THERMAL UTILIZATION OPPORTUNITIES WITH A SMALL-TO-MEDIUM SIZED BWR

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Abstract

Hitachi-GE Nuclear Energy Ltd. (Hitachi-GE) has developed a conceptual design for a Double MS: Modular Simplified & Medium Small Reactor (DMS) under the sponsorship of The Japan Atomic Power Company. Recent efforts have yielded enhancements for improved safety and reactor core performance. The DMS is an innovative small-to-medium sized Boiling Water Reactor (BWR), which, based only on electricity generation, has been estimated to almost overcome economy of scale concerns when compared to proven conventional Advanced Boiling Water Reactor (ABWR) technologies.

In order to make the DMS more attractive, the University of Saskatchewan (U of S), Hitachi-GE and Hitachi Ltd. (Hitachi) have collaborated on a joint research and development (R&D) initiative to study the utilization of heat and steam from the Balance of Plant (BOP) associated with the DMS for thermal utilization (TU) applications. In this paper, the advanced features of the DMS and the individual projects of the R&D program will be described.

1. Introduction

The importance of nuclear power as an energy source is linked to the needs for energy security and reduced greenhouse-gas emissions. Development of nuclear power plants has primarily targeted large-capacity power generation in order to increase cost efficiency (construction cost per unit power output). On the other hand, demand for small-to-medium sized distributed nuclear reactors is increasing **[1]** due to their lower initial capital cost and the ability to replace other forms of power generation, such as coal or diesel, in similar-sized generating applications that may be off-grid or to avoid major modifications to existing electrical grids. While recent small-to-medium nuclear reactor designs have not yet reached commercial maturity, and their cost-competitiveness with conventional fuels in remote areas remains to be proven, they currently face an economic disadvantage as compared with large scale nuclear plants. Overcoming this disadvantage will be a significant factor in the broad-scale adoption of SMRs.

In Canada, 19 Canada deuterium uranium (CANDU) reactors are currently in operation[1], comprising about 15% of the country's overall generating capacity. Canada is the world's second largest producer of uranium, and all of Canada's uranium is produced in Saskatchewan. Thus, the Saskatchewan government, Hitachi-GE, GE Hitachi Nuclear Energy Americas LLC (GEH), and Global Nuclear Fuel - Americas, LLC (GNF-A) agreed in 2011 to collaborate on R&D projects of mutual interest, including the feasibility of small modular reactor technology and the enhancement of the nuclear energy value chain in Saskatchewan.

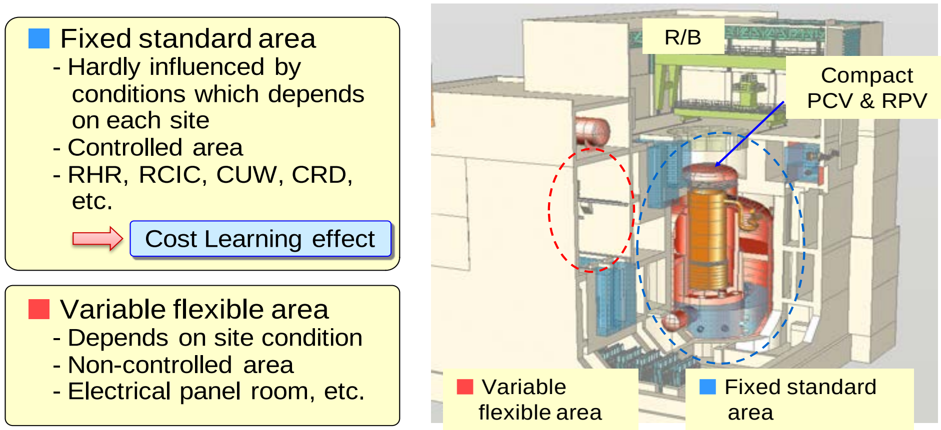
As the base system, Hitachi-GE has selected the DMS reactor **[2]-[6]**, an innovative small-to-medium sized BWR. In order to enhance the DMS design's economic competitiveness, three goals have been chosen: (1) simplification of the plant system, (2) elimination of equipment, and (3) standardization of the plant layout and modular installation method.

The University of Saskatchewan is leading the initiative to study the utilization of heat and steam from the Balance of Plant (BOP) associated with the DMS for TU applications. Although these applications will be studied on the basis of Saskatchewan TU application characteristics and climate conditions, the long term objective is to have techno-economic models that can be applied in other locations around the world. This R&D program includes (1) assessments of TU applications related to enhanced heavy oil recovery, district heating, desalination, and greenhouse horticulture, and (2) development of conceptual designs for suitable intermediate heat exchanger systems between the DMS BOP and these TU applications.

2. Features of DMS

Figure 1 shows a bird's-eye view of the Reactor Building (R/B) of DMS. The DMS has been designed by using well-developed technologies that are utilized in the large conventional ABWR. Furthermore, in parallel with enhancing accident tolerance, the design has been simplified and made more compact to overcome the scale disadvantage. There are fixed and variable areas in the R/B design. The fixed area is only marginally influenced by the circumference of the reactor vessel and standardization is possible at the design stage. The Compact Reactor Pressure Vessel (RPV) and Primary Containment Vessel (PCV) comprise the core of the design. Standardization in this area increases the cost learning curve effect, but this portion of the design is variable in order to optimize the reactor characteristics for the specific customer requirements.

[1] As of Summer 2014, ten reactors are operational at Ontario Power Generation, eight at Bruce Power, and one at New Brunswick Power.



RHR: Residual heat removal system, RCIC: Reactor core isolation cooling system,
CUW: Reactor water clean-up system, CRD: Control rod drive (system)

Figure 1 Bird's-eye view of R/B

Table 1 shows the DMS design specifications compared with those of an ABWR. The electric power generation capacity can be modified easily by changing the number of fuel assemblies and control rods, because there are no complex internal components such as a steam generator or an internal control rod drive in the RPV. A natural convection circulation system and free surface separation system have been adopted to create a compact pressure vessel. It is important during a reactor core design to evaluate the core thermal margins, MCPR (Minimum Critical Power Ratio), and MLHGR (Maximum Linear Heat Generation Ratio). For a DMS core with 10 x 10 fuel assemblies, the power density is lower than that of the ABWR, so that the DMS core has a sufficiently large thermal margin. The operation cycle length is 24 months, which is suitable for the US regulatory regime, but the operation cycle length can be lengthened by changing the reactor core size and the batch size.

Table 1 Specification of DMS and ABWR

Items	DMS			ABWR
Electric power (MWe)	210	300	428	1356
Core pressure (MPa)	7.2			7.2
Recirculation system	**Natural circulation**			10 RIPs*
Steam to water separation	**Free surface separation**			Separators
Number of fuel assemblies	284	400	568	872
Number of control rods	69	97	137	205
Active fuel length (m)	2.0 (short length fuel)			3.7
Power density (MW/m^3)	44			50.6
Operation cycle length (months)	**24 (Over 24 is also possible)**			13**

*RIP: Reactor internal pump **Current operation cycle length in Japan

Figure 2 shows the RPV of the DMS compared with an ABWR. The DMS adopts a design that not only eliminates Reactor Internal Pumps (RIPs), but also maximizes the advantage of a natural circulation system. The short length of the fuel rods causes an increase of the core flow rate, resulting in low core pressure drops and a high design margin for core stability. The short fuel rods create a further reduction of RPV height because the lower core pressure drop reduces the required chimney height. The low power density leads to a low upward steam velocity at the liquid-steam interface in the RPV, and enables steam separation from the steam-liquid mixture by gravity alone. This allows the free surface separation system to be applied to the DMS and eliminates steam separators used in the ABWR. The steam flows through a dryer to eliminate the remaining liquid, and the very low humidity steam is supplied to the steam turbine system. As a result, the use of short fuel rods and low power density reduces the number of floors necessary in the R/B, resulting in a shorter construction period and lower construction cost.

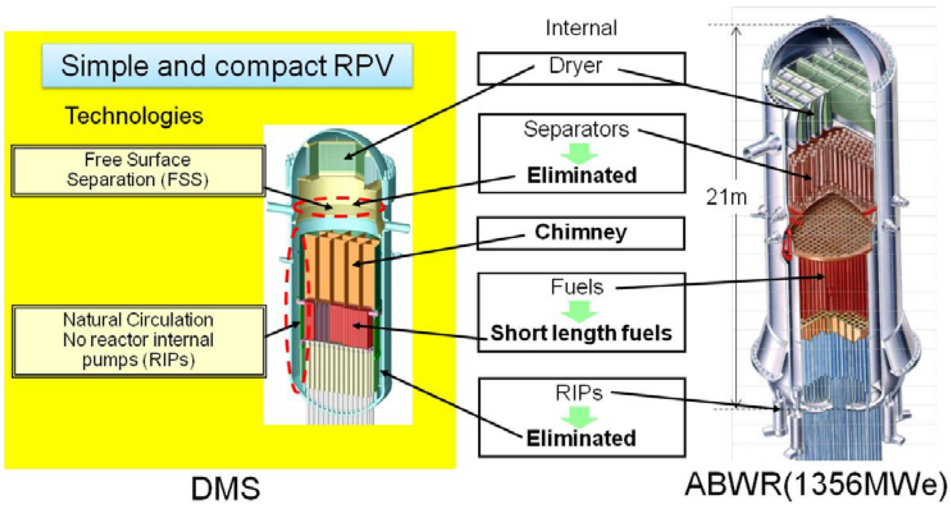


Figure 2 RPVs of DMS and ABWR

2.1 Advanced Reactor Core Design

In the case of conventional BWRs such as the latest ABWR, core power is controlled to the rated value in three ways: controlling the amount and arrangement of burnable poison such as gadolinium (Gd) in the fuel assembly, inserting or withdrawing the control rods (CR) and changing the core flow rate via the RIPs. Since the DMS is a natural circulation type BWR, the core power is controlled by the control rods and the burnable poison. The BWR type core has a strong void reactivity feedback as an inherent characteristic and thus the core power of the DMS can be set solely by the design of the Gd poison. However, it is challenging to keep core power constant using only the Gd design because the amount and the arrangement of Gd are not controllable during plant operation, which means the Gd poison design has to take into consideration how the Gd will burn in the core during operation.

In order to suppress the core power fluctuation during CR free operation, the Gd distribution is optimized in the fuel assembly. Lower concentration Gd fuel is inserted at the axially lower part of the fuel assembly, which contributes not only to core power flattening from the beginning of cycle (BOC) to the middle of cycle (MOC), but also to core power increase at the end of cycle (EOC) due to the spectral shift effect which is one of the inherent features of BWR type core. As a result, the core power fluctuation of the DMS during CR free operation can be suppressed significantly as shown in Figure 3.

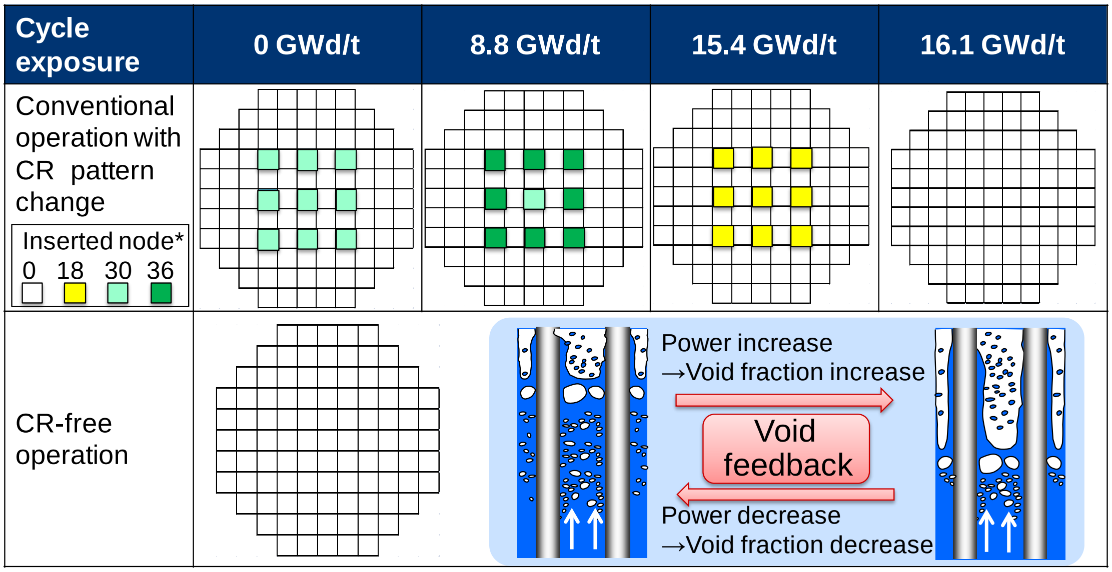


Figure 3 Concept of CR free operation

2.2 Free Surface Separation (FSS) System

Since the DMS uses a natural circulation system and the power density is relatively low, the steam evaporation rate is so low at the core outlet that the steam and water droplets can be separated by gravitational force. According to past experiments **[7]** and a semi-theoretical study **[8]**, steam separators are unnecessary if the steam evaporation rate is low and the height of the separation region is large. From these results, a gravity-based steam separation system (the FSS system) was proposed for the DMS. As shown in **Figure 4**, steam velocity at the surface of the water is estimated to be about 0.7 to 1.0 m/s. Setting the height of the separation region at 2.5m reduces the mass ratio of water droplets in steam to less than 1%, which is sufficient for a steam dryer to remove the remaining water droplets. The adoption of the FSS brings various advantages to the DMS. Since elimination of the steam separator decreases the pressure drop of the natural circulation loop, the chimney height required for natural circulation can be reduced. In addition, core internal components can be simplified, and the annual inspection period can be shortened.

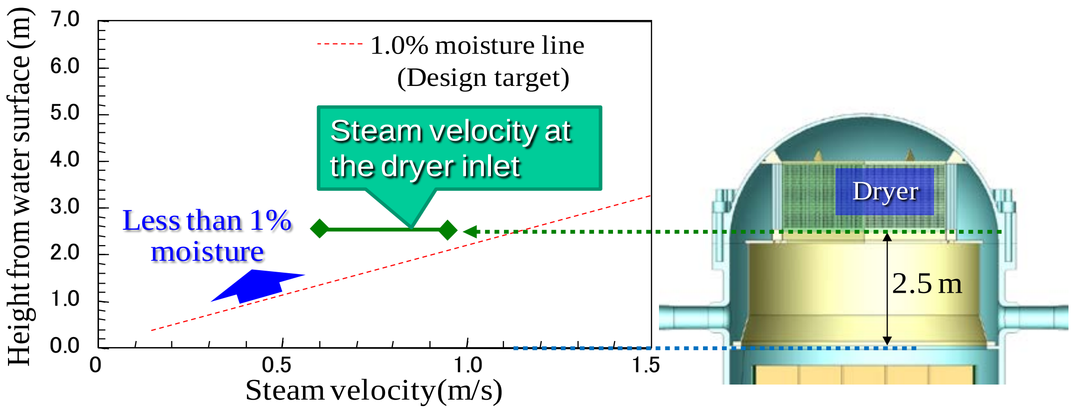


Figure 4 Free Surface Separation (FSS) system implemented on the DMS

2.3 Modular Installation

In order to reduce the investment risk by shortening the construction period, a modular installation concept is applied to the DMS. The modular installation concept is shown in **Figure 5**. Modules such as the “multi-floor module of electric panel room” and “compact PCV steel wall with shielding wall” are made in factories. The internals of the Compact PCV with shielding wall are fabricated as large blocks and assembled into modules in the factory, moved by truck or rail, and installed on site. The reduced amount of on-site fabrication (*e.g.* pouring reinforced concrete) substantially reduces the construction period.

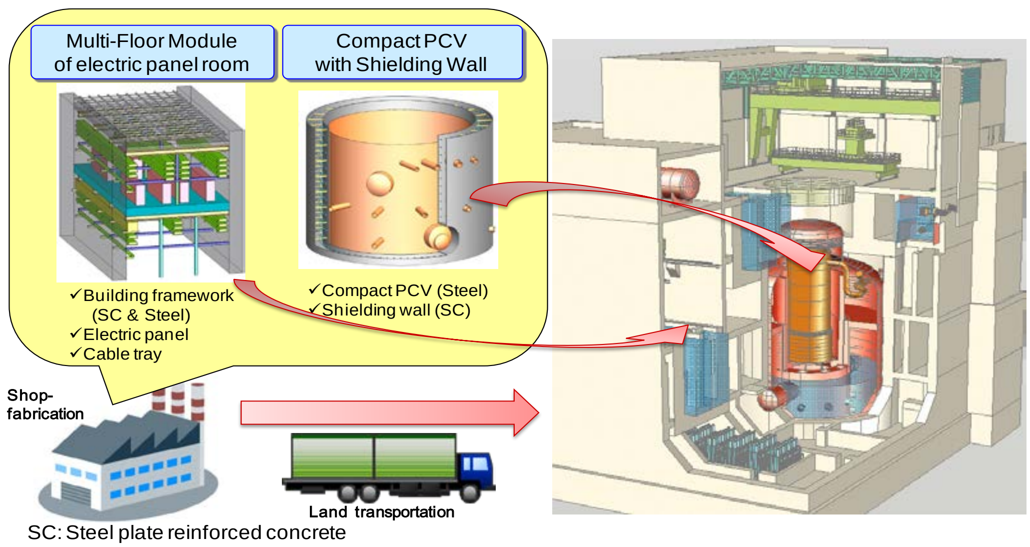


Figure 5 Modular installation concept

3. R&D Program of Thermal Utilization Applications

In collaboration with Hitachi-GE and Hitachi, and with the support of the Province of Saskatchewan, the U of S is conducting a number of projects investigating uses for the heat output of a small modular reactor.

3.1 Intermediate Heat Exchanger and Downstream Heat Exchanger Network Design

In the Intermediate Heat Exchanger (IHX) project, Drs. Carey Simonson and Gaoming Ge of the U of S and Eur Ing Andrew Aikman of SNC-Lavalin are working with Hitachi-GE to study how the heat exchanger network in the BOP of the SMR can be designed to flexibly and efficiently supply heat to meet the needs of users.

The heat exchanger network, consisting of the BOP heat exchanger (HX_{BOP}), IHX and the heat exchangers that deliver heat to the thermal utilization applications ($HX_{A,B,C, \ldots}$), must operate in energy-efficient and cost-effective ways to keep the overall system and energy (thermal and electric) costs low. This is a complex design and optimization problem for heat exchanger networks. The SNC-Lavalin team will focus on the design of the IHX, in order to accommodate a wide range of potential upstream heat characteristics and downstream TU applications. This will require the analysis of a broad range of potential heat exchanger types, fluid media and configurations, leading to element testing and analysis of the IHX system performance.

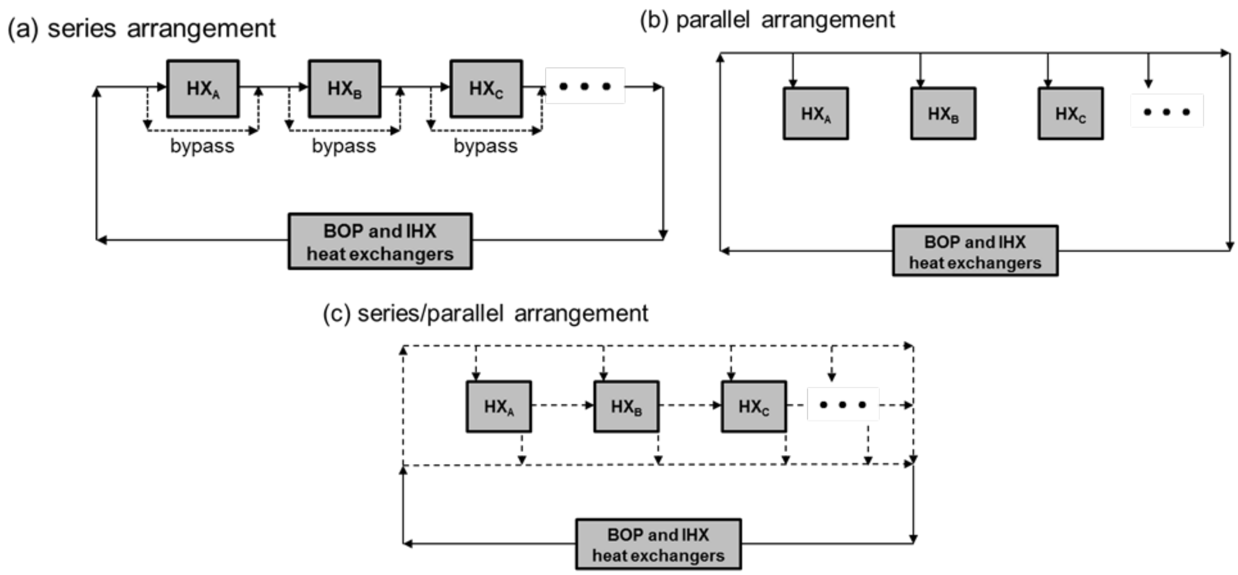


Figure 6 Schematic of a (a) series (b) parallel and (c) series/parallel heat exchanger network transferring heat from a BOP heat exchanger to multiple heat exchangers ($HX_{A, B, C, \ldots}$) that service thermal utilization applications A, B, C, ...

Figure 6(a) shows a schematic where all the TU applications downstream of the IHX require heat at all times and can be arranged in order of cascading energy quality needs. That is, thermal utilization application A requires the highest quality energy input (*i.e.*, the highest temperature) of all the TU applications. The fluid flows serially through exchanger A (HX_A), which serves application A, into HX_B, HX_C and so on until the fluid is returned to the IHX to be reheated and recirculated. In the simple series arrangement of Figure 6(a) each heat exchanger receives the same fluid flow but the temperature entering each heat exchanger is different.

Figure 6(b) shows the case where each TU application requires the same or similar quality of energy and therefore the application heat exchangers are arranged in parallel. Figure 6(c) shows a combination of the series and parallel (series/parallel) arrangement. This arrangement is the most complex to design and optimize but will allow more efficient heat utilization compared to the series or parallel arrangements, particularly when the TU applications are diverse (*i.e.*, the applications require different energy qualities and have different operating schedules).

The objective of this simulation study is to design series, parallel and series/parallel heat exchanger networks for feasible and optimal use of waste heat. The simulation will aim to be as realistic as possible with regards to quantity and quality of energy produced by the BOP and required by the TU applications. Initially, assumptions regarding the possible TU applications will be required to expedite the project. As more details of the energy requirements of TU applications become available through collaboration with SNC-Lavalin and the other project teams these details will be used to make the simulation more realistic as time and resources permit.

3.2 Process Heat

If there is heat to be consumed, then there needs to be an understanding of who the potential consumers might be, and a characterization of the quality and quantity of heat needed by various consumers. Understanding the needs of consumers and communities impacts decisions about siting, the proportion of energy devoted to electricity generation versus heating and the design and configuration of the heat exchangers required to deliver heat to consumers.

In order to understand representative industrial uses of the heat available from a nuclear reactor, Mr. Ray Knudsen, P.Eng, is leading a team at LeanOptions Consulting (LOC) to investigate the process heat requirements of a variety of Saskatchewan industries as a proxy for industries in similar geographies.

The work focuses on the following three areas:

- Determining the actual thermal energy utilization parameters for industrial processes at selected Saskatchewan industries;
- Summarizing the industrial thermal energy utilization parameters and provide details to the project participants involved in Balance of Plant (BOP) and (IHX) engineering design and related research activities, and
- Conducting engineering economic analysis to determine the potential economic impact of using waste thermal energy from a BWR/SMR in the selected industrial processes.

3.2.1 Determining Thermal Energy Requirements for Selected Industrial Processes

This phase of the work program involves identifying and interviewing existing industries in Saskatchewan that use thermal energy in their processes, determining the quantity, quality, flow rates/volumes, temperature/pressure requirements and the unit cost of their current thermal energy production/usage. As well, their capacity to utilize additional waste thermal energy in their processes will be assessed.

Targeted industries include heavy oil enhanced recovery projects in the Lloydminster-Kindersley area of West-central Saskatchewan; petroleum refining/heavy oil upgrading facilities at Regina, Lloydminster and Moose Jaw; and solution potash mining, fertilizer production and ethanol facilities located in the Belle Plaine area, between Regina and Moose Jaw.

3.2.2 Summarizing Thermal Energy Requirements

The results of information gathering and parameter analysis will be compiled and provided to the IHX heat exchanger network design project. The specific thermal energy utilization parameters for those industries that contribute to the requirements gathering phase will be compared to the potential thermal energy that may be available from an SMR.

During this project, LOC will facilitate liaison between the research and engineering team and the potential industrial end-users that contribute their process specifics to the project.

3.2.3 Conducting Engineering Economic Analysis

Certain TU applications may require more energy than a SMR can provide. Therefore, this project will determine the level of economic impact of waste heat, steam or water from a SMR for industrial processes including Heavy Oil Enhanced Recovery including SAGD (steam assisted gravity drainage), CSS (cyclic steam stimulation) and SF (steam flooding) projects, refineries, solution potash mining projects, fertilizer plants and biofuels (ethanol) plants.

Tasks 2 and 3 of this project interact with the IHX network design. As the engineering design and research activities progress, the simulation study output will be provided to LOC to integrate into the economic impact analysis process.

The potential synergies of the combined Belle Plaine industrial applications will also be included in this economic analysis.

3.3 Heat Utilization for Greenhouse Applications

Aside from industrial uses, there are other potential uses of SMR heat and steam, notably agricultural and residential consumers. In the Heat Utilization for Greenhouse Applications project, Drs. K. Tanino and H. Guo are investigating the heat requirements of greenhouses in northern climates, and are making a comparative analysis of greenhouses which employ waste heat and greenhouses designed to be heated primarily by solar gain.

3.3.1 Background

Sustainable regional food production has great potential to create economic development and enhance regional food security in remote communities. Northerners in Saskatchewan consume relatively low quantities of nutritious fruits and vegetables because of high food and transportation costs: typically 2.5X the cost of a similar perishable item in Saskatoon, making it unaffordable to many people in Northern Canada. Produce is generally transported from South America and Southern North America, which is costly and affects quality, but also has a large environmental footprint.

Greenhouses are used to grow a significant number of valuable crops, but in regions of extreme cold such as the Canadian Prairies and North, traditional greenhouse designs require a large amount of supplemental heat and thus are economically infeasible.

A design which integrates energy saving principles and uses alternative energy sources can reduce heating costs. Moreover, Saskatchewan has the highest number of sunshine hours of any provinces and this can be more effectively capitalized through solar greenhouse technology, which can then offset the need for supplemental heat by up to 80%. Solar greenhouses developed in China use a number of innovative techniques, and can provide suitable growing conditions with little or no supplemental heat. These designs require adaptation to meet Canadian greenhouse requirements, *i.e*. automated environmental control and mechanized cultivation.

3.3.2 Objectives

The major goals of the project are to design a large conventional greenhouse as a regional food hub to supply produce to multiple communities using waste heat from an SMR; and to design an energy efficient solar greehouse (Chinese solar greenhouse) for remote Northern communities.

The objectives of the project are:

- Conceptual design of a large conventional greenhouse as local food hub including designing the indoor environment control system for year-round production in high latitudes, including heating and ventilation systems, lighting and CO2 enrichment, *etc*.;
- Develop a computer model to predict heating energy requirements based on historical weather data in three selected locations (Belle Plaine, Prince Albert, La Ronge), type of greenhouse and crop selection;
- Conduct economic feasibility analysis of greenhouse operations considering capital costs; operating costs; and waste heat availability and utilization, and predict profits based on estimated crop price ranges and yields;
- Design the energy efficient greenhouse (Chinese solar greenhouse) including heating and ventilation system, lighting and other environmental control measures, and
- Evaluate the energy savings potential and economic feasibility of an energy efficient greenhouse.

3.3.3 Outcomes of the project

- The project will provide information on economically efficient greenhouse size, crops, yield and overall productivity using waste heat for a conventional greenhouse and an energy efficient greenhouse at a high latitude (49 to 55°N);
- A computer model which will predict the heating energy costs at a given location, based on the type of greenhouse, sustainable heating source, and crop type, and
- A business case will be developed to determine if growing vegetable crops through greenhouse technology using waste heat is economically feasible based on sales at Saskatoon prices.

3.4 District Heating

Another low-intensity use of heat produced as a by-product of nuclear power generation is district heating – providing the heat to residential and commercial consumers for building heat and hot water. In the District Heating (DH) project, Dr. C. J. Simonson is working with Hitachi-GE to determine the applicability of District Heating in a region such as Saskatchewan.

DH is widely used in many northern countries to improve the efficiency of power plants. R&D from other cold climate jurisdictions will be reviewed and applied to Saskatchewan to determine if district heating is feasible. Especially important will be Finland and Sweden where district heating makes up about 50% of residential heating market **[9]**. Since significant investment would be required to heat existing homes throughout the province (large piping networks in the province and retrofitted HVAC equipment in the homes), this project will focus on using DH in clusters of new residences.

The objective of this study is to determine the feasibility of using waste heat from an SMR BOP to heat new residential buildings in Saskatchewan. The project will consider three scenarios: (a) a new community in northern Saskatchewan (*e.g.*, close to a mine), (b) a new community in southern Saskatchewan, and (c) a new community close to a major city in central Saskatchewan.

In each scenario, the heat requirement of the residences will be estimated and the number of homes that could be heated with waste heat from a SMR will be determined. In addition, the heat loss in district heating networks will be analyzed and the energy requirements (quality and quantity) will be determined for space and domestic hot water (DHW) heating in the three scenarios. The economics of DH will be determined considering the equipment cost for the utility to deliver DH (piping, insulation, HXs, controls, *etc.*) and the payback period for the DH investment will be determined.

3.5 Desalination

3.5.1 Introduction

Principle Investigators Dr. J. R. Humphries and Professor A. Dalai will conduct an assessment of the uses of thermal energy in the form of steam and/or hot water from the Hitachi-GE SMR.

There is a long history of using nuclear reactors in cogeneration or heat-only facilities. This project will focus on nuclear desalination and water purification. In the context of this project 'nuclear desalination' is taken to mean the desalting of brackish water or purification of contaminated water in a facility in which a nuclear reactor is used as the source of energy for the desalination process. Electrical energy, thermal energy or a combination of electrical and thermal energy may be used in the desalination process. A nuclear desalination facility is an integrated facility in which both the reactor and the desalination system are located on a common site and energy is produced on-site for use in the desalination system.

3.5.2 Scope of Work

- **Design data collection**: The first activity that needs to be carried out is to collect information on the Hitachi-GE SMR design.
- **Desalination technology review**: A literature review will be carried out to assess the current state of the art in desalination technology. Advances have been made in recent years in the design and materials for both Reverse Osmosis (RO) and Multi-Effect Distillation (MED), the two predominant desalination technologies. Of particular importance in this project is their suitability for coupling with the Hitachi-GE SMR in a nuclear desalination facility.
- **Desalination technology selection**: Desalination technologies will be reviewed and the processes to be evaluated will be selected based on operability, safety and cost considerations
- **Site selection:** The intended application for a nuclear desalination facility, such as desalting brackish water or purifying contaminated water, affects both its design characteristics and the characteristics of the coupling between the reactor and the desalination plant. These will be considered in selecting two representative Saskatchewan 'sites' that will serve as the basis for setting a number of the input parameters for the study.
- **Technical Evaluation of the Coupling**: When a nuclear reactor is used to supply thermal energy for desalination, the method of coupling has a significant technical and

economic impact. The optimum method of coupling depends on the reactor design, the specific characteristics of the desalination process and the value of electricity generation as a co-product. The Hitachi-GE SMR will be evaluated based on the two sites selected above.

- **Safety and Licensing Considerations**: This task will include a limited assessment to provide a preliminary determination of whether an integrated nuclear desalination facility based on the Hitachi-GE SMR can meet Canadian licensing requirements and to identify any areas of particular concern.
- **Economic impact analysis**: A preliminary economic impact analysis will be carried out using the Hitachi-GE SMR in an integrated nuclear desalination facility.

3.5.3 Project Outcome

The results of this work will provide a preliminary assessment of whether there is sufficient economic impact to warrant further consideration and evaluation of the Hitachi-GE SMR in an integrated nuclear desalination facility.

4. Conclusions

The U of S, Hitachi-GE and Hitachi are collaborating on a joint R&D initiative to study the utilization of heat and steam from the Balance of Plant (BOP) associated with a small-to-medium sized reactor for TU applications. Small-to-medium sized reactors are expected to supply not only electricity but also heat for customers as a distributed local power source. As the base plant, Hitachi-GE has selected the DMS, an innovative small to medium-sized BWR which approaches cost competitiveness with conventional BWR reactors. As described in this paper, the DMS has a potential for simple operation (section 2.1), simple plant design (section 2.2), and simple construction (section 2.3).

In order to enhance the DMS cost competitiveness, projects led by the U of S are investigating the feasibility of representative TU applications, such as district heating, industrial process heat, desalination and greenhouse agriculture, as well as researching highly flexible heat exchange networks to optimize the delivery of thermal energy from an SMR.

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