Novel Small Modular Nuclear Reactors and Their Application Feasibility in Alaskan Cities

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Chapter 1. Introduction

Nuclear power, using the energy from nuclear reactions to generate heat and electricity, first made its appearance in the 1940's, and has been emerging as a major player in the world's energy market since then. Currently, there are over 440 commercial nuclear power reactors operable in 31 countries and providing over 11% of the world's electricity *(1)*. Nuclear energy has its popularity, as it has been thought as a continuous and reliable baseload power with no carbon dioxide or other greenhouse gas emissions, in another word, a "clean energy." It is also the most controversial energy source, with many arguments and concerns about its safety and social impacts. Current major nuclear power generating nations in the world include the United States, France, Russia, China and South Korea. Even though nuclear energy has been widely deployed, the forwardness of technology never ceased; innovative nuclear technologies are under development in many countries, some in cooperation with other nations. One of the newer technologies is in the development of small modular reactors (SMRs).

Small Modular Reactors defined by the International Atomic Energy Agency (IAEA) as reactors with a power rating lower than 300 MWe factory-built elements or modules designed for serial construction *(2)*. It is a term that has not been brought up for a long time, though it is becoming a spotlight in the field of nuclear energy with soaring public attention in recent decades. SMR, for the most part, is an unmatured technology, other than on naval ships *(2)*, that is still under development. This thesis will assess their projected efficacy in the 2030 timeframe (technical, environmental, social and economic). Further, their conceptual siting and use in two Alaskan cities, Fairbanks and Juneau, will be evaluated. These evaluations will be based on the anticipated best available (or soon to be available) fast SMR technology in 2030.

1.1 General Background of SMRs

Small reactors have been proposed for military uses for a long time, including the terrestrial application developed for remote military sites, as well as the propulsion system for warships, submarines, and spacecraft *(3)*. SMRs have several advantages over traditional large reactors including improved construction quality and efficiency, reduced costs, less critical reliance on active safety systems, higher safety with respect to natural and anthropogenic hazards, and less dependence on access to cooling water *(3)*. These advantages have encouraged several countries to develop new types of SMRs and to investigate the future commercial and civil use of this technology.

Advanced SMR designs include water-cooled reactors, high-temperature gas cooled reactors, as well as liquid-metal-cooled reactors with fast neutron spectrum *(2)*. High-temperature gas-cooled reactors (HTGRs) and liquid metal cooled reactors have an inherent safety benefit as higher temperature values can be tolerated without fuel damage, and thus this high-temperature heat can also be used for other industrial purposes *(4)*. Currently, there are more than 45 SMR designs under development internationally using a variety of technologies and for different applications *(2)*. In the U.S., however, issues like distinct concepts of operation, licensing process, legal and regulatory framework are still restraining the deployment of SMRs. As a result, most projected timelines for the deployment of SMR designs range from present to 2025-2030.

Fast neutron spectrum reactor (FNR) is also considered as a new potential technology for commercial SMR designs although the deployment schedule for this technology will lag that for the water-cooled reactors. Russia has had a commercial fast or breeder reactor in operation for some years and is completing the development of an 800 MWe FR at the same site *(4)*. Several countries have experimented with breeder reactors, including the U.S., France, Russia and Japan.

Fast neutron reactor differs from thermal (water-cooled) reactors in the possibility to achieve the breeding ratio, as they can convert fertile materials like Uranium-238 into fissile material like Plutonium-239 at a rate much faster than they consume the fissile material for fission reactions. Fast reactors allow fully exploiting the intrinsic energy potential of the fertile Uranium, which consists 99.3% of the natural Uranium resources on earth, by reprocessing the spent fuel and extracting the fissile materials which can be reused to produce fresh fuel. As a result, fast reactors can extract sixty-to-seventy times more energy from uranium than conventional thermal reactors do *(5)*. Fast reactors, burning more efficiently the long life transuranic wastes, can reduce the amount of highly radioactive wastes, the heat load to the geological disposal as well as the required isolation time for fission products.

Traditionally, fast reactors have been developed as breeders, meaning that they have high neutron economy and thus can generate more fissile material than it consumes. In recent years, the future deployment of this type of reactor has been encouraged as people are focusing on its sustainability and economic values. The major fast reactor options include the sodium-cooled fast reactor (SFR), the heavy liquid metal-cooled (HLMC) fast reactor, the gas-cooled fast reactor (GFR) and the molten salt fast reactor (MSFR) *(5)*. SFR features a fast-spectrum, sodium coolant, and a closed fuel cycle for efficient management of actinides and conversion of fertile uranium. The HLMC reactors have two possible coolant materials: pure lead and lead-bismuth eutectic. The lead-cooled fast reactor system features a fast-neutron-spectrum, lead or lead-bismuth eutectic liquid coolant, and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. GFRs feature a fast-neutron-spectrum, helium coolant and a closed fuel cycle. And finally, MSFRs use molten salt fluorides as fluid fuel and coolant, which has low pressure, high boiling temperature and optical transparency.

Until the year of 2017, there are only four countries in the world that have operating fast breeder nuclear reactors: China, Japan, India and Russia and only Russia has the only commercial reactors operating now *(6)*. Five other nations once owned fast neutron research reactors but decided to abandon them due to various reasons: USA, UK, France, Germany and Kazakhstan. The reasons include significant technical and materials problems, availability of the fuels that used as the input, the high cost of operating the reactors, the technological uncertainties, as well as the long time required to gain licenses from regulatory sectors.

For this thesis, although fast or breeder reactor development and NRC (Nuclear Regulatory Commission) acceptance is expected to lag behind light water reactor applications, this class of reactors will be considered for the application herein. The fast reactor has been chosen, mainly because of the refueling cycles, the production of considerably less toxic waste, and the availability of raw or waste fuel.

1.2 SMR in the USA

The United States is one of the earliest participants in the research, development and commercialization of civilian nuclear power. The US has more private sector participation in the production of civilian nuclear power than any other nation: today almost all the commercial reactors in the USA are owned by private companies. Nevertheless, the US government is still heavily involved in means of safety and environmental regulations, R&D funding, and setting national energy goals.

Development of clean, affordable nuclear power option is a primary element of the DOE-NE (Office of Nuclear Energy, Department of Energy) Nuclear Energy Research and Development Roadmap, and SMRs are an essential part of this strategy. In November 2015, DOE launched the Gateway for Accelerated Innovation in Nuclear (GAIN) initiative to accelerate innovation of advanced nuclear technologies. The SMR LTS (Licensing Technical Support) program promotes the accelerated deployment of SMRs by supporting certification, licensing and siting requirement for US based SMR projects *(2)*.

US DOE currently has a partnership with NuScale Power to enhance safety, opportunity and performance beyond designs now certified by the NRC. DOE has also awarded site permitting and licensing projects including a five-year Interagency Agreement with companies like TVA and B&W *(2)*.

Many factors are critical to the successful commercialization of SMR technologies, such as economic competitiveness, regulatory measures to reduce carbon emissions, market growth, etc. US DOE has two major interested areas: (1) manufacturing technologies to reduce cost and schedule for SMR parts and components and meet the demands of the industry as it grows; and (2) additional SMR capabilities beyond baseload electricity generation, including use of SMRs in hybrid energy systems and in meeting national security needs *(7)*.

In the US, licenses are issued by either NRC or in some case individual states with delegated authority. Federal regulations include the Title 10, Code of Federal Regulations (10 CFR) Part 50, 51 and 52. Utilities can license SMR designs using the 10 CFR Part 52 combined license (COL) or Early Site Permit (ESP) processes *(8)*. Designs that are applying for the license right now are NuScale of NuScale Power, LLC; BWXT mPower of BWXT mPower, Inc; SMR-160 or SMR Inventec, LLC; and Clinch River Site of TVA *(9)*. In January 2016, several developers and potential customers of SMRs, including BWX Technologies Inc, Duke Energy, Holtec, NuScale, SCANA, and VTA, signed a memorandum of understanding to set up the SMR Start consortium to advance the commercialization of SMR reactor designs *(10)*.

There are currently four integral pressurized water SMRs under development in the USA: mPower (B&W Generation mPower), NuScale (NuScale Power Inc.), Westinghouse SMR (Westinghouse Electric Company LLC), and SMR-160 (Holtec International). There are also two high-temperature-gas-cooled SMR designs under development in the US: SC-HTGR (AREVA) and Xe-100 (X-energy).

On the FNR side, through to 1985, the US DOE spent about 16 billion US dollars on sodium-cooled fast reactors, a significant proportion of its R&D budget *(6)*. In 1984, US DOE built the first prototype of the Integral Fast Reactor (IFR) -- the Experimental Breeder Reactor II (EBR-II), which was considered by the National Academy of Sciences to be the nation's highest priority research for future reactor types. Currently, USA has two sodium-cooled reactors, one heavy-liquid-metal-cooled fast reactor, and one gas-cooled fast reactor under development: PRISM (GE-Hitachi), TWR-P (TerraPower), G4M (Gen4 Energy Inc.), and EM^2 (General Atomics).

Chapter 2. Past Studies on SMR Feasibilities

Since the beginning of the SMR concepts, there have been plenty of studies and comments on the benefits and drawbacks of this new technology.

In general, it is believed that SMRs could be an appropriate option for dealing with the increasing energy demand in many parts of the world. SMRs could be beneficial in providing electricity to remote regions which are deficient in transmission and distribution infrastructures. They are ideal to be applied in countries with small, limited, or distributed power grid system as well as countries with limited financial resources for investment in large nuclear plants. Besides generating electricity, they can also be used to produce heat for industrial complexes, water desalination, and district heating. The modular concept indicates the potential of fabricating and assembling the reactors in factories and the reduced amount of work on-site, making it simpler and faster to construct. Besides, advantages including the long-life cycle and reduced need for refueling, the design simplicity, the passive safety, expanded potential siting options, low operation and maintenance costs, and proliferation resistance, all make SMR a good option for future energy structure *(4)*. However, several foibles may hinder the large-scale application of SMRs. First, the economics of SMRs needs more analysis to show advantages over large LWRs. Secondly, the transport of spent nuclear fuel from SMRs in remote regions might be more difficult and might cause potential spread. Thirdly, it might be hard for public to accept new concepts. And finally, the process of licensing may be longer than expected.

Several studies around the world have assessed the feasibility of SMRs, and most of them unanimously believe that there will be a bright future for this novel technology.

It is estimated that the world demand for electricity is likely almost to double over 25 years. In order to cope with the rising demand while also decelerating or even preventing the global warming, a revolution to the nowaday fossil-fuel-based energy structure is imperative. The share of renewable energies like solar and wind will be expanded, but unlike nuclear, the renewable technologies are not yet mature enough and are unable to be applied as the base load source. The nuclear industry today provides about 11% of the world's electricity. Large nuclear reactors are capable of fulfilling much of the future demand but face significant financing and infrastructure challenges; as a result, SMRs could provide a viable alternative, especially for regions or countries that are not suitable for large reactors. This SMRs feasibility study done for the UK government predicts that by the year of 2035, there will be a market potential of 65-85 GW globally for SMRs, with large markets in the USA, China, Russia and potentially the UK, if the technology can be made cost-competitive in comparison to large nuclear plants *(11)*, while district heating and desalination presenting even more additional opportunities for SMR technology. Another study has been conducted for the Ontario Ministry of Energy in Canada to assess the feasibility of SMR deployment for remote mines *(12)*. The study finds that the SMR designs are expected to be economically competitive against the incumbent diesel energy source, and will be a reliable electricity source for mining operations with a large amount of greenhouse gas production removed. Nonetheless, the feasibility of SMR application depends on other local factors, for example, the grid size, the availability of other clean energy, the public opinion, the policy supportiveness, the ability of properly disposing of the nuclear waste, and the security and stability of the reactor site.

Economic feasibility is a major factor that controls the commercialization of SMRs, and many different studies have analyzed the economic values of SMRs. SMRs exploit an "economy of multiples," strategy while the larger nuclear reactors stand for an "economy of scale" strategy *(13)*. However, the principles of economics point out that, in a capital-intensive business like nuclear power generation, an economy of scale is naturally more competitive than an economy of multiple. Studies have found that SMRs and larger reactors are of the same order in terms of cost effectiveness and investment profitability: the strategy of building multiple SMR units on the same site can reduce the marginal cost; modularized and simple designs can help reducing cost of each single SMR unit and meeting an acceptable investment return (13). Additionally, studies have also found that SMR has better behaviors when facing higher capital costs, construction delays and other unfavorable scenario conditions (13).

Another factor that has major impacts on the application and commercialization of SMRs is the security or safety concerns. For a long time, the development and wide application have been shadowed and hampered by the public fears. SMR designers have been advocating that SMRs would be safer than current designs due to the use of the passive cooling system, their smaller and less robust containment system, their underground siting, and so on. The passive safety system is a safety that does not require operator actions or electronic feedback to shut safely in the emergency, and may include systems like residual heat removal system, accumulator, condensation heat exchanger, suppression pools and safety injection system *(14)*. Many studies analyze the effectiveness and reliability of the passive safety system of different SMR designs and conclude that in some cases, a single passive safety system is not enough, and a diverse mechanism is required. Also, some studies believe that designs should include a reliable active backup cooling system in order to provide a full guarantee of security. There are also concerns about the proliferation issues related to SMRs.

Many feasibility studies have also been done in the United States. In April 2009, President Obama issued a call to harness nuclear energy as one way "to combat climate change, and to advance peace and opportunity for all people" *(15)*. A study done by the CNA Military Advisory Board in 2011 for the US DoD found that, as long as the "first of a kind" (FOAK) expenses were excluded, the benefits and the anticipated future developments of SMRs could make this technology be employed for military use, where FOAK costs refer to the costs required to obtain design certification and a combined construction and operation license from the NRC *(16)*.

As most studies have mentioned, licensing would be a major time-consuming process in the commercialization of SMRs in the United States. NRC, based on the regulatory policies that ensure adequate protection of public health and safety, the common defense and security and the environment, authorizes applicants to conduct activities including designing, siting, construction, installation and operation. Major licenses for nuclear reactors include design certification (DC), early site permit (ESP), limited work authorization (LWA) and combined construction and operating license (COL) *(17)*. However, it has been pointed out by many scholars that current standards for reactor licensing are primarily based on the experience with large light-water reactors (LWR) over the past 50 years, and might not be suited to SMR designs *(9)*. The NRC staff, the American Nuclear Society (ANS), the Nuclear Energy Institute (NEI), and others have been analyzing the current licensing structure for large LWRs. The ANS has identified several licensing issues related to SMRs including emergency planning zone (EPZ), operations and staffing and physical security *(18)*. A report of NRC in 2012 also indicated that more studies were needed in order to make the licensing process of SMRs more efficient and to promote the development of advanced reactors. NRC believes that the issues in licensing were expected to be solved by 2020 *(9)*.

Chapter 3. Study Sites and Time

3.1 Study Areas

3.11 Alaska Background

Alaska is the largest state by area and the northernmost state in the United States. Among all the 50 states, it is the only one with territory north of the Arctic Circle, and it has the highest mountains and longest coastline; on the other hand, it has the fourth-smallest population and is the least densely populated state *(19)*.

Energy supply in Alaska mostly relies on fossil fuels: natural gas accounts for about half of Alaska's utility-scale electricity generation; petroleum liquids and coal each account for about one-eighth of Alaska's net electricity generation. Hydroelectric power is another primary source of energy, from which 22% (2012) of total electricity in Alaska is generated. Wind and biomass together also have a share of less than 1% (2012) *(20)*. Many rural communities in Alaska rely primarily on diesel electric generators for power, and in 2015, Alaska ranked second only to Hawaii among all the states in the share of its electricity that is generated from petroleum liquids *(19)*. Alaska was also one of the earliest states that started generating electricity from geothermal energy.

Alaska's reliance on fossil fuel energy is a result of its abundant reserves and large productions of petroleum and natural gas. Alaska, owning some of the biggest oil fields and natural gas fields in the United States, ranks fourth in the production of crude oil and third in the natural gas gross withdraws among all 50 states in the US *(19)*. Alaska's coal resource is estimated to be larger than the combined resources of the lower 48 states, yet the production of coal is comparably small *(20)*; thus, coal is not used as a principal source of electricity comparing to oil and natural gas. Because of the small population, Alaska has a low total energy demand, and a large portion of the production of either crude oil, natural gas or coal is exported. The oil and natural gas industry is a key part of Alaska's economy. The extensive use of diesel electricity generators also contributed to the high consumption of petroleum liquid, as many small and remote communities largely or even entirely rely on diesel *(20)*.

Alaska, due to its unique geographical characteristics and energy structure, has been tangled with several dilemmas. First of all, the average electricity price in the state has been notoriously high: its electricity price ranks second highest in the nation *(21)*. Alaska, since not connected to any large, interconnected grids through transmission and distribution lines, has its small and local electricity utilities, which only serve a small region. Thus, many remote areas have no access to electricity and people have to import diesel fuel to generate electricity by themselves with diesel generators. The cost of importing the fuel adds significantly to the cost of electricity and space heat. According to a report in 2015, most remote locations in Alaska paid at least twice the national average for electricity; rates in some area even reached ten times *(22)*. In more populated areas, there are now electrical interties linking regional utilities such as the Railbelt grid, which connects the vast areas from the Kenai Peninsula all the way to Fairbanks and gives those communities access to electricity from natural gas. However, the constraints on natural gas supplies, generation, and intertie capacity still limit the amount of lower-priced electricity.

Meanwhile, many studies have demonstrated concerns about the effects of Alaska's fossil-fuel-based energy structure in the perspective of global warming. Though in comparison with other states, Alaska is never regarded as a large carbon producer. In the year of 2014, Alaska ranked 12th lowest in carbon dioxide emissions among the states, emitting 35 million metric tons of carbon dioxide *(23)*. However, the consequence of carbon emission must not be underestimated in the case of Alaska, which, with its unique geography and ecosystem, can be particularly sensitive and vulnerable to global warming. In recent years, Alaska has experienced warmer temperatures for longer periods of time during the year *(19)*; over the past 60 years, the average temperature across Alaska has increased by approximately 3 degrees Fahrenheit *(24)*. This increase is more than twice the warming seen in the rest of the United States. It is catastrophic to those world-famous glaciers in Alaska, which are currently measured to have average retreat near 66 ft (20 m) per year, and the speed of thinning and retreating will be accelerated with the warming *(25)*. Meanwhile, the permafrost, which lies underneath of more than eighty percent of Alaska's land, will also be melting as a consequence of the warming *(26)*. It is disastrous since this melting process will cause the soil above to sink, thus damaging the houses, roads and other structures. Considering all the impacts of warming, it is imperative to shift Alaska's energy structure to a less carbon-based structure, where nuclear would be one of the optimal candidates.

3.12 Fairbanks

Fairbanks is located in the central Tanana Valley in interior Alaska and is only 120 miles south of the Arctic Circle. With a population of 32,469 (2014), it is the largest city in the interior region of Alaska *(27)*. Its city area is 32.7 square miles.

Electricity in Fairbanks is provided by the Golden Valley Electric Association (GVEA). It owns seven generating facilities, as shown in Figure 1, including five fossil-fuel power plants, one hydropower project and one wind power project. It also purchases power from 3 other utilities, including a coal-fired plant, a natural-gas plant and another wind project. 32% of its electricity is from oil, 29% from coal, 27% from natural gas, and 12% from wind and hydro *(28) (29)*. Other utilities also provide electricity for Fairbanks, and diesel, naphtha and coal are the main sources. Fairbanks is the northernmost end of the Railbelt region that formed by the Railbelt electric grid. In the year of 2010, it was estimated that the annual residential use of electricity for Fairbanks was 8,121 kWh per person, ranking the third highest in Alaska *(20)*.

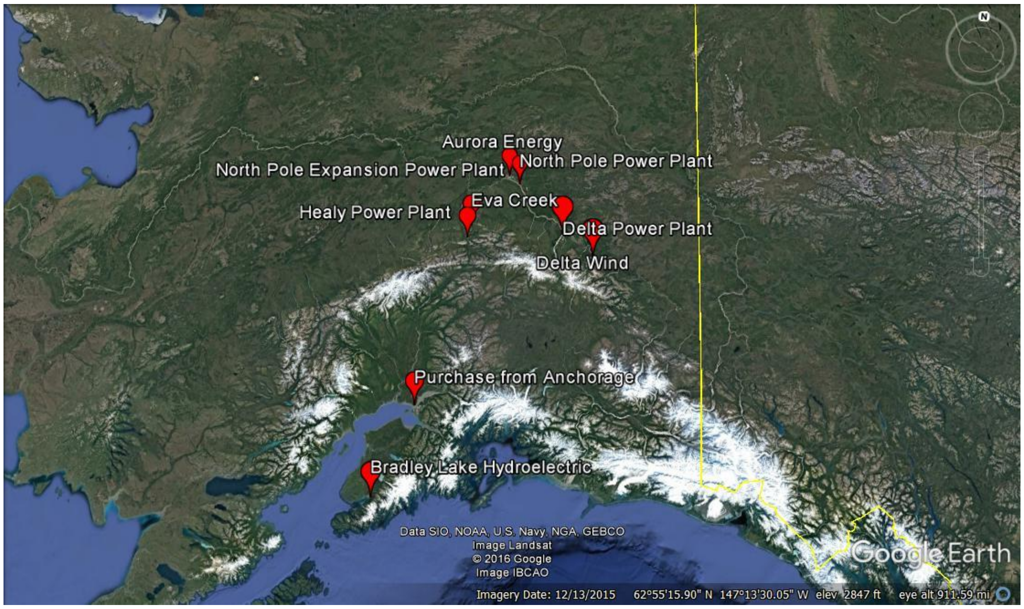


Figure 1. *Map of the generating facilities and power sources of GVEA. Aurora Energy site is in downtown Fairbanks.*

As shown in Figure 2, Fairbanks area is composed of downtown Fairbanks and satellite towns in the Fairbanks North Star Borough including College (where the University of Alaska Fairbanks is located), the airport region, Ester, Chena, Fort Wainwright, and the Northeastern part of North Pole. This study will focus on the populated areas close or inside of the downtown Fairbanks. And because the university, the army post and the airport all have their independent grid and power source, this two communities will also be excluded.

Figure 2. *Map of downtown Fairbanks region. The red-circled region is approximately the downtown Fairbanks.*

Fairbanks, commonly known as America's coldest city *(30)*, has a subarctic climate with long, very cold winters and short, warm summers. Winter generally lasts from late September to early May, where October through January is normally the snowiest. The snowpack is established during October, on average, and remains until the end of April. The average winter low temperatures range from -15 to -25 °F, buy extremes can range from -60 to -75 °F. The long-lasting severe winter makes heating critical to the residents and gives Fairbanks a unique energy consumption structure where heating will be a large component of the gross energy.

3.13 Juneau

Juneau is the capital city of Alaska. With a total area of 3,255 square miles covering land and water, Juneau is the second largest city in the United States by area. It hosts a population of about 31,275 people, according to the 2010 Census, and is projected to have a population of 32,756 in 2015 *(31)*. Juneau is unusual among US capitals in that it is isolated as it is surrounded by water and no roads are connecting the city to the rest of Alaska or the rest of North America. Ships and airplanes are the only methods of transportation for both people and cargo to and from Juneau. The downtown of Juneau is nestled at the base of Mount Juneau, which is the home of the Juneau Icefield, a large ice mass from which about 30 glaciers flow. As the capital of Alaska, the primary employer in Juneau is the state, federal and municipal governments, and the University of Alaska Southeast. Besides the government, another larger contributor to the local economy is tourism, especially the cruise ship industry, which generates most of its income in the summer months. In 2005, the cruises were estimated to bring nearly one million visitors to Juneau for up to 11 hours at a time, between the months of May and September, claimed by cruise industry officials *(32)*. So, there is a large daily fluctuation on the population in Juneau. The fishing industry is also a major part of the economy, as Juneau was recently ranked as the 49th most lucrative fisheries port in the US by volume, and the 45th by value.

Unlike the subarctic Fairbanks, Juneau is in a transition zone between a continental climate and an oceanic climate. It is milder in winter than most of the places in the same latitude and than Alaskan average due to the influence of the Pacific Ocean.

Juneau is also isolated regarding energy, as the city is not connected to any large power grid, and all the electricity consumed in this city must be generated locally. There is only one power utility in this city -- Alaska Electric Light & Power (AEL&P). Over 98% of the electricity comes from renewable hydro generation, most of which is from the Snettisham hydroelectric facility, a 78,210-kW power plant located 28 miles south of central Juneau *(33)*. It is also accessible only by boat or seaplane. The rest of the hydropower is generated at the Lake Dorothy, Annex Creek, Salmon Creek and Gold Creek Hydroelectric Projects. The city of Juneau, a major residential, political and tourist center in Alaska, suffers from frequent power outages. One example in April 2008, an avalanche destroyed three transmission towers, causing a large-scale outage and a soaring electricity price *(34)*.

Figure 3. *Map of the generating facilities and transmission lines of AEL&P for Juneau (33).*

Juneau differs from Fairbanks on the energy demand side primarily because of its tourism and fishery oriented consumption, and its large fluctuation in energy demand caused by daily population shifts. On the supply side, Juneau is isolated from any outside energy source; thus, locally produced hydropower becomes the main source.

3.2 Time Span

The time span of this study is decided to be between the years of 2025 and 2030. This particular time span is chosen as a result of following considerations. Firstly, although currently there are a variety of SMR designs, most of them still need time to finalize their designing phase and entering the certification and licensing stage. And the licensing progress is already tedious, not to mention the considerable uncertainties and possible difficulties involved. As a result, it is believed that most of the current mature and detailed designs will have their deployment around the year of 2025. On the other hand, the conceptual designs that have not yet started their detailed designing phases, are estimated to be able for deployment after 2030 or 2035. And it is difficult to discuss these designs and to examine their application feasibilities at this moment.

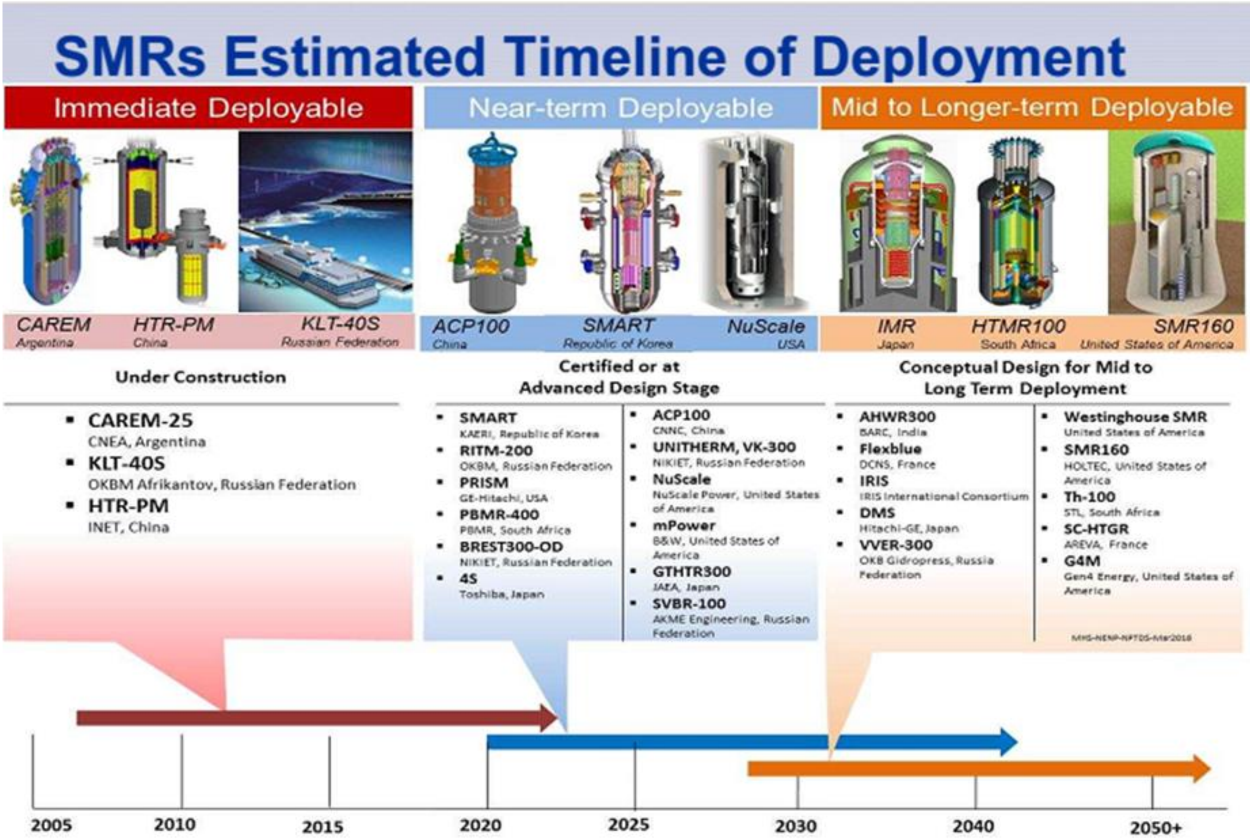


Figure 4. *Estimated timeline of development by IAEA (35).*

As the time of this study is selected to be between 2025 and 2030, it is also assumed that at this period all considered models will have completed their licensing process and are able to start construction or operation. Therefore, the varying difficulties and uncertainties of the licensing process will not be a considering factor in the analysis and model choosing in this study. Furthermore, the induced economic and time costs will also be neglected.

Chapter 4. SMR Designs

Both light water reactors and other advanced gas or liquid-metal cooled fast reactors will be considered in this study. Reactors must be SMRs and have anticipated deployment time before or around the year of 2025 in order to be considered. All the reactors considered are listed below.

Most of the detailed information for all designs are retrieved from IAEA *(36) (37) (38)*.

Name	mPower	NuScale	Westinghouse SMR	SMR-160
Developer	Generation mPower, LLC.	NuScale Power, LLC	Westinghouse Electric Company, LLC	Holtec International
Electrical Capacity (MWe)	195	50 (gross)	>225	160
Thermal Capacity (MWth)	575	160	800	525
Design Life (years)	60	60	60	80
Coolant	Light water	Light water	Light water	Light water
Fuel Type	UO2 pallet	UO2 pallet	UO2 pallet	UO2 pallet
Fuel Cycle (months)	24	24	24	24
Refueling Outage (days)	<25	10	17	10
Fuel Enrichment (%)	<5.0	<4.95	<5.0	<4.95
Seismic Design	Target 85% of contiguous US	0.5 peak ground acceleration	Based on CEUS sites	Robust
Plant Footprint (m^2)	160,000	130,000	65,000	20,500
Module per Plant	2	1-12	1	1
Number of Safety Trains	2	2	Three diverse decay heat removal method	2
Safety Features	Passive	Passive	Passive	Passive

Table 1. *Integral PWR of SMRs.*

Name	SC-HTGR	Xe-100	PRISM	G4M	EM^2	TWR-P
Developer	AREVA	X-energy LLC	GE-Hitachi	Gen4 Energy	General Atomics	TerraPower

				Inc		
Electrical Capacity (MWe)	272	35	311	25	265	600 Also support for low power (~300)
Thermal Capacity (MWth)	625	100	840	70	500	1475
Design Life (years)	60	40		5-15	60	40
Reactor Type	Prismatic block HTGR	Modular HTGR	Liquid metal cooled fast breeder reactor	Liquid metal cooled fast reactor	Modular high temperature gas-cooled fast Reactor	Pool-type, sodium-cooled fast reactor
Coolant/ Moderator (if applicable)	Helium/ Graphite	Helium/ Graphite	Sodium	Lead-bismuth	Helium	Sodium
Fuel Type	UCO TRISO Particle fuel in hexagonal graphite blocks	Pebbles	U-Pu-Zr	Uranium nitride	UC pellet	U-10%Zr fuel slugs with HT-9 ferritic-martensitic stainless steel clad
Fuel Cycle (months)	Half of the core replaced every 18 months	On-line refueling	18	120	360	18-24
Refueling Outage (days)	21				14	7-14 for "fuel shuffling"
Fuel Enrichment (%)	<20	10.61	26% Pu, 10% Zr	19.75	14.5	<20
Seismic Design		0.15g operating limit & 0.3 safety shutdown	Built on seismic isolators		seismic isolator platform	
Plant Footprint		100,000			90,000 (4	

(m^2)		or 160,000			modules)	
Module per Plant	Variable	2-8	2	1	4	
Number of Safety Trains				2		
Safety Features	Passive	Hybrid	Passive	Hybrid	Hybrid	Passive

Table 2. *Other types of SMRs. Cells are blank if no reference data available.*

4.1 PWR Design Details

4.11 mPower

Figure 5. *Reactor System Configuration of mPower (36).*

The mPower SMR is an integral PWR designed by Babcock & Wilcox mPower Inc. (B&W Generation mPower). In its standard plant design, each power plant is comprised of a "twin-pack" set, where two units together generate a nominal capacity of 390 MWe *(36)*.

The inherent safety features of the design include a low core linear heat rate, a large reactor coolant system volume, and small penetrations at high elevations. There is also an emergency core cooling system that can remove heat from the core and reduce containment pressure and temperature passively. In events like earthquakes, the deeply embedded mPower reactor and other connecting systems can dissipate energy and reduce motion, and are designed to be able to tolerate 85% of the earthquakes happened in the contiguous United States *(36)*.

The design adopts a digital instrumentation and control system (I&C) *(36)*, so it has a high level of plant automation, including control of startup, shutdown and loading.

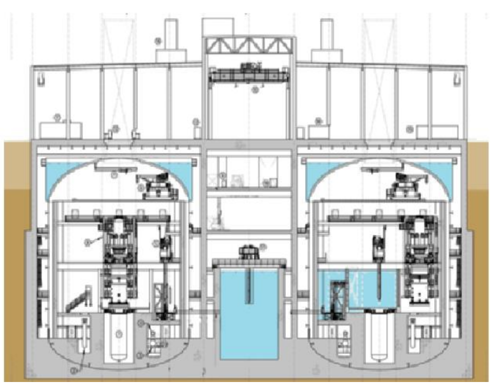
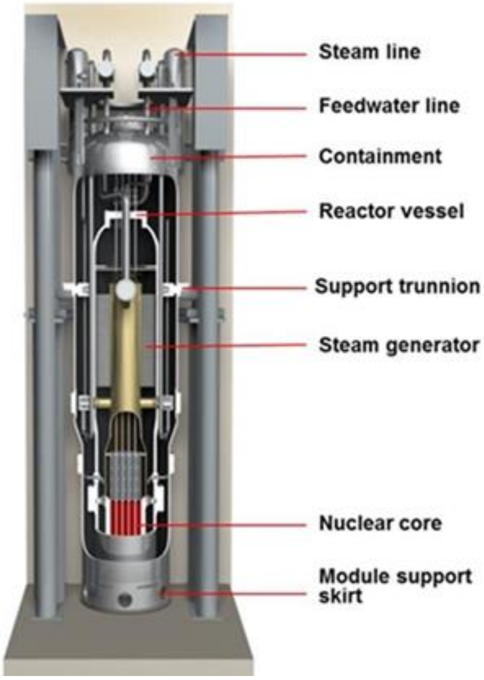


Figure 6. *The underground design of the mPower plant including the reactor, containment vessel and spent fuel storage pool (36).*

4.12 NuScale

Figure 7. *Nuclear reactor core, steam supply system and containment vessel of NuScale (39).*



NuScale is a small, light water cooled PWR designed by the NuScale Power Inc. A NuScale plant is designed to have a configuration of 12 modules together producing a maximum of 600 MWe power, with each module operating independently. All modules are managed from a single control room.

The design has a closed-loop decay heat removal system (DHRS) which ensures that the decay heat can be safely removed in a loss of coolant accident (LOCA). By conducting the heat to the water in the reactor pool, the module can remove the heat in an accident where off-site power is lost. Water inventory in the reactor pool is large enough to cool the modules for an unlimited time without adding water *(36)*.

Since each module works completely independently of other modules, during the process of refueling, a module is disconnected from its operations and moved to a common refueling area within the shared reactor pool. Other modules in the plant continue to operate while this single module is being refueled.

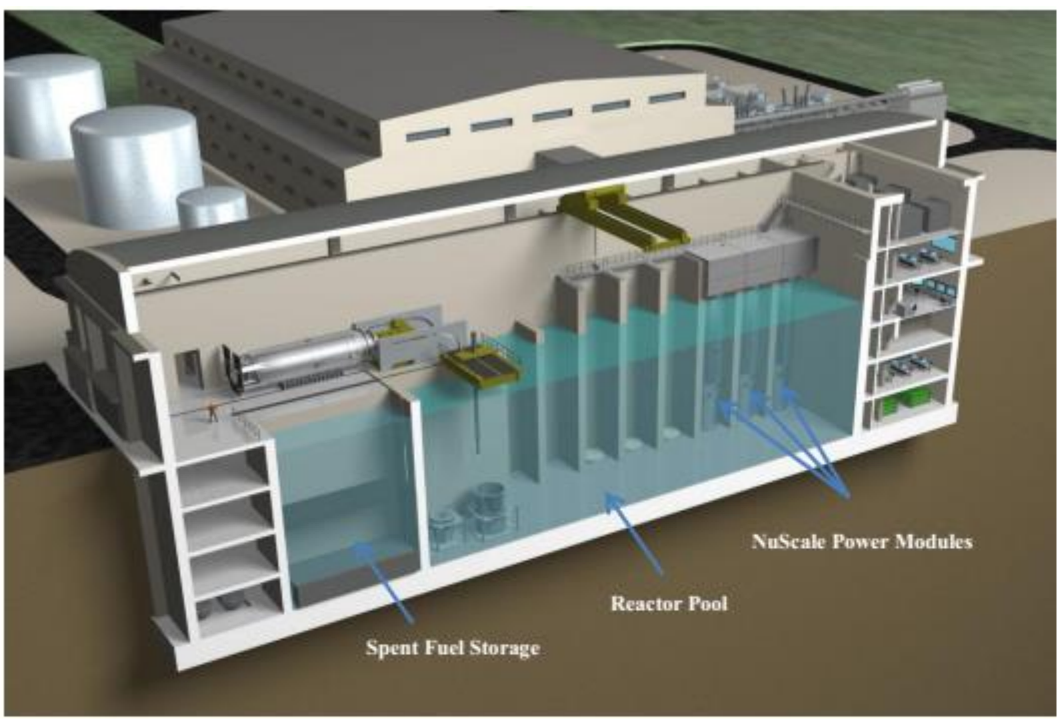


Figure 8. *Cut-away view of NuScale power plant (36).*

4.13 Westinghouse SMR

Figure 9. *Reactor system configuration of Westinghouse SMR (36).*

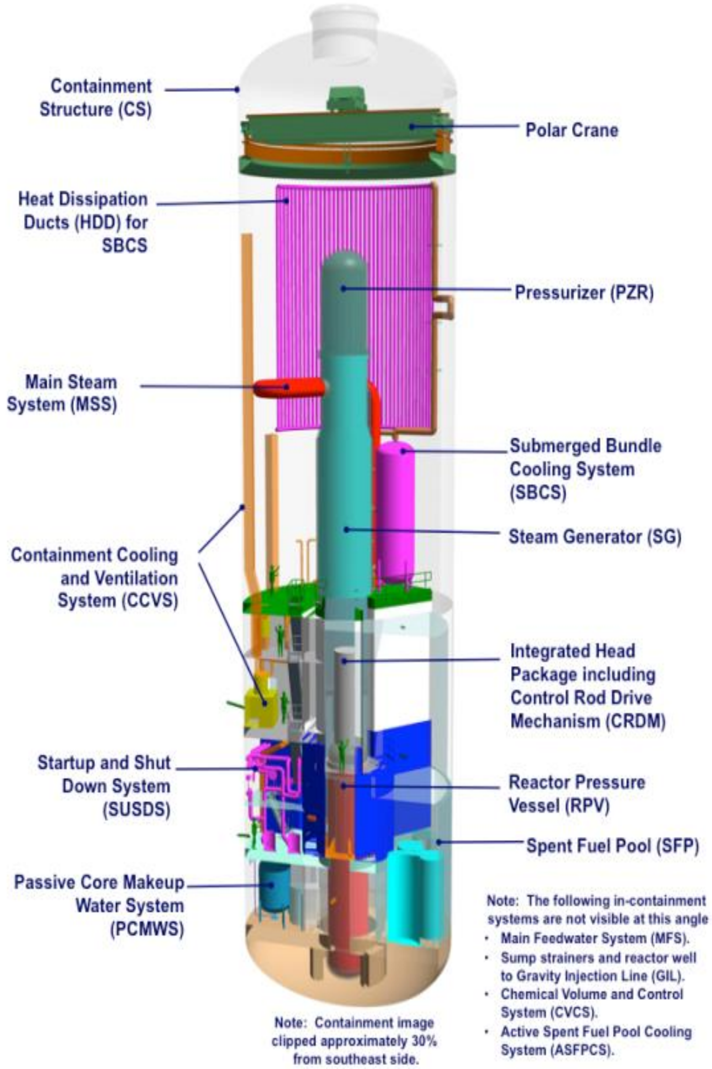
Designed by the Westinghouse Electric Company, LLC, the Westinghouse SMR delivers a net electrical output of greater than 225 MWe as a standalone unit and is completely self-contained on a compact plant site.

The plant is an advanced passive plant where the safety systems are designed to mitigate accidents through the use of natural driving forces such as gravity flow and natural circulation flow. It does not need offsite electricity to perform its safety functions and have a 7-day minimum coping time following the loss of offsite power *(36)*. The below grade locations of the reactor vessel, containment vessel, and spent fuel pool provide protection against external threats and natural phenomena hazards; a series of decay heat removal methods provides the reactor a safety guarantee over the unexpected circumstances.

Figure 10. *The below-grade reactor and containment vessel of Westinghouse SMR, and the conceptual plant layout (36).*

4.14 SMR-160

Figure 11. *Components inside the containment structure of SMR-160 (36).*



The SMR-160 conceptual design is developed by Holtec International as an advanced, above ground, PWR-type SMR with an electric capacity of 160 MWe. Its safety basis incorporates defense-in-depth via multiple and diverse, simple pathways for heat rejection from the core. All safety system are within the containment structure, so they are safe from external threats. A large inventory of water within a reservoir outside the containment structure provides long-term post-accident coping, facilitating air cooling for decay heat removal for an unlimited coping period.SMR-160 has an integrated containment system consisted of a free-standing steel containment structure supported within a reinforced concrete reactor containment enclosure structure, which also provides the missile protection.

In the event of abnormal transients or postulated accidents, SMR-160 will employ non-safety active cooling systems as the first line of defense. Failure of the active systems will actuate the passive safety systems, and the plant will shut down and remain safely cooled for an unlimited period without the need for power, make-up water or operator actions.

4.2 HTGR (thermal) Design Details

4.21 SC-HTGR

Steam Cycle High Temperature Gas-Cooled Reactor (SC-HTGR) by AREVA is a helium-cooled and graphite-moderated high-temperature SMR with a nominal thermal power of 625 MWth and electric power of 272 MWe. Its steam cycle-based concept is extremely flexible for serving a wide variety of near-term markets and is well suited to cogeneration of electricity and process heat. The design uses the high-temperature capabilities of TRISO-coated (tristructural-isotropic) fuel particles as fuel, which have ceramic coating system surrounding the fuel kernel to withstand extremely high temperatures without losing its ability to retain radionuclides even under accident conditions *(36)*. The high heat capacity and low power density of the core results in very slow and predictable temperature transients even without cooling. The coolant, helium, is chemically inert so it will not change phase during normal operation or accidents. Even without the presence of the primary coolant, the reactor can passively remove decay heat from the core with natural circulation cooling provided by the concrete walls around the reactor vessel, during both normal operation and accidents. No powered safety-related systems and no operator actions are required to respond to any of the accident scenarios.

Because this design is highly flexible, although a typical SC-HTGR plant might have four reactor modules, the specific number of modules in an actual plant will depend on the application itself and the customer’s needs.

One of the major distinctive features of the SC-HTGR design is the prismatic block reactor, which is a 102 column annular core. This geometry provides good radial heat conduction to maximize the benefits of passive decay heat removal.

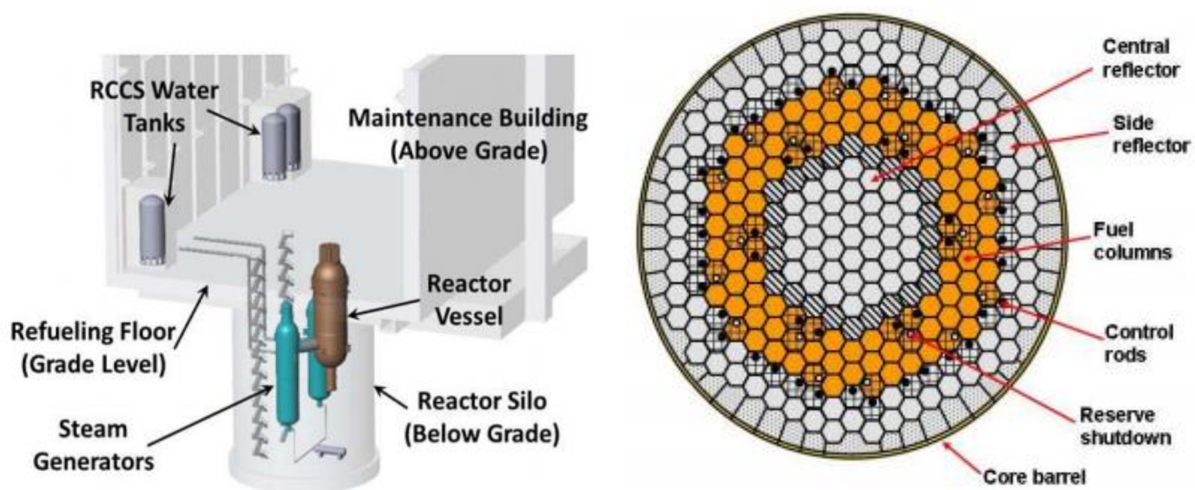


Figure 13. *Core configuration of SC-HTGR (36).*

4.22 Xe-100

The Xe-100 is a small-sized pebble bed high temperature gas-cooled reactor with an electrical capacity of 35 MWe designed by X-energy, LLC. It has a relatively large average burnup of 80,000 MWd/tHM, causing the bred fissile Pu to be utilized in-situ by about 90% and leading to well depleted spent fuel *(36)*. Each Xe-100 plant can consist at most of 8 modules, producing a 280 MWe electrical power. This design uses a lowly enriched fuel cycle with TRISO coatings embedding UCO fuel kernels.

The intrinsic safety characteristic of the plant is guaranteed by a relatively low power density but the high thermal inertia of the graphitic internal layout, and a strong negative temperature coefficient of reactivity over the entire operational regime of the reactor *(36)*. The unique system of independent fission product barriers, and the partially below ground layout, provide an enhancement of safety. The fact that the maximum fuel temperatures will remain below proven safety performance limits of TRISO fuel means that no core melt will be physically possible and no significant core damage is possible.

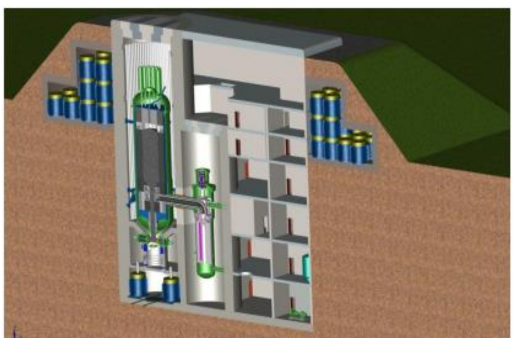


Figure 15. *Below-grade design of Xe-100 reactor (36).*

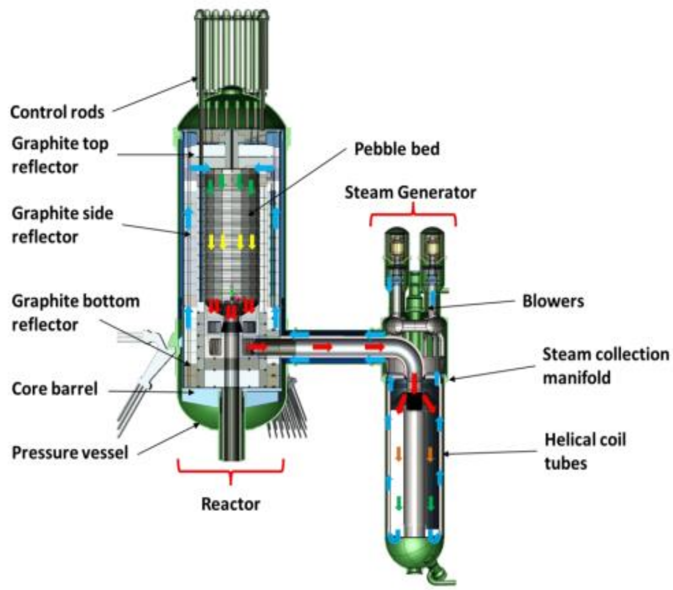


Figure 14. *Reactor system configuration of Xe-100 (36).*

4.3 FNR Design Details

4.31 PRISM

Figure 16. *Structure of the reactor core of PRISM (41).*

Designed by the GE-Hitachi, PRISM is a pool type, liquid-sodium cooled SMR with a nominal electrical capacity of 311 MWe and a thermal output of 840 MWth. It utilizes metallic alloy fuel comprised of uranium, plutonium and zirconium in the reactor core, which consists of 198 fuel assemblies, 114 reflector assemblies, 66 radial shield assemblies, 10 control and 3 shutdown assemblies *(38)*. As it uses long-lived isotopes as fuel and leaves short-lived isotopes for disposal, it is considered an alternative solution to long-term storage of nuclear waste. A PRISM plant design also comprises an Advanced Recycling Center (ARC) next to the reactors to reprocess, recycle and dispose of the used fuels *(40)*.

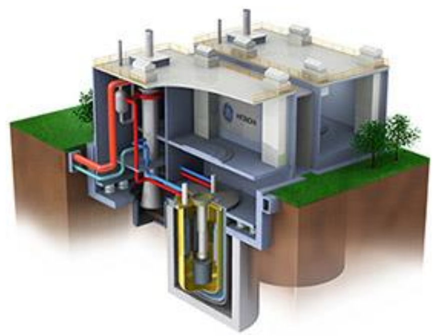


Figure 17. *Conceptual underground location of PRISM reactor (38).*

The primary heat transport system is contained entirely within the reactor vessel, and the pool-typed design prevents a LOCA. The design employs passive shutdown features that comprise several reactivity feedback properties. The passive Reactor Vessel Auxiliary Cooling System (RVACS) provides primary cooling during all design basis accident conditions and Anticipated Transients without Scram (ATWS), and can operate effectively without electricity or operator intervention for an unlimited amount of time *(38)*. The Auxiliary Cooling System (ACS) in the reactor can remove the excessive decay heat by natural circulation of air.

Figure 18. *A conceptual PRISM plant including both reactors and the ARC (40).*

4.32 G4M

The G4M, designed by Gen4 Energy Inc, is a portable, self-contained lead-bismuth cooled fast neutron spectrum SMR with a capacity of 25 MWe and 70 MWth. The long fuel cycle of 10 years without on-site refueling is a major attractiveness of this design. The reactor is intended to be sealed at the factory, sited underground and eventually returned to the factory for fuel recycling and refueling after ten years *(36)*. This design is strategically best suited for remote locations or harsh climate environments.

The design adopts uranium nitride pellets with 19.75% enrichment as fuel in the reactor core. The reactor, with core coolant lead-bismuth eutectic (LBE), has a mean exit temperature of 500 °C, limiting the cladding temperature thus making the maximum cladding creep over 10-year lifetime less than 1% *(36)*. The unique traits of the coolant chemical LBE, including its high boiling temperature, its near-atmospheric pressure, and its inability to react with air, water, fuel and metal, prevent potential radioactivity release due to vaporization, releasing of pressure or exothermic reactions of the coolant in a worst-case accident.

The design uses several passive safety features to guarantee the reliability of the reactor. For instance, during an operational shutdown, the natural circulation of LBE, the coolant, through a fixed bypass path in the core to bring the decay heat to the surface of the module, where the passive vaporization of water on the exterior of the module will effectively remove the heat. The backup decay heat removal system can provide cooling for up to 14 days without any power or operator action *(36)*. On the other hand, the underground siting of the containment vault provides isolation from the environment and avoids external threats.

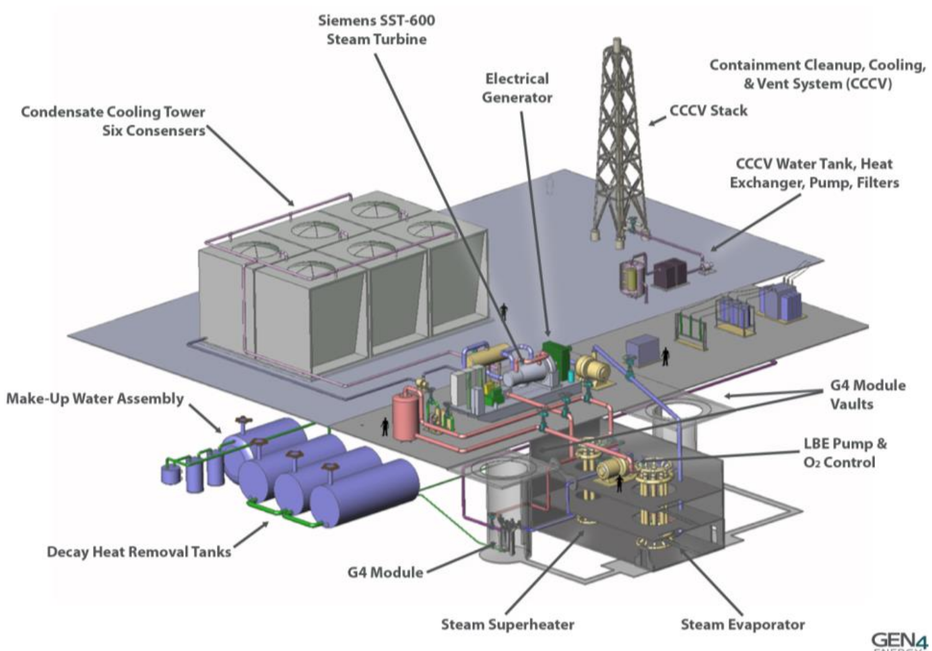
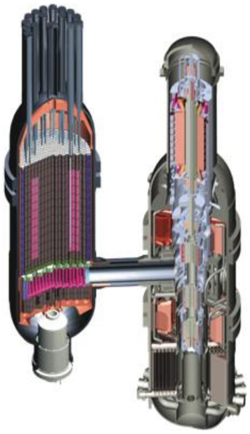


Figure 19. *Conceptual layout of G4M reactor (38).*

4.33 EM^2

Figure 20. *Reactor core of EM^2 (42).*



EM^2, designed by General Atomics, is a helium-cooled fast SMR with a net unit output of 265 MWe or 500 MWth. The reactor, using low-enriched uranium (LEU) with depleted uranium (DU) as fuel, can convert fertile isotopes to fissile materials and burn them in situ over a 30-year core life *(36)*. The core, thus, is divided into two sections: fissile and fertile. The fissile section contains about 14.5% LEU to sustain the chain reaction and provide excess neutrons to convert fertile DU to fissile material. The average enrichment of the total active core is 7.7%. Both the tri-bundle structural components that hold the fuels and the cladding are made of silicon carbide to withstand the high operating temperatures and long fuel cycle; this SiC-SiC material has a great stability under long term irradiation *(36)*. When refueling is needed, individual a tri-bundle assembly is withdrawn from the reactor vessel by an articulated arm from the maintenance hall floor, and then it is kept in a sealed container and moved to the fuel storage facility, where the spent fuel will be cooled by passive natural convection of air.

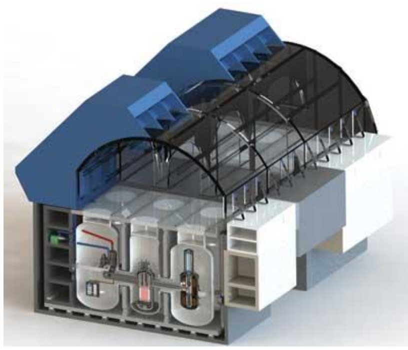


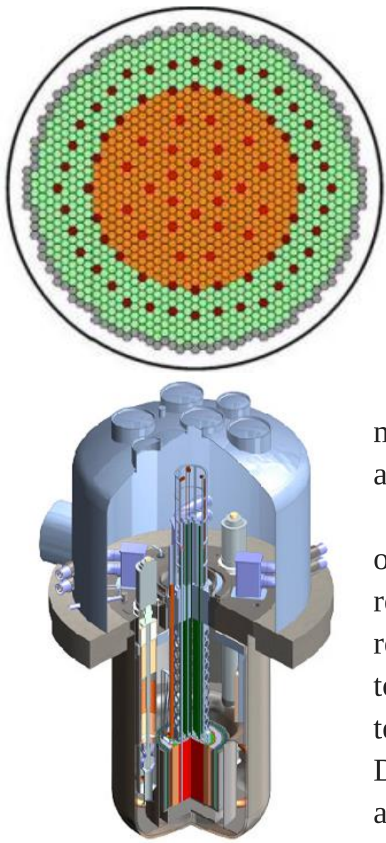
Figure 21. *Underground desian of EM^2 (43).*

To ensure the security, the reactor employs three successive, encompassing barriers, that ultimately rely on passive means, to prevent release of radionuclides: the high-strength SiC-SiC fuel cladding which can withstand high temperature; the primary vessel system that encompass the reactor and is able to provide heat removal; and the sealed, free-standing, below-grade containment along with an aircraft crash shielding roof per NRC regulations and a seismic isolator platform *(36)*.

Figure 22. *Conceptual layout of EM^2 plant (44).*

4.34 TWR-P

Figure 23. *Reactor core of TWR-P (38).*



TWR-P, designed by TerraPower, is a prototype of a novel class of reactor, the traveling-wave reactor, which is designed to operate for an extended period after a start-up period using only natural or depleted uranium *(38)*. This type of reactor is capable of sustaining energy-producing fission when fueled primarily with natural or depleted uranium. Only a small amount of enrichment is needed to start fission going, and no chemical reprocessing of spent fuel is required *(45)*. The breed and burn process is achieved through a “standing wave” by periodic reshuffling of the fuel so that higher burn-up assemblies are moved to the periphery of the core and depleted uranium fuel assemblies replace the high burn-up fuel.

The reactor is designed as a cool-type reactor as it consists of a cylindrical core submerged in a large sodium pool in the reactor vessel, which is surrounded by a containment vessel. In the reactor core, uranium metal, the fuel, is alloyed with 10% zirconium to dimensionally stabilize during irradiation and to inhibit low-temperature eutectic and corrosion damage of the cladding *(38)*. During the periods of reactor shutdown, if the grid power is not available, decay heat is removed by two decay heat removal systems which are both operated entirely by natural circulation. The reactor containment is formed by an underground containment vessel with an upper steel dome, which provides aircraft protection.

Unlike conventional TWR core design where the breed-burn wave moves through fixed core material, in this design, a “standing” wave of breeding and burning is established by periodically moving core material in and out of the breed-burn region. This process is referred as “fuel shuffling.” The core contains two types of assemblies: standard assemblies with depleted uranium for breeding in the periphery region, and a core center with a sufficient number of fissile assemblies to produce initial criticality and sufficient plutonium breeding to approach a steady breed-and-burn condition *(45)*. The initial core loading is configured to produce criticality with a small amount of excess reactivity and ascension to full power output shortly after initial reactor burnup; then the increasing reactivity is compensated by control rods that are gradually inserted into the core. After a period, the reactor will be shut down, and the high-burnup assemblies in the center will be moved to the periphery and will be replaced by depleted uranium assemblies. This shuffling process will be conducted with equipment installed in the reactor vessel and will take one to two weeks.

Chapter 5. Design Analysis and Comparisons

5.1 Comparing the Three Families

As listed above, there are three categories of reactors: four pressurized water reactors that belong to the light water reactor family, two high-temperature gas-cooled reactors, and four fast neutron spectrum reactors. All of the three families of reactors have their particular characteristics and benefits.

Light water reactors are the most common type of nuclear reactor around the world, in which light water is used as a moderator as well as the cooling medium. Uranium fuel is enriched to maintain the criticality of the reactor along entire fuel cycle. All the four reactors mentioned above belong to the PWR family, a major subcategory of the light water reactors. As the technology of LWR is already comparatively mature and widely adopted, the LWR SMR designs have their inherited advantages and are expected to be commercialized sooner than all other types of reactors. Generally, LWRs requires lower fuel enrichment (about 5% or less). This low enrichment, along with the technological readiness of LWR, will significantly reduce the expected duration for licensing those SMRs. PWR reactors are easier to operate from a stability standpoint; it also has a lower cost for operation. The economic benefits due to technical matureness, easiness of licensing and the lower operational costs make PWR SMRs attractive to vendors and investors. However, PWRs also have disadvantages. For instance, the coolant needs to be highly pressurized to remain liquid at high temperatures, and this induces vulnerability to the reactor during events like LOCA, while also increasing construction costs. Water as coolant will lead to a faster corrosion to carbon steel which is used as the construction material for many parts of the reactor, like the control rod drive mechanisms, limiting the lifetime of the reactor while also inducing potential risks.

Both HTGRs and fast neutron reactors are conceptualized more recently. Though more interesting and attractive, they also have much more difficulties and uncertainties than the traditional LWR designs.

HTGR reactors normally use gases such as carbon dioxide and helium as coolant and graphite as the moderator and have coated particles such as TRISO as fuel. The graphite has large thermal inertia, and the helium coolant is single phase, inert, and has no reactivity effects. So the graphite-composed core will have a high heat capacity and structural stability even at high temperatures. The coated fuel also allows high burn-up and retains fission products. However, the concepts of HTGR are still quite new; thus the costs for licensing, construction and operation will be higher.

Among the four fast reactors, there is one gas-cooled and three liquid-metal-cooled fast reactors. The idea of fast neutron reactor is not new in the US, but they have been mainly conceptualized as breeder reactors or for lab experiments, instead of for civil and commercial purposes. Fast reactors differ from thermal reactors as they use fast neutrons to sustain the fission chain reaction, and thus do not need a neutron moderator. This family of reactors is popular among scholars as they can reduce total radiotoxicity and the lifetime of nuclear waste, a distinguishing trait due to increased transmutation of plutonium and other actinides. Besides producing less waste, fast reactors also need less uranium fuel, as they permit nuclear fuels to be bred from almost all the actinides, including abundant sources of depleted uranium and thorium, as well as wastes from conventional light water reactors. This "breed and burn" process gives fast reactors a much larger efficiency as compared to other type reactors.

Nevertheless, several obstacles need to be conquered to promote the use of fast reactors. Firstly, critical mass in a fast reactor is much higher than in a thermal reactor because of the low cross sections of most materials at high neutron energies. As a result, significantly higher enrichment is normally necessary for the reactor; uranium fuels are enriched up to 20% *(45)*. The high enrichment induces a somewhat greater proliferation risk. Fast reactors are also more expensive to build and operate comparing to LWRs. Due to technological and political issues, the licensing process of fast reactors in the US is expected to be much longer and more difficult than that of the LWRs. Supply chains of fast reactors need to be developed and completed to commercialize fast reactors; it is also necessary to train skilled labor for building and operating these reactors. Thus, the commercialization of fast reactors may be a long and costly process.

However, as the designated time for this study is between 2025 and 2030, it is expected that all the chosen models, including both thermal and fast reactors, will complete their licensing process and are able to start construction and operation. With this concern, the licensing issue, along with its economic complications, will not be a factor that affects the decision of choosing models.

Regarding the study sites in Alaska, fast reactors are preferred. First of all, Alaska is not a large producer of uranium ores: there is only one discovered site with minable uranium deposit in Alaska located on Prince of Wales Island *(46)*, a southeastern island not far from Juneau. The deposit was mined several times before and has plans for potential reopening in the future. Even so, Alaska is not abundant with uranium, and import will probably be the only feasible way to obtain enough uranium, preferably from Canada, the largest and closest producer of uranium. Importing uranium from the US is also an option. As transporting uranium adds a considerable amount of money and risk of nuclear proliferation, it is imperative to reduce the amount of uranium fuel needed. Thus, fast reactors, with their distinctly higher efficiency, will be the top choice. On the other hand, the disposal of nuclear waste remains a major issue for a proposed nuclear plant. After each cycle, nuclear fuel will be moved from the core to be replaced by new fuel. According to researches, the heavy metal compositions for a typical light water reactor in US before and after running for three years are: uranium dropping from 100% to ~93.4%; from 4.2% enrichment to 0.71%; plutonium rising from 0% to 1.27%; minor actinide from 0% to 0.14% and fission products from 0% to 5.15% *(47)*. Most of the uranium, in the form of U-238, is still in the fuel. Both uranium and minor actinides, including Neptunium, Americium, and Curium, have very long half-lives, as seen in Figure 24. Normally nuclear reactors will store wastes at the site for a long time until the radioactivity of the wastes is low enough that the wastes can be safely transported to other storage sites. However, to store this large amount of spent fuel on site not only increases cost but also raises the safety and proliferation concerns, especially as in this study the plants will be designed close to the two largest population centers in Alaska. To transport the wastes from Alaska to the government-designated storing sites like Yucca Mountain is also impractical as the long-distance transport will add humongous costs and safety risks.

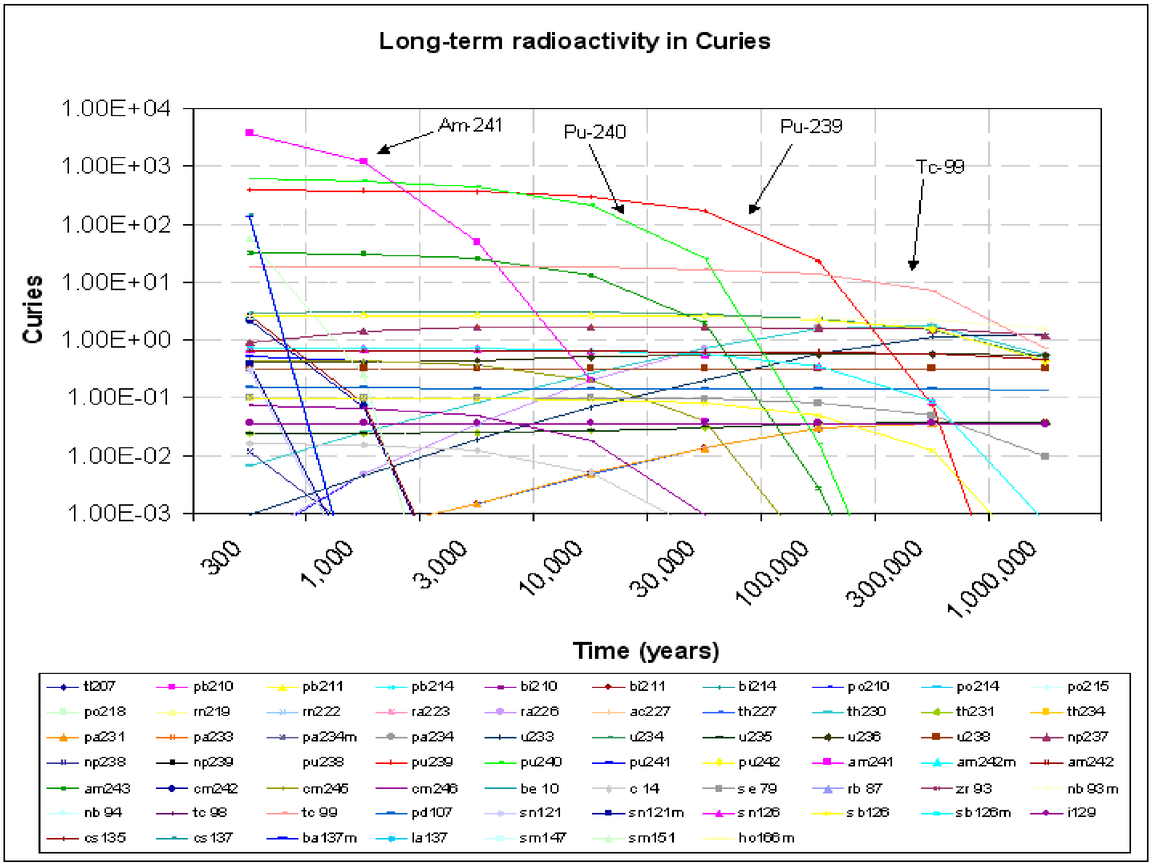


Figure 24. *The long-term activity of all the radioactive nuclides burnt to 45 MWd/kg. Data was computed by whatisnuclear.com (47).*

Among the three reactor categories, fast neutron reactors have the highest fuel efficiency while producing least radiotoxic wastes. Fast reactors allow fully exploiting the energy potential of uranium fuels by converting the fertile U-238 in the wastes to fissile Pu-239 and reusing the fissile materials; thus, they can extract sixty-to-seventy times more energy from uranium than thermal reactors do *(38)*. A higher efficiency means a smaller input required, for producing the same amount of energy. On the other hand, researches have indicated that actinides tend to have a higher probability of fission at fast energies *(40)*, so fast reactors can burn more efficiently the long life transuranic wastes and significantly reducing the activity and the required isolation time of the nuclear wastes.

Considering these factors above, it seems legitimate to put the four fast neutron spectrum reactors as best candidates for the study.

5.2 Comparing the Fast Reactors

5.21 Output Required

It is necessary to know how much electricity is needed in the study areas -- Fairbanks and Juneau -- in order to choose SMRs with appropriate sizes. However, there is no published data for energy consumptions for both two cities. As a result, the energy demand and the required SMR power output are estimated through the following way.

The data of electricity retails and retail prices for distribution utilities are obtained from EIA-861 survey database *(48)*. As the Golden Valley Electric Association is the major power provider in Fairbanks, its distribution data can be used as a rough estimation of the energy demand in Fairbanks region. From the database, the annual energy dispositions of GVEA from 2000 to 2015 was obtained.

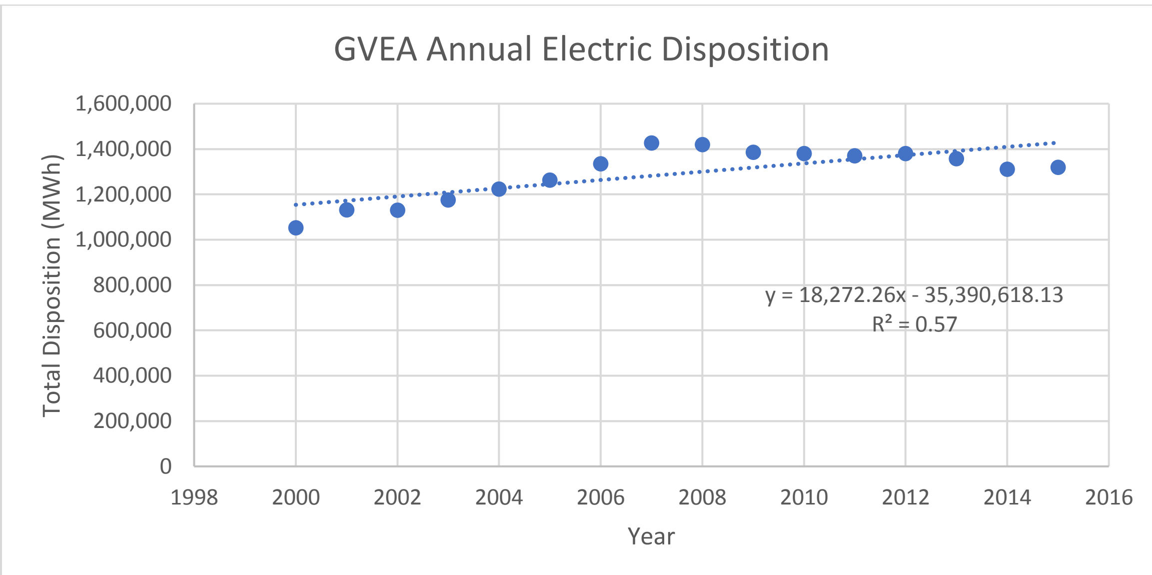


Figure 25. *The annual electric disposition between 2000 and 2016 for GVEA in Fairbanks.*

As indicated in Figure 25, the annual disposition of GVEA has an overall increasing trend through the 16 years. Assuming this increasing trend continues, from the regression line, the annual consumption of electricity for the years 2025 to 2030 can be roughly calculated (Table 3).

On the other hand, the annual disposition of Alaska Electric Light & Power (AEL&P), which is the only utility in the Juneau region, is a reliable indicator of the annual electric consumption of Juneau.

AEL&P's annual dispositions of electricity are presented in Figure 26 and indicate a relatively larger growth over the 16 years possibly as a consequence of the booming tourism brought by the rising cruise ship market. By assuming the growth of the electric disposition maintains annually, the energy consumption of Juneau between the years of 2025 and 2030 can be estimated (Table 3).

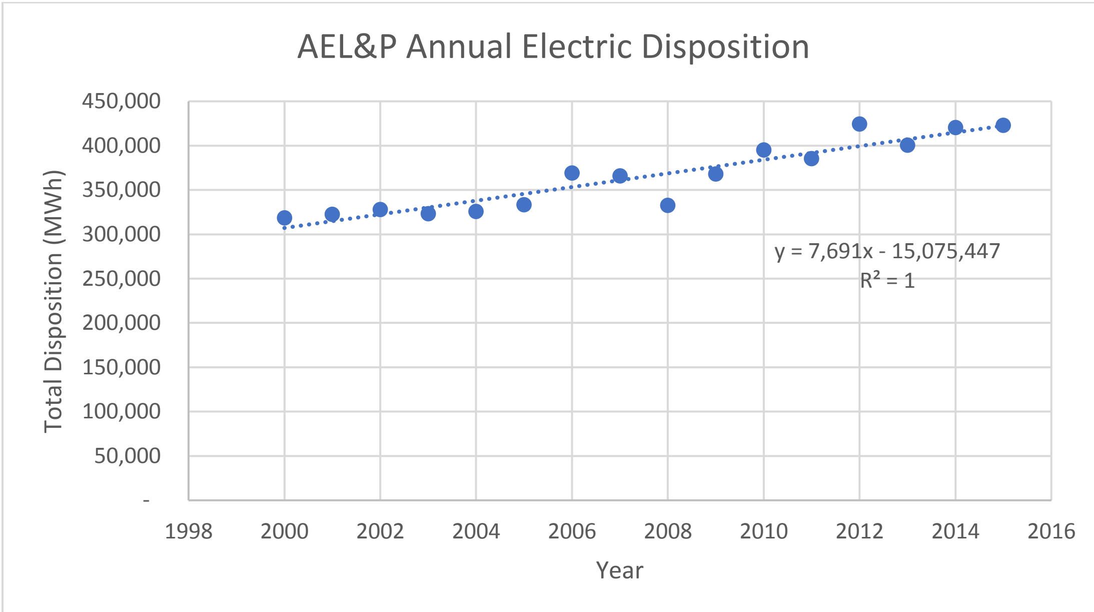


Figure 26. *The annual electric disposition between 2000 and 2016 for AEL&P in Juneau.*

Year	2025	2026	2027	2028	2029	2030	Average
Electric Capacity Required for Fairbanks (MWe)	183.69	185.77	187.86	189.94	192.03	194.11	188.90±50
Electric Capacity Required for Juneau (MWe)	56.94	57.82	58.70	59.58	60.45	61.33	59.14±50

Table 3. *Expected electricity requirement for Fairbanks and Juneau calculated with the regression function.*

However, there are errors with this method. Firstly, GVEA is the major but not the only utility serving the Fairbanks region. Other private or smaller public utilities do exist, and this method of estimation omits the contributions of these small utilities as their disposition data are not available through the EIA. Even though, since the small utilities do not have a considerable share in the Fairbanks market comparing to GVEA, this factor will not bring large discrepancies to the estimation. Meanwhile, Fairbanks is the major but not the only customer of GVEA. In other words, besides supplying the Fairbanks metropolitan area, GVEA also provides power for other parts of the Fairbanks North Star Borough and some other adjacent counties including Denali Borough. Regions such as Fort Wainwright, College, and the airport, though having their own power grids, might still purchase and use power from GVEA. And since Fairbanks is in the Railbelt grid, a minor portion of the produced power might be transmitted even further. With all the minor errors and uncertainties considered, and the seasonal and daily peak considered, the expected average capacity required for Fairbanks will have a 50-MWe fluctuation range.

On the other hand, since Juneau is not connected to other external grids and since AEL&P is the only utility company serving the Juneau region, the estimation done with power distribution will be more accurate. It is interesting to notice that Juneau, with approximately the same population, has a required power output much smaller than that of Fairbanks. This might be a combined result of that Juneau has a smaller industrial sector, a smaller transportation sector, less heating demand due to the warmer temperature, and smaller lighting demand due to the lower latitude. However, there will still be notable fluctuations on seasonal and daily peak due to the influx of tourists with cruise ship industry. Thus, the expected average capacity will also have a 50-MWe fluctuation range.

Reactor	Electric Capacity (MWe)	Modules per Plant
PRISM	311	2
G4M	25	1
EM^2	265	4
TWR-P	600 (300 also possible)	

Table 4. *Electric capacity of the four fast SMRs. Cells are blank if no information available.*

The electric capacities of the chosen four fast reactors are shown in Table 4. Normally a reactor design will indicate how many modules are ideal to be included in one conceptual plant. GE-Hitachi has indicated that each turbine generator will be connected to two PRISM reactors, thus providing a total capacity of ~600 MWe. The General Atomics has also indicated that each plant will have a bundle of four EM^2 modules, thus providing ~1000 MWe. Both two designs would be too large for both two study sites if the designated numbers of modules per plant are followed. G4M, on the other hand, only has a capacity of 25 MWe per module, and each plant will only have one module; thus, it will be too small for both sites. TWR-P is designed to produce 600 MWe electric capacity. However, some studies have indicated that TWR-P will also be designed for low-power (~300 MWe) applications *(45)*.

5.22 Safety

	Fuel Enrichment (%)	Seismic Designs	Safety Features	Underground	Pool-type	System Pressure (MPa)	Passive System Effective Duration	Distinct Characteristics
PRISM	26% Pu, 10% Zr	Seismic Isolator	Passive	Yes	Yes	Low pressure	Unlimited time	Passive air cooling ultimate heat sink
G4M	19.75		Hybrid	Yes	Yes	Low pressure	14 days	Sealed since production until reprocess
EM^2	14.5	Seismic Isolator	Hybrid	Yes	Not applicable	13.3		SiC-SiC composite cladding and gas vent system
TWR-P	<20		Passive	Yes	Yes	0.1		

Table 5. *Safety-related features of the four fast SMRs. Cells are blank if no information available.*

Among the four designs, PRISM has a high enrichment with 26% plutonium and 10% zirconium, and since Pu-239 can also be enriched to weapon grade, a high plutonium enrichment of PRISM brings more security and proliferation concerns. G4M also has a high enrichment of 19.75% uranium. TWR-P has only indicated that the enrichment will be lower than 20% but has not yet given any specific numbers. EM^2 has the lowest enrichment of 14.5%.

Seismic influence is a crucial factor to consider about in the case of Alaska as it is close to the Ring of Fire. According to USGS, Fairbanks has a very high earthquake risk, as Fairbanks had a total of 2,538 earthquakes since 1931 and has an 83.06% probability of having a 5.0 earthquake within next 50 years. The historical earthquake activity of Fairbanks is slightly above Alaska state average and is 572% greater than the overall US average. Juneau has a lower and more moderate seismic activity comparing to Fairbanks. There were only 144 earthquakes occurred in Juneau since 1931, and its historical record is below Alaska state frequency. However, there is still a 14.22% probability of a 5.0 earthquake in the next 50 years *(49)*. As a result, it is necessary for the designs to have proper measures against seismic activities, especially most of the designs are located below-grade. For all the four designs, only PRISM and EM^2 have clearly indicated that the reactors will be built on seismic isolators.

As mentioned before, many studies have found that a mix of passive and active safety mechanisms will be better rather than just passive safety system alone. EM^2 and G4M have hybrid safety features while PRISM and TWR-P only have passive safety systems. On the other hand, all four modules are designed to be buried underground during operation; the below-grade designs provide extra protection toward external anthropogenic and natural hazards and reduce the proliferation risks. All the liquid-metal-cooled reactors are also designed with pool-type containment, which can act as an ultimate heat sink and prevent the build-up of heat during LOCA. As for reactor system pressure, all the liquid-metal-cooled reactors have very low pressure; while EM^2, as a gas-cooled reactor, keeps a relatively high pressure in its system. Although helium is chemically inert, the high pressure might also increase physical vulnerabilities to the reactor system and the containment vessel.

Furthermore, PRISM will have passive air cooling as an ultimate heat sink, thus guaranteeing the reactor a removal of heat without any external power for an unlimited amount of time during an accident. According to Gen4 Energy, G4M will be sealed once it is manufactured in the factory, and will keep being sealed during transportation, installation, and operation, until being opened for recycling and refueling after the designated 10-15-year reactor life. The passive safety system of G4M can allow a 14-day coping time during accidents without external power or operator action. EM^2, although has not indicated the effective duration of its passive safety system, utilizes silicon carbide as a constructing material in many parts of the core, strengthening the reactor under long-term irradiation and high temperature.

5.23 Economics

Economics is another major factor to consider. Besides the designing and licensing costs which are excluded in this study, factors that determine if a nuclear power plant is economically competitive include the costs involved in construction, infrastructure, fuel purchase, fuel enrichment, fuel transportation, daily operation, and maintenance, as well as the thermal efficiency.

Nuclear energy is cost-competitive among all energy sources. According to EIA, electricity produced by advanced nuclear would be cheaper compared to petroleum, solar, offshore wind, conventional natural gas, and biomass; conventional coal production would have similar costs comparing to nuclear *(50) (51)*. In a long-term situation considering the potential economic and social costs for carbon emission, nuclear will have dominant advantages. On the other hand, nuclear is more expensive comparing to hydropower, but as nuclear would be more reliable and easier to operate, it would still be competitive comparing to hydro.

As the designs are still quite new, and because of concerns about trade secrets, there is not much economic information released about these designs. Thus, it is impossible to conduct a comprehensive analysis or comparison for the chosen fast reactor designs. But based on the released information about their individual life and fuel cycle, a brief comparison can be made with respect to the fuel-related costs.

	Design Life (years)	Refueling Cycle (months)	Refueling Outages (days)
PRISM		18	
G4M	5-15 (nominal 10)	120 (10 years)	
EM^2	60	360	14
TWR-P	40	18-24	7-14 for "fuel shuffling"

Table 6. *Design life, fuel cycle and refueling outages for the four fast SMRs. Cells are blank if no information available.*

As shown in Table 6, EM^2 has the longest reactor life and refueling cycle, and it only requires one refueling in thirty years. The reactor life of G4M is not long comparing to those of others. However, it does not have the refueling issue as fuels are sealed in the reactor, and after each fuel cycle, the reactor will be shipped back to the factory again along with the fuels inside. TWR-P has a quite long reactor life, but in its current design every 18 to 24 months it needs to be shut down for 7 to 14 days to perform the "fuel shuffling." PRISM has not indicated its reactor life but its 18-month fuel cycle is comparatively short.

As both sites are distant from uranium ores and fuel enrichment facilities, each refueling will induce considerable costs and security risks. Besides transportation, the refueling process itself at the site also costs a lot of time and money. Thus, designs with long refueling cycles would be preferable. Likewise, reactors with longer design life would also be better as many undesirable costs can be avoided.

5.24 Other Non-Electric Applications

Nuclear cogeneration, where the nuclear plants produce not only electricity but also heat and steam that can be used for various purposes, provide a more economic, efficient and environmentally friendly way of utilizing nuclear power. According to previous studies, common light water reactors and water-cooled SMRs are suitable for use in district heating, which requires a heat range of 100 to 150 °C, and industries like seawater desalination, pulp and paper or textiles, which require heat range up to about 200 to 300 °C *(52)*. Fast reactors, with working temperature about 500 to 1000 °C *(53)*, are suitable for more applications including process heat for chemical industry, oil refining, sand processing, coal gasification, hydrogen production, and metal production.

Fairbanks, with harsher and longer winter, as well as much larger industries, will have a larger demand for the district heating and industrial process heat than Juneau.

Reactors	PRISM	G4M	EM^2	TWR-P
Core Outlet Temperature (°C)	485	500	850	500

Table 7. *The core outlet temperature of the four fast SMRs (36) (38).*

As Table 7 shows, EM^2, the only HTGR module among the four fast reactors, has the highest working temperature; so it will have the widest application and the highest marginal safety. Other factors all have temperatures near 500 °C.

Chapter 6. Discussion and Conclusions

It will be feasible, assuming the developmental trends and the NRC approval process does not change, for SMRs to be used in both Alaskan cities studied in the 2025-2030 time frame.

The two study sites, Fairbanks and Juneau, are far from the uranium ores and enrichment facilities. As a result, the most important factors in deciding the appropriate designs are the efficiency and demand of fuels for the reactors, as well as the number of long-life radiotoxic wastes produced by the reactors. Fast neutron reactors, with their ability to convert fertile U-238 to the fissile materials, are sixty-to-seventy times more efficient than thermal reactors; and as they are able to burn up more actinides, they produce nuclear wastes generally with much shorter half-lives. So it is obvious that fast reactors have incomparable advantages over the two other categories of reactors in this aspect, and fast reactors are the best options for the two study sites.

In Fairbanks, most of the electricity is produced from fossil fuels, which are less cost-competitive and environmental-friendly than nuclear energy in a long-term perspective. As Alaska is more sensitive to global warming, and Fairbanks is close to some of the most vulnerable ecosystems in Alaska, e.g., Denali Nation Park, it is imperative to transfer Fairbanks into a less carbon-dependent energy structure. As a result, nuclear energy will be optimal if used as a baseload source replacing coal and natural gas in the grid of Fairbanks. In terms of required output, PRISM and EM2 would be good options with one module per plant. TWR-P would also be optimal if TerraPower develops a smaller version of TWR-P with about 300 MWe capacity. As for safety concerns, based on currently available information, PRISM and EM2 are the best options as they have seismic designs. EM2, with a low enrichment and a hybrid safety system, is attractive, though it has a high system pressure. On the other hand, G4M and EM2 have the longest fuel cycle, thus are the most appealing designs in terms of economics. Fairbanks has a large industrial sector and has a much higher demand for district heating, EM2 is the best candidate if thinking about nuclear cogeneration in Fairbanks. To sum up, for the case of Fairbanks, EM2 would be the best option for deployment.

Meanwhile, the case of Juneau is completely different from that of Fairbanks. The energy structure of Juneau is much cleaner as about 98% of electricity is produced from hydropower. Though hydropower is cheaper than nuclear energy, studies have also revealed the potential ecological impacts hydropower will have on the local ecosystem (54). And as hydro projects are normally far away from the population center (Snettisham project is 28 miles from central Juneau), the long-distance transmission will bring increased vulnerability to the grid in facing the frequent natural hazards including earthquakes and avalanches, such as the 2008 Avalanche near Juneau. However, as the dams are already built and in operation, it is impractical for nuclear power to replace hydropower completely. Unlike Fairbanks, Juneau often sees a dramatic daily fluctuation in energy demand due to cruise ship tourism. In considering all the factors, nuclear energy in the case of Juneau will be better if regarded as a supplement to the grid in response to the frequent power outages and daily fluctuations, while hydropower will still be the major baseload source. G4M, with its small power capacity, is ideal in considering the small energy demand in Juneau. On the safety side, G4M, though not as ideal as PRISM and EM2, has a hybrid safety system which is better than a passive system alone. The idea of all-the-way sealing of G4M is also an interesting but promising trait. The 10-year fuel cycle of G4M is appropriate in economic and security concerns. In considering other non-electrical applications, as Juneau does not have a large industrial power demand, G4M will be enough in fulfilling some basic requirements like district heating. In summary, for the case of Juneau, G4M will be the best option.

These conclusions are based on the information that is currently available. As the concepts of SMRs, especially the fast SMRs, are still very new, there is inadequate detailed information that can be used to conduct a more thorough and comprehensive analysis. The result presented herein may be completely different as the technologies become more mature. Meanwhile, in order to fully employ the SMR technologies in not only Alaska but also the whole US, as there are still issues: for example, the widespread misunderstandings about nuclear energy needs public support; many policies at both state and federal levels need to be reviewed and revised; and infrastructures and markets need to be established or completed for nuclear energy.

The strong potential of SMRs is obvious, and it is clear that this novel technology will be in the spotlight of the world and will have a dynamic adoption in the near future. The suggested feasibility of adopting nuclear energy, specifically SMRs, in Fairbanks and Juneau also provides a potential path to solve the electricity shortage and the notoriously high electricity rates in the rural and more remote communities in Alaska.

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Appendix. Abbreviations

ACS	Auxiliary Cooling System
AEL&P	Alaska Electric Light & Power
ANS	American Nuclear Society
ARC	Advanced Recycling Center
ATWS	Anticipated Transient without Scam
B&W	Babcock & Wilcox Inc.
CFR	Code of Federal Regulation
COL	Combined Construction and Operating License
DC	Design Certification
DHRS	Decay Heat Removal System
DOE	Department of Energy
DU	Depleted Uranium
EIA	Energy Information Administration
EPZ	Emergency Planning Zone
ESP	Early Site Permit
FNR	Fast Neutron Spectrum Reactor
FOAK	First of a Kind
FR	Fast Reactor
GAIN	Gateway for Accelerated Innovation in Nuclear
GFR	Gas Cooled Fast Reactor
GVEA	Golden Valley Electric Association
HLMC	Heavy Liquid Metal Cooled
HTGR	High Temperature Gas Cooled Reactor
I&C	Instrumentation and Control System
IAEA	International Atomic Energy Agency
IFR	Integral Fast Reactor
LBE	Lead-Bismuth Eutectic
LEU	Low-Enriched Uranium
LOCA	Loss of Coolant Accident
LTS	Licensing Technical Support
LWA	Limited Work Authorization
LWR	Light Water Reactor
MSFR	Molten Salt Fast Reactor
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
R&D	Research and Development
RVACS	Reactor Vessel Auxiliary Cooling System
SFR	Sodium Cooled Fast Reactor
SMR	Small Modular Reactor

Appendix. List of Figures

Appendix. List of Tables