ON THE POSSIBILITY OF A SMALL NUCLEAR REACTOR APPLICATION FOR ENERGY SUPPLY OF ISOLATED COMMUNITIES IN NORTHERN CANADA

by

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ABSTRACT

Isolated northern communities in Canada are currently satisfying their needs in energy using ineffective and environmentally unfriendly diesel generators. There has been long desire to find an alternative solution which would provide these settlements with electrical energy and heat inexpensively and with the least environmental impact.

One possibility is to adopt a well-developed nuclear submarine reactor technology which has been used for the past 60 years. Most modern nuclear submarines use uranium-235 enriched up to 98% and allow operating the nuclear reactor without refueling for up to 25 years. The second option which offers many benefits, such as abundance and availability of cheaper fuel, greater anti-proliferation benefits as well as better safety, is the thorium option, a new approach, which has not been extensively researched and tested yet but which could offer attractive benefits once implemented. This thesis investigates a possibility of a small nuclear reactor application based on the research in the field of nuclear submarine technology for peaceful purposes and molten salt reactor experiment conducted by the Oak Ridge Lab, and compares uranium and thorium options with the currently used diesel generator technology. Fossil fuel scarcity and greenhouse effect of their use require finding alternative energy sources, and, nuclear technology provides such opportunity, especially, when highly enriched uranium is not available or difficult to obtain due to proliferation concerns. Thorium which is abundant, and is not currently in high demand or use, could be a great opportunity for the following reasons: (1) thorium is significantly cheaper and requires less processing than uranium; (2) thorium fuel could be used as a circulating liquid mixed with molten fluoride salts instead of using solid fuel elements which need special preparation; (3) the fluoride salts can be used as a reactor coolant due to their better chemical properties.

PREFACE

The thesis is ultimately based on the official unclassified reports of the Oak Ridge Lab, prepared for the U.S. Atomic Energy Commission and other written and online sources quoted in the Bibliography section of this thesis on pages 70-74.

The unique contribution of this proposal includes summarizing the data available in the field of small nuclear reactor technology and investigating a possibility of developing a molten nuclear salt reactor with a capacity of 1 MWe.

This is a literature-based research; no actual prototype was ever created in the process of writing this work.

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List of Abbreviations

AEC	Atomic Energy Commission
CANDU	CANada Deuterium Uranium (reactor)
CNSC	Canadian Nuclear Safety Commission
COL	Combined construction and operating licence
FM	Fuel to moderator ratio (atomic)
GW	Gigawatt
IAEA	International Atomic Energy Agency
KLT	Russian abbreviation for a pressurized water reactor
kW	kilo-Watt
LFTR	Liquid fluorine thorium reactor (also known as MSR)
LMF(B)R	Liquid metal fast (breeder) reactor
LWR	Light water reactor
MSR	Molten salt reactor
MWe	Megawatt electrical
MWth	Megawatt thermal
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory (Tennessee, USA)
PWR	Pressurized water reactor
RWS	Radioactive waste system
SFP	Spent fuel pool
SNF	Spent nuclear fuel
THTR	Thorium high temperature reactor

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1 Introduction

The problem of diesel generators currently used in northern Canada, the rationale behind the development of the small nuclear reactor to replace those generators as well as the nuclear fission reaction which is fundamental to the nuclear processes occurring in the core, will be discussed in this chapter.

1.1 Problem statement

Most energy in British Columbia (B.C.) comes from hydroelectric power plants located in the southern region of the province. Transporting this energy via high-voltage transmission lines over hundreds or thousands of kilometers to the northern parts of B.C. is merely practical. Production of electricity locally makes more sense and is a more economically viable solution. Also, the population is spread out over vast territories and the settlements are small to justify power lines' construction and service in these remote locations.

According to Statistics Canada 292 remote communities with 195,000 people are located in the Northern Canada, with 86 in B.C. alone, require electricity and heat supply, and are currently dependent mostly on diesel power generation [1]. Alternative energy sources are needed to improve energy efficiency and reduce their dependency on diesel fuel.

Another problem is the scarcity of fossil fuel deposits which are currently being overused and which excessive greenhouse gases emission and pollution require finding an alternative solution. Therefore, there is a genuine need to find a cleaner and more abundant source of energy to provide for the increasing demands of growing population and industrial progress and substitute the fossil fuels resources option. The proposed design complies with CNSC regulations which stipulate design, operation and maintenance of all nuclear installations in Canada.

1.1 Rationale

The current situation in northern communities reveals 4 main issues:

(1) Burning of fossil fuels creates environmental problems because of greenhouse gases emissions and possible oil spills during fuel transportation;

(2) “Noise pollution” of the diesel generators which produce excessive amount of noise in quiet remote areas;

(3) Possible blackouts can leave those remote communities in freezing conditions and darkness if diesel-generators fail [2] and it can take days or weeks before repair personnel can help those communities due to a difficulty of accessibility of some communities during the off season;

(4) Fossil fuels require transportation over long distances to the remote communities which will increase the already high-cost of those fuels in the future [2].

Countries, such as Canada, the United States, the United Kingdom, Japan, Russia, China, and India, have been successfully developing and using nuclear power reactors to produce electrical energy and heat. Other countries, such as France rely mainly on nuclear energy production to supply their population with electricity.

Although there are currently a number of viable small nuclear reactors designs, their implementation requires further technological development and material and design testing. This thesis is based on research articles, journals, reports and presentations in the nuclear energy field from across the globe. It analyses a variety of designs and proposes a viable design of a small nuclear molten salt reactor with thorium fuel cycle, which can be used to provide population of the remote northern regions of Canada with electrical energy and heat. Additional application of this reactor design may include production of hydrogen, desalination of seawater, and recycling of the spent nuclear fuel.

Fossil fuel deposits are limited and pollution caused the greenhouse gases, produced as a result of using them, negate the benefits they create. Canada has its own nuclear fuel deposits in Alberta, Saskatchewan and Ontario. It is logical to find a way to utilize those resources, decrease dependency on fossil fuels and develop new environment-friendly technologies. CANDU nuclear reactors were built in Ontario and have been operated for over 50 years. These are large pressurized water reactors designed for larger cities and there is a need to develop a small reactor design suitable for small settlements in the north or even for a few households. Due to the remoteness of those communities, it is more practical to produce electricity and heat on-site rather than transporting it long distance because energy transit causes losses and high-voltage transmission lines are quite expensive to build and service.

The following challenges have to be resolved to successfully use small nuclear reactor technology to supply energy to these remote communities: (1) small nuclear power reactor technology must be economically competitive; (2) nuclear materials have to be handled safely and spent nuclear fuel must be properly disposed or recycled, and (3) local population need to have assurance that these reactors are safe [3].

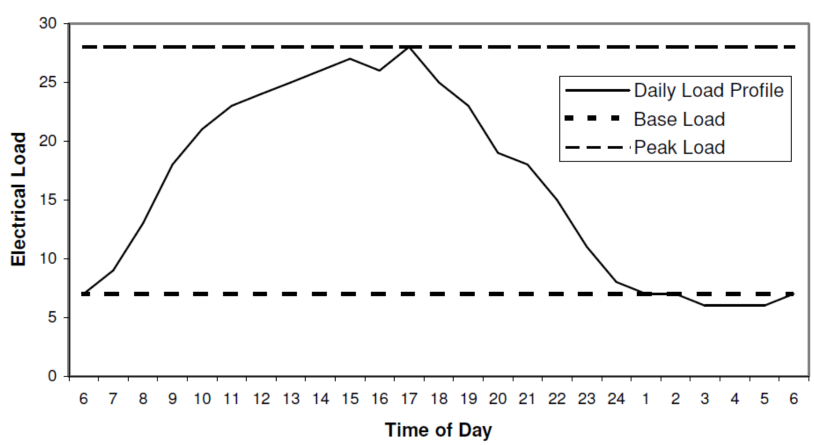
Complex technological processes of nuclear reactor operation, safety of the nuclear reactor and the risk of nuclear materials’ proliferation are the main concerns of the public and should be carefully developed, carried out and communicated to the local residents to assure of the safety of the technology and operation procedures. Nuclear accidents, such as Three Mile Island (1979), Chernobyl (1986), Fukushima (2011), create a significant negative public opinion towards the nuclear technology and the public has to have trust in the safety of the nuclear reactors to facilitate their development.

1.2 Current energy needs analysis of remote communities

Nuclear energy provides a huge benefit as heat is a by-product, produced during the nuclear fission. In warmer climates it would be rather an inconvenience but in these northern communities, it is highly beneficial and can significantly increase the output and efficiency of the nuclear power generation cycle.

Daytime changes in activities of the residence (morning and evening peak hours) as well as seasonal changes can cause a significant change in power demand. Small reactor design could include a possibility of a shutdown of the reactor in the evening and restarting it in the morning since the energy consumption decreases when people go to sleep. An alternative would be to store energy in batteries, fly-wheels, and other similar devices or use it for water decomposition producing hydrogen for cars and snowmobiles or water desalination to produce clean water on site. Day and night period last 6 months each in the higher latitudes due to the solar movement and it is easier to adjust the reactor usage, shutting down and restarting than in regular 12-hour day and night change so common in mid latitudes [4]. An example of a daily load is given in Figure 1.1below.

Figure 1.1 Daily load profile of electricity use



Daily load profile of electricity use with base electrical load and peak load.

(Source: http://www.thesolarvillage.com/energyplan/CEP%20Remote.pdf)

A typical household in North America consumes approximately 15,000 kWh of electrical energy annually (based on an average B.C. Hydro utility bill) and if we assume that the average settlement has 200 households, therefore the full annual energy consumption load can be calculated as follows:

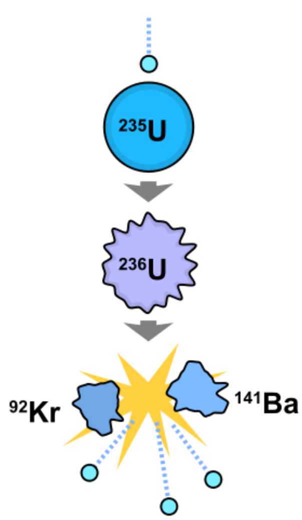
$$20{,}000\ \text{kWe}\times\text{h}\times 200\times 2\ /\ 8760\ \text{h/y}= 0.91\ \text{MWe per year} \qquad (1.1)$$

(Based on harsh climatic conditions and larger First Nations' families, 20,000 kWe×h was used in calculations. Also taking into account future development and possible additional applications, such as district heating and water desalination, factor of 2 was used to accommodate for future energy consumption increase).

1.4 The chain reaction: Why it is possible

Heavy elements with larger nuclei, such as uranium-235, contain significant number of protons and neutrons and, therefore, are relatively unstable. When such an atom absorbs a neutron, it undergoes a nuclear fission in which it splits into two lighter nuclei (see Fig. 1.2 below).

Figure 1.2 Nuclear fission



A typical nuclear fission chain reaction producing 2-3 neutrons as a result which produce more fissions.

(Source: http://www.petervaldivia.com/technology/energy/image/nuclear/Nuclear_fission.png)

As a result of such reaction the uranium atom splits into barium and krypton, releasing energy, gamma rays and 2-3 new neutrons. This process repeats again and again, and each neutron absorbed by a uranium atom produces more neutrons. Thus, the number of fissions considerably increases and the reaction sustains itself. Neutron moderators can be used to moderate and control this reaction. They absorb some neutrons and slow down those neutrons in the core influencing the energy reactor output [5].

Unfortunately, most of naturally occurring uranium is a non-fissile uranium-238 isotope. The fissile uranium-235 makes only 0.7% of all uranium isotopes [5]. If natural uranium is used in the reactor core, it would absorb most neutrons without fissions and the chain reaction will stop. Enrichment allows separation of fissile isotopes of U-235 from a non-fissile U-238 to increase U-235 concentration in the mix. It is also possible to slow down the neutrons and allow the less-enriched uranium to fission using slow (thermal) neutrons. Development and expanding of the nuclear reactor technology in Canada can help utilizing local nuclear fuel deposits because the country possesses one fifth of all deposits world-wide [6].

2 Overview of Existing Small Reactor Designs

There is a number of existing designs of small nuclear reactors developed in Canada, the United States, Russia, the United Kingdom, France and other countries for submarines, aircraft carriers and icebreakers as well as water desalination, aircraft propulsion and research purposes. Nuclear technology was developed initially for military applications, as well as energy production. Many governments financed the uranium-plutonium direction of the research rather than thorium due to their preference for the military application. Nevertheless, a few operational small reactor designs were developed and tested. The structural designs of most types of the reactors with the overview of their characteristics, including its advantages and disadvantages, will be further discussed in this chapter.

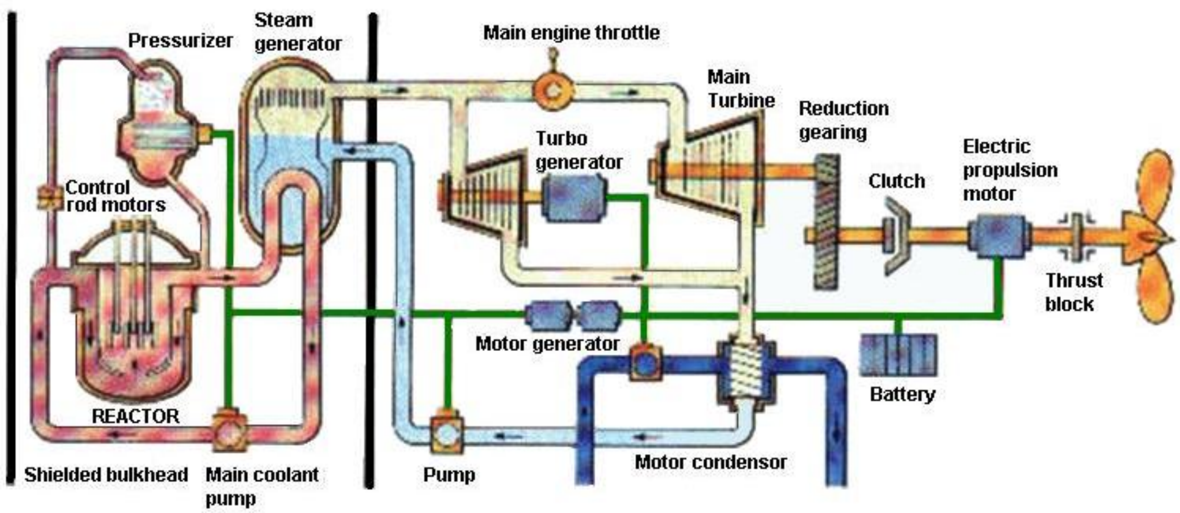
2.1 Submarine nuclear propulsion reactors (PWR and LMFR)

Nuclear-powered submarines were initially developed for the military to allow more autonomous and longer voyages as well as longer submersions to improve combat capabilities. Those requirements increase the success of military operations and allow longer periods without refueling of the reactors (up to 25 years) [7], making those reactors more attractive for the use in isolated northern communities of Canada.

Most American and British submarines use highly enriched uranium (up to 98%) to allow smaller size reactor core and longer periods of operation. These types of the reactors might have some proliferation risk as this highly enriched uranium-operated reactor in the north would lack the necessary security. On the other hand, most Russian and French submarines use low enriched uranium option which is more suitable for the purposes of this thesis but they require more frequent refueling and larger reactor cores.

Inside the reactor, uranium fission reaction heats up water in the pipes passing through the core and converts it into steam which in its turn heats up the water in the heat exchanger which spins the turbine by pushing the blades. The two water piping systems are separated to minimize contamination of the secondary loop and the areas beyond the core with radioactive particles. This turbine is connected to a generator in which rotating electromagnetic field generates electricity and rotates the shaft [7] (See Fig. 2.1 below).

Figure 2.1 Pressurized water naval nuclear propulsion system



PWR is the main type of a naval nuclear reactor used in the majority of submarines throughout the world.

(Source: http://www.fas.org/man/dod-101/sys/ship/eng/reactor.html)

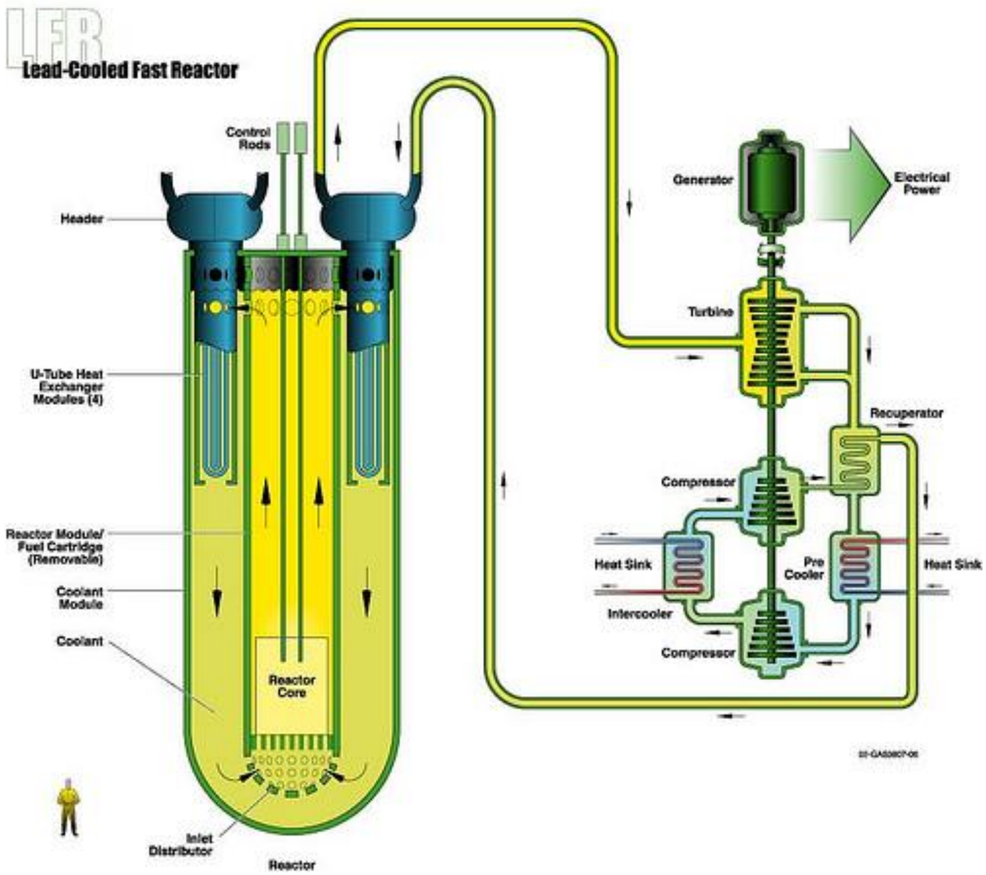
A completely different approach is the thorium method where the fuel is dissolved in molten fluoride salt kept at high temperature and atmospheric pressure instead of water at high pressure as in the previous PWR design. It is under low pressure and uranium-232 (which is produced from thorium-233 in the reactor blanket) is not suitable for military use without additional processing and, therefore, possesses less proliferation risk.

Most submarines also use highly pressurized pipes, reactor vessel and the reactor with water cooling which require more durable reactor vessel materials to contain the core and high-pressure pipes. In recent years, new American and Russian submarines with liquid metal-cooled reactors were developed which use similar cooling system as the proposed small molten salt reactor design and uranium as its fuel [7], [8]. In the Table 2.1 below comparison of uranium PWR and LMFR (which is similar to MSR) is made.

Table 2.1 Pros and cons of the pressurized water reactor compared to liquid metal fast reactor [9].

	Pros	**Cons**
Pressurized water reactor	(1) Stable and self-regulating because the power output decreases if the temperature increases; (2) secondary and primary piping is separated to avoid radioactive contamination;	(1) coolant (water) boils at 100°C and has to be under high pressure to stay liquid; (2) has higher price because needs more piping and the reactor vessel; (3) boric acid in the water can corrode the carbon steel pipes and decreases its lifespan; (4) cost of fuel fabrication is much higher for highly enriched uranium.
Liquid metal fast reactor	(1) Low construction costs because it can operate at low pressure; (2) liquid metal coolant (as well as molten salt in MSR) has higher power density compared to water used in PWR;	(1) liquid metal which is opaque creates difficulties for repairs and inspection compared to water which is transparent; (2) liquid metal coolant is corrosive unlike water.

Figure 2.2 Lead-cooled fast reactor



Lead-cooled fast reactor design used in some Russian and American submarines.

(Source: http://nukers2002.wordpress.com/2008/04/25/next-generation-of-reactors/)

Fig. 2.2 above demonstrates the layout of a typical liquid metal cooled reactor working on fast neutrons and the coolant based on liquid hot metals, such as mercury, lead, sodium and NaK which have good heat transfer characteristics compared to water used in PWR [7].

During the past 60 years attempts were made to use nuclear power reactors in a number of nuclear propulsion and other applications, such as nuclear-powered U.S. Nimitz-class aircraft carriers powered by two PWRs; Russian nuclear-powered icebreakers based on KLT-40S PWRs with highly-enriched uranium with refueling cycle of 12 years, floating nuclear desalination plants and experimentally developed but not realized nuclear-powered Tu-95 bombers [7].

2.2 Molten Salt Reactor Experiment (MSRE) by Oak Ridge Lab

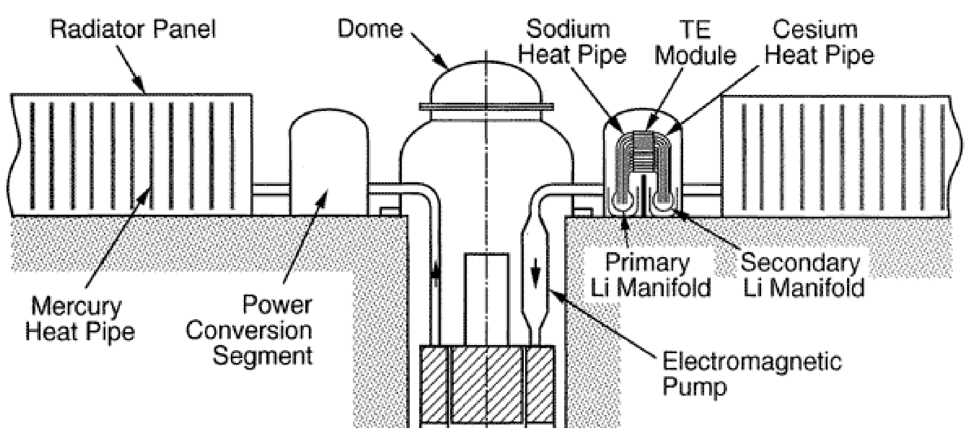
One of the earliest attempts to build an experimental model of the molten salt reactor was carried out by the Oak Ridge Lab in the United States in 1964 and lasted for 5 years. It was designed to initially operate on U-235 and later U-233 fuel and lithium-beryllium fluoride salt as its primary coolant. It had an output of 10 MWe and served to demonstrate that a molten salt reactor can be constructed and operated as well as to test the materials. Unfortunately, a few years later the project was abandoned due to the uranium being a preferred fuel for military applications and possible plutonium production [11].

2.3 Liquid metal cooled small reactor designs by Toshiba (Rapid L, 4S)

Toshiba Corporation in Japan has developed two different designs of small liquid metal reactors which are described and compared below.

Rapid-L design. This small 5 MWth, 200 kWe Rapid-L design uses lithium-6 as a neutron moderator (poison), its disposable cartridge has 2,700 fuel pins and uses 40-50% enriched uranium nitride [10] (See Fig. 2.3 below).

Figure 2.3 Rapid-L reactor design



The reactor is designed to be installed below grade so that the ground provides the necessary shielding.

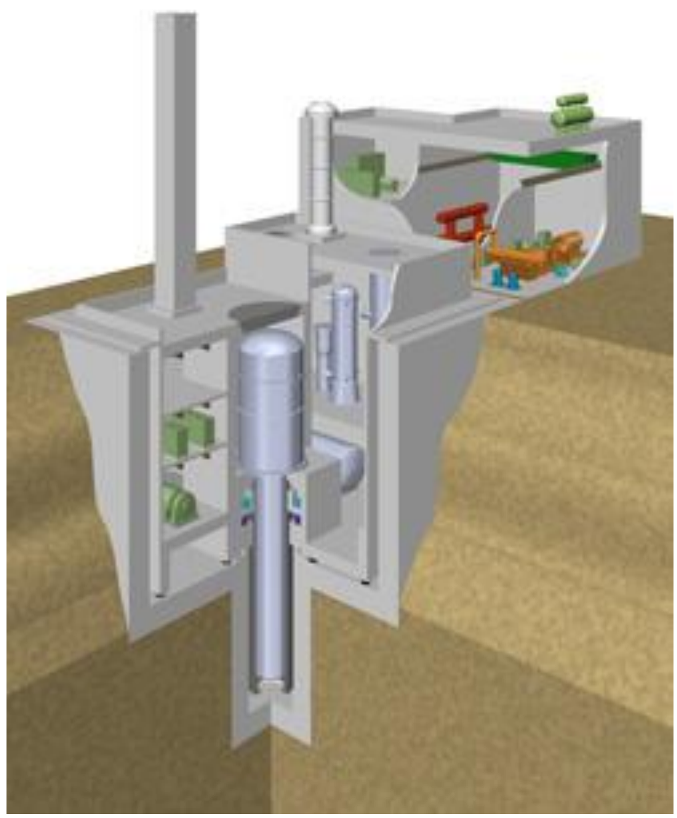
(Source: http://atomicinsights.blogspot.com/2007/12/rapid-l-reactor-designed-by-japans.html)

This reactor has passive reactivity control with molten sodium as a coolant and with special lithium modules which allow compensation for burn-up fuel. Rising of the reactor temperature will cause lithium-6 modules to expand adding negative reactivity [10]. To provide the required protection from radiation underground installation is used for this design.

Toshiba 4S (super safe, small, simple) reactor design in Galena (Alaska)

Figure 2.4 Toshiba 4S reactor layout

This new 10 MWe reactor can replace currently used diesel generators; it has liquid sodium coolant circulated by electro-magnetic pumps and does not require refuelling for 30 years. Its core has cylindrical shape 2×0.7 m, working temperature of 500°C and 18 hexagonal fuel assemblies made of U (10%) - Pu (24%) – Zr alloy enriched to 20%. The reactor will be 30 m below ground with the above-ground building on top with the following dimensions 22×16×11m [10].



Technical data of 4S nuclear reactor proposed by Toshiba.
10 MWe will supply over 600 residents of a small community in Alaska.
(Source: http://uruguayenergia.blogspot.com/2010/04/mini-reactores-nucleares-toshiba-10mw.html)

It is planned to be built at the factory, transported to the site and then installed underground. Neutron absorber at the core will be removed after 14 years and the reflector continues to move up the core for 16 years more. If there is power loss, the reflector falls to the bottom of the reactor vessel, slowing down the reaction. Control rods add safety because they can be dropped inside the core to slow down the reaction and decrease reactivity. After the cycle of operation is complete (30 years), the fuel will be allowed to cool down for one year, and then removed and transported for storage or disposal [10].

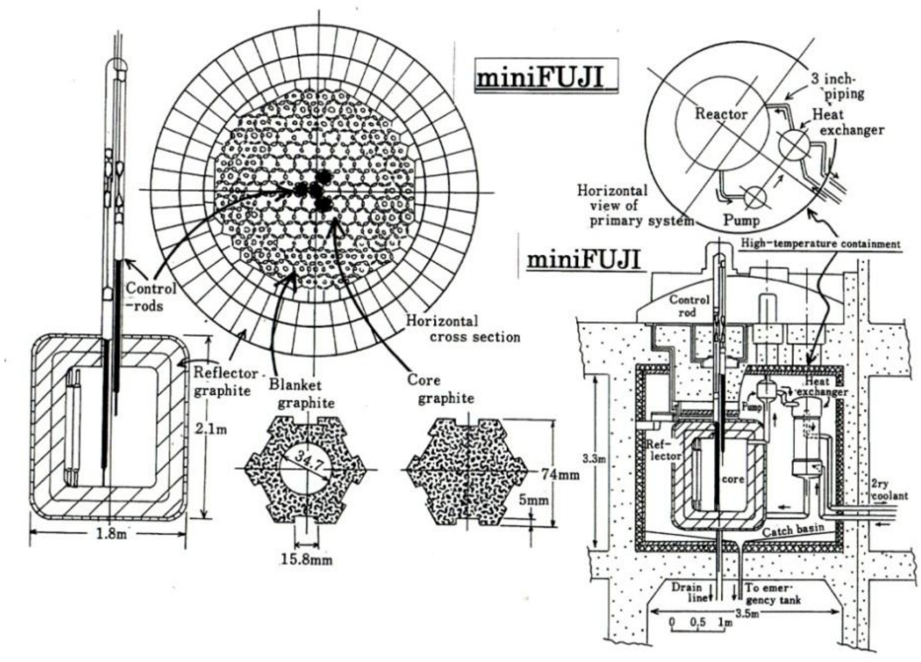
The plant cost is planned to be US$ 2,500/kW and power cost 5-7 cents/kWh which is competitive with the diesel power generation currently used there [10]. Toshiba plans to sell the units for power generation at remote mines, desalination plants and also for making hydrogen. The L-4S modification is a Pb-Bi cooled version of 4S [10].

There is a significant interest in Toshiba's project among mining companies in Alaska where generation of power with diesel fuel is a major challenge because of its high cost and fuel delivery. According to recent news release' local residents currently pay about $0.90 per kilowatt-hour for diesel power. The new Toshiba reactor will produce more affordable electricity to satisfy local needs at significantly lower cost.

2.4 Fuji molten salt reactor

Fuji MSR is a thorium-based breeder reactor which uses fluoride salt as coolant. The Mini Fuji reactor design was designed for ~10 MWe. Graphite is used in the reactor core because it has higher resistance to corrosion in fluoride salts than most metals. Piping is made from corrosion-resistant Hastelloy-N alloy based on nickel with addition of molybdenum and chromium to prevent corrosion and increase its life-span [11].

Figure 2.5 Mini Fuji MSR design concept



Mini Fuji design concept includes vertical pipes with circulating molten salt.

(Source: http://www.ithems.jp/e_minifuji.html)

Table 2.2 Mini FUJI reactor technical data [11]

Thermal capacity	20 MWth
Net electric generation	8.6 MWe
Thermal efficiency	43 %
Reactor vessel(diameter/height)	1800 mm / 2100 mm
Core: radius/height	300 mm / 900 mm
Blanket Thickness	200 mm
Fuel salt composition	$^{7}LiF–BeF_2–ThF_4–^{233}UF_4$ (71.5-16-12-0.47 mol%)
Volume	45 litres
Temperature	inlet 560^{o}C-700^{o}C
Fuel conversion ratio	0.58 (The ratio of number of new fissile nuclei / number of consumed fissile nuclei)
Inventory:	Fissile: ^{233}U-27 kg, Fertile: Th-650 kg, Graphite-8,800 kg

Source: http://www.ithems.jp/e_minifuji.html

2.5 Smallest reactors operated around the world (under 2 MWe)

A number of countries experimented with the smallest reactor designs which were primarily used as research or test reactors. According to AIAE, the current smallest operational nuclear reactor is the Russian 68 kWe Elena PWR developed by the Kurchatov Institute for supply of small towns and water desalination. The smallest ever built reactor was a research 10 kW Argonaut-type reactor developed by Argonne National Lab (USA) which operated during1957-1972 [12]. This certainly demonstrates that a 1 MW reactor is feasible and even smaller reactors of only dozen(s) of kW can be built to become critical and sustain nuclear chain reaction.

Reactors of 1 MW size and smaller were developed in Sweden (R1, operated in 1954-1970), Russia (2 MW Modular Transportable Small Power Reactor, high temperature type), Egypt (ETRR-1, 2 MWth, 1961), Poland (2 MW Ewa, 1958-1995) and other countries [12]. They operated using highly enriched uranium with up to 93% enrichment with no need for refuelling for 25 years. Canadair built its own small 10 kW research Pool Test Reactor which operated in 1957-1990 in Chalk River, Ontario.

3 Small Reactor Design Concept Application

This chapter describes the application of the design concepts as well as discusses challenges of the design and means to mitigate them to make such reactor design possible. Thawing is also discussed as low ambient temperatures in the location planned for the reactor installation throughout the year and permafrost conditions significantly affect construction and maintenance of the reactor due to thawing and possible ground shifting.

3.1 Benefits of molten salt reactor

The proposed molten salt reactor design offers the following five major benefits: (1) safety, (2) fuel efficiency, (3) nuclear waste disposal, (4) cheaper cost of fuel, and (5) economic efficiency [13]:

(1) The MSR has the passive safety features which allows to remove the fissile material with the coolant from the reactor core into the underground tank using gravity even if in the event of complete power loss causing the reactor shutdown [13], [17]; proliferation risks are also low as the reactor fuel and the waste do not contain enriched uranium or any materials which allow any military use or sabotage;

(2) thorium is quite abundant in Earth's crust with known deposits in Canada with high (up to 98%) efficiency of burning in the reactor core compared with the U-235 which is only 0.7% fissile and which require processing, enrichment and costly fuel fabrication [13];

(3) low amount of spent fuel compared to PWR;

(4) allows refuelling during reactor operation and does not require reactor shutdown because refuelling (adding of new breeding material and removal of spent fuel)can be done simply by adding new molten salt-fuel mixture to the reactor core through a sampling window [13], [19];

(5) absence of high pressure in MSR further reduces the cost of piping and exchanger, does not require containment and allows reduction of the construction costs [19]; further cost effective mass production of small MSR, once the design is tested, will significantly decrease the costs.

Certainly, the MSR design concept can offer significant benefits and further development will allow to reduce cost in the future by developing new, durable and cheaper materials and improving their manufacturing technology. Since considering of the MSR design would be incomplete without looking at possible drawbacks of the design, the next Section will review some disadvantages of the MSR and their possible solutions.

3.2 Design challenges and means to mitigate them

Although thorium molten salt reactors offer a number of benefits mentioned above, they also have some technological disadvantages, which need to be addressed to make best use of the MSR design and to safely and efficiently use it. Some of these disadvantages include:

(1) Protactinium-233 is created during the thorium breeding in the reactor core and begin absorbing neutrons interfering with the chain reaction and it needs to be separated from the molten salt to allow it to decay into fissile U-233 instead of a

non-fissile isotope; also, U-232 has to be removed as it decays into thalium-208 which emits strong gamma rays creating radiation hazard [13], [23]; possible solution is to remove these materials from the fuel salt;

(2) Water present in the pipes can produce hydrogen fluoride because the coolant mixture is based on fluoride salts; HF is a corrosive hazard and can escape during maintenance and repairs [13], [19]; possible solution is to find less corrosive materials or to remove the excessive HF during the reactor operation using an off-gas system.

(3) Graphite used in the reactor core, gets damaged by the active neutrons and needs to be replaced every four years [13]; possible solution is to find a more stable graphite material or use graphite balls added to the fuel and replenish them as they get damaged.

(4) Most piping is made from Hastelloy-N or similar iron- and nickel-based alloys which can become brittle in the harsh neutron environment of the reactor core [13]; solution is to continue research new materials and improve currently used Hastelloy-N allow changing its composition to decrease possible brittleness by adding titanium or niobium.

Successful addressing of these issues will make this small MSR design more feasible and economically attractive.

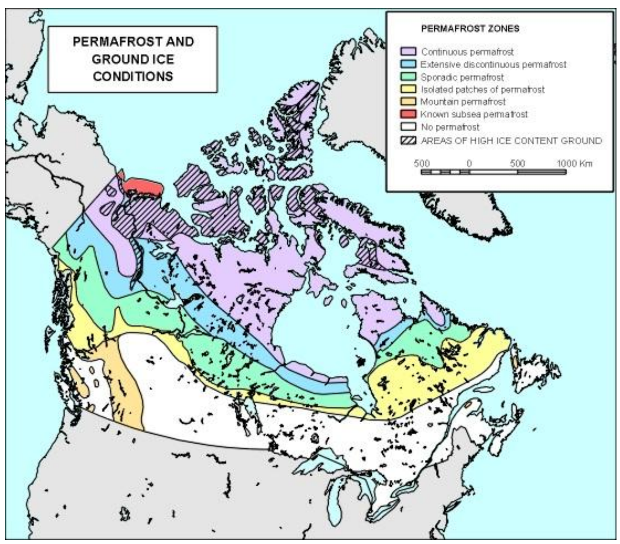
3.3 Permafrost and its impact on the reactor design

Since the designed small nuclear reactor is planned to be used in the northern areas of Canada, where ambient temperatures are quite low throughout the year, and, even in the summer the ground remains frozen all year round at certain depth, permafrost condition have to be taken into account.

Ice has less density than water and thawing creates empty pockets underground which cause soil shift. Thawing can also cause various landslides and soil shifts; this should be taken into account when designing and building the reactor in the areas affected by the permafrost conditions. Wood chips from wood mills or log prospecting in the northern areas can be used to cover the slopes to help to reduce thawing [14].

Fig. 3.1 below shows areas of Northern Canada which are affected by thawing and it is crucial to get a detailed geological survey completed before any construction can begin in the areas of the MSR installation. Also ground water should be studied to prevent any damage from flooding during summers in the area of the reactor construction.

Figure 3.1 Permafrost and ground ice conditions



Most of the northern Canada has permafrost condition which has to be taken into account for this MSR design.

(Source: http://gsc.nrcan.gc.ca/permafrost/wheredoes_e.php)

Thawing can be minimized by cooling down the ground adjacent to the contraction site by creating cold air ducts and circulating cold air using mechanical means, such as fans. Since molten salt reactor will operate at temperatures above 500°C [17], insulating it from the surrounding ground is also crucial to prevent thawing. This Chapter only briefly talks about some important challenges of the design; the next chapter will discuss the design and its main components in more detail.

3.4 Some ideas on existing designs' improvement

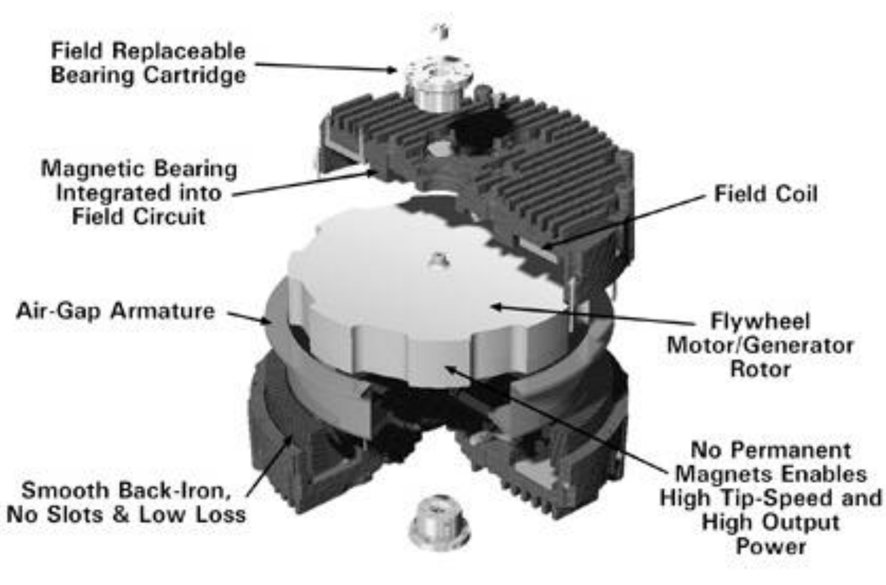
Having studied several sources on thorium small reactor designs, it is possible to suggest that successful attempts to use MSR for power production were made but nevertheless these designs did not see wide industrial production or implementation due to the larger PWR designs becoming more widespread because the governments worldwide invested in research based on uranium fuel designs for military application and for obtaining weapon-grade enriched uranium or plutonium as a spent fuel. Nowadays, there is a growing interest worldwide to alternative designs of small nuclear reactors which do not use traditional highly-enriched uranium which is a big proliferation concern and this thesis hopes to inspire and advance such interest and facilitate alternative MSR design development and its serial production.

The thesis further investigates: (1) developing of a smaller reactor design of 1 MW(e) as well as a possibility of creation even smaller designs, such as 100 kW(e), limited mainly by the sustainability of the chain reaction itself, (2) storing some of the produced energy during off-peak hours in devices such as flywheels or sets of batteries for the reactor's auxiliary power supply and emergencies, (3) using heat produced by the nuclear reactor for heating the residential houses, therefore, re-using the heat which is a by-product of the nuclear reaction and increasing the efficiency of the reactor; (4) cooling down the areas outside the building adjacent to the reactor site to prevent possible shift in the soil surrounding the reactor due to thaw as the reactor produces significant amount of heat. Let us investigate those ideas more closely:

(1) The reactor designs built earlier were usually larger with a few recent ones of 10 MWe and less. Based on possible applications and small size of most northern communities, smaller design are preferred with a possibility of further reducing the size of the reactor to 100 kWe MSR for a single household use similar to diesel generators some households currently own. Some realised designs were discussed in chapter 2.5 above. The minimal capacity is limited by a critical mass of the fissile fuel and further downsizing could render a chain reaction unsustainable.

(2) Flywheels store electric energy using a spinning wheel's kinetic energy and can have efficiency close to 80 or 90%; flywheels are made of a strong durable materials to withstand constant stress and forces. Special bearings are used which can keep the flywheels running for up to 6 months intervals and can be used efficiently for up to 30 years [15]. Beacon Power in Massachusetts (U.S.A.) manufactures carbon fiber flywheel generators which can be used for this design.

Figure 3.2 Flywheel



Flywheel is made of various parts which have to be light and durable to withstand strong mechanical forces.

(Source: http://mragheb.com/NPRE%20498ES%20Energy%20Storage%20Systems/Kinetic%20Energy%20 Flywheel%20Energy% 20Storage.pdf)

Alternatively, batteries can be used as a back-up source of energy and as means to store excess electrical energy produced by the reactor and can provide an alternative to flywheels but batteries usually have more limited application, higher cost and need more frequent replacement [15]. Also, batteries used as multiple cells require costly electronics to control their parameters and coordination of all cells. One such solution is newly developed Hitachi’s CrystEna energy storage system which is a 1 MW lithium-ion battery assembly the size of a railroad carriage container made of 1620 cells and lasting for up to 10 years.

Other possible applications include redox flow batteries and hydro pump storage. The former is a type of a storage battery with a possibility of making separable liquid tanks and its long service life which is an interesting option to consider and the latter will be less effective in cold northern climate with extremely low temperatures all year round and constant freezing of the water which needs to be pumped. The flow batteries are good for load balancing but have a low operating current density. Their capacity usually ranges from 1 kWh to 10 MWh [15] which is suitable for the current MSR design.

(3) Since small reactors are designed for northern areas where the ambient temperatures throughout the year are quiet low and heat is a by-product of the nuclear reactor operation, it is quite attractive to use this heat for district heating applications for both dwellings and small businesses in these settlements.

Instead of using electrical energy to generate heat (electrical heaters) and boil hot water for residents, heat can be collected from the reactor heat exchanger and used directly by the residents. Certainly, this secondary circuit must be separated from the primary circuit which is flowing through the reactor and might contain the products of nuclear fission.

There is a practical experience worldwide to use cogeneration for producing both electricity and heat energy in Scandinavian countries, Austria, Germany and Russia. The heat can be delivered in a form of steam or hot water; the former is more suitable for industrial applications and the latter – for residential heat supply for both the central heating of the dwellings and hot water supply for residential needs. The hot water can run in thermally-insulated below the ground pipes (see Fig. 3.3 below) and return to the reactor site to complete the cycle. Using district heating in addition to the electricity supply will surely improve the efficiency of the nuclear reactor as the unwanted heat, produced as a part of the chain reaction, will now be used instead of just venting it out into the atmosphere.

Figure 3.3 District heating pipe in Germany

(Source: http://2005-08-30-district-heating-pipeline.jpg/)

Hot water meters can be installed to collect additional funds from the residents for hot water usage which will help to reduce the amount of annual running cost of the reactor operation and decrease the effective cost of electricity produced. Main hot water supply pipes can be 200 mm in diameter with distributive pipes - 25 mm in diameter connecting up to 50 households as per world practice.

Based on the equation (4.1) annual energy produced by the 1 MW nuclear reactor is 3.77×10^{13} J. Taking into account electricity production efficiency of 30% and cogeneration (both heat and electricity) – 80%, thermal efficiency alone accounts for 50%. Losses in district heating systems usually are 10%. According to Statistics Canada, an average household uses 105 GJ of thermal energy annually. Therefore, the designed 1 MWe small MSR can theoretically supply the following number of households with thermal energy:

$$(3.77\times10^{13}\ \text{J} / 105\times10^{9}\ \text{J}) \times 0.5 \times 0.9 \approx 160 \text{ households} \qquad (1.1)$$

These calculations above correlate with the proposed 1 MWe MSR to supply a settlement of about 200 households. If the cost of 1 GJ of heat energy is $4.58 (Statistics Canada), it will allow receiving the following amount to decrease operating costs per annum:

$$\$4.58/\text{GJ} \times 105\ \text{GJ/household} \times 160 \text{ households} = \$77{,}000 \qquad (1.2)$$

(4) First of all, since the reactor produces a lot of heat, the surrounding building has to have excellent insulation to prevent this heat from dissipation in the environment [16].

Secondly, to prevent permafrost surrounding the building from thaw, measures which cool down the adjacent areas should be considered. One solution is to construct air ducts and use fans to blow cold air to prevent thawing of surrounding soil and possible shift of the ground or the reactor's below-the-ground structures. This can improve efficiency and attractiveness of the proposed molten salt reactor design.

Additional applications of the molten salt nuclear reactor include water desalination and the use of this water for residential water supply or agriculture to grow fresh vegetables and fruits in the greenhouses, as well as a production of hydrogen by water hydrolysis for cars and snowmobiles to use as fuel, and using the reactor's breeding blanket to produce isotopes for medical and scientific purposes or burn nuclear waste.

4 The Proposed Design and Its Key Components

The proposed reactor design is based on earlier developments in the area of small reactors beginning with Oak Ridge National Lab (ORNL) reactor experiment in 1964-1969 as well as current reactor designs, such as Toshiba corporation proposal for Galena, Alaska of 10 MW ‘4S’ which was proposed but not realized yet, Mini Fuji reactor designs and some others. The concept proposed in this thesis summarizes international developments in the field of small nuclear reactors for the last 50 years and offers a possible viable design solution based on the previous research and experience, new materials such as Hastelloy-N, and thorium as fuel which will be bread into fissile uranium-233 isotope inside the reactor blanket.

4.1 Proposed design overview

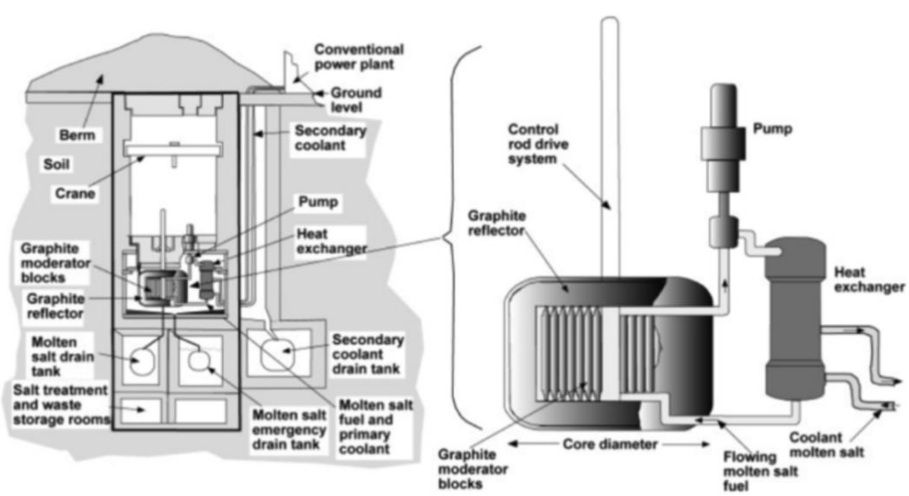
The proposed design is a molten salt reactor with a power output of 1 MWe, downsized from the Oakridge Lab 10 MWe (7.4 MWth) prototype, circulating the fuel salt composed of a mixture of LiF, BeF_2 and Th-232 through a cylindrical-shaped reactor vessel with graphite blocks inside [17]. The fissile isotope of U-233 is produced inside the reactor by breeding in the fuel blanket area [18] which in turn undergoes a chain reaction releasing heat and neutrons to continue the chain reaction.

The heat transfer occurs inside the heat exchanger at 1100°F (~590°C) where the coolant flowing through the pipes absorbs the heat from the fuel salt. This heat then dissipates in the air-cooled radiator and the coolant salt returns to the heat exchanger [19]. Electrical heaters constantly heat up the fuel salt to keep its temperatures above the melting point. Xenon (Xe) and krypton (Kr) are produced continuously in the fuel salt as a result of the reactor operation and need to be constantly removed to prevent the reactor's chain reaction slowing down and the MSR become subcritical because of the neutrons' absorption. Three control rods will be used to control reactor's reactivity (the rate of the nuclear chain reaction) and the heat removal from the heat exchanger will allow the control of the output of the MSR [19].

The reactor is located underground and is enclosed in a reactor cylinder-shaped vessel for safety and stability of its normal operation [17]. This molten salt reactor uses thorium dissolved in the liquid Li-Be fluoride (FLiBe) salts to produce both electrical energy and heat. Additionally, this reactor can be further used for additional applications to produce hydrogen gas through water electrolysis, for burning of various actinides, fissile fuels production, desalination of seawater, and other applications.

Hastelloy-N alloy, based on nickel, which is a newer version of INOR-8, is used for all piping and most other metal applications of MSR design. The reactor vessel is made of steel. Concrete with thickness from 60 cm to 1 meter thick is used for biological shielding to protect the operator and the repair personnel from radiation [17]. The MSR layout is shown in Fig. 4.1 below.

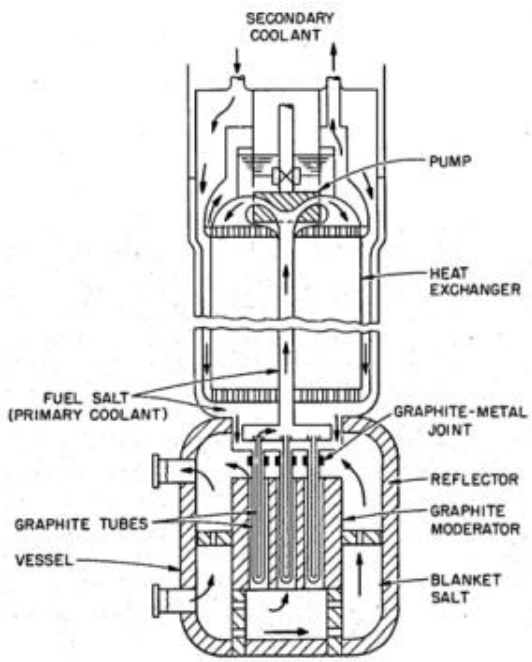
Figure 4.1 MSR layout



(Source: http://atomicinsights.com/alvin-weinbergs-liquid-fuel-reactors-part-1/)

Containment structure prevents the release of nuclear materials into the surrounding environment during the operation and maintenance of the reactor. It has cylindrical shape with a dome-like structure on top [19]. This is a standard design solution used in many nuclear reactors and it is pictured in Fig. 4.2 below.

Figure 4.2 Containment structure



(Source: http://climateconfidential.com/2014/06/24/what-will-it-take-to-make-nuclear-energy-work/)

According to the Oak Ridge Lab design specifications, any containment should have at least 2 layers of protection to avoid escape of radiation [17]. Thus, the reactor core and outer walls create the first layer of protection and the reactor vessel and the enclosure make the second level.

Biological shielding should be used to protect the areas normally designated for the operator and the areas where repair and maintenance team work [20]. These areas should not have background radiation level above the natural level for the annual occupational exposure of 0.7 mSv (1 Sievert =1 joule/kg) [21]. This will be monitored by the radiation monitors. Therefore, the most dangerous areas of the reactor site are the reactor itself and the areas around it, fuel processing zones and the drain tanks. Those areas should not be entered during the reactor operation or immediately after the reactor shut down. It is advisable to check the radiation level prior to entering these areas.

Reactor vessel should have stainless steel walls and a concrete block on top for shielding radiation (at least 60 cm thick). Other areas, where coolant cell and drain tank cells are located, are also shielded with concrete 60-90 cm thick to protect them from radiation [17].

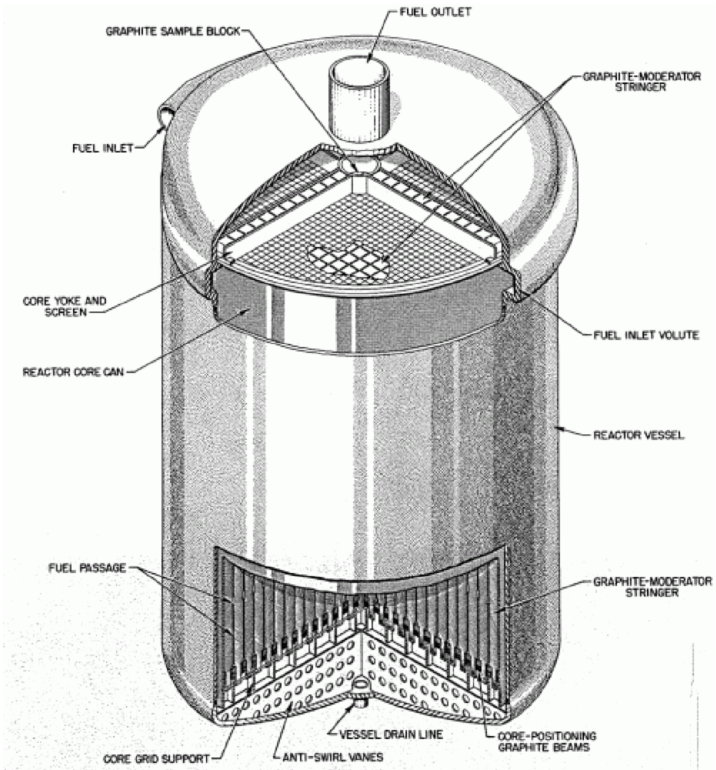
Ventilation system allows some gases, produced as a result of normal reactor operation and during maintenance and repairs, to vent off to keep them out of main building. Two fans, operated by two motors, blow the air to create negative pressure and serve as the third layer of containment. Air flow, produced by these fans, can be adjusted manually using dampers [19].

The containment structure includes the reactor vessel with the reactor assembly, heat exchanger, fuel pump, and freeze valve. The reactor's main components will be discussed in this chapter beginning with the reactor vessel containing the reactor core where the chain reaction occurs.

4.2 Reactor vessel and reactor assembly

The prototype reactor vessel in the MSR experiment had a cylindrical shape made of carbon steel and was measured 1.5 m (diameter) by 2.3 m (height). It had the inner cylinder which contains the reactor assembly with its graphite core [17], shown on Fig.4.3 below.

Figure 4.3 MSR reactor vessel



MSR design reactor vessel which contains the reactor assembly

(Source: http://energyfromthorium.com/msrp/ornl3014/sec01/)

The proposed 1 MWe reactor has similar design but being 10 times smaller in power has only about 1/10 of its volume and is 1/3 of height (0.8 m) and 1/√3 of the diameter (1 m) and contains 534/√3=370 graphite fuel cells. The number of rods is the same (3) but they are shorter accordingly (by a factor of √3 or 1.7).

Energy, produced in the reactor core, can be calculated knowing that a single fission can produce 193.7 MeV or 3.1×10^{-11} J of energy [5]. If the molar mass of uranium-235 is 235 g/mol, one mole contains $6.02\text{x}10^{23}$ (Avogadro's number) fissionable atoms of uranium-235, taking into account the burn-up rate of 50%, 1 kg of U-235 at 95% enrichment can produce the following amount of energy in joules:

$$3.1\text{x}10^{-11}\times 0.5 \times 6.02\times10^{23}/235\times1{,}000 \times 0.95 = 3.77\times10^{13}\text{ J} \qquad (4.1)$$

Dividing this energy by $3.16x10^7$ seconds in a year, the power produced annually is

$$3.77x10^{13}J / 3.16x10^7 s/year = 1.12x10^6 \text{ W or } 1.1 \text{ MW} \qquad (4.2)$$

The calculations show that about 1 kg of enriched uranium is needed to produce 1 MW of energy during 1 year of operation of the reactor. This data correspond to the experimental data obtained by the Oak Ridge Lab which reported that during MSR experiment the thorium fuel inventory for 1 MWe was about 1 kg of pure thorium [17].

Thorium fuel will be constantly added to compensate for the burn-out fuel. High concentration of fissile fuel, use of neutron reflectors and materials to slow down neutrons, will allow reducing the amount of the critical mass needed to start and maintain the chain reaction. Also, bearing in mind that even smaller research reactors were developed, 1 MWe is a feasible design.

The reactor assembly is made of unclad graphite matrix 5x5 cm which is 0.8 m high. The fuel salt comes at the top of the reactor vessel and flows around the inner cylinder. When it reaches the bottom, it is then pumped through the graphite matrix to the top of the reactor vessel. The flow canals, in which the fuel salt travels, run across the whole length of the graphite assembly and are 1x3 cm wide. The fuel salt can be added through the sampling window at the top of the reactor vessel to compensate for burn-up.

Once assembled, the structure has to be tested for leaks [19]. The reactor core is of a round shape and surrounded by a reflective material to minimize the amount of neutrons lost during the chain reaction and to improve criticality, minimizing the amount of fissile material needed to sustain the chain reaction. Also, high-concentration thorium is used to fuel the reactor which further decreases the critical mass needed. Table 4.1

below compares the original Oak Ridge Lab experimental reactor of 10 MWe, its data specification conversion to metric units and the proposed MSR scaled down to 1 MWe.

Table 4.1 MSRE reactor vessel and proposed MSR design data [19]

Design data	MSRE (Imperial units)	MSRE (Metric units)	Proposed MSR
Inlet pipe	6 in	**15.2 cm**	**5 cm**
Outlet pipe	8 in	**20.3 cm**	**7 cm**
Core vessel			
- outer diameter	58-3/8 in	**148.3 cm**	**100 cm**
- inner diameter	57-1/4	**145.4 cm**	**98.6 cm**
- wall thickness	9/16 in	**1.4 cm**	**1.4 cm**
- design pressure	50 psi	**3.52 kg/cm^2**	**3.52 kg/cm^2**
- design temperature (T)	1300°F	~**700°C**	~**700°C**
- fuel inlet T/outlet T	1175°F/1225°F	**635°C/**~**660°C**	**635°C/**~**660°C**
- overall height of core tank	8 ft	**244 cm**	**82 cm**
- head thickness	1 in	**2.5 cm**	**2.5 cm**
Graphite core			
- diameter	54 in	**137 cm**	**96 cm**
- core blocks	2x2x67 in	**5x5x170 cm**	**5x5x60 cm**
- number of fuel channels	1064	**1064**	**740**
- fuel channel size	1.2x0.2x63 in	**3x0.5x160cm**	**3x0.5x52 cm**
- reactor length	65 in	**165 cm**	**55 cm**
Core container			
- inner diameter	54-1/8 in	**137.5 cm**	**96.4 cm**
- outer diameter	54-5/8 in	**138.7 cm**	**97 cm**
- wall	1/4 in	**0.6 cm**	**0.6 cm**
- length	73-1/4 in	**186 cm**	**62 cm**

Structural material. INOR-8 (Ni-Mo-Cr alloy) was developed at the Oak Ridge Lab and specifically used for the MSR experiment. It proved to be a reliable material resistant to the fluoride salts at high temperatures [20].

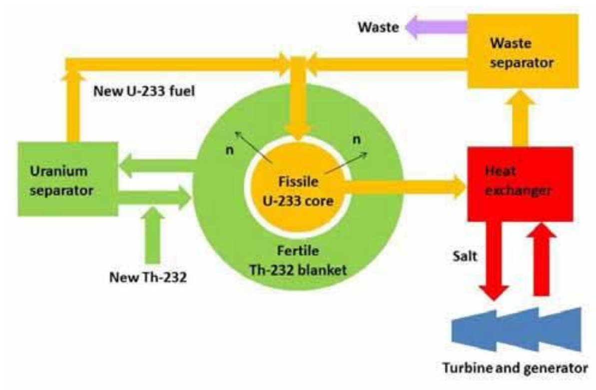
Newer material named Hastelloy-N composed of Ni-15~18%, Mo-6~8%, Cr-5%, and Fe, is proposed for the use for MSR, which is based on nickel and has similar properties as INOR-8. The experiment conducted by the Oak Ridge Lab proved compatibility of the materials and its resistance to corrosion and irradiation over time [17].

Moderator material. It is necessary to use additional graphite moderation as it allows decrease neutron losses in addition to Li-Be fluoride salt's moderating properties. Unclad graphite was used in the MSR experiment and proved to be an operationally viable solution [17]. Harsh conditions inside the reactor core with constant neutron irradiation damage the graphite which requires replacement every few years.

4.3 Fuel breeding

Uranium-233 is the fissile fuel which will be bread from thorium-232 inside the reactor core (see Fig. 4.4 below).

Figure 4.4 Fuel breading in the reactor core



Fissile uranium-233 is bred in the core using naturally occurring thorium-232 which is then undergoing nuclear fission to produce energy. (Source: http://www.aps.org/units/fps/newsletters/201101/hargraves.cfm)

Inside the blanket thorium-232 captures a neutron and after undergoing a series of fissions, turns into fissile uranium-233 [23]. The neutrons will come from the chain reaction of fission, so the reactor will make (breed) new fuel during its operation. The more detailed process of breeding the fissile fuel from thorium will be discussed in chapter 6 dedicated to thorium fuel. The fuel will be added to the reactor without interrupting its operation or the reactor shutdown. This will assure continuous normal reactor operation and decrease losses associated with the reactor not producing energy.

4.4 Reactor control systems

The main control panel has a colour display of the main reactor systems: fuel salt, coolant salt, pumps, off-gas system, all three control rods' positions, and control switches. Control systems are connected to the main control panel using electric cables [19]. The emergency indicators are located on the main control panel as well. These will indicate any abnormal parameters and warn the operator about a possible problem.

The main computer will monitor the processes inside the reactor and will record the parameters comparing them with the normal operating data and if any discrepancy in the reactor operation parameters is found, will take appropriate action, such as further insertion or withdrawal of the control rods to change reactivity of the reactor, opening and closing of valves or changing speed of the blowing fans to affect the operating temperature of the reactor or influence the heat transfer from the radiator or the heat exchanger.

Control rods are operated by the control rods' drives with a help of a computer which allow pulling out or insertion of these rods, therefore, changing the length of the rods inside the reactor core and the number of neutrons absorbed affecting the rate of the reaction [19]. Three control rods, made of GaO (gadolinium oxide) [19], serve as neutron poison. They allow the fission reaction to be controlled to maintain the necessary neutron ratios (criticality) and the chain reaction from either slowing down or accelerating uncontrollably which could lead to an explosion.

This proposed design also has a passive control system as well as graphite material which serves as a moderator and neutron poison (to slow down and capture neutrons).

4.5 Heat exchanger, radiator and piping

The heat exchanger is designed to transfer heat from the fuel to the coolant salt and has U-shaped metal tubes inside to facilitate the heat transfer [19]. The radiator allows cooling the heat exchanger through the process of convection when the cold air blown by fans dissipates the heat. Alternatively, the heat can be used to heat the secondary circuit, isolated from the primary circuit to avoid contamination with the products of nuclear decay, which in turn can supply the hot water for heating of the residential areas adjacent to the reactor. Using the heat for heating purposes rather than just allowing it out into the atmosphere will allow to increase significantly the efficiency of the reactor as well as to provide the residents with central heating and hot water.

Since the specific heat capacity of Li-Be-F salt is 4,540 kJ/m^3, and the energy, produced in the reactor core, is 3.77×10^{13} J or 3.77×10^{10} kJ, the energy in kJ produced in the reactor core per second:

$$3.77\times10^{13}\text{ J} / 3.16\times10^{7}\text{ s/year} = 1.12\times10^{6}\text{ J/s} = 1.12\times10^{3}\text{ kJ/s} \qquad (4.3)$$

Fuel salt flow in m^3/s can be calculated by dividing the energy produced by the fission material in the core per second by the fuel salt heat capacity:

$$1.12\times10^{3}\text{ kJ/s} / 4{,}540\text{ kJ/m}^3 = 0.25\text{ m}^3\text{/s} \qquad (4.4)$$

Taking into account density of the fuel salt at 1.94 g/cm^3 or $1.94x10^3$ kg/m^3, the mass of the fuel salt flow per second can be calculated as follows by multiplying the volume by the density:

$$m = V \times \rho = 0.25\ m^3/s \times 1.94\times10^3\ kg/m^3 = 485\ kg/s \qquad (4.5)$$

According to the Law of conservation of energy, the heat which is removed from the fluid 1 (fuel salt) has to be transferred (minus losses) to fluid 2 (coolant salt). Therefore, the change in the heat of both fluids $\Delta Q_1=\Delta Q_2$ can be written as:

$$Q_1=Q_2 \text{ or } C1\times\Delta T_1=C_2\times\Delta T_2 \qquad (4.6)$$

Fuel salt is at 1225°F or ~660°C incoming and 1175°F or 635°C outgoing and coolant salt is at 1100°F or ~590°C incoming and 1025°F or ~550°C outgoing [19], specific heat C_2 of the secondary (coolant) salt is 4,540 kJ/m^3, therefore, the volume of the coolant salt can be calculate as follows:

$$V_2=C_1\times V_1\times\Delta T_1/\Delta T_2\times C_2=4{,}540kJ/m^3\times(660-635)\times0.25m^3/s/4{,}540\ kJ/m^3\times(590-550)$$
$$=4{,}540\times25\times0.25/4{,}540\times40=0.16\ m^3 \qquad (4.7)$$

Flow of coolant needed to remove this heat from the heat exchanger:

$$0.16\ m^3\times10^3kg/m^3=160\ kg/s \qquad (4.8)$$

Piping. 5-inch Hastelloy-N pipes are used for all piping to connect the pumps with the reactor vessel and heat exchanger. Smaller size pipes are used for drain and other auxiliary tanks. Hastelloy-N is resistant to corrosion and high temperature at which MSR operates. Since this designed reactor works at normal pressure, no thicker piping is required, which is common in PWR working at significantly higher pressure.

4.6 Fuel salt and coolant

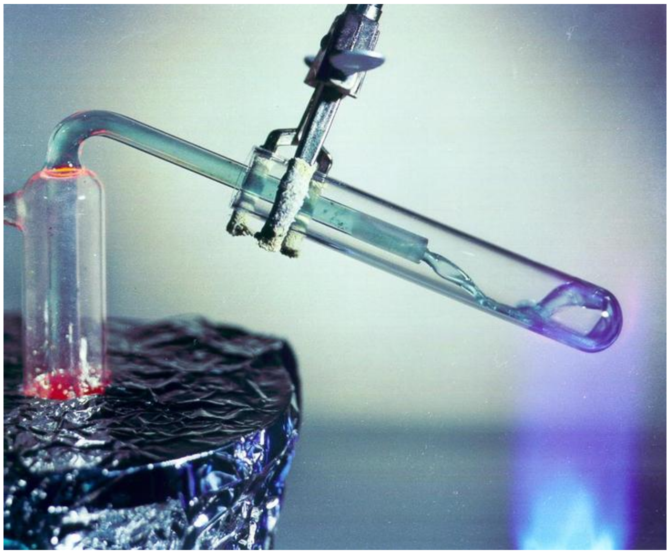
The proposed molten salt reactor design will has thorium tetra-fluoride (ThF_4) in a molten LiF-BeF_2 salt as its fuel salt. Beryllium fluoride allows decreasing the melting point of the fuel salt but it is toxic to humans [19]. The MSR experiment used U-235 tetra-fluoride mixed with ZrF_4 and considered adding thorium to the mixture but using primarily uranium-235 as a fuel [17]. This current proposal plans to operate primarily on thorium which can be added during the reactor operation through the sampling window. This mixture was tested in MSR experiment and proved to be operational and optimal for neutron absorption and moderation [17] as well as having adequate physical properties, such as freezing point.

Zirconium was added in the original MSRE to prevent forming UO_2 and precipitating it in the salt [17]. Since the proposed MSR design uses thorium, there is no need to add Zr to the salt mix.

In the original MSR experiment three different combinations of salts (called salt A, B and C) were tested at various stages of the experiment and it turned out the mixture of LiF-BeF_2 had the best performance [17]. They all have similar component elements but slightly different concentrations.

Lithium-fluoride salt is favoured for this design because fluoride isotope is more stable in the radioactive environment than, for example, chlorine-35, which turns into sulphur-36 after absorbing a neutron and undergoing a beta-decay [17]. Lithium-7 has to be separated from lithium-6 isotope because Li-6 creates corrosive compound called lithium hydrogen by absorbing tritium, a heavy hydrogen isotope.

Figure 4.5 Molten FLiBe salt



A sample of the lithium-beryllium fluoride salt in a test tube

(Source: http://web.ornl.gov/~webworks/cppr/y2001/pres/120507.pdf)

In the proposed MSR Li-7 and Be salt will be used as coolant salt. The composition of the coolant salt is similar to the fuel salt except it does not contain thorium. Flush salt is of the same composition as the coolant salt and is used to flush the system after reactor shutdown to cleanse the system from contamination [17].

4.7 Fuel system components

Fuel and coolant pumps. The fuel pump is a vertical shaft type design driven by a motor and which is connected to an expansion tank, which is designed to collect gases in the salt during reactor operation and other by-products [17]. If an emergency occurs, such as overheat or expansion of the salts, an emergency tank, located under the motor, can absorb excessive salt to prevent explosion.

Drain and storage tanks. Two water-cooled fuel-drain tanks are planned for this reactor as storage of fuel when they are not being used. Each of the fuel tanks should hold the all of the fuel and the second fuel tank is a back-up. Flush tank and a coolant drain tank are also planned for this reactor. Flush tank is used to flush the system for maintenance and the drain tank serves for emergencies when all coolant can be drained for the reactor scheduled shutdown [17].

Freeze valves are normally cooled using fans therefore, cut the drain tanks from the main pipes during the reactor normal operation. In case of an emergency or loss of power (partial or complete), they melt and the coolant along with the fuel is drained down into the tank until the reactor's normal operation is restored. Recent events in Fukushima (Japan), when a power loss, caused the reactor overheat and meltdown, has demonstrated that the passive safety system, based on freeze valves, is crucial for maintaining reactor safety when the power is lost and even emergency power goes off.

4.8 Electrical and auxiliary systems

Electric heaters are used to prevent the molten salt from freezing because the outdoor temperatures are usually below zero in the location of the proposed reactor. They keep the fuel and the coolant at the operating temperature of ~500°C [17] and the designed physical properties of the fuel salts, such as viscosity, to allow normal operation. The electric heaters as well as other auxiliary equipment will use the energy produced by the reactor for power supply.

Electric fans are proposed to blow the cold air in the ducts around the foundation of the reactor building to prevent permafrost from melting since the reactor produces heat as a by-product of the nuclear fission and this dissipated heat can cause thawing and the soil shift.

Electricity is also required for lighting fixtures inside the building, emergency panel operation, pumps, control rod drivers, motors, and other electrical appliances to maintain reactor's normal operation.

This chapter looked closely at the detailed design of the main reactor components and how they operate; the next chapter will discuss overall construction procedures, operation of the reactor as a whole, safety and decommissioning procedures. All nuclear installations in Canada are subject to CNSC regulations.

5 Construction, Operation and Reactor Safety

Once the reactor is designed, approved and manufactured, it is necessary to deliver the reactor components to the construction site and assemble the reactor. Making the proposed MSR made of pre-fabricated modules can significantly decrease the complexity of installation, assembly and the final cost of the reactor significantly improving its attractiveness for potential customers. Prior to the reaction installation, the site has to be surveyed and properly prepared. This chapter reviews the construction, operation and safety of the reactor.

5.1 Transportation, construction, and supervision

The objective of this project is to design a reactor that can be delivered by a truck or a plane to a remote northern location selected for the reactor installation, and operated for long periods with minimum supervision. Special machines, such as cranes and forklift, can be used to deliver and install the reactor components. MSR salts can be delivered by trucks (or cargo planes to some inaccessible locations) based on complexity of access to some northern locations depending on a season and weather conditions.

The proposed MSR will be made of modules which can be repaired individually, maintained or replaced by a visiting supersizing team during their regular inspections once every 1-2 months as well as to check and adding fuel/coolant as needed. On-site supervision is carried out by a local employee who will perform daily check-ups, small maintenance and repairs and who will call for the specialized crew to attend more serious problems between regular inspections. Such employee can be trained on-site from the qualified local residents who can provide daily supervision, maintenance and security of the reactor site between regular visits of the repair and maintenance crew.

5.2 Reactor maintenance and repairs

Nuclear fuel is burnt during the reactor operation and need to be added along with the fuel salt through the sampling window of the reactor. If no new fuel salt is added, spent fuel, which acts as a neutron poison, will slow down the chain reaction and will decrease the reactor reactivity eventually causing the reactor to shut down. The visiting reactor maintenance team can add the fuel salt during their scheduled maintenance visits.

The reactor is designed to operate with minimal supervision where control of the reactor is performed by a specialized computer system and the information will be displayed on the dash board. In the event of an emergency an alarm would go off and the operator will get a signal and would have to investigate the alarm by checking the parameters and making sure that the cause of the alarm attended and the alarm was checked and cleared.

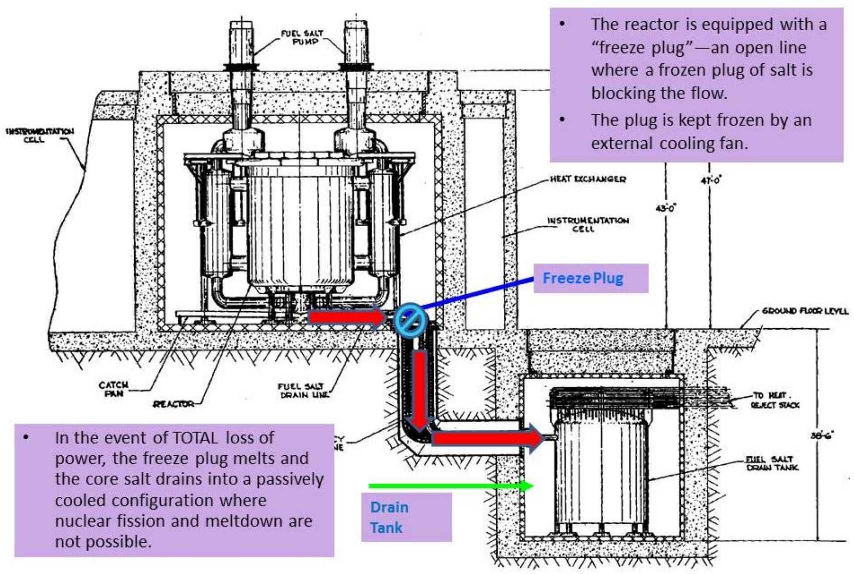
If the operator is unable to clear the alarm and restore normal operation of the reactor, he will contact his supervisor who will take control of the problem. If a fault is found, then the operator and his supervisor will drain the salt and shut down the reactor. Then the repair crew will be called in to attend the repairs.

They will begin by identifying the location of the fault and cutting the hole in the containment directly in the area of the fault and replacing the faulty equipment, if necessary, or repairing the older parts. The repair crew has to entertain precaution as parts removed for repairs can be radioactive, and perform the repairs behind a shield. Video cameras can be used to view the fault area before deciding what work must be done on the faulty parts [17]. Once the repairs have been completed and checked, the hole in the containment will be sealed and the reactor restarted.

5.3 Nuclear safety systems

Recent nuclear disasters at Fukushima Plant, Japan (March 2011), Chernobyl, USSR (1986) and Three Mile Island, USA (1979) raise safety concerns of the public and negative perception of nuclear power generation. The major cause of all three accidents was a coolant leak and subsequent reactor meltdown due to overheating due to emergency power failure caused by flooding. Fig. 5.1 below shows the MSR passive safety system.

Figure 5.1 MSR passive safety systems



Freeze plug is the main part in the passive safety system of the proposed MSR

(Source: http://ndreport.com/op-ed-the-elephant-and-yucca-mountain/figure-2/)

Such disasters are quite rare but the negative reaction is usually quite extensive as public opinion and the decontamination costs affect the governments and business investors' decisions to finance construction of nuclear reactors. Passive safety used in the MSR design allows dumping the salts along with the fuel in the dump tanks located below the reactor and, therefore, shutting down the reactor even though the electricity is cut off and the pumps are non-operational. This passive safety feature makes MSR safer in the loss of coolant or meltdown disasters mentioned above.

5.4 Accidents overview and measures to mitigate them

Safe operation and maintenance are extremely important for normal reactor operation. The proposed reactor design employs several safety measures. Similarly to the MSR experiment, the proposed reactor will have three control rods which drop inside the reactor core in case if the reactor output reached or exceeded 15 MWe or 1300°F (~700°C) [17]. Additionally, the MSR design will have the passive safety system (discussed above), which allows the freeze plugs valves to melt and the reactor fuel and salt drain because of the gravity when the fans would normally cool those freeze plugs, fail to operate [17].

Another type of accident can develop if the fuel and salt which are put inside of the reactor are below the subcritical temperature. This can cause the quick drop of the core temperature and cause negative reactivity inside the reactor. Also, if the fuel pump stops, it will not be possible to restart it unless all three control rods are inserted fully in the core. A problem can occur if the reactor criticality is reached before the reactor core is completely filled with fuel and salt. According to MSR experiment data, it can happen because of control rods are not inserted in the core, the temperature inside the core is too low, and the concentration of the radioactive material in the fuel is too high [17]. Special start-up procedures are developed to prevent this from happening. Thus, the rate with which the fuel salt can be added is limited and the danger of this accident can be minimized.

Loss of flow accident occurs when fuel pump fails and the fuel salt circulation stops, causing the reactor core reactivity and temperature to increase [17]. At the same time, if the coolant circulation stops, the heat exchanger will continue to give away heat without the heat addition from the reactor core; that will cause the fuel salt to freeze. To prevent this from happening, the reactor safety and control system is designed to start inserting the rods automatically when it detects the slowdown of the fuel salt circulation. If the temperature will continue to rise, the control system will drop all three rods as soon as the temperature reaches 1300°F (~700°C).

As a precaution, to prevent freezing coolant inside the radiator, the door shuts down automatically when the temperature of the fuel salt outside of the radiator reaches 900°F (480°C).

Additionally, accidents can develop as a result of external (earthquakes, flood, missiles, arson, sabotage or terrorist attack) or internal (salt spill or oil line rapture).

Earthquakes and floods are rare events in the north, and, remoteness of the reactor from major cities and small population which it serves, make the sabotage or terrorist attack unlikely. Most structures are made fireproof with sprinkler systems widely installed feeding from the main water line as well as low ambient temperatures will make arson very difficult. In an even of fire, the personnel should be removed immediately from the area and the fire alarm sounded alerting the operator's supervisor and the fire department.

Salt spill can result in significant pressure increase and containment leaks due to temperature increase and salt corrosion properties. Fuel pump contains oil as lubricant and the oil line rapture can cause oil to come into contact with hot surfaces of the reactor and piping. The oil will evaporate and can create an explosive mixture with oxygen which is a part of the atmosphere and makes about 21%. To minimize the possibility of this accident to happen, nitrogen should be pumped inside and the concentration of oxygen be kept under 5% as in the MSR experiment [17].

Beryllium is a toxic material and a part of the fuel salt, so in the event of its release in case of leak, an alarm will sound. The personnel should wear protective clothes and respirators and be evacuated promptly.

5.5 Decommissioning and site release

The small reactor design is intended for 25-30 years of operation [20]. After the completion of the working cycle of the reactor, the MSR can be decommissioned, dismantled, loaded on trucks and removed from the reactor site. Fuel mixed with the fluoride salt usually allows to freeze first to allow easier transportation. It is drained into the drain tank located underneath the reactor prior to its removal. The site will be surveyed and released afterwards. Alternatively, the reactor can be refuelled, tested for leaks, repaired (if necessary) and allowed to operate for an additional term.

6 Nuclear Reactor Fuel and Waste Management

Most current larger reactors use fissile uranium-235 which has to be enriched for use as the natural occurrence of this isotope is quite low. Uranium fuel has to be usually manufactured into pellets which require additional processing and increases cost of the final energy production. This chapter describes the processes inside the reactor and compares uranium and thorium fuel usage as well as discuses the waste handling and disposal.

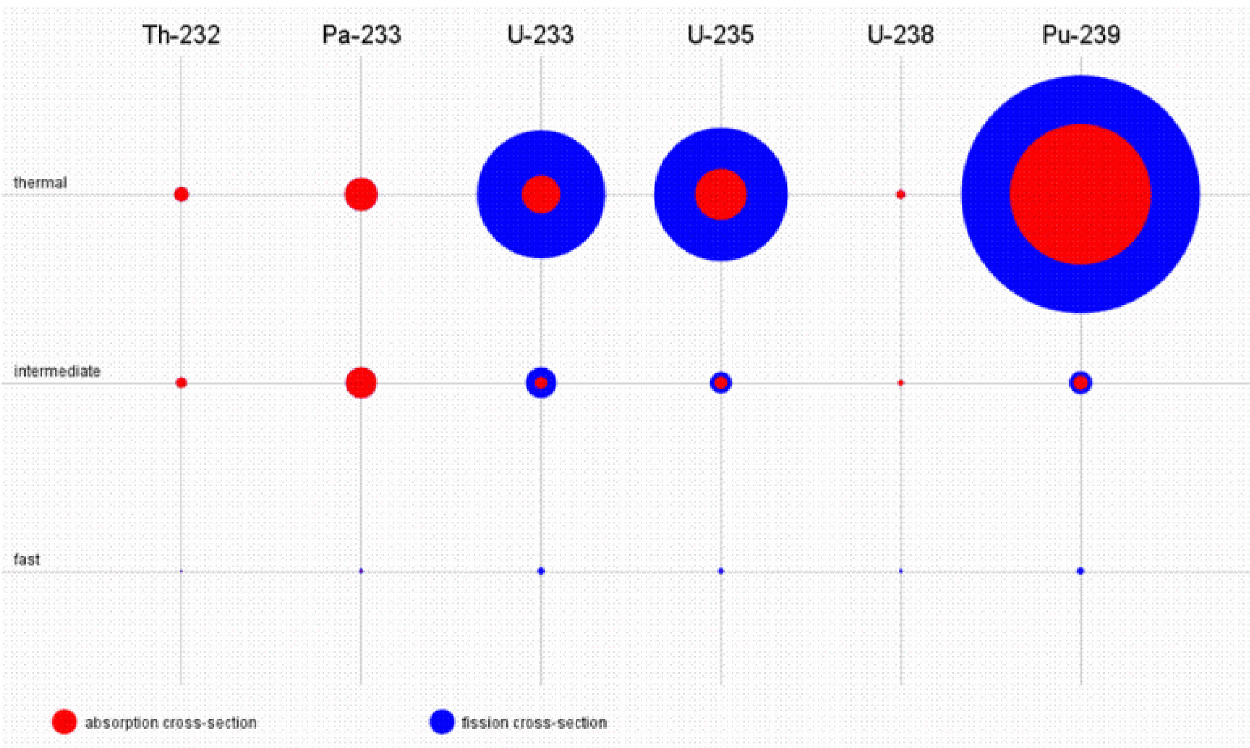
6.1 Physical processes inside the reactor

The reaction of nuclear fission inside the reactor causes it to overheat as the reaction releases heat as a by-product. To prevent this, coolant is used. Most uranium-fuelled reactors are pressurized reactor type which use water as coolant which has to stay under high pressure to remain liquid. On the other hand, thorium-fuelled current design uses molten fluoride salt as coolant. The advantage is that fluoride salts can absorb more heat and the high pressure is not required as they remain liquid at high temperatures of over 600°C at which MSR normally operates unlike water which boils at 100°C.

The chain reaction of nuclear fission causes atoms to split and needs neutrons production rate at least ≥1.3 to allow the reaction to proceed. If the rate is lower, it could slow down the reaction or stop it completely causing the reactor shut down; and the higher rate of >2 can cause nuclear reactor overheat (meltdown) and even a possible explosion. In PWR, control rods are used to moderate and control such reactor [28]. On the other hand, MSR has fluoride salts, which act as moderator as well as graphite, which is also used to maintain a certain reaction rate. In MSR, the graphite slowly reacts with the chemicals inside the reactor and requires replacement every 4 years.

To facilitate neutron capture and the chain reaction, neutrons have to be slowed down to be absorbed by the fissile material inside the rector [23]. The Figure 6.1 below represents the probability of various nuclei absorbing a neutron. The size of a circle represents a probability of absorption and fission and is directly proportionate to the area of a circle. Blue colour represents absorption and fission and the red – absorption only [23].

Figure 6.1 Neutron absorption cross section chart



This figure demonstrates that uranium-233 produced from thorium-232 has a high probability of fission and therefore is a good fuel (Source: http://growingnewlife.com/web_images/fission_absorption_cross_sections.gif)

The following conclusions can be inferred from this table (from right to left):

1. Plutonium-239 is a good neutron absorber but many absorptions do not cause fissions (both red and blue sectors are quite large) [23], so it can impede the reaction;

2. Uranium-235 and U-233 easily absorb neutrons and fission as a result of such absorptions [23], making both excellent fuel; U-233 is bred from Th-232 making thorium an excellent fuel material as well;
3. Th-232 only causes absorption (red) but no fission [23], so it is not a good fuel if used directly without breeding.

6.2 Spent fuel disposal and long-term storage

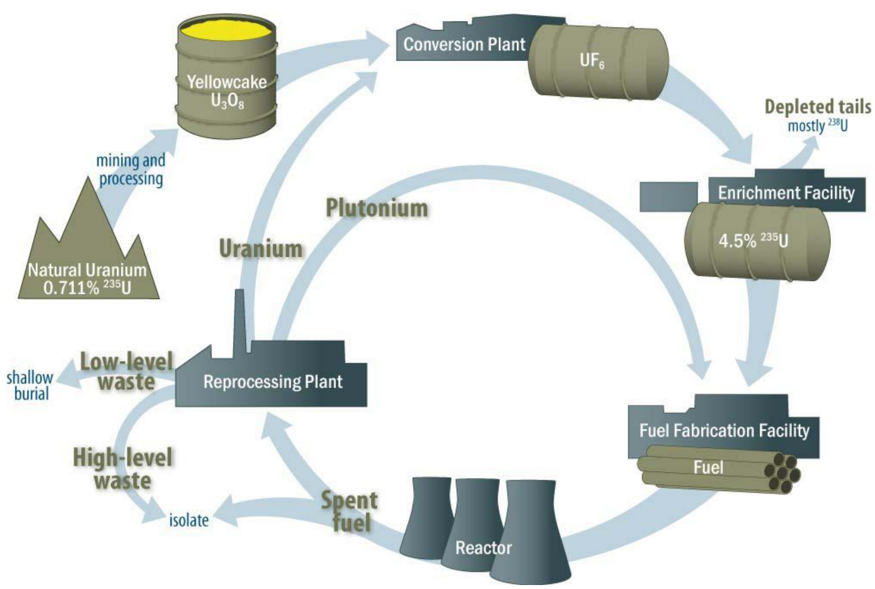
The spent fuel is extremely radioactive with long half-life of hundreds and thousands of years. Therefore, the waste has to be transported and stored in special storage underground or underwater facilities. Underground facilities are normally used for a long-term storage and underwater ones for a short-term storage, which sometimes include further processing of the spent fuel. Thus, it can be either disposed completely by breaking it down into safe or low-radioactive materials or re-processed to extract some useful isotopes for medical and other applications.

The spent fuel waste processing and extracting of the long-lived actinides significantly decreases the time necessary to break down those actinides to make them safer, therefore, decreasing the length of necessary storage and costs associated with the storage of the spent fuel. Handling and disposal of spent fuel is the responsibility of the producers and users of the radioactive fuel.

6.3 Uranium option

Although Canada has relatively large uranium deposits in Athabasca region in Saskatchewan, fissile uranium-235 makes a small fraction of the natural uranium and has to be separated from a non-fissile uranium-238, which makes >99% of all uranium isotopes. Uranium ore is turned into a yellowcake and converted to UF_6 (uranium hexafluoride), and then being enriched at a special enrichment facility [24]. Later, it is transported to a fuel fabrication plant, and fuel rods are fabricated. Uranium spent fuel is then sent to a reprocessing plant and later to the storage facility. Uranium oxides, such as U_3O_8 and UO_2 are the most stable forms and are used as a form of storage for spent fuel [24]. The rods which were removed from the reactor after a few years of usage, will have to cool down at a temporary storage, and later transported to a long-term storage facility after separation and extraction of some long-lived actinides [24]. This process is shown in the Fig. 6.2 below.

Figure 6.2 Uranium fuel cycle



Uranium has to undergo many steps from mining and processing to fuel fabrication.
(Source: http://www.fas.org/sgp/crs/nuke/RL34234.pdf)

Although uranium is the main radioactive fuel used world-wide and its processing and fabrication technique is well-developed, this fuel process uses only <1% of natural uranium [25] and, therefore, the processing, manufacturing and the use of this type of fuel have higher costs. So, thorium option looks attractive as a cheaper and more abundant alternative to uranium fuel.

6.4 Thorium fuel cycle

Thorium is available throughout the world, and Canada has its substantial deposits. Since thorium does not require costly enrichment and processing unlike uranium, as well as fuel fabrication [26], [27], the process of its extraction and processing is more advantageous. The Table 6.1 below demonstrates the breakdown of the thorium reserves according to the United States geological survey.

Table 6.1 Estimates of economically available thorium reserves [29], [31].

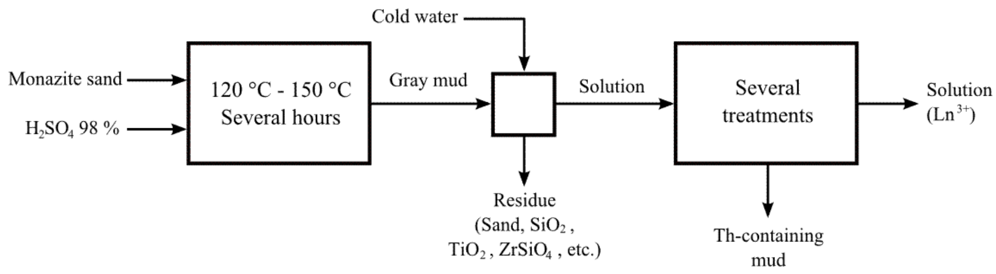
Country	Reserves (tonnes)	Reserve Base (tonnes)
Australia	300,000	340,000
India	290,000	300,000
Norway	170,000	180,000
United States	160,000	300,000
Canada	**100,000**	**100,000**
South Africa	35,000	39,000
Brazil	16,000	18,000
Malaysia	4,500	4,500
Other Countries	95,000	100,000
World total	1,200,000	1,400,000

According to US Geological Survey Canada has at least 100,000 tonnes of thorium deposits, which can be used to fuel the projected reactor and does not require importing of the reactor fuel

Source: http://minerals.usgs.gov/minerals/pubs/mcs/2007/mcs2007.pdf

From the Table 6.1 above, one can conclude that Canada has at least 100,000 tonnes of thorium. Unlike uranium, thorium deposits are made of mainly one isotope - thorium-232 but before this material can be used as fuel in a reactor, it needs to be extracted and processed as shown in Fig. 6.3 below.

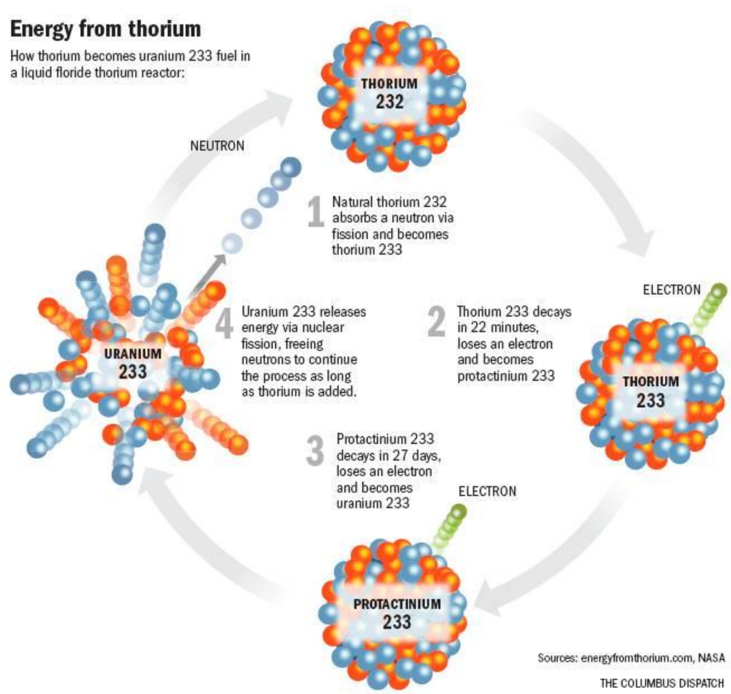
Figure 6.3 Thorium processing



Thorium processing includes a few steps but it is easier and cheaper than uranium processing as it does not include isotope separation. All thorium consists of mostly one isotope thorium-232. (Source: http://thoriumsingapore.com/content/index.php?option=com_content&view=article&id=48&Itemid=34)

Thorium comes from a mineral called monazite which has to be broken down into smaller pieces and mixed with hot concentrated sulphuric acid (H_2SO_4), then thorium is extracted as it precipitate using nitrate, carbonate and chloride salts [30], [32].

Figure 6.4 Breeding of nuclear fuel from thorium



Thorium fuel cycle produces a fissile uranium-233 from a natural non-fissile thorium-232

(Source: http://www.dispatch.com/wwwexportcontent/sites/dispatch/science/stories/2010/03/07/atom_large.jpg)

Thorium-232 cannot be used in MSR directly; it has to be bred into U-233 which is fissile. Firstly, natural Th-232 absorbs a neutron and becomes Th-233, which in turn decays into protactinium-233 by means of losing an electron, and finally decays into U-233 losing an electron [32]. The nuclear reactions can be written below as follows:

$$^{232}Th + {}^{1}n \rightarrow {}^{233}Th \tag{6.1}$$

$$^{233}Th \rightarrow {}^{233}Pa + {}^{0}e \tag{6.2}$$

$$^{233}Pa \rightarrow {}^{233}U + {}^{0}e \tag{6.3}$$

Natural thorium-232 can be put around the reactor as a blanket to absorb neutrons and to decay into fissile U-233 which is then mixed with fluoride salts to fuel the reactor.

7 Reactor Economics

This chapter will discuss the economic aspects of the proposed small nuclear reactor design and will compare the currently used diesel generator technology with the nuclear technology for both uranium and thorium options.

7.1 Overview

Nuclear fuel produces 20,000 times more power density than burning of the fossil fuels such as diesel used in diesel generators [34]. This advantage of the nuclear fuel creates attractive applications including cleaner environment and using heat, which is a by-product of the nuclear fission, to heat residents' homes as well as supply them with hot water and is, therefore, more economically efficient.

The following costs have to be examined to assure the economic viability of the proposed small nuclear design: (1) licensing and financing, (2) construction, testing, and operating, including fuel management and local personnel training, and (3) site decommissioning and land release.

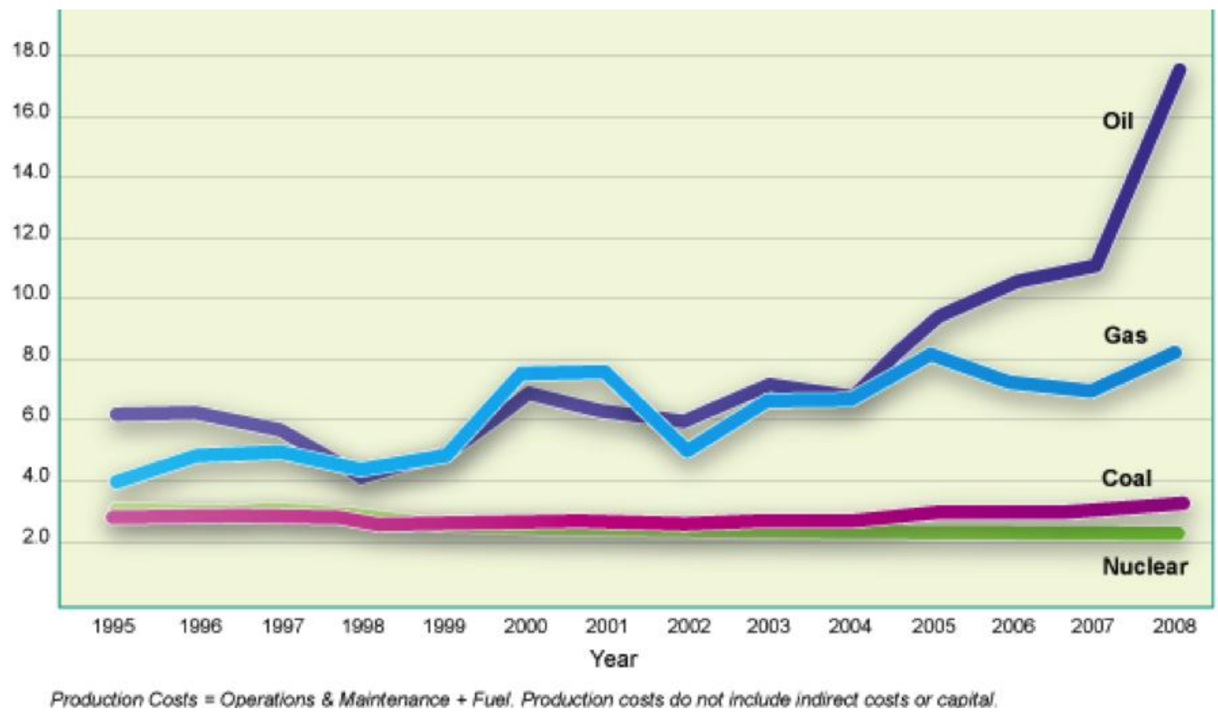
(1) First, the design has to be approved by the government agencies and necessary licences obtained as well as financial resources found [34];

(2) Secondly, the reactor has to be manufactured and delivered to the construction site which has to be prepared accordingly considering the permafrost conditions. Then the unit has to be assembled, tested and prepared for use with training provided for local personnel [34];

(3) At the end of the operational cycle (20-25 years), the reactor unit has to be decommissioned and/or replaced for a new one [34].

Overall the electricity production cost of nuclear fuel is significantly lower than the traditional fossil fuels. Thus, the oil fuel price of producing 1 kW was around 17.5 cents, gas – 8 cents and nuclear – only 2 cents [34] (see Fig. 7.1) below. Only coal price per kW energy is relatively close to the nuclear but in the view of the absence of nearby coal mines and problems with transportation to remote northern locations, nuclear option remain extremely completive.

Figure 7.1 U.S. electricity production costs 1995-2008 (cents per kW×h)



Nuclear technology has lower production costs and has not shown any increase in cost in 13 years

(https://newnuclearenergy.files.wordpress.com/2011/12/nuclear-economic-graph1.png)

Also with the rising prices of oil and gas in the future due to dwindling fossil fuel resources and the price of nuclear fuel being relatively stable, it is expected that economic benefits of using MSR will rise with time [34]. Even though the initial capital investments for nuclear reactors are higher, the operation costs are lower. So, the projected MSR design requires bigger initial funding for construction and development but it is expected that money will be saved in a long run and overall the nuclear power generation tends to be more economically viable long-term.

7.2 Currently used diesel technology

Diesel generators, used today to power the isolated northern communities, allow varying the load during the day, depending on the required amount of power but require qualified personnel to run them as well as back up units. They have to be loaded at least 2/3 of their rated power output [35]. Insufficient load of the diesel generators causes them to depreciate faster and require replacement sooner. Also, carbon and sooth, which builds up inside the diesel generators during their operation, require periodic cleaning to prevent damage to the generators. One of such units is pictured in Fig. 7.2 below.

Figure 7.2 600 kW Cummins VT28 diesel generator

A typical 600 kW diesel generator made as an easy-to-transport unit inside the container.

Source: http://www.wotol.com/images/thumbs/800x800/208771_e8bd193b5563823d814fce21bbdf4d29.jpg

Diesel generators can produce either one or three-phase power, can be launched on short notice and run for at least 20,000 hours before first repairs needed [35]. These advantages can make diesel generators a possible temporary measure before the small nuclear technology can be developed and implemented.

Table 7.1 Technical data of a typical 600 kW Cummins diesel generator

Engine Make: Cummins **Country of Origin:** United Kingdom **Generator Make:** Cummins **Model:** C600 D6, **Hours:** 1,000 **Hz:** 60, **KW:** 600 **Phase:** Three Phase **Fuel Type:** Diesel **Description:** Cummins 600 kW, Rugged 4-cycle in-line industrial diesel generator, Three Phase, 60 Hz. **Overall Weight (dry):** 5,491 kg **Price:** US$ 60,000 (CA$ 75,000)

(Source: https://powersuite.cummins.com/PS5/PS5Content/SiteContent/en/Binary_Asset/pdf/KentData/SpecSheets/SS13-CPGK.pdf)

According to Natural Resources Canada as of March 31, 2015 diesel fuel cost in Western Canada is $1.03/litre.

Two units of Cummins Diesel Generator Set VT28 rated 600 kW and one reserve unit have been selected for this option. According to Diesel Service and Supply the fuel consumption at full load of one 600 kW diesel generator is 42.8 gal/h [38].

Table 7.2 Diesel generator economics calculations

Capital cost, (2units at full load + 1 reserve), $	75,000×3 units=$**225,000**
Annual fuel cost, $/year	Hourly fuel need (gal)=42.8 gal/hour×2 units=85.6gal/hour Hourly fuel need (l): 128.4 gal/hour×3.78=324litres/hour Annual fuel need: 324litres/hour×8,760 hours=2,840,000litres/year Annual fuel cost: 2,840,000litres/year×$1.03/litre =**2,925,000**
Operational and management cost, $/year	1 person on-site supervision: **60,000**
Total annual operational cost, $/year	225,000/25+2,925,000+60,000=**2,994,000**
Effective cost of electricity production, c/kW h	**=$2,994,000×100/8,760h/year/1,000=34.2c/kW h**

It is possible to conclude that the most expenses of the diesel generator option comes not from the units manufacturing cost ($225,000) but rather from the annual cost of operation ($2.9 mil.) where cost of fuel makes the biggest part. With the price of the fossil fuels rise, these already huge expenses are going to increase even more. Therefore, the nuclear option offers economic advantages in the long run and can be a way out of the coming shortage of fossil fuels in the near future.

7.3 Uranium option

Uranium has been long used as a nuclear fuel for a variety of nuclear technology applications, such as nuclear power plants, submarines, ice breakers, and aircraft carriers reactors desalination plants, and some other. One of the reasons uranium was found attractive, compared to thorium, was the possibility to use the products of the reaction for weapons or convert them to plutonium. Uranium fuel can be used as low-grade uranium or higher grade enriched uranium. Both options are considered below.

Advantages of using the low-enriched uranium (<20%) are the high proliferation resistance (as this fuel cannot be used for weapons unless higher enriched) and cheaper fuel. Disadvantages will include the lower power density than higher enriched uranium, shorter period of operation before refuelling, and more waste.

Highly Enriched (>90%) or weapons-grade uranium has higher power density, longer periods before refuelling (up to 25-30 years) and less amount of nuclear waste because it burns more efficiently. Disadvantages include low proliferation resistance and high price of fuel fabrication and processing.

According to UXC website, the spot price of uranium oxide (U_3O_8) as of August 3, 2015 is US$35.25 per pound [33]. Taking into account the conversion rate of US$1=CA$1.25 (per Vancouver Bullion Currency Exchange rate) and 1 lb=0.454 kg, the price is CA$44/lb or CA$96.90/kg.

$$\text{US\$35.25} \times 1.25 \text{ CA\$/US\$} = \text{CA\$44} \tag{7.1}$$

$$\text{CA\$44} / 0.454 \text{ kg/lb} = \text{CA\$96.90} \tag{7.2}$$

Table 7.3 Low enriched uranium (20%) option economics calculations

Expenses, $	**Calculations**
Capital cost, $	$2,000/kW×1,000=2,000,000
+5% extra piping for PWR, $	2,000,000×1.05**=2,100,000**
Annual fuel and waste management cost, $/year	96.90×1/0.20+2,000=2,485
Operational and management cost, $/year	
- on-site supervision ($/year)	1 person × $60,000/year = 60,000
- fly-in crew ($/year), 2 people crew, every two months inspection	=2people×6visits/year×10h×$60+$500/ticket×2×6 =7,200+6,000 =13,200
Sub-total, $	60,000+13,200**=73,200**
Indirect costs [36-37]:	
- Cost of outage (10%) (use of back-up diesel generators), $	10% off grid × 8760h ×1,000kW×$0.16/kWh=140,000
- Taxes (1%), $	20,000
- Insurance (private) (1%), $	20,000
- Interest (5%), $	100,000
- Depreciation (5%), $	100,000
Indirect costs (sub-total), $	**380,000**
Decommissioning cost (9-15% of capital cost), $	12%×2,000,000**=240,000**
Total annual operational cost, $/year	2,100,000/25+2,485+73,200+380,000+240,000/25 =**550,000**
Electricity production:	
- Power	1 MW=1,000 kW
- Number of hours per year	24h/day×365days/year=8,760 h/year
- Electricity production	1,000kW×8760h/year=8,760,000 kWh/year
- Capacity factor 90% (operation at full load)	0.9x8,760,000=**7,880,000 kWh/year**
Effective cost of electricity production, c/kW h	**$550,000/year**×**100c/$/7,880,000kWh/year =7.0 c/kWh**

Note: Total annual operation cost (for all fuel options) includes capital investment cost divided by the number of years in service, annual cost of fuel and waste management, maintenance, indirect costs and decommissioning.

Table 7.4 Highly enriched uranium option economics calculations

Expenses, $	**Calculations**
Capital cost (reactor life – 25 years), $	$2,000/kW×1,000=2,000,000
+5% extra piping for PWR, $	2,000,000×1.05**=2,100,000**
Fuel and waste management cost (no need refuelling for 25 years), $	US$98.5x1.20×1kg+2,000/25y**=$118+80=198**
Annual fuel and waste management cost, $/year	210
Operational and management cost, $/year	
- on-site supervision ($/year)	1 person × $60,000/year = 60,000
- On-site armed guard ($/year)	1 person $50,000/year = 50,000
- fly-in crew ($/year), 2 people crew, every two months inspection	=2people×6visits/year×10h×$60+$500/ticket×2×6 =7,200+6,000 =13,200
Sub-total, $	$60,000+$50,000+$13,200**=123,200**
Indirect costs [36-37]:	
- Cost of outage (10%) (use of back-up diesel generators), $	10% off grid × 8760h ×1,000kW ×$0.16/kWh=140,000
- Taxes (1%), $	20,000
- Insurance (private) (1%), $	20,000
- Interest (5%), $	100,000
- Depreciation (5%), $	100,000
Indirect costs (sub-total), $	**380,000**
Decommissioning cost (9-15% of capital cost), $	12%×2,000,000**=240,000**
Total annual operational cost, $/year	2,100,000/25+198+123,200+380,000+240,000/25 **=597,000**
Electricity production:	
- Power	1 MW=1,000 kW
- Number of hours per year	24h/day×365days/year=8,760 h/year
- Electricity production	1,000kW×8,760h/year=8,760,000 kWh/year
- Capacity factor 90% (operation at full load)	0.9×8,760,000=**7,880,000 kWh/year**
Effective cost of electricity production, c/kW h	**$597,000/year×100c/$/7,880,000kWh/year= =7.5 c/kWh**

7.4 Thorium option: MSR design concept

Thorium fuel requires less processing and has very high proliferation resistance. Local thorium deposits found in Saskatchewan can be used and do not require importation and make it less dependable on foreign countries.

Thorium offers a much cheaper option as it requires less processing and no specific fuel fabrication. As of August 2006, the average value of thorium compounds was $30.28 per kilogram, and this cost slightly increased from the 2005 average of $29.35 per kilogram (gross weight) [32]. According to the World Nuclear Association study, the capital cost of a nuclear plant is $2,347-$2,972/kW [37]. Various studies give a range of numbers between $1,000/kW to $3,500/kW of capital cost investments for nuclear reactors. It largely depends on the reactor type, fuel used, country and many other factors. Thus, MIT study quotes $2,000/kW [37], which is the average and will be taken into account for the small MSR design concept calculations. Therefore, the capital cost of the proposed small reactor design of 1 MWe is estimated at 2 million dollars with additional annual expenses for operation and maintenance. The following inventory, presented in the Table 7.5 below is based on the Mini FUJI design. The coefficient used to calculate similar inventory required for 10MW is 10/8.6=1.16. Salt composition: $^{7}LiF–BeF_2–ThF_4-^{233}UF_4$ 71.5-16-12-0.47 mol% and density is 2 g/cm^3 or 2 kg/m^3 [17].

Table 7.5 Inventory of the MSR 10MWe and the design MSR 1 MW

	Inventory for 10 MWe	**Design MSR Inventory 1 MWe**
Fissile: ^{233}U, kg	31	3
Fertile: Th, kg	754	75
Graphite, kg	10,200	1,000
Fuel salt (volume), litres	52	5
kg	105	10

This section outlines the economic calculations of the small molten salt nuclear reactor concept with thorium cycle and effective cost of electrical energy production based on capital cost, operating cost (including cost of fuel and salts), maintenance and other economical data. Table 7.6 below summarizes such calculations and allows estimating the cost of electricity produced.

Table 7.6 Molten salt reactor economics

Expenses, $	**Calculations**
Construction (Capital) cost, $ - Physical plant equipment with labour and materials - Engineering and labour costs - Systems' testing and staff training	This figure is based on reference material of actual construction cost of similar plants.
Total, $	**$2,000/kWx1,000=2,000,000**
Repeated cost, (Operation and Maintenance), Materials cost, **$**	(based on Mini FUJI design)
- Thorium fuel, $	75 kg×$30/kg=2,250
- Uranium (initial load), $	3 kg×$109×1.25/kg=1,200
- Li-Be Fluoride Salts, $	$170/kg×10=1,700
- Graphite, $	1,000 kg×$2/kg=2,000
- Delivery, $	$0.5/ton km×2,000km×3.5ton=3,500
- Reprocessing, $	$1/kg×105 kg=105
Material cost (sub-total), $/year	$10,755/30**=360**
Operational and management cost, $/year	
- on-site supervision ($/year)	1 person × $60,000/year = 60,000
- fly-in crew ($/year), 2 people crew, every two months inspection	=2people×6visits/year×10h×$60+$500/ticket×2×6=7,200+6,000 =13,200
Sub-total, $	60,000+13,200**=73,200**
Maintenance (sub-total), $/year **Indirect costs, $** [36-37]:	
- Cost of outage (10%) (use of back-up diesel generators),$	10% off grid×8,760h×1,000kW×$0.16/kWh=140,000
- Taxes (1%), $	20,000
- Insurance (private) (1%), $	20,000
- Interest (5%), $	100,000

Expenses, $	Calculations
- Depreciation (5%), $	100,000
Indirect costs (sub-total), $	**380,000**
Annual expenses, $	**453,500**
Decommissioning cost (9-15% of capital cost), $	12%×2,000,000**=240,000**
Waste disposal, $	$85/kg×75 kg=6,400
Total annual expenses, $	**$2,000,000/30+$453,500+$240,000/30+ +$6,400/30=528,000**
Electricity production:	
- Power	1 MW=1,000 kW
- Number of hours per year	24h/day×365days/year=8,760 h/year
- Electricity production	1,000kW×8,760h/year=8,760,000 kWh/year
- Capacity factor 90% (operation at full load)	0.9×8,760,000=**7,880,000 kWh/year**
Effective cost of electricity production, c/kW h	**$528,000/year×100c/$/7,880,000 kWh/year=6.7 c/kWh**

The economic comparison of diesel, uranium and thorium options will be considered in the following section.

Taking into account $77,000 per year cost of heat energy sold to customers (see equation (1.2)), the total annual expenses will be $528,000-$77,000=$451,000 and the effective cost of both electricity and heat energy production will be:

$451,000/year×100c/$ / 7,880,000 kWh/year = 5.7 c/kWh (7.3)

Using cogeneration and selling heat energy will allow decreasing the effective cost of electricity production by 1 c/kWh or 15% and increase cost effectiveness of the project.

The cost of electricity production in nuclear industry in the U.S.A. is about $100/MWxh [34] or 10 cents/kWh with is comparable with the results obtained above:

$100/MWh×100 cents/$1 / 1,000 kWh/1 MWh = 10 cents/kWh (7.4)

7.5 Reactor economics: summary and conclusions

The proposed economic estimation of the total cost and the cost of electrical energy production allows one to conclude that the effective cost of the proposed MSR design concept is within the economic range for other nuclear reactors types [36]. Although the nuclear reactors have higher capital cost, they can produce electrical energy at comparable or cheaper rates than thermal power plants, and are cost effective on a long run. Small MSRs being new designs might have a higher cost per kWe×h of produced energy in the beginning, but are expected to decrease the cost as test design prove their reliability and decrease the investor risk as well as mass-production and new materials development allow further reduction of the capital and operational and maintenance costs.

Table 7.7 Economic calculations comparison

	Diesel generators	**Submarine PWR, U-235, 3.6%**	**Submarine PWR, U-235, 97%**	**Thorium MSR**
Capital cost, $	225,000	2,100,000	2,100,000	2,000,000
Annual fuel and waste management cost, $/year	2,925,000	2,550	216	360
Operational and management cost (personnel), $/year	60,000	73,200	123,200	73,200
Total annual operational cost, $/year	2,994,000	550,000	597,000	528,000
Effective cost of electricity production, c/kW h	**34.2**	**7.0**	**7.5**	**6.7** **(5.7 with cogeneration)**

For the reactor economic analysis, the following four options were considered: (1) two plus one reserve diesel generators 600 kWe each, (2) submarine version of a small PWR using low enriched uranium (3.6%), (3) U.S. submarine version of a small PWR using highly enriched uranium (97%), and (4) the proposed thorium MSR design concept. The results are compared in the Table 7.7 above.

After analyzing the data for all four options, the following conclusions can be made:

- Diesel generators currently used in most remote locations in the north have relatively low capital cost ($225,000 for a set diesel generators), but the annual cost of fuel ($2.9 mil.) is a significant investment, which makes diesel generators expensive and less effective in a long run;
- nuclear reactor capital investments are higher than of the diesel generators ($ 2 mil. vs. $0.2 mil. but annual fuel cost is significantly lower: $2,500 for low-enriched uranium to even smaller amount of $200-300 for highly-enriched uranium and thorium which is naturally pure;
- therefore, once the reactor is built, annual operating cost allows to save significant amount of money instead of burring expensive diesel fuel;
- thorium option appears slightly better economically than uranium option due to the lower fuel cost of thorium, simpler and cheaper design (absence of high pressure expensive piping, pressurisers, etc.) and lower proliferation risks.

8 Concluding Chapter

This chapter will summarize the MSR design characteristics and will look at possible future development of the current design to improve its efficiency and decrease costs of operation and energy production. Isolated northern communities urgently require finding an alternative to currently used obsolete diesel generator technology, and the suggested molten salt reactor design can provide such an alternative.

8.1 Discussion

Thorium is cheap and abundant nuclear fuel and offers a variety of fuel cycles which allows more flexibility of fuel choice depending on the current needs. Moreover, no special fuel fabrication is necessary and the fuel cycle can be changed without any reactor design alteration [39]. Molten salt reactors, which were developed more than 50 years ago, and put aside by the uranium option nuclear generation because they did not produce plutonium needed for weapons, became preferable nowadays due to higher proliferation resistance and increased possibility of misuse of the fuel itself or its products.

The proposed molten salt nuclear reactor design with fluoride salts as coolant offers a practical economic solution of providing isolated communities in Canada with both electricity and heat and to replace currently used ineffective diesel generators. This MSR design reflects the current interest worldwide to return to this old idea of a small molten salt reactor design and use this concept for powering off-grid isolated communities in northern Canada. This Thesis offers an overview of a possible thorium application and the first step on the path of investigating such possibility. It is necessary to further explore this design to reduce costs of construction and maintenance, and to increase economic advantage compared to other sources of energy, including renewable energy production options, such as solar, wind or geothermal. Although this small MSR design is an interesting proposal and a viable solution for the isolated northern communities energy supply, further research and tests are needed to develop a working prototype.

8.2 Conclusions

Building large thermal or hydro power plants for small remote communities is not very practical due to low density of the population and greater distances between the population hubs. Thus, supplying those isolated areas using high-voltage transmission power lines is inefficient and expensive. Higher voltage used to decrease energy losses during transmission, will cost significantly more due to the cost of the pylons with higher clearance, more cables and insulation needed and increased land loss.

Small molten salt nuclear reactors would allow electricity and heat production on-site and could provide these remote areas with energy at lower cost. Also, producing the power and using it locally without high-voltage transmission, saves costs on building step-up and step-down transformers and electric power substations. Risks of polluting the environment if an accident occurs and radioactive materials released into atmosphere or environment are minimized because those areas are scarcely populated.

The proposed MSR design, which is based on abundant thorium deposits as well as a safe and simple design, could provide a sustainable energy supply. The economical and technological efficiency of molten salt reactor design can become more competitive in the future with more development and testing when compared with bigger nuclear plants utilizing a uranium cycle.

Developing of new innovative modular designs which can be mass-produced, transported, assembled, maintained and repaired on-site can help to overcome those challenges and increase the safe use of nuclear energy. Thorium is a cheap and abundant reactor fuel allowing greater flexibility of fuel cycles and high proliferation resistance [40]. Therefore, molten salt reactor based on thorium cycle can be an economically feasible solution to boost development of Canada's north.

8.3 Further research

Advancing fuel cycle research and improving the reactor design will allow longer periods before refuelling as well as achieving higher economic and technological efficiency and lower the cost of the reactor production and maintenance and decrease of the electricity cost. Further research in reactor installations will allow development and testing of new, cheaper, and more efficient equipment and new types of coolant to increase reactor efficiency and safety allowing further advance of nuclear reactor technology.

Consider a possible use of other substitute molten salts, such as $NaCl+MgCl_2$, which have similar physical properties as $LiF+BeF_2$ due to the toxicity of beryllium [41]. Further research is required to create cheap and suitable carbon composite materials for molten salt reactor application as they need replacement due to radiation damage.

To summarize further research the following need to be developed for successful implementation of the small nuclear design for northern communities:

(1) To improve the MSR reactor efficiency and design simplicity by advancing thorium fuel cycle research and developing more durable, cheaper and safer materials;

(2) to develop different sizes and power ratings of MSR to suit various residential and industrial customers;

(3) to create and test a variety of molten salt reactor prototypes by putting them in different operating conditions and collecting and analyzing data on successful design application;

(4) to facilitate creating of a modular design to allow mass-production of the small molten salt reactors to make them cheaper and more cost-effective;

(5) to improve international cooperation in the area of reactor technology and exchange of ideas within the international community [39], [41].

New energy resources must be developed as the technological progress can slow down as fossil fuels become scarce. Hydro power, wind, solar and other alternative resources of energy are not always and readily available in remote areas of the north or transporting is difficult and inefficient, especially in cold winter conditions. Small nuclear reactor technology will expand the current reactor technology which is mostly based on medium and large size reactors and will bring electricity and heat directly to the remote northern communities without the need of long-range transportation of energy and therefore, saving on construction of long and expensive high-voltage power lines and substation equipment to lower the voltage after the transmission as it will be produced and consumed locally without the necessity of using step-up and step-down transformers.

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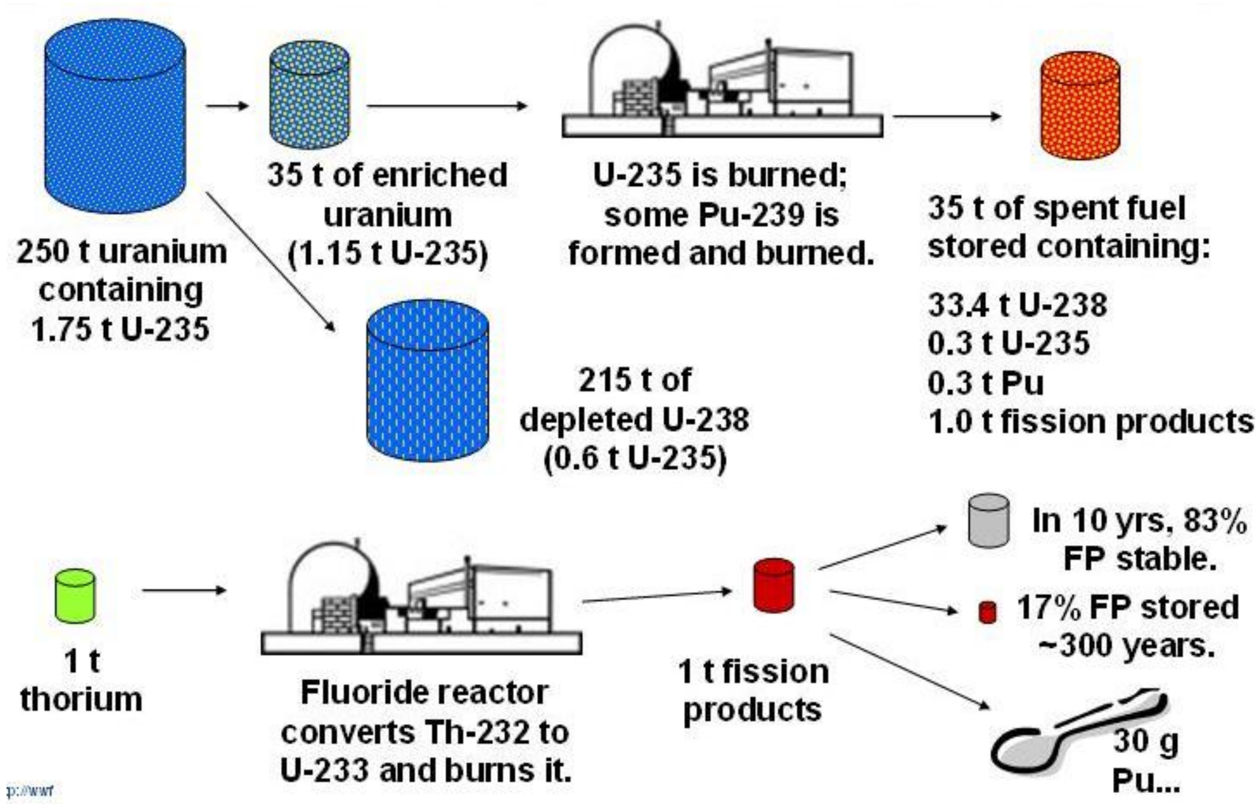
Appendices

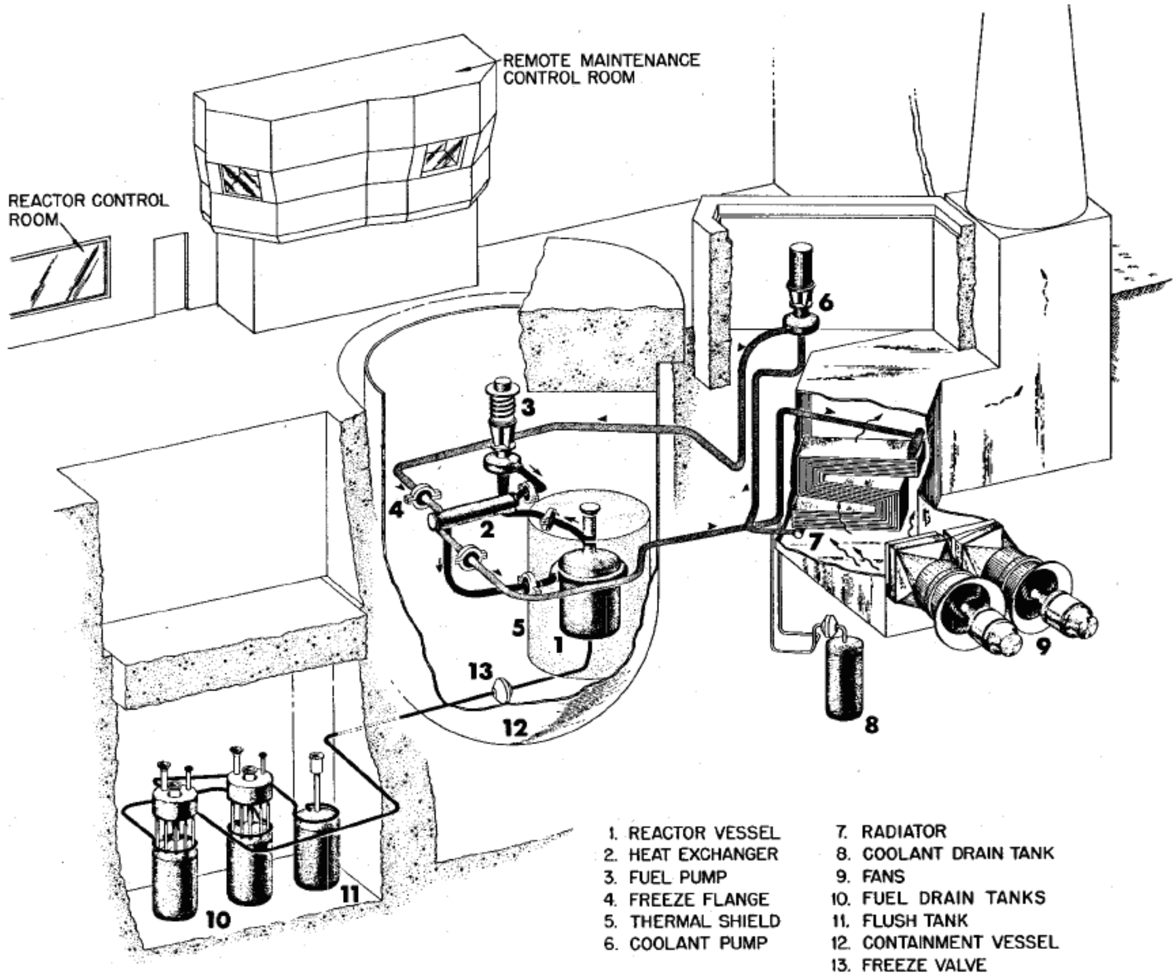
Appendix A: Thorium fuel cycle vs. uranium one



Source:http://www.coal2nuclear.com/Liquid%20Thorium%20Reactor.jpg

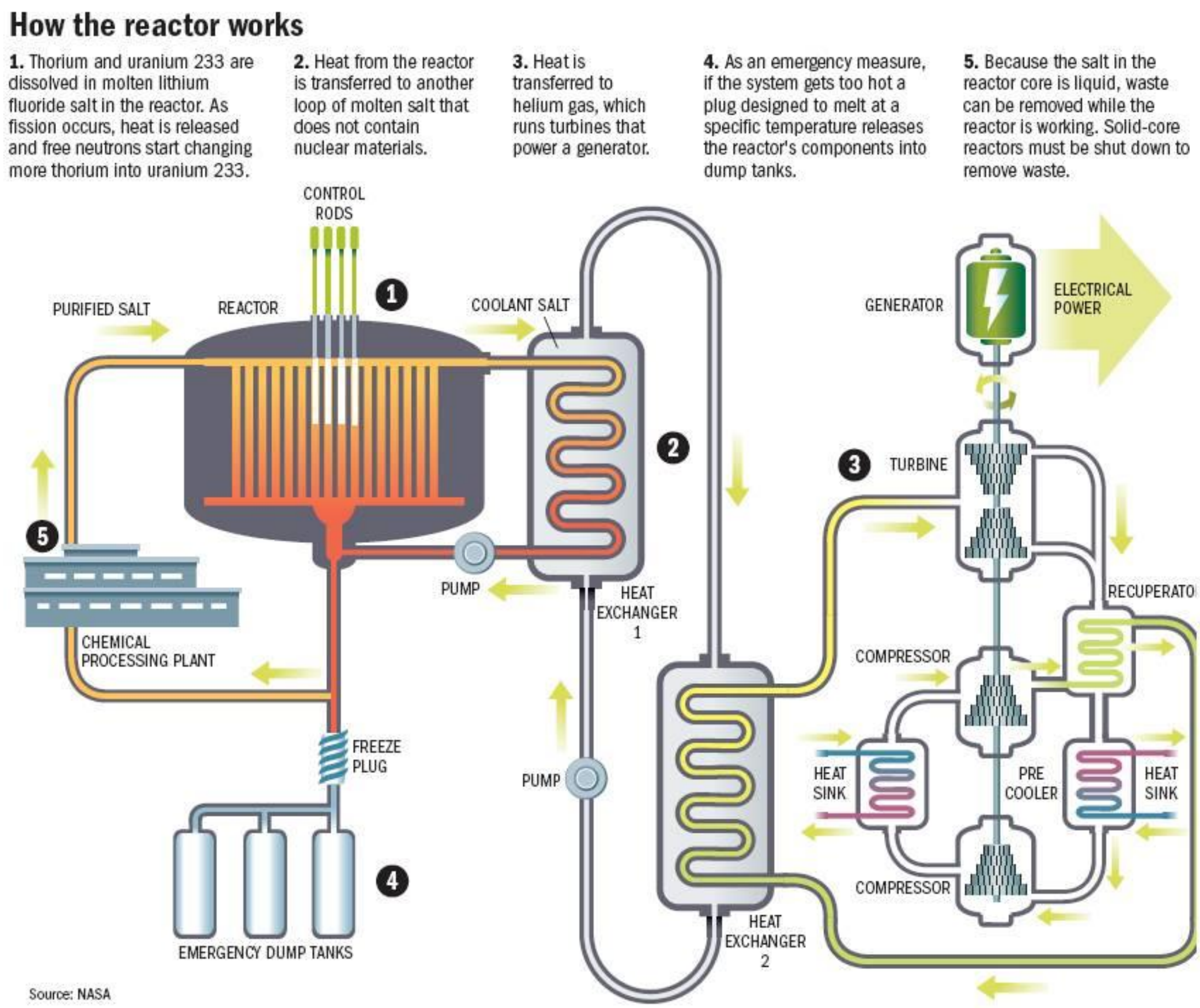
Based on the proposed 1 MW reactor, the values of the pictured 1 GW reactor should be divided by a factor of 1,000. Thus, 250 kg of uranium will produce 35 kg of enriched uranium and will account for 215 kg of depleted uranium and 35 kg of nuclear waste per year including 0.3 kg of plutonium. On the other hand, only 1 kg of thorium fuel is needed for the proposed MSR, which will make 1 kg of fission products by fully burning it and only 0.03 g of plutonium waste will be left as a result of burning it.

Appendix B: Molten salt reactor design layout



(Source: http://photos1.blogger.com/blogger/4956/2802/1600/MSRE%20building.gif)

Appendix C: Reactor operation



Source: http://www.dispatch.com/wwwexportcontent/sites/dispatch/science/stories/2010/03/07/reactor_large.jpg