design based on modular construction is expected to resolve the risks associated with a capital-intensive project in areas where construction costs are difficult to predict and heavy equipment delivery options are limited.

Moving from natural gas firing to an "Advanced SAGD" nuclear steam supply systems requires a radical shift in risk management variables from potentially volatile and unpredictable future natural gas pricing to a capital intensive business model where plant availability, asset management and remnant life are critical. However, the prospect of SAGD expansion with a nuclear option that eliminates reliance on gas and eliminates CO_2 emissions provides an important new option for the oil sands industry that is confronted with the prospect of expensive CO_2 capture and sequestration, and the risk that gas prices will rise dramatically as demand increases and supplies decline.

Deploying a number of nuclear reactors in this service provides a strategic option to shift from gas dependency and vulnerability to expensive CO_2 control options. Ongoing life cycle analyses of energy options for the oil sands industry will compare a number of nuclear options and provide additional insights to this opportunity

10. References

[1] R.B. (Bob) Dunbar, Melanie Stogran, Pauline Chan, and Kok-sum (Sam) Chan, "Oil Sands Supply Outlook: Potential Supply and Costs of Crude Bitumen and Synthetic Crude Oil in Canada 2003-2017", Canadian Energy Research Institute Study 108, March 2004.

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[2] e.g US and UK HTGR and AGR operating history

[2] Canadian Association of Petroleum Producers, Industry Facts and Information Natural Gas Reserves at 2006 year end

[3] Kuhr R., Wallace E., Kriel W., Greyvenstein R., "PBMR Update and Status on Process Heat Applications", Proceedings of ASME Power 2007, POWER 2007-22054.

[4] Kuhr R., "Planning a Nuclear Oil Sands Project," Energy Frontiers International Conference February 25-27, 2008, Miami, Florida

[5] Kuhr R., Morris A., McKinnell J., "Nuclear Steam and Power for Oil Sands Applications", Canadian Institute's 6th Annual Oil Sands Conference, November 27, 2007, Calgary Canada