ABSTRACT

Title of Thesis:	THE NEW CLEAR NORMAL, MEETING ENERGY DEMANDS OF THE FUTURE
	Austin Benham, Master of Architecture, 2022
Thesis Directed By:	Professor Michael Binder, School of Architecture, Planning, and Preservation

Both within the United States and abroad, the nuclear industry has seen a sharp decline in utilization due to a loss of public trust and/or economic factors. As energy demands grow on a global scale, and countries look to sustainable methods for meeting these needs there has been an opportunity for new advancements within the nuclear industry to viably present themselves. This thesis proposes the design of a nuclear power plant which utilizes small-modular-reactor(s) to be used for energy production and address other needs within the surrounding community, with integrated public facilities where possible. Through design, this facility will help to alleviate the damaged public perception of nuclear power and exhibit the new nuclear industry and its benefits over other forms of energy; It will provide context on past events and technology within the field, showing that, through architecture and site design the multiple aspects of a nuclear power plant site can be portrayed in a more upstanding manner to better accentuate the positive aspects that are inherently present within the industry. This thesis will ultimately establish that healing the social and environmental issues of the past will aid in the creation of a new, safe, sustainable, and reliable nuclear industry.

THE NEW CLEAR NORMAL,
MEETING ENERGY DEMANDS OF THE FUTURE

by

Austin Benham

Thesis submitted to the Faculty of the Graduate School of the
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Advisory Committee:
Professor Michael Binder, Chair
Professor David Cronrath
Professor Juan Burke

Preface

Not knowing exactly where I had gotten my fascination with nuclear energy from, I have always enjoyed researching its history and application through documentaries and other facets. Growing up just outside of Harrisburg, Pennsylvania I was always familiar with the surrounding nuclear power plants, especially that of Three Mile Island, as its steam clouds could be seen from the turnpike and other prominent roadways around the area. The large concrete cooling towers which are prevalent in many existing power plants along the east coast have always been a landmark to look out for as one travels. This is especially true of the Limerick Generating Station, where much of my extended family resides around. As I began this thesis project, it solidified my interests within the technology as I realized more and more how the new advancements within the industry could be a potential solution to the need for sustainable energy. My hope as one reads this document is that it acts as a case study into why nuclear power can possibly solve the challenges of energy demands and beyond, gifting others the shared allure of this technology that I have had.

Dedication

I would like to dedicate this research paper to my parents, for whom I would not have been able to reach this level of education without. Through years of support from them I have been able to progress through college and graduate school thus allowing me to pursue my dreams. Their emotional support along this journey is what allowed me to put in the effort in creating this project along with so many works before it. Ultimately, it was my parents who helped me to find what interests me and solidify the topic of this thesis. Thank you for everything you have done and continue to do.

Acknowledgements

I would like to acknowledge the chair of my advisory committee, Professor Michael Binder for helping navigate me through the multiple qualms which presented themselves throughout this thesis project. Through countless emails and weekly meetings Professor Binder aided in making sure the research was on track and encompassing all topics it needed to touch on. I would also like to thank Neil Numark, my professional mentor who works within the field of energy consulting, with facets in the nuclear industry. Neil helped proof this research article and gave enlightening feedback as a professional within the industry. Both Professor Binder and Neil Numark helped to solidify the information presented throughout the body of this paper and piece together the many facets which are seen through the lens of nuclear energy.

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Chapter 1: Background Context

What is Nuclear Energy?

Nuclear energy begins at the scale of a single atom, which has a large amount of energy holding its nuclei together. Depending on what elements the atom is a part of it can be split and will release part of its energy as heat. This process of splitting the atom and releasing its energy is called fission. Uranium-235 (the refined version of uranium-238, which is found in nature) is one of the isotopes that fissions easily. During fission, uranium-235 atoms absorb loose neutrons, which causes uranium to become unstable and split into two lighter atoms called fission products. The combined mass of the fission products is less than that of the original atom. This reduction occurs because some of the matter changes into energy, this energy being the aforementioned heat. These neutrons then have the chance of hitting other atoms, causing more fission.[1]

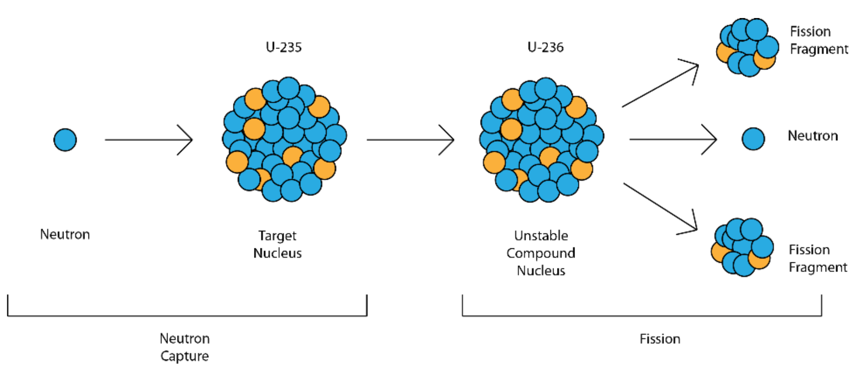


Figure 1.1: Diagram which shows the process of nuclear fission (Source: Author)

[1] "How Does a Nuclear Reactor Work - World Nuclear Association." n.d. Accessed May 16, 2022. https://world-nuclear.org/nuclear-essentials/how-does-a-nuclear-reactor-work.aspx.

A series of fissions is called a chain reaction. If enough of the fissile material is brought together under the right conditions, a continuous chain reaction occurs and is called a self-sustaining chain reaction. A self-sustaining chain reaction creates a copious amount of heat, which can be used to generate electricity. Nuclear power plants generate electricity similar to any other steam-electric powerplant. Water is heated, and steam from the boiling water turns turbines and generates electricity. The main difference in the various types of steam-electric plants is the heat source. This delicate balance of chain reactions is what is repeated over and over within nuclear power plants across the world, the only difference being in the reactors design which can vary from country to country.

How Does a Nuclear Reactor Work?

Nuclear reactors are what produces the heat needed to create power within a nuclear power plant. Currently, there are 94 nuclear power plants within the United States, and nuclear power continues to be one of the largest sources of carbon-free electricity available. The uranium fuel is mined and then refined into small ceramic pellets and is stacked into sealed metal tubes called fuel rods. A reactor core is typically made up of a couple hundred fuel rods, each one containing a few hundred more uranium fuel pellets. These numbers can vary depending on the plants intended power level. Inside the reactor, the fuel rods are submerged in water which acts as both a coolant and moderator. The moderator slows down the neutrons produced by fission to sustain the chain reaction. Control rods can then be inserted or withdrawn from the core to either reduce the reaction or increase it. The heat created by fission turns the water into steam, which spins a turbine to produce electricity. Within the

US, there are two main types of reactor designs used in traditional plants: pressurized water reactors (the majority) or boiling water reactors. The difference between the two being at what point the water is heated into steam for use within the turbine.[2]

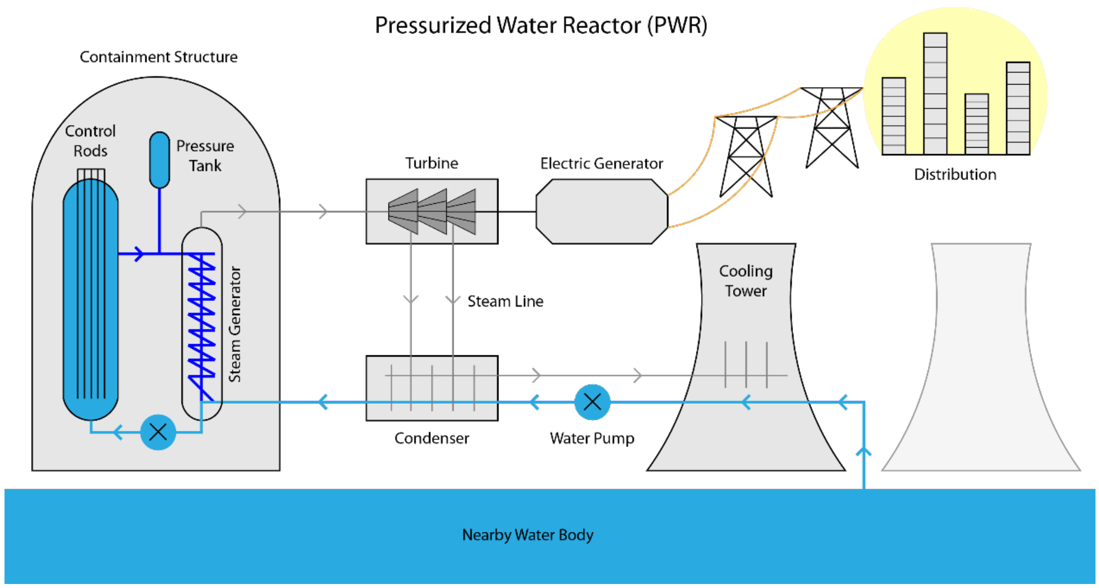


Figure 1.2: Diagram which shows how a typical U.S. PWR operates (Source: Author)

Enrichment and Re-enrichment Processes

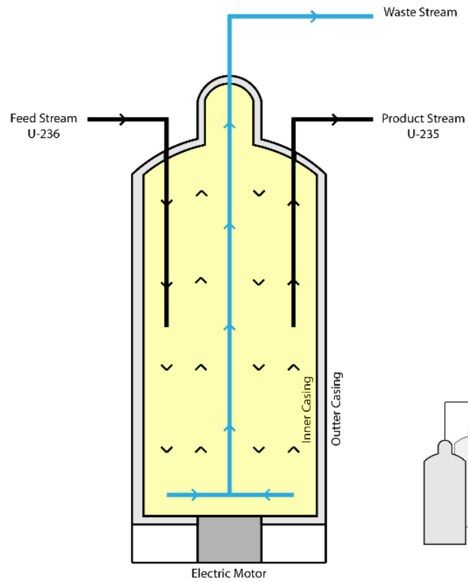
As touched on earlier, uranium-235 is the preferred fuel source used within current commercial light-water reactors. However, U-235 does not occur naturally within the environment and must be produced through manmade processes. These processes are what is commonly referred to as “enrichment”. When uranium is first mined out of the ground, it is in a state called uranium-238, this meaning that it has 238 neutrons present within its nucleus. Being a higher number than U-235 this means that the natural uranium is too stable to undergo the necessary fission. This

[2] “NUCLEAR 101: How Does a Nuclear Reactor Work? | Department of Energy.” Accessed March 13, 2022. https://www.energy.gov/ne/articles/nuclear-101-how-does-nuclear-reactor-work.

being bad because more energy is then needed to get the U-238 to split into fission fragments. Therefore, the U-238 undergoes enrichment which purifies the uranium into having less neutrons (uranium when mined is 99.3% U-238 and only 0.7% U-235). Having less neutrons makes it easier to fission and therefor can release more energy.

Enrichment is done in several ways across the world, mainly through gaseous, or laser separation methods. With laser separation still under development, the main process of enrichment within the United States is through the use of gas centrifuges. The basis behind a centrifuge is to create enough pressure that the differing masses of the elements found in U-238 are separated, leaving U-235 closest to the center of the apparatus, and eventually being extracted through the top. On its own, a singular centrifuge is not efficient enough to purify the uranium in one step. Therefore, conversion plants have hundreds of them lined up in banks to continuously pass the uranium through until it is at a purity suitable for use within a reactor.[3]

[3] NRC Web. "Uranium Enrichment." Accessed March 17, 2022. https://www.nrc.gov/materials/fuel-cycle-fac/ur-enrichment.html.



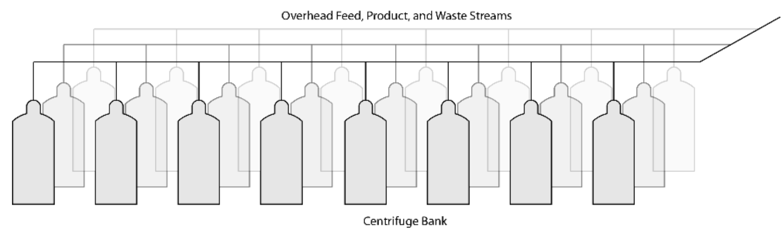


Figure 1.3 & 1.4: Diagram showcasing how a gaseous centrifuge works (left), and an image of a centrifuge bank (right). (Source: Author)

After the uranium carries out its life of being mined, enriched, and used as fuel within a nuclear reactor, it either becomes a waste product or can be re-enriched for further use. Although expensive and complicated the re-enrichment process can prolong the life of U-235 and lead to less new fuel consumption/production, therefor less waste is produced short-term. Re-enrichment involves the U-235 being bombarded with other radioactive isotopes to activate the spent fuel again so that it can undergo fission. These processes are not practiced within the United States due to the high costs seen within their operations, but can be seen in countries such as France, which powers large parts of their electrical grids primarily with nuclear power.

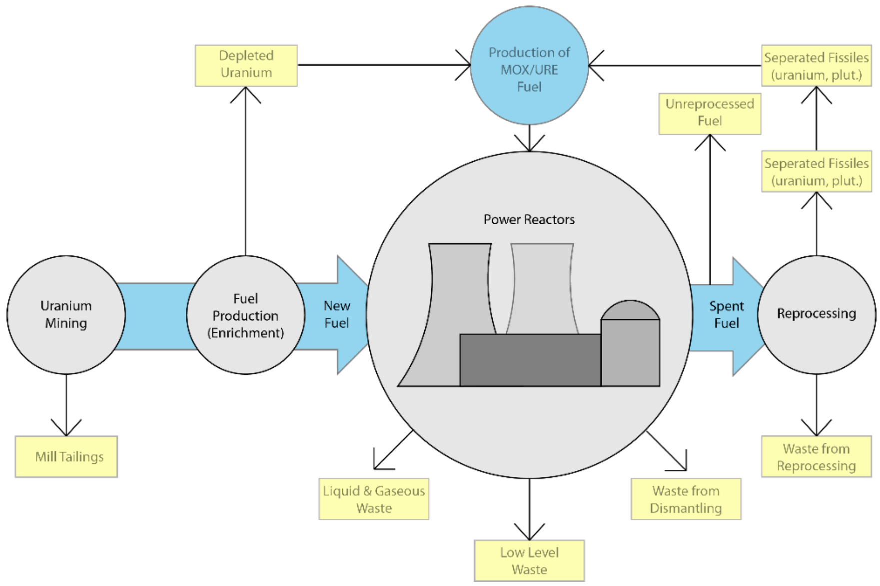


Figure 1.5: Diagram showing the different outlets nuclear fuel can take throughout its lifecycle. (Source: Author)

Laying the Framework

Since the advent of nuclear technology within the US, the country has seen a fluctuation in how utilized the know-how is employed within fields such as medicine, industry, science, food, and agriculture, as well as power generation. Beginning in 1942 when the first sustained nuclear fission was achieved at the University of Chicago, it has been a goal of the United States to build power stations in order to produce energy for the country's needs. This plan led to the creation of 104 plants across the United States and saw a boom within the nuclear industry. Eventually giving birth to dedicated organizations such as the Nuclear Regulatory Commission and other entities tasked with governing this new frontier.

Throughout the 20th century, the nuclear industry saw substantial growth across the country and plants kept being proposed, built, and brought online. People even began to envision nuclear technology being used within commonplace items such as cars and kitchen appliances. It was not until the occurrence of several key events and other social, political, and economic factors that changed this paradigm and partially tarnished the nuclear industry within the eyes of the public. This caused the popularity of nuclear to fluctuate, seeing drops in utilization once an incident occurred, but always making a return to somewhat normalcy as time progressed. Since then, the industry has seen further stagnation and reduction within its use for power generation, thus leading to existing plants being decommissioned and no new plants being built from 1977-2016 within the confines of the United States.[4]

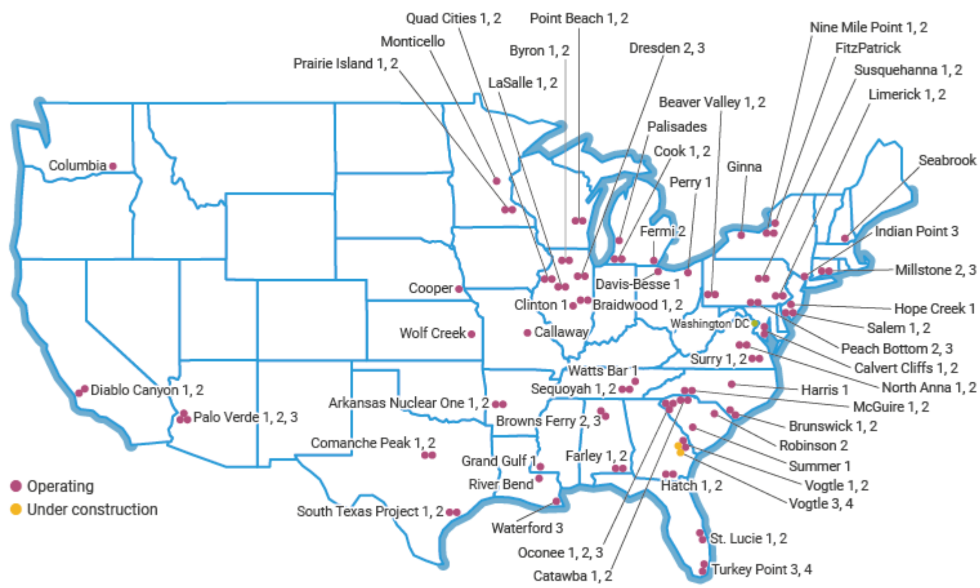


Figure 1.6: Location of all operating and newly built nuclear power plants (Source: World Nuclear Association)

As we move further into the 21st century the United States and other world superpowers continue to look for alternative ways to produce energy without the

[4] "Nuclear Power in the USA - World Nuclear Association." World Nuclear Association, accessed March 8, 2022, https://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx.

means of relying on fossil fuels and other traditional methods of carbon-producing power generation that are detrimental to the environment. Since this turn towards sustainability, the nuclear industry has seen a reawakening as it is realized to be a carbon-free means to meet energy demands. Although still fragile within the public eye, the industry strives to reinvent itself as new reactor designs and alternative fuel sources are being developed and put to practical use within the field. Along with the move towards privatization of the industry these new reactors have explored technology previously unseen within the typical government-run facilities and are beginning to diversify the nuclear energy scene within America.

Figure 1.7: Image of the Vogtle Power Plant, representative of most traditional U.S. reactor designs. (Source: Google)

Companies such as Terrapower, NuScale, and Kairos are beginning to explore the use of small modular reactor design which allow for reactors to be more compartmentalized and power smaller regions than their larger counterparts. Which has once again started to make nuclear more appealing to the energy market as these innovations are driving down construction costs (a current main factor against the construction of new plants) and advancing the technology. One other aspect of nuclear power to note would be the continued promise of nuclear fusion, which has yet to be harnessed for use on Earth.

Fusion, being another form of converting mass to energy (like fission), involves the collision of two or more atoms to produce the energy. This is a topic that newer companies are beginning to explore and seems to be closer than ever to being achieved as other multiple countries are making breakthroughs to maintain artificial fusion long enough to harvest more power out of it than what is put in to create it. Benefits to fusion include the ability to create energy without any waste generated in return and having the potential to create far more energy than the process of fission can produce. Regardless, the constant pursuit of progress within the nuclear industry is where this thesis began its roots and has progressed from.

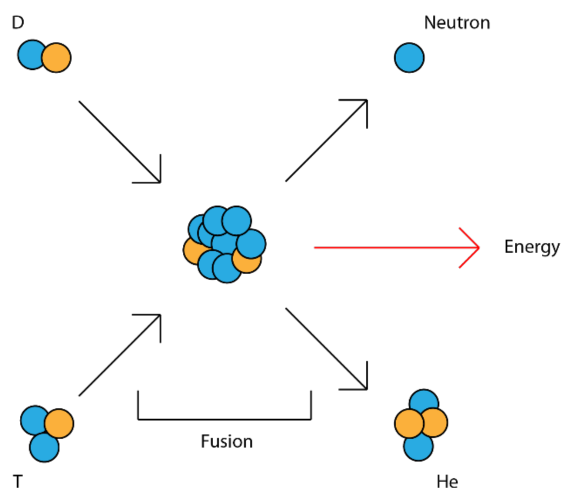


Figure 1.8: Diagram showcasing how the process of nuclear fusion is carried out. (Source: Author)

Project Vision

This thesis will explore aspects of the afore mentioned technologies to revive public interest, heal the industries public image, and test the viability of nuclear power within the coming decades. This vision will be achieved within two main aspects seen within the complex. Starting with the creation of integrated areas for public discourse throughout the plant, which will act as a catalyst for people to come and start discussion on the nuclear industry while learning about the past, present, and future of the industry. In addition to this will be the second leg, which sees the construction of a next generation nuclear power plant with the intended purpose of showing the real-world application of the technology being shown within the discourse center. The power plant will also fulfill the important primary task of generating power to meet the growing demand for sustainable energy and explore other methods to interface with its surrounding context.

Through architecture and site design, these facilities will need to uphold the vital uses which need to be carried out within a nuclear facility, such as security, engineering, physics, and power generation. It will also need to grapple with their image as perceived by the public. An example being how to create a secure perimeter around the power plant that doesn't intimidate the public (such as barbed wire fences) and still meets the requirements of safety. Many of the uses within a nuclear power plant are a double-edged sword, that being, their literal intended uses that need to be upheld, and how they are perceived by the public. These public views may be drastically different than their actual intended purpose. As stated, the architecture will also have to become non-passive and avoid becoming too utilitarian (as seen with most traditional power plants) so that its elements can push across the unique aspects only found within nuclear power and begin to positively shift the damaged paradigm.

Figure 1.9: Artistic rendering of a showcase nuclear fusion facility which architecturally addresses the currently lacking designs of architecture and site design within power plants. (Source: AL_A Studios)

In the end, this thesis will meet the criteria of the construction and design of a generation five nuclear power plant, integrated public facilities, and gauge ways in which through the afore mentioned standards, it has to some margin, reinstated public trust within the industry. This would further assist by allowing the approval of more next generation power plants to be built around the country to meet the growing need for sustainable energy, while also relieving the stigmatism around nuclear sites, so that they may be reused as brown-field sites for other forms of development. Furthermore, the project will explore important questions such as how the thesis design can embody not only the reduced risk, but also the greater promise of nuclear power. These criteria (some tangible and some non-tangible), will gauge the progression of the thesis project and lay out its context, which will be discussed further within the following chapters.

Chapter 2: History of the US Nuclear Energy Industry

Advent of Nuclear Energy

Beginning in the early 1930's, a man by the name of Enrico Fermi began experiments in Rome to test how neutrons could split atoms. Fermi, who had originally been a physicist in Italy, had eventually come to the US to pursue work for the government on nuclear technology. Through Fermi's research and experiments done by German scientists Otto Hahn and Fritz Strassman, they began to realize the possibility of this newly found technology. It was through the help of Lise Meitner, who began to publish their works that scientists around the world began to believe a self-sustaining chain-reaction may be possible.[5]

By early 1942, a group of scientists, led by Fermi, gathered within the United States at the University of Chicago to develop their theories on nuclear energy. The scientists had come together mainly because they had created plans for the world's first nuclear reactor, which became known as Chicago Pile-1. The pile was built on the floor of a squash court underneath the university's athletic stadium. In addition to uranium-235 and graphite, it contained control rods made of cadmium, cadmium being a metallic element that absorbs neutrons and thus controls the reaction. When the rods were in the pile, there were fewer neutrons to fission uranium atoms and the reaction was slowed. But when the rods were pulled out, more neutrons were

[5] "History of Nuclear Energy - World Nuclear Association." n.d. Accessed August 17, 2022. https://world-nuclear.org/information-library/current-and-future-generation/outline-history-of-nuclear-energy.aspx.

available to split atoms and the chain reaction was sped up. After many attempts at this process, on the morning of December 2nd, 1942, the scientists were ready to begin a demonstration of Chicago Pile-1 to a group of spectators. Fermi ordered the control rods to be withdrawn a few inches at a time from the pile, and after several hours the nuclear reaction became self-sustaining. Fermi and his group had successfully transformed a scientific theory into a technological reality.[6]

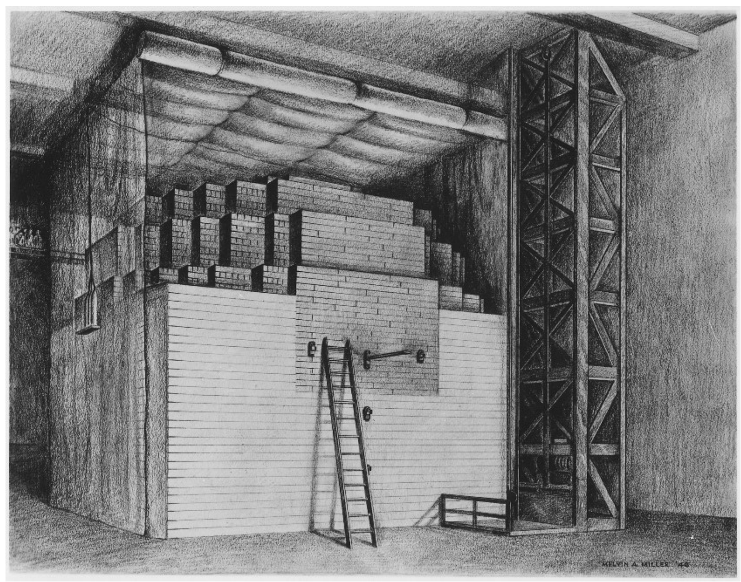


Figure 2.1: Artistic rendition of what Chicago Pile-1 looked like when constructed. (Source: Google)

Development of Power Plants

It was shortly after the demonstration of Chicago Pile-1 that the United States Congress created the Atomic Energy Commission so that further research could be done on nuclear fission and its use within peaceful applications. An early goal for the

[6] "10 Intriguing Facts About the World's First Nuclear Chain Reaction." n.d. Energy.Gov. Accessed May 17, 2022. https://www.energy.gov/ne/articles/10-intriguing-facts-about-worlds-first-nuclear-chain-reaction.

Atomic Energy Commission was to prove that the energy produced by reactors could be used to generate electricity for commercial use. This involved the construction of “breeder reactors”, which could create additional fissile material to be used to create more energy, hence the name. It wasn’t long before this goal was met, and by 1951, in the town of Arco, Idaho, the Experimental Breeder Reactor #1 (EBR-1) was finished construction and began tests. By 1955 a nearby reactor by the name of BORAX III was constructed to produce electricity for the town, and on July 17th, 1955, Arco became the first town in the world to be lit with atomic power.[7]

Many of these early reactors had only been meant to produce power for around a decade and then be shut down after the intended purpose was achieved. Both the private sector and public run “civilian” power plants made breakthroughs across the country as electricity was produced for towns like Santa Susana, California. These breakthroughs were not just confined to land-use either, as nuclear reactors even began to evolve for naval use onboard ships and submarines. These onboard reactors allowed the vessels to have longer operations at sea without returning for refueling.

Shortly after the success in Idaho, within the town of Shippingport, Pennsylvania, the first large-scale commercial electricity-generating power plant came online. After this, the private industry became more interested in the development of additional reactors like the one in Pennsylvania. The nuclear industry grew exponentially throughout the 1960’s as utility companies witnessed this new form of energy production, which was economical, environmentally clean, and safe.

[7] “Nuclear Power in the USA - World Nuclear Association.” n.d. Accessed August 16, 2022. https://world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx.

This trend of growth within the nuclear industry continued into the 1970s and 1980s until demand then began to slow for electricity produced by fission because of several questions which had presented themselves in the years prior. Reactor safety, waste disposal, and other environmental and social considerations were chief among these concerns.

Figure 2.2: Photograph of the early nuclear facility at Shippingport, PA. (Source: Google)

<u>*Nuclear Incidents (US and abroad)*</u>

A major aspect within this thesis is the exploration of how the public currently perceives nuclear power. The main reason for this is the events which are covered within this section. It is important to note that, as with anything, there are positives and negatives, but with nuclear power the former inherent negatives of the past had started to show themselves on the global scale. As stated earlier, the nuclear industry had grown fast throughout the middle part of the 20^{th} century. With close to one-hundred nuclear power plants operating within the US (by the 1970s) and an equivalent value being built and operated by other world superpowers such as the former Soviet Union. There were bound to be growing pains within the domestic and abroad industry.

Ever since the first nuclear power plants were made, it was noted by scientists that there were risks within the traditional designs. The most dangerous of these risks being a “nuclear meltdown”, which occurs when core damage is done to the reactor from overheating. This overheating can be caused by design flaws, mechanical and electrical problems, and other external factors. It is worth noting that the term “nuclear meltdown” is not an official term as defined by the U.S. Nuclear Regulatory Commission nor the Department of Energy and serves as an example of how the public have taken to describing faults within the nuclear industry. The results of a “nuclear meltdown” are what was witnessed within the following case studies.

Three Mile Island

The Three Mile Island nuclear power plant is located just south of Harrisburg, Pennsylvania, sitting across the Susquehanna River from the town of Middletown. Constructed between 1968 to 1974, the nuclear plant consisted of two reactors (TMI-1 and TMI-2), each reactor having two corresponding cooling towers. Unit 1 came online in 1974 and unit 2 became operational in 1979. Other than unit 2 being overbudget during construction the plant operated as normal for the first few years of service with the designed power output of 819 megawatts (MW).

Beginning at 4am on the 28th of March 1979, the TMI-2 reactor began to experience either mechanical and/or electrical problems within the feedwater pumps which provide water to the steam generators that remove heat from the reactor core.

Automatically, the generators and reactor core began to shut down, which caused pressure to start rising within the core because it did not have the proper water levels to cool it down. In the event of such an occurrence, the plant was designed with a pressure valve automatically opening at the top of the chamber to begin releasing the pressure within the core and drop levels back down to normal. However, the valve did not close and became stuck open, giving false readings to the workers who were on staff in the control room that day and made them unaware that cooling water was being vented from the pressurizer in the form of steam. Unaware that the cooling water was not at preferred levels, the plant staff took a series of actions which led to the top of the reactor core becoming exposed and overheated. Eventually, causing what had made the event so infamously remembered, which was a hydrogen bubble that had formed within the reactor which had the potential to combust. Consequently, radioactive gases were vented into the surrounding environment to relieve core pressure. There was also contaminated water, which had been in the reactor core that nearly overflowed the containment vessel.[8]

[8] "Backgrounder On The Three Mile Island Accident | NRC.Gov." Accessed March 14, 2022. https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html#top.

Figure 2.3: Aerial imagery of the TMI Plant as seen inactive post incident. (Source: PennLive)

Following the event there was large-scale backlash from the public and hundreds of tests were done on the surrounding environment and inhabitants to ensure that the radiation leaked was of non-dangerous levels. Government officials, including Jimmy Carter (the president at the time), came to the site so that the power plant could prove it could continue safe operations and clean-up of the affected areas. To date, the incident at Three Mile Island marked the worst nuclear disaster within the United States and prompted many changes in reactor design, personnel training, and other leading guidelines. TMI was shut down in 2019 due to failure of PA state legislature to advocate for the plant to economically compete against other forms of energy for electricity production. State representatives voted to give subsidies to coal and gas-powered plants and fracking that made it so that they could provide less costly energy than TMI. Currently the nuclear plant is in the process of being decommissioned.

The reactor vessel which will be looked at to be used within this thesis project is that of a small modular reactor. A huge improvement to these vessels is that they operate on more passive means, therefore do not have to rely on pumps and other cumbersome systems which can break and lead to the core becoming overheated. New designs allow the water to take advantage of natural convection and circulate around the closed loop system, which also does not need the large intakes of water seen at Three Mile Island. Passive systems also extend into the designed shutdown of these vessels in the event of an emergency, allowing the reactor to power down on its own, eliminating possible human error or ill-advised intervention. These aspects will be highlighted in greater detail within later sections on newer case study projects.

Chernobyl

Chernobyl, a more common name given to the Vladimir I Lenin nuclear power plant was a sprawling complex of nuclear reactors built under the communist leadership of the Soviet Union. Now outside of present-day Kyiv, Ukraine, it stands as a testament to the respect which must be shown to nuclear technology and how a flawed reactor design combined with inadequately trained personnel and other faults within the USSR leadership could lead to the worst nuclear disaster in human history.

Beginning in the early morning hours of April 25th, 1986, the reactor crew on the Chernobyl 4 reactor began preparing for a test to determine how long the turbines would spin to supply power to the circulation pumps in the event of a loss in electrical power to the plant. This test was not unique and had been carried out at Chernobyl in previous years, however this time a series of operator errors such as the disabling of automatic shutdown mechanisms preceded the attempted test. Adding to this an already faulty design of the Soviet RBMK-1000 reactor it was a disaster waiting to happen.

As the test was carried out the control room workers took a series of steps which placed the reactor 4 core into dangerously unstable conditions. Compiling this problem was that the RBMK-1000 reactor had graphite tipped control rods, which when inserted caused a temporary surge in power levels (even though control rods are supposed to dampen the reactions). Realizing something was wrong, the workers attempted to intervene. This led to the combination of extremely hot fuel being mixed with cooling water which managed to cause fuel fragmentation along with rapid steam production and an increase in pressure from the graphite rods. The design of the RBMK-1000 reactor was such that substantial damage to even three or four fuel assemblies resulted in the destruction of the reactor. The overpressure caused the 1000-ton cover plate of the reactor to become partially detached, rupturing the fuel channels, and jamming all the control rods in place. At that time the rods were only halfway down. Intense steam generation then spread throughout the whole vessel, causing a steam explosion, and releasing fission products to the atmosphere. About two to three seconds later, a second explosion threw out fragments from the fuel channels and hot graphite. The second explosion was likely to have been caused by the production of hydrogen from chemical reactions inside the core which caused a bubble to build up at the bottom of the reactor. There were no sensors at the bottom to indicate the looming danger to the control room.[9]

[9] "Chernobyl | Chernobyl Accident | Chernobyl Disaster - World Nuclear Association." Accessed March 14, 2022. https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/chernobyl-accident.aspx.

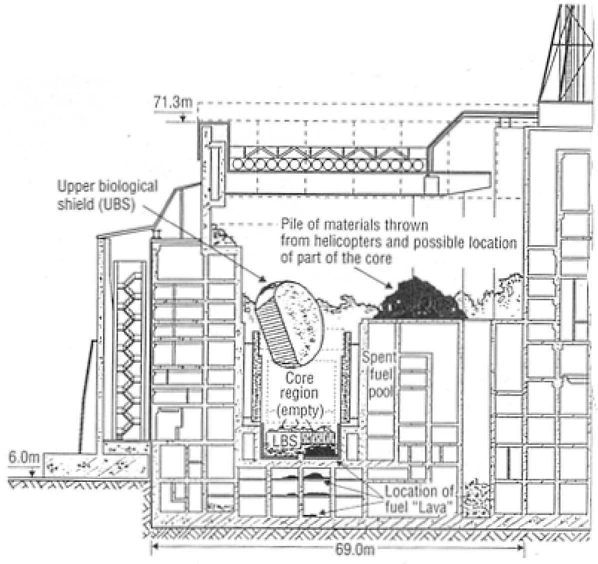


Figure 2.4: Diagram depicting the Chernobyl 4 reactor building post-accident (Source: World Nuclear Association)

Over the following days, a fire burned inside the reactor hall which released tons of radioactive particles into the atmosphere, along with the already exposed reactor fuel from the prior explosion (which was laying on the reactor building roof and surrounding areas). As this event had never happened in human history, the Soviet Union took unproven steps to try and extinguish the fire and contain the radiation leaks. Although many of these steps were not carried out using the best practices, Soviet leadership tried to contain the spread of news about the reactor explosion, which only compounded the problems. To this day it is hard to tabulate the cost on human life and environmental impacts this event had, although we know in both cases it had a wide range of both immediate and long-term effects.

Today, Chernobyl sits within an exclusion zone of its own creation, where nobody is allowed to live and everything within its confines has been abandoned. Although radiation levels have dropped since the 1986 incident, it is predicted that it could take thousands of years for levels to return to normal. Chernobyl reactor 4 is now contained under a “safe confinement shelter”, in which robots and people in protective gear are slowly working to dismantle the damaged parts of the core and safely contain any left-over radioactive material. This has been a decades-long effort from multiple countries and has recently seen further turmoil as the Russian invasion of Ukraine aims to reclaim the site.

Figure 2.5: Image showing the present-day Safe Confinement Shelter covering the damaged reactor 4 at Chernobyl. (Source: Google)

Being far safer than the designs of the RBMK-1000 reactor, the small modular reactor(s) proposed within this thesis project are based on decades of safety tests, design critique, and licensing procedures. Furthermore, being of smaller scale means that their power output is far less than that of large plants such as Chernobyl, meaning that the danger of such an event as Chernobyl simply isn’t there. As highlighted earlier, the passive systems relied on in newer U.S. designs means that people are not placed in a situation as to cause such catastrophe. Finally, with the use of newer fuel forms such as pebble bed reactors, the fissile material is better contained and easily controllable.

Fukushima

Fukushima Daiichi is a nuclear power station on the eastern coast of Japan's main island. Being the first of two power plants built in the region (Fukushima Daini being the second, sister plant), it was originally constructed in 1971 with six boiling water reactors. It also made history as being the first nuclear power plant to be operated entirely by the Tokyo Electric Power Company. Daiichi was one of many nuclear plants constructed post-WWII to meet Japan's need for energy to get industry back up and running, while also undoing the decades of technological loss they had suffered from the war. Nuclear fit well within the island nation because of the country's lack of other natural resources (such as coal) and was backed by other political policies around the time of its conception in Japan.

Since the reactor buildings were constructed in Japan, it is no surprise that they were designed to handle seismic events such as earthquakes. However, nobody could predict the anomaly of events which took place in March and April of 2011. Beginning on March 11th at 2:46 PM of that year, a record-breaking 9.0 earthquake took place off the coast of one of Japan's smaller islands of Honshu. As designed, the Daiichi plant automatically shut down units 1,2, and 3 (units 4,5, and 6 were already offline for scheduled maintenance) and sustained no notable damage from the initial earthquake. An hour later, a 46-foot-tall tsunami wave hit the plant and overtook the seawall which was put in place to stop surge waters from inundating the plant.

Overtaking these seawalls and flooding the power plant, the tsunami waters shut down all but one of the underground generators used to cool the reactors. In response workers on shift that day took steps to try and bring back-up systems online and were successful. Still, an emergency evacuation order was given to the surrounding areas that night.

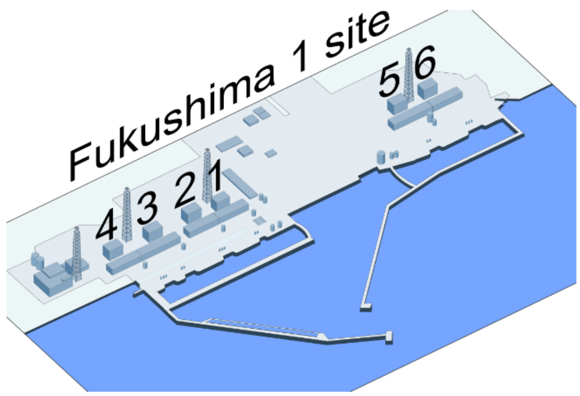


Figure 2.6: Diagram showing the location of each of the six nuclear reactors and their corresponding seawalls at Fukushima Daiichi (Source: Google)

On the following day (March 12th, 2011) these back-up systems ran out of battery power and begin to leave the core of unit 3 exposed, thus starting to melt itself and sustain damage. Emergency levels were raised for each of the individual reactors just before a major (suspected) hydrogen explosion occurred within the unit 3 building, which would have further damaged the cooling systems of unit 2. A series of smaller explosions occurred which damaged reactor 4 and started fires within the plant. Workers began to establish power back to the emergency cooling systems as Japanese and U.S. fire tankers tried to extinguish the flames. Radioactive smoke and contaminated water poured out of the reactors, entering both the surrounding Fukushima region and the sea.

Over the following days the fire was brought under control and water was continuously circulated into the damaged reactors thanks to the workers who successfully returned power to parts of the plant. The largest radiation release happened on March 15th from an unknown source within the unit 2 reactor. Although some of the events which took place during the crisis are still not confirmed due to the recency its occurrence, there are ongoing international investigations to determine this information. What is known is that the fire was extinguished and all six of the reactors were brought under control to begin decontamination processes.[10]

Today, the region of Fukushima serves as a modern-day case study to what was witnessed during and after Chernobyl, as the Japanese government created a "safe zone" around the plant which extends for miles in diameter around the nuclear power station. Although people had to be evacuated and be displaced from the emergency, we are seeing radiation levels being remediated in areas which are safe enough for people to reinhabit. This is thanks to the lessons learned at Chernobyl, and the proactive steps taken by the Japanese government. At the Daiichi plant, cleanup efforts continue and will continue for decades as the damaged fuel is extracted out of the affected reactor cores. Both soil and water are excavated, treated, and stored until the radiation levels subside enough to be reintroduced back into the environment. This aspect of the cleanup continues to be under debate and make the news for the potential harm it may cause to the surrounding environments.

[10] "Fukushima Daiichi Accident - World Nuclear Association." Accessed March 15, 2022. https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-daiichi-accident.aspx.

Figure 2.7: Aerial image showing the current state of the Fukushima Daiichi nuclear complex, with the sprawling number of extracted containments in temporary storage around the site. (Source: Google)

Newer, small modular reactor designs proposed within this thesis project are sounder than the reactor vessels seen deployed at Fukushima. With many of them being built in the American mid-west they are far from distressed geographic regions which are prone to natural disasters such as earthquakes, flooding, hurricanes, and other phenomenon which can cause harm to power plants. Adding to that, since SMR's operate on passive systems, loss of power to the plant does not affect the operations of the reactor vessels themselves and are able to maintain a safe temperature while it powers down.[11]

[11] "What Should I Do If a Small Modular Reactor Loses Off-Site Power?" n.d. Energy.Gov. Accessed May 18, 2022. https://www.energy.gov/ne/articles/what-should-i-do-if-small-modular-reactor-loses-site-power.

Current Standing of the US Nuclear Industry

Although the events outlined within each of the previous three case studies do not speak well on the use of nuclear power, it is important to highlight both the positive and negatives seen within the nuclear industry so that one may put into context how the industry has evolved to overcome these adversities. As each of these historical events had widespread implications to the policies, opinions, and infrastructure governing nuclear power.

Within the United States, nuclear energy now produces 19.7% of the country's electricity across 93 nuclear power plants. This being a higher percentage than previously seen within the country and abroad. Although there have been proposals for new reactors to be built within the U.S., a hiatus has been seen due to improved techniques to upgrade existing facilities. In 2016, the country saw the first new nuclear-powered reactor enter operation in the country for 20 years. Despite this, the number of operable reactors has reduced in recent years from a peak of 104 down to 93, as previously mentioned. Early closures have been brought on by a combination of factors including cheaper natural gas, market liberalization, over-subsidy of renewable sources, and political campaigning.

With the separate nuclear spheres of the United States and Soviet Union no longer existent, the exchange of technology across the nuclear industry is happening on a global scale. New reactors being built in China may have parts manufactured in France or Canada, and the fuel needed may come from as far away as Australia or Namibia. This exchange of information at a more open rate has allowed people working in the nuclear industry to create safer working environments, open new plants, and achieve a total of 18,000 reactor years of experience. It has also allowed nuclear technology to extend far beyond the means of energy production into the industries of medicine, space exploration, and other areas with a need for sustainable development.

New Reactor Designs

In addition to the numerous commercial reactors across the United States, which have been the focus of the first part of this thesis, it is important to note the evolution of newer reactors which are changing the industry. Until now, nuclear has been seen mainly as a generating source for electricity but, in addition to the 93 commercial reactors currently operating in America, there are another 220 research reactors operating within the United States and abroad used to produce isotopes used in the medical and industrial trades. This differing in reactor designs and they're intended purpose has been a hot topic within the international nuclear community. Some entities are even creating a scale to which all reactors, past, present, and future, fit into, gauged off of what "generation" they are. As of now, there are five generation classifications for nuclear reactors.

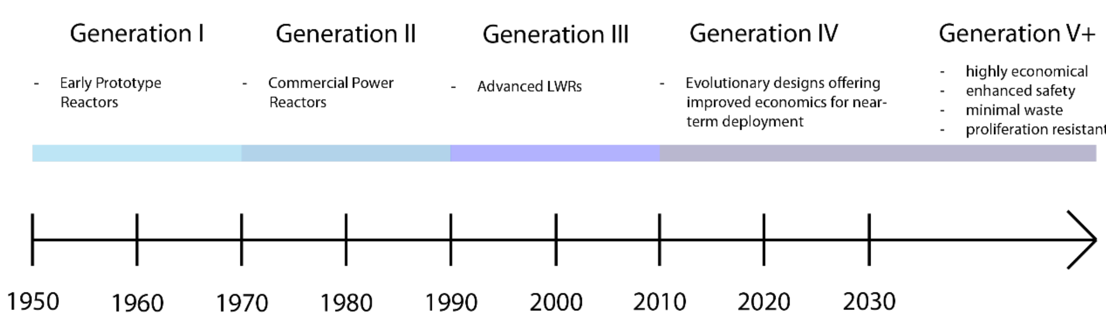


Figure 2.8: Timeline of generational evolution seen across nuclear power plants. (Source: Author)

Private companies such as BWX Technologies, Holtec, and other power companies are developing a plethora of new types of reactor designs, many of which aim to be either under construction or operational by the 2030's. Many of these reactors are smaller than the large-scale power plants discussed in earlier sections and rely on an overall design known as "small modular reactors". This classification of reactors allows for them to be safer by eliminating many of the accident initiators (seen to be the cause in the previous case studies) and take advantage of passive heat removal. Other than these designs being simpler, they are meant to have lower power output and supply energy to more localized regions, rather than vast electrical grids spanning over large regions. Positives to these newer reactors also include lower capital investment, greater efficiency, flexibility, and job growth. Additionally, these newer designs build on the lessons learned from past events.[12]

Developing Alternative Fuel Sources

With new reactor designs comes the tandem development of alternative fuel sources to be used both within the reactor core as fissile material and as moderators. Primarily, the material which has been studied to be a replacement for uranium-235 is the naturally accruing isotope thorium-232, which does not need to be enriched in order to be used within a nuclear reactor. Thorium is also unable to undergo fission on its own and needs to be bombarded with neutrons within a reactor to undergo the processes for creating energy. Therefore, thorium is more stable than uranium and can be controlled more easily, thus being a safer alternative. Another difference between

[12] Energy.gov. "Benefits of Small Modular Reactors (SMRs)." Accessed March 17, 2022. https://www.energy.gov/ne/benefits-small-modular-reactors-smrs.

uranium and thorium are the projected world resources found on earth. While U-238 is a somewhat rare material (U-235 being in even lower supply) which may run out as more reactors are built, thorium is estimated to have 6,355,000 unmined tons.

Another form of fission reactor are the molten chloride reactors, which still use uranium or thorium as the fuel source but integrate a molten salt mixture as the primary nuclear coolant. Molten salt reactors have the added benefits of higher efficiencies than reactors which use water as coolant. They also generated lower waste than the already minute amounts seen produced by pressurized water reactors. Some designs also do not call for solid fuels, which eliminate the need for the manufacturing and disposal of it. It is important to know that the development of molten salt reactors goes back to the 1950's and is not a new concept, however recent advancements in reactor technologies and changing political/economic drivers have made their design more practical in use within today's energy markets.

More specific to this thesis project, the classification of pebble bed reactors operates using the traditional fuel sources of uranium as the fissile material but packages the fuel differently than reactors, which use traditional fuel rods. Looking to be applied within this project, pebble bed reactors use large metallic spheres which house the fuel and are then placed into a reactor vessel with a number of other kernels (depending on the desired energy output). This allows the fissile material to be individually contained, instead of having large fuel rods filled with thousands of uranium pellets. The uranium kernels can also withstand much higher heats and form airtight seals around the fuel, allowing the overall plants to be constructed much closer to factories or urban areas.[13]

Figure 2.9: An enhanced image of what the inside of a uranium pebble looks like. (Source: X-Energy)

Specific examples of projects which use these technologies will be discussed further in the next chapter. Additional elaboration on their benefits and practical uses will also be highlighted. It is important to note that there are many more types of nuclear reactors under development, but the ones discussed earlier (such as pebble-bed reactors) are what are being currently seen as the most plausible for energy production.

Applications of Nuclear Energy

The focus of this thesis is on the application of nuclear technology for the use of energy production, but it has far more uses within society today than one may realize. Of course, many large-scale power plants are developed and used to create

[13] "X-Energy Is Developing a Pebble Bed Reactor That They Say Can't Melt Down." n.d. Energy.Gov. Accessed May 18, 2022. https://www.energy.gov/ne/articles/x-energy-developing-pebble-bed-reactor-they-say-cant-melt-down.

electricity within the United States, but there are hundreds more research reactors and others forms of nuclear expertise that have applications within the food and medical industries which make modern life possible for everyone. In addition, other forms of reactors are used onboard ships as reliable sources of long-term fuel and can create excess power for remote communities. An example of this being Russia's floating nuclear power stations which supply electricity and heated water to remote population centers.

Figure 2.10: Image of the floating Russian nuclear reactor, The Akademik Lomonosov (Source: BBC)

An example of how research reactors are used is seen within the reactor employed on the University of Maryland's campus, which does not actually produce any electricity and is instead used for academic purposes to teach students within associated majors about the operations of a reactor and its applications. One major application which the UMD research reactor and many others like it are utilized for is the harvesting of neutrons to be used within medicine to treat conditions such as cancer and other illnesses.

Figure 2.11: Image of the UMD research reactor. (Source: University of Maryland)

Apart from use within the medical industry, radiation is used within the food industry to help sterilize equipment and treat food products as to make sure everything meets the high-quality standards set in place, while also ensuring that the food lacks any harmful bacteria. This in turn prolongs the life of certain foods, preventing decay and allowing shelf life to be longer as to alleviate food waste. These applications are all for the health and safety of the general public and are the constant unacknowledged reasons why key aspects of many fields within America and abroad are made possible by nuclear technology.

Chapter 3: Precedent Projects

Nuclear Reactor Case Studies

To elaborate on the current uses of nuclear power within the United States (as constrained to energy production) several case study projects were looked at to show the plausible application of these technologies. All three of the projects analyzed are companies which are within the private sector and represent the renaissance happening within the industry as new technology is being developed and put to use for electrical generation. Although, one should know that many of these developing technologies are older designs used within reactors for decades now, these companies have found ways to refine their designs, making reactors safer, more economical, and reliable. Each of the three entities highlighted within the following sections was also looked at for aspects of their design which could plausibly be put to use within this thesis project to explore the advancements in nuclear power while also interfacing with other facets of the industry.

Terrapower

As stated by Terrapower, their "innovators create technologies to provide safe, affordable, and abundant carbon-free energy. They devise ways to use heat to drive economic growth while decarbonizing industry. And they develop processes to extract radioisotopes for medical use in lifesaving cancer treatments."[14] This shows the many ways people within the field have made possible advances within the

[14] "TerraPower." n.d. TerraPower. Accessed April 22, 2022. https://www.terrapower.com/.

private sector. A Terrapower project which aims to use the company's molten chloride fast reactor technology is the Natrium site.[15]

Natrium is a project presently under construction on a site in Wyoming intended to help shift the states detrimental reliance on coal fired power plants to a source of much cleaner power. Being one of the fastest and lowest-cost paths to providing this carbon-free technology, the Natrium plant features a 345MWe reactor that can be scaled to produce as much as 500MWe of power for the notable fluctuation in energy demand seen throughout a given day. This is made possible by a sodium fast reactor, combined with a molten salt energy storage system. Molten chloride fast reactors use salt as both the fuel and coolant in the reactor, which are based off designs tested in the 1950's through the 1970's. The now refined design allows the reactor to function at higher temperatures than traditional plants, which cause the reactor to be more efficient in its use of fuel, while eliminating all byproducts of fission and other contaminants. The plant is also compartmentalized so that the reactor and its workers are separate from the molten salt storage use groups, creating a safer and more streamlined design.[16]

[15] "TerraPower." n.d. TerraPower. Accessed April 22, 2022. https://www.terrapower.com/.
[16] "TerraPower." n.d. TerraPower. Accessed April 22, 2022. https://www.terrapower.com/.

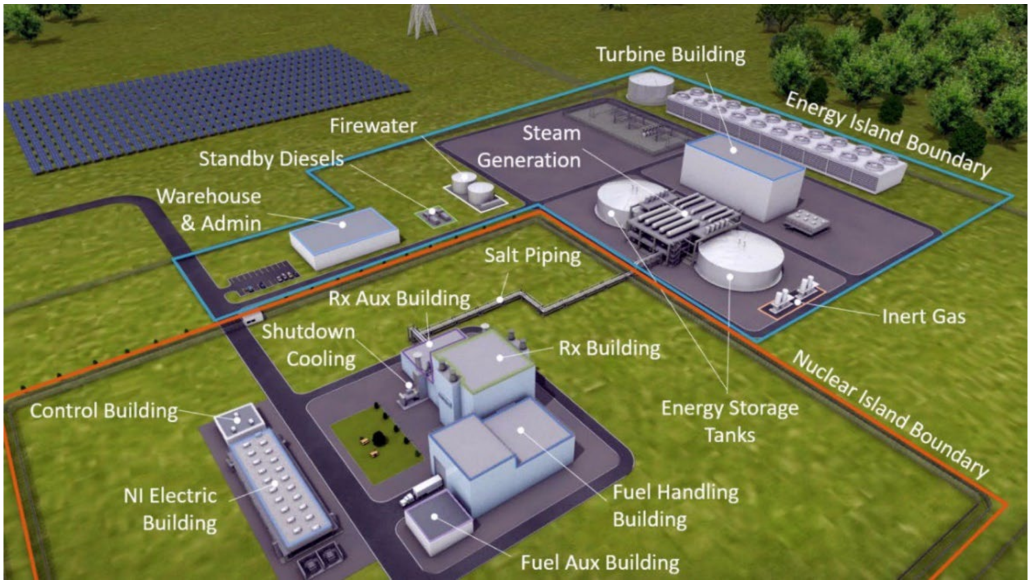


Figure 3.1: Perspective diagram showing major elements which compose the Natrium plant. (Source: Terrapower)

Slated for completion in the late 2020's, the Natrium plant will provide electricity to nearby towns and redevelop the land currently used by the coal-fired Naughton Power Plant. This project will present to the public ways in which the nuclear industry has advanced within the means of energy production, design, and adaptive reuse of previously developed land, while also showing ways nuclear power plants can work in tandem with differing forms of renewable energies.[17]

Terrapower's use of molten salt was a large factor as to why this company was selected to be a case study within this research as molten salt reactors are widely believed to be a plausible nuclear technology within the advancing industry. Also, their thought behind sistering other forms of sustainable energy production (wind, solar, etc.) into the overall project scope is something this thesis project sees as

[17] "TerraPower." n.d. TerraPower. Accessed April 22, 2022. https://www.terrapower.com/.

important as we cannot rely on just one form of carbon-free outlet to meet future energy demands.[18]

NuScale

Like Terrapower, NuScale utilizes reactor technology which has been in place for decades now within the United States, but their critique of the design is what allows their proposed power plants to be improved over traditional types. Utilizing the pressurized water-cooled reactor as highlighted earlier, NuScale aims to create power plants that are scalable based on their intended need within a given environment. Being the size of small modular reactors means this scalability can happen based on how many reactors are grouped together within a plant. Given the name VOYGR, the plants that employ this technology are meant to be used both within the United States and elsewhere.[19]

Figure 3.2: Rendering of a proposed VOYGR power plant as seen from an aerial view. (Source: NuScale)

[18] "TerraPower." n.d. TerraPower. Accessed April 22, 2022. https://www.terrapower.com/.
[19] "NuScale Power | SMR Nuclear Technology." n.d. Accessed April 22, 2022. https://www.nuscalepower.com/.

Other than being of modular design, the reactors that are to be used within VOYGR plants use passive principles to circulate water through the core and thus cutout the need for pumps and other cumbersome equipment that have the potential to not function properly. As water is heated by passing over the fuel rods it naturally rises through the core and becomes cooler. As it cools, it then sinks back down to the bottom of the core where it began its journey and thus continues the process of convection. The overall containment vessel, which houses the core components only, measures 76' tall by 15' in diameter, which is smaller than currently established plants and has a power output of 250MWt.[20]

NuScale has always focused on scalable, modular designs for their power plants as the upsides to this improved design are extensive. Additional advantages to using a small modular reactor include having the tried-and-true reliability of reactors which have seen service for decades now, but can be easily transported via truck, rail, or barge to wherever the need arises. Being on the smaller side also makes their reactor design more efficient as the water which is used to cool the reactor and turn the steam turbines for the generators eventually gets recycled back into the core and repeats the process; With that process, large amounts of new water do not have to be constantly pumped in.

Although no VOYGR plants have been constructed yet, it seems to be the closest of the three case studies to gaining real-world usage. As economics is a large driving force within the nuclear industry. The cost of these reactors is much smaller

[20] "NuScale Power | SMR Nuclear Technology." n.d. Accessed April 22, 2022. https://www.nuscalepower.com/.

than other forms of energy production. This low cost is achieved by the smaller scale of the power plant, and by modular design, allowing for shorter construction times. Other benefits to NuScale include their reactor's design being able to use less enriched fuel and having to be offline for shorter periods of time to conduct refueling operations.

As the NuScale technology relates back to this thesis project, the ideas of creating a plant whose architecture is not passive to its utilitarian needs but also creates pleasing spaces is important. Its modular design and scalability are aspects that are to be incorporated into the thesis project. VOYGR plants also incorporate public buildings around the site of the reactor complex, which is an important aspect of this thesis project. Additionally, elaborating on a tried-and-true reactor design is also commendable, as this means the prospective plant will be safe, reliable, and economical.

Kairos Power

Differing from the previous two precedents, Kairos was grown from a broad research effort at U.S. universities and national laboratories, therefore was founded to accelerate the development of an innovative nuclear technology that has the potential to transform the energy landscape both in the United States and abroad. Kairos aims to reduce technical risk through a novel approach to test iteration often lacking in the current nuclear industry. Their schedule is driven by the progressive goal of having a demonstration plant built in the U.S. before 2030 and a rapid deployment thereafter. This also being why the name Kairos was chosen, it being a Greek word that relates to the importance of a timeless call to action. In this case, that action is the perceived need to accelerate innovation within nuclear power and lead the charge to a future of clean energy.

To meet these momentous goals, Kairos has designed a reactor which has years of design philosophy, testing, and licensing procedures behind it. This reactor is the Kairos Power FHR, which is an advanced reactor technology that leverages fuel within a pebble form combined with a low-pressure fluoride salt coolant (similar to what was outlined within Terrapower's design). This design shares the common name of a "pebble-bed reactor", as touched on earlier. This means that instead of large fuel rod bundles which must be inserted into the core, the reactor replaces the rods with small balls that each have self-containing fuel within them. Resembling a large ball-pit, these reactors are seen to be safer than traditional designs as it cuts out the need for large coolant systems since the fuel pebbles rely on passive cooling strategies. Also, their material make-up of ceramic can withstand the high temperatures within the core, speculating that this cuts out the risk of a meltdown. From there, the technology within a pebble-bed reactor uses an efficient steam cycle to convert heat from fission into electricity much like any other steam-electric power plant. This also can help to complement other renewable energy sources.

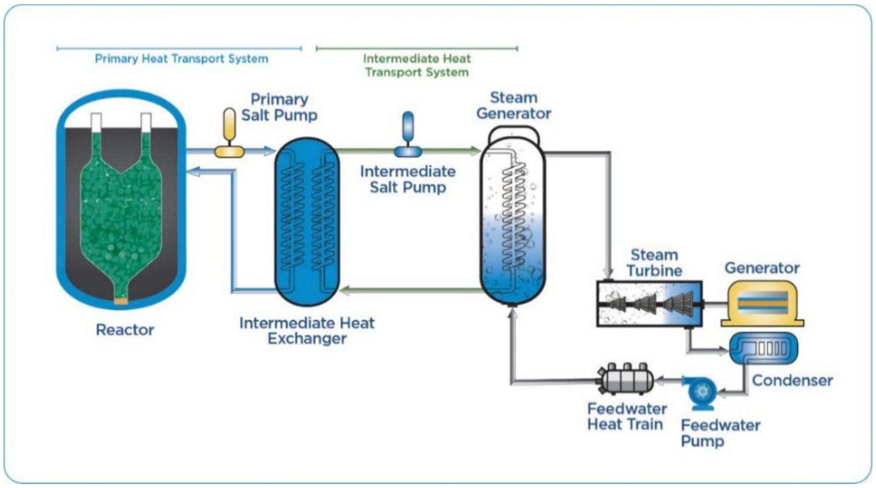


Figure 3.3: A diagram which visualizes how Kairos's pebble bed reactor will function. (Source: Kairos Power)

The main driving factors behind the development of this type of reactor are characteristics which are important to customers of any energy production company, those being the licensing ability, constructability, operability, and responsibility of the power plant. Physical sites have been chosen to provide real-world feedback on how their designs and philosophy will be applicable to the nuclear field and overall energy market. These sites are within the states of New Mexico and Tennessee. Albuquerque, New Mexico was chosen to host the research and development center, while an abandoned technology park within eastern Tennessee was selected to be the site of a low-power demonstration reactor. Both sites show how the industry can reuse formerly developed land to host new development (a theme within this thesis project) and therefore create sustainable construction practices. Another way in which the Kairos case study relates to this thesis project is the way each site thinks about the surrounding communities' best interests and how it can be used by the public domain. With respect to Kairos Power, they are doing this by forecasting how many highpaying local jobs the facilities will create for the nearby town(s) and the money which will help economic growth.[21]

Overall, Kairos Power was researched as a case study within this thesis project for their progressive goals of having a plant built before 2030 and finding timely and plausible methods for meeting energy demands. Secondly, the design of a pebble-bed reactor, similar to molten salt reactors, is seen as a technology which can easily lend itself to real-world application. Possibly even becoming the reactor design which is pursued for use within the designed thesis project.

Figure 3.4: Artistic rendering of what the proposed Hermes plant will look like, as proposed by Kairos. (Source: World Nuclear News)

[21] "Company." n.d. Kairos Power (blog). Accessed April 22, 2022. https://kairospower.com/company/.

Power Plant Visitor Centers

The most important aspect to this thesis project is the understanding of how public perception impacts the nuclear industry and reversing that view. It is important to also explore how the nuclear industry affects the public domain. One way for both the public and the nuclear industry to communicate is using visitor centers. All nuclear installations which were built in the past or commissioned in recent years (both in the U.S. and abroad) have had a corresponding center designed with them to act as a place for public outreach. A visitor center is the primary communication tool used by the nuclear industry to reach out to the public. In a national poll, which was conducted in 1992 by the U.S. Department of Energy, members of the public were asked if they have visited a center located at a nuclear power plant in the U.S., of which sixteen percent answered yes. Of this group, seventy-two percent of people said they walked away feeling as though nuclear energy is a good way to produce electricity. This shows that much of the distrust and/or fear towards the nuclear industry is only in part because of the incidents covered in earlier chapters, but more so due to a lack of understanding of the technology, thus highlighting why the need for visitor centers is paramount to the operations of nuclear facilities.[22]

Visitor centers of existing, large-scale plants have even been retrofitted to continue their usage as tools to be utilized by the public. Examples such as the centers at Fort Saint Vrain and Sequoyah Nuclear Power Stations have had new exhibits put into place to show the representations of technology currently in use within the

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[22] OSTI.gov. "Should The Public Be Encouraged To Visit Nuclear Plant Sites." Accessed April 17, 2022
https://inis.iaea.org/collection/NCLCollectionStore/_Public/36/018/36018053.pdf?r=1&r=1

facility. Against this background, it is clear that information centers help considerably to familiarize the public with nuclear energy and to establish or reinforce confidence in the ability of the utility company to manage such facilities safely. The public can read, listen, and talk about the subject, they can see and touch models, and become engaged through interactive displays. Members of the public can also put a human face to the company which runs the plant by meeting plant personnel. Finally, visitor centers act as a focal point for a range of community relations that will help to build trust and credibility for the company and nuclear installation.[23]

It is also important for the visitor center to strike a balance between being closely related to the corresponding nuclear facility, but not to be seen as a public acceptance tool and more so as a neutral information opportunity. The following examples, although all outside of the United States, have (or had) been good examples of these ideas and act as case studies to show how the interaction with the public is of utmost importance within the nuclear industry.

British Nuclear Fuels Plc

British Nuclear Fuels Plc, which ran several nuclear fuel cycle activities across the UK, had established in 1988 an important visitor center at the Sellafield nuclear fuel cycle complex. The communication approach selected was based on openness, open information and an open door to the public, with the aim to reestablish the credibility of the nuclear industry and promote a more positive image of the company's activities, which in the past had suffered from a bad reputation. The

[23] Sumihara, Noriya. "FLAMBOYANT REPRESENTATION OF NUCLEAR POWERSTATION VISITOR CENTERS IN JAPAN: REVEALING OR CONCEALING, OR CONCEALING BY REVEALING?," n.d., 17.

communication strategy of the Sellafield visitor center sought to create a feeling of space and relaxation for the visitor as they proceeded from the reception area, through various exhibits and audio-visual areas or media viewing rooms, to animated models and "hands-on" equipment. Sound and feel were used to guide the visitor through a simulated reactor where they would discover safety and control concepts. This concept of a simulated reactor is something which ties into the program of this thesis. Radioactive waste management was also addressed, which united the themes of the exhibition and showed the full life cycle of materials used in nuclear energy.

Figure 3.5: Aerial photograph of the former visitor center at the Sellafield nuclear complex. (Source: Google)

Nuclear Electric Plc

Nuclear Electric Plc runs nuclear power plants across England and Wales and has developed at its visitor centers a communication strategy which is aimed at progressively involving the visitor into the subject of nuclear electricity. This strategy is based on a sequence of five steps: inspiration, exploration, understanding, involvement, and action. Visitors are first led to realize the nature of the energy problem in modern society. Second, they are briefed on the potential of nuclear energy to meet future demands. Third, visitors can then proceed to more specific exhibitions within the center. Fourth, visitors become interested in visiting the nuclear power station itself. Lastly, the content from the previous steps is summarized and the individual can decide on their stance on nuclear power.

Electricité de France

With France having 73% of its electricity generated via nuclear power, EDF saw it important to create extensive programs across all 20 visitor centers at each of their nuclear power plants. Each center has a common approach, which is based on openness and transparency of information. The use of such centers is as a privileged communication tool with the public. This approach can be seen at the nuclear power site in Chinon, France. Here, the visit to the information center is followed by a tour of the first commercial nuclear power station ever operated by EDF, now transformed into a museum of nuclear power. The visit of the museum has presentations of a film which puts the operation of this first plant beginning in 1963, in perspective with major world events of the time. The visitor walks through all major parts of the plant, which has the shape of a one-hundred-foot diameter ball. It houses a control room, heat exchangers, and reactor core, each of which is for show only. The coupling of the visitor center and the museum allows a hands-on discovery of the functioning of a nuclear power station, including, of course, the safety aspects. The visit can also be continued by a tour of the modern 900 MWe PWR units on the site.

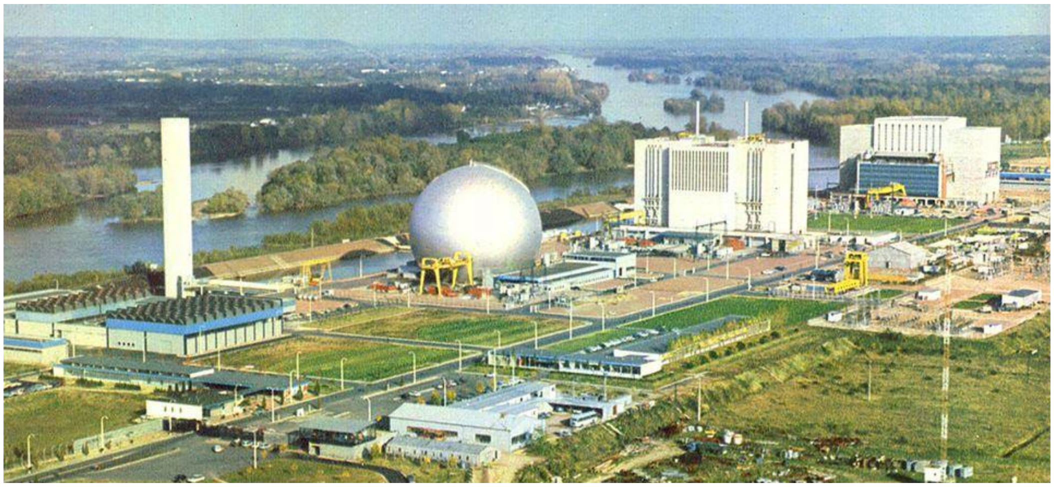

Figure 3.6: Picture showing the spherical information center sitting within the Chinon Nuclear Power Plant. (Source: Google)

Although these case studies are older examples, the ideas they expound are just as relevant today as when these facilities were originally built. It is important for the nuclear industry, both within the United States and abroad, to have transparency throughout their operations. Of which, their architecture can express. This ensures that members of the public are consistently getting reliable information and can live in harmony with the power plants built in or around their communities. Moreover, integrated public facilities are a hallmark of this thesis project and will take precedence from these examples as to show the permeability of how the areas of the power plant and civilian areas can coexist while still maintaining the essentials of safety and security.

Chapter 4: Nuclear Power and Public Relations

Public Perception, Then and Now

Background

Nuclear power has a complex history within the United States; since the advent of the technology people have been either strongly in favor of its use or just as evenly opposed. When it comes to nuclear energy, there is rarely ever a middle ground in people's opinion, mostly because of the environmental, safety, political, and economic impacts some see as negatives which outweigh the inherent positives. Negative connotations of nuclear power have also been brought into front page news when nuclear incidents such as the events at Three Mile Island and Chernobyl have happened in the past, thus compounding peoples misguided judgments. However, there was a time when many people in the U.S. thought of nuclear as the answer to many of the world's problems and saw unlimited potential in its usage.

Around the advent of nuclear energy within America, people saw this new technology as a solution to many of society's problems, spanning beyond simple energy production and into the incorporation of micro reactors into cars (Ford Nucleon) and other elements of everyday life. It wasn't until the events at Three Mile Island along with several other smaller-scale incidents during the nuclear industry's development that the view of nuclear power began to tarnish within the public eye. However, after each major incident (TMI, Chernobyl, Fukushima) the outlook on nuclear has always bounced back to a median point where the public does not completely reject its idea, nor do they entirely accept it. For decades now, the nuclear industry has lain within this middle ground of whether to be cared for more and placed on a pedestal, to solve the worlds growing need for sustainable energy, or to be completely forgotten about as a controversial relic of the past.

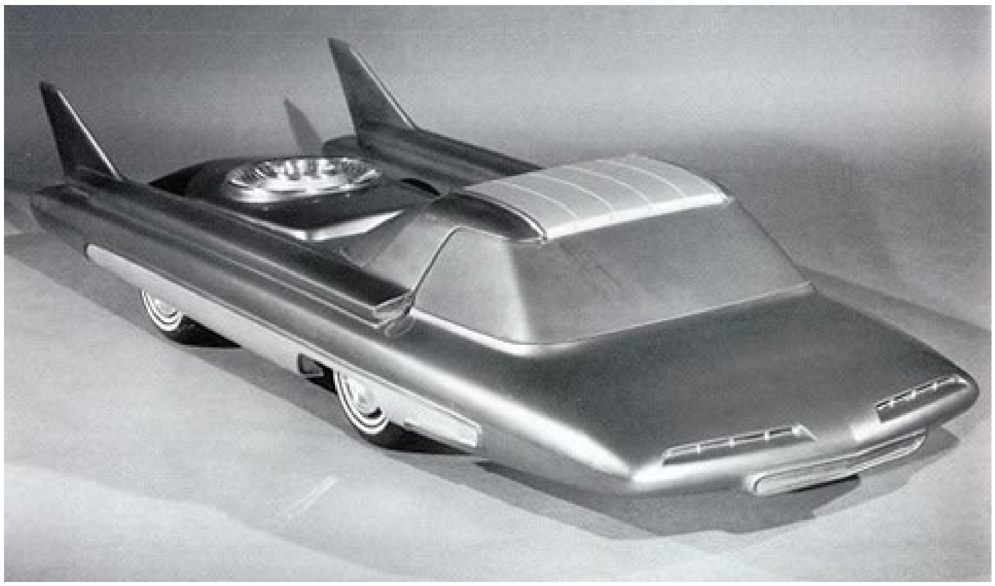

Figure 4.1: Image showing Ford's nuclear powered concept car, known as the Nucleon. (Source: Google)

Throughout 1950's America, there was a lot of activity centered around nuclear technology. This period became to be known as "The Atomic Age". This was mainly because of the technological arms race between the capitalist West, against the communist East (United States and the former Soviet Union). Much of this was driven by political tensions and paranoia following the nuclear detonations during and following the events of World War II. Many people even became numb and were unfazed by the above ground tests being conducted in the western United States, seeing it more so as a tourist attraction. By 1955, President Eisenhower wanted to shift this obsession with nuclear weaponry to a more productive matter, that being nuclear technology used for energy production and solving other problems within society. He himself, along with the Atomic Energy Commission created a movement known as “Atoms for Peace”, which highlighted the need for advancements in nuclear power plants and their usage to meet the country’s energy demands. This positive outlook on nuclear continued throughout the 20th century until the 1970s, when electricity demand fell and construction costs rose, causing destabilization internationally and creating economic difficulties within the industry and public opposition.[24]

Nuclear in Pop Culture

As America moved into the middle and later parts of the 20th century the relationship with nuclear power became ever more prevalent throughout people’s lives. Although wary from the complex past nuclear technology had, people still found its potential to be fascinating. Thus, nuclear energy played a large part in many pop-culture icons seen created in the 20th century, as well as today. With the original 1966 Batmobile being envisioned to be nuclear powered and charged by the “Bat Reactor” people saw this as the technology of the future. Since production of cars such as the Ford Nucleon never came to fruition, people’s imaginations still wanted to see what nuclear had in store in movies, tv shows, and other media.

Moving forward into 1985, people saw how nuclear technology could once again be used to power a car of the future (literally) in the movie *Back to the Future,*

[24] “The Atomic Age | American Experience | PBS.” Accessed April 20, 2022. https://www.pbs.org/wgbh/americanexperience/features/lasvegas-atomic-age/.

which showcased Doc Brown's plutonium-powered DeLorean car capable of traveling through time. Seemingly farfetched and laughable by today's standards, the allure of nuclear is nothing to take lightly as its constant interpretation in pop culture represents how integrated it has become within American society. This is a possible reason behind why even after several real-life nuclear incidents, people still bounce back to being somewhat supportive of the industry: its promises of future progress are still prevalent.

Current Standing

In recent years there seems to be an increase in the acceptance of nuclear power within the U.S., according to an environmental poll done by Gallup as an annual gage on energy statistics. Although down from the high of a 62% acceptance rate in 2010, the Gallup poll conducted in 2019 showed a 49% acceptance rate which has been on the rise since the dip in 2011 following the incident at Fukushima. Statistics taken since 1994 show that negative incidents within the nuclear industry are not the main factor for people to be accepting of the technology or not. This more so has to do with the fluctuating prices of oil. To support this, other polls have been conducted by Nuclear Newswire, Pew Research Center, and other entities, each showing slightly differing results. Nonetheless each result shows an increase in public acceptance over the past few decades, anywhere from 49% up to 62% of people clearly in favor of the use of nuclear energy.[25]

[25] "US Public Opinion Evenly Split on Nuclear: Nuclear Policies - World Nuclear News." Accessed April 20, 2022. https://world-nuclear-news.org/Articles/US-public-opinion-evenly-split-on-nuclear.

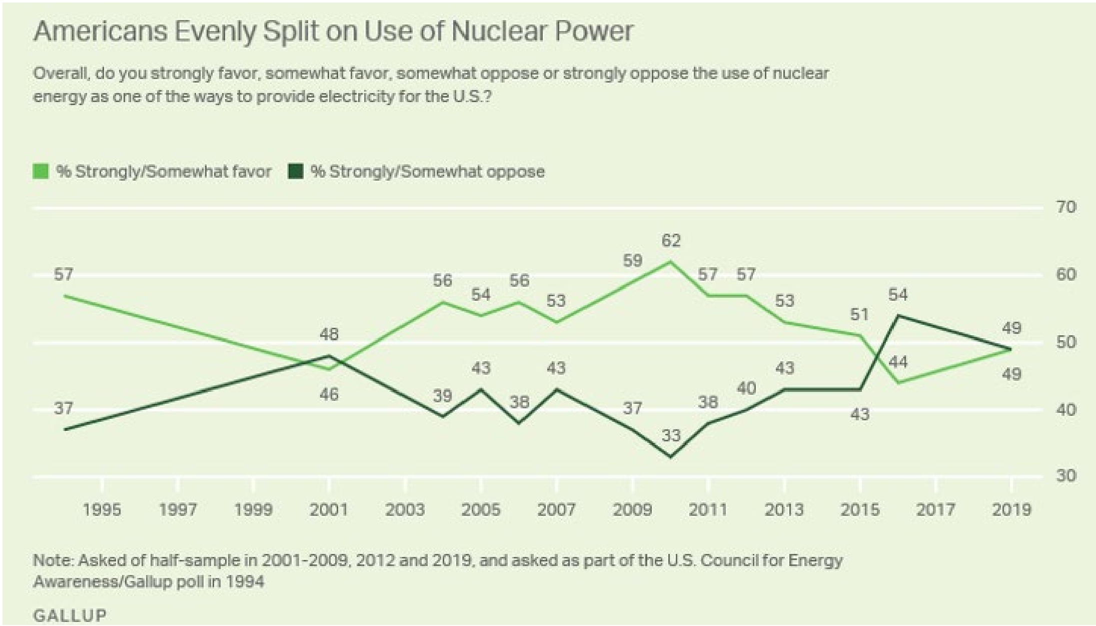

Figure 4.2: Graph showing the fluctuating acceptance factor of nuclear power within the U.S. (Source: World Nuclear News)

To elaborate on nuclear incidents and their impacts on the public perception of nuclear power, further research was done to determine why and how each event damaged the paradigm of the nuclear industry. The Three Mile Island accident in March 1979 and the much more severe Chernobyl accident in April 1986 had a significant impact on public attitudes toward nuclear power. This can be seen in the abrupt change in public opinion in Finland in 1986. One factor heavily influencing trust in nuclear plant operators is any significant time delay between an event and the release of information to the public. For the Three Mile Island and Chernobyl events, this period was long. Additionally, the information that was known to the public was sometimes incorrect or not the full story (for Chernobyl, this censoring was done on purpose). Today, response times have been drastically shortened and even small events (such as simple refueling exercises) in nuclear power plants can be followed through the media and news outlets with a high degree of transparency.

Shifting the Paradigm

A major aspect of the nuclear industry is simply making people aware of all the positives the technology inherently has. For instance, many people favor the United States going carbon neutral by 2050 and the support of renewable energies as well as valuing modern amenities such as clean air, clean drinking water, preservation of natural resources, and minimal waste, but do not realize what needs to happen to sustain and/or achieve these goals. Without the growth and advancement of nuclear power, many of these things we take for granted now will simply not be possible within the coming decades. For this reason, a major element that the nuclear industry will need to cater to is showcasing that which is made possible solely by nuclear power.

Largely controlled by political actions, the nuclear industry must always strive to assert itself as an economical, reliable, sustainable, and most of all as a safe form of energy production. A major reason as to why Three Mile Island began its decommissioning process in 2020 was the failure of the Pennsylvania state legislature to allow nuclear energy to keep costs down and compete with other power companies, mainly ones dealing with natural gas. Unable to sell their electricity to enough clients to be considered viable, the power plant was unable to keep operating. This is only one example of many where the states and/or federal government has ultimately led to the downfall of nuclear power plants.

This shift within the nuclear industries paradigm must start at either the top or bottom of the political ladder, i.e., by either winning over the general public first or by convincing political entities of the technologies plausibility within the coming decades. In either case, a willingness to communicate information must be at the forefront of any venture such as this. Dialog must go both ways, as voices from the public need to be heard by the stakeholders so that the industry is made aware of people's concerns. Additionally, stakeholders can help reach out to policymakers, media, community planners, and other important parties involved in the processes of a region's development.[26]

Most importantly, people must realize that nuclear power is the safest option for leading the U.S. and other international powers to a carbon-free sustainable future. In the months following the world's worst nuclear disaster at Chernobyl, 50 people died. Although tragic, this number is far less than other elements caused by the harvesting and burning of fossil fuels. Even following the events at Three Mile Island in 1979, and the later incident at the Fukushima nuclear plant in 2011, no one died as a direct result of the events at the power plants. Furthermore, nuclear power does not release harmful byproducts into the environment like fossil fuels and does not require the daily consumption of natural resources to keep operating. Furthermore, even after thousands of years of cumulative reactor-years in service across 36 countries, there have only been three major accidents within the program. A safety record that few

[26] "Stakeholder Involvement." Text. IAEA, April 13, 2016. https://www.iaea.org/topics/stakeholder-involvement.

technologies in human history can boast. The statistics show how nuclear power is the safest route to take for a sustainable future.[27]

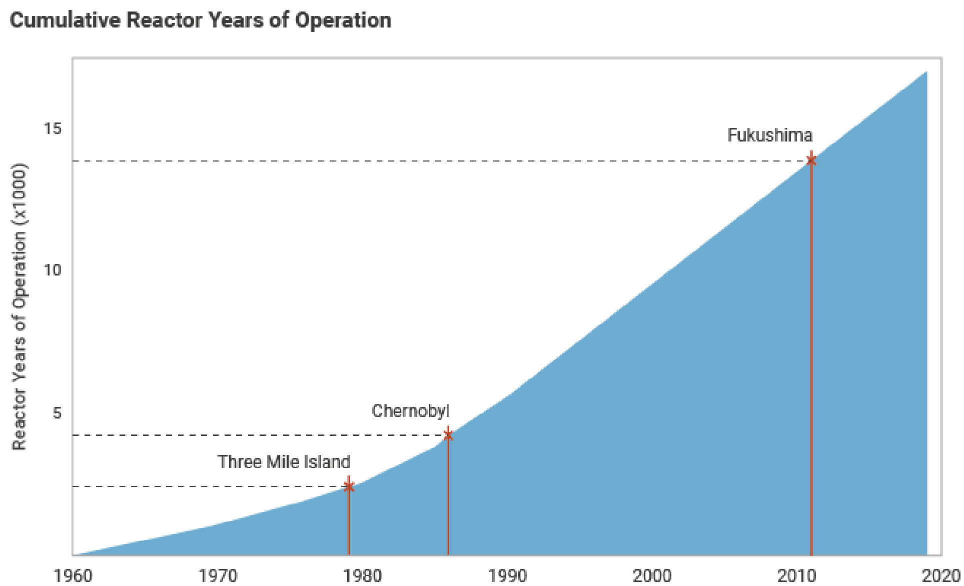

Figure 4.3: Graph showing the three major accidents within the civil nuclear program's history according to how many reactor-years of operation each one had at the time of accident. (Source: World Nuclear Association)

These aspects of the politics involved in nuclear power, as well as the safety statistics, and other upsides to the technology are what needs to be brought across to the public. Therefore, a major aspect of this thesis is the design of corresponding areas for public discourse: to allow people the chance to have their voices be heard, while also being balanced out by feedback from people who work within and alongside the nuclear industry. Additionally, the power plant which will be designed alongside the public facilities will find ways to interface with the community around

[27] "Safety of Nuclear Reactors - World Nuclear Association." Accessed April 21, 2022. https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/safety-of-nuclear-power-reactors.aspx.

the chosen site so that it can exemplify the opportunities made possible by nuclear power. Examples of this can be simply powering a nearby neighborhood using the electricity from the plant or by powering water treatment plants to provide safe drinking water. Possibilities also extend to using the byproduct of heat generated from the plant for use within the community, such as to keeping roads ice-free during colder months or purifying brackish ground water. This all pairs with the importance of showing the public how minimal of an impact the power plant operations have on the surrounding environment and generation of waste.

Perceived Aspects of the Nuclear Industry

With the specialized nature of nuclear power, the plants that are operated within the United States and abroad must follow many standards set in place for their successful operations. Thereby, this section is a conjectural analysis on main components that nuclear power plants consist of and their perceived image by the public. Some of these elements such as the architecture, and site design of the facilities, are what will be explored within the thesis design to better communicate the afore mentioned positive aspects of nuclear power. Much of the infrastructure that comprises a nuclear power plant can be seen to have double meanings, that being their intended purposes and then the way they are interpreted by the public.

Architecture

Often lacking any sort of proper architecture, power plants tend to focus on the utilitarian needs of the engineering over extravagant building designs. Although practical, this eliminates any meaning behind the buildings, which comprises a plant and leaves much up to interpretation. The expansive halls and immense cooling towers which make up many of the large-scale nuclear power plants across the U.S. have become the icons of the industry but have caused people to think of nuclear power solely in the traditional sense. Ironically, the cooling towers, which only discharge water vapor, have been used in numerous shows, movies, and other pop culture outlets to show production of pollution where pollution simply isn't present. This interpretation is a prime example of elements within a nuclear plant which have an identity to the public which is far different than their intended purpose.

Besides being used to make nuclear power look bad, the monolithic appearance much of the nuclear infrastructure has can be daunting from an onlooker's perspective. While much of this is done for safety, security, and to meet other regulatory guidelines, it should be explored how critiques of these designs can help alleviate tense feelings towards nuclear power. For this reason, NuScale was researched as a case study project for their elaboration of established designs. For many industrial projects, there is often a tradeoff between engineering and architecture, with the latter half usually being value-engineered out of the equation. If it were not for sacrificing architecture and the two fields worked in tandem with one another to achieve a power plant which fulfills its duties to generate power, while also keeping in mind its commitment to the public realm, power plants would begin to take on a very different role within society. One of beauty, place making, and having multifaceted offerings.

Safety and Security

Considered by most to be the pinnacle of importance across all power plants, both non-nuclear and nuclear, the safety and security within a given facility is for the protection of both the public and plant operators. Possibly the most obvious physical examples being the barbed wire fences and guard booths one can see when approaching a nuclear plant. While these elements fit the traditional methods for security, one should investigate lower-profile methods of protecting the site as to not give off negative connotations to the surrounding community. An example of this may be the use of “ha-ha” ground features which allow for clear lines of site to represent the transparency seen across the industry today but also still meet the needs of keeping people at safe distances away from the plant’s operations.

With features such as barbed wire fences and guard booths, one must realize the history they have and how that can negatively impact the public perception of a given plant. For instance, people may associate barbed wire and other prominent security measures with prisons and develop a fear or uneasy feeling toward the power plant. One example of how to hide security features within an installation is to look at embassy buildings. Because these buildings must represent the countries they belong to, many of the security measures are low-profile or hidden out of site as to give the look of an architecturally pleasing building while still fitting the criteria to be a fortress underneath.

Site Design

Site design can offer an important first impression of what one is to expect when entering a nuclear power plant. Therefore, key thoughts need to be addressed within the site design to implicate the correct ideas wanting to be portrayed to the visitors. Similar to safety and security, much of the design around nuclear power plants has to do with maintaining a secure perimeter as to ensure people do not wander into areas they aren't supposed to be. While large swaths of land are typically given over to power plants for development, much of the land becomes open space between the actual program of the buildings and their security perimeter. This is known within the industry as B.O.P, or Balance of Plant, which refers to all the supporting components and auxiliary buildings needed to maintain the energy generating process. One-way current designs can be critiqued as to push across sustainable attributes to the public would be the exploration of solar and/or wind energy within areas that are typically underutilized within many established plants.

Moreover, the land can be managed in more sustainable ways (not just grass fields) as to show the public how the facility can be a good steward of the environment while also diversifying the means of energy production. By this method, people are kept at a distance but can still see the site while the land is upkept by the power plant and associated personnel. Other design options such as recreational activities and campus planning can be explored to keep the utilitarian nature of the plant functional while appealing to the desires of visitors. Site designs such as this are what will be applied to the design sections of this thesis project.

Chapter 5: Comparison of Nuclear to other Energy Production Methods

Power Output

Background Context

Power output is an important element within both nuclear and non-nuclear power plants as this determines the size of the plant, how large of an area it will supply energy to, as well as other factors. With nuclear power plants having the highest capacity factor out of any other form of energy currently known (out of both renewable and non-renewable methods), it is no secret that their power output is much higher than rival forms of energy production. As will be discussed in this section, there are many other reasons why nuclear power plants have such high energy yield compared to other forms of electricity production. A major aspect being the fissile fuel source and how energy dense the materials can be. Because of this, one can have a generation-five nuclear power plant that produces as much electricity, if not more, than traditional power plants while being a fraction of the size of large, cumbersome hydroelectric or waste-energy plants.

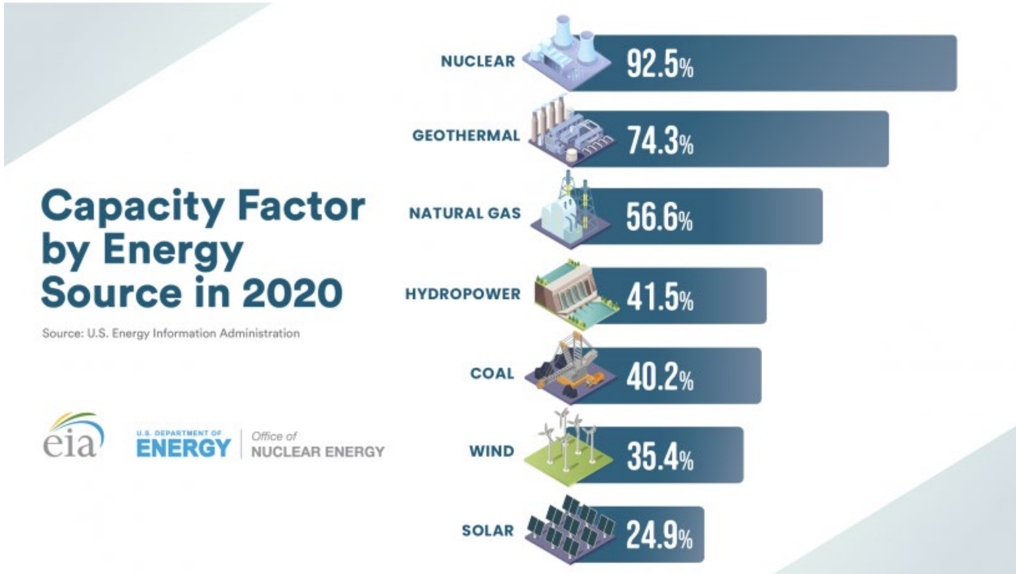

Figure 5.1: Graphic showing the comparison of capacity factors between nuclear and other forms of energy production. (Source: Energy Information Administration)

Non-Renewables

Compared to fossil fuels, nuclear energy is both cleaner and more reliable when it comes to power output. Within the United States, a typical nuclear reactor produces about 1 gigawatt of electricity each year. Such a high yield of electricity means that you can't simply replace a nuclear power plant with another form of energy generation. For example, if you were to shut down one nuclear power plant, two coal-fired plants would need to be constructed to make up for the energy deficit.[28] Comparing this by other means, this means that nuclear fuel is extremely energy dense and therefore a lot less of it needs to be used compared to fossil fuels.

[28] "Nuclear Power Is the Most Reliable Energy Source and It's Not Even Close." n.d. Energy.Gov. Accessed May 17, 2022. https://www.energy.gov/ne/articles/nuclear-power-most-reliable-energy-source-and-its-not-even-close.

One uranium pellet has the energy of 17,000 cubic ft of natural gas, 120 gallons of oil, and approximately one ton of coal.

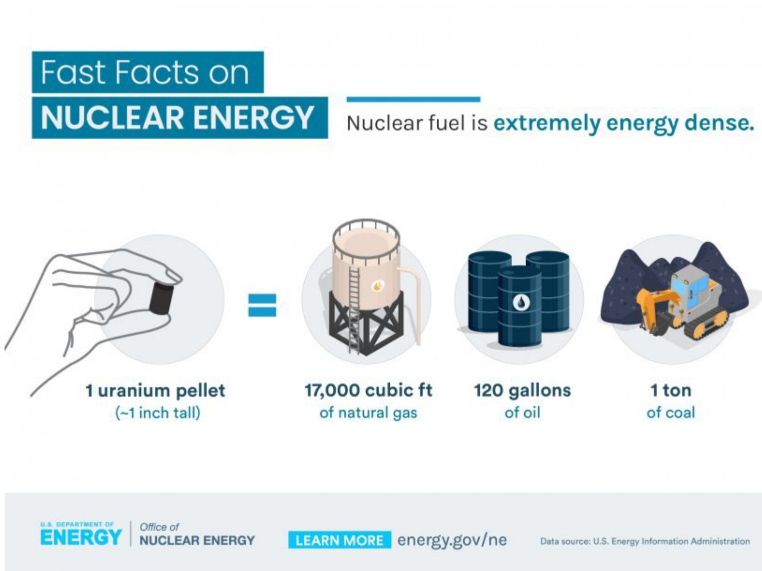

Figure 5.2: Graphic showing the comparison of uranium to other sources of energy (Source: Energy Information Administration)

When examined by acres per megawatt produced, nuclear occupies around the same amount of land as coal and natural gas fired power plants at around 12.71 acres per megawatt, with coal and natural gas occupying 12.21 to 12.41 acres.[29] Although nuclear occupies more acres on average than its fossil fuel counterparts, it is important to realize that there are not as many nuclear plants in the current fleet as compared to the hundreds of coal, natural gas, and other plants spread across the United States. Furthermore, these metrics represent the current set of aging nuclear plants that still rely on centralized power, meaning that they need to be massive in

[29] Watch, National Wind. n.d. "Footprint of Energy: Land Use of U.S. Electricity Production." National Wind Watch. Accessed May 18, 2022. https://www.wind-watch.org/documents/footprint-of-energy-land-use-of-u-s-electricity-production/.

order to feed the large regions they supply power to. This thesis will be gauging the use of small modular reactors which occupy much less land than traditional plants and operate on the idea of de-centralized power, only supplying electricity and other services to localized areas. Concluding that, although their acreage will shrink, the power output will still be measurable to that of full-scale coal and natural gas plants, especially with their modularity and ability to add reactor vessels to the plant as power demand grows.

Renewables

The difference in power output of nuclear when compared to renewable energies is where the biggest margins are seen. As stated previously, if one nuclear plant producing one gigawatt of electricity is shut down, two coal plants would have to be built to make up for the loss in energy generation. If this same metric is applied to renewables such as wind and solar power, it would take three to four more power plants to equal the same energy output as one nuclear plant. Adding to this, if we look at the metric of number of acres per megawatt produced again, the difference between nuclear and renewable sources is staggering. With current nuclear facilities occupying 12.71 acres per megawatt produced, this number is miniscule compared to the 43.5 need for solar, 70.64 needed for wind, and 315.22 acres needed for hydroelectric to produce one megawatt of electricity.[30]

Elaborating further, renewable plants are considered intermittent or variable sources of energy generation and are mostly limited by a lack of fuel (i.e., wind, sun,

[30] Watch, National Wind. n.d. "Footprint of Energy: Land Use of U.S. Electricity Production." National Wind Watch. Accessed May 18, 2022. https://www.wind-watch.org/documents/footprint-of-energy-land-use-of-u-s-electricity-production/.

or water). Even with the vast swaths of land taken up by their infrastructure, they aren't producing electricity constantly (see Figure 5.1). As a result, these plants need a backup power source such as a large-scale storage system (which is not currently available for use on the grid), or they can be paired with a reliable baseload power like nuclear energy.[31]

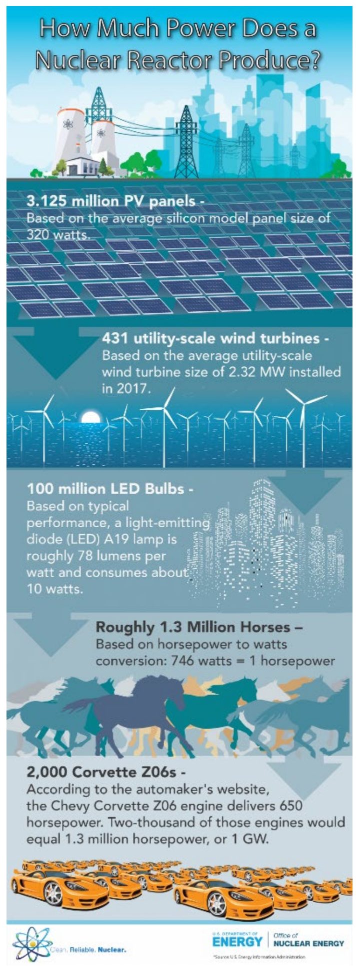

Figure 5.3: Infographic of roughly how much energy a nuclear reactor produces. (Source: Google)

[31] "Nuclear Power Is the Most Reliable Energy Source and It's Not Even Close." n.d. Energy.Gov. Accessed May 17, 2022. https://www.energy.gov/ne/articles/nuclear-power-most-reliable-energy-source-and-its-not-even-close.

Handling Waste

Being one of the most discussed topics within the nuclear industry, the handling of a reactor's fuel after it is done being used for energy production is a complex subject. Unlike any other form of waste, the fissile material within a reactor vessel can contain low levels of radiation for thousands of years. Special care must be taken to ensure it is properly extracted from the reactor, transported to its final destination, and stored properly. Although there are processes for re-enriching the spent uranium to be used again within a reactor core and other recycling measures, there is currently no widely accepted means as to what to do with the material once it has truly met the end of its useable life besides entombing it underground.

Non-Renewables

Nuclear waste is a solid material which must be stored and dealt with properly, therefore it is governed by many political and environmental regulations. The material only needs to be extracted from a reactor every 1.5 to 2 years. Meaning that, unlike plants which are powered by fossil fuels, nuclear reactors do not produce constant waste as a byproduct of daily energy production. This relates back to the discussion on power output. Nuclear fuel is so energy dense very little of it is required to produce a lot of power, in turn meaning less waste.[32]

Firstly, the generation of electricity from a typical 1,000-megawatt nuclear power station, which would supply the needs of around a million people, produces

[32] "Radioactive Waste Management | Nuclear Waste Disposal - World Nuclear Association." n.d. Accessed May 19, 2022. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx.

only three cubic meters of nuclear waste per year. Out of those three cubic meters, even less becomes waste as it has the potential to be recycled. In comparison, a 1,000-megawatt coal-fired power station produces approximately 300,000 tons of ash and more than 6 million tons of carbon dioxide, every year. Even if all the nuclear waste produced by the U.S. nuclear industry from the past 60 years was compiled, it could all fit within a football field at a depth of less than ten yards.[33]

Secondly, even with the minute amounts of waste produced by the nuclear industry, none of it causes carbon dioxide to be released into the atmosphere and surrounding environment as is seen within fossil fuel fired power stations on a daily basis. It is much easier for people to see nuclear waste stored within containment vessels or hear about it through media due to its radioactive and controversial nature, therefore people focus on this aspect of the nuclear industry more than that of fossil fuel waste. Waste from fossil fuels is easy for people to ignore as it escapes directly into the environment as smoke or other pollutants which aren't as tangible as nuclear waste. This production of greenhouse gases and other pollutants by fossil fuels has become an acceptable collateral to meet our current energy demands.

Renewables

Although renewables such as solar, wind, and hydro do not produce typical pollutants such as greenhouse gases, smoke, and toxic run-off like fossil fuels they have the potential to cause harm later in their lifecycle of materials. When certain components, which make up a renewable power plant ware out, there are no current

[33] "What Is Nuclear Waste and What Do We Do with It? - World Nuclear Association." n.d. Accessed May 19, 2022. https://world-nuclear.org/nuclear-essentials/what-is-nuclear-waste-and-what-do-we-do-with-it.aspx.

solutions to recycle them. They have to be either stored or otherwise disposed of unlike nuclear waste, which can be recycled or stored in proper containment vessels. Parts such as wind turbine blades end up being buried in large landfills and become pollutants themselves as the fiberglass breaks down into smaller pieces, causing potential harm to groundwater and other facets of the environment.

Figure 5.4: Aerial imagery of a wind turbine landfill being covered by dirt via a bulldozer. (Source: Bloomberg)

Focusing more on wind turbine blades which have a lifespan of around 20 to 25 years, they end up in landfills after they are used due to no largescale recycling operations currently available for the renewables industry. With some of the largest wind farms in the United States having upwards of 150 turbines (largest having 4,800) and each utilizing three blades, one can realize that roughly 450 fiberglass turbine blades are being buried in landfills every two decades. That is 2,700 tons of fiberglass waste being produced, with the average wind turbine blade weighing six tons. It is estimated that 720,000 tons worth of wind turbine blades will end up in landfills over the next 20 years.[34] Compared to nuclear which produces 2,000 metric tons of waste every year across the entire U.S. nuclear fleet (40,000 tons over 20 years). Unfortunately, unless recycling practices progress the problem of wind turbine waste will only compound as the operating fleet of wind farms age.

Solar power shares the same problem of having an exponentially growing waste stream headed for landfills. Although recycling within the solar industry is better than what is seen with wind power, it is the incentives which govern these recycling practices that are causing the shortcomings within solar power. With many panels being made up of glass, metals, and electronic parts, it is easy to see where money can be made when they are recycled properly. However, with the current costs of recycling estimated at twenty to thirty dollars a panel and landfills only charging two dollars to burry that same panel, the economic incentives are not there. Adding to that, recycling of solar panels requires skilled labor and proper removal of the panels from rooftops without damage, whereas landfills do not care in what condition the panels are in when buried.[35]

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[34] Atasu, Atalay, Serasu Duran, and Luk N. Van Wassenhove. 2021. "The Dark Side of Solar Power." Harvard Business Review, June 18, 2021. https://hbr.org/2021/06/the-dark-side-of-solar-power.
[35] Atasu, Atalay, Serasu Duran, and Luk N. Van Wassenhove. 2021. "The Dark Side of Solar Power." Harvard Business Review, June 18, 2021. https://hbr.org/2021/06/the-dark-side-of-solar-power.

Figure 5.5: Image of solar panels dumped at a landfill waiting to be buried. (Source: Google)

There are no zero waste methods to producing energy, and every form of energy production has its specific shortcomings as per this fact. As examined, nuclear power plants do indeed produce solid radioactive waste, although the amount produced is far less than that of both its non-renewable counterparts and other forms of renewable energies. Stored properly, the waste produced by nuclear stations does not cause harm to anyone or the environment, unlike the pollutants that are seen to be acceptably discharged into the environment by coal, oil, natural gas, wind, and solar power plants. For this fact, it is important to see nuclear as a viable option for sustainable energy production and a major reason as to why it was picked for exploration within this thesis project.

Storage

Used nuclear fuel must go through a few critical steps as it is prepped for either storage or recycling. When the used fuel is first extracted from the reactor it is both hot and radioactive. It must be stored in water for a period of time to allow the material a chance to cool. After its time in wet storage, it is then transferred into a dry facility for temporary storage whilst the heat and radioactivity further diminish before it can be transported for either more permanent storage or recycling. Two waste management strategies are used for nuclear waste across the world: one is recycling and the other being permanent storage in a repository known as "direct disposal". These two strategies are taken at a national level and mainly driven by political and economic, as well as technological, considerations.[36]

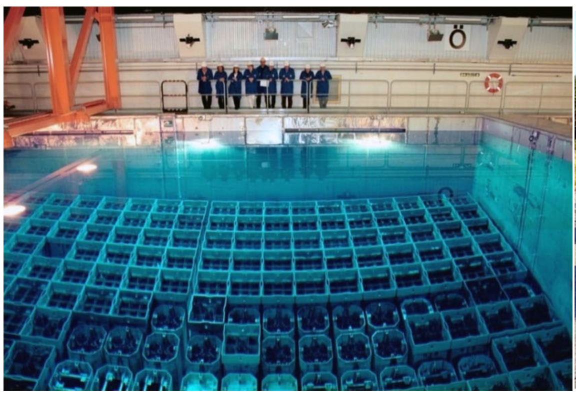


Figure 5.6 & 5.7: Cooling and storing of used nuclear fuel in pools (left) and used nuclear fuel in dry storage casks (right). (Source: World Nuclear Association)

Within the U.S. only the latter solution of direct disposal is available. Within this country, used nuclear fuel is currently designated simply as waste however, other countries such as France, and Japan have extensive recycling operations in which 97% of the usable uranium and trace amounts of plutonium are harvested to be used within a conventional reactor again. The U.S. uses direct disposal, which involves the

[36] "What Is Nuclear Waste and What Do We Do with It? - World Nuclear Association." n.d. Accessed May 19, 2022. https://world-nuclear.org/nuclear-essentials/what-is-nuclear-waste-and-what-do-we-do-with-it.aspx.

used nuclear fuel being disposed of in an underground repository, without any recycling. The used fuel is placed in canisters which, in turn, are placed in tunnels and subsequently sealed with rocks and clay. Waste from the 3% of fission material unable to be recycled can also be placed in repositories.[37]

<u>*Safety*</u>

Similar to the production of waste, it is important to note that every form of energy generation has its safety concerns. It is up to people to mitigate those risks and decide whether the safety concerns within each type of energy generation are worth the continued support of that technology. Safety is of paramount importance across any industry, especially within the field of nuclear. Because of this, nuclear energy is one of, if not, the safest form of energy production. The significant aspect of safety is yet another reason why nuclear was chosen to be the technology of choice to produce sustainable energy within this thesis project.

Non-renewables

It is no secret that the burning of fossil fuels to produce electricity is extremely harmful to both the surrounding environment and populations of people who reside around the plant. The air pollution of fossil fuels causes the premature deaths of countless people each year and puts many more in danger as the future risks of climate change loom.[38] Carbon dioxide is the main pollutant created as a byproduct

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[37] "What Is Nuclear Waste and What Do We Do with It? - World Nuclear Association." n.d. Accessed May 19, 2022. https://world-nuclear.org/nuclear-essentials/what-is-nuclear-waste-and-what-do-we-do-with-it.aspx.
[38] Ritchie, Hannah, Max Roser, and Pablo Rosado. 2020. "Energy." Our World in Data, November. https://ourworldindata.org/nuclear-energy.

from the burning of fossil fuels, which accounts for 33 billion tons per year being released into the atmosphere globally. Of that number, about 44% is from coal, 34% from oil, and 21% from gas.[39] These statistics only cover the negative consequences of air pollution as there are two other categories which are seen to be areas of concern within the energy industry, those being accidents and greenhouse gas emissions.

These three categories of air pollution, accidents, and greenhouse gas emissions are looked at when calculating the toll on human life within each of the industries for energy generation. Combined, the fossil fuel industry is responsible for 43 premature deaths per year, of which 25 are from coal, 18 because of oil, and 3 due to gas. Nuclear cannot have this statistic applied to it because annually, nobody dies. However, the metric of 0.07 deaths per terawatt-hour can be examined, meaning it would take 14 years for a single person to die.[40] Even more staggering is the safety record of nuclear energy since its advent in the 1940's. In the eight decades since the technology has existed, only three large accidents have occurred within the industry, a safety record which no other technology created since can claim.

[39] "Carbon Dioxide Emissions From Electricity - World Nuclear Association." n.d. Accessed May 20, 2022. https://www.world-nuclear.org/information-library/energy-and-the-environment/carbon-dioxide-emissions-from-electricity.aspx.
[40] Ritchie, Hannah, Max Roser, and Pablo Rosado. 2020. "Energy." Our World in Data, November. https://ourworldindata.org/nuclear-energy.

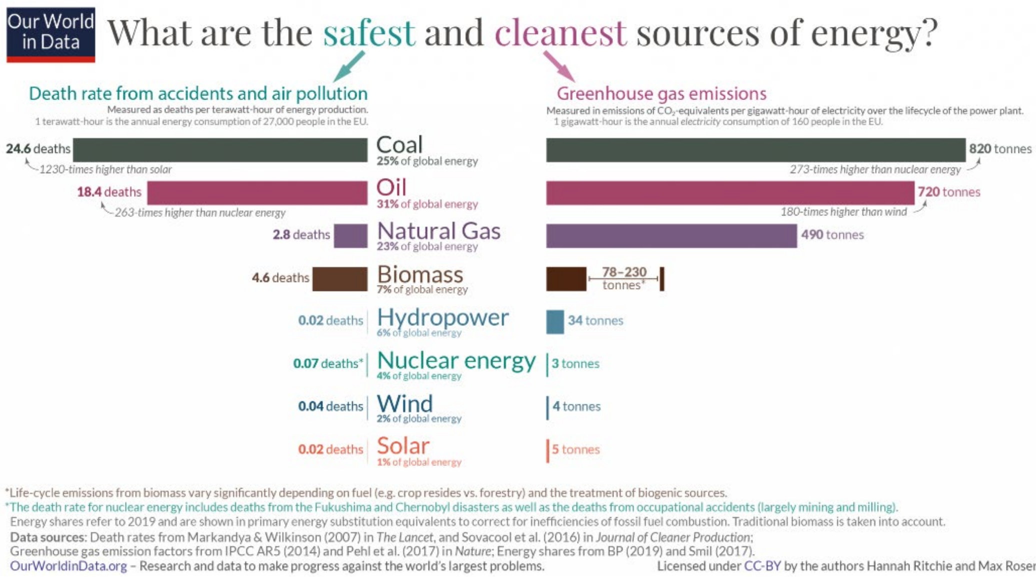


Figure 5.8: Charts showing the comparison of death rate and greenhouse gas emissions across differing types of energy production. (Source: Our World in Data)

With these statistics, one can begin to see how safe the nuclear industry really is. Not only has nuclear been responsible for very little deaths as direct results of accidents within the industry, but it has been seen to save people as well. Not including the production of radioisotopes used within medicine to treat sick people, the reactors used in energy production help combat greenhouse gas emissions. In a study published in the 2013 journal of *Environmental Science and Technology*, Pushker Kharecha and James Hansen aimed to answer the question "how many lives has nuclear power saved?". They analyzed how many more people would have died over the period from 1971 to 2009 if nuclear energy had been replaced by fossil fuels. The death toll would have depended on the mix of fossil fuels used to replace nuclear and how many more would have died if more coal was used than oil or gas. They estimate that nuclear power has globally saved about two million lives.[41]

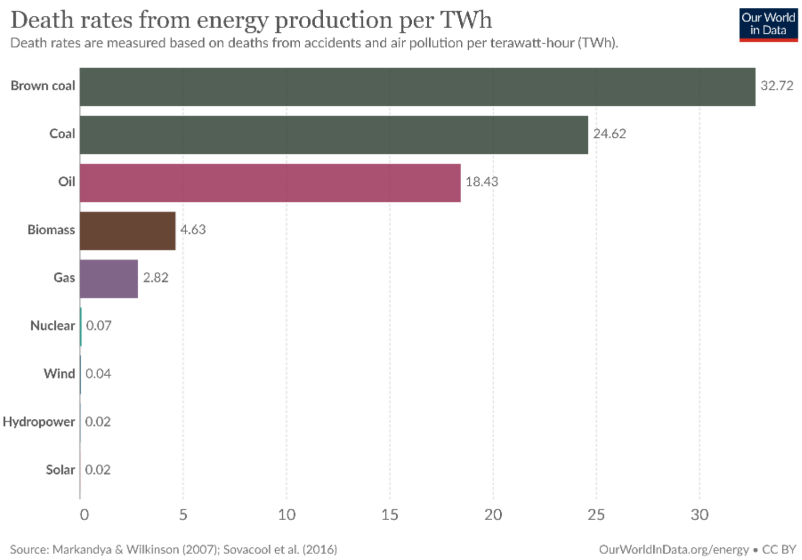


Figure 5.9: Chart showcasing the deathrate per terawatt-hour of each type of energy production. (Source: Our World in Data)

Renewables

As seen within the charts above, nuclear has a slightly elevated hypothetical statistic of people who may die per terawatt hour compared to that of wind, hydro, and solar. Far safer than fossil fuels, these three main renewable technologies are indeed great intermittent sources of energy to be paired with nuclear as a means to meet growing energy demands. Because of these renewable sources only being variable sources of power, nuclear will need to be the backbone of the mission to create carbon-free energy. Depicted in figure 5.8, nuclear still produces less

[41] Ritchie, Hannah, Max Roser, and Pablo Rosado. 2020. “Energy.” Our World in Data, November. https://ourworldindata.org/nuclear-energy.

greenhouse gas emission than that of wind, solar, biomass, and hydropower. Fortunately, clean, and safe renewable technologies are becoming economically competitive in their own right.

Another metric to keep in mind when it comes to the impact of power plants on the environment is their life-cycle emissions. This can produce just as much, if not more CO_2 emissions, leading to other environmental health risks. Thankfully, both renewables and nuclear have some of the lowest life-cycle emissions due to advancements in construction and manufacturing techniques. Most of the CO_2 produced by power plants comes from the concrete and steel used within their construction. This has gotten better as generation five nuclear stations do not require as much concrete as traditional plants and large hydroelectric complexes. Other factors which will help drive down emissions include the decarbonization of energy, electricity being clean at the final point of use, and making sure the generation of electricity is reduced as much as the final use point.

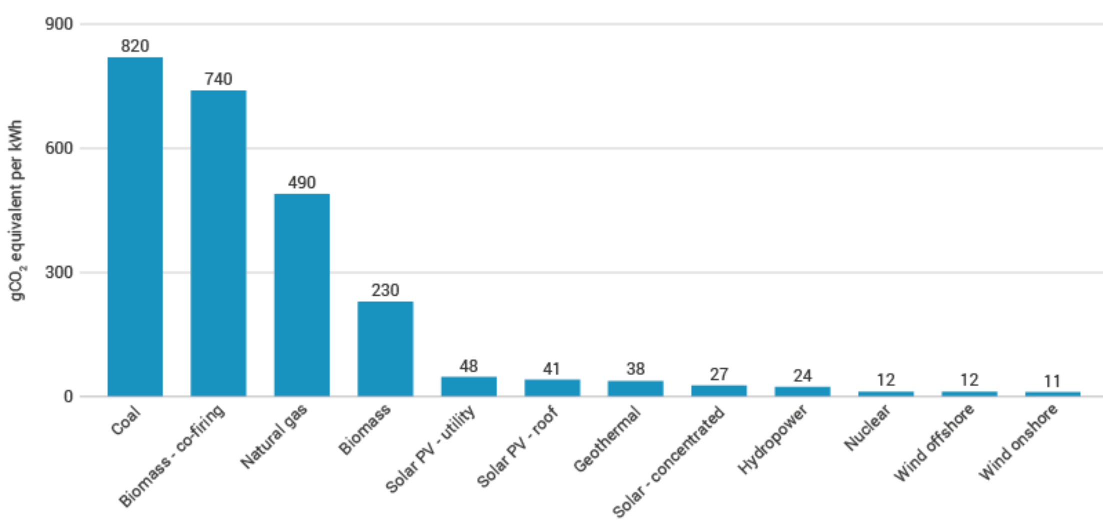


Figure 5.10: Bar chart showing the comparison of each main type of energy production versus their output of CO_2 over their life cycle. (Source: World Nuclear Association)

Conclusion

Much of the concern based around nuclear is from a misunderstanding: the belief of it being an unsafe form of energy production. As the statistics help to support the facts of it being one of the safest sources of energy currently available today. People lost trust in the nuclear industry because of the spotlight being cast on a few events. Yet people ignore the prevalent dangers within the fossil fuel industry because their health risks and unsustainable methods are seen to be acceptable collateral in order to keep the way of life we have known for many decades. Nuclear can be seen as a new way of thinking about energy generation, which will always draw backlash from some people. However, it is important to upkeep this technology and be good stewards of it as to make sure advancements are happening to continue the pursuit of a safe, sustainable, and carbon-free future.

Chapter 6: Design Solution

Project Vision & Goals

Vision

As stated earlier, this thesis will explore aspects of the afore mentioned technologies to revive public interest, heal the industries public image, and test the viability of nuclear power within the coming decades. This vision will be achieved within two main aspects seen within the complex. Starting with the creation of integrated areas for public discourse throughout the plant, which will act as a catalyst for people to come and start discussion on the nuclear industry while learning about the past, present, and future of the industry. In addition to this will be the second leg, which sees the construction of a next generation nuclear power plant with the intended purpose of showing the real-world application of the technology being shown within the discourse center. The power plant will also fulfill the important primary task of generating power to meet the growing demand for sustainable energy and explore other methods to interface with its surrounding context.

Through architecture and site design, these facilities will need to uphold the vital uses which need to be carried out within a nuclear facility, such as security, engineering, physics, and power generation. It will also need to grapple with their image as perceived by the public. Many of the uses within a nuclear power plant are a double-edged sword, that being, their literal intended uses that need to be upheld, and how they are perceived by the public. These public views may be drastically different than their actual intended purpose. As stated, the architecture will also have to become non-passive and avoid becoming too utilitarian (as seen with most traditional power plants) so that its elements can push across the unique aspects only found within nuclear power and begin to positively shift the damaged paradigm.

In the end, this thesis will meet the criteria of the construction and design of a generation five nuclear power plant, integrated public facilities, and gauge ways in which through the afore mentioned standards, it has to some margin, reinstated public trust within the industry. This would further assist by allowing the approval of more next generation power plants to be built around the country to meet the growing need for sustainable energy, while also relieving the stigmatism around nuclear sites, so that they may be reused as brown-field sites for other forms of development. Furthermore, the project will explore important questions such as how the thesis design can embody not only the reduced risk, but also the greater promise of nuclear power. These criteria will gauge the progression of the thesis project and lay out its context, which will be discussed further within the following chapters.

Goals

Primary goals for the project include the making sure the power plant is sized correctly to meet the configured energy budget, while also making sure the integrated public spaces are adequate to meet the needs of daily visitors to the complex. Letting the program dictate these spaces will help ensure that the power plant can fulfill its utilitarian needs, while allowing civilians to visit, learn, and view parts of the plant. Another primary goal to ensure the utilitarian and civilian demands work in harmony is finding ways that the power plant can interface with the surrounding community, outside of the realm of supplying electricity. Such uses can be expending excess heat from the reactor to keep sidewalks and roads ice free in the winter, then switching to desalinating brackish groundwater in the summer months.

Secondary goals for this thesis include incorporating other forms of renewable energies into the project to diversify the means of energy production happening on the site. This can be done by placing PV panels on rooftops or around parts of the plant not being used for other infrastructure, and/or deploying micro-hydro in the adjacent river to compliment the carbon-free means of nuclear energy. Tertiary goals will be utilizing any existing site infrastructure that can be repurposed for use within the power complex. This also includes the preservation of existing bike and walking trails, along with as much green space as the project will allow. Preserving green space will be complimented by the last goal, that being making sure sustainable construction methods are used during the project's duration. These methods being resourcing materials that have low embodied carbon and limiting materials which have high embodied carbon to only areas that they are needed.

Site Documentation

Site Criteria

Idaho Falls, Idaho is the city that was selected to host the site for this thesis project. This location was chosen for the abundance of criteria it met, criteria which were made to help select the site best suited for the power plant and associated public facilities. These criteria include proximity to population center, a national laboratory, higher education which specializes in nuclear technology, ability for phased development, presence of existing power plant, historical significance, existing recreation activities, proximity to water, presence of nuclear waste, and the status of any existing reactors. The criteria categories were applied to each prospective site and descriptions were written to explore each sites context (see Figure 6.1).

Site Matrix Description	 Idaho Falls, ID	 Shippingport, PA	 Calvert Cliffs, MD
Historical Significance	Developed many of the first prototype reactors in the world.	Original plant was the first large-scale commercial plant in the world.	One of the largest operational plants in the U.S.. Existing plant had precedence of integrated public spaces.
Proximity to Population Center	On outskirts of Idaho Falls	Short drive from Pittsburg, PA	Two hour drive from Washington, D.C.
Ability for Phased Development	Much of the site is already open space.	Pre-developed land taken up by still opperating power plant.	Balance of plant is already taken up by existing structures. Site has plenty of open land around it.
Proximity to National Laboratory	Developed many of the first prototype reactors in the world.	Close to National Energy Technology Laboratory in Pittsburg, PA.	Multiple national organizations located within D.C. but are far away.
Proximity to water	Just east of Snake River	On shores of Ohio River	On shores of Chesapeake Bay
Pressence of Existing Visitor Center	Offers guided tours but has no visitor center	No existing visitors center	No existing visitors center
Existing Plant Reactor Type	Developmental / Experimental	Pressurized Water Reactor	Pressurized Water Reactor
Pressence of nuclear waste	Kept at seperate facility	Kept in On-site dry casks	Kept in On-site dry casks
Status of Existing Reactor	N/A	Original plant is decommissioned with a still opperating plant adjacent to the site	Still Opperational

Figure 6.1: Site Matrix showing the criteria and their description applied to each prospective site. (Source: Author)

Site Matrix

After considering the contextual details seen with each site, each of the categories were assigned a point value as to rate which site would be the most suiting to host the project. The site criteria were listed on the site matrix in order of importance, therefore the criteria that was deemed more important had higher point values assigned. This system weighted the ratings to properly swing in favor of sites which had more of the amenities needed to support the overarching themes of the thesis project. An example being the proximity to population center, as this can encourage walkability and other forms of transport to allow visitors to easily access the proposed integrated public facilities. Ultimately in the hopes of normalizing nuclear power within the public eye and allowing people to learn of the greater promise offered by next-generation power plants.

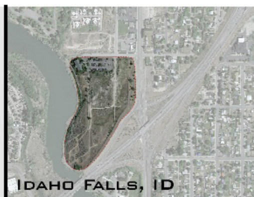
Site Matrix	 Idaho Falls, ID	 Shippingport, PA	 Calvert Cliffs, MD
Proximity to Population Center	10/10	8/10	5/10
Proximity to National Laboratory	9/9	8/9	6/9
Proximity to (Nuclear) Education	8/8	7/8	4/8
Ability for Phased Development	5/7	5/7	5/7
Pressence of existing Power Plant	3/6	6/6	6/6
Historical Significance	5/5	5/5	1/5
Existing Recreation Activities	2/4	2/4	3/4
Proximity to water	3/3	3/3	3/3
Pressence of nuclear waste	2/2	2/2	2/2
Status of Existing Reactor	0/1	0/1	1/1
Total	**47/55**	**46/55**	**36/55**

Figure 6.2: Site Matrix with scores applied to each site based off the information derived from the descriptions. (Source: Author)

Master Planning

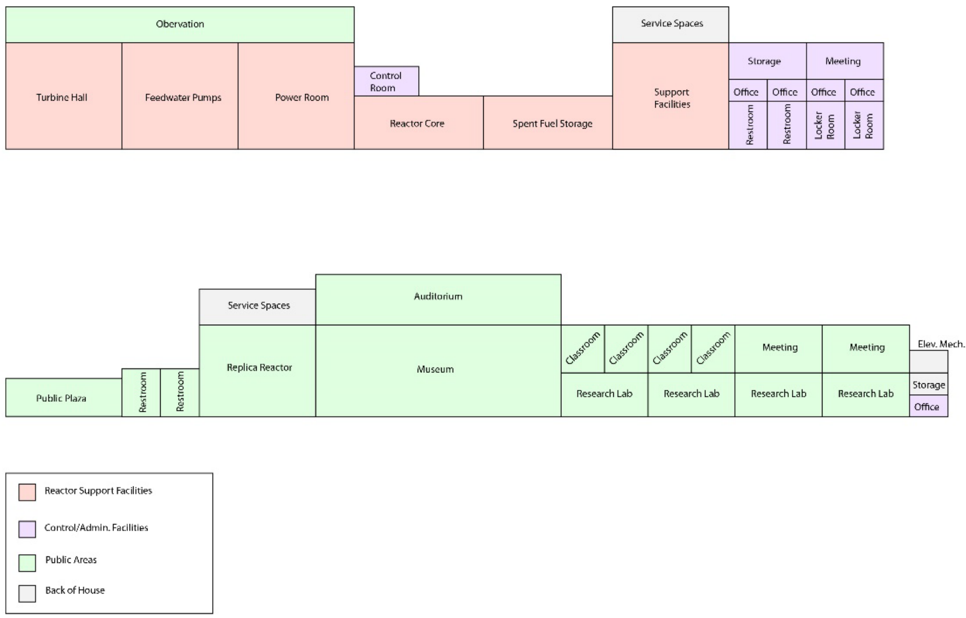
Once the site was chosen, preliminary master planning strategies were explored in order to find optimal layouts for the main blocks of the sites program. Since one of the goals of this project is to utilize and/or preserve existing site infrastructure master planning was needed to find optimal layouts that allow for new construction to operate in tandem with the multiple bike and pedestrian pathways already located on the site. Being a nuclear power plant there are the needs of the buildings vital to produce power and need to be located first. After this, areas such as the administrative offices, public areas, and parking were placed where conditions allowed.

Figure 6.3 & 6.4: Diagrams showing the preliminary blocking locations of the site programs. (Source: Author)

<u>*Program Tabulations*</u>

Blocking & Stacking

After the site of Idaho Falls was selected and preliminary master planning was done in plan the next step was to explore the program in section. This was done through blocking and stacking diagrams as to see what areas needed adjacencies or to be placed far away from one another. Below one can see that both the program adjacencies of the power plant itself were explored, as well as the layouts of the associated public and research & academic facilities.



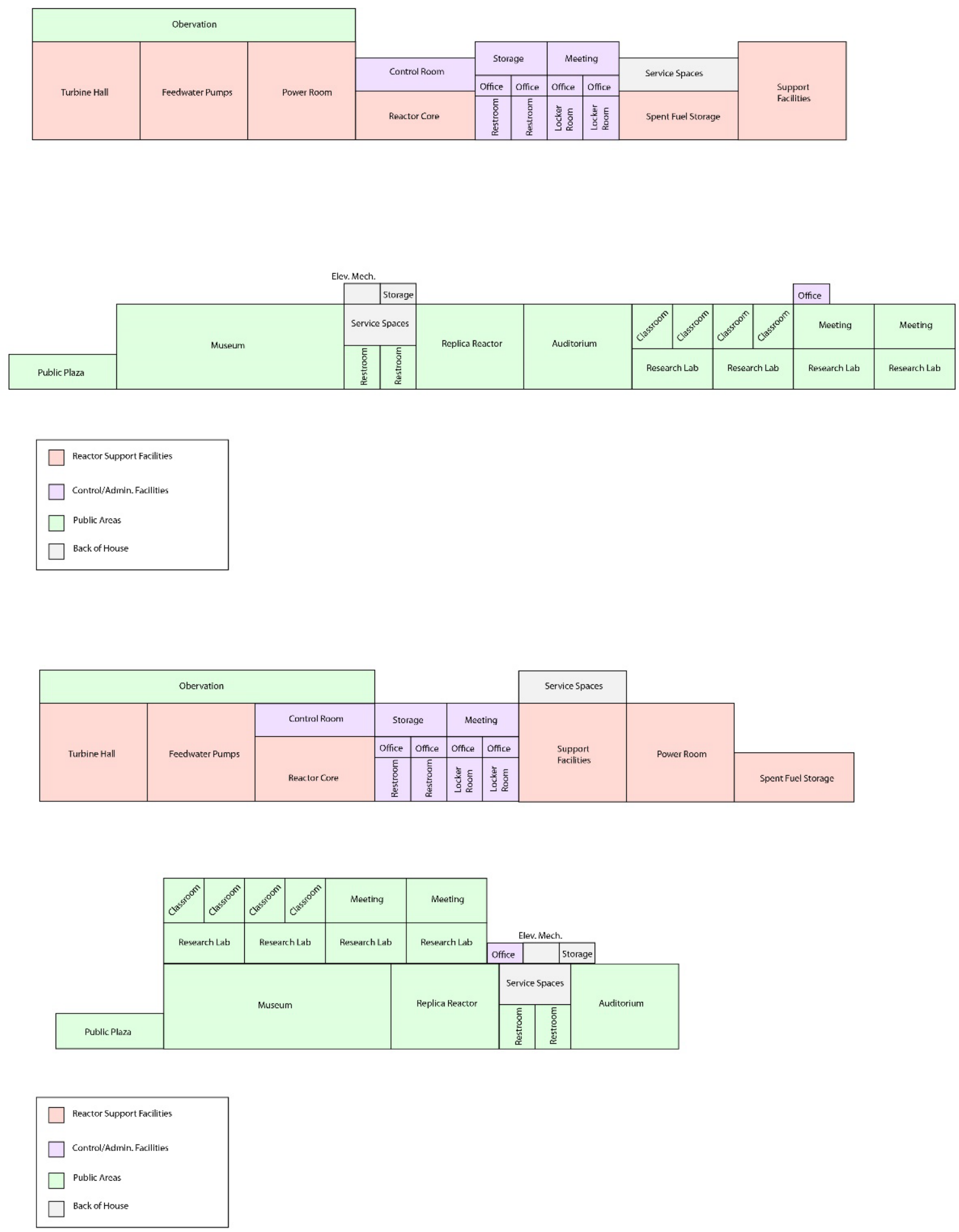


Figure 6.5, 6.6, & 6.7: Blocking and Stacking diagrams showing program adjacencies in section.

(Source: Author)

Program Development

Moving into the programming, the goal is to normalize nuclear power as safe, sustainable, and reliable, establish interplay between the differing groups which have access to the site, and highlight the ideas of discourse, transparency, and trust. To complete these objectives the umbrella areas of public, research & academic, and the nuclear complex itself were brought in to explore the topics of this thesis (see Figure 6.8).

Program Tabulations				
Room/Space Description	**Description**	**Quantity**	**Size**	**Total**
Nuclear Complex	Reactor Core	1	7,000	110,000 sq ft
	Spent Fuel Storage	1	3,000	
	Turbine Hall	1	20,000	
	Power Room	1	20,000	
	Control Space	1	8,000	
	Support Facilities	1	10,000	
	Feedwater Pumps	1	18,000	
	Coolant Systems	1	16,000	
Public Building	Museum	1	5,000	21,000 sq ft
	Auditorium	1	2,000	
	Lobby	1	1,000	
	Obervation Area	1	1,000	
	Flex Space	2	800	
	Office	2	150	
	Service Spaces	1	2,000	
	Classrooms	6	800	
Academic & Research Building	Classrooms	8	800	25,000 sq ft
	Lobby	1	1,000	
	Auditoirum	1	2,000	
	Mock-Up Reactor	1	7,000	
	Observation Area	1	1,000	
	Service Spaces	1	2,000	
	Library	1	2,000	
	Conference Room	1	800	
	Office / workstations	4	150	
	Teaching Labs	4	1,000	
Total (net)				**156,000 sq ft**
Total (gross)				**206,360 sq ft**
Grossing Factor				**1.34**

Figure 6.8: Table showing the program areas within the buildings of this thesis project. (Source: Author)

For public spatial uses, areas are created to foster learning opportunities and offer interactive areas for people to see the technology utilized on the site, while offering the opportunity to come across people who can speak on the topics of nuclear energy. The ways in which this is achieved will be highlighted later within the final design portion of the chapter. The research and academic areas include lab spaces that are curated to interface with the classes and topics discussed within the Idaho National Laboratory and University of Idaho which are located just north of the site. These topics include nuclear fuel processing, materials, radioactive waste treatment/management, thermal behavior & measurement, nuclear systems design & modeling, and applications of nuclear process heat; a topic which is applied within the actual systems of the buildings in this project.

Lastly, is the nuclear complex itself which consists of the areas that are needed to have proper operation. These include the reactor hall, turbine hall, coolant and power facilities, as well as control facilities. The reactor hall being the most vital of these areas as this is where the core is held which produces all the power and heat to be used within the building campus, and community beyond. The turbine hall converts the steam generated by the core into usable electricity, while the coolant and power facilities supply important cooling water to the reactor core while also distributing the electricity generated by the turbines (see Figure 6.9). Perhaps most importantly are the control facilities which monitor all the before mentioned areas.

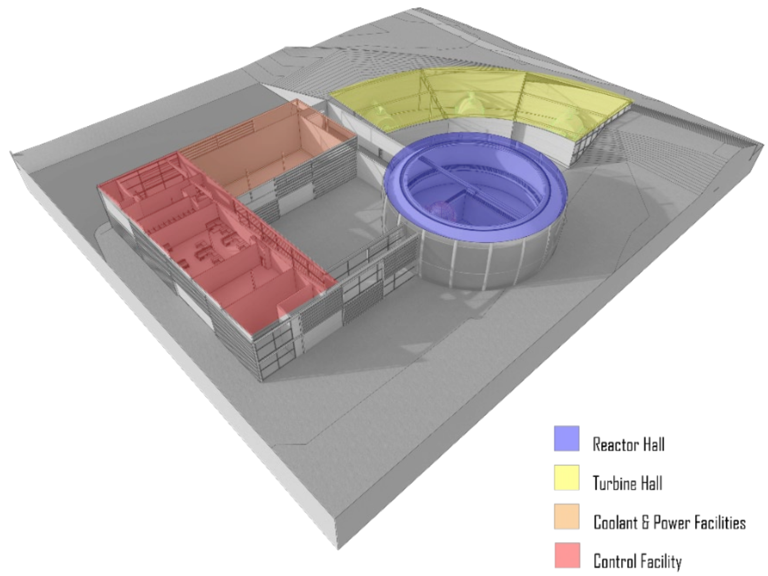


Figure 6.9: Diagram showing the before mentioned spatial uses as laid out within the projects designed nuclear power plant. (Source: Author)

Final Design

Site Analysis

Additional reasons as to why this reactor and its corresponding complex were to be located within Idaho are due to the states extensive past in nuclear technological development, its existing infrastructure from this past, and its current leading status as a place for research and academics within the nuclear industry. Additionally, Idaho has a growing population to support the benefits of a microreactor which could curve their current dependency on natural gas. Located within Idaho, the city of Idaho Falls sits in the south-east of the state. This city sits far from areas of geological and climatic distress making it a safe place to construct a power plant.

On the scale of the city proper, the actual site sits to the north-west of the city just north of the downtown area. Harping back to the states impressive past within the nuclear industry, the Idaho National Laboratory sits just to the north of the site, which is responsible for developments within the industry, as well as the University of Idaho branch campus which offers graduate programs in nuclear engineering (see Figure 6.10). Important bordering features to the site include the Snake River which starts to constrain it and offer planning opportunities (see Figure 6.11). Additionally, the site sits at or near many major thoroughfares which offer ease of access to the property. These also constrain the site, especially Freemont Avenue which runs directly north-south past the site and the elevated U.S. Route 20 highway (see Figure 6.12). Nearby railway corridors offer means of nuclear fuel delivery, with the main depot being adjacent to the downtown area (see Figure 6.13).

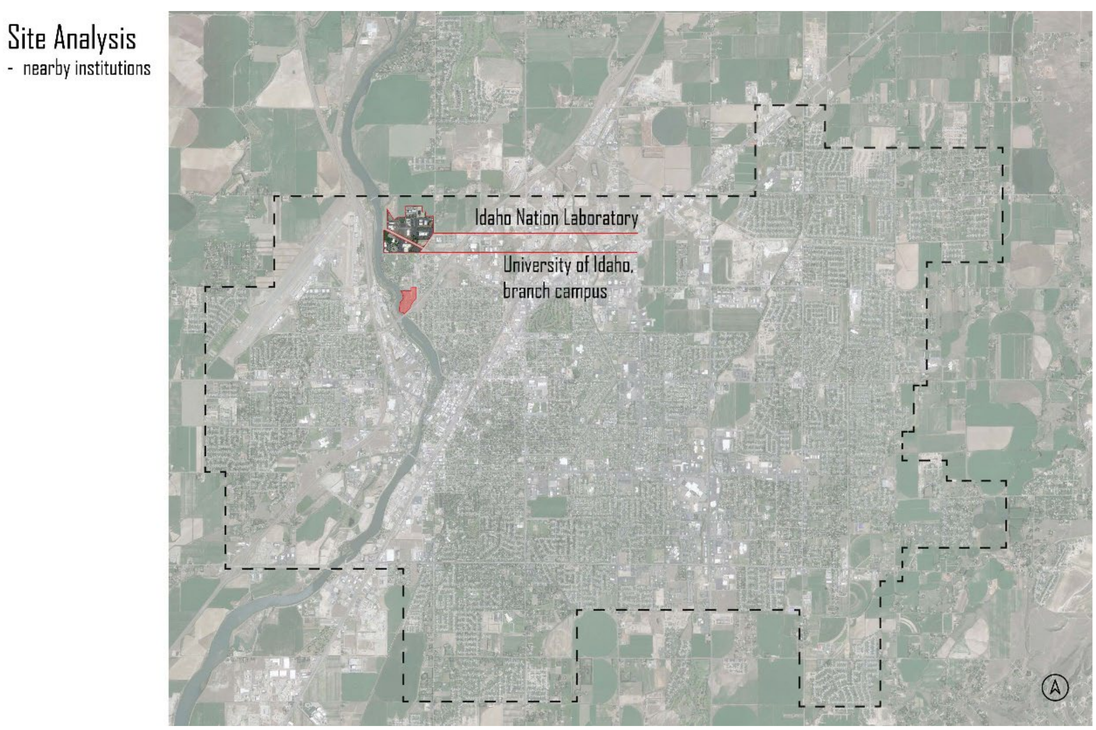


Figure 6.10: Diagram showing the location of important nearby institutions. (Source: Author)

Figure 6.11: Diagram showing the path of the Snake River as it runs past the site. (Source: Author)

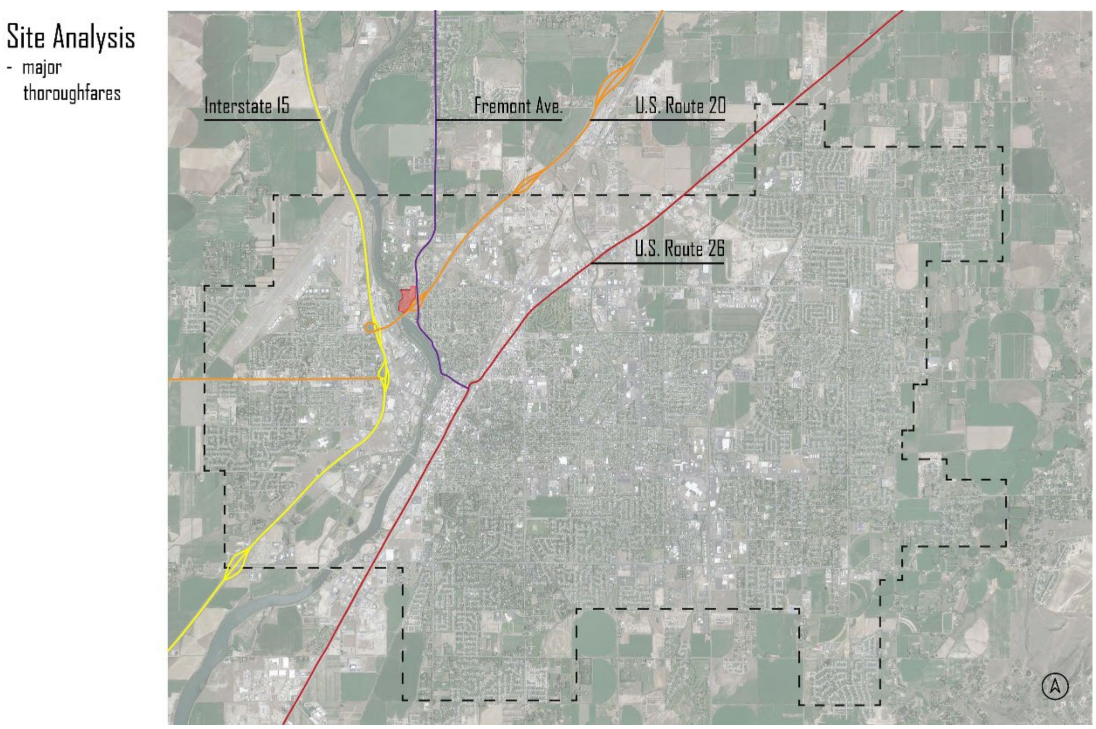


Figure 6.12: Diagram showing paths of major thoroughfares through the city. (Source: Author)

Site Analysis
- railway corridors

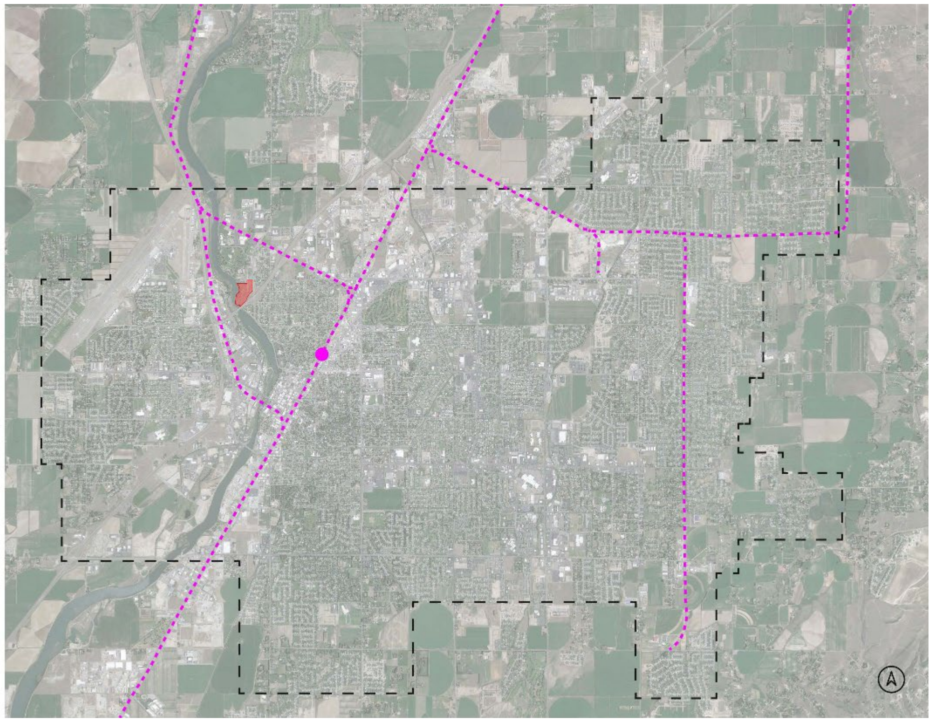


Figure 6.13: Diagram showing railway corridors throughout the city and the location of the main depot. (Source: Author)

For the actual microreactor, the power output will be 5-13MW, enough to feed the city and its suburbs and compares similarly to the existing three 8MW hydroelectric plants which currently service some of the city. This reactor is thus right sized to the population of 66,000 people of Idaho Falls (see Figure 6.14). Being a non-intermittent source of energy, this power plant will function similarly to how many existing nuclear plants are currently utilized by power companies. That is, when the local hydroelectric and wind sources of energy are not able to create power and/or produce enough, the nuclear plant is tapped into to make up for the slack in demand.

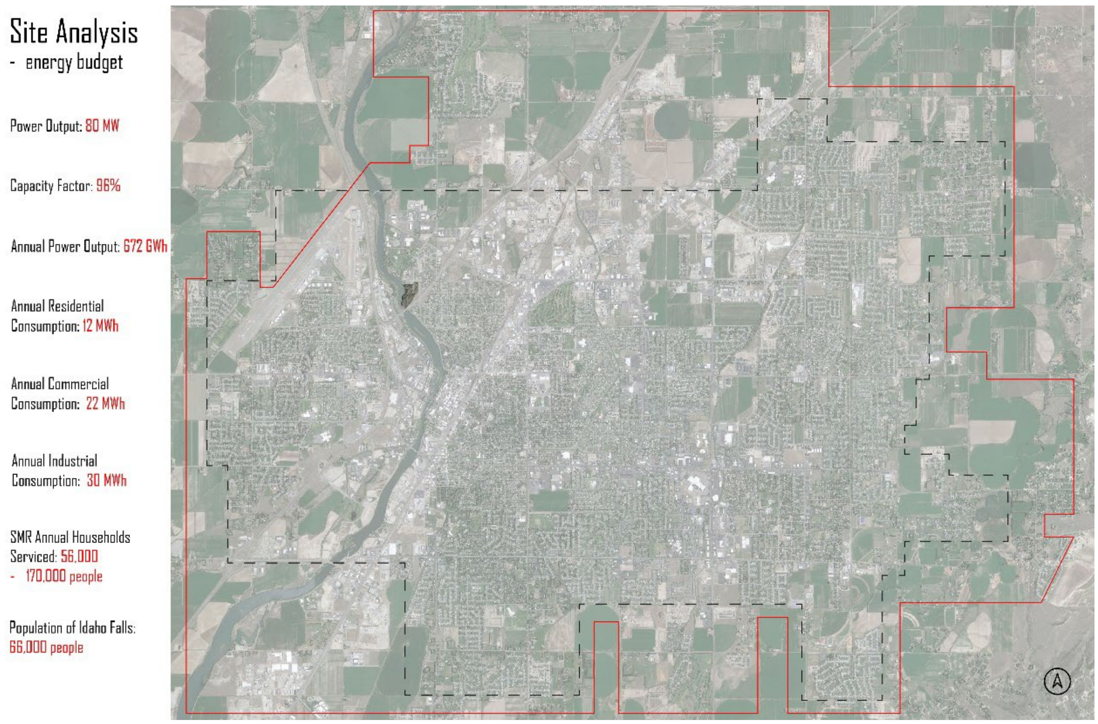


Figure 6.14: Diagram showing the established energy budget and limits of the reactors intended power zone. (Source: Author)

Looking at the use groups directly around the site you begin to see the diverse collection of development which include residential, commercial, institutional, research, and open spaces all of which can potentially be interfaced with by the nuclear complex (see Figure 6.15). Related to this, population density around the site shows that the residential areas are the densest and therefor offer the positive criteria of having the population serviced by the power plant nearby, thus cutting out the need for large electrical transmission centers and other cumbersome infrastructure (see Figure 6.16).

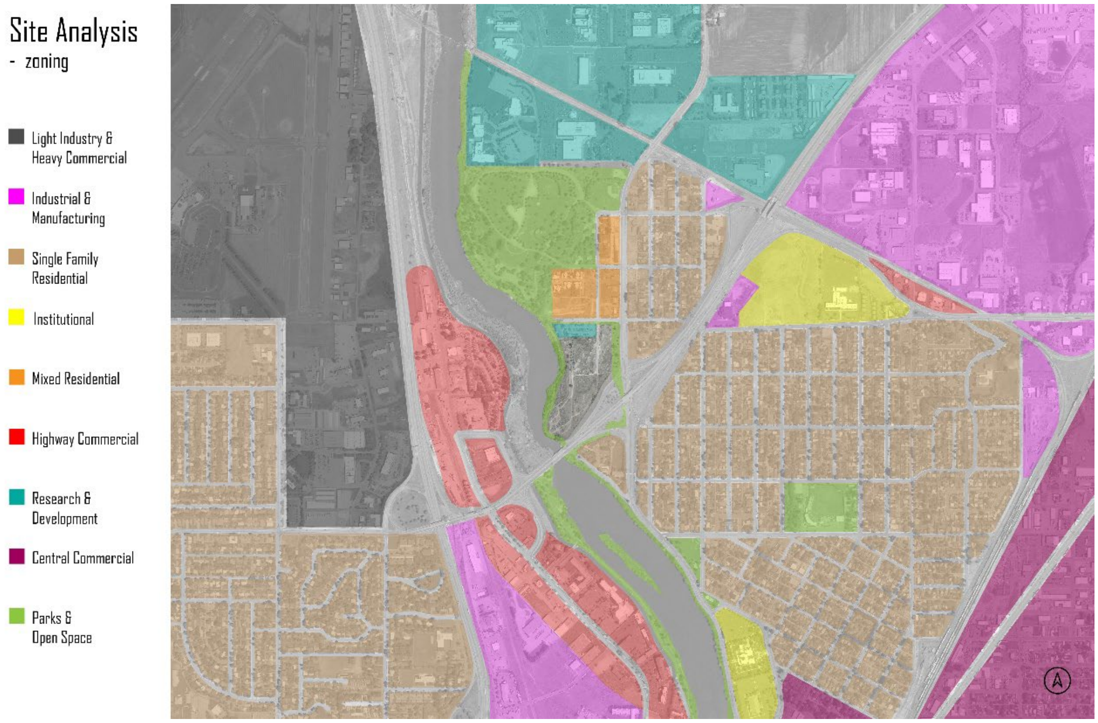


Figure 6.15: Diagram showing the differing use groups around the site. (Source: Author)

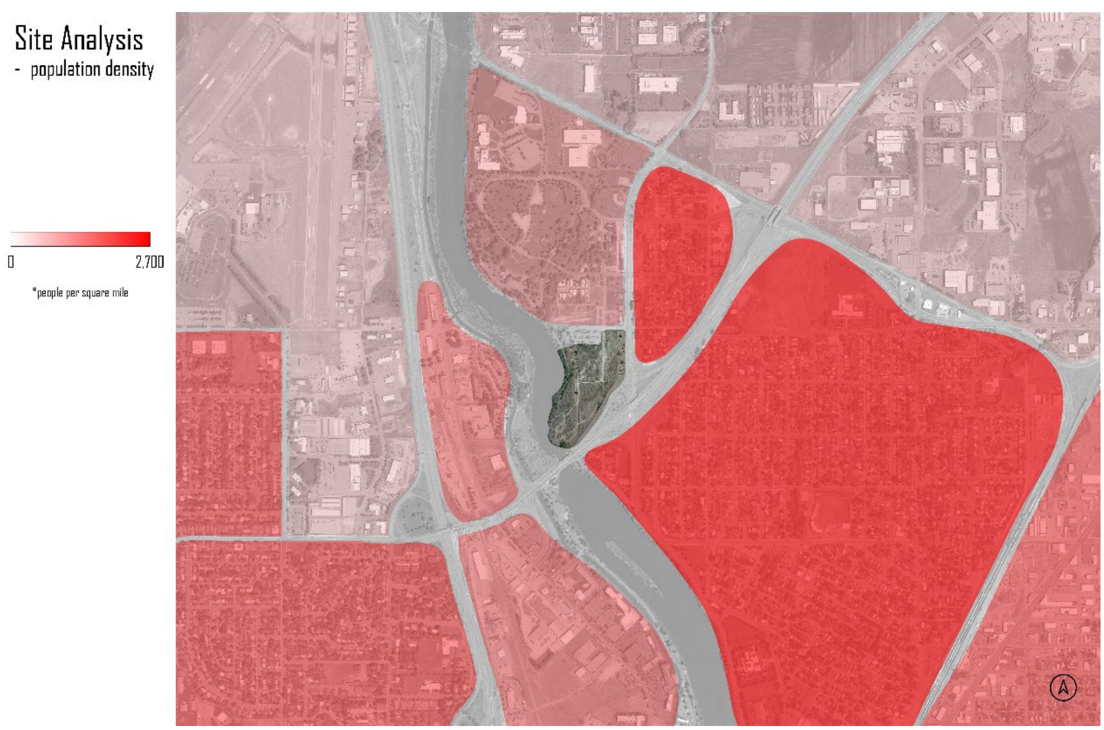


Figure 6.16: Diagram showing the differing population densities around the site. (Source: Author)

Looking at the site at a closer scale, one can begin to see how the macro features of the city covered prior begin to affect the site directly and ultimately inform design solutions. As stated earlier the Snake River constrains the site. This is seen through its projected flood plains which encouraged some of the design's response (see Figure 6.17). To the east the elevated U.S. Route 20 highway runs past the site with Freemont Ave and one of the railway corridors being the only underpasses (see Figure 6.18).

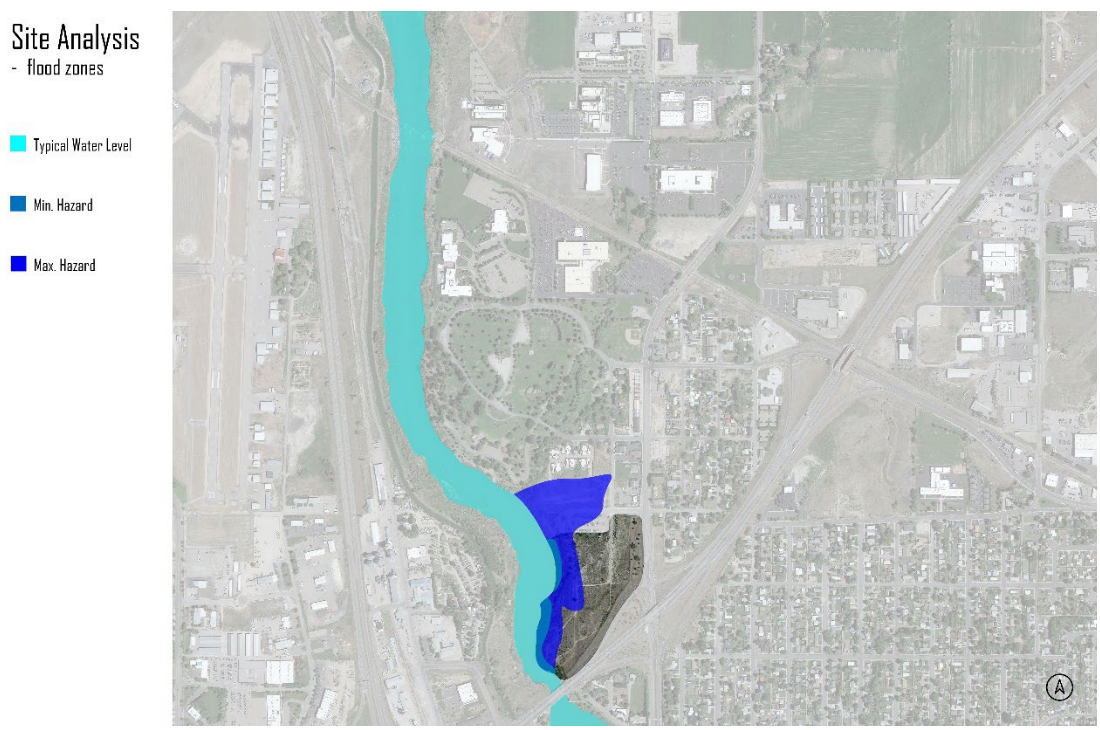


Figure 6.17: Diagram showing the Snake Rivers projected flood zones. (Source: Author)

Figure 6.18: Diagram showing the path of U.S. Route 20 and its associated underpasses. (Source: Author)

Between the river and the highway is Russ Freeman Park, which is a part of the cities greenbelt and starts as a large greenspace to the north of the site and becomes a linear park space as it snakes around the site (see Figure 6.19). Also, between these bordering elements, sitting just to the north of the site, is the Idaho National Laboratory and University of Idaho which have access to the site via Freemont Ave and the walking trails through the park (see Figure 6.20).

Figure 6.19: Diagram showing the location of Russ Freeman Park. (Source: Author)

Figure 6.20: Diagram showing the location of important nearby institutions. (Source: Author)

These elements create a pocket within the city and host a variety of use groups. The bordering features of the Snake River and U.S. Route 20 make the southern portion of the site mostly secluded with it becoming more permeable as you move north (see Figure 6.21).

Synthesis Diagram
- layers of accessibility

Figure 6.21: Diagram showing the permeability of the site. (Source: Author)

Looking at the site directly, you get a better understanding of the other footpaths around the site which allow people access from the bordering communities outside this implied "pocket" (see Figure 6.22).

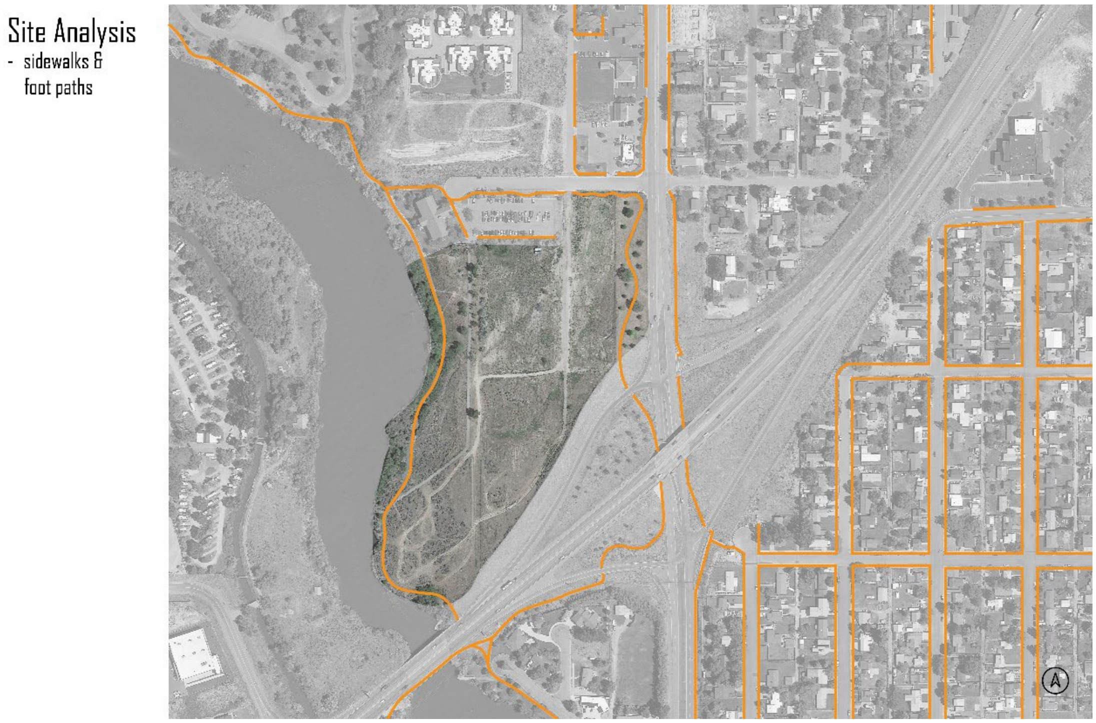


Figure 6.22: Diagram showing pathways and their routes, both in and around the site. (Source: Author)

The topography of the site is relatively flat with maximum grade changes of 10ft from point elevation to point elevation. This landscape is representative of much of Idaho, with the site being flat rolling hills with low lying plant growth (see Figure 6.23).

Figure 6.23: Diagram showing topographic information and views both into and from the site. (Source: Author)

Project Summary

Getting into the project's response to these program layouts, guidelines were created to address the site conditions. Foremost, is for the design to provide for the safe and effective operation of the nuclear power plant, this is seen as the reactor complex sits at the semi-secluded southern point of the site. Stemming from this, spaces are created with implied connections to the reactor complex, such as the berm which snakes up the western edge of the site from the power plant and connects to the public and academic buildings, this being a practical element as to block potential flood waters, but also becomes architectonic as it acts as an extension of the buildings themselves, linking them and housing other infrastructure which will be highlighted later. Other guidelines are to preserve existing site circulation such as the greenbelt paths on the eastern and western edges of the site and to create buffers to adjacent thoroughfares by use of the eastern access road to the power plant and “ha-ha” site feature which encircle the plants perimeter (see Figure 6.24).

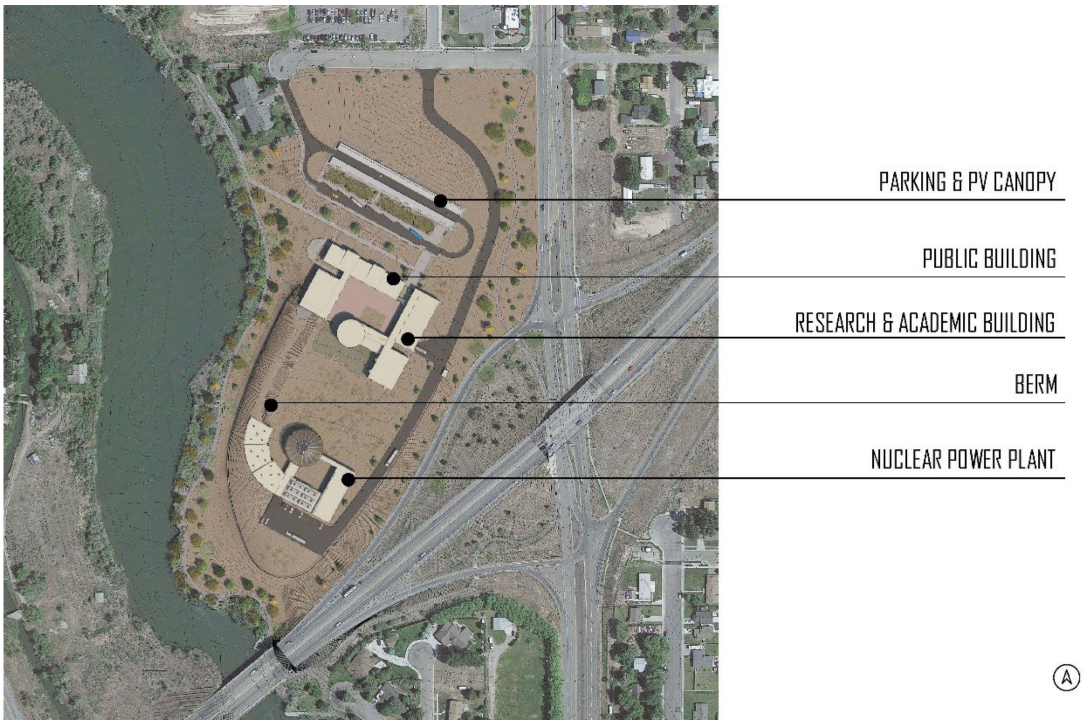


Figure 6.24: A site plan of the nuclear complex and its associated public, research, and academic facilities. (Source: Author)

The public and research & academic buildings include important spaces such as classrooms, labs, a mock reactor to showcase the technology used within the nuclear plant, and a museum to put into context the complex past of nuclear power. All of which is centered around a courtyard to foster discourse between the differing groups who will use the site. Stemming from this is also a shared auditorium which both public and academic entities can use. The site around these buildings includes a loading area for the back-of-house lab spaces, greenbelt access, the berm and service tunnel (which will be highlights later), and a water retention area. This water retention area sits between the publicly accessible domain and that of the more private power plant. This retention area holds all stormwater runoff from the public and academic buildings. This water basin acts as a moderator between the publicly accessible domain and the more private power plant (see Figure 6.25). Also symbolizing the use water plays as a moderator within nuclear reactors.

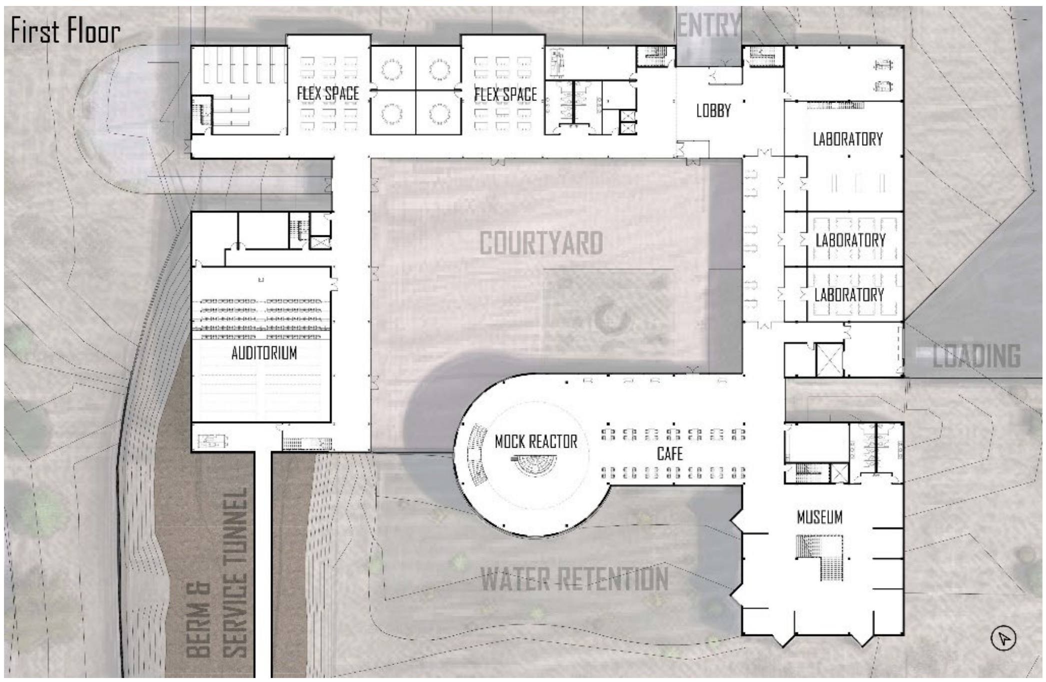


Figure 6.25: First floor plan view showing the layout of the important programmatic areas. (Source: Author)

Key areas such as the lobby entry between these buildings and the nexus (café) space housed in the connector between the mock reactor and museum offer points at which the public and research groups can mix, thereby fostering discourse on topics of nuclear energy. These areas of discourse also include the courtyard itself (see Figure 6.26).

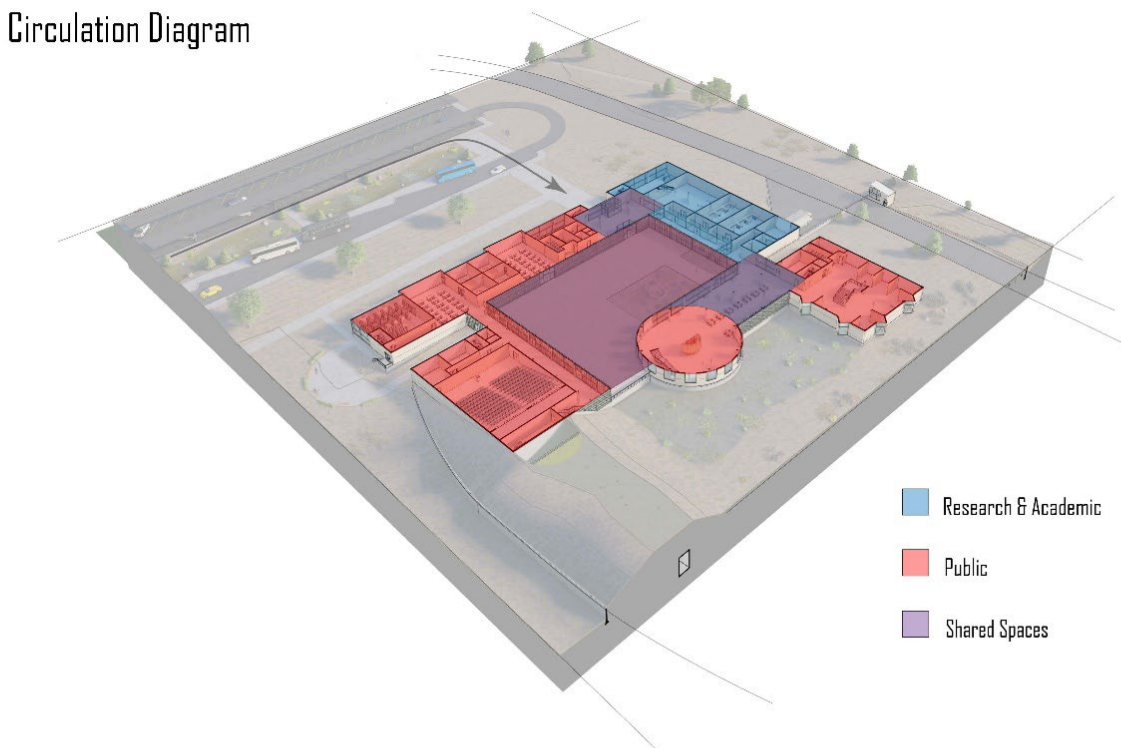


Figure 6.26: An axonometric showcasing the important programmatic areas and how they can overlap to create discourse. (Source: Author)

The lobby being the first of these potential mingling experiences offers views of what is to come within the courtyard and mock reactor spaces, as well as the veil of the nuclear power plant beyond. Acting as a filter, the lobby allows people from the differing backgrounds who have access to the site the ability to go to their allocated areas. Students and professionals are able to proceed into the lab spaces, while members of the public can proceed to classroom, and flex spaces, as well as the auditorium (see Figure 6.27).

Lobby

Figure 6.27: Rendering showcasing the lobby experience. (Source: Author)

As one progresses from here into the courtyard one begins to get a better understanding of the mock reactor and nuclear complex beyond. While also coming across the native landscape which the power plant sits within being pulled into the courtyard. As mentioned previously, it is important for this project to create implied connections to the power plant due to the nuclear plants unique nature and it being largely inaccessible to members of the public. By pulling the landscape that the power plant resides into the courtyard users can feel as though they are a part of the sites holistic design approach with the power plant, public building, and research and academic realm being seen as one element (see Figure 6.28).

Courtyard

Figure 6.28: Rendering showcasing the courtyard experience. (Source: Author)

The courtyard area is flanked by corresponding spaces which create dialog with one another, such as the flex space which offers learning opportunities and the mock reactor being the application of what was learned (see Figure 6.29).

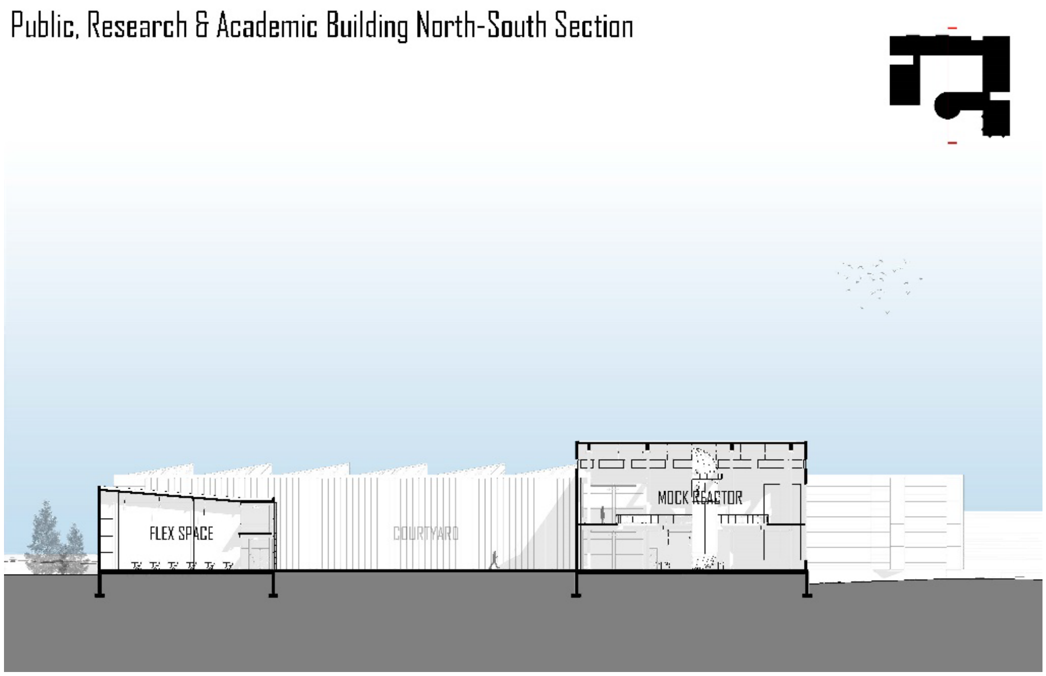


Figure 6.29: A building section through the public and research & academic buildings. (Source: Author)

Finally arriving off the courtyard one enters the café space that sits in the connector between the mock reactor and museum. From here one is given the choice to proceed into either a space which highlights the past of nuclear energy or its present. Both being important bookmarks to the topic (see Figure 6.30).

Cafe

Figure 6.30: Rendering showcasing the cafe experience. (Source: Author)

Offering views out to key areas of the nuclear power plant, the two-story mock reactor space highlights the present status of nuclear power. To do this, the space showcases a cross-section replica of the reactor used within the power plant. Across the café connector from this is the museum which houses exhibit spaces that too offer scenes at each display that look out to the actual nuclear power plant. Thus, putting into context, the history of nuclear energy with the present technology seen on site. Exhibits within this museum would feature many of the topics covered in the previous chapters of this paper (see Figures 6.31 & 6.32).

Mock Reactor

Figure 6.31: Rendering showcasing the mock reactor experience, the center piece being the cross section of an inactive reactor. (Source: Author)

Museum

Figure 6.32: Rendering showcasing the museum experience as it looks out to the nuclear power plant. (Source: Author)

The second floor of the research & academic building offers double height spaces for the museum, mock reactor, and additional lab spaces. As well as the upper areas of the auditorium which back up to the observation platform that sits atop the berm. Back-of-house areas to the north of the plan include administrative areas such as office space and meeting rooms, all of which back up to the double height spaces of the flex areas. This layout reinforces the ideas of overlap in plan and caries across the ideas of encouraging discourse (see Figure 6.33).

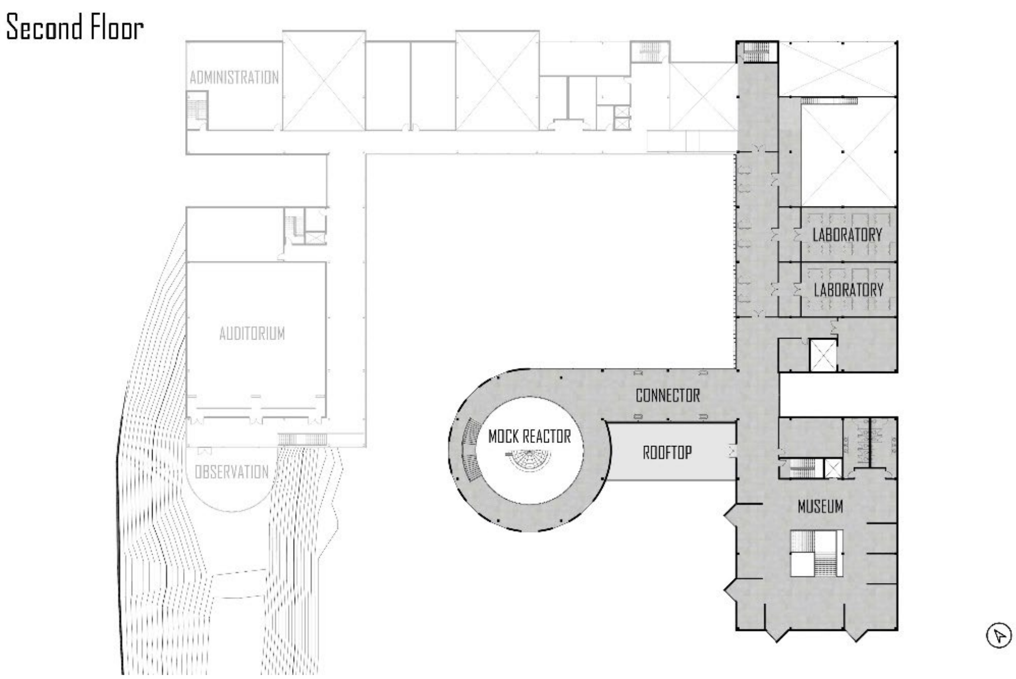


Figure 6.33: Second floor plan view showing the layout of important programmatic areas. (Source: Author)

This observation area atop the berm highlights the implied connections that the public domain shares with the power plant. While also offering views into less vital parts of the facility such as the turbine hall. Visitors also get an understanding of the veil which wrap the reactor hall, showcasing the idea of transparency (see Figure 6.34).

Figure 6.34: Rendering showcasing the observation experience, allowing visitors to look across the site to the power plant and some of its internal facilities. (Source: Author)

Moving onto the materiality of these buildings the primary façade material is a terracotta rainscreen system, with its tight horizontal lines terracotta represents the orderly uses within these buildings while also having a color like the native landscape of Idaho. The orientation of the terracotta panels also emphasizes the horizontality of Idaho landscape. Terracotta louvers are used in front of glazed areas to share in the veil-like architecture of the power plant (see Figure 6.35).

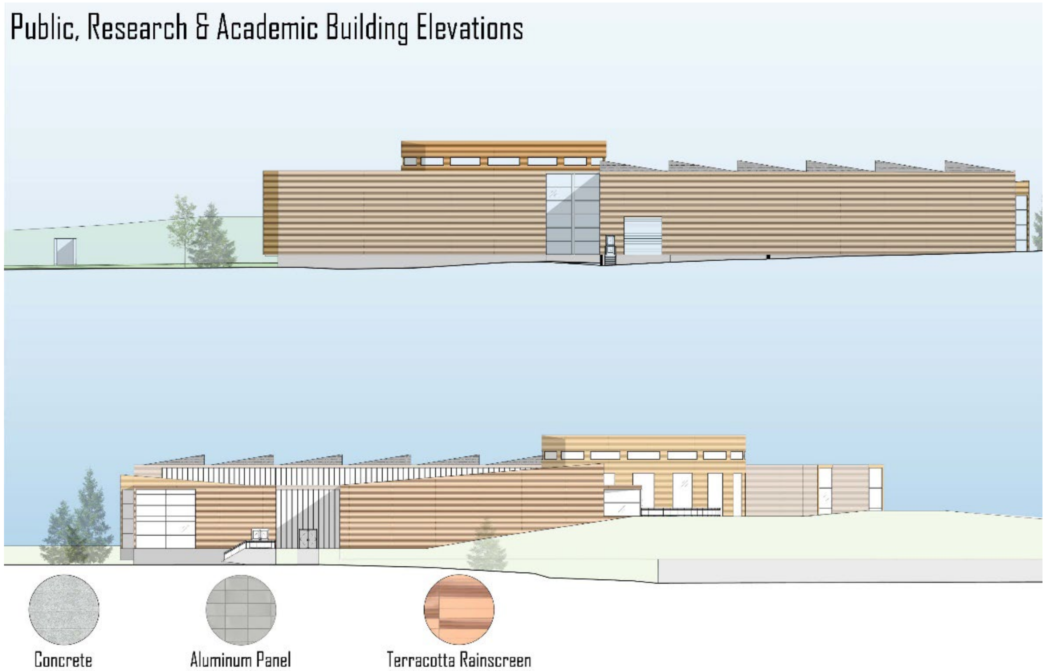


Figure 6.35: East and West elevations of the public and research & academic buildings which highlight the buildings primary materials. (Source: Author)

Moving to the southern portion of the site where the power plant is located one can begin to understand how it becomes the focal point of the associated public and academic buildings to the north. Laid out in a way to maximize views of its functions wherever possible (such as the turbine hall) while optimizing its functionality. The power plant starts more sculptural with the turbine hall as it is built into the berm and then orients its spatial uses around the reactor hall as to frame the intended "center-piece" of its operations (see Figure 6.36).

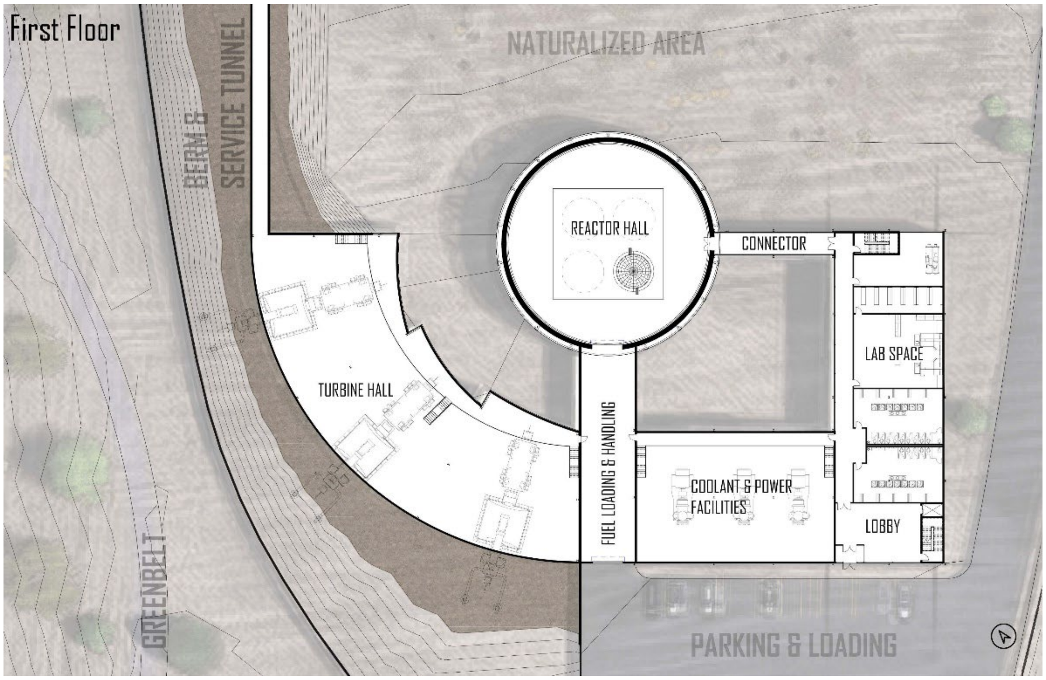


Figure 6.36: First floor plan view showing the layout of the important programmatic areas of the power plant. (Source: Author)

Double height spaces are needed for large equipment such as the reactor core and turbines. Second floor space is also allocated for administration and control areas. The control areas have access to the reactor hall via a connector hallway which leads to catwalks that encircle the reactor(s). Architectural elements such as the connector, courtyard spaces, and the overall “c-shape” layout of the power plant can also be seen across the public and academic buildings, once again making them read as one, instead of two separate halves (see Figure 6.37).

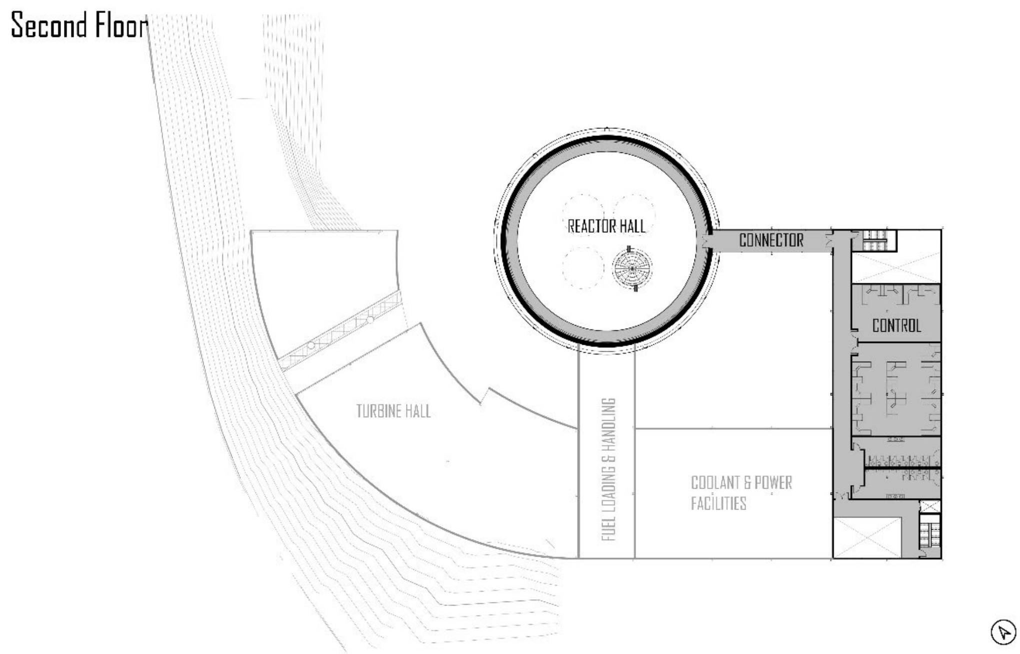


Figure 6.37: Second floor plan view showing the layout of the important programmatic areas of the power plant. (Source: Author)

Perhaps the most important aspect of the power plant is the way in which it presents itself to its surroundings. Including aesthetically subdued security features as to not impose itself on the community. These include main features such as the berm and "ha-ha" sunken wall which encircles the nuclear complex. The public and academic buildings themselves create the northern boundary with a naturalized buffer between them and the power plant. To the south, the existing highway acts as a buffer between the power plant and the communities beyond (see Figure 6.38).

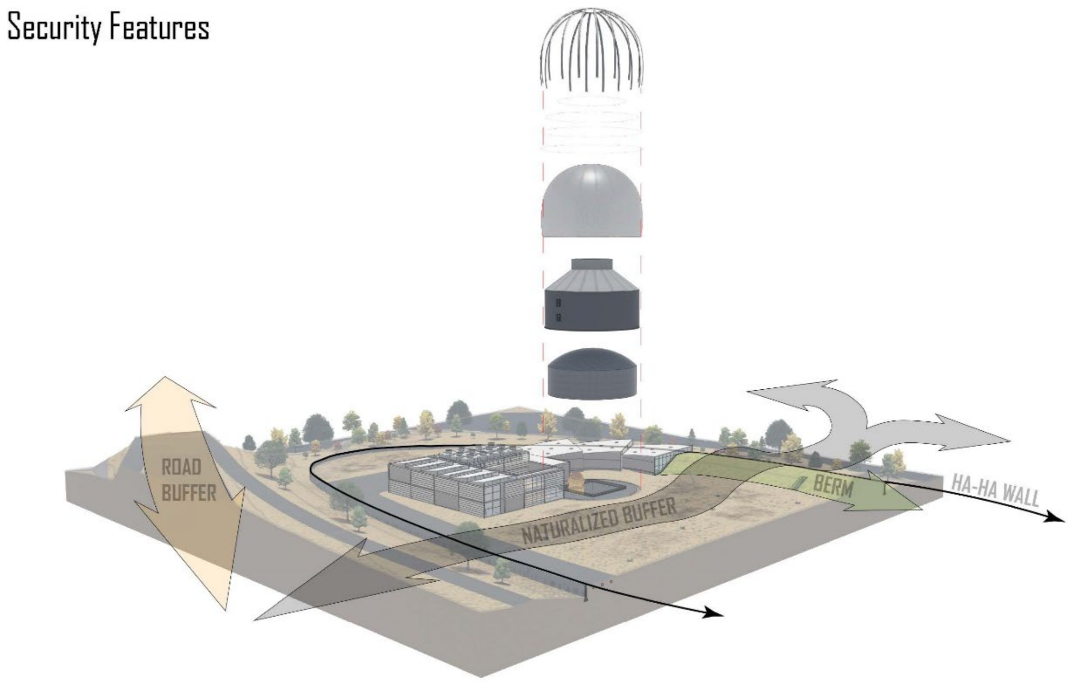


Figure 6.38: Axonometric showcasing the power plants aesthetically subdued security features. (Source: Author)

Another important aspect of the axonometric (pictured above) are the multiple layers of the veil system which wraps the reactor hall. Although people cannot directly see into the reactor hall, the veil symbolizes the multiple layers within. Adding to that, the containment buildings shape is seen through the veil, thus giving people an idea of what is happening within. This goes along with the overarching ideas of transparency and establishing a trust with the surrounding community (see Figure 6.39).

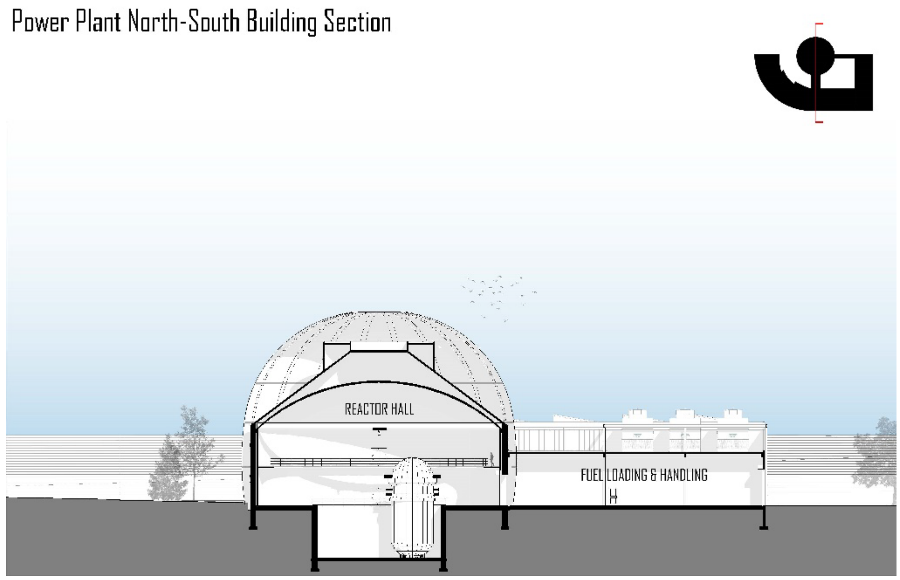


Figure 6.39: A building section of the nuclear power plant, showing how the veil structure wraps the reactor hall. (Source: Author)

This veil is made up of an aluminum screen system suspended from the steel structure. Other parts of the plant incorporate a terracotta façade as to form a homogeneous architecture across all buildings on the campus (see Figure 6.40).

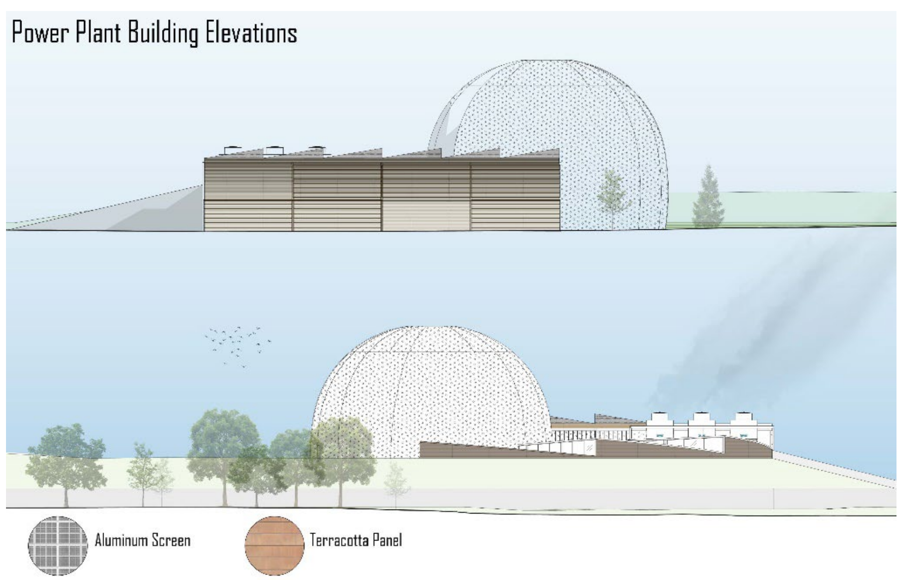


Figure 6.40: East and West elevations of the power plant. (Source: Author)

Other ways in which the plant can be normalized within the public eye past the means of architecture and programming include how the excess heat generated by the reactor is used. Traditionally this is vented as steam into the atmosphere. However, this complex uses the heat to both heat and cool the buildings by use of absorption chillers (see Figure 6.41).

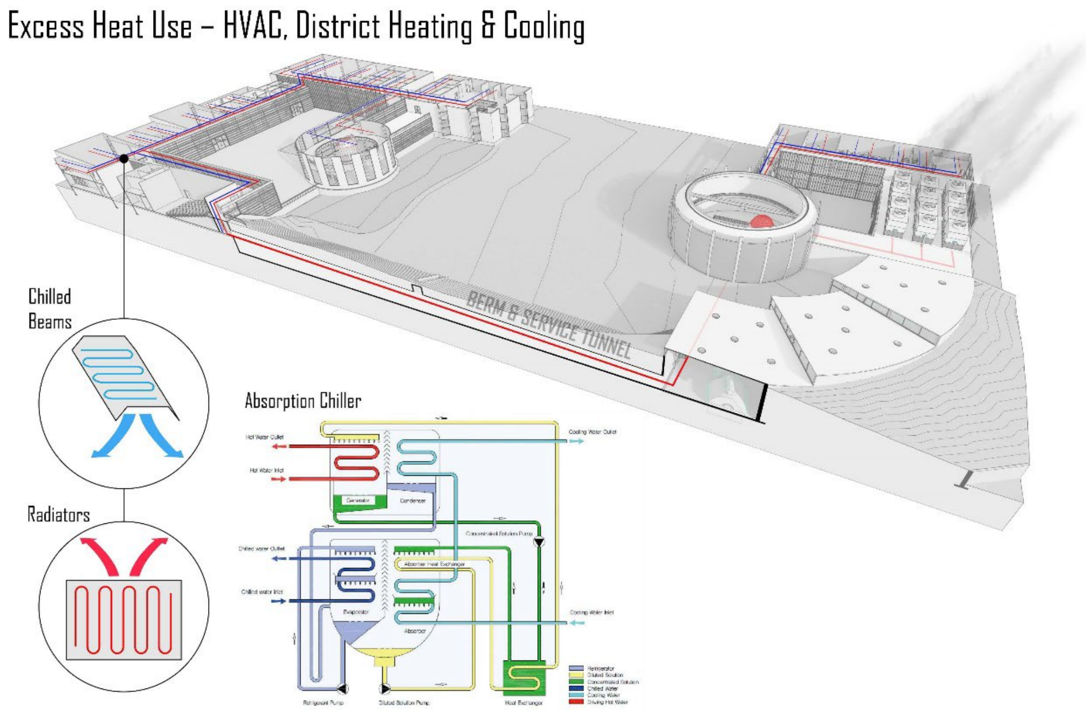


Figure 6.41: Diagrams showing how excess heat generated from the reactor is used to heat and cool the buildings on site. (Source: Author)

On a larger scale, the heated waters from the power plant can be piped under streets and sidewalks in the adjacent communities to keep them ice free during colder months. This being similar to geothermal methods of melting ice utilized on a large scale by countries such as Iceland (see Figure 6.42).

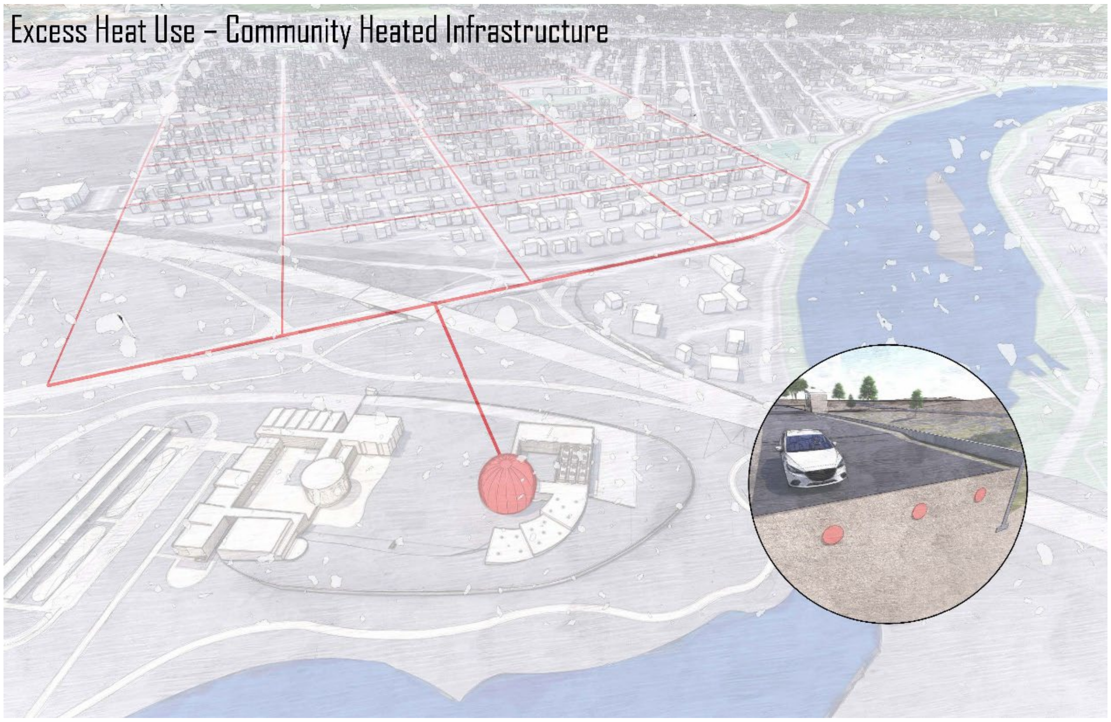
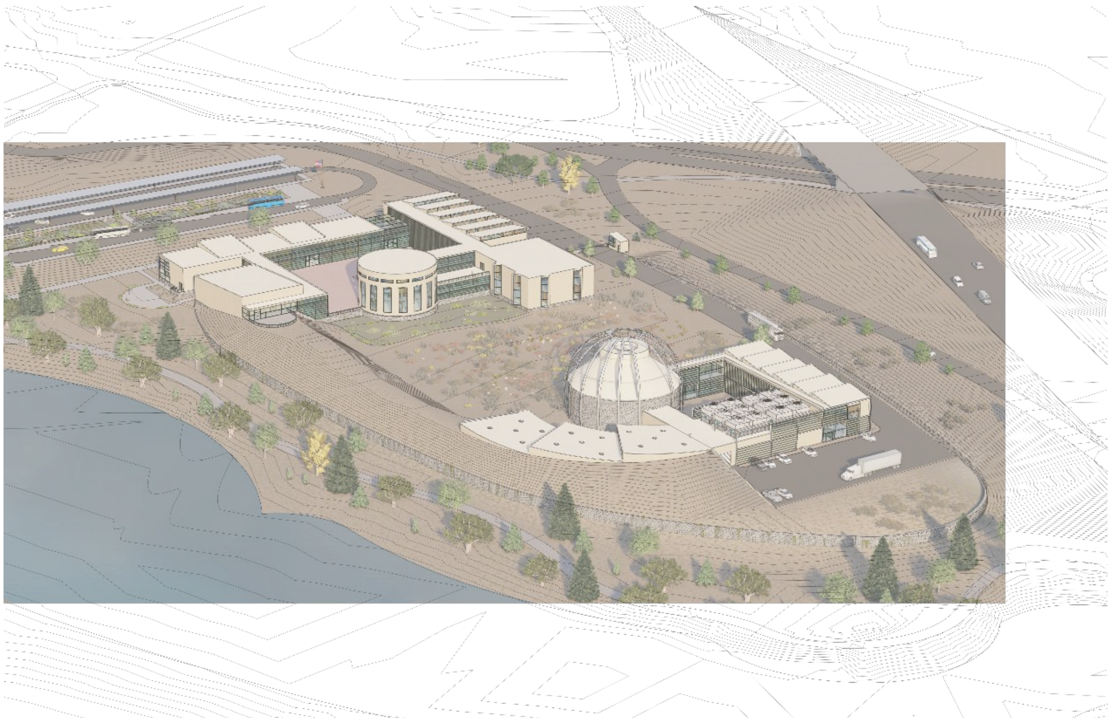


Figure 6.42: Diagram showing how excess heat generated from the reactor is used to heat community roadways and sidewalks. (Source: Author)

Takeaways

Idaho Falls acts as a case study to how a facility such as the one proposed within this thesis project could be deployed within an existing population center. To this, the microreactor would be a constant aspect of the project, while the public, research, and academic areas may change and/or be replaced depending on the needs of the community in which this facility is constructed. Other aspects such as how the reactors excess heat and energy are used could also be adapted. An example being if this project were to be deployed in a coastal region, then the excess heat could be used for desalinization efforts.

Through architecture, programming, site design, and systems this power plant interfaces itself within the established cityscape. Keeping a balance between its engineered functionality while upholding its duty to be a multifaceted positive element to both the public and the environment it resides. The new clear normal is atomic, designed in a way to expose the technologies inherent upsides and offer solutions to our growing need for sustainable energy.



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