Super Critical Water Reactor for Use in Steam Generation for Recovery of Bitumen Resources

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Abstract

The process of recovering the bitumen (oil sand) resources in Alberta requires steam at high pressures. To help reduce the carbon footprint of exploiting these fuel resources, an innovative new design of a CANDU super critical water reactor (CANDU-SCWR) is being considered to provide the high pressure steam required for the steam assisted gravity drainage (SAGD) process. The high temperature and pressure associated with the CANDU-SCWR allow for the high pressure, temperature steam to be produced without supplementary energy. The Petroleum Technology Alliance of Canada (PTAC) has specified the SAGD process requires steam at 11 MPa and near 100% steam quality, and net electrical power of 106 MWe.

This paper examines steam cycle and design options to meet the steam and power requirements defined by PTAC. Steam cycle options are examined focusing on the optimization of steam and power conversion. Additionally passive safety and cooling for both the heat transport and moderation systems are considered and their impact on performance are examined. As the CANDU-SCWR is at a preliminary stage of design, basic design parameters have been defined based on preliminary assessments. This paper is focused on a reactor with the following basic design assumptions:

- Vertical fuel channel
- Re-entrant fuel channels
- Pu-Th fuel
- Batch refuelling

Keywords: SCWR, Reactor, Steam Cycle, SAGD

1. Introduction

One of the common processes of extracting bitumen from the oil sands is the Steam Assisted Gravity Drainage (SAGD) method, which uses high temperature and high pressure steam to separate the bitumen from the surroundings. Traditionally natural gas has been used to produce the steam for the SAGD process, but due to the potentially very large increase in price of natural gas, alternative steam generation options are considered by the Petroleum Technology Alliance of Canada (PTAC). As such nuclear energy has been considered for use in bitumen extraction, but the operating temperature in the current generation of nuclear reactors requires additional reheat to achieve the required temperatures and pressures for the SAGD process. The supercritical water reactor (SCWR) operates at a much higher temperatures, which makes it ideal for the generating steam at higher temperatures and pressures.

This paper examines steam cycle and design options to meet the steam and power requirements defined by PTAC for the SAGD process. AECL is developing Generation IV supercritical water reactor technologies and steam cycle options, focussing on the optimisation of steam generation and power conversion.

1.1 Steam Assisted Gravity Drainage

SAGD is an enhanced oil recovery process applicable to recovery of crude bitumen from deep oil sands deposits. A typical SAGD application involves twin horizontal wells drilled with one a few meters above the other, as shown in Figure 1. The upper well is called the injection well and the lower one the production well. Medium pressure steam is injected into the underground deposit area through the injection well, to heat the reservoir of bitumen-sand mixture by conduction. The heating reduces the viscosity of the bitumen, allowing it to flow, and establishes pressure communication between the two wells along their length, so that a flow of fluids (mixture of bitumen and condensed water) can occur and be collected through the production well. The production liquid is transported to a central facility, where the bitumen is separated and the condensate is collected, treated, and sent back to the boilers.

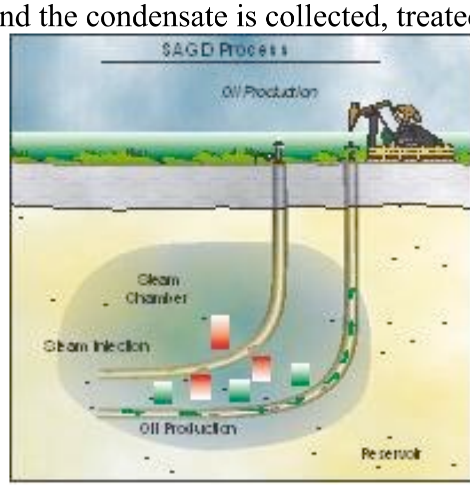

Figure 1 SAGD Process

The steam properties required during the process have been defined by PTAC as: 11 MPa, 318°C , and near 100% steam quality. Additionally the electrical demands of the SAGD process are specified as 106MWe.

2. Super Critical Steam Cycles

2.1 Power Generation

AECL has examined a number of potential steam cycles that will be applied to the SCWR plant for a sole electricity generation purpose. Options are considered to take advantage of the SCWRs high efficiency potential. Four options were proposed: reheat direct cycle, non-reheat direct cycle, reheat dual cycle, and non-reheat dual cycle. The system configurations of these cycles are shown in Figure 2 through Figure 5.

In a direct steam cycle, the steam generated from the reactor is directly introduced to the steam turbine that is located outside the reactor building. The direct cycle fully utilizes the steam pressure and temperature at the outlet of the reactor and ensures the highest possible cycle efficiency. In addition, since it does not need the steam generators (SG) and its associated equipment, there are fewer components in the system.

In an indirect steam cycle, the coolant from the reactor does not enter the turbine directly. Instead, an intermediate closed type heat exchanger, called steam generator, is introduced as barrier between the reactor and the steam turbine. The SG uses the reactor coolant as a heating source to produce steam that is then utilized in the steam turbine. This configuration uses a SG which reduces the cycle efficiency as the secondary side steam pressure and temperature, are always lower than that of the primary side.Since the SG in an indirect cycle SCWR plant will work at significantly higher pressure and temperature than that in the current CANDU and PWR plants, the design of the SG in an indirect cycle SCWR plant possesses a challenge and introduces technical uncertainties. Therefore, a dual cycle concept, as an alternative to the indirect cycle, was considered.

In a dual cycle (Figure 4 & 5), the high pressure and temperature steam from the reactor is directly introduced into the turbine in the primary side, and the exhaust steam is introduced into the SGs as the heating steam. The SGs generate the steam that is utilized in the secondary side system. The dual cycle possesses the same safety level as the CANDU and PWR plants, while significantly reduce the steam parameters inside the SGs. The secondary side steam pressures in the proposed dual cycles are 500 kPa and 4.5 MPa, for Option 3 and 4 respectively.

While each of these cycles has their challenges, all of them are superior in cycle efficiency compared with the conventional nuclear power plants, with the gross cycle efficiency varying from 47.2% to 50.4%.

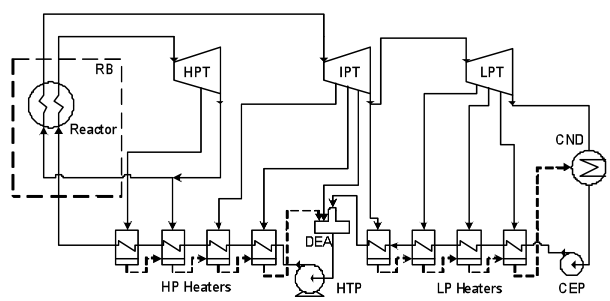

Figure 2 Option 1 for Electricity Generation, A Reheat Direct Cycle

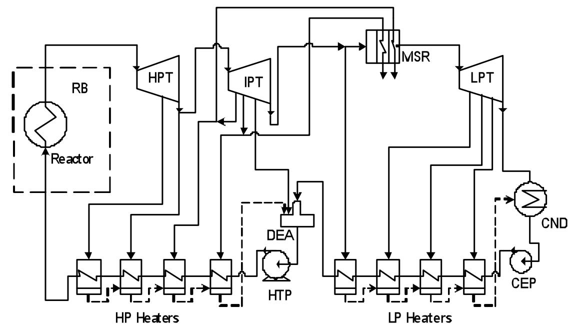

Figure 3 Option 2 for Electricity Generation, A NonReheat Direct Cycle

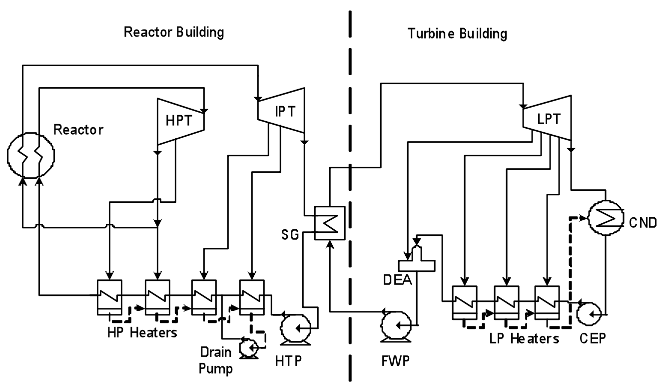

Figure 4 Option 3 for Electricity Generation, A Reheat Dual Cycle

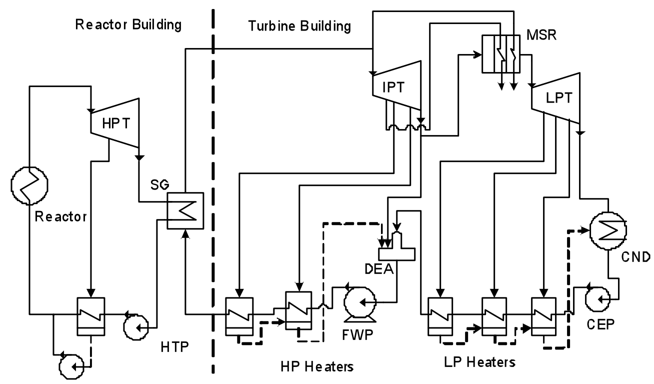

Figure 5 Option 4 for Electricity Generation, A NonReheat Dual Cycle

2.2 Steam Generation for SAGD

AECL has investigated using nuclear energy from CANDU plants to SAGD application as a novel concept. The preliminary study has indicated that in addition to the existing SGs in CANDU plants, intermediate heat exchangers (called reboilers) are required to produce the SAGD steam, in order to further reduce the possibility of the radioactive contamination at the SAGD site. This arrangement is called three-cycle configuration. From this aspect, a simple solution would be to add reboilers, which produce the SAGD steam to one of the dual cycles. However, the required SAGD steam pressure is higher than the secondary side steam pressure in either dual cycle options, which rules out this simple add-on option. Therefore, a plant configuration that will produce steam to meet the PTAC SAGD steam requirements will be significantly different from any of the proposed SCWR steam cycles.

Proposed Configuration

The proposed configuration of an SCWR custom designed for the SAGD application is shown in Figure 6. The system is designed to co-generate electricity and steam.

The steam coming from the reactor at super-critical conditions is introduced into a high pressure (HP) turbine. A certain amount of steam at around 19 MPa is extracted from the HP turbine. The steam generators use this high pressure extraction steam as a heating source to produce the secondary side steam at a pressure of 14.4 MPa on the cold side. On the hot side of the SGs, the heating steam condenses and this condensate is pumped back to the reactor as reactor coolant, and this completes the primary cycle. In order to increase the overall plant efficiency, a pre-heater is introduced before the SGs. The pre-heater uses steam extracted from the turbine at a relatively lower pressure to pre-heat the SG's feedwater.

To separate the reactor from the SAGD facility, the secondary side steam is sent to reboilers. The reboilers take the secondary side steam to heat the water, and generate the tertiary side steam at the required 11 MPa pressure. Drain coolers, which use the condensate from the reboilers to pre-heat the reboilers' feedwater, are included in this configuration to further cool the reboilers' drain water. The drain water from the drain coolers is then re-pressurized via pumps, and is heated in pre-heaters before returning to the SGs as feedwater.

The tertiary side steam generated from the cold side of reboilers is transmitted to the SAGD facilities and directed into oil wells. After heating the bitumen, the condensate is potentially recovered and treated being pumped it back through the drain coolers as feedwater to the reboilers at a temperature of 160˚C. This feedwater is pre-heated in the drain coolers before entering the reboilers.

The remaining steam in the HP turbine continues working in the turbine system to generate electricity.

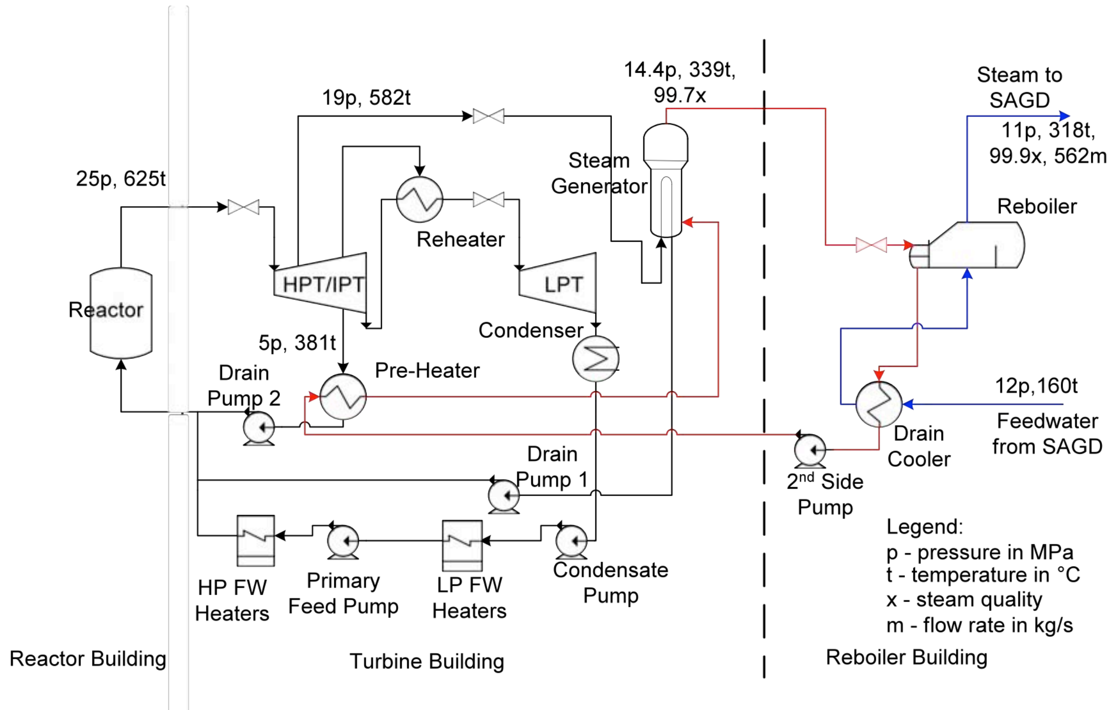

Figure 6: SCWR Steam System for PTAC SAGD

Thermal Performance Simulation and Results

A system thermal performance simulation was performed using GateCycle software for two cases: one that optimises the power generation and one that precisely meets the required power generation.

Case 1, a Full-Scale SCWR

In order to make the turbine design more economical, the system configuration is based on a full-capacity SCWR with the total reactor power of 2540 MWt. The system will produce more electricity than the PTAC's requirement.

In order to provide 1136 MWt power to the SAGD facilities, the required steam flow rate from the reboilers will be 562 kg/s. The results show that while providing 1136 MW thermal power through the 11 MPa steam to SAGD facilities, the gross electric output from the system will be 695 MWe.

Case 2, a Small SCWR
As an alternative, this option provides a small SCWR to explicitly meet the PTAC's requirements on both steam and electricity (106 MWe). Because the exact in-house load is not known now, the gross generator output of 180 MWe is chosen, which is considered to be able to meet the required 106 MWe electricity with certain conservatism. The system configuration does not change from Case 1, and the differences are the steam/water flow rates and equipment size, the latter of which is not the concern in the paper.

The simulation results show that the required reactor thermal power is 1444MW, and the corresponding main steam flow rate from the reactor is 625 kg/s. The resultant steam flow rates in IP and LP turbine are very small, which are not ideal condition for the turbines.

3. SCWR Design Concepts

Early in the GEN IV program in Canada a high level goal was established to utilize AECL CANDU pressure tube technology as a conceptual guide for the CANDU-SCWR GEN IV concept, to maximize the potential gains from a well established technology base. Due to the more intense operating conditions of a super critical system, that is higher temperature and pressure, a number of new design concepts have been assumed.

The new design concepts discussed in this document are in four main categories:

- Fuel channel
- Fuel handling
- Fuel
- Passive Safety

3.1 Fuel Channel

A vertical channel design was selected to take advantage of the buoyancy effects of SCW coolant in a vertical pressure tube. A top loaded, off-power fuelled, fuel assembly design, is being assessed as a candidate for use in CANDU-SCWR conceptual designs

One of the primary constraints on CANDU-SCWR conceptual fuel channel designs is the temperature limitation of current CANDU-type fuel channel materials. In general, pressure tube zirconium-alloy materials are unable to withstand the targeted maximum operating temperatures (~450 to 625 °C) at pressure (>25 MPa) for a 30 to 60 year design life of a CANDU-SCWR. In order to continue to take advantage of the low neutron cross-section of zirconium pressure tube a method of insulation or cooling is required to keep it under 450°C. Preliminary assessment of concepts has led to focus work towards a re-entrant channel design.

The re-entrant channel (REC) design is a vertically oriented fuel channel concept with single ended fuelling and single ended coolant entry/exit. In the REC design (Figure 7), the coolant enters the channel annulus as sub-cooled water (~315 °C) flowing downward and pre-heating the coolant until it reaches the bottom of the channel. The coolant is then redirected upward by the geometry of the channel, coming into contact with the fuel bundles/assemblies. The coolant is heated by the fuel assemblies to above the critical point of water and exits near the top of the channel (~450 to 625 °C). In the REC design, the inlet coolant keeps the pressure retaining components of the fuel channel (i.e. PT) at a low-temperature allowing them to withstand the high-pressure associated with SCW conditions.

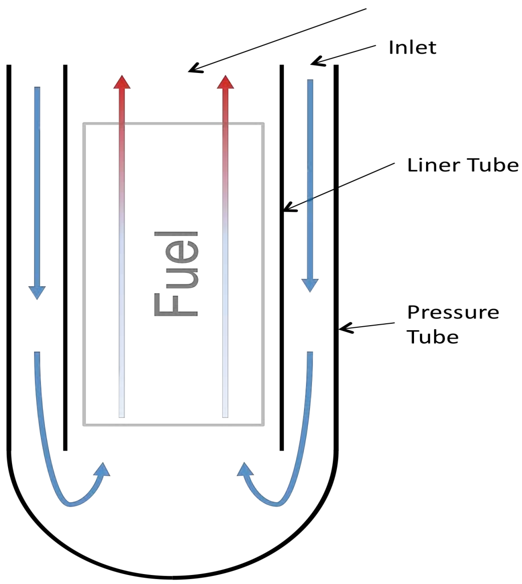

Figure 7: Re-entrant Fuel Channel Concept

3.2 Fuel Handling

The traditional on-power refuelling in CANDU style reactors have large challenges in a SCWR design. The increased pressure and temperature of the heat transport system require more robust closure plugs and fuelling machines. In order to meet these operating conditions new sealing for the closure plugs will need to be designed, and large modifications to the fuelling machine are required.

The modifications to the fuelling machine cannot be to simply increase the wall thickness on all pressure retaining components, to avoid large pressure pulses the fuelling machine cooling system will need to be maintained at a channel operating temperatures. The modifications are expected to at least double the weight of the fuelling machines, which would be virtually extremely difficult to seismically qualify.

It is clear that using an off-power fuelling system would simplify the design to a manageable level.

3.3 Fuel

As CANDU-SCWR is intended to be fuelled off-power, the flux shape in the core is no longer controlled with introduction of small excess reactivity, as is currently done in CANDU reactors. Instead, the reactor will be off-power fuelled once every 16~24 months with and enriched fuel containing higher fissile loading than natural uranium (NU).

The CANDU-SCWR will require a sustainable fuel that utilizes an advanced fuel cycle that can move towards high burn-up with options that are proliferation resistant and offer the highest potential to close the fuel cycle. For these reasons and the more favourable thermal properties, a Pu-Th fuel is considered for the SCWR.

Due to the nature of the supercritical steam cycle, there is significant variation in the coolant density along the fuel channel. As a result, the neutron moderation from the coolant will vary along the channel. To compensate for this variation a customized fuel with varied enrichment along its axis will need to be considered.

The fuel assemblies will be significantly different than earlier CANDU designs, requiring new materials and geometries. Based on the limitations of zirconium alloys at high temperatures alternate cladding materials needed to be considered (austenitic stainless steels and ceramics). Additionally to achieve the higher burnups associated with batch refuelling the fuel assemblies will need to be modified to be similar to a LWR fuel assembly.

3.4 Passive Safety

Passive safety systems such a flash driven moderator system and a natural circulation system to remove decay heat from the core were assessed for the CANDU SCWR.

For the flash driven moderator system calculations show that there is a considerable effect on natural circulation by changing height and inside diameter of legs, and outlet temperature of the moderator. Design can be optimized to the layout conditions at site. For a generic CANDU SCWR case the height of the riser and down comer are expected to be approximately 30m and 25m respectively

Similar calculations show that it should be possible to remove the decay heat from the SCWR core by Natural Circulation. By using a decay heat loop consists of a hot leg; a cold leg and 8 heat exchangers immersed in a pool of water with a capacity of ~5900 tons of water. In which initially all the 8 heat exchangers are required, but after some time when the decay heat reduces, only 4 heat exchangers are sufficient to remove the decay heat.

The pool water cooling system can be designed to remove the decay heat for indefinite period. In addition to removing decay heat the pool can be used as a gravity driven water source to:

1. Cool the reactor core during LOCA (loss of coolant accident) or Act as Suppression Pool and cool the steam-air mixture during LOCA

2. Remove containment heat in accident scenarios by condensing the steam from air-steam mixture across passive containment coolers provided below the water pool.

4. Conclusion

The concept of using a SCWR to recover bitumen from the oils sands is technically feasible, though further assessments are required to optimise the process.

From a steam cycle perspective the use of a full power SCWR (case 1) in the SAGD application is preferable to maximize cycle efficiency and turbine economy. Surplus electricity generated by the SCWR could be either fed into the surrounding power grid, or used in electric heaters to increase the steam capacity.

Design concepts for the CANDU SCWR presented show that some of the challenges can be reduced by moving away from traditional CANDU designs while still maintaining some of the key advantages of CANDU technology. Assessments have shown that passive safety features will be utilized in the SCWR design wherever possible.

Further work to enhance both the design and the steam cycles should be continued to develop the CANDU SCWR for this important market.

5. References

[1] Jerry Hopwood, Romney Duffey, Sermet Kuran, Xi Zhou, Michael Ivanco, Brian Rolfe, Alistair Miller, and Connie Mancuso, "Non-Electrical CANDU Applications", Paper No. 536, Proceedings of GLOBAL 2005, Tsukuba, Japan, Oct 9-13, 2005