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Beyond Electricity - Nuclear Process Heat

Abstract

To date, the overwhelming use of commercial nuclear energy has been in the production of electricity. This was the natural consequence of the initial broad application of light water reactor technology and its associated reactor coolant temperature range. The commercialization of high-temperature gas-cooled reactors (HTGRs) within the next decade will enable the use of nuclear energy for a range of high-temperature process heat applications. Attractive applications for HTGR technology are driven primarily by the opportunity to displace natural gas and other premium fuels, and to provide a cost-effective solution to the reduction of CO_2 emissions. Using medium-temperature process heat for the production of high-pressure steam for oil sands/heavy oil recovery, and for industrial steam and cogeneration, appear attractive in many economies. Another prospective application that requires relatively modest technology development is to provide the high-temperature heat of reaction for steam reforming of natural gas, thereby maximizing carbon efficiency for the production of synthesis gas ("syngas"). High-temperature water splitting technologies (both via steam electrolysis and thermo-chemical reactions) are also being developed that can produce bulk hydrogen and oxygen for broad industry use in current applications, for increasing carbon conversion efficiency in coal-to-liquids and coal-to-gas plants, and eventually as a substitute transportation fuel as part of the Hydrogen Economy. In addition to the above, low-temperature waste heat may be applied for water desalination co-production in many applications. This paper presents the results of conceptual design work on the Pebble Bed Modular Reactor (PBMR) and assessments developed for several of these applications.

1. Introduction

Increased energy demand, escalating and increasingly volatile natural gas and oil prices, and a desire for energy security and environmental sustainability are stimulating investments in technologies that will contribute to reliable, affordable and clean energy on a global scale. Fossil resources supply approximately 80% of global energy today, but their continued use is constrained by the increasing cost of available reserves and its projected adverse effects on the environment. Nuclear energy provides a solution to these broad-based societal issues.

Electricity generation from fossil fuels accounts for some one-third of global CO_2 emissions; over half of all emissions are generated from the industrial and transport sectors. An opportunity exists to introduce nuclear energy into the industrial and transport sectors by supplying process heat to displace premium fossil fuels to produce cleaner chemical products, and liquid or gaseous petroleum-based fuels. To effectively substitute for these fossil fuels, the nuclear heat source must be demonstrably safe, economic, match the process energy needs, and provide the required temperatures. South Africa's Pebble Bed Modular Reactor (PBMR) technology fits these requirements.

PBMR technology has unique features which make it well-suited as a heat source for process applications:

- High process temperatures up to 900°C (reactor outlet up to 950°C);
- Well-matched to industrial process sizes (400-500 MWt);
- Ability to co-locate with industrial process plants due to inherent safety characteristics and small exclusion zone;
- High plant availability due to continuous online refueling;
- Near-term deployment (middle of the next decade) building on the South African Demonstration Power Plant initiative;
- Economic benefits including displacement of premium fossil fuels, value from avoided CO_2 emissions, high plant availability, distributed generation, short construction times, and reduced financing costs;
- Well-suited for all markets, including industrial and

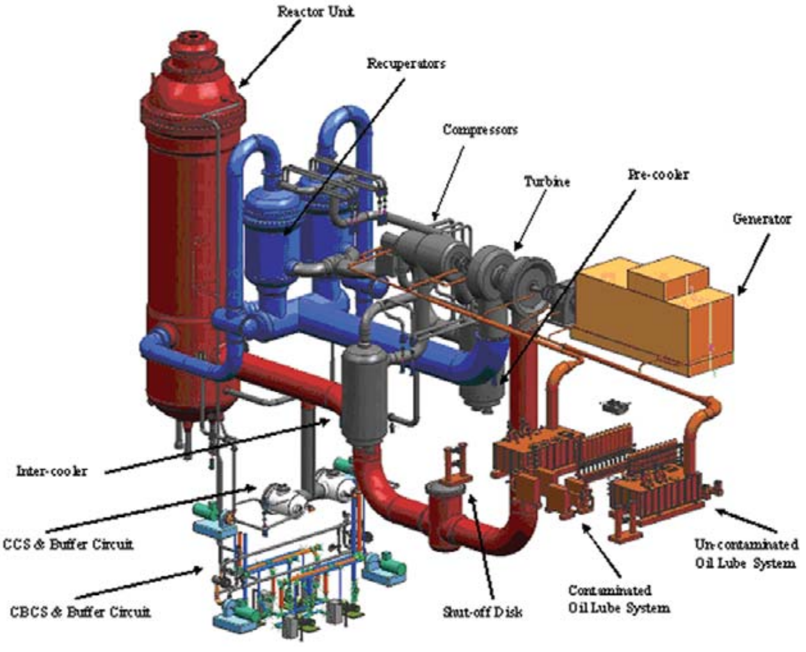

Figure 1 - PBMR main power conversion system

developing markets due to its proliferation resistance and investment protection features;

- Addresses distributed need for electricity and desalination/cogeneration functions.

The South African PBMR initiative includes the construction of a 165 MWe (400MWt) power plant at the existing Koeberg nuclear station near Cape Town and a fuel plant at the Pelindaba site near Pretoria, with construction starting in 2009 and fuel load scheduled for 2013. *Figure 1* shows the main power conversion system for this reactor plant. The power plant will demonstrate the basic technology for the subsequent commercial multi-module electricity plants and the future Process Heat Plant applications.

For such future plants, the nuclear energy heat source will be based on the Demonstration Power Plant's physical reactor design using the identical core dimensions. The follow-on PBMR process heat plants are envisaged to operate at power levels between 400-500 MWt with reactor outlet temperatures up to 950°C. The configuration of the PBMR process heat plants will depend on the specific application and necessary process temperatures. Though the reactor core dimensions will remain the same for different process heat applications, the technology can be differentiated into two main configurations, depending on the reactor outlet temperature:

- An Intermediate Temperature Gas-cooled Reactor (ITGR), operating at reactor outlet temperatures up to approximately 750°C; this is typical of process temperatures needed for steam applications.
- A High-Temperature Gas-Cooled Reactor (HTGR), operating at reactor outlet temperatures up to 950°C, which is essentially a Generation IV Very High- Temperature Reactor (VHTR).

2. Markets and applications

The unique characteristics of the PMBR relating to its smaller size, increased safety, and high-temperature heat delivery open up a number of new applications and markets not previously available to nuclear energy. A PBMR adapted for process heat delivery must be able to match the energy needs of many common industrial thermal applications, and the virtual absence of nuclear accident risk allows co-location of the nuclear heat source adjacent to the point of use.

Heat from the PBMR can be used for a variety of industrial process applications that require both intermediate and high temperatures. Intermediate (up to 750°C) temperatures can be used to generate process steam for cogeneration applications, electricity production, *in situ* bitumen recovery from oil sands, ethanol processing, refinery and petrochemical applications. Higher temperatures (up to 950°C) can be used to produce electricity with advanced, higher efficiency power cycles; to reform methane and steam to produce syngas (where the syngas can be used as feedstock to produce hydrogen, ammonia and methanol); and to produce hydrogen and oxygen by decomposing water thermo-chemically. Bulk hydrogen can be sold as a merchant product, or directly supplied to various industrial operations such as coal-to-liquids, coal-to-gas, refineries, petrochemical applications, and steel production operations. Low-temperature waste heat can be used in combination with high and intermediate temperature applications to desalinate water or to produce low-pressure steam or hot water, e.g. to supply district heating.

Economically attractive applications for nuclear process heat are driven primarily by the opportunity to displace natural gas and other premium fuels, and to respond to incentives to reduce CO_2 emissions. Even with conservatively low forecasts for growth in long-term gas prices, clear commercial benefit exists in reducing exposure to natural gas price increases and volatility. Economic assessments of PBMR process heat applications, based on current trends, suggest that PBMR is likely to become economically competitive in many markets, especially markets relying on premium fuels to comply with tight emission limits, where CO_2 emission constraints are already announced or anticipated.

Today, steam for *in situ* bitumen recovery in the Alberta, Canada, oil sands comes almost entirely from burning natural gas. From 2005 to 2010, oil sands production will roughly double from slightly less than 1.0 million bbl/day to 2.1 million bbl/day, and to approximately 4.0 million bbl/day by 2020. This 4.0 million bbl/day of bitumen production in 2020 could consume as much as 3.1 billion cubic feet of natural gas per day, or nearly 20% of the projected natural gas production in Western Canada at that time [1]. Much of this gas production is intended for export to the US and diversion of this supply to support the oil sands industry can be expected to significantly impact regional markets. This application to oil sands recovery represents a potential market for dozens of PBMR reactors supplying high-pressure steam and in some cases cogenerated electricity to support several stages of oil sands expansion starting the latter part of the next decade.

Use of hydrocarbon fuels and feedstocks for the production of steam, power, transportation fuels and chemicals will continue for many decades. The imposition of CO_2 emission penalties or taxes is likely to cause a progressive shift to natural gas as the preferred source of hydrocarbons for combustion and power generation.

However, natural gas is a premium fuel that is best deployed in domestic heating, in the production of high value products, and in specialized applications in power generation. In the absence of a shift to non-carbon sources for such resources, the use of natural gas will increase and the prices of this commodity will rise rapidly, offsetting their advantages in sequestration and flexibility. Over and above this, the cost of hydrogen production by means other than water splitting, e.g. steam methane reforming, will become less attractive for the same reasons. Several industrial applications require a source of hydrogen for their products, notably coal-to-liquid plants. Thus, the modification of the "carbon footprint" of gas-to-liquid and coal-to-liquid plants depends on new heat sources that do not use carbon to produce the needed hydrogen to make these conversion processes viable.

Most of the bulk hydrogen in the world is currently produced from natural gas using steam methane reforming. As the price of natural gas has increased dramatically over the last few years, many industries (i.e. ammonia and methanol production) have shut down their existing facilities and moved to areas where cheap, stranded natural gas is available. The demand for hydrogen at refineries will grow over the next few decades to sweeten progressively lower grade crude oils, and to achieve tighter specifications on transportation fuels.

Opportunities for the use of high-temperature reactors like the PBMR to produce bulk hydrogen are currently being explored across the globe. Use of high-temperature nuclear heat to replace a portion (30-40%) of the natural gas used in conventional steam methane reforming plant to produce the required process heat appears attractive. Syngas produced by a reformer is a flexible chemical product that can be used for producing ammonia, methanol and hydrogen at scales that match the thermal output of a PBMR. Syngas can even be used to deliver heat to distant locations by pipeline where heat can be recovered by methanation. This could provide a thermo-chemical heat delivery system in the future where the methane and syngas are not consumed, but only used as carriers to deliver thermal energy.

Depending on evolving economic conditions related to natural gas pricing, new hydrogen capacity requirements, and conventional steam methane reforming plant technology, the market for high-temperature reactors to support hydrogen and steam requirements for new refinery expansions and oil sands bitumen upgrading after 2020 would be about one new nuclear reactor for each new hydrogen plant needed after that date.

The conversion of coal to transportation liquids and to methane has been commercially demonstrated (specifically in South Africa where 30% of today's requirements are supplied in this manner) and is now proposed for various new projects. However, transportation fuels (gasoline and diesel oil) require much more hydrogen per carbon molecule than is available in coal. Therefore, roughly half of the coal in such processes is currently used to create the hydrogen that is needed to convert the rest of the coal to liquid fuels.
Similarly, more than half of the coal used to make synthetic natural gas is consumed to provide the additional hydrogen. Unfortunately, most of the coal used to make hydrogen ends up as CO_2 and is released into the atmosphere. Therefore, splitting water with high-temperature nuclear heat to make large amounts of hydrogen and oxygen not only eliminates the wasteful use of coal to make hydrogen, but also provides the oxygen which is used by the gasification process, eliminating the requirement for expensive oxygen generation plants. It takes a lot of energy to split water (conversely, burning hydrogen produces a lot of heat). A significant number of high-temperature nuclear reactors, like the PBMR, would be needed for modest size coal-to-liquids and coal-to-gas plants to provide the required amounts of oxygen and hydrogen. Even with high CO_2 penalties and increasing capital costs of coal gasifiers, oxygen plants and other facilities that would be displaced, the economics of applying nuclear thermo-chemical water splitting are uncertain due to the early stage of design and cost development. Also, the technology for water splitting using nuclear heat will require considerable R&D and engineering demonstration, such as is currently underway through the US Department of Energy's Next Generation Nuclear Plant (NGNP) program. Should economical nuclear thermo-chemical water splitting systems be developed, this would become a very large market (tens of reactors per coal-to-liquids or coal-to-gas plant) for high-temperature nuclear reactors like the PBMR.

3. Intermediate Temperature Gas-Cooled Reactor - steam applications

The production of steam from a PBMR reactor plant is probably the simplest process heat application for this technology. To achieve this, the direct recuperative Brayton cycle used for the electric plant is replaced with a simple circulator and heat exchanger (compare *Figures 1 and 3*). Also, for most steam plant applications, the reactor coolant outlet temperature can be significantly lower (i.e. ~750° C), providing a less challenging environment for component design, material selection, and conventional steam operations utilizing an indirect cycle.

3.1 RISK AND OPPORTUNITY

Opportunities for steam and cogeneration using PMBR process heat units are driven primarily by the opportunity for rapid expansion of the oil sands industry in Alberta, Canada, for example, and by unique project specific opportunities to integrate heat, power and desalination where maximum value can be obtained from the displacement of premium fuels, reduction of CO_2 emissions, and availability of capital required for alternative facilities.

The greenhouse gas (GHG) emissions due to natural gas use for oil sands extraction and upgrading in 2020 could be over 150 megatons (millions of tons) of CO_2 equivalent. This would account for approximately 17% of Canada's total projected emissions in that year. For an industry that is highly concentrated in a fairly small portion of the country, this indicates a staggering GHG emission intensity that must be reduced if Canada hopes to decrease its total emissions appreciably. If the oil sands are to continue to grow rapidly, they will have to become carbon-neutral or they will impair any progress toward addressing climate change.

South Africa has a similar dilemma related to the extensive use of coal for power generation (approximately 90% of power production is from coal-fired stations) and for the production of roughly 30% of its liquid fuels in coal-to-liquids (CTL) conversion plants. A significant amount of CO_2 emissions result from the use of coal for steam and power generation in CTL plants that could be displaced by PBMR reactors in steam-only and cogeneration configurations.

The principal challenges in implementing projects to displace natural gas and coal used for generation of steam lie in the capital intensity of nuclear units relative to fossil-fired plants (particularly natural gas-fired plants) and the long regulatory approval process for nuclear plants, particularly for those that are first-of-a-kind. The proposition of using nuclear heat to displace premium fuels and CO_2 over a reasonable plant life involves replacing the cash flow of escalating fuel and CO_2 values with a large initial capital investment offset by lower operating costs. Installation of PBMR units in Alberta, South Africa, or elsewhere, will require special financing and risk mitigation arrangements until the first-of-a-kind, financing and licensing risks are reduced. The economic viability of these nuclear applications lies primarily in the ability to manage construction risks and to achieve construction cost expectations as well as in securing a low cost of capital. Reducing capital cost and obtaining a low cost of capital both have a first order impact in determining the unit cost of steam delivered. The capital intensity of nuclear projects has historically challenged the capacity of private investment to deal with the magnitude of construction risks. Essentially, all commercial nuclear facilities worldwide have been financed with some form of government or public risk sharing. These include, but are not limited to, incorporation into the rate base for regulated utilities, which was accepted on the basis of long-term environmental and economic benefits provided by these projects. The opportunities for nuclear steam and cogeneration applications, which may become available technically in the near term, may ultimately succeed financially, based on the judicious use of public and private support mechanisms based on the societal need to mitigate climate change impacts of carbon, predictable licensing and financing of build programs, and where applicable price support or special equity arrangements are employed until nth-of-a-kind learning is embedded in the industry.

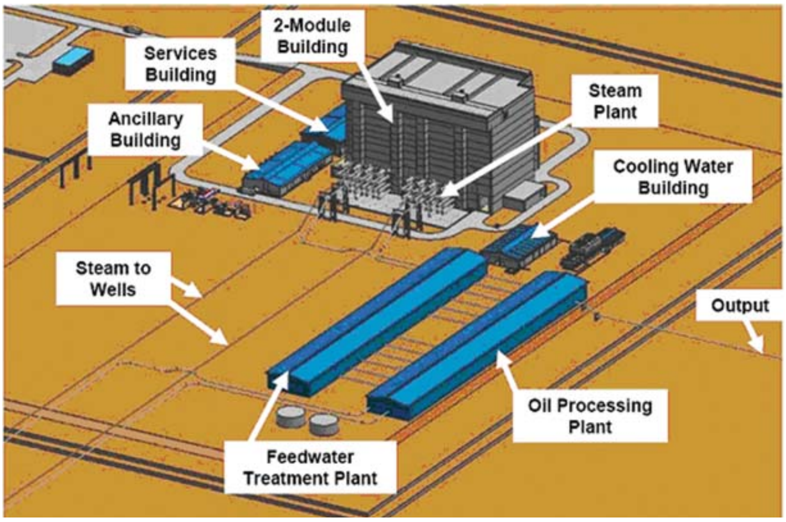

Figure 2 - Example PBMR layout for an oil sands SAGD application

The other principal area of risks that will be critical to commercialization of nuclear steam and cogeneration involves the nuclear regulatory process. Small reactors, like the PBMR, are more vulnerable to the cost of regulatory review and the potential addition of redundant and/or safety features that do not recognize the differences from current generations of reactors. Given the different scales, larger reactors can spread such costs over larger energy production rates. Acceptance of the intrinsic safety characteristics of the PBMR is critical to the economical implementation of this technology. The risk of overregulation is the loss of benefits to industrial users and to the public. In contrast to the light water reactor industry, there is currently little or no regulatory guidance that can be used to determine the safety adequacy of a high-temperature gas-cooled reactor. This means that early reviews of this technology will entail development of regulatory guidance and acceptance criteria probably in an iterative process before the technology can be approved.

3.2 CURRENT INITIATIVES

One of the earliest opportunities for the application of PBMR steam generation is for *in situ* oil sands recovery of bitumen using the Steam Assisted Gravity Drain (SAGD) process. This process injects high-pressure steam into the ground to heat the heavy bitumen crude, thereby allowing it to flow into drain pipes that recover and transport it to the surface for processing. The steam required for this application is typically at a pressure of 12 to 16 MPa, depending on the depth of the deposits. This steam pressure is beyond that normally produced by water-moderated nuclear reactors and thus gives a significant advantage to modular high-temperature reactor plants like PBMR. The output of a PBMR steam unit is also well matched to the incremental energy requirements currently planned for regional oil sands expansion schemes. An example layout for an oil sands SAGD application is shown in *Figure 2*.

Another important potential near-term application of PBMR process heat includes the use of high-pressure steam for enhanced oil recovery where CO_2 injection is not feasible because of the

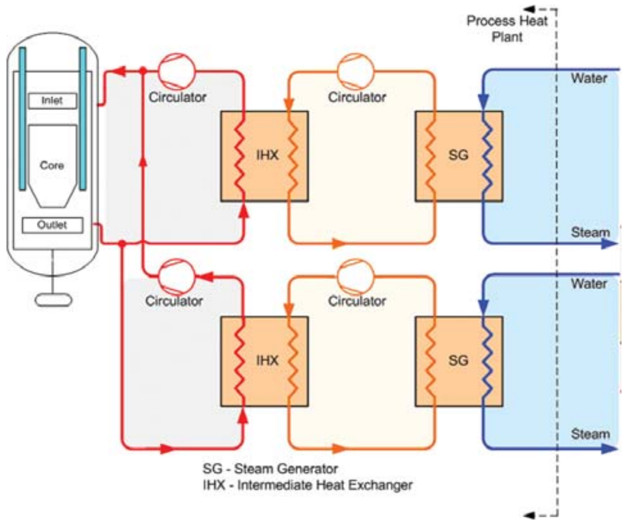

Figure 3 - Process flow diagram for typical steam application

geological formations of the region, and the use of steam in plants that process hydrocarbon feedstocks, such as refineries and coal-to-liquid conversion plants. These processes require large amounts of steam and electrical power, which are well suited to gas-cooled reactors like PBMR. Such reactors can provide steam and power with substantial savings on energy costs, CO_2 emissions, and capital cost of displaced equipment.

3.3 TYPICAL CONCEPT

The process flow diagram shown in *Figure 3* is a typical PBMR process heat configuration for steam production. The reactor configuration being considered here is one with a single PBMR reactor with two parallel primary helium loops, each coupled to its own secondary helium loop and an intermediate heat exchanger (IHX). The secondary loop transfers heat through a steam generator. A secondary loop is chosen for this application in order to isolate the reactor from the possibility of steam ingress or contamination of the primary helium circuit from feed water impurities, and to allow normal (non-nuclear) maintenance on the steam generators during operation of the nuclear plant. The choice of two primary loops gives added reliability to the steam supply in that a maintenance requirement in one loop may not require full shutdown and also results in smaller components that are more easily transported to the plant site.

The hot helium exits the bottom of the reactor and passes through helium-to-helium heat exchangers; circulators located on top of the heat exchangers drive the gas back into the top of the pressure vessel as shown in *Figure 4*. Helium in an intermediate loop (concentric pipes) transfers the heat to a series of process coupling heat exchangers (not shown). The intermediate loop's helium enters and leaves the two secondary heat exchangers via the concentric pipes shown. For steam applications in the 700°C temperature range, the intermediate heat exchangers will be virtually identical to the recuperator of the Demonstration Power Plant that is scheduled for construction in South Africa.

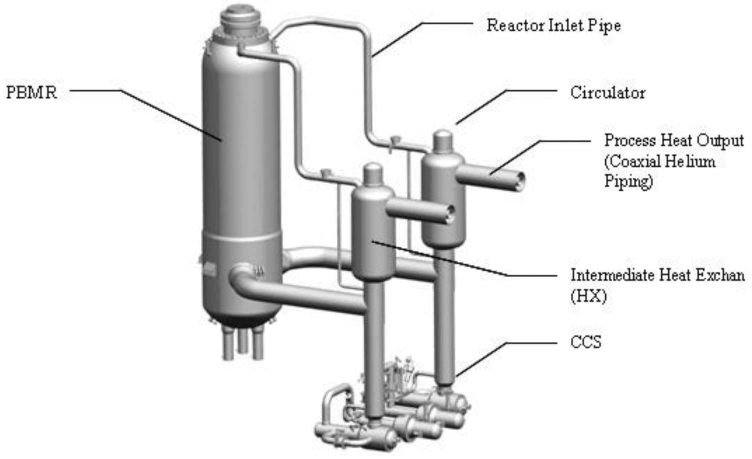

Figure 4 - Typical PBMR steam generation plant design

4. High-Temperature Gas-Cooled Reactor - hydrogen applications

Current hydrogen production technologies include Steam Methane Reforming (SMR); the partial oxidation, auto-thermal reforming and gasification of coal or other organic fuels; and small-scale water electrolysis. The vast majority of bulk hydrogen is produced from fossil fuels with a small percentage of hydrogen derived from water electrolysis for applications where delivery of bulk hydrogen is uneconomical or where low-cost, off-peak electricity is available. One of the most promising long-term markets of the PBMR reactor is to provide high-temperature process heat and/or efficient electricity production for the generation of hydrogen. Hydrogen produced from water using nuclear energy would avoid both the use of fossil fuels and the attendant greenhouse gas emissions (or CO_2 capture/sequestration costs). Hydrogen can be produced from high-temperature nuclear heat by several means. The processes identified by PBMR (Pty) Ltd as the most promising include Steam Methane Reforming, High-Temperature Steam Electrolysis and the Hybrid Sulphur Thermo-Chemical Water Splitting process. In a thermo-chemical process, all the reactants, other than water, are regenerated and recycled. Such thermo-chemical water splitting processes offer the promise of high efficiencies of the order of 45-50%. Water splitting cycles that involve at least one electrochemical reaction step are classified as hybrid thermo-chemical cycles.

4.1 RISK AND OPPORTUNITY

In addition to fuel for hydrogen powered vehicles and a variety of fuel cell applications, the availability of clean non-carbon derived hydrogen holds numerous benefits to industries which rely on hydrogen to build their products, notably coal-to-liquids producers, refineries, and the steelmaking industry. It is expected that co-location of a nuclear thermo-chemical hydrogen production facility with a process facility to produce captive syngas or hydrogen from methane will leverage limited gas supplies and serve as an important practical interim step towards greater use of hydrogen.

Primary economic benefits are derived from the displacement of coal gasification capacity and downstream processing to make the additional hydrogen needed for the product, as well as displacement of expensive oxygen plants used to feed the gasifiers. Given that the scale of PBMR process heat plants is 500 MWt per reactor, many reactor systems will be required to produce sufficient hydrogen and oxygen for a large coal-to-liquids or coal-to-gas facility. Therefore, the capital intensity and construction risk are multiplied by the number of reactors required. However, providing an onsite fleet of reactors introduces the opportunity for additional gains from sharing support systems and efficient integration into the production plant which will reduce the delivered net energy cost. As with other nuclear applications, the "carrying" cost of capital is as important as the total capital cost, and the management of construction risks associated with many billions of dollars of front-end investment will be critical. Given the long-term benefits associated with reduced CO_2 emissions and stable energy pricing, an appropriate mix of government and public support mechanisms are likely to be necessary for commercialization as mentioned earlier.

4.2 CURRENT INITIATIVES

The PBMR team and its partners are currently working on two fronts to apply nuclear process heat to the generation of hydrogen. First, it is working with a prominent international specialty gas company to evaluate the use of nuclear heat to replace heat from burning natural gas in the Steam Methane Reforming process. Secondly, it is working with the US Department of Energy and the Idaho National Laboratory to develop the Next Generation Nuclear Plant (NGNP), which is a high-temperature gas-cooled reactor for the cogeneration of electricity and hydrogen. The initial design and planning studies of the NGNP project have just been completed and the second round of design development studies has been announced. Thus far, pre-conceptual studies of a cogeneration demonstration plant have been completed along with a variety of trade studies, technology roadmaps, R&D plans, and economic analyses of the viability of nuclear process heat to generate hydrogen. Current program plans are to have a full-size demonstration plant operating in the latter part of the next decade.

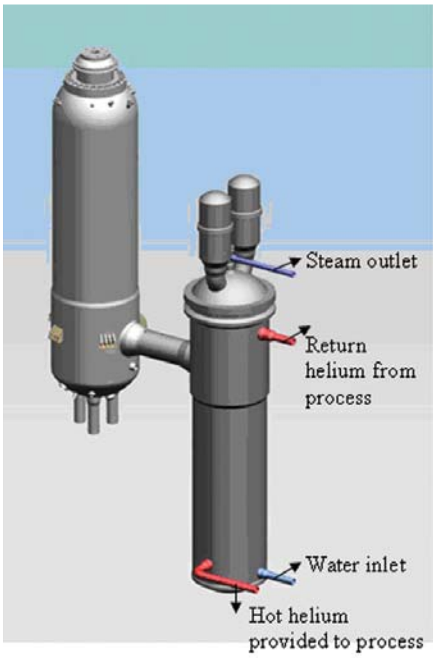

Figure 6 - Typical PBMR SMR plant design

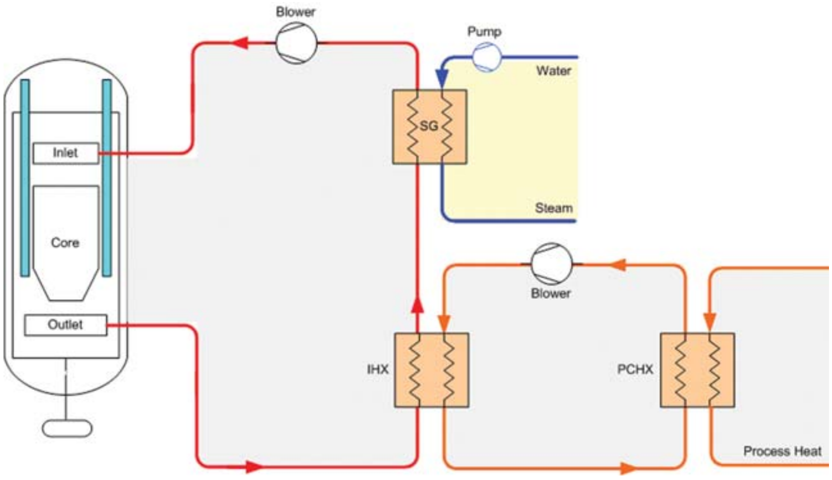

Figure 5 - Process flow diagram for typical SMR application

4.3 TYPICAL CONCEPT SMR

Steam Methane Reforming (SMR) produces syngas ($CO + 3H_2$) by reforming methane with steam. Syngas as feedstock can be used to produce hydrogen, ammonia, methanol and other products. The heat from the PBMR reactor can be used to replace approximately 30% of the natural gas which is burned to get the right temperatures for the endothermic reforming reaction. Nuclear heated SMR would reduce CO_2 emissions and/or sequestration requirements if they become necessary and extend the life of natural gas reserves. Initial economic analyses have shown that PBMR SMR is competitive with new SMR facilities at today's natural gas price and projected CO_2 penalty cost projections in most international markets. The development of plant designs and costs is under way to determine the best points of market entry.

Figure 5 shows a process flow diagram for a possible heat delivery system to a SMR plant. Two heat exchangers are placed on the primary helium loop with the reactor. The first drives an intermediate helium loop to the reformer, while the second is a steam generator. *Figure 6* shows a typical PBMR plant design that can be coupled to a process plant to produce both high-temperature process heat and process steam, where the PBMR reactor is coupled in a series configuration with an intermediate heat exchanger, steam generator and a circulator. The PBMR reactor is located within the pressure vessel to the left. The hot helium from the PBMR reactor outlet transfers its energy (via co-axial piping) first to the intermediate heat exchanger (located within pressure vessel to the right) where after it passes through the steam generator before the circulator returns the helium (via co-axial piping) to the reactor inlet. The piping shown to the right ultimately connects the heat source with the process application.

4.4 TYPICAL CONCEPT THERMO-CHEMICAL WATER SPLITTING PROCESS

The energy crisis of the 1970s instigated a large global R&D initiative in thermo-chemical water splitting processes. More than 200 thermo-chemical cycles have been proposed. As fossil fuels approach record prices, interest in thermo-chemical cycles has been revived. Thermo-chemical water splitting has not yet been commercialized, and international interest is driving R&D and engineering studies on a variety of different technology approaches around the world.

Following a review of the leading options for nuclear water splitting, the PBMR team selected the Hybrid Sulfur (HyS) process as the preferred reference. This process, demonstrated at laboratory scale in the 1970s, uses two thermo-chemical electrolytic reactions that sum to the dissociation of water. HyS uses the same high-temperature sulphuric acid decomposition step as the Sulphur-Iodine (SI) process (currently used, for example, in the Japanese hydrogen program), but replaces the iodine reaction sequence with an electrolytic conversion of SO_2 to H_2SO_4.

$$H_2SO_4 \longleftrightarrow SO_2 + H_2O + {}^1/_2\, O_2 \qquad \text{(>800°C heat required for decomposition of } H_2SO_4\text{)}$$

$$2H_2O + SO_2 \longrightarrow H_2 + H_2SO_4 \qquad \text{(electrolytic conversion of } SO_2 \text{ at 100°C)}$$

Figure 7 shows the process flow diagram of how the heat and electricity from a PBMR (operating as a cogeneration plant) is used to generate hydrogen, oxygen and export the residual electricity to affect the HyS process. The high-temperature heat of the PBMR reactor is transferred to the HyS process via an intermediate heat exchanger (IHX) to the decomposition reactor. The steam is used in a Rankine bottoming cycle to provide input power to the HyS electrolysis step. Any remaining power not used in the hydrogen generation plant is exported to the grid. Alternatively, a configuration could be utilized where a single PBMR is dedicated to process heat and another to electricity production. The Rankine configuration is only a typical representation and does not reflect an optimized solution. *Figure 8* shows the pre-conceptual design of a typical PBMR HyS plant design.

5. Desalination

The supply of fresh water and energy is fundamental to quality of life. Fresh water is needed in agriculture, as drinking water, and in process applications. Because of the growing worldwide population, many regions are faced with increased fresh water demands that greatly exceed the capability of existing supply infrastructures. The problem is compounded by increases in both pollution and increasing salinity of previously accessible fresh water resources. Development of adequate water resources, their conservation, and their preservation have thus become a very important world-wide challenge.

It is generally recognized in most international settings that desalination is an attractive, non-conventional water source to meet rising water demand for the following reasons [2]:

- A large fraction of the populations of water-stressed countries reside near the coast.
- Seawater reserves are practically unlimited for the purpose of desalination.
- Desalination, which was once a high-cost technology for the developed world, is becoming an affordable process, based on high levels of innovation and new technology platforms.
- Desalination costs are still challenging but there remain for some desalination processes further research and innovation opportunities which may offer improved economics.
- Affordable desalination applications occur when low-cost energy (power or steam) is available, e.g. waste heat from a nuclear power generation application.

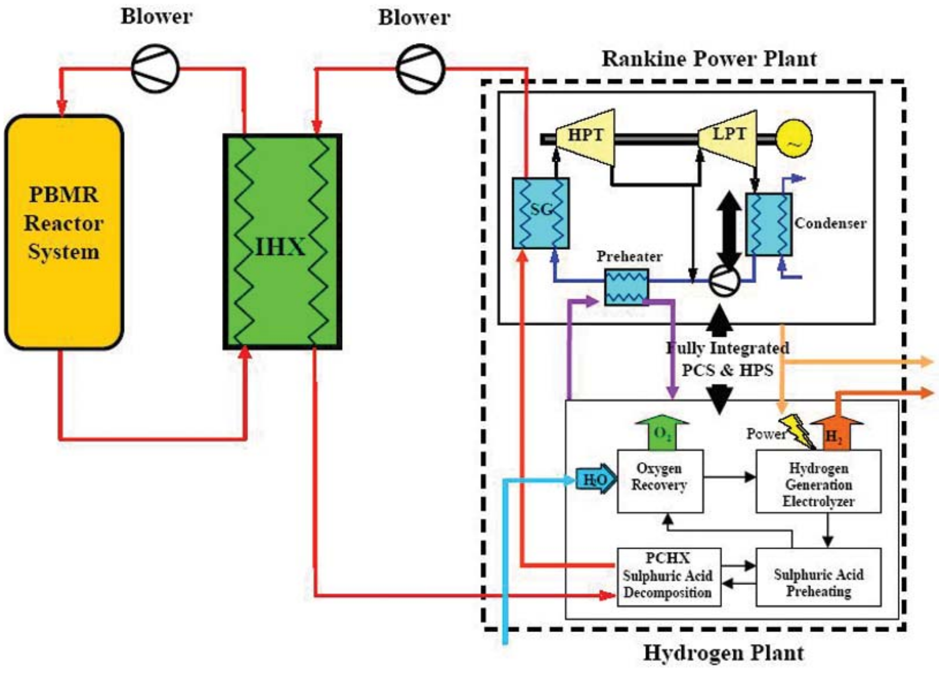

Figure 7 - Process flow diagram for typical HyS water splitting application

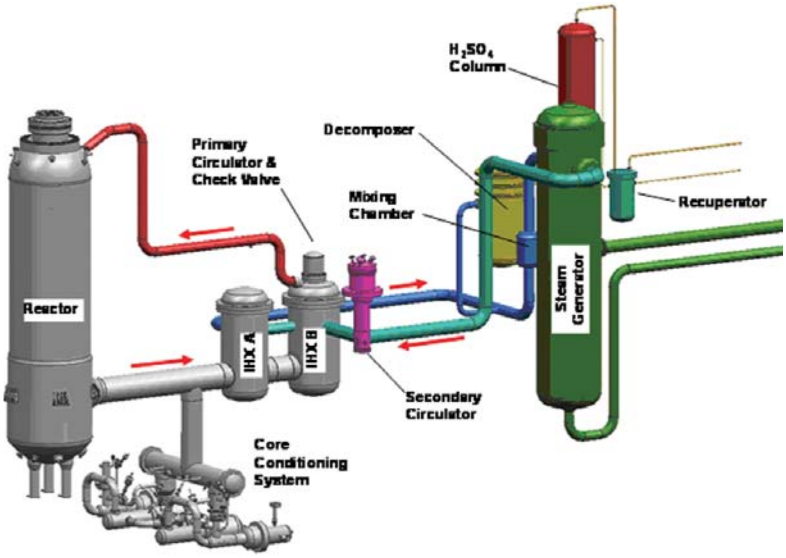

Figure 8 - Typical PBMR HyS plant design

All PBMR process heat applications and electricity applications discussed earlier in this paper will normally have some low-grade waste heat available that, unless otherwise utilized, would be rejected to the environment. The waste heat can be in the form of low-pressure steam or even hot water and can be utilized for nuclear desalination of seawater/brackish and low-grade water sources. Low-temperature multi-effect distillation (LT-MED) is a thermally driven desalination process, which utilizes low-temperature waste heat and incorporates a number of recent technology advances that makes the process very reliable, durable and economical. LT-MED is one of the more efficient thermal desalination processes and produces high purity product water [3] fit for industrial use or human consumption (after passing the product water through a potable water processing system).

Waste heat from a PBMR plant can be effectively utilized for desalination. The amount of waste heat available for this purpose would be specific to the process application. As an example, for the PBMR electric plants (cf. *Figure 1*), the waste heat from the pre-cooler and inter-cooler can be used for desalination. Representative costs resulting from ongoing PBMR evaluations of desalination using LT-MED technology are US\$1.60-US\$2.80/kgal H_2O for 200 MWt waste heat at 60°-70°C rejection temperature and 25 000 m^3/day H_2O total output.

6. Conclusion

The opportunities to expand the use of nuclear energy beyond electricity into process heat applications are extensive with the use of high-temperature gas-cooled reactors such as the PBMR. These applications can touch every part of our daily lives once process industries integrate these heat sources into their facilities to displace high-cost premium fossil fuels. An economic case can be made today (i.e. at today's natural gas prices) to apply nuclear heat to the simplest of these process heat applications - steam generation. However, the predictability and application of sound regulatory processes remains a challenge before such applications can be demonstrated in specific markets and jurisdictions. Given the capital intensive nature of nuclear applications, the economics of early applications will need to rely on appropriate risk management support from the public based on the long-term benefits of this technology to the environment, energy security, and price stability.

High-temperature reactors can assist in the economic generation of bulk hydrogen in the near term by increasing the efficiency of converting methane in SMR plants. Longer term use of heat produced by high-temperature gas reactors such as the PBMR to drive thermo-chemical water splitting plants could provide bulk hydrogen in the future and can also provide hydrogen and oxygen to improve the carbon efficiency of converting solid fossil fuels to make substitute premium gas and liquids. Hydrogen from non-fossil sources can become a key ingredient in many process applications as carbon constraints and natural gas pricing have increasing impacts. However, significant R&D on thermo-chemical water splitting is still needed to make hydrogen generation economical compared to the use of SMR. As CO_2 emissions become monetized and the price of natural gas continues to rise, the incentives for the generation of hydrogen from nuclear heat will increase and help drive the needed R&D.

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