PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE
ESCUELA DE INGENIERÍA

SUSTAINABLE ENERGY FOR SCIENTIFIC ANTARCTIC STATIONS: DEVELOPMENT OF A CONCEPT POWER PLANT USING A SMALL MODULAR REACTOR COUPLED WITH A SUPERCRITICAL CO2 BRAYTON CYCLE

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Tesis para optar al grado de:

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In the hopes that this work may in some way contribute to the development of new settlements not only in Antarctica and in isolated places but also hopefully in outer space, this is dedicated to all people who put their effort and ambitions in the exploration and understanding of our universe. If only I could join them in their exciting endeavors.

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I would like to express my gratitude to:

- My father and my mother
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- My professor and other researchers

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ABSTRACT

Antarctica is the continent with harshest conditions on Earth, but despite this it gathers a large amount of population due to its importance in scientific research. Because of its role in scientific knowledge, it is inevitably going to become more populated as new areas of exploitation will be opened. This thesis develops a concept power plant based of a very Small Modular Reactor coupled with a Supercritical CO_2 Brayton cycle as a sustainable alternative energy solution for Antarctica. In order to do this, a complete analysis of Antarctic stations energy requirements was conducted with main focus in McMurdo-Scott cluster, South pole and South Shetland islands. Also a comparison between SMR's technologies and energy conversion cycles was carried out. For the optimization of the cycle, a mathematical model is used prior to an analysis of the total conductance value in the recuperators. The result is a Heat Pipe SMR with a supercritical recompression CO_2 Brayton cycle with net electrical power of $1500kW$ and efficiency of $40,73\%$ cooled by air.

Keywords: Sustainable energy, Antarctica, Small Modular Reactors, Heat pipe reactor, Supercritical CO_2 Brayton cycle

RESUMEN

Antártida es el continente con las condiciones más severas de la Tierra, a pesar de ello, reúne una gran cantidad de población debido a su importancia en la investigación científica. Por su rol en el conocimiento científico, este continente indefectiblemente estará más poblado en el futuro debido a que nuevas áreas de investigación serán abiertas. Esta tesis desarrolla un concepto de planta de energía basado en un reactor modular pequeño (SMR) acoplado a un ciclo Brayton de CO_2 supercrítico como una solución sustentable alternativa para la Antártida. Para ello, se realiza un completo análisis de las estaciones científicas y sus requerimientos de energía con especial énfasis en las estaciones McMurdo-Scott, Estación polar Amundsen-Scott y estaciones de la isla Rey Jorge. Además, una comparación entre diferentes tecnologías de Reactores modulares pequeños (SMR) y tecnologías de conversión de energía fue realizada. Para la optimización del ciclo térmico fue utilizado un modelo matemático junto a un análisis del valor total de conductancia en los recuperadores. El resultado es un Reactor Modular Pequeño de tubos de calor acoplado a un ciclo Brayton de CO_2 supercrítico con potencia eléctrica de $1500\,kW$ y una eficiencia de $40,73\%$ enfriado por aire.

Palabras clave: Energía, Antártida, Small Modular Reactors, Heat pipe reactor, Ciclo Brayton de CO_2 supercrítico

Introduction

1.1 Life in Antarctica

Living in Antarctica is not an easy task; temperatures range from just above $0\,^{\circ}$C near the cost to $-30\,^{\circ}$C in the interior. In the winter temperatures near the cost are close to $-15\,^{\circ}$C while in the interior drops to $-65\,^{\circ}$C (Walton [2013]) and can also reach lower temperatures such as measured in Russian Vostok station of $-89.2\,^{\circ}$C on 1983, the lowest ever recorded on ground level. In 2010 satellite observations measured a surface temperature of $-93.2\,^{\circ}$C near the south pole surpassing the previous record but this time not directly recorded. These extremes temperatures are due to the high latitude of this continent so that the sunlight has to travel further and in an acute angle. Besides, the ground, mostly ice, reflects up to 80% of the incoming radiation so there is very little warming of the Antarctic surface, in addition to the fact that it is emitting longwave radiation, which leads to a net loss of energy and therefore cooling, instead of the opposite as occurs in more temperate locations. This phenomenon described above occurs during the Antarctic summer months. In winter, no solar radiation reaches the ground and the cooling due to longwave radiation emission is even greater. Furthermore, Antarctica is the highest continent with maximum elevations over 4000 m and with average height of 2400 m, making it even colder since temperature decreases with elevation in the troposphere.

This continent is also the windiest, strong currents develops due to density differences between air adjacent to the ice sheet (coldest) and less dense air further from the surface. The so-called katabatic winds are produced by dense air sinking from the sloping edge of a high plateau accelerating down the surface of the ice sheet. Initially they flow straight downhill, but eventually they are turned left due to the Earth's rotation resulting in a spiral wind current from the high interior of the continent. The katabatic winds can reach velocities up to 327 km/h as once measured in french station Dumont d'Urville.

Opposed to what most people would think, Antarctica is a desert. With an average annual precipitation of 13 cm, it is the driest continent on Earth. This is because as air temperature decreases the air is able to contain less water vapour and also because global atmospheric circulation around the polar cells tends to cause clouds to dissipate, and suppresses the development of precipitation (Walton [2013]).

Despite all these extremes conditions that makes Antarctica the harshest continent on Earth, human has been able to overcome these challenges and conquer the ice region starting from the early expeditions of Captain James Ross Cook whose assessment about the continent was bleak:

> The risk one runs in exploring a coast in these unknown and Icy Seas, is so very great, that I can be bold to say, that no man will ever venture farther than I have done and that the lands which may lie to the South will never be explored

Years later, different expeditions from different countries race for the conquer of the south pole and the sovereignty of the region establishing research stations and slowly began to populate the region. In order to maintain healthy relationships between the countries involved, several agreements were signed annually until superseded by the Antarctic Treaty. This later arrangement promotes solely peaceful purposes in the region such as scientific investigation and cooperation among the signatories of the treaty.

Nowadays the antarctic population is distributed among 77 scientific stations from 31 different countries (Michael and Lopes [2019]). Most of them live during summer season, including tourism, providing an opportunity for over 35000 people a year to visit the region. However, during the long winter, population decreases since less shelters are suitable for the extreme conditions. During the time they are in Antarctica different types of scientific work and research are carried out, such as environmental, biological, climatological, geological, marine and even astronomical studies.

One of the main reasons this region is so appealing to scientific research and exploration is because the unique archives of past climate and environmental changes found in polar ice sheets. They provide information on local, regional and global climate, through the physical and chemical composition of the water and air preserved inside the ice matrix. The drilling and analysis of ice cores reveal the natural variability of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) concentrations back in time, and highlight the planetary effects on the atmosphere and the paleoclimate.

An example of this is the article by Petit et al. (1999) (Petit et al. [1999]) where a detailed analysis of an ice-core taken from East Antarctica near Russian Vostok station is carried out. Through Vostok records it can be seen that climate is not static but rather been in a state of change during the past 420000 years, however, there are certain boundaries and cyclic pattern in which climate oscillates. Strong correlations between atmospheric data can be pointed out from this research, such as CO_2 and temperature ($r^2 = 0.71$) and CH_4 and temperature ($r^2 = 0.73$) indicating a possible contribution from greenhouse gases to global temperature. Finally, the unprecedented concentrations of these gases nowadays added to the correlations just mentioned support some anthropogenic nature of climate change and global warming.

Scientific community and researchers are also interested in Antarctica because of its important role in global atmospheric and oceanic circulation. The net loss of energy from this region is critical in creating the temperature gradient with the equator which turns on the transportation mechanisms trying to remove this temperature difference on Earth, providing the climate we have today. Measuring different types of changes in the Antarctic region such as ice cover and atmospheric conditions is key to understand the alterations in global weather and climate around the planet where many of us live.

There is also a concerning aspect regarding Antarctica and global warming. Since this region is responsible for the climate stability, changes in concentration of greenhouse gases in its atmosphere may alter the radiation balance of the continent and as a consequence climate system can experience some disorder in precipitation and atmospheric circulation patterns. Changes in this region temperature can also alter the ice mass and ice coverage of the surface leading to a positive feedback loop as the albedo of the hard rock, found beneath the ice, and ocean is lower than the albedo of the ice shelf, resulting in less incoming radiation reflected back and more absorbed by the ground increasing temperature and consequently reducing ice surface (Walton [2013]).

Measuring the mass balance of Antarctica to assess the state of the ice shelf is key, as the melting of the Antarctic ice might represent $10 - 30\%$ of the current sea level rise (Walton [2013]). If this trends continues to develop, coastal cities and population could suffer from sea level rising as the total volume of the ice sheet is estimated at 30 million km^3, representing 80% of global freshwater, and can rise up the sea level up to 57 meters if the entire ice sheet melts (estimated by calculating the volume on ice in Antarctica over the entire sea surface).

Overall, Antarctica has been indispensable in understanding Earth and climate, and today's value is even greater. The almost pristine environment next to the comprehensible external influences make this continent a great indicator of the state of the global climate and under the current circumstances, regarding climate change and global warming, it's our best tool to understand the consequences of human actions.

1.2 Objectives

Because of these different roles of Antarctica in scientific knowledge, it is inevitably going to become more populated and new areas of exploitation will be opened up. The main objective is to allow this growth while also being able to preserve the pristine condition of the region by developing a clean and reliable energy solution for the Antarctic stations. To achieve this, specific objectives for this work are proposed:

- Complete review of the Antarctic stations energy requirements.
- Small Modular Reactor analysis and comparison for Antarctic applications.
- Energy conversion analysis.
- Energy plant proposal combining both Small Reactor and thermal cycle technologies.

1.3 Hypothesis

Given the environmental conditions at Antarctica; high speed wind, low temperature, low humidity added to difficult access and lack of a reliable source of water, Antarctic stations could be supplied by a small nuclear energy source coupled with a supercritical CO_2 Brayton cycle to fulfill most of their energy requirements.

Energy in Antarctica

2.1 Fossil energy in Antarctica

In order to overcome Antarctica the difficulties of living in Antarctica, energy is needed permanently in research stations to support different vital activities such as lighting, heating, transport, water pumping and purification, waste systems and also non vital such as the requirements for science equipment. In general, this energy is provided by Diesel fueled electrical generators with redundancy and emergency backups, while vehicles in this region are also powered by gasoline, Diesel or jet fuel. This is due to the reliability this kind of fuels delivers in an environment where energy security is essential as any shortage in a facility immediately puts its occupants in danger.

Fuel consumption in this continent is difficult to assess since most stations do not have a rigorous way of measuring and also varies depending of levels of activity, research funding and operation schemes. Besides, fuel supply is sometimes provided through mediatory stations since not all of them have access to air transport or an adequate harbor. Inspection reports are most of the time the only source to obtain this type of information.

Inspection Reports are documents under the Article VII of the Antarctic Treaty and Article 14 of the Protocol on Environmental Protection. These two articles provides the right to each Consultative Party of the Treaty to designate observers to undertake inspections in Antarctica in order to promote the objectives of the Treaty and ensure observance of its provisions. The inspection team can have access to all areas of Antarctica including all stations, installations and equipment within those areas. Once inspection is finished, a document gathering all information is developed and then published, it is through this tool that information regarding different stations can be obtained.

Inspection teams control stations grouped together in a certain area in order to avoid large displacements via land or sea. The largest one (in population) consists of United States McMurdo station and New Zealand base located on Ross Island about three kilometers away from each other, connected by a robust road. McMurdo station is the largest permanent facility on the Antarctic continent, it can accommodate up to 1100 people at summer and around 200 people in winter. This station supports scientific research and also serves as a logistic hub to support different activities all along the Ross Sea region, the South Pole and other remote sites on the high plateau. To sustain this station, six generators assemble 7800kW and alternate between each other to meet the peak demand of 3000kW. This power plant was remodeled in 2009-2010 season and has a waste heat recovery system going through different buildings reducing the need for heating and thus saving fuel. Despite savings, McMurdo requires 3000000 liters of fuel to produce electricity and another 1900000 liters of fuel to heat buildings per year, without taking into account flights throughout Antarctica and fuel used to replenish other stations. Fuel tank capacity at this station goes up to 64 million of liters in 17 fuel tanks as of 2005 (Klein et al. [2008]). On the other hand, New Zealand Scott base has a smaller capacity and benefits greatly from its proximity to U.S. McMurdo Station since they appear to have a limited capacity to provide ship resupply. Fuel has to be purchased and delivered by truck from the neighbour tank farm. Storage is held up by four fuel tanks with a total capacity of 61000 liters which equals approximately a year´s worth of storage since the installation of the three wind turbines in 2009. The wind farm can provide up to 100% of the amount of power needed by Scott Base, and any remaining energy offsets the power needs of McMurdo Station. Overall, the three-turbine wind farm contributes to approximately 15% of the joint electric load.

U.S Amundsen-Scott South Pole Station is another preferred site for nuclear power since it is the southernmost structure on the continent and susceptible to energy shortage during winter. Within their approximately 50 buildings, 4 underground vaults and 15 mobile temporary buildings, Amundsen-Scott can accommodate up to 168 people during summer and 45-50 people over winter. Supplies can be delivered during the austral summer by air using the compacted snow-skiway, used predominantly by LC-130 Hercules aircraft, Twin Otter aircraft and BT-67 Basler aircraft or by land as the overland traverses that deliver fuel among other supplies from McMurdo Station. A total of 1378000 litres of fuel are delivered each season to the Station, two thirds by overland traverses and the remaining one third on the LC-130 Hercules aircraft. Power generation is through three $750kW$ primary generators with a $250kW$ peaking generator and two $250kW$ emergency generator, high level of heat recovery is accomplished, including heating mechanisms to run an in situ water reservoir known as Rodriguez well and also glycol heated clothes dryers.

Despite high energy recovering systems, powering this station is not an efficient process since when fuel is brought by air, around one liter is burned in order to deliver another liter of fuel.

An station cluster can be found in the Antarctica Peninsula region on the South Shetland Islands. Chilean base Presidente Eduardo Frei located on King George island provides the main logistic facility to the whole area since the airport support frequent operations made by different countries, specially during summer, because of the tourists flights and the increase in the logistical needs. This station is a large and multi-functional collection of facilities which operates with a certain degree of autonomy, the main components are i) The Presidente Eduardo Frei M. Antarctic Air Base ii) The Lieutenant Rodolfo Marsh Airstrip and associated facilities operated by Dirección General de Aeronáutica Civil (DGAC) iii) the Fildes Naval Station run by the Chilean Navy and iv) the Escudero station run by INACH (Instituto Antártico Chileno), but as they share key infrastructure and services can be analyzed as a single entity. Frei Air Force Station supply the others stations with electricity obtained by one $400kW$ caterpillar generator backed up with two emergency generators of $472kW$ and $292kW$. To power the station diesel fuel with Antarctic quality is used and stored in 18 storage tanks with a total capacity of 1200 cubic metres. The other main components of this station have less storage capacity used mainly for their emergency generators and motorised vehicles.

Only 1 kilometer south of Chilean Frei Station, Chinese Great Wall Station can be found. This station is connected by a system of gravel roads to Frei, Russian Bellingshausen and Uruguayan Artigas Stations on Maxwell Bay. Great Wall Station have three Volvo generators powered by Gas Oil Antarctic producing $124kW$ each, but usually only one of the generators is running, changing from one to another every few days. Fuel is stored in eight $50m^3$ tanks installed in year 2014 refuelled every three years by the R/V Xue Long ice-breaker.

Bellingshausen Station is also in the neighbourhood, this year-round base operated by Russian Federation has been active since 1968 with scientific investigation as main purpose. In order to accomplish this purpose, three Cummins electric generators with respective power of 110, 120 and 140 kW are used alternately fed with diesel. The station uses $150m^3$ of diesel annually and have three $1000m^3$ tanks for their storage located approximately $3,5$ kilometers away. Linked by a track with Bellingshausen is Uruguayan Artigas Station, until year 2015, Artigas rented one 1000 cubic metres tank to the Russian Station for fuel storage, nowadays eight $33m^3$ double skin fuel tanks are used to this purpose. The station uses one $100kW$ and two $140kW$ electric generators that generate a power of $80kW$ and consumes $600L$ fuel in summer. Waste heat from the electric generator is not used for heating; instead, sole electric heating is used.

South Korean King Sejong station is in the vicinity of King George cluster also, this year-round scientific research station with maximum capacity for 68 people takes advantage of the infrastructure from nearby stations to transfer personnel and minor cargo. To power up this station three Caterpillar electricity generators work in 10-day rotating shifts, each with a capability of $275kW$. There is an extra $275kW$ emergency generator for backup. King Sejong uses around $380m^3$ of Antarctic diesel per year, stored in six $150m^3$ stainless steel tanks set on concrete anti-spill containers.

Henryk Arctowski Station operated by Poland located on King George Bay can accommodate up to 35 people. In order to re-supply fuel, MV Polar Pioneer uses floating hosepipes connected to the tank farm once a year, or eventually every two years. Main tank farm is made up of five $25m^3$ tanks resting on pre-cast concrete slabs floor located 800 meters away from the station, meaning that transportation of fuel must be performed between main tank farm and smaller ready-to-use tanks connected directly with diesel electrical generators. Generator facility have one $120kW$ and two $60kW$ units with an annual consumption of about $77m^3$.

Argentinean Carlini Station concludes the small neighbour on King George Bay, this medium sized base with 21 building can shelter up to 105 people with a clearly focus on scientific research and monitoring. Antarctic Gas Oil is the main energy source with annual consumption of $280m^3$. Storage facility have 28 tanks with $10m^3$ of capacity each exclusively for power generation fuel. Carlini Base has four generators, one with $240kW$, two $180kW$ and one $200kW$ operating alternately according to the Base planning.

There are other stations in the continent that do not belong to any particular cluster and are considered as an isolated base. These type of stations rely heavily on fossil fuel specially those that work in a year-round basis. Logistical support to inland isolated stations is near impossible during winter, therefore special safety measures must be taken into account in order to prevent any disaster in case of energy shortage, key equipment failure or exhaustion of supplies. Concordia Station jointly operated by France's Polar Institute and Italy's National Program of Research in Antarctica falls into this category, the remote inland location provides an excellent site for astronomy, astrophysics, glaciology and atmospheric research. Logistical support for this station is performed only during summer (end of November - beginning of February), the rest of the year, operation is fully autonomously and only communication systems allow access to the outside world. For power generation, the station utilizes diesel which arrives by tractor traverse from Dumont d'Urville station, approximately 150 tons of cargo is brought on each traverse, two thirds of which is fuel. Generation capacity consist of three diesel generators of $110kW$ each and a third of $193kW$. Emergency response capability is a matter of vital importance within these isolated inland stations since external assistance during winter cannot be rendered. In order to maximize reliability on the station's life-support systems unique space technologies and engineering solutions were incorporated into the design of Concordia Station with the contribution of European Space Agency (ESA). Having Concordia's living facilities distributed amongst the different buildings decreases the risk of casualties in the event of an emergency situation, also Concordia does maintain a "safety camp" stocked with food, clothing, heaters, small generators and other necessary supplies to sustain personnel until rescued.

Overall, stations that fall under this category must have an emergency plan in case of fire, damage or if main station becomes inaccessible for some reason since support during winter is complex and dangerous. Stations such as Halley VI, Neumayer III, Princess Elisabeth, Troll have special modules that provides emergency shelter, other stations such as Syowa, Zhongshan, Bharati, SANAE IV have evacuation and emergency plans but rely on near logistical support which may not be available during particular periods. One of the most recent accidents in Antarctica is the fire which devastated Brazilian Station Comandante Ferraz in February 2012. This station, located in eastern shore of King George Island, does not belong to the immediate neighbourhood of stations in the area but is close enough to rely on them for logistical support. People from Chilean Frei Station were the first to arrive for help successfully evacuating part of the crew members back to Frei Station. Nevertheless during Ferraz Station accident, two crew members passed away and one suffered injuries properly treated in Arctowski Station.

This recent accident brought up the danger of using fossil fuel in Antarctic Stations since the severe fire that consumed Comandante Ferraz Station was due to a fuel leak (Simonetti et al. [2018]). Nevertheless, risk of fire accidents is not the only problem regarding the use of fossil fuel in Antarctica.

Fuel transport requires heavy logistics as stations are isolated during winter because of the sea-ice cover making them inaccessible so all cargo requirements alongside fuels are supplied only during summer. For inland stations, resupply has to be performed by overland vehicles like snowmobile or special polar tractors. This trips can last 2 to 3 weeks through safe travelling routes indicated by marker poles, but when the trip diverts and has to go through less travelled areas, quadrilles must stop regularly to check the thickness of the ice by drilling, otherwise thin ice layers can give away causing an accident with serious consequences. Resupply by aircraft can also be accomplished but it is restricted to the short summer season, and bad weather often postpone previously planned trips, moreover the different landing platforms, gravel, sea ice, compacted snow and blue ice, must be well suited, long and flat as pilots cannot rely on brakes to slow down but in reverse thrust instead.

Field trips in Antarctica must be planned well in advanced in order to avoid any drawback, every detail must be considered and emergency backup included as the harsh environment put the travellers life immediately in risk and rescue activities are extremely hazardous and improbable when the storm comes up. Because of everything that involves a voyage in this continent, transporting fuel is a costly exercise, price can increase several times from the original and inland can be up to seven times higher than in the antarctic coast (Baring-Gould [2005]).

Higher prices are not the only drawback to fuel transport in Antarctica, risk when transporting this products is also a big problem since it is brought to the continent by sea and may result in spills. Those have happened before and can be categorized in three different classes depending on the size of the spill (Hughes and Stallwood [2005]):

- Minor spills: These type of spills are the most common throughout Antarctica, and they consist in spills less than a 1 liter usually during vehicle or machinery refuelling. These could be easily avoided with more careful during these operations.
- Medium spills: Less common spills that may be caused by leakage of fuel drums (around 200 litres).

• Large spills: These type of spills are very unusual, nevertheless, there have been some cases. The largest spill recorded was on January 1989 when the Argentinian ship *Bahia Paraíso* ran aground in Arthur Harbor, Antarctica, near the U.S. research base Palmer Station. In this accident an estimated 680.000 liters of fossil fuels were released during the initial phase of the spill (Karl [1992]). Another big fuel spill occurred in 1989 on Williams Field on the Ross Ice Shelf, 13 km away from U.S. research station McMurdo (Hughes and Stallwood [2005]). This time 260.000 litres leaked through several bladders where about 100.000 litres were recovered during clean up but the rest soak into the ground.

These type of accidents affect different properties of the soil. In first place, as fossil fuel pollutes the antarctic surface the albedo decreases and ice melting rate increases developing the aforementioned positive feedback loop. In second place, oil contamination can cause a depletion of nutrients, specifically in nitrate concentrations, when hydrocarbon-degrading microorganisms degrades the fossil fuel (Stallwood et al. [2005]). Finally, these type of accidents could have different levels of impact for different fauna species, as this region is often in the path of bird migration or breeding season beside the natural indigenous fauna. During *Bahia Paraíso* spill, seven bird species were in the middle-to-end of the breeding season and could have been potentially impacted alongside native wildlife (Sweet et al. [2015]).

Oil spills must be cleaned up since The Protocol on Environmental Protection to the Antarctic Treaty states in its third annex that:

> Past and present waste disposal sites on land and abandoned work sites of Antarctic activities shall be cleaned up by the generator of such wastes and the user of such sites.

Therefore, countries involved must take care of the cleaning despite the high costs of removing oil spills from Antarctica. Usually, the addition of microorganisms to enhance oil degradation, known as bioaugmentation, its a great help in solving this type of accidents, nevertheless, it is against the Antarctic Treaty to introduce genetically modified or non-indigenous organisms to the region. In order to properly remove the oil spill in Antarctica physical methods are used such as absorbent pads and removal or containment of the oil contaminated soil. The latter is difficult and prohibitively expensive since the extreme conditions and remote location of stations, besides it is a hazardous work since working with combustible can lead up to combustion specially in poorly ventilated areas and also inhalation of hydrocarbon fumes which can be toxic.

Taking adequate precautions can reduce the likelihood of oil spills, nevertheless, since majority of the activities in this region are supplied by fossil fuels, accidents, including oil spills, will continue to happen.

2.2 Energy efficiency in Antarctica

The first approach into fossil fuel savings in Antarctica is energy efficiency. Enhancing building insulation is a key measure to reduce fuel burn by diminishing the need for heating. New stations such as German Neumayer III are based on efficient designs as double shell principle, on the other hand, older stations like UK's Rothera replace poor energy efficient buildings whenever possible for newer ones with better designs and technologies. Temperature control within closed spaces, energy efficient lightning (replacing older lamps with LED for example) and better use of daylight are other simple measures achieved through an appropriate infrastructure management system. Swedish Wasa Station, built in 1989, was designed with energy conservation in mind, with walls and ceilings insulated by 30 to 50 cm of rock wool, triple glaze windows and none of them facing south. Building designs can also take care of snowdrift by integrating wind engineering during the initial design of the station, minimizing the amount of snow deposited either on the structure or on the down-wind side as the wind loses velocity while transiting the building. By doing this, the need for snow clearance is reduced, and so the energy needs of the station since this is a very energy intensive process. Belgian Antarctic Base Princess Elisabeth was built including wind engineering since the beginning of the design process, achieving 40% drag reduction thanks to the aerodynamic shape of the building supported with wind tunnel testing and CFD modeling (Sanz Rodrigo et al. [2012]).

Another energy efficiency measure used across the Antarctic continent consists in recovering heat waste from the diesel generator system. French-Italian Concordia Station must limit their diesel consumption since is an isolated inland base as mentioned before, hence all space heating needs are met using Diesel generator set's waste heat recovered from the jacket water cooling system and the exhaust. At full load, 155 kW of waste heat is recovered in the powerhouse and distributed inside the three station buildings through the heating circuit. Additional heat is generated within the buildings by all electrical appliances. The external insulation and ventilation system have been designed to ensure that heat loss will remain under $70kW$ even under the most unfavorable conditions in order that the two main buildings can be sufficiently heated without the need for additional heat to be generated (Godon and Pierre [2000]). Waste heat from the generator exhaust can also be used for melting snow or heating water for the base such as in Korean King Sejong Station.

2.3 Renewable energy in Antarctica

The so-called renewable energies have had a fast worldwide growth during the last 20 years and Antarctica has been moving forward in this matter as well. Despite the harsh environment of the Antarctic continent, renewable energies can satisfy part of the total energy needs of a station providing savings in fossil fuel but not replacing it, this is traduced as budget savings and decreasing the possibility of an accident.

Regarding renewable energy sources, wind energy has been exploited for the longest time in Antarctica. Australian Mawson Station installed two $300kW$ wind turbines back in 2003 which provided 35% of the station load during the years 2003 to 2008 with 93% availability (Tin et al. [2010]). This experience proves that environmental conditions such as strong winds in Antarctica can support the use of wind energy, nevertheless, technical challenges need to be overcame in order to meet critical conditions mentioned before such as extreme cold, extremely strong winds and snow accumulation. Australian Antarctic Division worked together with Enercon, German turbine manufacturer, and with Powercorp, Australian company, to come up with an according solution for Mawson Station energy needs. The outcome was the Enercon E-30 $300kW$ wind turbine with special modifications to meet the Station conditions, these are the following:

• Low temperature steel used in all tower sections, castings and structural components due to an annual average temperature of $-12°C$.

• High grid penetration (up to 100%) demanded a high degree of turbine control to ramp-down output power when the wind speed was in the range of $25m/s$ to $34m/s$.

• Limited ice-free land dictated a small number of turbines, therefore they must be larger to make up for the needed total power output. Nevertheless, size was limited by the maximum size of mobile crane which could be shipped to Mawson. The solution was a 34 meters tower which is shorter than normal.

• Special cold-porch attachment at tower entrance to exclude snow.

The type of commercial turbines installed in Mawson are technically difficult and costly to install on the continental ice-sheet or on ice-shelves due to the type of foundations required. Therefore, special designs with lightweight and efficient materials that could be installed without using heavy cranes or heavy lifting gears must be used. This is Germany's Neumayer Station case, where the high wind energy potential of about $165W/m^2$ with speeds ranging from $10m/s$ to $30m/s$ and $40m/s$ led to the installation of a $20kW$ prototype Vertical Axis Wind Turbine (VAWT) in 1991. This specially developed turbine had a minimum operating temperature of $-55°C$, could survive wind speeds of up to $68m/s$ and withstand a snow accumulation rate of $70cm/year$ thanks to the base frame that can be raised accordingly. The performance of the VAWT was better than expected, providing, on average, $4kW$ of electrical power or $35000kWh/year$ directly into the energy supply system of the station and lowering annual fuel consumption by about 6% or 12000 liters. Nowadays, Neumayer Station has a special $30kW$ horizontal axis wind turbine designed to compensate the snow accumulation by lifting itself about 1 meter every year. This turbine was rated to provide $120000kWh$ at a mean speed of $9m/s$ and can operate at wind speed ranging from $2,5m/s$ up to $40m/s$ supplying about 12% of annual energy demand.

New Zealand Scott Base installed a wind turbine farm consisting of three $330kW$ generators in agreement with the neighboring U.S. station McMurdo. This *Island power grid* can provide almost 100% of the amount of power needed by Scott Base, and during high energy output, the remaining energy offsets the power needs of McMurdo Station. Diesel reduction is about 463000 liters annually which means cutting down CO_2 emissions by 1242 tonnes a year (Ayodele and Ogunjuyigbe [2016]). This project proved that renewable energy can be successful in this region, specially after the Initial Environmental Evaluation made by New Zealand that concluded:

> “. . . the negative environmental impacts resulting from this activity will be outweighed by the positive environmental benefits. The predicted reduction in fuel usage and consequent reduction in greenhouses gases being released to the atmosphere, combined with the reduction in the risk of an environmental incident through less handling of less fuel outweigh the predicted impacts (mainly disrupting the area and possibly wildlife) the installation of the turbines will create.”

This statement has reached different stations along the whole Antarctic continent. Poland Arctowski Station, Johann Gregor Mendel Station, Juan Carlos I Station, St.Kliment Ohridski Station, Zhongshan Station and Princess Elisabeth Station own wind turbines for their power requirements as of their respective inspection year. Meanwhile, other stations have manifested their interest in this type of energy source, but they are still in the research phase.

Solar energy has also found application in the Antarctic region in the form of thermal power for heating purposes or photovoltaic for direct energy. Wasa Station is an example, 48 solar panels manufactured by Neste/Fortum with a capacity of $55kW$ each produce the power to meet most of the operational power needs of this seasonal station. For backup, a bank of Fiber Nickel Cadmuim (FNC) batteries manufactured by Hoppecke which can each store $1160Ah$ was installed alongside with a diesel generator which provides supplementary energy very early or late in the summer season.

Japan’s Syowa Station takes advantage of various forms of solar energy. First, $55kW$ of photovoltaic solar panels produce an annual output of $44000kWh$ displacing about $3-5\%$ of the station power needs, also, air type solar collectors that capture heat from sunlight and then transfer it to the walls produce about $86318MJ/year$ displacing fuel from the heating system. Finally, a solar hot water system that uses evacuated glass tube to heat the water was installed to feed with hot water specially during summer. The capacity of this thermal solar system is $1355MJ/day$ and can heat water from $0°C$ to $30°C$ within one minute (Tin et al. [2010]).

The versatility of solar power has allowed many other stations to reduce their fossil fuel consumption by implementing different kind of solutions. Arctowski Station, Johann Gregor Mendel Station, Princess Elisabeth Station, Rothera Station, St-Kliment Ohridski Station had solar energy systems as of their respective inspection year. Aboa Station and Palmer Station have solar systems for remotes stations or field work. Some other stations manifested their intentions in developing solar energy solutions in their inspection reports.

Among renewable energy efforts in Antarctica, Princess Elisabeth Station is the one leading them. This seasonal-only station was built with energy efficiency on mind and aims at being zero-emissions, making use of renewable energy as the primary energy source and integrating passive building design in a comprehensive energy management regime, thereby minimizing the use of fossil fuels. As of 2012, the power budget of the station was composed of 48% wind power from nine wind turbines, 20% solar photovoltaic from $380m^2$ of solar panels and 12% solar thermal with $22m^2$, remaining energy was provided by the backup diesel generators. The last station inspection mentions that generators had been in use only three times for short periods during 2017-2018 season, meaning that the building has reached a point where the green energy system is working close to the zero-emission vision with annual fuel consumption estimated in less than 2000 liters.

2.4 Former nuclear energy in Antarctica

During 1962 to 1972 a nuclear reactor powered the U.S. McMurdo Station. This nuclear reactor was developed as an attempt to find cheaper ways to maintain stations in remote locations. In the late 1950's, almost half the supplies hauled from the United States to Antarctica consisted of fuel oil to provide heat and power. Logistic costs could not be cut by reducing the amount of fuel shipped because without a minimum fuel supply antarctic stations could not survive the austral winter.

According to early Army cost analysis, the electricity generated by the nuclear plant would have costed about $0,564$ cents per kilowatt-hour. By that time, diesel fuel was selling at 12 cents a gallon and had its cost risen to 40 cents a gallon because of the transport to McMurdo. As a result, each kilowatt-hour produced at McMurdo diesel plant cost about $0,975$ cents (National Science Foundation [1980]).

McMurdo Station, it seemed then, was one of the few places in the world where, given the price of diesel fuel after it had reached Antarctica and given the existing state of nuclear technology, a nuclear power plant promised to be more economical than a fossil fuel plant. The U.S. Congress approved the development of a nuclear reactor in Antarctica with the confidence that, if the reactor worked, more units could follow for South Pole and Byrd Station.

The reactor, called PM-3A, was a pressurized water reactor with a primary closed system and a secondary system connected to the turbine. Its capacity was about $1,8MW_e$ and its life expectancy was about 20 years. PM-3A could also be loaded onto a C-130 airplane and flown wherever it was needed, although it was finally carried by ship. The plant began producing power about 6 months after its deployment on July 10 1962.

Over its 10-year life the reactor produced approximately 78 gigawatt-hours of electricity. From 1966 to 1972 a water distillation plant, using steam from the nuclear plant, produced 13 million gallons of freshwater by evaporative distillation. Over its life the reactor ran at 78 percent capacity factor. At October 8, 1966, the plant achieved 3390 hours of continuous power operation; at that time, the 141-day run was the best ever for nuclear power plants operated by military crews and was just 18 days short of the U.S. record for large commercial pressurized-water nuclear power plant (Shafer [1967]). When the reactor was running, it produced enough electricity to satisfy almost all of McMurdo's heat and power needs.

From 1962 to 1966, operating malfunctions and scheduled maintenance shutdowns kept the reactor from becoming a continuous source of power. The only serious problem occurred in 1962, when hydrogen produced by the radiolytic decomposition of water under high gamma radiation caught fire in the containment vessel. Apparently hydrogen decomposition had not been encountered even theoretically at that stage in nuclear technology, but it was quickly mastered by installing a hydrogen recombiner. The problem never recurred. Damage to the reactor was slight. There were no injuries and there was no release of radioactivity. The reactor, however, was put out of commission for 8 weeks.

After 1966, when the reactor had attained some reliability, it was still subject to precautionary shutdowns, inspections, and core changes, none of which ever indicated a serious or dangerous problem. But it was becoming increasingly apparent that the costs involved in maintaining the plant were making the reactor more expensive than had been expected.

In May 1972 National Science Foundation published an analysis of the U.S. Antarctic Program, which included a cost-effectiveness study of the reactor Performed, by Bechtel incorporated. The report concluded that PM-3A should be decommissioned as soon as possible because operation of the facility was not economical. The report recommended that PM-3A be replaced with an up to date turbine or diesel electric generator to supply power and heat and an oil-fired boiler to operate the water distillation plant. Not only would the diesel plant be more reliable, but fewer personnel would be required to man it.

Plans for the decommissioning were made in March 1973. While the Antarctic Treaty did not specifically require the removal of the reactor, Article V stated, ”Any nuclear explosions in Antarctica and the disposal there of radioactive waste material shall be prohibited.” The United States felt that the spirit of the treaty made it proper to remove not only the core, but also the reactor and soil at the site that received the normal discharge of effluents from the reactor, The Navy and NSF also decided that after all the removal efforts had been completed, a contractor would perform an independent radiological survey of the area (National Science Foundation [1980]).

This is the only nuclear energy experience in Antarctica up to date, and despite not being completely successful it left some good impressions and performances during certain periods. Given the current technological development of nuclear reactors, this type of energy source should be reconsidered, at least as a possibility, since antarctic stations continue to rely upon diesel power plants for heat and electricity with all that this means.

2.5 Energy assessment

Based on the experience from Antarctic stations and the state of the art of the energy technologies a comparison matrix shown in table 2.1 is made.

Table 2.1: Comparison matrix between energy technologies for Antarctic application

Energy Type	Reliability	Transportability	I.Investment	Pollution	Land use	Total
Fossil	5	4	5	-5	5	14
Solar	1	5	4	-2	2	10
Wind	1	3	4	-1	3	10
Small Nuclear	5	3	1	-1	5	13

The main items for Table 2.1 are valued from 1 to 5, and depending if is a negative or positive feature the scores are accordingly. The meaning of each of the scored properties are as follows:

• Reliability: The capacity of the power source to deliver power at all conditions.

• Transportability: The capability of the power source to be moved to Antarctica without mismatching logistics and with low chance of accidents.

• Initial Investment: The cost of acquisition and its implementation.

• Pollution: Contamination emitted by the power plant during its operation and decommissioning.

• Land Use: Total amount of land needed for the power plant to operate.

Fossil fuel is an excellent energy source for Antarctica, its high energy density allows for small land use and provides high reliability, thus making it the main power source for the stations nowadays. Nevertheless, despite its useful features for the region, pollution, oil spilling and other accidents give rise to a possible introduction of new energy sources as this factors are becoming increasingly important. Solar and wind sources are a way to reduce the pollution and accident risk with a slightly higher initial investment and land use. Several stations have implemented this energy strategy and despite the good results, they only manage to reduce a fraction of the oil consumption and have to rely on it anyways.

Small nuclear, is a way to solve the pollution and spilling problem associated with fossil fuels while also being reliable enough on its own. The main disadvantage is that it is still in development stages, but, as research and development continues on the subject this issue will be overcame. For this technology, the initial investment is punctuated with the minimum since the cost involves the research and investigation yet to be developed.

Fossil fuel and small nuclear score the highest among the technologies, while solar and wind score slightly below mainly because of their lack of reliability when used as a standalone energy source. Based on this, the possibility to overcome its main disadvantage in investment and the increasing value attributed to pollution issues under current circumstances, small nuclear is the selected technology for feasibility evaluation and a design proposal for Antarctic Stations in this research.

Nuclear Energy

3.1 Evolution of nuclear reactors

Nuclear energy is one of the main base-load electricity-generating sources available in the world today, generating $10,15\%$ of the global power production (Schneider and Froggatt [2019]). This nuclear energy trend started in 1954 with Soviet reactor at Obninsk followed by several connections to the grid in different countries. The first peak of reactor startups was in 1974 with 26 grid connections, 10 years later, 33 grid connections were achieved, followed by the same number of startups in 1985. The rising trend started to faint after 1986 (year of Chernobyl accident), and in 1990 for the first time the number of reactor shutdowns outweighed the number of startups. During the last years, between 2011 and mid 2017 the startup of 41 reactors, of which 24 in China alone, narrowly outpaced the closure of 38 units over the same period.

The use of nuclear energy in the present belongs to 31 countries operating 417 nuclear reactors (as of end 2018)(Schneider and Froggatt [2019]), with a total capacity of $370GW$ combined, which is a new historical maximum, exceeding the previous peak of $368,2GW$ back in 2006. As of 1 July 2019, 46 reactors were under construction in sixteen different countries, the total capacity under construction is $44,6GW$, $3,9GW$ less than one year earlier.

Up until now, the capacity of nuclear power reactors used for generating electricity have tended toward large nuclear power reactors exceeding even $1000MW$ in capacity. For example,the total capacity under construction, as of mid-2017, has an average unit size of $987MW$. The problem with nuclear power plants that large is the cost of construction combined with obtaining permits, securing insurance and meeting legal challenges from environmentalist groups and the public, can push the cost of a conventional 1000 MW nuclear power reactor towards as much as US$9 billion (Morales Pedraza [2017]).

While the current Generation II and III nuclear power plants designs provide a secure and low-cost electricity supply in many markets, further advances in nuclear energy system design can broaden the opportunities for the use of nuclear energy. Suggesting an important role for nuclear power in future energy supply, especially when taking into account concerns over energy resource availability, climate change, air quality and energy security. The next generation of nuclear energy systems known as ”Generation IV” seeks to explore these opportunities in order to meet future needs for clean and reliable electricity. Generation IV designs will use fuel more efficiently, reduce waste production, be economically competitive, and meet stringent standards of safety and proliferation resistance (Zohuri [2019]).

Alongside to the development of Generation IV systems a new class of nuclear reactors differing from the ”business as usual” approach can be detected. This new type is not led by giant gigawatt power plants like the ones now operating in several countries, but by batteries of small nuclear power reactors. This new type of nuclear reactors called ”Small Modular Reactors” (SMR) are an option to fulfil the need for flexible power generation for a wide range of users and applications, offering the possibility to combine nuclear with alternative energy sources while being flexible and affordable power generation. They also display an enhanced safety performance through inherent and passive safety features. In addition, they offer options for remote regions with less developed infrastructures (Zohuri [2019]).

3.2 Nuclear power plants as a mitigation technology

According to the 2018 Energy Outlook from International Energy Agency (IEA) and accounting the New Policies Scenario which considers today's (mid 2018) policy frameworks and ambitions, energy demand will rise from $162500TWh$ in 2017 to over $205850TWh$ in 2040. Electricity demand grows at a $2,1\%$ a year, twice the rate of overall energy demand and nearly 90% of electricity demand growth is in developing economies. Coal-fired tends to stagnate at today's level but remains the largest source to 2040 with 26% while the share of natural gas holds steady at 22%, with reductions in advanced economies offset by expansion in developing countries, especially in Asia. Variable renewables would rise from 6% in 2017 to over 20% in 2040. Nuclear energy provide about 10% throughout the whole period, though the centre of gravity shifts, as nuclear capacity in China overtakes that in the United States by 2030. (Agency [2018a]).

This scenario means that global CO_2 emissions from the power sector increase by 2% to 2040, while electricity generation rises by almost 60%. Thanks to rising share of renewables and also the efficiency improvements in coal and gas-fired power plant fleets, the global average carbon intensity of electricity generation would decline by one-third from today to 2040 (from 484 grams of carbon dioxide per kilowatt-hour [$g\,CO_2/kWh$] to 315 $g\,CO_2/kWh$) (Agency [2018a]).

Despite emissions remaining constant in New Policies Scenario by International Energy Agency (IEA), observed global mean surface temperature (GMST) would continue to rise beyond the $2°C$ proposed as objective in Paris Agreement on climate change meaning that following our current path is not enough to achieve the goal (Agency [2018a]). This rise has severe consequences as stated by Intergovernmental Panel on Climate Change (IPCC) in their last report called Global Warming of $1,5°C$. Associated risks with reaching a $2°C$ rise in global warming include increases in: mean temperature in most land and ocean regions, hot extremes in most inhabited regions, heavy precipitation in several regions, and the probability of drought and precipitation deficits in some regions. Also, according to the IPCC, sea level rise would put in risk human and ecological systems located in small islands, low-lying coastal areas and deltas. Biodiversity and ecosystems on land would be impacted as well, causing species loss and extinction. Increase in ocean temperature associated with increase in ocean acidity and decrease in oxygen levels risking marine biodiversity, fisheries, ecosystems, and their functions and services to humans. An increase in global warming beyond $2°C$ will amplify the risk in health, livelihoods, food security, water supply, human security, and economic growth (IPCC [2018]).

It should be emphasized that this impacts are thought to be happening as human activities are estimated to have caused approximately $1°C$ of global warming above pre-industrial levels, with a likely range of $0,8°C$ to $1,2°C$. The objective is to reduce climate change under $2°C$ or better yet under $1,5°C$ as proposed in Paris Agreement aiming to lessen the consequences and impacts of global mean surface temperature rise. In order to do so a change in our current path must be accomplished, reducing emissions by about 45% from 2010 levels by 2030 and reaching net zero around 2050 will lead to $1,5°C$ with no or limited overshoot global warming, and for limiting below $2°C$ global warming, emissions are projected to decline about 25% by 2030 and reach net zero around 2070.

Net emissions reductions that would be required to follow a pathway that limits global warming to $1,5°C$ with no or limited overshoot can be achieved through different approaches and strategies. In the Global Warming of $1,5°C$ report made by IPCC, four different scenarios leading to $1,5°C$ global warming with no or limited overshoot are broken down. In three of these four pathways, CO_2 emissions are reduced at least 41% by 2030 relative to 2010 and all of them reach a reduction of at least 91% by 2050 relative to 2010 as well. These scenarios differ a lot from the New Policies Scenario projected in IEA Energy Outlook where CO_2 emissions increase by 2% by year 2040. These projected pathways modeled by IPCC follow different strategies among them, therefore, global indicators are different between each other. For example, final energy demand in 2050 relative to 2010 range from -32% to $+44\%$ and primary energy from gas also has a wide range from -74% to 21% in 2050 relative to 2010. Nevertheless, in order to fulfill the goal of limiting global warming to $1,5°C$ these scenarios converge into common solutions. On one hand, primary energy from coal is reduced to a large degree while non-biomass renewables experience an enormous growth of 833% to 1327% through the different scenarios. On the other hand, nuclear energy also experience a growth in all scenarios ranging from 98% to 501% in 2050 relative to 2010. These scenarios are just among different possible paths and the likelihood of each of them remains unknown.

Through the analysis of these different scenarios it can be concluded that there is not a single solution for limiting global warming under $1,5°C$ as proposed in Paris agreement but rather a spectrum of alternatives. Each of these scenarios has a mitigation cost associated which tends to increase as the global warming goal becomes more demanding. In the case of pathways limiting global warming to $1,5°C$, additional annual average energy related investments are estimated to be around 830 billion USD (as of 2010) compared to pathways without new climate policies. Also, total energy related investments are about 12% higher in $1,5°C$ pathways relative to $2°C$ pathways (IPCC [2018]).

The importance of nuclear power comes when exploring the costs of the different mitigation pathways. An investigation carried out in 2014 assessed the implications of the availability of Small Modular Reactors under a policy scenario limiting global warming to $2°C$. The results indicated that in absence of climate target, the future energy system is dominated by fossil fuels because of the lower capital costs making nuclear less competitive, nevertheless, under a CO_2 target, technologies such as renewables, carbon capture and storage (CCS) and nuclear need to be deployed on a large scale to mitigate carbon emissions (Iyer et al. [2014]).

Relative degrees of mitigation efforts across scenarios can be seen in terms of net present value (NPV) of mitigation costs allowing comparisons between each of them, as a result, abatement costs in scenarios where SMR's are deployed are lower than when this technology or large nuclear does not compete for a place in the market. Furthermore, even pessimistic assumptions about SMR technology costs and technological advance can lead to reductions in mitigation costs (Iyer et al. [2014]).

Nuclear power also offers baseload energy unlike solar or wind energy, meaning that replacing this type of energy with renewables would require a higher installed generation capacity, substantial backup generation and land use, as well as additional transmission capacity if reliable power and grid frequency are to be maintained. An investigation regarding the consequences of phasing out nuclear power on Sweden was realised in 2017 and the main conclusions where the three. In first place, replacing Swedish nuclear power with non-dispatchable renewable sources, such as onshore wind and solar photovoltaic with natural gas as backup, will massively increase greenhouse gas emissions with a substantial increase in cost. In second place, will keep greenhouse gas emissions during the combustion process low, but massively increase costs. Finally, this result will be relevant to any other countries attempting to replace nuclear power with non-dispatchable renewables (Hong and Brook [2018]).

Nuclear energy therefore, seems mandatory if we want to prevent global warming from making irreparable impacts such as those mentioned before. But, a greater contribution can be made by this technology. At first, nuclear power is constrained to electricity generation since its use is limited to this sector exclusively, and emissions from this sector represent only 25% of the total greenhouse gas emissions (IPCC [2014]).

3.3 Small Modular Reactors

Small Modular Reactors (SMR) are defined as nuclear reactors generally $300MW_e$ equivalent or less, designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times.

Small Modular Reactors follow the same technological paths than larger reactors with four main options being pursued:

- Light Water Reactors (LWR)
- Fast Reactors (FR)
- High Temperature Reactors (HTR)
- Molten Salt Reactor (MSR)

The SMR's are expected to have greater simplicity of design, economy of series production largely in factories, short construction times, and reduced siting costs. Most are also designed for a high level of passive or inherent safety in the event of malfunction. Also many are designed to be emplaced below ground level, giving a high resistance to terrorist threats and enhanced safety. A 2010 report by a special committee convened by the American Nuclear Society showed that many safety provisions necessary, or at least prudent, in large reactors are not necessary in the small designs forthcoming. This is largely due to their higher surface area to volume (and core heat) ratio compared with large units. It means that a lot of the engineering for safety including heat removal in large reactors is not needed in the small reactors. Since small reactors are envisaged as replacing fossil fuel plants in many situations, the emergency planning zone required is greatly reduced.

SMR's have the potential for applications beyond electricity generation thanks to its versatility and wide range of power output. The first possible application for SMR's outside power generation can be found in heat applications, this would increase nuclear energy's scope to substitute fossil fuel combustion, either via combined heat and power or dedicated heating reactor. The second application can be found in transport thanks to the rising trend of electric vehicles, this opens the door for nuclear among other clean energies to substitute fossil fuel in the sector. In third place, technical advances in the storage of electricity, or in the production of hydrogen as an energy fuel, would likewise offer new potential for expanding the use of electricity, and hence the use of nuclear power, specially for the new class of SMR's which are suited for this type of applications. Finally, the possibility for this type of reactors to be installed in isolated areas allows for fossil fuel displacement since usually electricity for these type of areas comes from fossil fuel combustion, such as the case of Antarctica.

3.4 SMR's Advantages and disadvantages

Small Modular Reactors offer many different benefits and advantages over large reactors and other types of energy plants, these advantages are listed below:

1. **Modularity**

   This refers to the ability to fabricate major components of the nuclear system in a factory environment and ship them to the point of use. Unlike larger nuclear reactors, SMR's are envisioned to require limited on-site preparation and substantially reduce the construction times. SMR's provide simplicity of design, enhanced safety features, economics and quality afforded by factory production and more flexibility (financing, siting, sizing, and end-use applications) compared to larger nuclear power plants. Furthermore, additional modules can be added incrementally as demand for energy increases.

2. **Siting Flexibility**

   SMR's can provide power for applications where larger plants are not needed or sites lack the infrastructure to support a large unit. This would include smaller electrical markets, isolated areas, smaller grids, sites with limited water and acreage, or unique industrial applications. SMRs are expected to be attractive options for the replacement or re-powering of aging/retiring fossil plants or to provide an option for complementing existing industrial processes or power plants with an energy source that does not emit greenhouse gases (Morales Pedraza [2017]).

3. **Efficiency**

   Small Modular Reactors can be coupled with other energy sources, including renewables and fossil energy, to leverage resources and produce higher efficiencies and multiple energy end-products while increasing grid stability and security. Some advanced SMR's designs can produce higher temperature process heat that can be use for industrial applications, electricity generation (Morales Pedraza [2017]) or in complex processes to obtain hydrogen.

4. **Capital Investment**

   SMR's can reduce the initial capital investment since they have a lower plant capital cost. Modular components and factory fabrication can reduce construction costs and duration also (Morales Pedraza [2017]).

5. **Non-proliferation**

   Some SMR's will be designed to operate for extended periods without refueling. Some type of Small Modular Reactors could be fabricated and fueled in a factory, sealed and transported to sites for power generation or process heat, and then returned to the factory for defueling at the end of the life cycle. This way, local handling of nuclear material is minimized (Morales Pedraza [2017]).

6. **Safety**

   SMR's provide several levels of safety. SMR's can be built below grade for safety and security enhancements, addressing vulnerabilities to both sabotage and natural phenomena hazard scenarios. Furthermore, their design simplicity and modularity enables passive safety features that do not depend on the availability of electric power.

7. **Low operation and maintenance**

   Since SMR's designs require less or none refuelling, maintenance and operation costs are reduced. Also, simplistic designs require less complex machinery and therefore maintenance.

8. **Land use**

   Small Modular Reactors can have smaller exclusion zones reducing the associated legal costs.

9. **Regulatory issues**

   The reduced land use and low operation and maintenance could simplify the regulatory procedures for new nations that wish to use nuclear energy for electricity generation.

Despite all these advantages and benefits from Small Modular Reactors over large reactors and other technologies, some challenges must be solved in the near future or they become disadvantages:

1. **Economics**

   Technology readiness for this type of reactors is not fully developed and more research must be done in order for this technology to be commercially available. The costs for this development are very difficult to estimate, and therefore the economics of this type of reactors is still uncertain, making it difficult to assess against other technologies, nuclear or non-nuclear.

2. **Public acceptance**

   Perhaps one of the main barriers to this technology lies in public perception caused by the nuclear accidents that occurred in the past as Three Mile Island, Chernobyl and Fukushima, despite the proven low mortality and morbidity effects. Additionally, the misconception between nuclear fuel for energy generation and nuclear weapons continue to being an issue. To solve this problem, more effort is needed to inform and interact with the public and other stakeholders.

3. **Certification and licensing**

   Development of regulatory frameworks must evolve as the technology emerges enabling a correct deployment. However, this is not the case and regulatory institutions are subject to path dependencies, leading to a potential bias of regulations toward incumbent technologies. SMR proponents suggest that as demand grows locally, SMR's would allow investors to make incremental capacity additions to existing sites leading to co-siting economies. However, current licensing rules in some countries such as the United States do not allow more than two reactors to be operated from a single control room (Iyer et al. [2014]). Furthermore, several SMR, depart from dominant water-cooled technologies.

3.5 Small Modular Reactor Types

Among SMR's different types of reactor concepts are being developed.

Table 3.2: Small Modular Reactor models classification

SM Reactor Type	Concepts
LWR	KLT-40S, RITM-200M, CNP-300, SNP350, NuScale, Holtec SMR-160, mPower, BWRX-300, IRIS, Westinghouse SMR, VVER-300, VK-300, ABV, ABV-6M, CAREM, SMART, MRX, Nuward NP-300, NHR-200, ACP100, CAP200/LandStar-V, CAP150, CAP50, ACPR100, ACPR50S, Flexblue, UNITHERM, SHELF, KARAT-45, IMR, Rolls-Royce SMR, TRIGA, FBNR.
HWR	PHWR-220, AHWR-300 LEU.
HTGR	HTTR, GTHTR, HTR-PM, HTR-10, EM^2, Urenco U-Battery, X-energy, StarCore HTR, Ultra Safe Nuclear Corporation micro-modular reactor, Hybrid SMR concept, Antares – Areva SC-HTGR, Adams Engine, GT-MHR.
FR	PRISM, ARC-100, CEFR, Rapid-L, 4S, Oklo micro-reactor, BREST-300, SVBR-100, Hyperion, Westinghouse LFR, STAR-LM, STAR-H2, SSTAR, LSPR, SEALER.
MSR	LFTR, Flibe LFTR, TMSR, Fuji MSR, AHTR/FHR, Integral MSR, Transatomic Power TAP, ThorCon, Moltex SSR, Elysium MCSFR, MOSART, Seaborg Waste Burner – SWaB.
Heat Pipe Reactor	Kilopower, Megapower, eVinci, NuScale microreactor.

3.5.1 Light Water Small Modular Reactors

These reactors have the lowest technological risk because their similarity to most reactors operating today. Ordinary water is used as coolant and moderator while fuel enriched to less than 5% with no more than six year refuelling interval is used. These reactor designs can have the conventional pressure vessel plus an external steam generator or the steam supply system inside the reactor pressure vessel in what it is called ”integral” design. These kind of reactors are the closest to being operational, therefore are analyzed.

NuScale

NuScale is an integral pressurized light water reactor operated under natural circulation primary flow conditions. The reactor is housed within its own high pressure containment vessel, which is submerged underwater in a stainless steel lined concrete pool. Power output for this reactor is $200MW_{th}$ and $60MW_e$. It uses standard PWR fuel enriched to $4,95\%$ in normal PWR fuel assemblies, with 24-month refuelling cycle. It has full passive cooling in operation and after shutdown for an indefinite period, without even DC battery requirement. It will be factory-built with a three-metre diameter pressure vessel and convection cooling, with the only moving parts being the control rod drives, reactor would be inside containment vessel, with dimensions of $4,6m$ diameter and $22m$ height and 650 tons weight, with the steam generator above.

CAREM

CAREM (Central Argentina de Elementos Modulares) is a project of Argentina's National Atomic Energy Comission (CNEA) whose purpose is to develop, design and construct an innovative, simple and small nuclear reactor. The first step of this project, construction, is in progress near the Argentine town Lima. This prototype is interesting because of power size ($27MW_e$) and thanks to design characteristics. CAREM has its entire primary coolant system within the reactor pressure vessel (11m high, 3.5m diameter), self-pressurized and relying entirely on convection (suitable for modules less than 150 MWe). Fuel is standard $3,1$ or $3,4\%$ enriched PWR fuel in hexagonal fuel assemblies, with burnable poison, and is refuelled annually.

Unitherm

This is an integral $30MW_{th}$, $6,6MW_e$ conceptual design from Russia's Research and Development Institute of Power Engineering (RDIPE or NIKIET) based from the experience of marine nuclear installations. Fuel is designed in such way that can operate during the whole specified core lifetime. The UNITHERM design makes extensive use of passive systems and devices based on natural processes without external energy supply. These systems include:

• The control element drive mechanisms (CEDM's), designed to provide secure insertion of rods in the core by gravity.

• Locking devices in the CEDM to avoid unauthorized withdrawal of control rods.

• An independent passive heat removal system acting as a cooldown system in emergency shutdown of the reactor.

• A containment capable of maintaining primary coolant circulation as well as providing reactor cooldown and retention of radioactive products under the loss of primary circuit.

• Passive systems for heat removal from the containment and biological shielding tanks.

The mass of one unit with shielding is 180 tonnes, so it can be shipped complete from the factory to site

3.5.2 Heavy Water Small Modular Reactors

These types of reactors use heavy water or deuterium oxide D_2O as coolant and moderator. While heavy water is significantly more expensive than light water, it does not absorb neutron generating and enhanced neutron economy allowing the reactor to operate without enriched fuel and making possible to operate with alternative fuel cycles.

3.5.3 High Temperature Gas Cooled Small Modular Reactors

These type of reactors use graphite as moderator and either helium, carbon dioxide or nitrogen as primary coolant. These reactors are being developed to deliver high temperature ($700°C - 1000°C$) gas, usually helium, either for industrial application via a heat exchanger, or to make steam conventionally in a secondary circuit via a steam generator, or directly to drive a Brayton cycle gas turbine for electricity with almost 50% thermal efficiency possible. Improved metallurgy and technology developed in the last decade makes High Temperature Reactors (HTR) more practical than in the past.

Fuel for this kind of reactors is in the form of TRISO (tristructural-isotropic) particles less than a millimetre in diameter containing uranium dioxide or uranium oxycarbide enriched up to 20%, though normally less. TRISO particles are arranged in blocks, hexagonal prisms of graphite, or in billiard ball-sized pebbles of graphite.

Safety from this reactors is high thanks to negative temperature coefficient of reactivity, meaning that fission reaction slows as temperature increases, and passive decay heat removal. HTR's therefore are put forward as not requiring any containment building for safety. They are sufficiently small to allow factory fabrication, and will usually be installed below ground level.

HTR-PM

This Chinese design was first tested using the HTR-10 experimental reactor to later develop the full size reactor.

HTR-10 is a Chinese high temperature gas cooled experimental reactor with $10\,MW_{th}$ power which reached full power in 2003. It has its fuel as a 'pebble bed' (27000 elements) of oxide fuel with average burn-up of 80 GWday/t U. Each pebble fuel element has 5g of uranium enriched to 17% in around 8300 TRISO-coated (triple coated isotropic) particles. The reactor operates at $700\,^{\circ}C$ (potentially $900\,^{\circ}C$) and has broad research purposes. Safety features from this reactor are high thanks to high surface area relative to volume, and the low power density in the core. This has been proven in 2004 when the reactor was subject to an extreme test of its safety when the helium circulator was deliberately shut off without the reactor being shut down. The temperature increased steadily, but the physics of the fuel meant that the reaction progressively diminished and eventually died away over three hours. At this stage a balance between decay heat in the core and heat dissipation through the steel reactor wall was achieved, the temperature never exceeded a safe $1600\,^{\circ}C$, and there was no fuel failure.

This reactor corresponds to a larger version of the Chinese HTR-10 comprising twin $250\,MW_{th}$ reactors driving a single $210\,MW_e$ steam turbine. Each reactor has a single steam generator with 19 elements (665 tubes). The fuel as 60 mm diameter pebbles is $8,5\%$ enriched (520000 elements in the two reactors) giving $90\,GWd/t$ discharge burn-up. Core outlet temperature is $750°C$ for the helium, steam temperature is $566\,°C$ and core inlet temperature is $250\,°C$. It has a thermal efficiency of 40%. Core height is $11\,m$, diameter $3\,m$ in a $25\,m$ high, $5,7\,m$ diameter reactor vessel.

Urenco U-Battery

U-Battery is a very small nuclear reactor moderated with graphite and cooled by helium in a primary circuit with nitrogen in a secondary circuit. It has an output of $4\,MW_e$, $10\,MW_{th}$ in cogeneration mode or can also deliver process heat at $750\,°C$. This micro-SMR U-battery would run for five years before refuelling and servicing. It would use TRISO fuel with $17 - 20\%$ enriched uranium and possibly thorium with a beryllium oxide reflector. It would have a $1,8\,m$ diameter and can be installed above or below ground.

EM^2

The energy multiplier module (EM2) is a helium-cooled fast reactor with a core outlet temperature of 850°C. It is designed as a modular, grid-capable power source with a net unit output of 265 MW(e). The reactor converts fertile isotopes to fissile and burns them in situ over a 30-year core life. EM2 employs a direct closed-cycle gas turbine power conversion unit (PCU) with a Rankine bottoming cycle for 53% net power conversion efficiency assuming dry cooling. EM2 is multi-fuel capable, but the reference design uses low-enriched uranium (LEU) with depleted uranium (DU) carbide fuel material with accident tolerant cladding material (Agency [2018a]).

3.5.4 Fast Small Modular Reactors

Fast neutron reactors are smaller and simpler than light water types, they have better fuel performance and can have a longer refueling interval reaching up to 20 years. They have no moderator, a higher neutron flux and are normally cooled by liquid metal such as sodium, lead, or lead-bismuth, with high conductivity and boiling point. Automatic power regulation is achieved due to the reactivity feedback, loss of coolant flow leads to higher core temperature which slows the reaction. Fast reactors typically use boron carbide control rods.

Fuel for this type of reactors are mostly uranium enriched up to 15%-20%, and they are designed to use full energy potential from uranium. Most coolants are liquid metal, either sodium, which is flammable and reacts violently with water, or lead/lead-bismuth, which is corrosive but does not react with air or water. It eliminates the need and associated expense of extra components and redundant safety systems required by other technologies for protection against coolant leakages. Both coolants can be used at or near atmospheric pressure, which simplifies engineering and reduces cost.

There are two exceptions to liquid metal cooling: gas and salt. Gas cooled Fast Neutron Reactor concept is a mix between this technology and High Temperature reactors mentioned before. Salt cooling can be labeled under a new category, Molten Salt Reactors.

4S (Super-Safe, Small & Simple)

The Super-Safe, Small & Simple reactor is sodium cooled without on-site refuelling. It is developed as a distributed energy source for multipurpose applications and has two different configurations: $30MW_{th}$ and $135MW_{th}$. The reactor core has a lifetime of approximately thirty years in which the movable reflector gradually moves, compensating the burnup reactivity loss over the lifetime. To reduce the probability of component failure, the design eliminates active systems and feedback control systems from the reactor side as well as components with rotating parts. There is also limitation of the radioactivity confinement area, since there is no refuelling during the life of the reactor. Technical features of the 4S contributing to a high level of proliferation resistance include the use of uranium based fresh fuel with ^{235}U enrichment less than 20% by weight and a low plutonium content in the spent fuel (less than 5% by weight). The reprocessing technology available for metal (alloy) fuel, such as U–Zr or U–Pu–Zr, ensures that plutonium is always recovered together with the accompanying minor actinides, which include highly radioactive and radiotoxic nuclides. The whole unit would be factory-built, transported to site, installed below ground level, and would drive a steam cycle via a secondary sodium loop. After 30 years the fuel would be allowed to cool for a year, then it would be removed and shipped for storage or disposal.

Rapid-L

A small-scale design developed by Japan's Central Research Institute of Electric Power Industry (CRIEPI) in cooperation with Mitsubishi Research Institute and funded by the Japan Atomic Energy Research Institute (JAERI) is the $5MW_{th}$, $200kW_e$ Rapid-L, using lithium-6 (a neutron absorber) as control medium. It would have 2700 fuel pins of $40 - 50\%$ enriched uranium nitride with $2600°C$ melting point integrated into a disposable cartridge or 'integrated fuel assembly'. The reactivity control system is passive, using lithium expansion modules (LEMs) which give burn-up compensation, partial load operation as well as negative reactivity feedback. During normal operation, lithium-6 in the LEM is suspended on an inert gas above the core region. As the reactor temperature rises, the lithium-6 expands, moving the gas/liquid interface down into the core and hence adding negative reactivity. Other kinds of lithium modules, also integrated into the fuel cartridge, shut down and start up the reactor. Cooling is by molten sodium, and with the LEM control system, reactor power is proportional to primary coolant flow rate. Refuelling would be every 10 years in an inert gas environment. Operation would require no skill, due to the inherent safety design features. The whole plant would be about 6,5 m high and 2 m diameter.

Hyperion power module (Gen4 module)

The Gen4 Module is a $70MW_{th}$, $25MW_e$ lead-bismuth cooled reactor concept using 19.75% enriched uranium nitride fuel. The reactor vessel housing the core and primary heat transfer circuit is about 1,5 metres wide and 2,5 metres high. It is easily portable, sealed and has no moving parts. A secondary cooling circuit transfers heat to an external steam generator. The reactor module is designed to operate for electricity or process heat (or cogeneration) continuously for up to 10 years without refuelling. Another reactor module could then take its place in the overall plant. The old module, with fuel burned down to about 15% enrichment, would be put in dry storage at site to cool for up to two years before being returned to the factory.

3.5.5 Molten Salt Small Modular Reactors

These type of reactors use molten fluoride salts as primary coolant at low pressure since this remains liquid without pressurization up to $1400°C$, in contrast to a Pressurized Water Reactor which operates at about $315°C$ under 150 atmospheres pressure.

In the normal MSR, the fuel is a molten mixture of lithium and beryllium fluoride salts with dissolved enriched uranium (U-235 or U-233) fluorides. The core consists of unclad graphite moderator arranged to allow the flow of salt at some 700°C and at low pressure. Higher temperatures are possible but not yet tested. Heat is transferred to a secondary salt circuit and thence to steam. The basic design is not a fast neutron reactor, but with some moderation by the graphite, may be epithermal (intermediate neutron speed) and breeding ratio is less than 1.

Thorium can be dissolved with the uranium in a single fluid MSR, known as a homogeneous design. Two-fluid, or heterogeneous MSR's would have fertile salt containing thorium in a second loop separate from the fuel salt containing fissile uranium and could operate as a breeder reactor (MSBR). In each case secondary coolant salt circuits are used.

The liquid fuel has a negative temperature coefficient of reactivity and a strong negative void coefficient of reactivity, giving passive safety. If the fuel temperature increases, the reactivity decreases. The MSR thus has a significant load-following capability where reduced heat abstraction through the boiler tubes leads to increased coolant temperature, or greater heat removal reduces coolant temperature and increases reactivity.

This technology has great potential to work alongside renewables and their intermittent nature thanks to high outlet temperature achieved of about $600°C$, enough for heat from the reactor to be transferred to a nitrate salt storage tank for later use through a turbine when demand rises. This heat storage technology is already used with concentrated solar power (CSP) but isn't suitable for conventional nuclear reactors, which produce heat at around $300°C$

3.5.6 Heat Pipe Small Modular Reactors

Heat Pipe Reactors are fission reactors that take advantage of the great heat transfer capacity from heat pipes to transfer fission energy from the core to the converters in order to produce electricity. By avoiding the pumping of coolant through the core, heat pipes reactors achieve simplicity and high reliability.

A Heat Pipe Reactor is typically a solid block core with the fuel in holes inside the solid block. The heat pipes remove the heat from the block as the liquid in the heat pipe is vaporized. The heat is deposited in the condenser region of the heat pipe. The condenser region can be sized to accommodate multiple heat exchangers, such as one for power conversion and two for redundant decay heat removal.

Kilopower

Kilopower, as the name implies, is a nuclear reactor with a range of power between $5kW_{th} - 50kW_{th}$, $1kW_e$ to $10kW_e$ intended for outer space applications. This reactor utilize heat pipes to transfer fission energy from a solid block of fuel to a power conversion system which in this case are Stirling engines. The Kilopower solid core eliminates potential movements of fuel rods/pieces relative to others, and the surrounding geometry is fixed (except for small potential relative movements due to thermal expansion), thus the only major reactivity effects are changes in neutron leakage/reallocation due to material expansion. This makes the startup and operational system dynamics easy to predict and verify. The simplicity of the system also leads to high reliability. The reactor is essentially solid-state, with the control rod being the only moving part. Actually, at low powers (10 kW) the burnup reactivity is so small that long lifetime (10+ yr) could be achieved without any control movement after startup; higher power systems would require occasional movement to maintain reactor temperature. Another system attribute that leads to high reliability is inherent redundancy in heat transport. Each heat pipe is an independent, highly reliable mechanism. In all proposed Kilopower systems, full power can be delivered even with several heat pipes or Stirling engines failed (Poston et al. [2019]).

Two different fuel configurations have been considered for Kilopower reactor; ^{235}U enriched to 93% (HEU) and ^{235}U enriched to $19,75\%$ (LEU). Both configurations had pros and cons, but overall, HEU concepts were superior from a performance and technology perspective, and the only significant reason to consider LEU is rooted in non-proliferation policy. The mass and size of this reactor is dependant on fuel choice, being HEU version lighter than LEU one, the $10kW_e$ version range from $1068kg$ in its HEU version with relaxed shielding to $2258kg$ in the LEU version with tight dose requirements.

The operation of this technology has already been proven in a nuclear powered system test called KRUSTY (Kilowatt Reactor Using Stirling Technology), which offers the first realistic shot in over 40 years to affordably and quickly establish fission power in space.

Megapower

Los Alamos National Laboratory, based on their success with KRUSTY reactor, developed an scaled up version of their kilowatt power reactor using the same operating principles. The Megapower reactor, as it is called, is built around a solid steel monolith with channels for both heat pipes and fuel pellets. The monolith is stainless steel and the fuel is commercial uranium oxide (UO_2), both well-characterized nuclear materials with high technology readiness levels. These two components alongside with heat pipes, which are not familiarized to the nuclear industry but are mature and robust with a large experimental test database to support implementation of the technology into nuclear applications, made this reactor unique and simple.

The Megapower reactor has a nominal core thermal power of $5MW_{th}$, and capable of providing $2MW_e$ with its respective power conversion system (Brayton cycle). The heat pipes remove the heat from the monolith as the potassium liquid in the heat pipes is vaporized; no pumps or valves are required. The heat is subsequently deposited in the condenser region of the heat pipe. The condenser region can be sized to accommodate multiple heat exchangers, such as one primary heat exchanger for power conversion and one or two additional heat exchangers for redundant decay heat removal. The reactor uses an alumina (Al_2O_3) neutron side reflector, with 12 embedded control drums that contain an arc of boron-carbide (B_4C) poison for reactivity control. The active part of the core is about 1 meter flat-to-flat and 1.5 meters high. The outer diameter of the Al_2O_3 reflector is 1,5 meters. In the proposed concept the monolith core is fabricated in six identical segments, forming a central hexagonal volume for two emergency shutdown control rods.

eVinci

eVinci reactor is the product of an alliance between Los Alamos National Laboratory and Westinghouse. This reactor assembles the core and heat pipes conceptual system from Megapower with an engine-generator system to convert reactor heat into electricity. The main goal for Westinghouse eVinci Micro Reactor is to serve remote off-grid or micro-grid markets where electricity demand size is small and currently commands a price premium (Levinsky et al. [2018]).

One of the main features of eVinci is the flexibility and scalability from $0,2MW_e$ to $15MW_e$ in order to address the diverse energy needs of the off-grid market. The unit is planned to be fully assembled and fueled in the factory. Placed in a secure canister, the reactor has a compact size and can be transported via ice roads, highways, rail, as well as water and air cargo. The reactor canister installation is to be completed on site within thirty days or less according to the current plan. After ten years of operation without refueling, the eVinci reactor will be disconnected and transported back to the factory in its original canister for either refueling and redeployment or for long-term storage, which can be accomplished in the eVinci reactor canister itself.

eVinci reactor is a epithermal spectrum reactor using fuel pellets enriched to $19,75wt\%$ and metal hydride as neutron moderator.

Small Modular Reactor assessment for Antarctica

The diversity of designs allows for SMR's to be useful in many different scenarios, nevertheless, for a niche application, such as Antarctica, a particular design is needed since not all reactor models can be suitable for the specific requirements. In this chapter, station requirements such as energy demand, installed capacity and annual fuel consumption together with station restrictions such as transport, maintenance and logistics will be analyzed alongside reactor characteristics resulting in reactor technology selection for the main Antarctic clusters.

4.1 Station Requirements

In Chapter 1 a brief description of the main clusters and isolated stations in Antarctica was made, in this section a more exhaustive analysis will be made considering installed capacity, annual consumption, storage capacity in order to determine the suitable power capacity a reactor must have to supply these stations.

The information regarding capacities and consumption from the stations was obtained through the Inspection Reports mentioned in Chapter 1, the objective of these documents is to keep activities from the different countries and station totally transparent. The inspection is performed each time by a different mix of countries and personnel, thus the document is different each time as well, and sometimes information about logistics as installed capacity, power consumption and fuel storage is left out.

The data in Table 4.3 is taken exclusively from the last inspection report made for each of the stations, and for a couple of them older reports were used since the last one did not provide energy information.

Installed capacity in Table 3.1 shows the number and power for each generator in their respective station, the first observation from this information is that almost every station has at least 2 fossil fuel generators. The objective of this arrangement is to provide energy security through redundancy. Usually, generators do not operate simultaneously but rather in a cyclical way, alternating between the main generators after certain time while having sometimes an emergency backup.

Table 4.3: Installed capacity and fuel consumption of Antarctic stations

Station	Country	Installed Capacity [kW]	Annual Consumption [L]
Aboa	Finland	2x18.9	6000
Amundsen-Scott	USA	3x750 + 3x250	1378000
GARS	Germany	2x104 + 60	120450
Arctowski	Poland	120 + 2x70	77000
Artigas	Uruguay	100 + 2x140	
Arturo Prat	Chile	3x55 + 3x30	122000
Belgrano II	Argentina	-	-
Bellingshausen	Russian Federation	110 + 120 + 140 + Emergency	171000
Bharati	India	3x100 + 75	120000
Brown	Argentina	4x4.5	-
Camara	Argentina	2x45 + 31 + 7	7000
Carlini	Argentina	300 + 2x225 + 250	280000
Casey	Australia	-	700000
Comandante Ferraz	Brazil	2x410	-
Concordia	France-Italy	2x110 + 193	-
Davis	Australia	-	700000
Decepción	Argentina	2x24	12000
Druzhnaya-4	Russian Federation	-	-
Dumont d'Urville	France	3x80 + 130	
Esperanza	Argentina	2x140 + 150 + 140	330000
Fildes Maritime Station	Chile	17	-
Frei Montalva Station	Chile	400 + 472 +292	
Gabriel de Castilla	Spain	2x150	24900
Gabriel González Videla	Chile	2x75 + 2x16	-
Gondwana Station	Germany	-	-
Great Wall	China	3x120	171000
Halley	UK	-	365000
Jang Bogo	South Korea	-	-

Table 4.3: Installed capacity and fuel consumption of Antarctic stations

Station	Country	Installed Capacity [kW]	Annual Consumption [L]
Johann Gregor Mendel	Czech Republic	22 + 25	2400
Juan Carlos I	Spain	3x95	
King Sejong	Republic of Korea	3x275 + 275	380000
Kohnen	Germany	-	-
Kunlun	China	-	-
Leningradskaya	Russian Federation	-	-
Machu Picchu	Perú	-	-
Maitri	India	2x135 + 4x75 + 4x62	400000
Marambio	Argentina	700 + 600 + 500	722490
Mario Zucchelli	Italy	2x300 + 2xemergency	-
Mawson	Australia	-	700000
McMurdo	USA	-	7500000
Mirny	Russian Federation	3x320 + 500 + 100	547200
Molodezhnaya	Russian Federation	-	-
Neumayer III	Germany	-	230000
Novolazarevskaya	Russian Federation	-	-
O'Higgins	Chile	2x250 + 125	1825000
Orcadas	Argentina	4x75	205200
Palmer	USA	2x250 + 150	290000
Pedro Vicente Maldonado	Ecuador	-	-
Petrel	Argentina	31	
Princess Elisabeth	Belgium	2 Backup Gen	2000
Professor J.Escudero	Chile	2x58 + 35	-
Progress	Russian Federation	-	-
Risopatrón	Chile	-	-
Rothera	UK	4x144 + 2x144	716200
Ruperto Elichiribehety	Uruguay	-	-
San Martín	Argentina	3x48 + 25	80000
Sanae IV	South Africa	-	260000
SANAP	South Africa	-	-

Table 4.3: Installed capacity and fuel consumption of Antarctic stations

Station	Country	Installed Capacity [kW]	Annual Consumption [L]
Scott Base	New Zealand	-	61000
Signy	UK	3x120 + 2x60	190000
Soyuz	Russian Federation	-	-
St. Kliment Ohridski	Bulgaria	50 + 7	3500
Syowa	Japan	2x240 + 2x200	425220
Troll	Norway	2x240 + 3x64 + 48	250000
Vernadsky	Ukraine	3x80	140000
Vostok	Russian Federation	-	150000
Wasa	Sweden	-	-
Yelcho	Chile	30	4000
Zhongshan	China	3x165	-

McMurdo Station last inspection was in 2005 prior to their power plant remodeling in 2009, thus no relevant information about this station can be found in Table 3.1. New power plant consists of $7800kW$ of installed capacity from 6 Caterpillar generators running alternately with a peak during day of $2000kW$ and during night of $1200kW$. This group of stations is the largest in Antarctica and one of the main focus for this research. Scott Base uses about 61000 liters of fuel per year which most part goes to boilers that provide station heating, for power needs Scott Base relies on the wind farm consisting of three $330kW$ turbines which provides most of the time 100 percent of the amount of power needed and offsetting the remaining to McMurdo Station.

Table 4.4: Station requirements for McMurdo-Scott bases

Group 1	Installed Capacity [kW]	Peak Demand [kW]	Annual Fuel Consumption [L]
McMurdo	7800	2000	7500000
Scott	990	990	61000

The next focus of study consist of Amundsen-Scott Polar Station as this represent the most southern and isolated station in all the Antarctic continent. Last inspection to this station was carried out at the end of 2016, annual consumption is 1378000 liters of AN-8 fuel, an special blend for operating at below $0°C$ temperature. The $750kW$ generator provides baseload capacity for the station while the $250kW$ generator is for peaking energy, together they meet the load of the station.

Table 4.5: Station requirements for South Pole base

Group 2	Installed Capacity [kW]	Peak Demand [kW]	Annual Fuel Consumption [L]
Amundsen-Scott	3000	1000	1378000

Located in the Antarctica peninsula region, specifically on King George Island is the third focus of this work. The station Presidente Eduardo Frei provides the main logistic facility to the whole area since the airport support frequent operations made by different countries, specially during summer, because of the tourists flights and the increase in the logistical needs. This station is a large and multi-functional collection of facilities which operates with a certain degree of autonomy, the main components are i) The Presidente Eduardo Frei M. Antarctic Air Base ii) The Lieutenant Rodolfo Marsh Airstrip and associated facilities operated by Dirección General de Aeronáutica Civil (DGAC) iii) the Fildes Naval Station run by a Capitán of the Chilean Navy and iv) the Escudero station run by INACH (Instituto Antártico Chileno), but as they share key infrastructure and services can be analyzed as a single entity. Frei Air Force Station acts as the main logistic component and supply the others stations with electricity obtained by one $400kW$ caterpillar generator backed up with two emergency generators of $472kW$ and $292kW$. To power the station diesel fuel with Antarctic quality is used and stored in 18 storage tanks with a total capacity of 1200 cubic metres. The other main components of this station have less storage capacity used mainly for their emergency generators and motorised vehicles.

Also part of the Cluster is Chinese station Great Wall, Russian station Bellinghausen, Uruguayan Artigas Station, South Korean King Sejong Station, Henryk Arctowski Station operated by Poland and Argentinean Carlini Station.

For most of Antarctic stations, only one generator is working while the others are shut down waiting for an emergency, maintenance or rotation in order to be turned on. This means peak demand is equal to the power of the generator currently operating with the exception of a few stations such as Amundsen-Scott where a peak generator is used as well. These are the main parameters to consider when evaluating an energy replacement system.

Table 4.6: Station requirements for King George bases

Group 3	Installed Capacity [kW]	Peak Demand [kW]	Annual Fuel Consumption [L]
Presidente Frei	1164	400	Uninformed
Great Wall	375	125	171000
Bellinghausen	370	110-140	150000
Artigas	380	80	Uninformed
King Sejong	1100	275	380000
Arctowski	260	70-120	77000
Carlini	800	180-240	280000

Table 3.5 summarizes the information for the three group of stations described before. The results show that installed capacity is about three times the peak capacity and that this last parameter ranges between $3MW$ and $1MW$. These values are specially important for technology selection.

Table 4.7: Installed Capacity and Peak Demand summary

Group	Installed Capacity [kW]	Peak Demand [kW]
1	8790	2990
2	3000	1000
3	4450	1240 - 1380

These three Station groups in Antarctica are the main focus for this study. Identifying the feasibility of an energy solution which can be replicated and escalated for all of them is the main objective.

Identifying loads and daily energy profile for the stations can be a useful tool for analyzing consumption within each particular station and allows for a better understanding of the systems that participate in fuel consumption. This analysis can segregate fuel load information into different types and equipment's such as generators, boilers, incinerator, vehicles among others. Can also segregate electric load information by equipment as well such as heating, lightning, accommodations, laboratory, security systems, general loads among others. This analysis can lead to the identification of inefficiencies or inefficient trends within the system. Once the energy dynamics of the station is understood, it is easier to properly enhance efficiency, assess a new power generation system such as solar or wind, or optimize the loads for a smoother profile reducing peaks and increasing savings.

Despite how useful it can be this tool for optimizing energy within any station, this information is not available. In order to obtain a daily load profile, specific measurements must be obtained for each station together with spreadsheets for fuel consumption. Not all Antarctic station keep track periodically enough to develop a profile and even if they do, such information is not available worldwide. Nevertheless, a daily load profile is not necessary for assessing a new baseload energy alternative since the idea is to feed the same loads but with a sustainable source.

That said, it is important for the energy source to have the capacity to follow loads such as fossil fuel generators do. This feature is a must, since daily energy profiles for the Antarctic stations are variable in nature and energy must be provided at all cost, also, a new energy system cannot mean a downgrade from the previous one.

4.2 Station Restrictions

Fossil fuels have endured as the main energy source in Antarctica because of many reasons; reliability and the capacity to operate under any weather condition, relative low capital costs for infrastructure and installation, high energy density and suitable power ratings for all Antarctica needs, and finally because it fits Antarctic logistics, meaning that can be provided by ship or airplane during summer and remain stored for winter.

Reliability and the capacity to operate under any weather condition is the first restriction for any baseload power source in Antarctica. As mentioned earlier, energy security is essential since energy shortage immediately compromises the safety of the station occupants. Nuclear energy fulfills with this restriction as it is a reliable power source with around 90% capacity factor capable of operating under any weather condition.

Low capital cost for installation is an important restriction, especially for countries developing their first station in Antarctica, as investing too much in an uncertain bussiness as Antarctica, would prevent a lot of nations from entering to this region slowing down worldwide scientific development. Fossil fuels excel in this aspect as initial capital cost is low while operation is the most expensive component. The advantage of this scheme is that it allows for stations to spend the exact amount of fuel they need, ideal feature for summer station which are also usually the type of stations from incoming countries.

Power ratings from fossil fuel are adjustable to demand and also high enough to allow the operation of multiple systems within the stations. If at a certain point, any station requires more energy because of a peak demand or because of a growth of the station and thus in general demand, an extra generator can be turned on if available or in case of need an extra generator can be installed without the need to make big changes in the power system. A nuclear reactor that overcomes this restriction will need to be powerful enough to provide total energy demand while also flexible enough to decrease its power when not needed.

Different nuclear power schemes can accomplish the power rating restrictions:

• **Load Following Reactor**: This is a feature from some small modular reactors in which they are capable of load following thanks to their reactivity feedback mechanisms. When energy demand is low, temperature will rise generating thermal expansion within the reactor and subsequently activating the negative reactivity feedback which will ultimately reduce the rate of fission causing a decrease in power. The same process will occur in the opposite way if the energy demand is high.

• **Reactor with Fossil Fuel Backup**: A system comprising a nuclear reactor alongside fossil fuel generator can achieve the performance needed for Antarctic station. This system would provide baseload energy through an underrated nuclear reactor and diesel generator would be turned on for peaking purposes.

• **Reactor with energy storage**: This scheme will comprise a nuclear reactor with power output over the baseload but under the peak with an additional storage system. Nuclear reactor would produce constant energy supply during the day, in periods where power output from the reactor is superior than energy demand remaining power will be directed to storage system, and, in periods where power output is lower than the energy demand additional energy coming from the storage system will assist the nuclear reactor. Storage system can be a bank of electrical batteries, fly-wheels or hydrogen cells which can also be used to power vehicles. Major development of storage subject will be discussed further ahead.

• **Reactor with Power By-pass**: A simpler way to address the matter comprises a light water nuclear reactor with a power by-pass. This scheme consists in a nuclear reactor with uniform power output where the load following feature is by simply releasing surplus energy in the form of steam through a by-pass between the reactor and the power conversion system. This scheme is not ideal since it is less efficient than the others, but represent a simpler method to begin with. An inconvenience with this layout is the lack of a water source in Antarctica to replace the lost steam.

• **Recovering Reactor Heat**: Similar to the Reactor with Power By-pass, this scheme consists in a nuclear reactor with uniform power output where thermal energy not needed by the power conversion system is redirected to a heat exchanger and used either for space heating within the station or producing water by melting snow.

Finally, adjusting to Antarctic logistics is a key feature for any power source to be viable in this region. Transportation, weight, size, maintenance and refuelling intervals are crucial.

Transportation, Weight and Size

Cargo for Antarctica is mainly shipped by sea inside standard containers to coastal stations. For inland stations, cargo is delivered by overland vehicles or by air during the brief summer season. Alternative energy solutions ideally follow the same procedure as any other cargo for the continent.

Oversized cargo can be shipped as well under the category of Break Bulk cargo. This shipment can be delivered with more or less difficulties to coastal stations, this is the case of cranes for example, where each can weight more than 300 metric tonnes. For inland stations, there are weight and size limits for air transport and overland transport. Air transport is limited by the capacity of LC130 aircraft, which is usually loaded with almost 10 metric ton of cargo during flights to Amundsen-Scott Station. Overland transport can deliver much more payload while also could deliver over-size cargo that would not fit inside LC130 aircraft. Tractors used for South Pole Traverse voyages can drag twelve 3000 gallons fuel bladders equivalent to 113 metric tonnes when strapped to a sheet of low-friction ultra-high molecular weight (UHMW) polyethylene, which is far more than the maximum in LC130 aircraft (Lever and Weale [2011]).

Maintenance and Refuelling

One of the main issues with fossil fuel for Antarctica is the increase in price due to the transport implications, the difficulty along with the safety measures involved in these exercises increase the original fuel value in up to seven times as said in Chapter 1. For nuclear technology, specially for Small Modular Reactors, refuelling intervals can be much longer, avoiding annual expenses while also reducing the possibility of an accident.

Furthermore, climate in Antarctica makes impossible or extremely risky for expeditions during certain periods of time, which translates in isolated periods for stations and clusters with no room for refuelling or external maintenance to the power systems. This means that the nuclear reactor technology selected for Antarctic applications must be self sufficient and reliable enough to avoid the need for maintenance within this periods.

4.3 Small Modular Reactor Technology Comparisons

Several Small Modular Reactors were briefly described in Chapter 2, in this section, these reactors are contrasted regarding its usefulness in Antarctica and for how suitable they are for this niche application.

Table 4.8 present the main parameters of the Small Modular Reactors assessed, it is noted the difference between Light Water Reactors (LWR) and the other technologies, as water reactors require higher pressure and reach lower temperatures. Fuel cycle for this type of reactors is longer than for previous generations reactors thanks to their smaller power output but also thanks to new development in core design and fuel design motivated mainly to improve safety and proliferation risks.

Physical parameters for reactors are detailed in Table 4.9, where RPV stands for Reactor Pressure Vessel, it is noted from this table that pebble bed reactors (HTR-10) are bigger than the others, this is due to the structure of the fuel which leads to a low energy density, enhancing safety levels.

Finally, Table 4.10 summarizes the design status for each of the Small Modular Reactors.

Table 4.8: Operation parameters of Small Modular Reactors

Reactor	Power [MW_e]	Pressure [MPa]	Temperature [$°C$]	Fuel Enrichment	Fuel Cycle
Carem	25	12,25	326	$3,1\%$	14 months
Unitherm	2,5	16,5	330	$19,75\%$	25 years
HTR-10	10	3	700	17%	Open
U-Battery	4	4	750	$17-20\%$	5 years
4S	10	0,3	510	$20-24\%$	30 years
Rapid-L	0,2	4,1	1100	$40-50\%$	10 years
Gen4	25	0,1	500	$19,75\%$	10 years
Kilopower	0,01	N/A	800	93%	10 years
Megapower	2	2	675	$19,75\%$	5 years
eVinci	0,2-15	Not-pressurized	600	$19,75\%$	10 years

Sources: Levinsky et al. [2018] Agency [2018b] Wu et al. [2002] Sterbentz et al. [2017] Ding et al. [2011] Kambe et al. [2017] Poston et al. [2019] Aydogan [2016]

With all this information collected, a comparative matrix was made between all Small Modular Reactors assessed. Table 4.11 rates each reactor feature on a scale from 1 to 5 based on how suitable it is for an Antarctic application. A brief description of the parameters compared and how they impact in the technology selection is shown below.

• **Power**: Power requirements in Antarctica range from as low as $4,5kW$ in Brown Station to a couple of megawatt in McMurdo Station, over this power range, reactors need to be scaled down meaning that the original design must be modified in such a way that all the features and benefits from the original reactor are maintained. This redesign implies a higher cost as new research and testing must be done from the manufacturer, furthermore, scaling down an Small Modular Reactor conflicts with their economy of scale nature.

• **Pressure**: The pressure is not a parameter that presents major inconveniences for the operation of a reactor in Antarctica. One of the only issues associated with higher pressure is the fact that reactors tend to be more robust and consequently bigger and/or heavier. Higher pressure also implies the need for pumps which increase the complexity of reactors. Security is also a factor as higher pressure leads to higher risk of coolant loss.

• **Temperature**: Temperature is a parameter linked to reactor type and technology. For Antarctica purposes, both high temperature and low temperature have advantages and disadvantages. High temperature reactors are useful for waste heat applications such as recovery heat for space heating

Table 4.9: Physical parameters of Small Modular Reactors

Reactor	RPV Diameter [m]	RPV height [m]	Weight [ton]
Carem	3,2	11	267
Unitherm	2,9	9,8	180
HTR-10	5,9	25	N/A
U-Battery	1,8	5,9	N/A
4S	3,5	24	N/A
Rapid-L	2	6,5	N/A
Gen4	1,5	2,5	N/A
Kilopower	N/A	1,5	1,5-5
Megapower	1,8	3,65	35-45
eVinci	N/A	N/A	N/A

Sources: Morales Pedraza [2017] Agency [2018b] Wu et al. [2002] Ding et al. [2011] Kambe et al. [2017] Poston et al. [2019] Mcclure et al. [2015]

Table 4.10: Design Status and country of origin of Small Modular Reactors

Reactor	Design Status	Country
Carem	Under Construction	Argentina
Unitherm	Conceptual Design	Russian Federation
HTR-10	Tested	China
U-Battery	Under Development	United Kingdom
4S	Detailed Design	Japan
Rapid-L	Conceptual Design	Japan
Gen4	Conceptual Design	United States of America
Kilopower	Detailed Design	United States of America
Megapower	Under Development	United States of America
eVinci	Under Development	United States of America

or for melting snow to produce water. Low temperatures reactors have less surplus energy for recovery heat purposes but have less needs for decay heat removal.

• **Size**: Size is an imperative factor for Antarctic applications as transport restrictions impose an upper limit for reactor dimensions. The smaller the reactor, the easier it is to transport, install and accommodate within the station facilities. This translates into lower cost since existing buildings can accommodate the new reactor or an smaller building needs to be built.

• **Weight**: Similar to size, weight is an imperative factor for nuclear reactors as transport and installations restrictions impose an upper weight limit.

• **Design Status**: Design status is not an imperative factor for Antarctic application, nevertheless, the more advanced the reactor development is, the closer it is to a possible application.

• **Fuel Intervals**: It is mandatory for refuelling to be at least on an annual basis in order to adjust to Antarctic logistics and climate. Beyond this time interval, longer refuelling cycles implies lower operation cost since fewer expeditions are needed which also reduces the accident possibilities.

Table 4.11: Comparison matrix between reactor technology for Antarctic applications

Reactor	Power	Pressure	Size	Weight	Design Status	Fuel intervals	Total
NuScale	1	3	1	2	2	4	18
Carem	1	3	2	2	4	3	20
Unitherm	3	3	3	2	2	5	23
HTR-10	1	4	1	1	5	5	22
HTR-PM	1	3	1	1	4	5	20
U-Battery	2	4	4	3	2	4	24
EM_2	1	3	2	2	2	5	20
4S	1	5	1	1	3	5	21
Rapid-L	5	4	4	3	2	5	26
Gen4	1	5	5	5	2	5	28
Kilopower	3	5	5	5	4	5	32
Megapower	5	5	5	5	2	4	31
eVinci	5	5	5	5	2	5	32

The results of 4.11 indicate that Heat Pipe Reactors are the most suitable technology for Antarctic applications, specially when considering ”Power”, ”Size” and ”Fuel cycle” as the most important features for this niche application.

4.4 Heat Pipe Small Modular Reactor Advantages

Heat Pipe Reactors have potential advantages that position it as one of the best alternatives for sustainable energy generation, these are listed below:

• **Size**: Enrichment of the fuel to nearly 20% or higher, the use of a fast neutron spectrum and the use of a highly reflected core allow for a very small reactor core size and weight. These features are specially important when deciding on transportable or mobile technologies.

• **Orientation**: Heat Pipe Reactors can remove heat in any orientation, thus their potential for outer space applications in lack of gravity. Having the ability of the heat pipes to effectively remove heat in any orientation is an advantage for safe transportation.

• **Safety**: In a Heat Pipe Reactor, an array of heat pipes are used to remove heat from the core using simple, reliable and well characterized physics (capillarity, boiling and condensation). Also, if one heat pipe fails, heat can be removed through the remaining heat pipes and failure of multiple heat pipes will be much lower that the failure rate associated with a coolant system. Monolithic core from Heat Pipes Reactors are also a safety feature since voids in the core can't occur, eliminating issues with positive reactivity. In addition heat pipe reactors are at ambient pressure inside the core. This again eliminates issues with high pressure as might occur in a high-pressure system such as a gas-cooled reactor design. Depressurization accidents are a major concern for high-pressure systems. Finally, given that there are no pumps or valves in Heat Pipe Reactors core or vessel, overall reliability and safety are improved.

• **Self Regulation**: One of the key features of small highly reflected fast reactors is the simple and predictable reactivity feedback mechanism that allows for the reactor to be load following. Thanks to thermal expansion and subsequent negative reactivity feedback, the reactor power will decay if less heat is extracted by the power conversions systems.

• **Solid State**: Heat Pipe Reactors lack mobile parts as pumps or valves making them near solid state. Other than control rods (or drums), moving parts can be limited to power conversion system. The implication is that a near solid state reactor could potentially be more reliable than reactor designs with many moving parts.

• **Heat Transfer Surface Area Moved Outside Core**: Heat Pipe Reactors uses heat pipes to remove heat from the core instead of passing a fluid through the core. This configuration moves the heat transfer to the working fluid outside the core, meaning that the choice of working fluids does not impact the radiation transport inside the core. In addition, a cycle such as an open-air Brayton system is available as an attractive option for power conversion. Since the air would pass through the heat pipe heat exchanger and not the reactor core, the issue of the air becoming activated is removed. An open-air Brayton cycle would not need a second system for removing residual heat in the thermodynamic cycle. This greatly simplifies the reactor system.

• **High Temperatures**: Heat Pipe Reactors can work with temperatures ranging from $650°C$ to over $1000°C$ depending on the choice of alkali metal used in the heat pipes. This feature allows the reactor to extend the range of applications by delivering a working fluid at a high temperature.

4.5 Technology Selection

Given the results, the proposed design will consist of a Heat Pipe Reactor based on Westinghouse eVinci model. The selection of this reactor over the other heat pipes reactor is due to the flexibility in electric and thermal power of its design (from $0,2MW_e$ to $15MW_e$).

This Westinghouse eVinci micro reactor shown in Figure 4.1 is a semi-autonomous, very Small Modular Reactor (vSMR) that is based on heat pipe technology. This reactor utilizes proven heat pipe technology developed by Los Alamos National Laboratory (LANL) for space application. This uranium-fuelled reactor does not use a bulk primary coolant. Instead, heat is removed from its solid monolithic core using passive heat pipes, limiting the number of its moving parts and providing overall plant simplicity.

The reactor system consists of uranium nitride or oxide fuel, and metal hydride moderator housed in a compact monolith, constructed of creep-resistant, high-temperature materials with embedded heat pipe channels arranged in a hexagonal pattern with the fuel channels. The monolith core by itself is subcritical; to achieve criticality the core must be surrounded by large radial and axial reflectors. Control drums in the reflector are used to control reactor temperatures and power levels. A central emergency safety shutdown or the hydrogen release in the metal hydride moderator is used to perform the safe shut down the reactor. High-temperature, double-ended sodium heat pipes are used to move heat from the core region to various heat exchangers. Alkali-metal heat pipes are

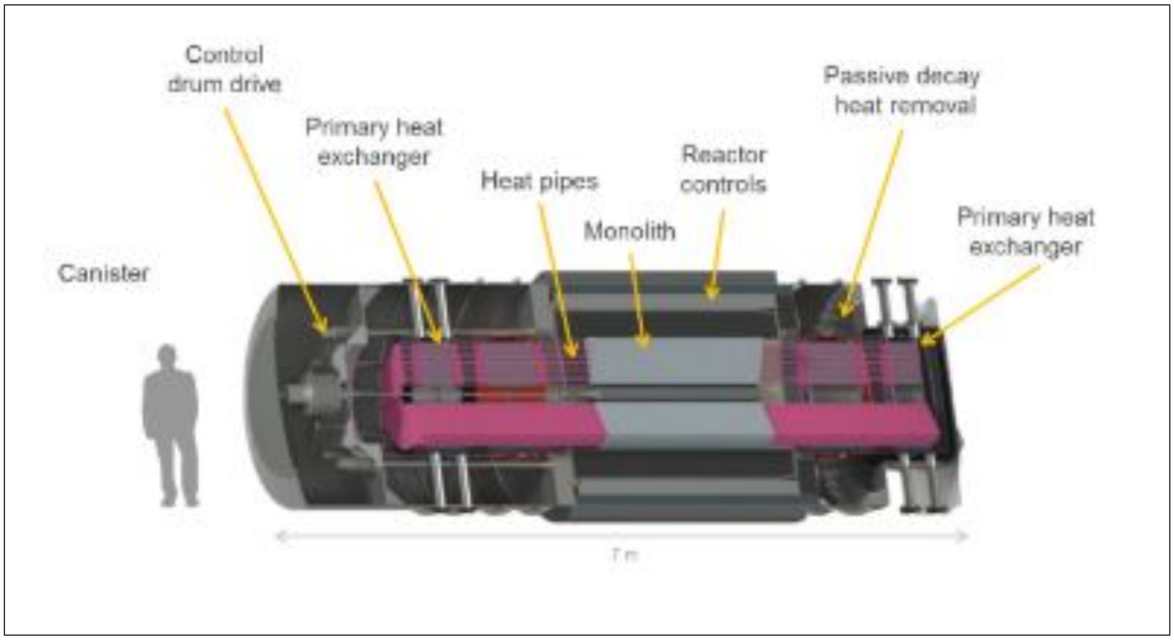


Figure 4.1: eVinci Reactor System Overview. Source: Levinsky et al. [2018]

extremely effective at moving heat with minimal temperature drop, eliminating the need for reactor coolant pumps and other auxiliary systems related to primary reactor cooling.

A high reliability is obtained through the selection of a heat pipe solid core block with nearly no moving parts. The only mechanically moving part in eVinci (excluding power conversion) is the reactor control drum. The limited moving parts and autonomous operation reduce the need for personnel and periodic maintenance, further enhancing the economic case. The solid monolith core block enables proliferation resistance by encapsulating fuel in the monolith. Heat pipes eliminate the need for reactor coolant pump and all its auxiliary fluid systems, thereby leading to plant simplification. The inherent load following capability of heat pipes, self-adjusting solid core and inherent decay heat removal via solid state conduction and air rejection, enables the autonomous operation and superior safety of the eVinci Micro Reactor (Agency [2018b]).

A few challenges related to the deployment of the Westinghouse eVinci reactor needs to be overcome for this technology to be commercially available.

In first place, the eVinci reactor will use fuel enriched to $19.75wt\%$. Currently, the availability of industrial-scale amount of uranium enriched to more than 5%, suitable for commercial reactors, is

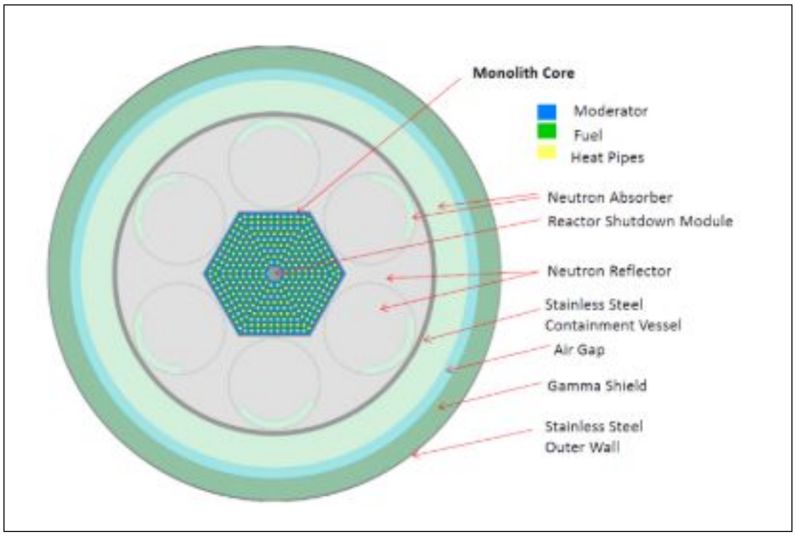


Figure 4.2: eVinci reactor cross section, showing the core and surrounding structures. Source: Levinsky et al. [2018]

limited. This challenge is common to the vast majority of advanced reactors proposed domestically and internationally, as they also require enrichments above 5%. Since the demand of such a fuel is increasing, national campaigns are currently increasing in momentum to identify solutions for this cross-cutting challenge.

In second place, it is envisaged that the eVinci reactors will be manufactured and completely assembled in a factory. The first reactor startup should happen on the production site as well. Consequently, the factory must be equipped with radioprotection equipment, safety and security systems adequate to handle this novel activity, and must have the appropriate license from the regulator. Transportation of the new and used reactors must be organized in compliance with the regulator's requirements taking into account appropriate level of shielding, cooling of the unit in case of the used reactor, and other safety and security aspects.

The eVinci reactor is conceived to operate autonomously, which is a novel concept for nuclear power plants, and as such it introduces challenges in licensing, instrumentation for remote reactor monitoring, and logistic, including personnel (Levinsky et al. [2018]).

System Design

Given the technology selection for the Antarctic Stations, the next step in developing an integral solution is the design and selection of the power conversion system. The eVinci micro reactor allows for operation with a variety of power conversion systems without having to redesign the core each time. The reference design can be easily adapted to work with Brayton cycle or Stirling engines. Rankine cycle, despite having the largest operating experience and lower technology uncertainty, requires large water resources for cooling which are not found throughout Antarctica and air-cooling option is generally very difficult and economically expensive. Furthermore, due to water chemistry control system and other complex supporting system, designing a compact and highly performing power conversion system with the steam Rankine cycle is very challenging (Bae et al. [2015]). Therefore, Rankine cycle will not be further discussed.

5.1 Power Conversion System

In order to compare Brayton and Stirling power conversion cycles for a Heat Pipe Small Modular Reactor, a model considering the thermal cycle and all the major subsystems such as heat source, power conversion and heat rejection must be developed while also considering the specific masses of the cycle components to determine the total system mass. This comparison among power conversion systems has been done before for space nuclear power systems.

Space nuclear power concepts are similar to terrestrial very Small Modular Reactors in power level, specially to Heat Pipe reactors since this technology is inherited from space development, being the main difference the heat rejection system as space reactors takes advantage of the coldness of outer space.

NASA, as part of their research in expanding human presence into the solar system, examined the performance and mass of Brayton and Stirling space power systems for a wide range of power levels and mission applications, while considering the impact of advanced supporting technologies, such as high temperature materials and lightweight radiators. The category ”Surface Outposts and Bases” refers to the initial human emplacements with a centralized reactor as power source. The

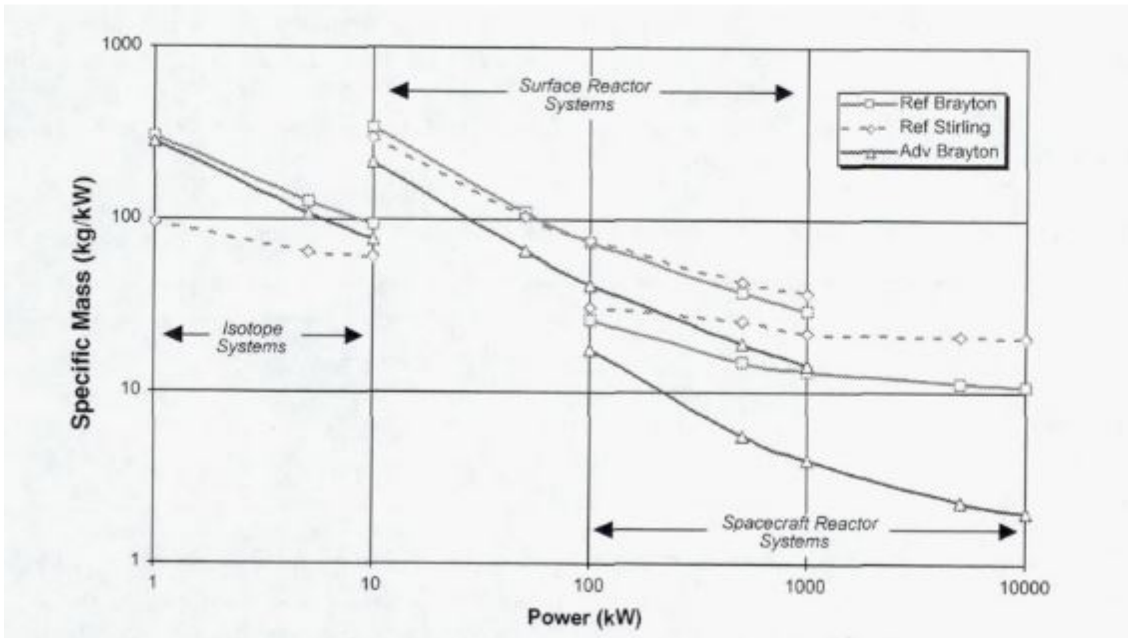


Figure 5.3: Summary of Specific Mass Projections for Brayton and Stirling Power Systems. Source: Mason [2001]

analysis of this particular class is very useful as Antarctic Stations are the terrestrial counterpart of this scheme. The results for this section indicates that substituting the Brayton converter for Stirling provides a mass benefit for power levels below $100kW$ and a mass penalty above that power quantity as shown in figure . One important parameter to take into account is power distribution voltage, as increasing this value significantly decreases the conductor mass allowing the optimum separation distances to increase, thus, reducing shield thickness and mass (Mason [2001]).

An overall summary of the study suggest that for low power radioisotope systems, Stirling engine is the obvious choice from a mass perspective, being the mass cross-over point in the $15 - 20kW$ range, which is beyond the practical limit for radioisotope systems. The preferred technology for surface stations varies between Stirling engine below $50kW$ and Brayton above that power level. For high power systems, the results indicate Brayton as the clear favorite (Mason [2001]).

A similar research conducted by Lee S. Mason years later, reached a similar conclusion in which a $50kW$ space system could use either Stirling engine or Brayton system with the optimum depending on the type of reactor (Mason [2006]). A valuable contribution from the research comes from the mass breakdown for different solutions. Stirling engine systems require less radiator area which translates into less mass from the heat rejection system, this means that on Earth, where heat rejection through radiation is not appropriate, Brayton systems becomes more convenient for power levels of $50kW$ and beyond.

Given that the focus of the study is regarding Scott-McMurdo, Amundsen-Scott and King George cluster, and each of them has a peak capacity of $1MW$ or more and an even larger installed capacity, Brayton cycle will be the selected power conversion system. Stations with lesser demand and capacity can make use of this concept as well but with the power generation system scaled down and reactor power output diminished. The analysis of such stations is beyond the scope of this study.

5.2 Supercritical CO_2 Brayton cycle

During the 1960´s, the most commonly used thermodynamic power cycles for closed cycle engines were Rankine and recuperated Brayton Cycle, back then, limitations of both cycles were clear. Ernest G. Feher stated in his 1968 work ”The Supercritical Thermodynamic Power Cycle” (Feher [1968]) the major limitations of the Rankine Cycle and Brayton cycle:

• The temperature range of the cycle is severely limited by the nature of the working fluid. Adding superheat in an attempt to circumvent this will depart the cycle from isothermal heat addition. Increasing the temperature range without superheat leads to excessive moisture content in the turbines, resulting in blade erosion.
• Simple recuperator cannot be employed to recover heat from the turbine exhaust.
• Expansion ratio of the cycle is usually large, requiring in some cases several turbine stages.

Major limitations for recuperated Brayton Cycle according to E.G. Feher:
• The compression process requires large energy input, therefore the net work to gross work ratio is small.

• The cycle is very sensitive to compressor efficiency and pressure ratio.

• Heat transfer surfaces are large for pressure levels that are typical for current Brayton engines.

Feher proposed a new thermodynamic cycle called ”Supercritical Cycle” which operates entirely above the critical pressure of its working fluid, avoiding most of the problems Brayton and Rankine had and yet retaining many of their advantages. The main benefit of this supercritical Brayton cycle is its reduced compression work compared to an ideal gas, enhancing the global efficiency alongside the capacity of the cycle to transfer back the heat to the working fluid by regeneration. Another desirable characteristics of this cycle are, low volume to power ratio, no blade erosion in the turbine, no cavitation in the pump, single stage turbine and pump and single phase fluid in the heat rejection process.

Feher proposed Carbon Dioxide as the working fluid of the Supercritical Cycle instead of other fluids for several reasons. First, its critical pressure is one third that of water, allowing lower operating pressures. Second, it is a stable and inert material throughout the temperature range of interest. Third, Carbon Dioxide is abundant, non-toxic and relatively inexpensive.

The non-ideal properties of the CO_2 causing the reduction of the compressor work also cause a pinch-point in the recuperator. Due to the radical temperature and pressure dependence of specific heat, the temperature difference between the hot and the cold fluid varies widely within the recuperator. The pinch-point is the location in the recuperator with the lowest temperature difference. Thus, even for the single-phase state of the CO_2 working fluid the minimum value of the temperature difference is not always achieved at the recuperator inlet or outlet, but sometimes somewhere along the recuperator. Feher was well aware of this problem as he transparently illustrates it using an enthalpy temperature diagram. Figure (5.4) shows that for two constant pressure lines, if the same enthalpy increments are taken the temperature increments are different, causing as consequence the pinch-point problem.

The Supercritical Cycle was discussed by other authors during this decade, Gokhstein and Verhivker (1969) in the Soviet Union (Gokhshtein and Verkhivker [1969]), Angelino in Italy (1967-69) (Angelino [1967] Angelino [1968] Angelino [1969]) alongside Feher in United States are the most important among others.

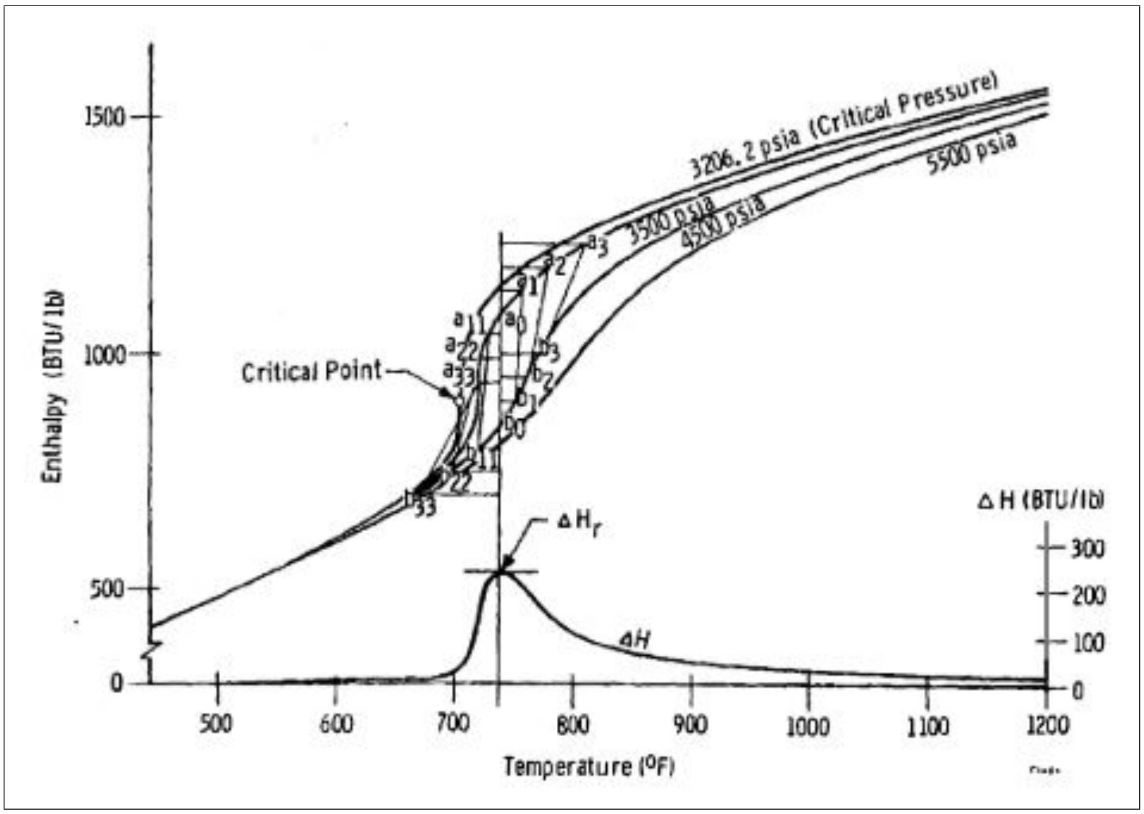


Figure 5.4: Enthalpy-Temperature diagram of CO_2 ilustrating the Pinch-point problem. Source: Feher [1968]

Angelino performed a detailed investigation of the supercritical cycle, he selected CO_2 as working fluid as well because of its many attractive characteristics. It is abundant and inexpensive, it exhibits a very good thermal stability (up to $1500°C$), a high chemical inertness and a precious nuclear behaviour with a small neutron absorption cross section. The objective of his research was to obtain the maximum possible efficiency by taking full advantage of the reduction of specific volume and, at the same time, minimizing the detrimental effect of the differing heat capacity between the expanded and compressed fluid within the recuperator (Pinch-point problem) by organizing the cycle conveniently.

Despite being focused on condensation cycles and cycles with sub-critical temperature, the research made by Angelino is useful as he introduces four different cycle layouts, known as compound cycles, to overcome the pinch-point problem represented in figure (5.5 Angelino [1968]). Cycle A also known as Recompression cycle is the most promising as diverting the low pressure flow into two portions, regeneration can take place between equal heat capacity flows, thereby partially removing the Pinch-point irreversibility. Cycle B is made in order to make the turbine exhaust pressure independent of the condensation pressure. Cycle C is a variation of cycle A made in order to reduce the mechanical stresses in the high temperature heater at the cost of a slight reduction of efficiency. Finally, cycle D is a pre-compression cycle.

Based on his results, Angelino concluded that at about $650°C$ the efficiency of cycle A is equal to a reheat steam cycle with the same maximum pressures. He suggested two possible fields of application for CO_2 cycles. At high temperatures ($650 - 800°C$), a supercritical CO_2 cycle could represent a substitute for steam cycles owing to its efficiency and simplicity, chiefly in the highest power level. At low temperatures ($450 - 550°C$), a supercritical CO_2 cycle could prove economical on account of simplicity and compactness despite its inferior efficiency with respect to steam cycles.

During the following years, investigations about supercritical CO_2 cycle continued but it failed to be deployed in practice. The main reasons were the absence of a suitable heat sources to take advantage of this process, insufficient turbomachinery experience and lack of suitable compact heat exchangers.

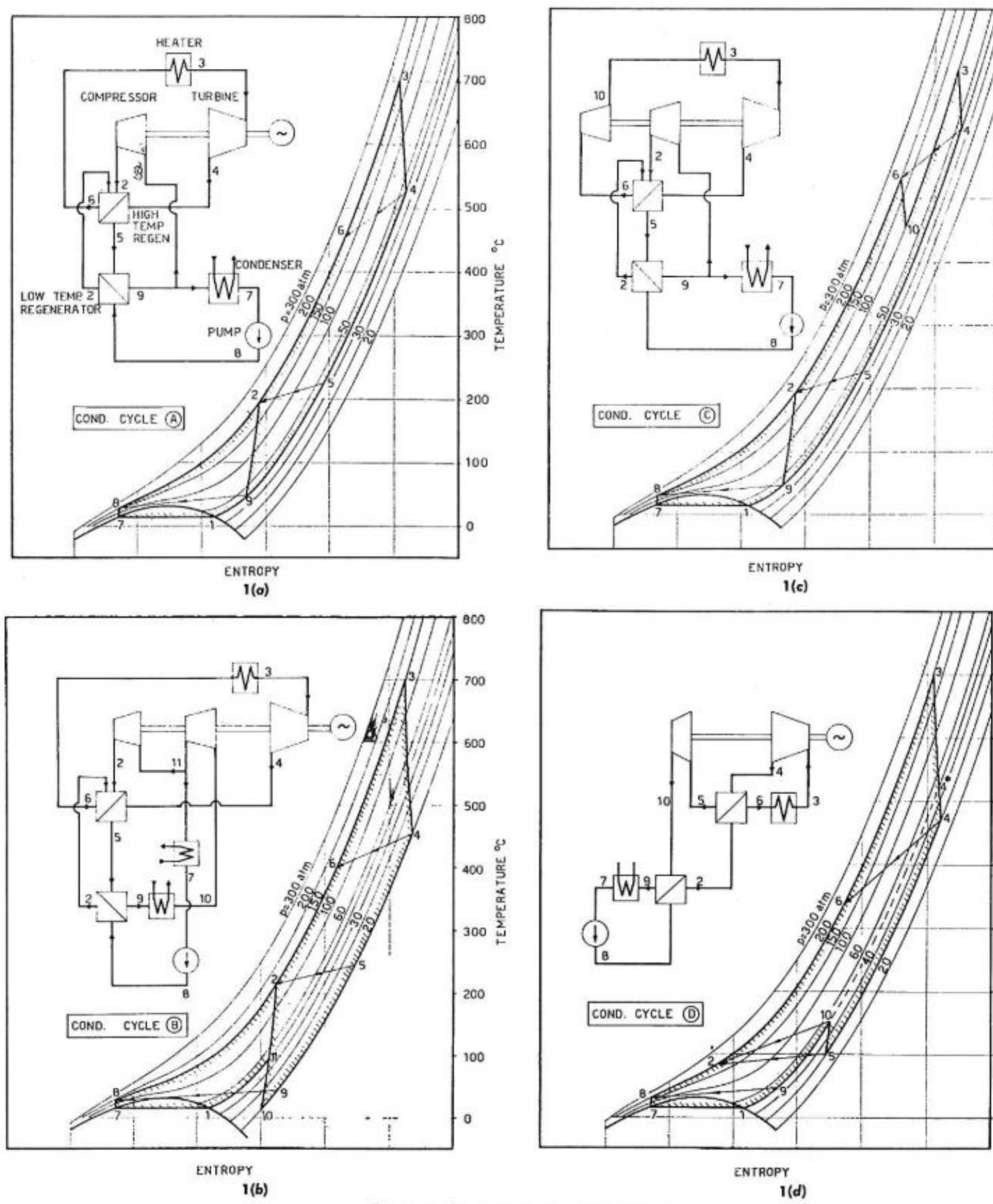


Figure 5.5: Supercritical Carbon Dioxide cycle configurations by Angelino. Source:Angelino [1968]

The rebirth of interest in Supercritical CO_2 cycle came with the development of high temperature reactors and medium temperature liquid metal or molten salt reactors. Economics of the overall power station, including the power conversion system, play a key role in determining whether their actual deployment take place, therefore thermal efficient power cycles became of prime interest. Furthermore, given the significant technological development of turbomachinery and compact heat exchangers during the last decades of the twentieth century the closed gas turbine cycles are getting a second look.

Modern investigation of the supercritical CO_2 took off with Vaclav DostalFLs investigation (Dostal [2004]). In his work, he developed a computational model to evaluate the performance of different Brayton cycle layouts as well as to optimize their efficiency. Based on the research made by Angelino about the compound cycles (Angelino [1968]), Dostal identified the recompression cycle as the cycle with the biggest potential for efficiency improvements and proceeds to optimize a set of parameters (the pressure ratio, the ratio of pre-cooler volume to the total volume of recuperators, the ratio of the high temperature recuperator volume to the low temperature recuperator volume, the pre-cooler length, the high temperature recuperator length and the low temperature recuperator) and analyze it in depth.

The outcome of this research is a systematic, detailed major component and system design evaluation and multiple parameter optimization under practical constraints of the family of supercritical CO_2 Brayton power cycles for application to advanced nuclear reactors. Table (5.12) shows the operating conditions for six different supercritical CO_2 Brayton recompression cycles designs, three main configurations with a different turbine inlet temperature, $550°C$ for the basic design, $650°C$ and $700°C$ for the advanced and high performance design respectively, each with two schemes according to the turbomachinery efficiency.

This results demonstrated the potential that the supercritical CO_2 cycle offered, even in its basic design form. Additionally, the economic analysis results obtained by DostalFLs investigation shown in figure (5.6) together with the efficiency comparison with other advanced power cycles shown in figure (5.7) positioned this cycle as a very well suited alternative for the next generations of nuclear reactors and promote further investigations of this technology.

Table 5.12: Operating conditions of selected designs by Vaclav Dostal.

	Basic Design		Advanced Design		High Performance Design	
Turbomachinery Design	Con.*	B. E.**	Con.	B. E.	Con.	B. E.
Cycle Thermal Power (MW_{th})	600	600	600	600	600	600
Thermal Efficiency (%)	45.27	47.36	49.54	51.35	51.27	53.14
Net Efficiency (%)	41.00	43.08	45.25	47.06	46.96	48.87
Net Electric Power (MW_e	246	258	272	282	282	293
Compressor Outlet Pressure (MPa)	20	20	20	20	20	20
Pressure Ratio	2.6	2.6	2.6	2.6	2.6	2.6
Primary System Pressure Drop (kPa)	130	130	130	130	130	130
Turbine Inlet Temperature (°C)	550	550	650	650	700	700
Compressor Inlet Temperature (°C)	32	32	32	32	32	32
Cooling Water Inlet Temperature (°C)	27	27	27	27	27	27
Mass Flow Rate (kg/s)	3209	3246	2953	2990	2801	2839
Recompressed Fraction	0.41	0.41	0.41	0.41	0.39	0.41
Total Heat Exchanger Volume (m^3)	120	120	120	120	120	120
Turbine Efficiency (%)	90	92.9	90	92.9	90	92.9
Main Compressor Efficiency (%)	89	95.5	89	95.5	89	95.5
Recomp. Compressor Efficiency (%)	89	94.8	89	94.8	89	94.8
Generator Efficiency (%)	98	98	98	98	98	98
Mechanical Losses (%)	1	1	1	1	1	1
Parasitic Losses (%)	2	2	2	2	2	2
Switch Yard Losses (%)	0.5	0.5	0.5	0.5	0.5	0.5

*Con. – conservative turbomachinery design

** B. E. – best estimate turbomachinery efficiencies

Source: Dostal [2004]

Following the work and achievements at MIT from Vaclav Dostal, the Supercritical CO_2 Brayton cycle was taken more seriously and was adopted by different laboratories in the United States. Argonne National Laboratory, Sandia National Laboratory, Naval Nuclear Laboratory and Idaho National Laboratory began working and testing as well as other institutions in different countries (Brun et al. [2017]). An international symposium was held for the first time at MIT in November 2005 to later become a technical meeting bringing together industry, academia, and government agencies to advance in supercritical carbon dioxide power cycle technology, held once every few years (2007, 2009, 2011, 2014, 2016 and 2018). A more complete review of the developments made during the last fifteen years regarding Supercritical CO_2 Brayton cycle and nuclear engineering can be found in Qi, Gui, Yang, Tu and Jiang (2018) review (Qi et al. [2018]).

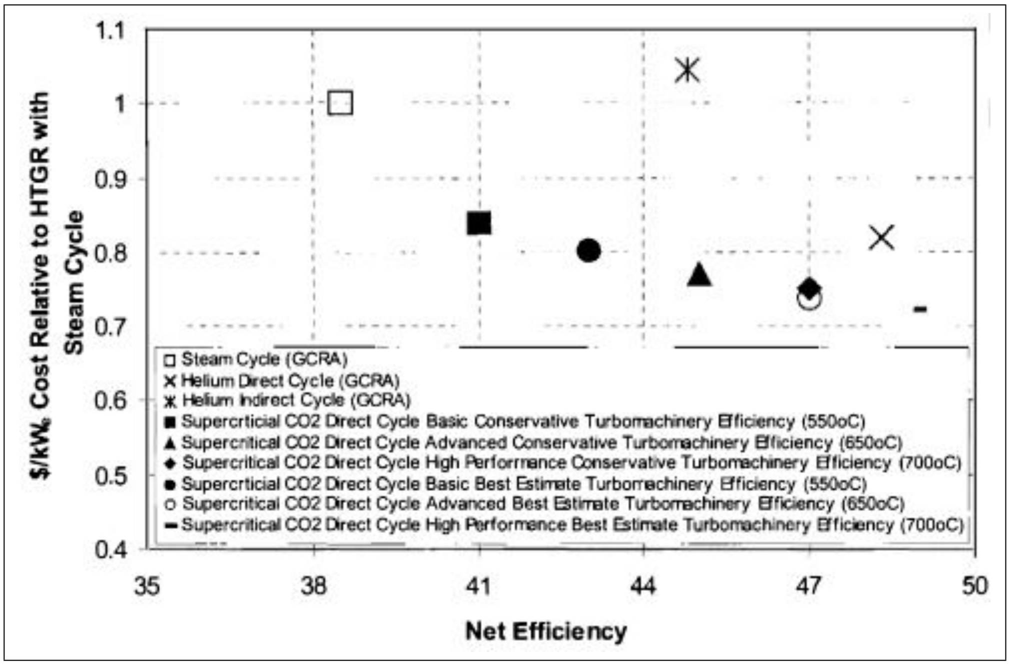


Figure 5.6: Net efficiency and relative costs for different power cycles ($\$/kW_e$). Source: Dostal [2004]

5.3 Power Conversion System Design

Based on the information obtained in the reactor analysis, it is possible to establish the main design parameters for the power conversion system for antarctic stations.

In the first place, Westinghouse eVinci reactor provides up to $600°C$ to the CO_2 as shown in table 4.8. Secondly, total net power of the cycle must be $1500kW$ as this specific number is the best suited to cover both installed capacities and peak capacities of the three main clusters described in table 4.7. This net power capacity offers the possibility to develop a common solution for the stations considered in this research, by doing this, the actual implementation is simplified as only one scheme is analysed deeply instead of developing a particular solution for each case. Furthermore, the supercritical CO_2 Brayton cycle is best suited for base load operation with efficiency declining almost linearly with full power percent (Dostal [2004]). Given these reasons, the best configuration for the clusters is summarized in table 5.13.

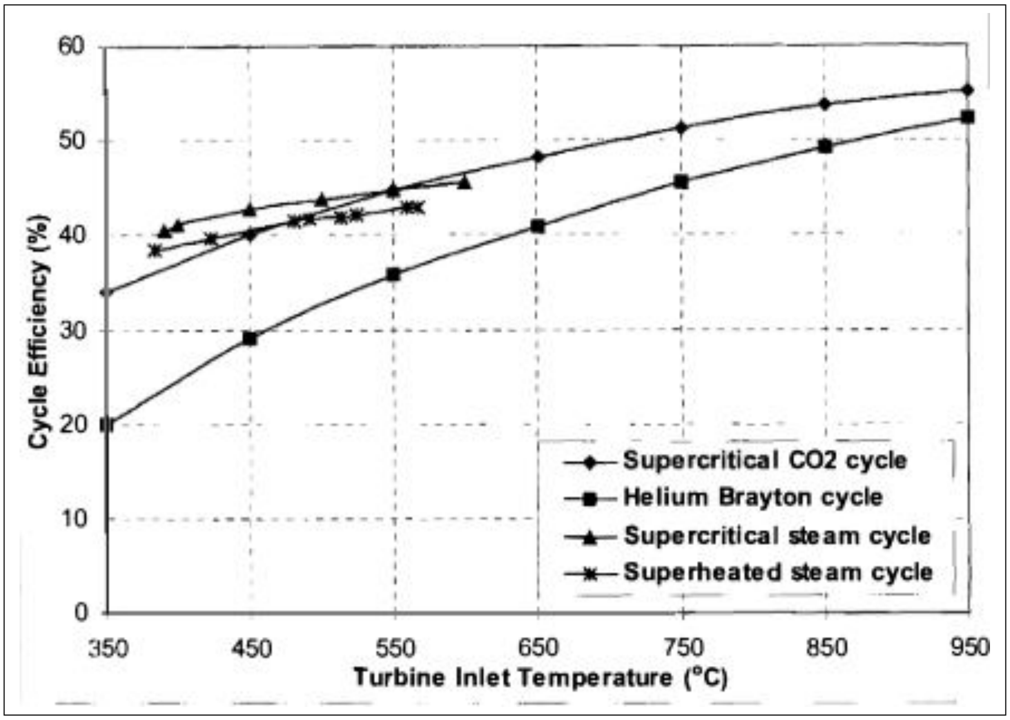


Figure 5.7: Cycle efficiency comparison of advanced power cycles. Source: Dostal [2004]

Table 5.13: Clusters Installed Capacity, Peak Capacity and Proposed Nuclear Installed Capacity

Group	Installed Capacity [kW]	Peak Capacity [kW]	Proposed Solution [kW]
Mcmurdo-Scott	8790	2990	2 x 1500
South-pole	3000	1000	1500
King George	4450	1240 - 1380	1500

The next step is to determine the configuration of the cycle as there are plenty of different schemes. Crespi, Gavagnin, Sánchez and Martínez in ”Supercritical carbon dioxide cycles for power generation: A review” (Crespi et al. [2017]) reviewed 42 different stand-alone cycle layouts and 38 combined cycles for later making a comparison between them. It is important to note that the comparison between the cycle layouts is not under the same boundary conditions but instead under the conditions from the original papers, therefore, thermal efficiencies can present some discrepancies based on differences in parameters such as turbine inlet temperature or pressure ratio. Despite this issue, a decision making process can still be performed with the information obtained through this comparison.

Among the Stand-alone cycles with nuclear application compared in Crespi et al. [2017], the Recompression cycle has the second best thermal efficiency with $\eta = 46,5$ just behind the forced Cooler layout with $\eta = 48,7$. Nevertheless, the Forced Cooler version it is not ideal since the minimum temperature is $-40°C$ (Purjam et al. [2016]), which is reached through a refrigeration cycle increasing the complexity of the scheme. Furthermore, the maximum temperature of the cycle is $826°C$ which is beyond the temperature that the selected reactor can reach.

Recompression cycle layout it is simpler and smaller than most other schemes, more efficient (besides Forced Cooler) and moreover, it is by far the most extensively researched cycle in literature along with the Simple Recuperated. This last feature makes the Recompression cycle ideal to be studied for out-of-the-box and niche applications as there are already experimental facilities available and mathematical models to predict the performance. Consequently, the Recompression cycle is the selected scheme for the power conversion system.

Figure 5.8 shows a diagram of the major components and their arrangement in the recompression cycle configuration. In bold letter are the main design parameters for this particular scheme.

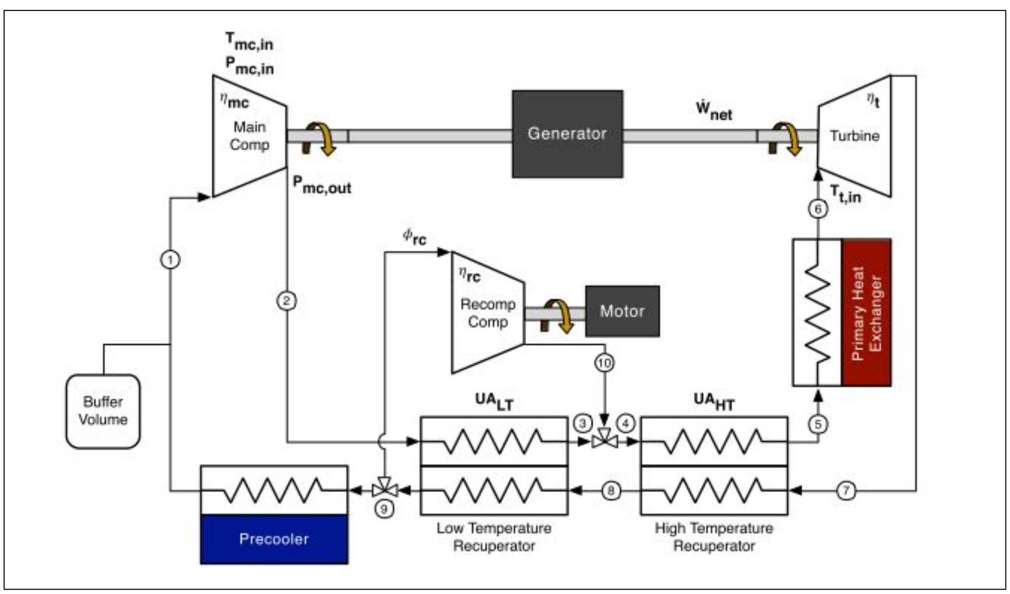


Figure 5.8: Recompression cycle diagram. Source: Dyreby [2014]

Main compressor inlet temperature is a design parameter that must be determined prior to the analysis of the cycle. This point of the cycle is the closest to the critical point of the CO_2 located in $T_c = (30,9782 \pm 0,015)°C$ and $P_c = (7,3773 \pm 0,003)$ MPa Span and Wagner [1996] allowing for the reduced compression work. For entirely supercritical cycles, the temperature should not be less than the critical temperature at any given point, thus, main compressor inlet temperature is limited at $31°C$ approximately. Cycle efficiency decreases linearly with the increasing compressor inlet temperature (Dostal [2004]); hence, in order to maximize efficiency the minimum temperature must be sought.

The main compressor inlet temperature for this investigation will be set initially in $35°C$. This temperature allows for high efficiency while, at the same time, staying away from the critical temperature in which cavitation might be an issue. The environmental conditions at Antarctica can also support cooling the CO_2 to the required temperature unlike other geographical areas where there is no cold water effluent either.

Main compressor inlet pressure in this investigation is fixed at 8 MPa, this pressure is close enough to the critical pressure to benefit from the reduction of compressibility work. Also, this low pressure is, at the same time, distant enough to the critical point that changes in the main compressor inlet temperature will not degrade efficiency as much as in lower operating pressure cycles. This phenomenon is especially important in dry air cooled cycles since seasonal temperature variation can influence the compressor inlet temperature. Figure 5.9 shows the efficiency sensitivity of different supercritical CO_2 configurations with increasing compressor inlet conditions. From this picture it is possibly to note that increasing cycle low-side pressure is able to contain this effect as temperatures continue to rise (Conboy et al. [2015]). The design compressor inlet pressure of 8 MPa allows for a more even performance when operating off-design at the cost of a reduction in the efficiency.

Pressure ratio or compressor outlet pressure for the following analysis will be fixed at 24 MPa since this pressure allows for the maximum efficiency when considering also the main compressor inlet pressure and temperature already determined (Moisseytsev et al. [2016]). Figure 5.10 shows the effect of cycle maximum pressure on plant efficiency for different inlet pressures and temperatures, it can be concluded that working further from the critical point is detrimental to the overall efficiency and also that as lower pressure increases the optimum efficiency is found with a higher maximum pressure. From Figure 5.10 the 8 MPa, $35°C$ scheme found its optimum at 24 MPa.

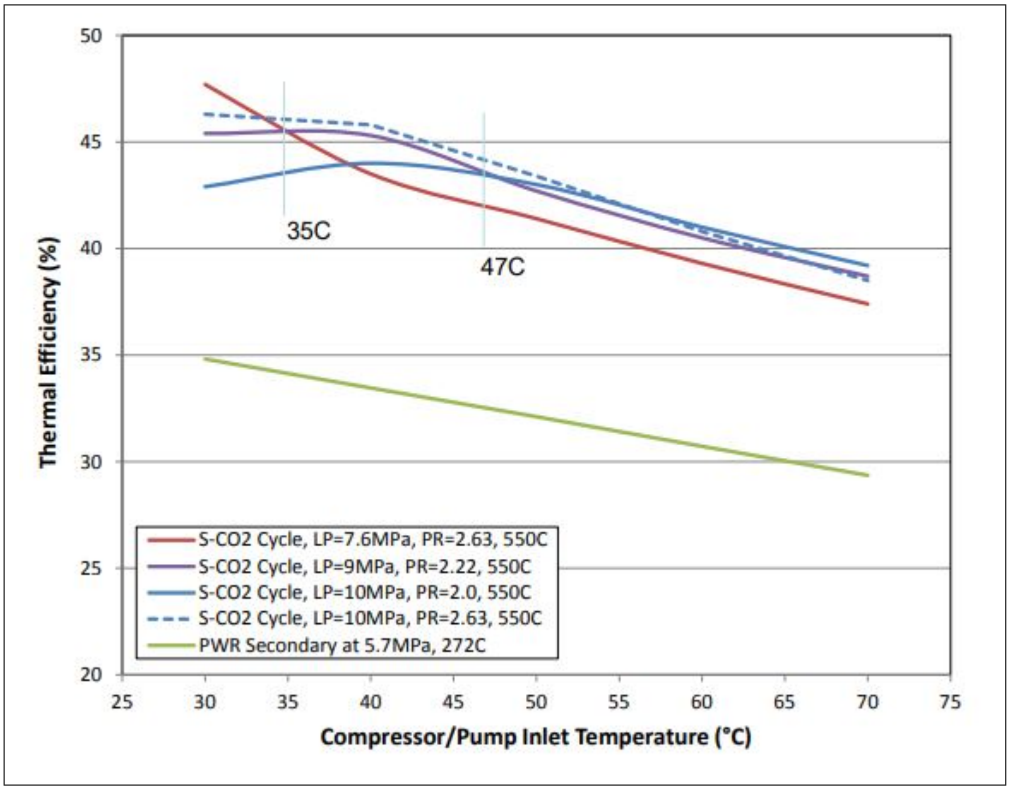


Figure 5.9: sCO_2 power cycle efficiency at $550°C$ with increasing compressor inlet conditions. Source: Conboy et al. [2015]

Summarizing, the design parameters for the supercritical CO_2 Brayton cycle for Antarctica application are detailed in table 5.14. Global conductance (UA) as a design parameter will be part of the mathematical analysis and turbomachinery efficiencies are determined by the current state of the art.

Table 5.14: Main design parameters

Design Parameter	Design Value
Net Power [kW]	1500
Turbine Inlet Temperature [$°C$]	600
Main Compressor Inlet Temperature [$°C$]	35
Main Compressor Inlet Pressure [MPa]	8
Turbine Inlet Pressure [MPa]	24

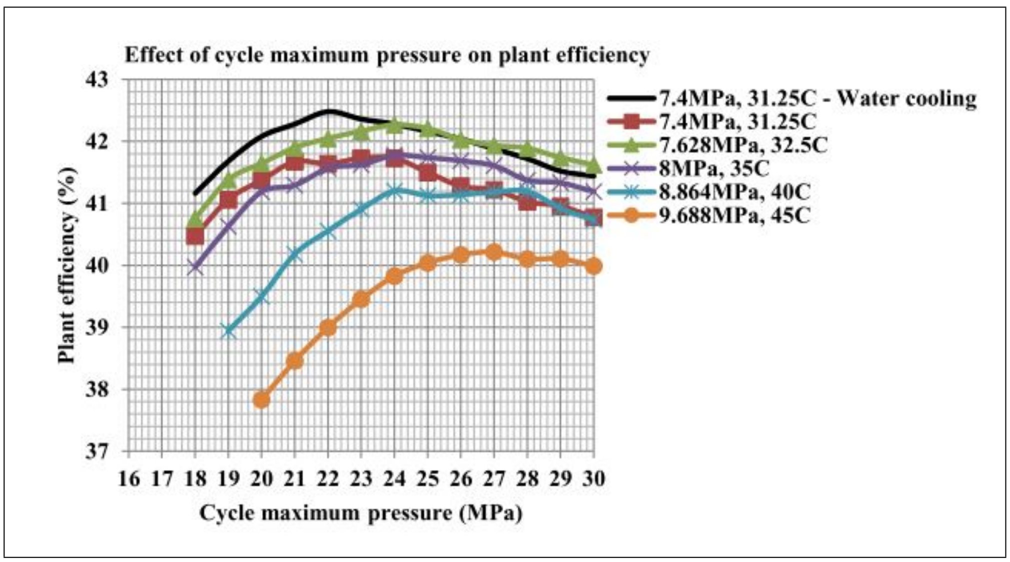


Figure 5.10: Effect of cycle maximum pressure on plant efficiency. Source:Moisseytsev et al. [2016]

Energy Conversion

Supercritical CO_2 Brayton recompression cycle shown in figure 5.8 cannot be solved in a closed-form way despite severely constraining the set of equations derived from energy and mass balances on the components with the initial design parameters. Thus, an iteration process is necessary to solve the set of equations and subsequently optimize the cycle. Different models and iteration process have been created from different authors for this particular purpose with subtle differences in their approach. For this investigation the computational model used will be the one developed by Faustino Correa (Correa [2019]).

6.1 Energy Model

The model is built based on the mass and energy balances of every component in the cycle. Thermophysical properties of supercritical CO_2 and air are extracted from COOLPROP (Bell et al. [2014]). Both turbine and compressor power is based on energy balance and mass equations dependant on their respective turbomachinery isentropic efficiencies, which are set in $\eta_t = 0,86$, for the turbine, and $\eta_c = 0,677$ for the compressors. Recuperators are simulated as counterflow heat exchangers with conductance value (UA) and pressure drops. The heater, is a generic component allowing for the model to adapt to different heat sources such as nuclear, fossil or solar.

The particularity about this model is that the cooler is simulated as a gas-to-gas counterflow heat exchanger allowing the analysis for a dry-cooled design. In order to overcome the changing properties of supercritical CO_2 near the critical point, the heat exchanger is discretized and solved for each particular section. Through this method is possible to obtain the state of the fluid at the outlet of the cooler.

Thermal efficiency of the recompression Brayton cycle is then calculated as follows:

$$\eta = \frac{\dot{W}_{neto}}{\dot{Q}_{in}} = \frac{\dot{W}_t - \dot{W}_c - \dot{W}_{rc}}{\dot{Q}_{in}} \tag{6.1}$$

where:

W_t = turbine net rate work

W_c = compressor net rate work

W_{rc} = recompressor net rate work

$\dot{Q}_{in}$ = rate of heat supplied by the reactor

Once the cycle is modeled, the optimization process takes place. The optimized parameters are: recompression fraction (φ) and value of conductance (UA) of both high temperature recuperator and low temperature recuperator. The algorithm takes one variable at a time, thus the model becomes a double layer optimization process. The output parameters are: optimized thermal efficiency, mass flow of supercritical CO_2, recompression fraction (φ), rate of heat supplied by the heat source, conductance values from both recuperators, turbomachinery diameters, rate of heat rejected in the cooler, cooler conductance value and air mass flow in the cooler (Correa [2019]).

6.2 Results

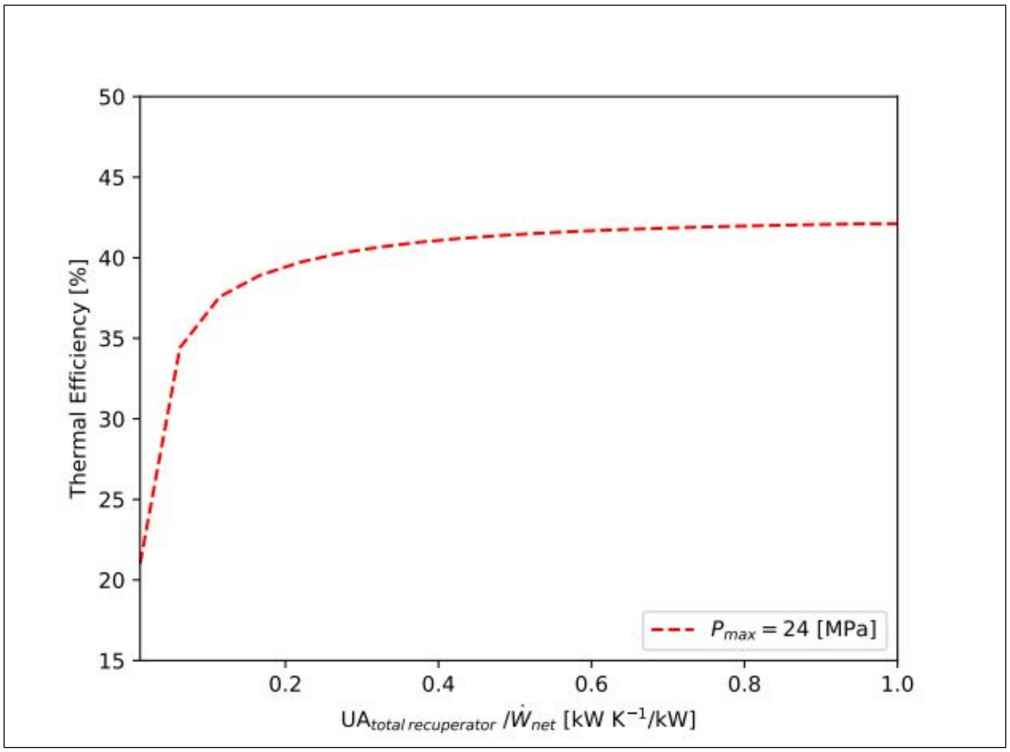
The design conditions developed in Chapter 4 and summarized in table 6.15 are the input parameters for the model. The last input parameter needed for the model to work is the total conductance (UA), however, there is not much information about what the value of this parameter should be.

Table 6.15: Main design parameters

Design Parameter	Design Value
Net Power [kW]	1500
Turbine Inlet Temperature [$°C$]	600
Main Compressor Inlet Temperature [$°C$]	35
Main Compressor Inlet Pressure [MPa]	8
Turbine Inlet Pressure [MPa]	24
Turbine Isentropic Efficiency	0,86
Compressor Isentropic Efficiency	0,68
Shaft Rotation Speed [rpm]	75000

For the analysis of the cycle, the conductance is normalized by dividing it by the net power output. For example, a $1500kW$ cycle with $500kW$ total conductance will have a $0,\overline{3}\,(kW/K)/kW$ normalized conductance. The normalized conductance is varied from $0,01$ to 1 and optimized for each configuration. Figure 6.11 shows the thermal efficiency of the cycle as the total conductance value varies. It is possible to observe from figure 6.11 that total conductance has a positive impact on efficiency, nevertheless, this increase stagnates at $0,4\,(kW/K)/kW$ approximately as can be seen in figure 6.12.

Figure 6.11: Optimal thermal efficiency for a supercritical CO_2 cycle with different total conductance values.



To properly assess the recuperators size and conductance value, a economic analysis must be performed since, at some point, the efficiency improvement will be offset by the additional cost of the recuperators. Nevertheless, information about cost of reactor and machinery for this type of cycle is very scarce or non-existent, besides, an economical analysis is not in the scope of this research. Therefore the selected conductance value is $500000\,(kW/K)$ since from this point efficiency increase at a very small pace.

With the selected conductance value fixed, the complete cycle analysis can be made and the results are summarized in table 6.16. Temperature breakdown throughout the cycle can also be obtained and it can be seen in figure 6.13

Figure 6.12: Efficiency improvement per extra recuperation

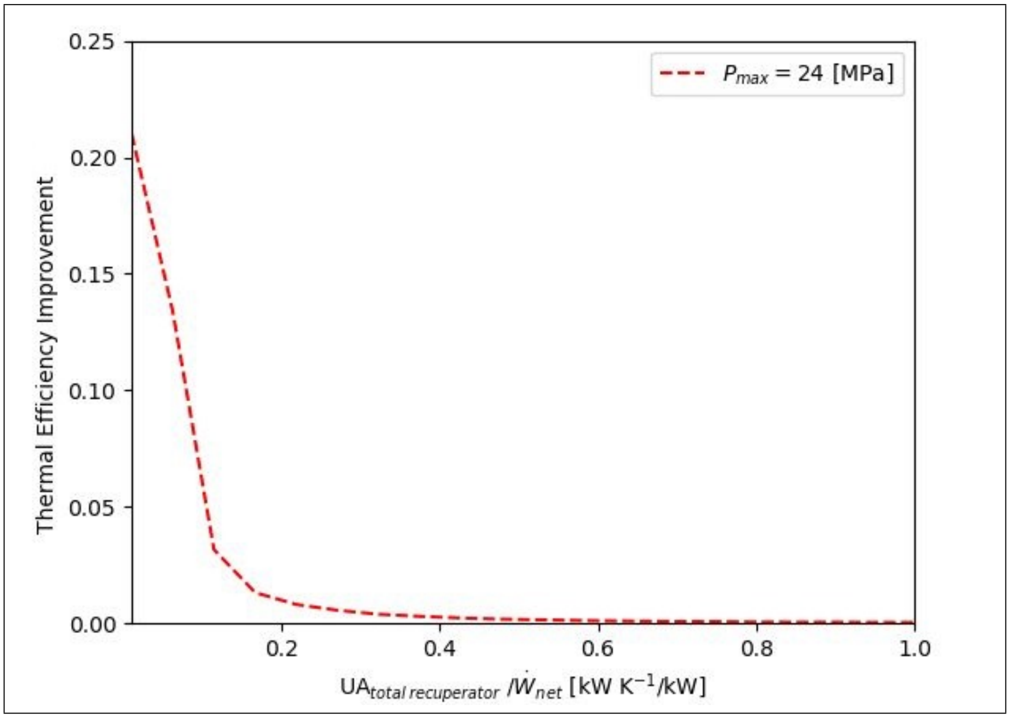
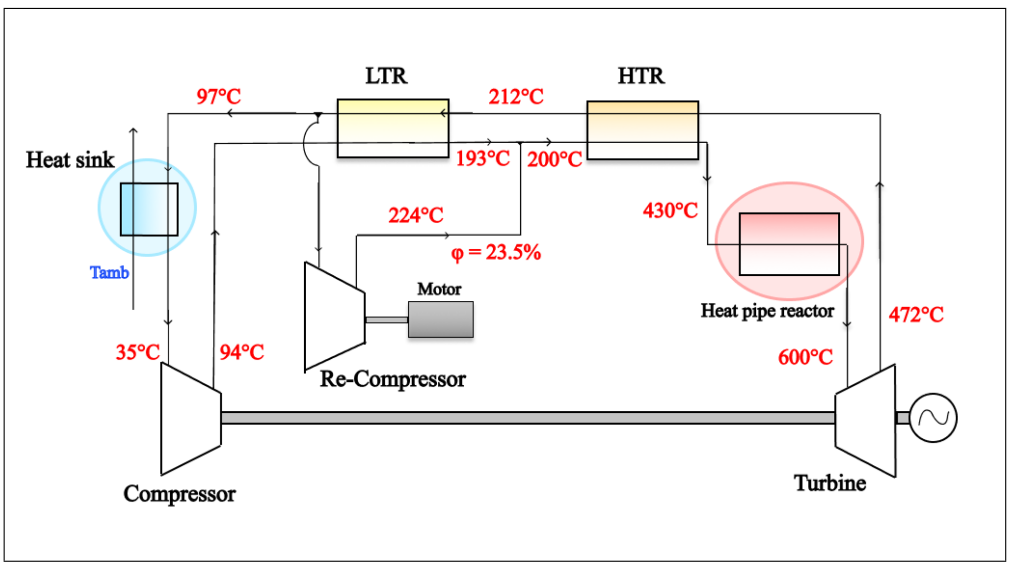


Table 6.16: Main parameters of the design point

Parameter	Value
Net Power [kW]	1500
Efficiency [%]	40,73
Turbine Inlet Temperature [$°C$]	600
Main Compressor Inlet Temperature [$°C$]	35
Main Compressor Inlet Pressure [MPa]	8
Turbine Inlet Pressure [MPa]	24
UA High Temperature Recuperator [kW/K]	214,49
UA Low Temperature Recuperator [kW/K]	285,51
UA Air Cooler [kW/K]	88,68
sCO_2 Mass Flow [kg/s]	17,37
Air Mass Flow [kg/s]	86,77
Turbine Diameter [cm]	11,02
Compressor Diameter [cm]	6,42
Recompressor Diameter [cm]	6,22
Reactor Thermal Power [kW]	3682,24
Recompression Fraction [%]	23,52

Figure 6.13: Recompression cycle diagram with temperature breakdown.



Conclusions

7.1 Synthesis of Thesis Achievements

Despite Antarctica extreme weather conditions, humans have been able to develop settlements with scientific objectives. Investigation in Antarctica has led society to a greater understanding of our climate and about the planet we live in.

Under the current global warming circumstances Antarctica value as a tool for understanding global climate is more indispensable than ever. Changes in concentration of greenhouse gases in its atmosphere can alter the radiation balance and as a consequence climate system can experience some disorder in precipitation and atmospheric circulation patterns. Keeping track of ice shelf mass balance is a must, since this continent represent a large fraction of the global freshwater and its melting can rise up the sea level putting at risk a high percentage of the coastal population that turns out to be a large percentage of the world's population. Because of the different roles of Antarctica in scientific knowledge, it is inevitably going to become more populated and new areas of exploitation will be opened. The main objective is to allow this growth while also being able to preserve the pristine condition of the region. This will be accomplished by developing a sustainable solution to one of the main issues in Antarctica: Energy consumption.

In order to design a sustainable energy solution for Antarctica four major stages were necessary. In the first place, a complete survey of the Antarctic stations and their energy requirements, consumption and installed capacity. Secondly, a review of different Small Modular Reactors (SMR) technologies and models to then subsequently select a particular technology based on a decision matrix and engineering criteria. Thirdly, an investigation was conducted on the different energy conversion systems that were suitable with the reactor and the specific Antarctic requirements, in addition, key design parameters were identified in order for a supercritical CO_2 Brayton cycle to operate alongside the Small Modular Reactor. Finally, considering the previously selected technologies, the Antarctic energy requirements and restrictions, a supercritical CO_2 cycle was simulated and a plant design was proposed.

By going through all the Antarctica Inspection Reports, which are the only way to obtain information from the stations infrastructure it is possible to gather data about installed capacity, fuel consumption, fuel storage and renewable energy alternatives, this information is summarized in table 4.4. The survey shows that fossil fuel is a must in every Antarctic station independently if it is a summer only or year-round station. The high energy and low density characteristic that fossil fuels have unlike renewable energy sources is crucial in such a harsh environment as Antarctica, where any energy shortage can become catastrophic.

Despite fossil fuel being excellent at providing a reliable energy source for Antarctic stations, it has some related issues. Fossil fuel transport is not an efficient process, due to the big distances and difficult access the price can increase several times from the original and inland can be up to seven times higher than in the antarctic coast. It is a dangerous exercise as well, for inland stations, resupply has to be performed by overland vehicles like snowmobile or special polar tractors. This trips can last 2 to 3 weeks through safe travelling routes indicated by marker poles, but when the trip diverts and has to go through less travelled areas, quadrilles must stop regularly to check the thickness of the ice by drilling, otherwise thin ice layers can give away causing an accident with serious consequences. Fossil fuel can produce oil spills, damaging the soil and different fauna species, and also may cause fires such as the one that consumed Comandante Ferraz Station in 2012.

Renewable energy has reached Antarctica, as it has done it in the rest of world, in an effort to help solving some of the fossil fuel issues. On one hand energy efficiency became the first measure for several stations to help reduce energy consumption, as well as heat recovery and other simple measures for enhancing efficiency. Wind energy on the other hand, is the renewable energy source with most history on the region and it has helped to reduce fossil fuel consumption in different stations. Although, for wind turbines to work properly technical challenges need to be overcome in order to meet severe conditions such as extreme cold, extremely strong winds and snow accumulation. Solar energy has also found some summer applications in Antarctica, low temperatures and high albedo help mitigate low solar radiation and both thermal or photovoltaic solar panels can alleviate fossil fuel consumption.

Nuclear power had a very short history in Antarctica, which lasted only 10 years between 1962 and 1972. The nuclear reactor operated at McMurdo Station in an attempt from the U.S. to find cheaper ways to maintain stations in remote locations. The PM-3A reactor was a pressurized water reactor with $1,8MW$ power capacity and a 20 year life expectancy. During the 10 years period, the reactor worked at a 78% capacity factor and produced 78 million kilowatt-hours of electricity, when running it produced enough electricity to satisfy almost all of McMurdo's heat and power needs. It was then decommissioned because operation of the facility was not economically convenient as the costs involved in maintaining the plant were making the reactor more expensive than had been expected.

Furthermore, based on the past and current experience in Antarctica alongside the new development in energy technologies a comparative matrix was made between different type of power sources. New nuclear energy technology based of Small Modular Reactors emerge as the most indicated power source for the region as it is reliable, transportable and does not emit pollutants.

Small Modular Reactors are a new class of nuclear reactors differing from the ”bussiness as usual” approach with several advantages: modularity, high efficiency, reduced capital investment, proliferation resistance, low operation & maintenance and improved safety features. Among these reactors, several types can be found and a review was developed concerning the main lines of investigation with some interesting designs for potential Antarctic applications.

An specific concept was selected among the possible candidates based of the Antarctic stations requirements. Power, weight, size, maintenance, refuelling and design status are the main characteristics to assess the feasibility of the reactors for this particular purpose. The decision matrix results indicate that heat pipe reactors are the most suitable reactor technologies for providing energy and heat to Antarctic stations. The selected concept was the eVinci model developed by Westinghouse.

Supercritical CO_2 Brayton cycle was investigated and identified as the best possible power cycle over Rankine, Stirling and normal Brayton thanks to the high efficiency when working with medium to high temperatures heat sources, such as eVinci reactor, to the low volume to power ratio and the possibility to be dry-cooled among other advantages.

Specific design parameters were identified for the supercritical CO_2 Brayton cycle, net power, turbine inlet temperature, working pressures, inlet compressor temperatures and turbomachinery efficiencies. Air temperature was fix at $10°C$ which is the historical maximum in the selected stations. Conductance of the recuperators was set as a variable to the model since there is not available information in literature of what this value should be.

Initial results indicate that the higher the conductance value were, the higher the total efficiency of the cycle. Nevertheless, efficiency stagnates rapidly as conductance value continues to grow, so a convenient conductance value was selected. A final simulation considering all the design parameters was made resulting into an energy system concept solution proposed for the Antarctic stations shown in figure 6.13.

Overall, the specific objectives were met and a Small Modular Reactor concept plant coupled with a supercritical CO_2 Brayton cycle was developed to fulfill most of the energy requirements for a group of different Antarctic stations.

7.2 Future Work

Alongside Antarctica, isolated communities around the globe can be benefited by implementing this energy plant. Geographic limitations can often preclude the electrification of rural and isolated zones denying their population access to energy. For countries, this is a very important topic as energy consumption and economic development are closely linked (Ahadi et al. [2016]).

Military bases can also benefit from the implementation of a Small Modular Reactor plant to provide energy for their diverse operations. The growing complexity of logistics operations plus the constrained resources make nuclear energy more likely to reach the energy requirements to meet the future demand. Also, the readiness and transportability of the reactor to be deployed anywhere within a short period of time is a key feature for any army in the world. The capacity of this power plant to be independent from fuel supply prevent the resupply convoys to be captured, damaged, or destroyed.

Mars, with virtually no atmosphere, no liquid water for cooling and temperatures below $0°C$, requires a power plant such as the proposed in this research if human settlements will be established in near future. The Moon or any other station in the outer space that requires energy in the order of Megawatts, can use this solution modified in some way, since transporting fuel is no longer an option when talking about million of kilometers and for regions far away from the sun, radiation to feed solar panels can be too low.

Despite this possible applications may seem too narrow, it is important to continue developing the technologies involved since the knowledge generated from research can reach to other applications or can help solve energy problems in the future. Both Small Modular Reactors and supercritical CO_2 Brayton cycle are emerging technologies that with the right focus can be applied to a wide range of energy solutions.

There are some challenges that must be overcome in order for the Antarctic nuclear power plant to work in the way it is intended. Both Heat Pipe Reactor and supercritical CO_2 Brayton cycle still have some work to do before being deployed and commercially available.

The eVinci reactor will use fuel enriched to $19,75wt\%$. Currently, the availability of industrial-scale uranium enrichment beyond than 5%, suitable for commercial reactors, is limited. This challenge is common to the vast majority of advanced concepts, as they also require enrichments above 5%. Since the demand of such a fuel is increasing, national campaigns are currently increasing in momentum to identify solutions for this cross-cutting challenge. It is envisaged that the eVinci reactors will be manufactured and completely assembled in a factory. The first reactor startup should happen on the production site as well. Consequently, the factory must be equipped with radioprotection equipment, safety and security systems adequate to handle this novel activity, and must have the appropriate license from the regulator. Transportation of the new and used reactors must be organized in compliance with the regulator's requirements taking into account appropriate level of shielding, cooling of the unit in case of the used reactor, and other safety and security aspects. The eVinci reactor is envisioned to operate autonomously, as proposed to other concepts, and as such it introduces challenges in licensing, instrumentation for remote reactor monitoring, and logistic, including personnel (Levinsky et al. [2018]).

Some concerns that will require additional development and understanding are the machining and drilling of holes in the monolith block to the specified tight tolerances. Failure of heat pipes must also be tested to identify possible failures and thermal stresses. Welding and operation of heat pipes under long-term irradiation are also subjects that need to be further explored (Sterbentz et al. [2017]).

For the supercritical CO_2 Brayton cycle additional research and development is required to overcome technology gaps in the areas of cycle optimization, transient modeling, turbomachinery, high-temperature materials, corrosion protection, heat exchangers, heaters, process gas quality, and balance of plant integration (Brun et al. [2017]).

These challenges require careful risk management and planning, but they are not considered showstoppers. Research, development and testing of these technologies will continue as they are promising solutions to energy problems, specially under the current global circumstances.

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