Canadian Energy Research Institute

Green Bitumen: The Role of Nuclear, Gasification, and CCS in Alberta's Oil Sands

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LOW GHG OPTIONS TO FUEL THE OIL SANDS
PART IV – ALTERNATIVE FUELS FOR OIL SANDS DEVELOPMENT BEYOND 2020

Green Bitumen: The Role of Nuclear, Gasification and CCS in Alberta's Oil Sands
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TABLE OF CONTENTS

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LIST OF FIGURES

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CHAPTER 1
INTRODUCTION

The previous parts of this study looked at the issue of coal gasification and nuclear power as alternatives that currently exist. They are by no means the only options that could be used, especially as we look beyond 2030 and into the future. The purpose of this part of the study is to provide a very brief overview of some of the options that could be considered and have been widely talked about by industry. Due to the lack of public data available, it would be extremely difficult to provide a detailed supply cost assessment for each option, in addition to understanding the full extent of greenhouse gas (GHG) reductions that are possible. This Part of the study will be restricted to a selection of options to reduce or eliminate the consumption of natural gas, excluding efficiency improvements.[1]

The report is organized as follows:

- Chapter 2 Thermal Recovery
- Chapter 3 Nuclear Energy
- Chapter 4 Conclusion

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[1] This means that potential changes in the truck and shovels being used are not considered, in addition to other minor improvements in areas (such as pumps on tailing ponds) that individually could have a limited impact on emissions, relative to the point source emissions and reductions options available for consideration.

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CHAPTER 2
THERMAL RECOVERY

2.1 Overview

In general, the heavy, viscous nature of the bitumen means that it will not flow under normal reservoir temperature and pressure conditions. Numerous in situ technologies have been developed that apply thermal energy to heat the bitumen and reduce its viscosity thereby allowing it to flow to the well bore.

The most common thermal techniques involve steam injection into the oil sands deposit using either cyclic steam stimulation (CSS) or steam-assisted gravity drainage (SAGD) recovery technology. These techniques are being used today in almost all commercial thermal in situ projects. There are some alternatives/enhancements that are being considered.

2.2 Toe-to-Heal-Air-Injection (THAI)

THAI is a new thermal recovery process proposed for the recovery of oil sands using in situ combustion.[2] THAI combines vertical air injection wells with horizontal production wells. During this process, a combustion front is created where heavy bitumen residues left on the sand grains during the production process are burned in the reservoir. This generates heat, which reduces the viscosity of bitumen, enabling it to flow, by gravity, to horizontal production wells. The combustion front sweeps the bitumen from the toe to the heel of the horizontal producing well efficiently recovering an estimated 80 percent of the bitumen in place, while partially upgrading the bitumen in situ.

Whitesands Insitu Ltd. (a wholly owned subsidiary of Petrobank Energy and Resources Ltd.) is carrying out the world's first field pilot test of this technology at its Whitesands Project located at Christina Lake. The project, which was approved by the AEUB in 2004, consists of three horizontal wells (500 metres long and 100 metres apart), three vertical air injection wells, and 19 vertical observation wells (17 for temperature and 2 for pressure observations). Positive results from the Whitesands Project has motivated the company to move to the commercial development stage with the multi-phase May River Project. Ultimate production capacity is anticipated to be 100,000 b/d.

In a supplemental information package provided to the Alberta Energy and Utilities Board (AEUB) and Alberta Environment (AENV), results from an analysis of produced fluids from 3-D cell tests were reported.[3] Oil produced using the THAI technology had an API gravity of 20.63 degrees, compared to 10.1 degrees for crude oil produced using SAGD, and a density level of 930.1 kg/m3 compared to 999 kg/m3. Additionally, the oil produced with THAI technology had much lower

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[2] THAI technology was developed by Dr. Malcolm Greaves from the University of Bath and Dr. Alex Turta from the Petroleum Recovery Institute/Alberta Research Council.

[3] The test was conducted by Dr. T. Xia at University of Bath, July 4, 2003, using Wolf Lake Bitumen.

viscosity at 20^{0}C (33 cST compared to 80,000 cST), and relatively lower levels of carbon, nitrogen, sulphur, iron, nickel, vanadium, molybdenum, saturates, resins, and asphaltenes.[4]

The horizontal and vertical wells are steamed to facilitate air injection and bitumen flow. A combustion zone, with temperatures ranging between 400^{0}C and 700^{0}C, is created when the air injected ignites the oil.[5] The hot combustion gases coming into contact with the bitumen will cause thermal cracking and upgrading of the bitumen. The lighter oil at the combustion front and vaporized reservoir water flow into the horizontal wells while the coke remains underground and functions as a fuel source for further combustion as the combustion process moves through the formation.

Other potential benefits of THAI technology include minimal natural gas and fresh water usage, partially upgraded oil quality (high-temperature oxidization of coke is left underground), lower capital and operating costs, 50 percent less GHG emissions[6], reduced diluent requirement for transportation, and the potential to operate in lower pressure, lower quality, thinner and deeper oil sands reservoirs than current steam-based methods.[7]

2.3 Solvent-Based Recovery Processes - VAPEX

VAPEX is a recovery technique that uses gaseous solvents to increase bitumen recovery by reducing its viscosity. Vaporized hydrocarbon solvents are injected into the oil sands reservoir. The solvent mixes with the bitumen, reduces its viscosity, and causes it to drain by gravity to a horizontal production well.

Since VAPEX is a non-thermal method, it has the potential to reduce CO_2 and other greenhouse gas emissions substantially – estimated to be as much as 85 percent over thermal processes.[8] Other driving forces for VAPEX include potential for dramatically reduced water consumption compared to other extraction technologies, and related lower water-handling and surface facility costs. The technology also has significant potential economic advantages because it can be used to recover bitumen from zones that are considered too thin for traditional thermal recovery methods, and offers the potential for an upgraded and higher-value product by promoting in situ upgrading. Paraffinic solvents cause asphaltenes to be precipitated and left behind in the reservoir (i.e., partial upgrading occurs).

Like SAGD technology, the VAPEX process uses horizontal well pairs to recover the bitumen. However, the process uses a hydrocarbon solvent instead of steam. This eliminates the need to

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[4] Orion Oil Canada Ltd., WHITESANDS Project Supplemental Information Requests and Responses, January 2004. http://www.petrobank.com/webdocs/whitesands/whitesands_eub_response.pdf

[5] Results from early combustion operations, released in September 2006, showed that combustion zone temperatures reached a peak of over 700^{0}C. http://www.petrobank.com/webdocs/news_2006/2006_09_12_WHITESANDS_Update.pdf

[6] This reduced amount of GHG's should be taken as an estimate that hasn't been rigorously or independently verified and may reflect an expectation and not a reality.

[7] Ibid.

[8] However, as is the case with many alternatives, the GHG reductions will only be realized if the technique can be proven and deployed commercially for oil sands operators to use.

burn fuel (usually natural gas) to create the steam, resulting in reduced GHG emissions. In addition, the solvent in the VAPEX process can be reused. With the VAPEX process, vaporized solvents are injected into the reservoir via an upper horizontal well. The bitumen in the reservoir is diluted with the solvent, which reduces its viscosity and allows the bitumen-solvent mixture to drain by gravity to the production well. On the surface, the solvents are separated from the produced bitumen and recycled.

Research carried out thus far suggests that up to 90 percent of the solvent used can be recovered and recycled, offering the potential for dramatic cost savings over other extraction methods. Results have also shown the quality of produced bitumen to be superior because some of the heavier fractions are left in the ground.

2.4 Hybrid Thermal/Solvent Recovery Processes

Most of the hybrid thermal coupled with a solvent recovery processes are based upon the belief that oil recovery could be increased by over 68 percent (of current levels) while simultaneously reducing water and energy consumption (by 45 percent). This would imply reduced emissions by the project by an amount equal to the reduction in energy consumption. Unfortunately, there is little public information pertaining to the estimated costs associated with hybrid processes.

2.4.1 Steam Assisted Gas Push (SAGP)

SAGP is a variation of the SAGD process involving the addition of a small amount of non-condensable gas such as natural gas or flue gas with the injected steam. Through improved energy efficiencies, the SAGP process presents opportunities for reducing steam consumption by up to 70 percent compared to SAGD.

2.4.2 Hybrid Steam-Solvent Processes

The Alberta Research Council (ARC) is undertaking research into a number of hybrid steam-solvent processes combining SAGD technology with different solvent injection strategies. The new processes are aimed primarily at improving recovery and energy efficiency, and reducing water requirements. These enhanced thermal processes include Expanding-Solvent SAGD (ES-SAGD), Low-Pressure Solvent SAGD, and Tapered Steam Solvent SAGD (TSS-SAGD). Research is also under way on characterizing asphaltene behaviour with the objective of controlling and exploiting asphaltene precipitation.

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CHAPTER 3
NUCLEAR ENERGY

3.1 Pebble Bed Modular Reactor

Located in South Africa, the Pebble Bed Modular Reactor (PBMR) Ltd. has been developing a small scale, helium-cooled, graphite-moderated high temperature pebble bed nuclear reactor. Eskom (South Africa's state-owned utility), Westinghouse from the U.S., Mitsubishi Heavy Industries of Japan, and Nukem of Germany have all contributed during the development phase, and recently the U.S. Department of Energy awarded PBMR Ltd. with a $3 million engineering contract for the Next Generation Nuclear Plant.[9] The PBMR is a 4th generation nuclear reactor that can generate a maximum of 165 MWe per module, and will operate at 41 percent efficiency. Construction of a pilot project is expected to start in 2009, with electrical production projected to begin in 2013.[10] These dates are likely highly optimistic for a first of a kind unit. Commercial deployment of the reactor could take several years after a successful pilot project has been proven.

The PBMR essentially comprises of a steel pressure vessel connected to a turbine on a horizontal drive shaft. Each module will cover an area of 4,320m^2 and the main building will have a height of 66 meters, of which 23 meters will be bellow ground. The pressure vessel which houses the reactor is 6.2 meters in diameter and about 27 meters high and will be lined with 1 meter thick graphite bricks. These bricks are drilled with vertical holes to house the control elements, and will act as both an outer reflector as well as a way to passively transfer heat away from the reactor. The fuel core is located in the space between the centrally located reflector column and the outer reflector.[11]

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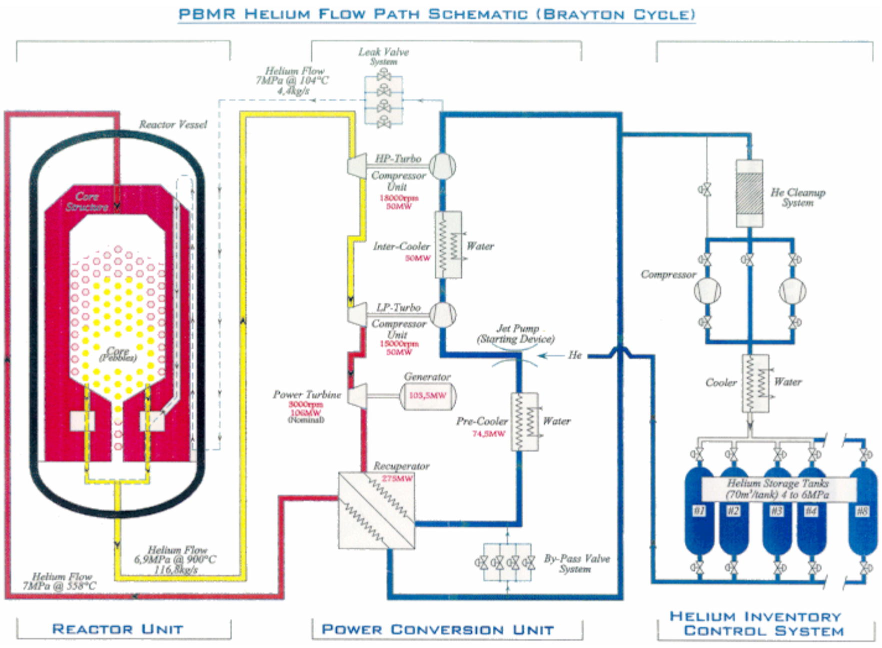
[9] *Pebbles Making Waves*, Lee S. Langston, Mechanical Engineering, February 2008. http://www.memagazine.org/contents/current/features/pebbles/pebbles.html

[10] *Nuclear Power in South Africa*, World Nuclear Association, June 2008. http://www.world-nuclear.org/info/inf88.html?terms=PBMR

[11] Pebble Bed Modular Reactor Limited. https://www.pbmr.com/

Figure 3.1
PBMR Schematic[12]



For fuel, the PBMR will use low enriched uranium triple coated isotropic (LEU-TRISO) particles which will be contained in a moulded graphite sphere. Each pebble is 60mm wide and weighs 210 grams, of which 9 grams is uranium. It will take roughly 6 months for each pebble to pass through the reactor core, and each pebble will contain enough fuel for 6 passes (or 3 years) before it will be depleted of usable fissile material. The fuel is to be manufactured near Pretoria, South Africa, with an initial yearly production capacity of 270,000 fuel pebbles.

Running at full capacity, the PBMR will use approximately 450,000 pebbles at a time, and generate 32 tons of spent fuel pebbles per year. During PBMR's 40 year projected lifespan, it will consume a total of 15 full fuel loads. Since fuel pebbles are individually taken out of the system, new fuel can be introduced at the same rate, resulting in a continuous fuelling process.[13]

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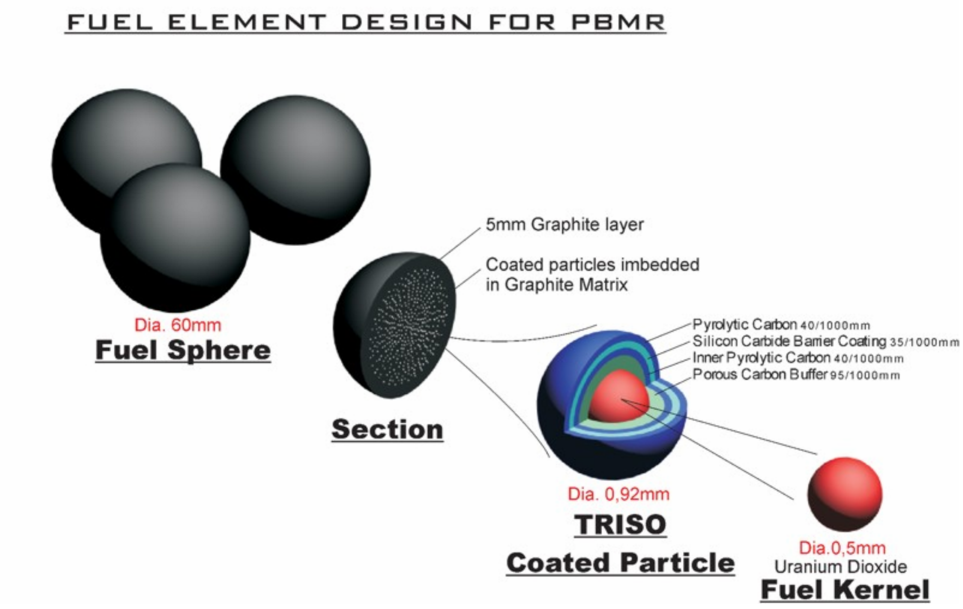
[12] Pebble Bed Reactor Technology, Eskom. http://www.eskom.co.za/nuclear_energy/pebble_bed/pebble_bed.html

[13] https://www.pbmr.com/index.asp?Content=216 and Pebble Bed Reactor Technology, Eskom . http://www.eskom.co.za/nuclear_energy/pebble_bed/pebble_bed.html

Figure 3.2
Fuel Design for the PBMR[14]



Fuel pebbles will enter the reactor vessel from the top, where gravity will slowly pull them down through the annular packed bed where they exit the reactor vessel through the defueling chute. The pebbles are then analyzed, and if containing enough fuel are sent pneumatically back to the top of the reactor vessel for re-insertion into the reactor. Used up pebbles are instead routed to one of the 10 on site spent fuel storage tanks (total spent fuel capacity: 6,000,000 pebbles).[15]

Helium is used to remove heat from the reactor vessel and exits the reactor at 1,652 °F where it enters into the turbine which drives the 165 MW generator. From here the helium transfers some of its heat by going through a recuperator before entering a pre-cooler and low-pressure compressor. It then moves on to an intercooler and high compressor where it is brought up to 1,300psi and completes a Brayton cycle. The last step for the helium is to pick up some heat from the recuperator before re-entering the reactor vessel at 932° F.[16]

The PBMR has the capability to load follow by bleeding helium from the closed coolant system. This reduces the mass flow of helium, thereby lowering the power output despite gas velocity, turbine rpm and efficiency levels remaining constant. This load flexibility is fast reacting, and one independent estimate calls for the PBMR to operate anywhere between 40-100 percent of total

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[14] https://www.pbmr.com/
[15] *Pebbles Making Waves*, Langston, Mechanical Engineering, February 2008.
[16] *Pebbles Making Waves*, Langston, 2008.

load.[17] The ability to quickly follow the load being placed on the reactor is common with smaller nuclear energy facilities.

There are 2 active safety features in the design of the PBMR. The first is the control rods which can be inserted through holes drilled into the outer reflector wall. The second is "absorber spheres" which are inserted into the reactor through the central reflector. In addition to these 2 active safety systems, the PBMR has passive means to keep temperatures within a safe range. With no cooling, the core would reach a maximum temperature of 2,900°F when the Doppler broadening effect begins to lower the reactor output as the uranium-238 nuclei begin to absorb more neutrons. This decrease in output necessarily means a decrease in reactor temperature. During this period of lost coolant, heat is transferred away through radiation, conduction and convection to the steel reactor vessel, which is designed to dissipate the heat. The highest temperatures reached during loss of cooling are not high enough to damage the structural integrity of the fuel or the reactor.[18]

In June 2008, the World Nuclear Association asserted that the cost of construction and subsequent electrical generation costs when 8 modules are constructed together would be "competitive".[19] Another independent estimate calls for overnight costs of $1,000 per kilowatt of capacity for n^th^ of a kind modules.[20] However, no detailed cost estimates for the construction and operation of the PBMR exist in the public domain, and all estimates should be taken with a "grain of salt" as the expression goes.

3.2 General Atomics Gas Turbine – Modular Helium Reactor (GT-MHR)

The GT-MHR is a "Generation IV" nuclear reactor[21] and is currently being developed through the "Agreement between the Government of the United States of America and the Government of the Russian Federation on Scientific and Technical Cooperation in the Management of Plutonium that has Been Withdrawn from Nuclear Military Programs". In addition, both Japan and the European Union are providing support. The goal is to have a module of the GT-MHR built in Russia that is ready for operation in 2009, with a full 4 module GT-MHR completed by 2015. The process for constructing a functional reactor in the US will be taken as well, following a delayed schedule compared with Russia, which can be seen in the figure bellow. [22]

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[17] Nuclear Power in South Africa, 2008.

[18] Pebble Bed Reactor Technology, Eskom and *Pebbles Making Waves*, Langston, 2008.

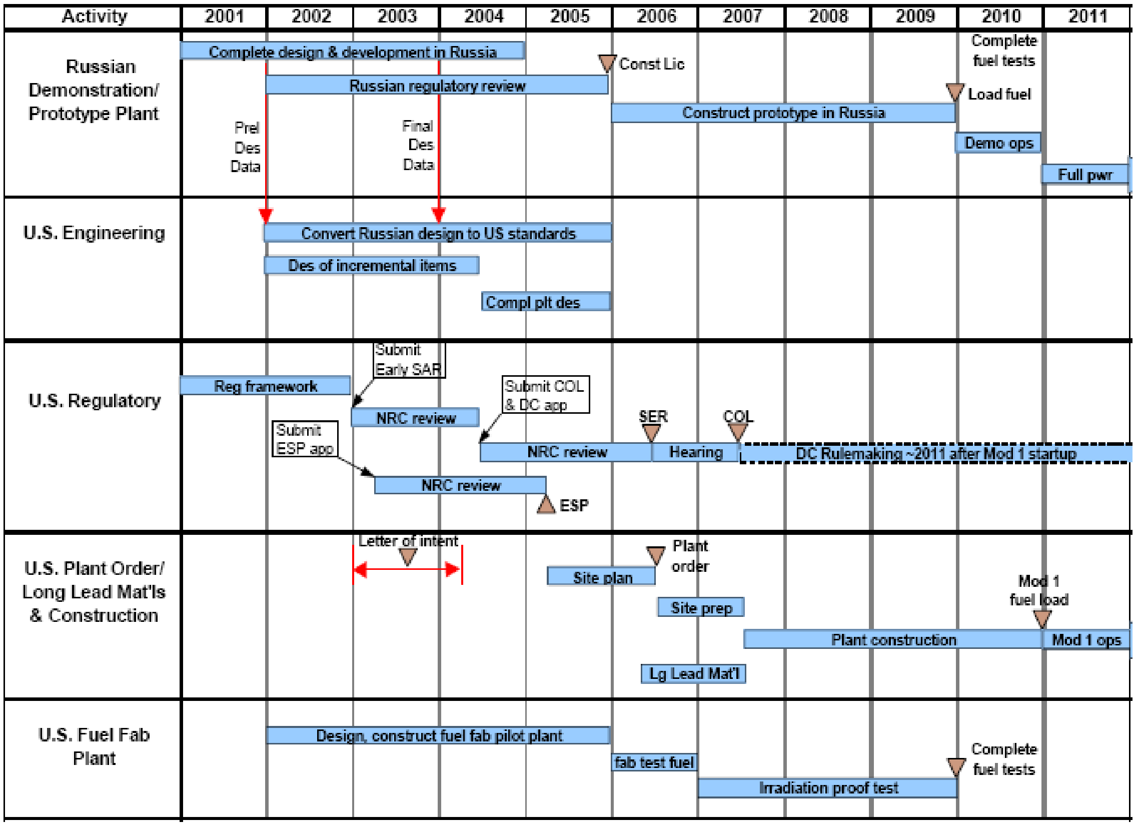
[19] *Nuclear Power in South Africa*, June 2008.

[20] *Pebble Bed Modular Reactors—Status and Prospects*, Jim Hardin, February 2004. https://www.rmi.org/images/PDFs/Energy/E05-10_PebbleBedReactors.pdf

[21] *Status of the GT-MHR for Electricity Production*. World Nuclear Symposium 2003. http://www.world-nuclear.org/sym/2003/labar.htm

[22] *The Gas Turbine – Modular Helium Reactor: A Promising Option for Near Term Deployment*. General Atomics, April 2002. http://gt-mhr.ga.com/images/ANS.pdf

Figure 3.3
GT-MHR Construction Schedule



Recent key developments in technology such as industrial turbines, gas-to-gas heat exchangers and large, active magnetic bearings have enabled the Brayton conversion system to be possible. This conversion system gives high thermal conversion efficiency resulting in 50 percent less waste heat, as well as removing the need for the power conversion equipment required by traditional steam turbine plants. This reduction in the complexity of the power conversion equipment reduces both capital requirements and operation and maintenance costs.

The GT-MHR is designed as two interconnected pressure vessels enclosed in an underground concrete silo. The first vessel contains the reactor system and is based on the steam-cycle MHR, while the second contains a high efficiency Brayton cycle gas turbine energy conversion system.[23] A typical power plant would be made up of four of these paired vessels and be able to generate around 1145 mega watts of electricity (MWe).[24]

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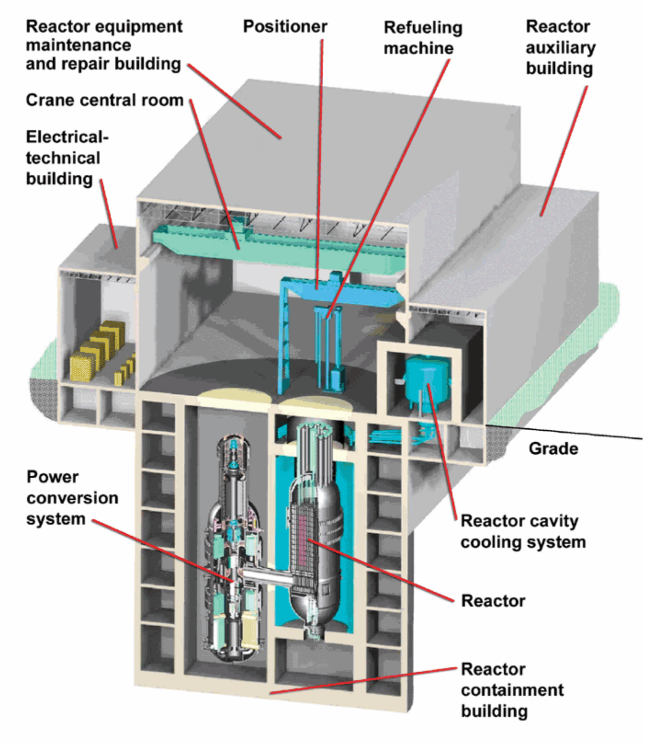
[23] http://gt-mhr.ga.com/

[24] *The Fifty Percent Efficiency Nuclear Power Plant*, Alan Wong, Department of Nuclear Engineering, University of California, Berkeley,1994. http://www.nuc.berkeley.edu/thyd/ne161/alwong/ne161.html#General%20Descriptions

Figure 3.4
GT-MHR Design[25]



For fuel the GT-MHR uses TRISCO coated particle fuel, consisting of spherical kernels of appropriate fissile material that are given multiple coatings which form a thin, highly corrosion resistant pressure vessel around the particle. This acts as a barrier against the release of gaseous and metallic fission products, as well as a barrier for containment of the radionuclides during storage and geological disposal of spent fuel. Cylindrical fuel made of TRISO coated particle fuel mixed with a carbonaceous matrix is loaded into fuel channels in the graphite fuel elements. The annular core consists of 102 columns of these graphite fuel elements, and reflector graphite blocks are present both inside and outside the active core.

Inside the GT-MHR, helium coolant flows downward through coolant channels in graphite fuel elements and then through the cross-vessel to the power conversion system. In the second vessel, the expanded helium gas passes through the gas turbine driving the generator and gas compressor. The helium then flows through the hot side of the recuperator, precooler and then the low and high-pressure compressors. After passing through the cold, high-pressure side of the recuperator the helium then returns to the reactor.[26]

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[25] http://www.world-nuclear.org/sym/2003/fig-htm/labf2-h.htm

[26] *Status of the GT-MHR for Electricity Production.*

In addition to 2 active heat removal systems, the GT-MHR has an independent passive means for the removal of core decay heat through heat conduction, thermal radiation and natural convection. These passive design features result in a reactor that can withstand the loss of active heat removal systems and maintain fuel temperatures below damage limits.

Overnight cost for the nth of a kind GT-MHR is estimated to be US$1,115 million or 975$/kWe, with a construction timeline projection of 3 years until the first module is producing electricity. The levelized busbar costs of the GT-MHR was estimated at around US$29.00 for an nth of a kind unit.[27] This costs is likely far lower than the actual nth of a kind costs will be given the rapid rise in commodity prices (may of which will be inputs into the construction of the GT-MHR) and labour. The reader is cautioned to view the estimated cost with a sceptical eye and an understanding that the true costs will not be known until the first unit is constructed and some lessons learned can be applied to estimate an nth of a kind cost.

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[27] *The Gas Turbine – Modular Helium Reactor: A Promising Option for Near Term Deployment.*

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CHAPTER 4
CONCLUSIONS

The purpose of this part of the study was not to provide a definitive list of options that could be considered in the future. The list of options will continue to grow as entrepreneurs seek new opportunities and deploy new ideas. Gasification exists today and is an option that is already being used to reduce the oil sands dependency on natural gas (this was discussed in Part III). Other alternatives could reduce the need for, or compliment gasification. THAI, VAPEX, and Hybrid approaches could increase in situ production while helping to reduce the total emissions from the oil sands. As more tests are performed and cost information starts to seep out into the literature a better understanding of their potential will emerge.

Nuclear energy is here, or 20-years out, depending on perception and where the technology would be deployed. While the potential exists to deploy a small reactor such as the PBMR or GT-MHR for in situ development, the financial risks of deploying a new reactor in an area with limited infrastructure will no doubt delay the deployment. Located in support of a mine or upgraders is the more likely future of non-electricity applications of nuclear in Alberta. However, newer designs like the PBMR and GT-MHR will require extensive pilot testing prior to their deployment in Canada.

Whether it is a fuel swap from gas to nuclear, or a technology change with THAI, the options extensive and it will take time to bring these to market. Today, we must rely on what exists and what could be easily proven. The challenge of reducing greenhouse gas emissions is being met by industry; however it will take years for some of these other alternatives as discussed in this part of the report to be deployed. THAI, VAPEX and hybrid approaches are more likely to be commercially deployed within the next 20-years, relative to the PBMR and GT-MHR and other small nuclear reactors that haven’t been discussed in this report.

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