THE FEASIBILITY OF USING THE 25MW SUPER NEAR BOILING NUCLEAR REACTOR (SNB25) TO PROVIDE THERMAL AND ELECTRICAL ENERGY FOR A LARGE CANADIAN FORCES BASEIN THE CANADIAN ARCTIC

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ABSTRACT

A feasibility study of a power plant using the Super Near Boiling 25 MWt (SNB25) nuclear reactor as a heat source and capable of supporting the electrical and thermal requirements for a base the size of Canadian Forces Base (CFB) Kingston in the Arctic was carried out. Such a power plant would allow the Canadian Armed Forces (CAF) to have a self-sustaining operational base in the Arctic to conduct Search and Rescue (SAR) and sovereignty missions.

The thermal and electrical requirements for a base the size of CFB Kingston are determined to be 31.63 MWt and 7.16 MWe, respectively. Using the Heating Degree Days (HDD) approach to account for temperature differences between Southern Ontario and the Arctic, a base the size of CFB Kingston in the Arctic would require 75.16 MWt to operate. A chemical engineering software program, UniSim, was used to simulate the energy cycle of the base which consisted of a district heating loop to provide hot water and an Organic Rankine Cycle (ORC) using n-pentane as the working fluid to provide the electrical energy. The UniSim simulations determined that the cycle would use six shell and tube heat exchangers, two axial gas turbines coupled to generators, and twelve centrifugal pumps, in addition to a group of five SNB25 reactors that could provide 25.03 MWt and 2.63 MWe to a base in the Arctic with energy requirements about a third of those of CFB Kingston. The design foresees redundancy which is essential to safe operation in the Arctic.

1. Introduction

Canada's sovereignty in the Arctic is becoming an increasing concern. The Arctic sea floor and islands hold promise of significant oil and gas deposits, while shrinking ice caps are expanding useful transport routes that are of great interest to powerful countries such as Russia and the United States. To protect Canadian soil, it is important that the Canadian military displays a significant presence in the far North. Presently, the Prime Minister of Canada has stated the nation's commitment to the Arctic. "The geopolitical importance of the Arctic and Canada's interests in it has never been greater. This is why [the Canadian] government has launched an ambitious Northern Agenda based on the timeless responsibility imposed by our national anthem, to keep the '*True North strong and free*' [1]. Communities in the far North lack access to roads, natural gas pipelines and power grids, which are the usual methods of providing power and electricity. Although there is a station in Alert, Nunavut, a larger and more operational base that has access to a consistent fuel source is required to conduct effective sovereignty missions. Due to the harsh environment in the Arctic, including cold temperatures, very high winds and insufficient daylight, CFS Alert only receives fuel supplies twice a year during Operation

BoxTop [2]. A CFB the size of Kingston uses between 7.0 MWt to 31.6 MWt [3] for heating for the summer and winter seasons respectively. The electrical power requirement for a large CFB is estimated at 7.6 MWe [4]. Without even considering the difference in temperature and therefore thermal energy requirements between a location in southern Ontario and the Arctic, it is not logistically viable to bring fuel supplies semi-annually from southern to northern Canada to adequately supply a large base. In addition, the use of fossil fuels contributes to carbon emissions and it would be beneficial to explore different fuel sources that are less harmful to the environment. For this reason, nuclear reactors have been researched as more realistic fuel sources for a large CFB in the Arctic. The Super Near Boiling 25 MWt Nuclear Reactor (SNB25) [5], conceptually designed by LCdr Stephane Paquette, is seen as a viable candidate for this project. The hot water from the reactors would supply heat to two separate cycles: an Organic Rankine Cycle (ORC) to produce electricity and a heat transfer process to provide hot water for district heating. The aim of this design project is to verify the feasibility of using the thermal energy supplied by a maximum of six (6) SNB25 reactors to support the electrical and thermal requirements of a base the size of CFB Kingston in the Arctic, while taking redundancy into consideration.

2. Background

2.1 Organic Rankine Cycle

The Organic Rankine Cycle (ORC) [6] is a process of generating energy by expanding a high pressure organic fluid over a turbine. The necessary equipment for a simple Rankine Cycle includes a heater (2), turbine (3), condenser (4), and pump (1) as seen in Figure 1. The heater evaporates the organic fluid from a liquid into a vapour which then proceeds to expand over the turbine. The turbine converts the expanding vapour into electrical energy by rotating a shaft which is then connected into a generator. This vapour then moves through the condenser where it is cooled to below the fluid's boiling point. Having the fluid in the liquid form facilitates its transportation around the cycle. The pump is the driving force that keeps the fluid in motion around the cycle, as well as pressurizes the fluid before entering the turbine. The fluid is then pumped back to the heater and the cycle begins again.

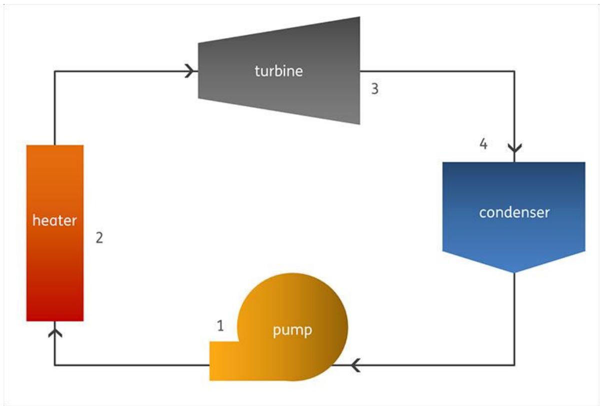

Figure 1: Organic Rankine Cycle.

2.2 SNB25 Nuclear Reactor

The Super Near Boiling 25 MWt (SNB25) nuclear reactors are used in this design project as the thermal energy supply to provide heat and electricity for a base in the Arctic. The reactors were conceptually designed by LCdr Stéphane Paquette for his Masters of Applied Science in Nuclear Engineering degree [5]. The aim of this project was to design a small inherently safe nuclear reactor to supply district heating and electrical energy to Canadian Forces bases located in the Arctic or Northern remote communities, such that the base would not have to be reliant on fossil fuels as a source of energy. This eliminates the challenge and cost of transporting fuel on a consistent basis to a base in the Arctic as the reactor only needs to be refuelled once every 12 years, which also contributes to DND environmental efforts to limit fossil fuel consumption. As illustrated in Figure 2, the reactor core is hexagonal in shape, with a radius of 93.9 cm and a height of 150 cm. The SNB25 operates at a pressure of 1 atm and is fuelled by 300 kg of uranium dioxide TRISO fuel particles, with a 20% enrichment of U-235. TRISO fuel particles are 1 mm spheres containing a uranium dioxide (UO_2) fuel kernel enriched to 20% and surrounded with four consecutive carbon coatings [7]. The first layer is a porous carbon buffer which absorbs the gaseous fission products that build up inside the kernel. The Inner Pyrolytic Carbon, Silicon Carbide and Outer Pyrolytic Carbon layers (second, third and fourth layers respectively) act as a pressure vessel to contain the gases produced by fissions, as well as a barrier for metallic fission products [7]. The reactor moderator and coolant is light water, which enters the top of the reactor at 30^0C and is then routed to enter the core at its bottom, to finally exit the top of the reactor at 95^0C at a flow rate of 63.45 $kg \cdot s^{-1}$, ensuring the core is always filled with coolant. The reactor is surrounded by six 15 cm beryllium moveable reflector plates which act as a moderator and improve the neutron economy of the reactor. The SNB25 can run in automatic mode, monitored by operators with limited training due to its inherent safety. The SNB25 is inherently safe due to its low pressure operating conditions and its inability to self-sustain an uncontrolled chain reaction. This ensures that if control is lost, the reactor will not become supercritical and incur damages leading to the release of radioactive material.

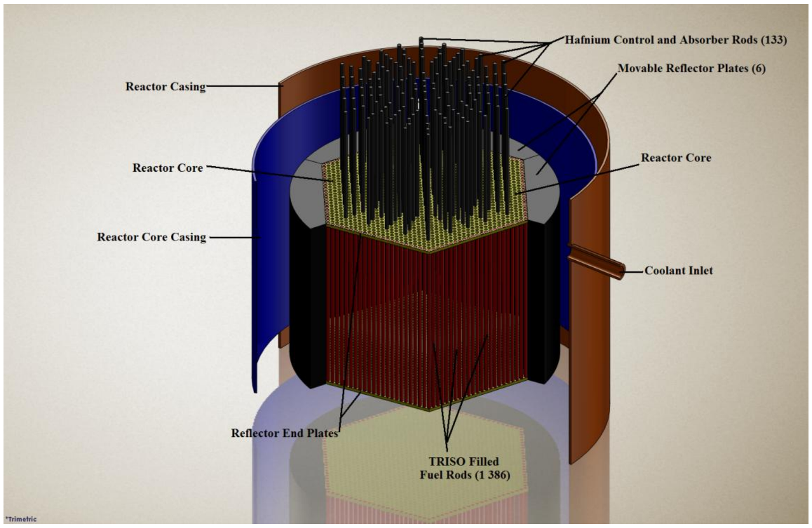

Figure 2: Configuration of the SNB25 nuclear reactor [8].

2.3 Choice of Location

Three areas were researched as possible locations for a CFB Kingston sized base in the Arctic. Alert, Nanisivik, and Resolute Bay were all considered and compared in order to determine which location would be the most suitable for a large CFB in the Arctic. The location's sovereignty influence was initially considered the most important factor because it was a significant reason this project is being investigated. The location must display a prominent Canadian presence in order to serve its purpose. Previous military connections are also significant as constructing a fully operational base in the Arctic will be expensive and time consuming for the Canadian military. If there were already a station or post present, it would decrease the amount of time and resources required to construct the base. The location's weather conditions and civilian population support are not weighted heavily considering the fact that anywhere in the Arctic will have unfavourable weather conditions that will affect base operation in the same way, no matter the location. The low density population will not be greatly affected by a military presence, and no resistance to outposts in the Arctic have been made clear by the civilian Inuit population in the past. CFS Alert is the most northerly, permanently inhabited location in the world and was officially taken over by the Canadian Air Force April 1, 2009. Since then, the station has performed signals intelligence, geotechnical, and sovereignty operations [9]. The Prime Minister of Canada, the Right Honourable Stephen Harper, has announced plans to develop an Arctic deep-water port in 2007 at Nanisivik, which would serve to re-fuel Arctic vessels travelling in the Northwestern Passage. However, construction has not yet begun and the station is not expected to be operational until 2016. Resolute Bay is located on the south of Cornwallis Island, which is approximately 1100 km further south than CFS Alert. Canadian Armed Forces Arctic Training Centre opened August 15, 2013 in Resolute Bay, Nunavut, to serve as a facility for Army sovereignty operations, Canadian Forces joint exercises, and the Arctic Operations Advisor Course [10]. Alert was initially chosen as the most suitable location because it is positioned at the highest location in the Arctic, compared to Nanisivik and Resolute Bay, and has the most established infrastructure, including 90 buildings and an airfield.

However, after discussion with Dr. Richard Bathurst, a civil engineer at the Royal Military College of Canada in Kingston with experience with constructing in the Arctic, namely Alert, it was evident that Alert would be a poor location for a large base. The soil at CFS Alert contains a thick layer of bedrock, which would require significant excavation and soil removal in order to complete even minimal foundation construction for buildings. In addition, Alert has a very small window for construction due to the short summer season and also has no ocean port access as the ocean surrounding the station is frozen. In order to transport the amount of goods associated with constructing a large base, ocean access is crucial. The requirement for ocean access overrides the location in Arctic as the base would have to be constructed before it completed any operations. Therefore, Nanisivik was chosen as the location for a base in the Arctic, which also decreases the energy requirement due to higher average temperatures. Nanisivik is still at a high position in the Arctic, such that a base would be capable of effectively conducting sovereignty operations. In addition, due to Nanisivik's position on the Northwestern passage, it is more capable of monitoring naval operations and international shipping than CFS Alert.

2.4 Thermal and Electrical Energy Requirements

CFB Kingston uses 90,000 lb·hr^{-1} of steam [11] at a temperature of 177°C and a pressure of 820 kPa and consumes 5,227,800 kWh of electrical energy [12] during peak seasons. These values were provided by the chief engineer at the steam generation plant and the accounts clerk at the engineering support squadron for CFB Kingston respectively. These parameters converts to a supply of 31.6 MWt and 7.16 MWe for the base. In order to compare what the energy requirement of a large base in the Arctic would be, it is necessary to determine the effect the temperature difference between Southern Ontario and the high Arctic has on heating requirements. This problem was approached by using the Heating Degree Days (HDD) method. Heating degree days are defined as, "a measure of how much (in degrees), and for how long (in days), outside air temperature was lower than a specific "base temperature". They are used for calculations relating to the energy consumption required to heat buildings" [13]. In order to determine the HDD of Kingston and Alert, an online degree days calculator was used, which uses *BizE E Software* and is based on temperature data from *Weather Underground* [13]. A base temperature of 15.5 °C was chosen as this is the temperature heaters are programmed to turn on. The program calculated the HDD for each location from 01/01/2013 until 01/12/2013. In order to calculate the energy requirements of a CFB Kingston sized CFB in the Arctic, a ratio of the peak energy requirement of CFB Kingston over the average of the winter months HDD (considered as November to April) was calculated. This number was multiplied by the average of the winter months HDD at CFS Alert to show that a CFB Kingston sized CFB in the Arctic would require 75.2 MWt to operate. The electrical requirement for a base in the Arctic, considering a 10% safety factor, would be 7.88 MWe. In order to supply the heating cycle and the ORC with sufficient thermal energy, while taking into consideration reactor redundancy, 8 SNB25 reactors would be required. Therefore, it is not feasible to use the thermal energy supplied by six SNB25 reactors to support the electrical and hot water requirements of a base the size of CFB Kingston in the Arctic, while taking redundancy into consideration.

If the electrical and energy requirements in relation to the size of a base were considered linear, a base half of the size of CFB Kingston in the Arctic would require 37.6MWt and 3.94MWe. Similarly, a base one third of the size of CFB Kingston in the Arctic would require 25.07MWt and 2.63MWe. Therefore, a base a third of the size of CFB Kingston in the Arctic would require 5 reactors including redundancy. The intent is to account for 2 redundant reactors: one would be in maintenance mode, while the other would be on stand-by mode. A total of 3 reactors would be on-line at all time, providing the required thermal energy for district heating and electrical power generation. These values were determined by using the UniSim simulation detailed in Section 3.3. Therefore, due to the constraint of six available reactors, the remainder of this paper considers a base with one third the energy requirements of Kingston located in the Arctic.

3. Simulation Results and Discussions

3.1 Choice of Organic Fluid

Due to the multitude of options available for organic fluids, the evaluation was done in three stages. First, all organic fluids commonly used in ORCs were considered based on their boiling point. Due to the project problem statement, the fluid must have a boiling point between 30°C and 95°C within the ORC. From this constraint, 27 viable options were selected. For the second level of evaluation, the potential candidates were compared against their freezing point, environmental impact, impact on human health and flammability. Scores for this level of evaluation were dictated using respective Material Safety Data Sheets (MSDS). The top one third viable organic fluids were chosen for the next evaluation. These nine fluids were input into an ORC simulation in order to determine their thermal efficiency.

3.2 Choice of Organic Fluid - ChemCAD Simulation

ChemCAD (version 6.5.3) is used to run thermodynamic simulations in order to determine the thermal efficiencies of the nine different organic fluids used in an Organic Rankine Cycle.*“ChemCAD is a chemical process simulation software that includes libraries of chemical components, thermodynamic methods and unit operations to allow steady-state simulation of continuous chemical processes from lab scale to full scale”* [14]. The thermal efficiency can be determined using ChemCAD, as it provides values for the work produced by the turbine, work required by the pump and the total energy transferred into the organic fluid in the evaporator, while taking their respective efficiencies into consideration. The simulation is also used to determine the flow rate of the organic fluid within the closed loop in order to ensure the steam is at the highest possible pressure prior to entering the turbine. Tables 1 and 2 present the Organic Rankine Cycle parameters used and the thermal efficiencies calculated for the nine (9) viable organic substances, respectively.

Table 1: Values Used for ChemCAD Simulations

Temperature of Water from Reactor	95°C [5]
Temperature of Water into Reactor	35°C [5]
Flow Rate of Water from Reactor	$126.9 kg\cdot s^{-1}$ [5]
Pressure of Expanded Organic Steam Leaving Turbine	0.5bar (0.5×10^5 Pa)
Temperature Leaving Condenser	Sub-cooled by 5°C
Efficiency of Turbine	0.9
Efficiency of Pump	0.8

Table 2: Thermal Efficiencies Calculated by ChemCAD

Organic Fluid	Thermal Efficiency
Acetone	12.4%
Butanone	6.7%
Ethanol	6.7%
Ethyl Acetate	7.3%
Hexane	9.0%
Hexene	10.0%
Isopropyl Alcohol	5.6%
Methanol	9.9%
Pentane	16.8%

As seen in the results above, pentane is the organic material that gives the best thermal efficiency for the ORC. This is not surprising as various other studies have yielded similar results. For example, the design project done by Bouchard, Jolly and Walker in 2010 concluded that pentane was the most appropriate in the same situations [15]. Lemort, a professor at the Université de Liège, also recommended pentane as a viable working fluid for a waste heat recovery unit which operates between 60°C and 100°C, similar to the working conditions in this project [16]. The thermal efficiency of 16.8% found in that report is also similar to other literature values. Calise, Capuozzo and Vanoli, all professors at the University of Naples, discovered in their research of various organic materials used in an ORC to harness solar power, that pentane achieved a thermal efficiency of 16% [17]. Another group of researchers from the University of Science and Technology of China, Gang, Jing and Jie also discovered in their analysis of an ORC that the thermal efficiency for pentane is 16% [18].

The reason pentane has such a high thermal efficiency when compared to the other fluids can be attributed to its boiling point as pressure increases. Since it is able to be at a relatively high pressure and still be complete vapour at 95°C, pentane allows for the largest enthalpy change over the turbine, and in turn the most power produced. As explained by Gang, Jing and Jie, pentane has various properties which make it viable as an effective working fluid. Pentane has a high latent heat of vaporization and molecular weight and also operates at super-atmospheric pressure at low temperatures, which is sought after for small scale operations and maximum efficiency [18].

As per the material comparison and evaluation previously carried out, it is evident that pentane is not the best material based on environmental, health and fire concerns. In this project, the flammability of materials is of small concern due to the closed loop design and the harsh Arctic environment. The health consideration is very similar to all other materials selected for simulation and there are no great environmental concerns. In addition, the fluids thermal efficiency is the most important factor because of the requirement to generate the most electrical power with the least amount of reactors. Therefore, n-pentane is chosen as the organic working fluid for this project.

3.3 Organic Rankine Cycle and District Heating loops - UniSim Simulation

"*UniSim Design Suite is a powerful process modeling software that provides steady state and dynamic process simulation in an integrated environment. It provides powerful tools to help engineers evolve process optimization designs with lower project risks, prior to committing to capital expenditures*" [19]. In this project, UniSim was used to simulate the Organic Rankine Cycle and District Heating loops in a combined environment. This allowed for the determination of the power output of the system as well as the temperatures and flow rates of all streams in the cycle.

The cycle was split in two identical systems in order to reduce the size of the heat exchangers and turbines required for successful power generation, although, the combined cycle is used for simulation. Below is a screenshot of the system used:

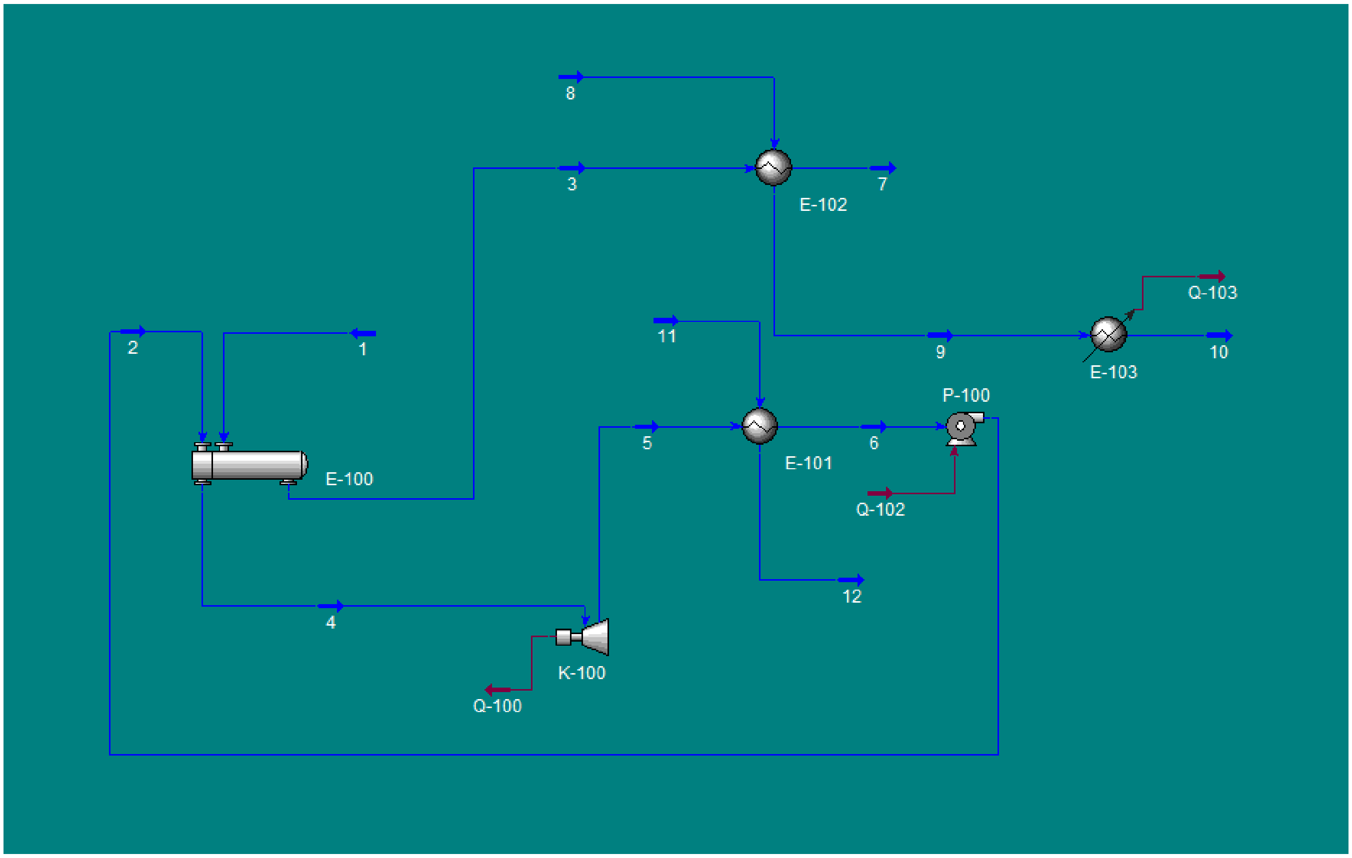

Figure 3: Process Flow Diagram (PFD) for UniSim Simulation.

Tables 3 and 4 provide the UniSim PFD symbols and parameters, respectively.

Table 3: Description of UniSim PFD Symbols

Symbol on Diagram	Equipment
E-100	ORC Heater
E-101	ORC Condenser
E-102	District Heating Heater
E-103	CFB Heat Exchanger
K-100	ORC Turbine
P-100	ORC Pump

Table 4: Description of UniSim PFD Streams

Identification Number	Description	Known Variable(s)
1	Water leaving the SNB25 Reactors	T = 95°C P = 1bar (1.0×10^5 Pa) $\dot{m}$ = 253.8kg·s^{-1}
2	Pressurized liquid pentane entering evaporator	T = 15°C P = 3.0bar (3.0×10^5 Pa)
3	Water used to heat District Heating loop	$\dot{m}$ = 253.8kg·s^{-1}
4	High pressure pentane vapour to move across the turbine	X = 1 (Superheated Vapour) P = 3.0bar (3.0×10^5 Pa)
5	Expanded, low pressure pentane vapour	P = 0.5bar (0.5×10^5 Pa)
6	Low pressure liquid pentane	Sub-cooled by 5°C P = 0.5bar (0.5×10^5 Pa)
7	Water being returned to SNB25	T = 35°C P = 1bar (1.0×10^5 Pa)
8	District Heating cold water entering plant	T = 15°C P = 1bar (1.0×10^5 Pa)
9	District Heating hot water	T = 70°C P = 1bar (1.0×10^5 Pa)
10	District Heating cold water leaving CFB	T = 20°C P = 1bar (1.0×10^5 Pa)
11	"Cold" process water	T = 0°C P = 1bar (1.0×10^5 Pa)
12	"Hot" process water	T = 1°C P = 1bar (1.0×10^5 Pa)
Q-100	Electricity Produced by Turbine Generator	Q = 2.626MW_e
Q-102	Pump electricity requirement	N/A
Q-103	Thermal energy available for use at CFB	Must be greater than 31.6MW_{th}
K-100	ORC Turbine Generator Unit	$\eta = 0.90$
P-100	ORC Pump	$\eta = 0.75$

This simulation calculated the required flow rate of pentane as well as the required heat exchange area for the evaporation of pentane into a high pressure gas. Unfortunately, when a phase change occurs in a heat exchanger, UniSim does not accurately represent the situation if only one heat exchanger is used. Therefore, the heat exchanger must be simulated in three separate stages [20]. A phase change requires latent heat as well as the heat of vaporization or condensation. In this simulation, there are both, although only the condensation of pentane is presented in this report as it is the most complicated:

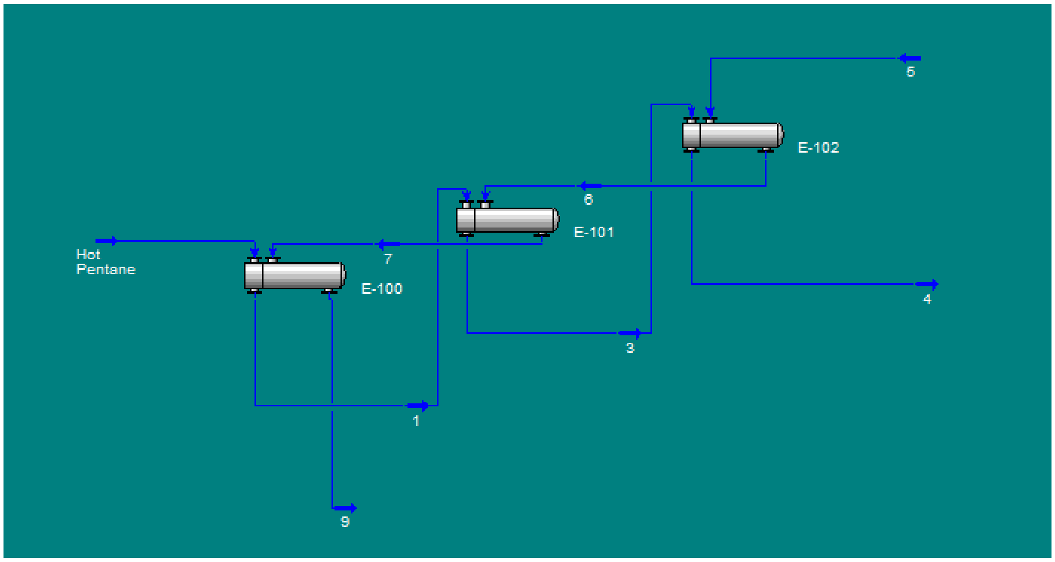

Figure 4: UniSim Simulation of a Heat Exchanger with Phase Change.

Table 5: Description of Heat Exchanger Simulation Streams

Identification Number	**Description**	**Known Variable(s)**
Hot Pentane	Pentane to be condensed	T = 35.57°C (From simulation results above) P = 0.5bar (0.5×10^5 Pa) $\dot{m}$ = 45.55kg·s^{-1} (From simulation results above)
1	Pentane at its dew point	X = 1 P = 0.5bar (0.5×10^5 Pa)
2	Pentane at its bubble point	X = 0 P = 0.5bar (0.5×10^5 Pa)
3	Condensed and sub-cooled pentane	Sub-cooled by 5°C P = 0.5bar (0.5×10^5 Pa)
4	“Cold” process water	T = 0°C P = 1bar (1.0×10^5 Pa)
5	Process water	P = 1bar (1.0×10^5 Pa)
6	Process water	P = 1bar (1.0×10^5 Pa)
7	“Hot” process water	T = 1°C P = 1bar (1.0×10^5 Pa)

In this simulation, the use of the three areas in the heat exchange process is a more accurate representation of the total area required in a real heat exchanger. Because this is the combined area for the total cycle, and in reality the system will be split into two identical cycles, the area can simply be divided by 2.

The total required heat exchange area provided by the UniSim simulation for the three heat exchangers in the system are 1822m^2, 1566m^2, and 4400m^2 for the ORC evaporator, ORC condenser and district heating loop heater respectively. In accordance with the design of the cycle to consist of two separate ORC loops, the areas are divided into two; therefore, the required heat exchanger sizes are 911m^2, 783m^2, and 2200m^2. Babcock and Wilcox was selected to provide shell and tube heat exchangers since it is one of very few companies that manufacture equipment for the nuclear industry. A total of eight (8) companies have been contacted for this part of the work.

The turbine was selected using a pentane vapour flow rate of 22.8 $kg \cdot s^{-1}$, and an entrance pressure of 3bar. The outlet pressure of the turbine was selected to be 0.5 bar in order to have a net energy generation of 1.31 MWe, for a total of 2.63 MWe for the entire plant. Enertime provided a timely cost estimate which met the projects specification requirements; therefore, it was selected to build the project's turbine generator units. Four (4) other companies have been contacted for this part of the work.

Pumps were selected based on the volumetric flow rate of material to be transported, since the value of head loss is insignificant within the cycle due to the assumptions of flat terrain, straight piping and absence of valves or fittings. The flow rates provided by UniSim are: 130.2 $m^3 \cdot h^{-1}$ for the pentane in the ORC, 1507 $m^3 \cdot h^{-1}$ for the district heating water and 2117 $m^3 \cdot h^{-1}$ for the condenser water. A large range of manufacturers produced a pump with the required specifications, although, after several enquiries, Pioneer Pump was the only company which responded with equipment which met the project's minimum specifications.

4. Conclusion

This design project determined that five SNB25 reactors, including two redundant reactors, can support a base with one-third of the thermal and electrical energy requirements of CFB Kingston in Nanisivik, Nunavut. When coupled to an organic Rankine cycle engine with an efficiency of 16.8%, the SNB25 reactor has an electrical power generation capacity of 4.2MWe, which exceeds the requirement of 2.63 MWe. Therefore, two reactors would be dedicated to district heating, providing a total capacity of 50 MWth, while one reactor would be dedicated to electrical power distribution. This configuration leaves enough margins to absorb power spikes during peak hours or/and peak (cold) seasons. All reactors would be connected in series, allowing for cross-connectivity. The energy cycle also requires six shell and tube heat exchangers (four for 2 organic Rankine cycle engines and two for district heating) provided by Babcock and Wilcox, two axial turbines with generator coupling from Enertime, and twelve centrifugal pumps provided by Pioneer Pump in order to supply the electrical and thermal energy to the base. In addition, the environmental effects of nuclear reactors would be minimal in comparison to the use of fossil fuels, and the reactors would only require refuelling once every twelve years. A base in the Arctic powered by SNB25 nuclear reactors is a feasible project and would help Canada's mission to strengthen its sovereign presence in the Arctic from the land, sea and air.

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