Conceptual Design For a Small Modular Nuclear Reactor in an Urban Environment

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Honors Thesis

Environment and Ecology

University of North Carolina at Chapel Hill

April 10, 2014

Approved:

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Abstract

Given the worldwide necessity to reduce anthropogenic contributions to global climate change, an increased focus on nuclear energy over traditional fossil fuel based sources is arguably justified. This paper attempts to analyze whether it is possible for small modular nuclear reactors in particular to contribute to that transition, specifically through their utilization in an urban environment. For this analysis, an urban setting is defined as a large American university that currently produces a portion of its electricity demand at an onsite cogeneration facility. The University of North Carolina at Chapel Hill is used as a basic model for this university setting in this analysis. All relevant considerations were evaluated to determine overall feasibility of potential SMR implementation in this setting, as well as the requirements for specific design selection. Based on these requirements, three models were selected for further analysis: SVBR-100, TWR-P, and EM^2. All three were found to be suitable for university implementation, thus confirming the overall feasibility of SMR implementation in the described urban setting. While the most appropriate model depends on the specific inputs to the developed ranking system (which can be adjusted for various potential universities), overall EM^2 and TWR-P can be considered the more suitable of the three.

1. Introduction

As the effects of increased greenhouse gas concentrations in the atmosphere intensify and the negative environmental and health-related consequences of continued fossil fuel use escalate, the necessity to transition to more sustainable and cost effective energy sources becomes more pronounced. While arguments can certainly be made for increased reliance on solar, wind, and other renewable energy sources, these technologies are still fairly new and under engaged in America's energy landscape. Full reliance on these sources cannot yet be achieved without first obtaining significant improvements in the nation's grid system - the ability to transport electricity - and in energy storage technologies, as solar and wind cannot be reliably utilized without backup energy production systems. Thus, while a future in renewable technologies will develop over time, the fact remains that immediate action must be taken to reduce the nation's greenhouse gas output, its dependence on foreign fuels, and the environmental degradation associated with domestic coal mining. Nuclear energy, despite long existing (and arguably somewhat misguided) reservations concerning safety and security, can be viewed as an alternative energy approach with the ability to provide enough safe and reliable power to meet current and future demands. Small modular nuclear reactors (SMRs) in particular, offer substantial benefits in safety, security, operational flexibilities, and economics, and may play a key role in the nation's transition from fossil fuel use to more environmentally friendly sources of energy [14]. SMRs, while still a fairly new concept for the commercial market, are based heavily on already existing, trusted technologies and possess a diversity of applications given that they can be implemented either above or underground and as single units or as modules in a larger complex. While initially conceived for specialized applications or for use in remote locations, SMRs are, in fact, applicable to a broader commercial market and will likely play a key role in the transition away from traditional fossil fuel use toward nuclear power [23].

The current use of SMRs is limited to specialized applications, e.g., providing power for submarines and other naval vessels as well as for use in remote locations where the existing electrical grid cannot handle the output of larger reactors. However, no SMRs currently operate in the U.S. for commercial electricity production. The goal of this conceptual design is thus to evaluate the possibility of implementing an underground small modular nuclear reactor in an urban environment as a key source of baseload electricity and steam heat generation and to determine the ideal setup for this scenario. As the use of such a reactor in an urban setting has not yet been carried out, all considerations involved in the construction, implementation, and use of an SMR in this type of environment are evaluated to determine the overall feasibility of such implementation as well as the appropriate design and siting.

In general, the model for the "urban setting" used in this evaluation is a typical American college town with a large university that includes a hospital and produces a portion of its electricity demand at an on-campus, coal-fired plant. Specifically, the model siting chosen for this conceptual design is the University of North Carolina and its Cogeneration Power Plant. Implementation of a properly sized SMR would eliminate the university's need to purchase the remaining required electricity from a local utility, which in the University of North Carolina's case, is Duke Energy. Additionally, as 37% of the electricity generated in the US is produced by coal-fired power plants, the reduction of electricity purchased and used from such utilities in favor of electricity produced by an onsite nuclear reactor results in a contribution to reduced greenhouse gas emissions [36]. A model site that currently produces a portion of its electricity demand on site is chosen since the presence of an existing plant decreases construction requirements given that a distribution system is already in place. While the implementation of an SMR at a site that does not possess such infrastructure is certainly conceivable, it is not within the scope of this study.

This feasibility analysis begins with an evaluation of the required considerations associated with the implementation of a small modular reactor in this specific type of urban setting, which will determine the most applicable and feasible design for the setting in question. These considerations include (1) required power output, (2) costs, (3) safety requirements, (4) security requirements, (5) waste disposal, (6) integration of the SMR into the current facility setup, (7) total emission considerations, and (8) public reception. Given a few baseline requirements determined in this section, including required electrical output, a few potential models will be chosen for consideration. Then, each model will be further evaluated for its potential to meet the considerations mentioned above and the plausibility of the implementation of each model will be discussed. Finally, the ideal conceptual design(s) and setup, if one exists, will be presented.

Should it be possible to determine a particular model that can feasibly be implemented in this type of urban setting, the findings of this analysis would present an exciting opportunity for large universities, similar to the University of North Carolina, that currently produce a portion of their own electrical demand. Given the proposed set up, these universities would be able to implement an SMR that would produce all electricity demand on site, reducing costs associated with the continued purchase of power from a utility and emissions associated with electricity production from a fossil fuel. Such a set up would also equip the university to be prepared for any growth in electrical demand that is likely to take place, as the power output of most SMR models currently being developed exceeds the current demand expected by a university in this type of scenario. Thus, interested universities would have the opportunity to make a significant statement concerning their commitment to energy independence and reducing greenhouse gas emissions, while providing safe and reliable power to their community. Before such implementation can take place, an in depth analysis of all contributing factors associated with the construction and use of a small nuclear plant in an urban setting must take place.

2. Brief Overview of SMRs

The International Atomic Energy Agency (IAEA) defines a "small" reactor as one with an electrical output of less than 300 MW(e) [14]. These reactors stand in stark contrast to the large units that have come to dominate the current nuclear energy landscape. Since the establishment of nuclear power generation in the 1950s, the electrical potential of reactor units has increased dramatically from about 60 MW(e) to more than 1600 MW(e). The economies of scale associated with such large reactors represent the key driving force of the growth in size and electrical output observed since the 1950s. Despite this transition, there has also been a consistent historical presence of smaller power reactors built for naval use and as neutron sources in research reactors, resulting in a great deal of expertise concerning the engineering of smaller nuclear units as well [29]. Due to the perceived benefits associated with lower initial capital investment, scalability, siting flexibility, factory construction, and design simplicity as well as the knowledge and experience gained through the previous use of small reactors, SMRs are seen as a promising development within the nuclear energy industry. The Department of Energy (DOE) believes that SMRs may play an important role in addressing the energy, economic and climate goals of the U.S. if they can be commercially deployed within the next decade [27].

Most modern SMRs are designed for a high level of passive or inherent safety in the event of malfunction. Additionally, most are intended for below grade implementation, resulting in a high resistance to proliferation and terrorist threats. In addition, SMRs are expected to be much safer than conventional large-scale reactors, with a greater simplicity of design. A 2010 report conducted by the American Nuclear Society concluded that many of the safety provisions necessary in large reactors are not necessary in the small designs currently being developed [29]. These smaller, compact designs are factory-fabricated and can be transported by truck or rail to the intended site, providing enhanced flexibility in site selection for SMR implementation [27]. Finally, small units are seen as a much more manageable investment than large-scale conventional reactors, as they offer economies of mass production, and reduced construction costs and duration [29], [27].

The benefits of this technology are evident in recent nuclear agency decision-making concerning SMR development. A 2009 assessment by the International Atomic Energy Agency (IAEA) under its Innovative Nuclear Power Reactors & Fuel Cycle (INPRO) program concluded that there could be 96 small modular reactors (SMRs) in operation around the world by 2030 in its 'high' case, and 43 units in the 'low' case [29]. While deployments in the US are yet to be formally scheduled, numerous US-based companies are in the process of finalizing SMR designs for potential future deployment. Likewise, a 2011 report for the US DOE by the University of Chicago Energy Policy Institute stated that the development of small reactors can create an opportunity for the US to recapture a slice of the nuclear technology market that has eroded over the last several decades as companies in other countries have expanded into full-scale reactors for domestic and export purposes. Additionally, the report explains that small reactors could significantly mitigate the financial risk associated with full-scale plants, potentially allowing small reactors to compete effectively with other energy sources [29]. Finally, begun in fiscal year 2012, the DOE Office of Nuclear Energy's Small Modular Reactor Licensing Technical Support program advanced the certification and licensing of domestic SMR designs that are relatively mature and can be deployed in the next decade. The DOE announced its decision in November 2012 to support the Babcock &Wilcox 180 MW(e) mPower design, and in December 2013 it announced that a grant would be made to NuScale on a 50-50 cost-share basis, to support design development and NRC certification and licensing of its 45 MW(e) SMR design [29], [16]. These designs, as well as many others, will be discussed in later sections to determine their potential for implementation.

3. Considerations Specific to Urban Environment

3.1 Required Power Output

One of the first factors that must be considered when attempting to implement a small modular nuclear reactor in conjunction with an existing electrical generation facility in a university environment is how much electricity should be produced by the

SMR. The fact that so much variety exists among universities that produce and purchase different sized portions of their electrical demand makes it impractical to pinpoint a specific required output for the site. However, it is desirable to distinguish a range broad enough to cover the model site's current demand while allowing room for future increases, but narrow enough to serve as means of eliminating various models from consideration. In the first full year of operation of the cogeneration facility the University's peak electrical demand was about 55 MW(e). Since then, the peak has been over 75 MW(e) and is anticipated to reach 100 MW(e) in the near future.

SMRs currently under development range in output from less than 2.5 MW(e) to 300 MW(e). Based on this particular university's peak demand, a suitable minimum required electrical capacity that allows ample room for future growth in demand is 100 MW(e). Most SMR models should possess the ability to be scaled down to the current demand (should their stated output exceed it). Such scaling down has taken place in other instances. For example, a Russian BN-350 fast reactor in Kazakhstan produced up to 135 MW(e) for heat and desalination although the reactor was designed as 350 MW(e). This ability, and the fact that reactors with power outputs greater than 300 MW(e) are not considered SMRs, establishes 300 MW(e) as an acceptable maximum requirement. Thus, the possession of an electrical capacity within the range of 100 and 300 MW(e) is established as a requirement for potential SMR models considered for implementation in a university setting in this conceptual design.

3.2 Economics

In implementing an SMR in an urban environment the cost of such a development is likely one of the most significant considerations, other than safety, for the university pursuing such implementation. However, given the variability in available resources and overall goals of these entities, developing a concrete budget for the construction and operation of an SMR in this particular setting that will serve as a guideline for what specific models may be considered is not realistic at this time. This paper, then, operates under the assumption that an entity considering the implementation of an SMR in this type of setting is committed to such implementation, independently of the expected variation in construction and operation costs for each particular reactor model. Therefore, a detailed economic analysis of each reactor model will not be considered in this analysis. It is assumed that any entity considering implementation of a SMR would develop a cost model for the technology or technologies under consideration. The input for such a model is yet to be developed. However, what cost information for each model that is available, while limited, is presented in later sections discussing particular reactor models.

Despite the exclusion of a detailed cost analysis, some basic statements can be made about the economics of SMR technology versus conventional large-scale reactors. The capital investment associated with SMRs is generally much lower than for traditional large-scale plants. Additionally, due to their modular components and factory fabrication, construction costs and duration are greatly reduced compared to large reactor construction [27]. However, despite some initial benefits associated with design simplicity and factory fabrication, SMRs do not produce the same economies of scale associated with large reactors. The modular nature of these designs combat this issue to some extent, but only plants that include multiple units benefit from such economies of scale. Additionally, the expectation is that such plants construct individual modules over time, meaning that economies of scale are not experienced after initial construction, but only after multiple modules are completed [4]. Additionally, this modularity feature does not apply to the situation examined in this conceptual design, as a university setting would only require one unit. The complexity of this issue contributes greatly to the lack of concrete predictions concerning the costs of constructing and operating an SMR. However, as stated previously, what cost information is available relevant to specific reactor models will be presented in later sections.

While specific SMR cost data is not extensive, various general cost considerations relevant to potential implementation in an urban environment can be examined to determine whether any of these considerations limit the overall feasibility of SMR implementation in this particular setting. One such consideration is staffing requirements. Given the existence of an electricity producing plant on campus, current plant staff could potentially take on the additional duties associated with the everyday operation of the SMR. Depending on the type of reactor selected, more or less staff may be needed, as the different fuel cycle options possess varying requirements concerning refueling and waste disposal. For example, if a reactor with a relatively long fuel cycle is selected, waste management will require much less manpower than would a reactor with a shorter fuel cycle. Additionally, it can generally be expected that more staff would be needed in a university-based urban environment as opposed to an offsite industry. However, the potential extra staff that is required should not serve as a barrier to feasibility of implementation of an SMR in this setting. In the event that the current cogeneration plant is decommission, the staff required for its daily operation could simply be transferred to the daily operation of the SMR.

Another relevant cost consideration is how the funding for potential implementation will be acquired. While it is assumed that the university considering the implementation of an SMR is committed to such implementation, independently of the expected variation in construction and operation costs for each particular reactor model, it is worth considering from where the funding for such a project will come. Given the novelty of this sort of 'new' technology, it could be possible that federal and/or state funding be provided.

3.3 Safety

Arguably the most important considerations when analyzing the feasibility of implementing an SMR in an urban setting are safety and security. Given the proximity of the reactor to the university community and the general public, additional safety issues beyond those associated with the construction and operation of typical nuclear reactors must be considered. This section will discuss various factors associated with ensuring safety when choosing potential models and when assessing the feasibility of implementing each of these models. These factors include (1) everyday operational risks given the proximity to the university, (2) risks associated with the refueling process, (3) the required emergency planning zone and its 'special' occupants, and (4) evacuation plans. Additionally, features or requirements that the ideal model should possess, given the proposed setting and these four safety considerations, are identified. Later, each SMR model considered in this paper will be evaluated for feasible implementation in the proposed setting based on these considerations.

3.3.1 Daily Operation

Many features typical of SMR models significantly reduce most, if not all, of the safety risks associated with the daily operation of a nuclear reactor, even given the proximity to a dense population that exists in the proposed scenario. Therefore, regardless of the particular model choice, some basic features exist that establish each SMR model as inherently safe, especially when compared to conventional larger reactors. One of the most prominent of these features is the small nature of the reactor itself. The source term of a nuclear reactor - the total radioactivity in the reactor core that is available for potential dispersion - is roughly proportional to its power level. Therefore, SMRs, by definition, possess a reduced source term [14]. Reactor safety essentially comes down to ensuring that a hazardous amount of radiation is not released to operations personnel or to the general public [15]. Reduced source term as a result of reduced power output significantly limits the amount of potential radiation that could be released in the event of a meltdown, contributing to the enhanced safety of SMRs.

Additionally, most SMR models currently in the design phase are intended to be housed entirely below grade, providing additional options for scramming and reducing any potential exposure. In addition to enhancing safety during day-to-day operations, such placement also severely reduces the consequences of a worst-case scenario, as any access to the reactor could effectively be sealed off and contained. Thus, the risks of a meltdown to nearby inhabitants are reduced significantly, as the consequences of such an event for an SMR placed underground are less severe. Additionally, such placement reduces the consequence of various natural disasters such as hurricanes and tornadoes [11]. However, while the below grade placement of most SMRs provides many benefits in the day-to-day, such placement may not affect the risk associated with other extreme events such as earthquakes [25]. One option to combat the risks associated with an earthquake, is to simply minimize the risk of earthquakes by choosing a location for the reactor with very minimal seismic activity. If the reactor must be placed in a location with more seismic activity, another option is to contain the key reactor components (which are generally housed within a single vessel) within a pool of water, a set up that some current models include in their design. This pool serves to dampen the effects of earth movement and to enhance the ability of the system to withstand earthquakes [25]. Therefore, whether by location selection or by seismic zone design (or a combination of the two), the improbable but existing risk of an earthquake given the underground placement of the reactor can be further minimized.

As stated previously, many SMR model designs include the main reactor components within a single vessel. This integral configuration further contributes to the inherent enhanced safety of SMRs compared to larger conventional nuclear reactors. Integral configuration, specifically, refers to the housing of the steam generators, pumps, pressurizer, and reactor core, within a single, high strength pressure vessel. This configuration eliminates the necessity of large external primary piping, eliminating the risk of a loss of coolant accident (LOCA) caused by a large break [25]. The probability and consequences of small break LOCAs are reduced due to the decrease in overall piping length associated with the general SMR design [2]. The presence of the steam generators within the vessel also serves as an effective heat sink for decay heat removal in a loss-of-flow accident (LOFA). A LOFA refers to the failure of the coolant pump, which can lead to a meltdown if the proper response mechanisms are not in place. The integral configuration contributes to the minimization of the risk of a meltdown associated with a LOFA by providing an effective heat sink.

Such vessels also accommodate relatively large pressurized volumes, which provide better control of under/overpressure transients [15]. Pressure transients describe a potential problem associated with boiling water reactors. In these reactors, an increase in pressure as a result of some other disturbance can result in an increased ratio of water to steam, which in turn results in increased neutron moderation and thus, an increased power output. Such an increase can cause overheating and potential meltdown. Maintaining appropriate pressure levels is crucial to regulating the water to steam ratio and thus, the power output. The integral configuration provides better control of these transients and thus, of overall power output. By minimizing the risk of potential accidents through integral configuration, SMRs are inherently safer, further contributing to the reduced everyday operational risks.

Additionally, smaller plants in general are better able to accommodate heat transfer through passive measures. The lower core operating power results in a lower decay power as the total decay power (like the source term) is proportional to the operating power. Additionally, the smaller core volume enables more effective conduction of this reduced decay power to the reactor vessel, as the smaller core radius contributes to a shorter conduction path from the core to the reactor vessel. Thirdly, smaller systems are more effective at removing heat from the external surface area of the vessel. This is due to the fact that the decay power is proportional to the core volume, which varies as a cube of the effective core radius. Alternatively, heat removal from the exterior surface of the vessel is proportional to the surface area of the vessel, which varies with the square of the core radius. Thus, as the power level is reduced, the volume of the core decreases more quickly than the surface area, meaning that the relative efficiency of external heat removal is improved. The result is that most SMRs possess the ability to easily achieve decay heat removal using fully passive, natural convection air or water circulation systems [15]. This enhances the safety aspect of SMRs compared to conventional reactors and contributes to the overall design simplicity.

Given the improved safety of SMRs over traditional large scale reactors, few requirements for potential models associated with minimizing everyday operation risks can be specified beyond the required below grade location, passive safety features and integral configuration. Since these are common, if not inherent, characteristics of SMRs currently under development, these requirements are easily achieved. This suggests that the feasibility of the implementation of an SMR in the proposed environment will not be limited by requirements associated with reducing daily operation risks. Additionally, most universities possess institutional safety programs, such as an Environmental Health and Safety department or a Radiation Safety Office; either such entity could monitor the daily operation of the SMR to further enhance the overall safety of its daily operation.

3.3.2 Refueling

While the safety benefits associated with the daily operation of SMRs are promising, they lose significance when the core must be removed for refueling. Therefore, a key characteristic when considering potential SMR models for implementation is core lifetime. Ideally, the refuel period of the core would be as long as possible, so as to limit risks associated with the refueling process. Current models possess refuel periods anywhere from two to sixty years and significant differences exist concerning the deployment schedule for reactors on either end of this spectrum, which must also be considered. Therefore, the ideal reactor model for this set up would posses the longest possible refueling period and be planned for deployment within the next twenty years. However, given that this conceptual design is intended for future SMR implementation planning (as opposed to immediate use), deployment scheduling considerations should not outweigh refuel period when considering potential models for implementation in the proposed scenario. The safety benefits associated with a long refuel period far outweigh any benefits associated with minimal differences in deployment schedules over the next ten to twenty years.

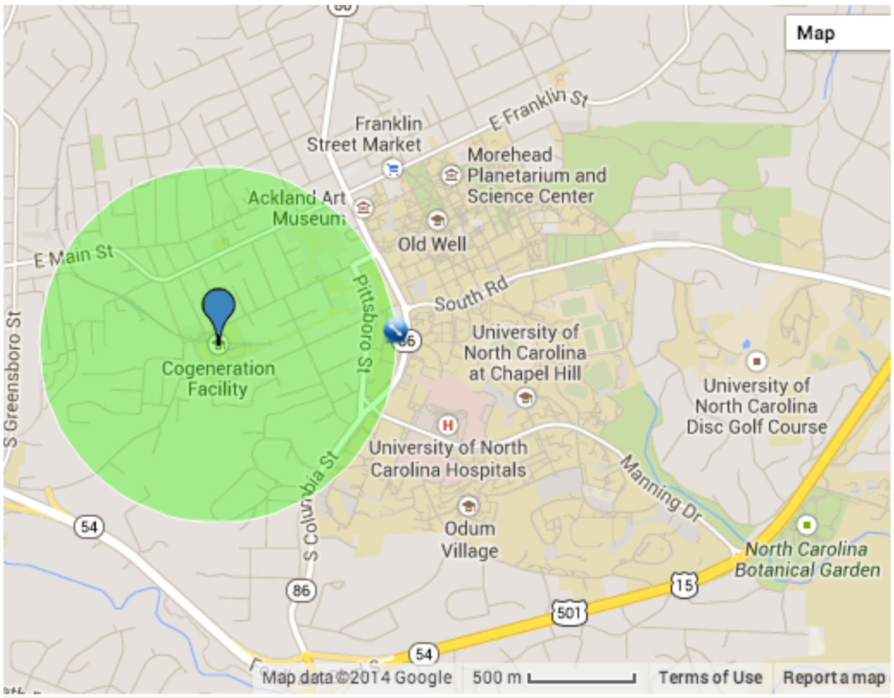
Additionally, depending on the type of reactor, different refueling methods may be required. For example, in some of the potential fast reactor designs, the entire core itself might be replaced, which would require vastly different refuel methods from a reactor that has part of its core removed and replaced more often. Ideally, a SMR design that involves full removal and replacement of the core once after a relatively long period of time will be chosen for implementation. Other specifics regarding refuel methods and the associated safety issues will be discussed in later sections regarding the technology of specific potential designs.

3.3.3 Emergency Planning Zone (EPZ)

Despite safety enhancements inherent to the small modular design, specific critical guidelines concerning the emergency planning zone must still be detailed. Since no SMR has yet been implemented in such a setting, there is no precedent for the required emergency planning zone. Typically, the NRC defines two zones around each nuclear plant, the exact size and configuration of which vary depending on specific plant characteristics. Typically, the Plume Exposure Pathway EPZ has a radius of approximately ten miles and includes areas where there could be an exposure of radioactive materials [7]. In the event of an emergency, those located in the area contained within this pathway could experience exposure from plume inhalation that exceeds EPA Protective Action Guides (PAGs). As a result, the Plume Exposure Path is subject to predetermined protective action plans designed to avoid or reduce exposure to radioactive materials. Protective actions include but are not limited to respiratory protection, sheltering in-place, or evacuation [35]. The Ingestion Exposure Pathway EPZ has a radius of about fifty miles from the reactor site and is identified to prevent potentially contaminated food, water, and vegetation from being consumed.

While the inherent safety features of SMRs surely justify the consideration of a reduced EPZ, the closer proximity to a large concentration of people must also be considered. According to the US DOE, there is potential for a significant reduction in the EPZ for SMRs [21]. Proponents or SMRs advocate for a reduction of the Plume Exposure Pathway EPZ from ten miles to as little as half a mile, or approximately 805 meters [1]. The World Nuclear Association argues for even further reduction, stating that the EPZ required for SMRs is designed to be no more than about 300 meters in radius, given the safety enhancements discussed previously [29], [28]. Consider the placement of an SMR according to the scenario outlined in this paper, in the center of a highly populated dense urban area, such as a university. Even if an EPZ of half a mile (the more modest reduction) is established for this reactor, only a very small portion of the campus or urban area would require extensive emergency plans in the event of a radiological emergency. Figure 1 depicts a one half-mile radius around the current cogeneration facility at the model university, demonstrating the relatively small portion of the university community that would be affected in the unlikely event of an emergency. Thus, given the enhanced safety features associated with SMRs and the resulting expected reduction in required EPZ, the feasibility of implementing such a reactor in this type of urban center is clearly feasible.

Figure 1: ***One half mile EPZ for the University of North Carolina.***



3.3.4 Evacuation Plans

Despite the apparent feasibility of such implementation given EPZ reduction estimates for SMRs, the evacuation plans relevant to the areas within the determined EPZ must be tailored to the specific environment being considered. The conceptual site for the implementation of an SMR in this study is a university setting that produces a portion of its electricity demand at an on-campus plant. In the case of conventional, large scale nuclear reactors, state and local agencies are required to develop detailed evacuation plans for populations within the ten-mile EPZ. Such plans include various scenarios that consider variables such as time of day, weather conditions, season, and population characteristics (i.e. whether the population is 'general' or if it includes special facilities such as schools and hospitals). These plans and evacuation time estimates are required to be updated periodically to reflect changes in population and the transportation networks [9].

Since such implementation is unprecedented, there is no model evacuation plan for the community surrounding the intended SMR. Additionally, the anticipated reduction in required EPZ affects the group of people affected by the evacuation plan, which has implications for the content of the plan itself. Given these factors, various evacuation plans associated with reactors located near special facilities (preferably schools), as opposed to a general population, should be examined and adjusted based on the enhanced safety features of an SMR and for the close proximity of the reactor to the surrounding community. Additionally, such an evacuation plan should include considerations specific to a university setting. It is beyond the scope of this paper to develop specific evacuation plans, as the setting in question simply serves as a model for the implementation feasibility analysis, and a specific evaluation plan would not be applicable to other universities considering such implementation. However, the purpose of discussing the evacuation plan associated with the proposed implementation is to determine whether evacuation plan considerations limit the feasibility of the overall proposed implementation or impose any restrictions on the particular type of model that can be realistically selected.

One consideration specific to the university setting that must be considered is the fact that a large portion of the affected population will be students, many of whom will reside on campus. Therefore, adequate plans must be laid out as to where these students will be sent in the unlikely event that evacuation of the area surrounding the reactor must take place. Given the unlikely nature of such an event, as well as the existence of possibilities for relocation of students, this consideration does not serve as a limitation to the feasibility of the implementation of an SMR in this scenario.

An additional effect of the nature of the urban setting on the required evacuation plan is the issue of increased traffic. The conceptual setting is defined as "urban," meaning that, by definition, a greater number of people will surround and thus be potentially affected by the SMR. In the event that the area surrounding the reactor must be evacuated, the evacuation will involve a greater number of people than is usually involved in the evacuation of an area surrounding a large-scale reactor. The fact that the EPZ is expected to be much smaller in the case of an SMR slightly modifies this issue, but even in the best case EPZ reduction scenario, some of the university population will need to be evacuated. Additionally, it must be anticipated that when the parents of students residing outside of the EPZ learn of any evacuation, they will surely assume the worst-case scenario and insist their child be evacuated as well. These considerations combined result in a scenario in which a very large number of people are attempting to evacuate an already congested area, resulting in severe traffic. Such an issue must be accounted for in the evacuation plan itself, but also in the way that information is presented to students and their parents. The latter will be discussed more thoroughly in section 3.9 Public Reception. This issue lends itself to a potential site restriction when it comes to the overall feasibility of the implementation of an SMR in the conceptual setting. Ideally, divided highways would lead out of the university area and connect quickly to an Interstate highway. This requirement is achieved for the particular model site, the University of North Carolina.

An evacuation plan for a nuclear reactor in an urban setting certainly requires some additional considerations, although none of these would negatively affect the feasibility of the potential implementation of an SMR. Only one factor (enhanced traffic) could, if an adequate network of roads was not available, actually affect the potential implementation, by limiting specific site selection. Additionally, none of the above considerations has a direct effect on the specific models being considered.

3.4 Security

While ensuring the safety of those near the reactor is of paramount importance, minimizing proliferation risk and maximizing security are also crucial considerations relevant to the potential implementation of any nuclear reactor. As with safety, the underground placement of the reactor contributes significantly to increased security. Therefore, by design, all SMRs intended for below ground implementation (which includes most currently in the design phase) are inherently more secure than their larger counterparts. This is partly due to the fact that such placement reduces the consequence of severe events such as aircraft impact [11]. Additionally, this set up provides a secure place in many types of SMR designs - particularly light water SMRs - to house spent fuel before it is transported to its final destination, reducing proliferation risk of the reactor [25], [16].

Additionally, the long operating cycle requirement imposed for enhanced safety, also contributes to heightened security. The longer the fuel cycle, the less often fresh fuel will have to be loaded into the reactor and the less often spent fuel will have to be unloaded. Both of these activities provide opportunities for potential proliferation, so the minimization of their occurrences greatly improves the security of the plant. Fast reactors in particular benefit from such a long lifetime, as the phases most susceptible to fissile material diversion - new fuel, routine spent fuel handling, and out of reactor fuel storage - are non-existent at a fast reactor plant site [3]. Additionally, many SMRs are designed to operate without any partial refueling, meaning that, during refuel periods, the entire core is removed and replaced, which further reduces the exposure of the core, resulting in heightened security.

Specific features associated with different types of reactors also contribute to improved security for nuclear reactors in general as reactors with different coolant types tend to possess their own particular security benefits. For example, many water-cooled SMRs employ low enrichment uranium, which is less favorable for proliferation. They also include an unattractive isotopic composition of the plutonium in the discharged fuel, and radiation barriers provided by the spent fuel, which further lessens proliferation risks [19]. Additionally, there are intrinsic proliferation resistance features common to all high-temperature gas cooled reactors (HTGRs). Some of these features include high fuel burn-up (low residual inventory of plutonium, high content of Pu-240), a difficult to process fuel matrix, radiation barriers, and a low ratio of fissile to fuel-bloc/fuel-pebble mass [19]. Liquid metal cooled reactors also possess features that establish them as secure by design. Liquid metal cooled reactors are fast reactors that can ensure a self-sustainable operation on fissile materials or realize fuel breeding to feed other reactors present in nuclear energy systems [19]. If the fuel cycle is closed, then for both of these cases the need of fuel enrichment and relevant uranium enrichment facilities is eliminated, thus contributing to enhanced proliferation resistance. Additionally, fast reactors in general involve no separation of plutonium and uranium at any fuel cycle stage and leave only a small fraction of fission products permanently in the fuel [19]. Therefore, given the security features associated with each different type of reactor (in terms of coolant), as well as the enhanced security features associated with small modular reactor models in general, any reactor model chosen will possess more than adequate proliferation resistance. As a result, no unusual or additional requirements for the chosen model must be met when it comes to plant security, given the enhanced secure nature of small modular reactors in particular.

3.5 Inconveniences

As the potential SMR will be implemented in a highly populated urban area, potential nuisance considerations must be considered that are not necessarily applicable to the implementation of a large-scale reactor in the traditional remote location. A potential inconvenience associated with the implementation of any power plant is the noise produced by power production. Generally, noise associated with power plants is a result of the operation of the turbines and generators, both of which are, in this scenario, components of the existing power plant. The noise associated with these systems, however, does not currently serve as a significant nuisance in the cogeneration setup. While the SMR system would also include a steam turbine and generator, the noise associated with these components would be even less than the noise produced by the existing set up. This is because, in the SMR design, these components are housed underground and within a containment vessel as part of the integral design. Therefore, the noise associated with the implementation of an SMR in conjunction with an existing electrical generation facility in an urban environment would be minimal, if at all noticeable.

3.6 Waste Disposal

Another important consideration when determining the feasibility of implementation of an SMR in the given scenario, as well as appropriate potential models, is waste disposal. Given the urban environment in question, space limitations exist for the implementation of an SMR in this setting that do not exist for the implementation of a reactor in more remote locations.

Generally, used fuel from the core of a nuclear reactor is stored for several years under water in cooling ponds on the reactor site. These concrete ponds as well as the water covering the spent fuel assemblies provide radiation protection and remove heat generated during radioactive decay. Final disposal of this waste is delayed a certain number of years, depending on the level of the waste. For example, disposal of high-level waste, such as the used fuel itself, is delayed anywhere from forty to fifty years to allow its radioactivity to decay. After this amount of time, less than one thousandth of its initial radioactivity remains, and it is much easier to handle. Final disposal of nuclear wastes requires their isolation from the environment for long periods of time. Burying the waste in stable geological formations appears to be the most favorable method [29]. In 1987, the Yucca Mountain Nuclear Waste Repository was designated by the Nuclear Waste Policy Act (NWPA) Amendments as the deep geological repository storage facility for spent nuclear fuel and other high level radioactive waste. However, in 2010, federal funding for the Yucca Mountain nuclear waste repository site ended, leaving no designated long term storage site for high level radioactive wastes. Since then, the issue continues to be debated and a final decision concerning the designation of the site has yet to be made [37].

This essentially means that, should an SMR be implemented according to this concept design in the near future, used fuel will not be transported off site until the federal government designates a long-term storage site. This does not serve as a limitation to implementation, however, as used fuel must be stored for decades before being transported to a long-term storage site. Many SMR models, notably LWR models, include the storage of spent fuel in underground pools as part of its design [25], [16]. Additionally, since the output of any reactor implemented in this setting will be much smaller than conventional large-scale reactors, less waste will be produced. There will be less high-level waste as a result of fission, and less medium- and low-level wastes as a result of operations including the cleaning of reactor cooling systems and the decontamination of equipment [29]. However, the urban nature of the setting in which this reactor will be located does pose some constraints on space availability for plant components, such as the storage pools. Therefore, a key consideration of the specific feasibility of implementation of an SMR in particular settings will depend on the space available within the urban setting, as well as the amount of space required to house particular reactor types. Therefore, this consideration only outlines specific requirements for potential models when the amount of space available is known. For the purposes of this concept design, models that require less space relative to other models will be considered first, but this consideration will not be interpreted as strictly as others, given the variability associated with space availability. Typical SMR vessels measure, on average, approximately 23 meters in height and 4.5 meters in diameter, which is not anticipated to serve as a major limitation to feasibility of implementation in most university settings [29]. Specific spatial information will be presented, as it is available, in later sections discussing particular reactor types.

3.7 Integration with Current Cogeneration Setup

A distinct quality of the proposed setting is the existing presence of a cogeneration facility on the campus being considered. Such existence improves the feasibility of implementing an SMR in many ways, as it means that the infrastructure required to transport the electrical and thermal energy supplied by the reactor is already in place. Additionally, the existence of the cogeneration plant provides enhanced reliance to the SMR itself; in the unlikely event of a required shutdown, the original plant can continue to provide electricity to the surrounding areas. Ideally, the coal-fired plant would eventually be decommissioned, meaning this benefit would eventually be irrelevant. There is potential to also utilize the currently existing generator, but as most SMR designs include this within the integral vessel, such utilization is unlikely. Overall, the existence of the existing plant provides significant benefits when it comes to energy distribution, as current infrastructure can be utilized and the construction requirements are reduced overall. Thus, this consideration involves no particular restrictions or requirements for potential SMR model or site selection.

3.8 Emissions

In general, an operating nuclear power plant has near-zero carbon emissions, as the only outputs are heat and radioactive waste. However, other steps involved in the eventual production and use of nuclear energy contribute to an overall carbon footprint of a nuclear plant. These processes however, contribute to fewer total emissions associated with the lifecycle of a conventional large-scale reactor than are generally produced over the lifecycle of a coal-fired plant. In fact, existing nuclear plants prevent approximately 681 million tonnes of carbon from being emitted each year in the US alone [30]. Through the consideration of twenty of the most reliable life cycle assessments of currently operating nuclear reactors, Benjamin Sovacool found[1] that the total life cycle carbon emissions of a nuclear plant are estimated at a range of 1.4 grams of carbon dioxide equivalent per kilowatt-hour (gCO_2e/kWh) of electricity produced up to 288 gCO_2e/kWh [31]. This large variation of emissions can be explained by the different methodologies used in the individual assessments; however, a mean of 66 gCO_2e/kWh is generally considered to be a reasonable approximation. The World Nuclear Association completed a similar analysis assessing the greenhouse gas emissions produced by various forms of electricity generation. The results are summarized in Figure 2, and demonstrate that generating electricity from fossil fuels results in greenhouse gas emissions far higher than associated with nuclear generation [12].

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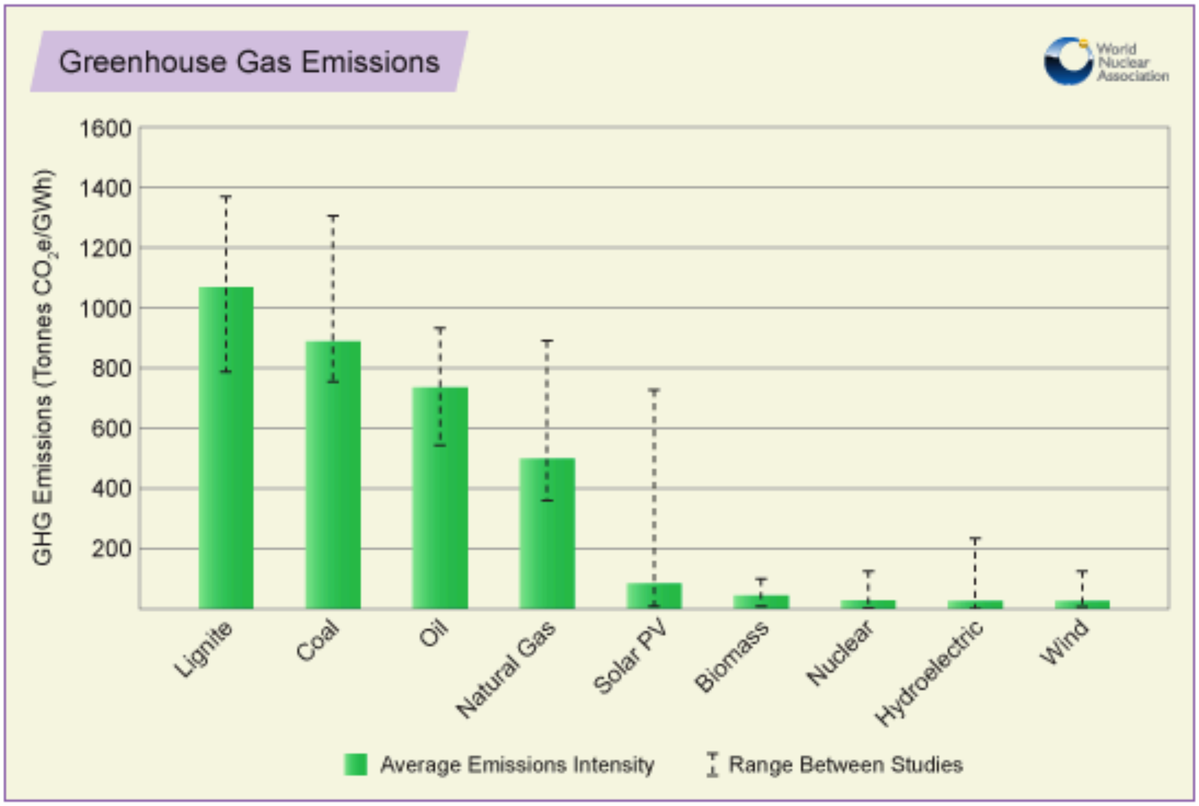
[1] *in his 2008 study entitled "Valuing the Greenhouse Gas Emissions from Nuclear Power: A Critical Survey,"*

Figure 2: ***Greenhouse Gas Emissions Associated with Various Energy Technologies*** [12].



Even on the high end of the range established by Sovacool, current emissions from nuclear plants are well below the emissions associated with scrubbed coal-fired plants, which emit, on average, 960 gCO_2e/kWh. Additionally, the 1.4 to 288 gCO_2e/kWh range and the 66 gCO_2e/kWh average represent emissions associated with various processes other than daily operation in the lifecycle of a large scale nuclear plant (since operational emissions are near zero). Therefore, the potential total emissions from an SMR are already expected to be much lower, as many of these processes are scaled down for an SMR. According to Sovacool's life cycle assessment study, the largest source of carbon emissions, which accounts for 38 percent of the average total, is the frontend of the fuel cycle. This includes the mining and milling processes for uranium ore, and the relatively energy-intensive conversion and enrichment processes [31]. Since less overall uranium is required for SMRs, the processes associated with its preparation are reduced, and emissions associated with the frontend of the fuel cycle are lower relative to large-scale reactors. Additionally, some of the proposed SMR technologies allow the reactor to utilize spent fuel as a portion of the required fuel component, further reducing the mining and milling requirements associated with the use of uranium ore. Should such a reactor be chosen for implementation, the emissions associated with fuel utilization are reduced even further [13], [8].

Despite a potential reduced demand for uranium ore, the sustainability of the uranium supply itself is still a consideration. Good quality uranium ore is becoming more difficult to procure, as the deposits of rich ores with the highest uranium content are being depleted. This leaves only lower quality deposits left to be mined. As ore quality degrades, more energy is required to mine and mill it and resulting greenhouse gas emissions increase [30]. However, the reduction in uranium ore requirements associated with the overall smaller size of SMRs, as well as the ability of some models to utilize spent fuel, combats this issue and contributes to an overall significant potential reduction in emissions associated with fuel procurement compared to large reactors.

Other key contributors to the total emissions associated with traditional nuclear reactors are construction (12 percent), operation (17 percent due to use of backup generators using fossil fuels during downtime), fuel processing and waste disposal (14 percent) and decommissioning (18 percent) [31]. All of these represent processes that are scaled down when applied to an SMR. For example, construction needs associated with SMRs are drastically reduced compared to large reactors. This is a result of the overall reduced size of the reactor, as well as the ability to fabricate the majority of the reactor components in a factory setting, where processes can be streamlined and efficiency can be maximized. The result is an expected reduction in emissions associated with SMRs compared to conventional reactors. Similarly, emissions associated with the operation of any SMR will be lower, as the total output of the reactor is lower. Fuel processing and waste disposal emissions are also anticipated to be reduced for SMRs since less overall waste will be produced and, ideally, more waste will be utilized by other SMRs that possess the ability to run off of spent fuel. Decommissioning emissions will also be lower given the smaller size of the reactors.

It is worth noting that, despite some major reductions in the emissions associated with fuel procurement, construction emissions may not be as dramatically decreased overall when compared to the emissions associated with large-scale reactors in general. This is largely due to the modular nature of SMRs. While the intended implementation in this concept design involves a single unit, it is anticipated that the future general implementation of SMR technology involves a greater number of total units in service. This would result in enhanced emissions associated with the construction of these units. However, given the scope of this study, the overall emissions produced by the individual university seeking SMR implementation will be reduced in the long run. Despite some initial emissions associated with the construction of the SMR and, potentially, fuel processing, the university will produce less overall total emissions by relying less (and ideally eventually not at all) on energy produced by higher emitting processes, such as coal burning.

3.9 Public Reception

Given both the lack of precedent for the proposed set up, as well as concerns held by a significant segment of the public regarding safety and waste disposal, an intensive public relations program would likely be needed before the SMR could operate regularly. While this consideration does not necessarily affect specific requirements for the ideal model, issues associated with public reception of the implementation of an SMR in the proposed setting certainly affect the feasibility of overall implementation, regardless of the specific model. Such implementation may be feasible as far as every other consideration, but without widespread public support, such a project could not take place. Therefore, assessing the most common views and opinions of the public when it comes to nuclear energy and determining the appropriate way to address significant misgivings, if possible, will be necessary for successful implementation of an SMR in the urban setting proposed.

According to recent studies, solid majorities of the public continue to oppose the construction of more nuclear plants [24]. The most common concerns Americans possess regarding nuclear energy include qualms about (1) the release of radioactivity, (2) potential catastrophic events, (3) waste disposal, (4) thermal water pollution, (5) fear of explosions, (6) operation risks. Waste disposal in particular has been a key obstacle (in addition to safety concerns) to the social acceptability of nuclear power [17]. This issue is only exacerbated by the cancellation of funding for the Yucca Mountain repository site.

The fact that the community surrounding this potential SMR is made up largely of university students and professionals may lead one to believe that the overall affected community possesses a significantly higher level of knowledge about nuclear energy. Since several studies suggest that the more people understand about nuclear energy, the more they tend to support it, such knowledge would suggest a more positive opinion of nuclear energy among this community [17]. However, the reality is that people in general are severely lacking in knowledge about nuclear energy, including university communities [18]. Thus, any educational campaign must focus on the facts surrounding nuclear energy in general, in addition to the specific benefits and safety qualifications of the implemented SMR. Since the majority of the affected population will be university students and professionals, such a fact-driven educational campaign is likely to be well received. It should also address the six main fears listed above, many of which are directly addressed by SMR technology. With an increase in knowledge about nuclear energy, particularly SMRs, as well as the presentation of information that directly addresses the most commonly held fears, the overall opinion of nuclear energy among the affected community should be improved.

Despite the logical and demonstrated link between improved knowledge and improved opinion of nuclear energy, this cannot be the only facet of the interaction with the public concerning the potential SMR. While numerous public surveys have demonstrated a clear connection between level of knowledge concerning nuclear energy and a more positive opinion, these findings are not universal. A few studies suggest a more tenuous link between level of education and support for nuclear energy [17]. Differences in these findings are likely a result in various knowledge acquisition methods. For instance, surveys involving media as a mode of knowledge acquisition likely produced smaller changes in support than did surveys involving more objective sources of information. Regardless, garnering support for the intended SMR implementation cannot be achieved purely through educational means. An additional element of the public campaign should include, after the initial education program, a means by which the community can voice specific fears or concerns and receive helpful responses. This could potentially require a small team of professionals available to provide such assistance during the initial operation of the SMR, assuming public opinion reaches a level such that implementation can take place.

In general, it can be assumed that, with the appropriate educational campaign, public opinion should reach a level such that implementation of the SMR in the university setting can take place without significant objection. Therefore, this consideration serves as more of a guideline for how to achieve successful implementation, rather than a potential restriction to the feasibility of implementation.

3.10 Summary of Requirements

In the above sections, the feasibility of implementing a small modular nuclear reactor in an urban setting was evaluated based on various considerations. Through this evaluation, certain key requirements associated with potential implementation were determined. These requirements include those relevant to the specific choice of reactor model, as well as those pertinent to the eventual site selection for the chosen SMR model.

3.10.1 Requirements Specific to Model

Feasible implementation of an SMR in the proposed setting requires that the selected model be designed for an output of between 100 and 300 MWe and implemented below ground, as most SMRs currently in the design phase are intended to be. Additionally, the chosen SMR model should possess integral configuration to provide enhanced safety, another feature common to almost all SMR models. If possible, to minimize consequences of any potential seismic activity, the design should include key reactor elements within a pool of water. A refuel period of at least five years is required, to minimize risks associated with handling fuel. Additionally, the core of an ideal reactor would be fully removed and replaced for refueling. Finally, potential models should, if possible, be planned for deployment within the next twenty years.

3.10.2 Requirements Specific to Site Selection

In addition to the above requirements specific to model selection, the following must be taken into account when potential sites are being considered for the implementation discussed in this scheme. Potential site selections should be in areas with the lowest possible seismic activity, and should possess high quality and numerous roads between the planned reactor site and nearby major highways to promote more efficient and safe evacuation.

4. Criticism and Challenges

Assuming the requirements summarized in sections 3.10.1 can be met through the selection of a particular model that is currently being developed, the feasibility of the implementation of an SMR in the proposed urban setting seems quite favorable. The specific design features of SMRs provide benefits in many areas (safety, security, cost, etc.), as discussed above, resulting in the seemingly achievable nature of the general requirements for model selection. However, despite the apparent feasibility of SMR implementation in the discussed urban setting, it is important to note that opinions regarding the advantages of SMR technology are not universal. While the opposition to SMRs among critics often stems from a pre-existing and overall objection to nuclear energy as a whole, addressing arguments against SMR technology in general is necessary to assessing the feasibility of implementation in an urban setting.

4.1 Economics

A complicated aspect of SMR technology and potential implementation is economics. While the capital costs associated with these smaller reactors are undoubtedly lower than the capital costs of conventional large-scale reactors, SMRs are penalized by the economics of scale of larger reactors. This results in an anticipated higher cost per kWh of electricity produced by smaller reactors compared to large. This economy of scale principle is considered to be what drove the previous nuclear industry to trend toward larger plants and the subsequent nuclear reactor landscape present in the US today [20]. Those in favor of SMRs argue that other factors could reverse these economies of scale and establish SMRs as even more cost effective than large reactors. These factors include potential cost benefits of assembly-line module construction relative to custom-built onsite construction, reduction in required control and security staff, and efficiencies associated with economics of mass production if SMRs are built and sold in large numbers. There are also less total capital funds at risk during the construction period due to the modular design [26]. However, critics purport that the cost saving effects of the assembly-line module construction are overstated and that, since potential mistakes on a production line could lead to defects that propagate throughout an entire fleet, control and security staff cannot reasonably be reduced. SMR opponents also suggest that the efficiencies associated with economies of mass production are only speculative at this point in time. Such efficiencies cannot actually be proven until hundreds of units have been produced.

While the nature of SMR economics is complex, it is generally more relevant to the discussion concerning widespread implementation of SMR technology across the US for large-scale energy production. Since the intent of this paper is to determine the feasibility of the implementation of SMRs in a very particular type of setting, and not as a widespread alternative to conventional energy production technologies, issues associated with cost lose at least some degree of severity. Ultimately, the feasibility of implementation in the proposed setting does not depend on economic challenges associated with large-scale production of SMR technology.

4.2 Renewable Energy Developments

Another popular argument among opponents of SMR technology is that, despite any potential benefits of these reactors when compared to large-scale conventional reactors, increased focus on developments in nuclear energy results in reduced time, manpower, and funding that can be focused on achieving developments in renewable technologies. Even if these reactors achieve every anticipated benefit, resulting in a form of nuclear energy technology that reduces previous associated risks without introducing any new ones, SMRs would still arguably contribute to environmental issues associated with resource depletion and waste production in ways that renewable technologies do not. As more funding and focus are poured into improving upon nuclear technology, SMR opponents argue that more promising and environmentally sound forms of energy technology are being neglected [20].

While there is perhaps some stock to this argument, some degree of time and funding has already been put into the development of SMR technology. Therefore, the discussion concerning the feasibility of implementing an SMR in the proposed setting does not necessarily contribute to detracted focus from renewable energy technology developments. This argument may propose problems for arguments concerning government funding for SMR research and development, but it does not serve as a barrier to the feasibility of developing an SMR in an urban setting as discussed in this conceptual analysis. Additionally, reactor technology is being pursued that would minimize the amount of processed uranium required for energy production. The Traveling Wave Reactor (TWR), being developed by TerraPower, is intended to utilize depleted uranium as its main fuel and could theoretically run, self-sustained, for decades without refueling or removing any spent fuel from the reactor [34]. Given the large amount of depleted uranium present in the US, the utilization of such technology would significantly reduce the required amount of processed Uranium. Additionally, the TWR is expected to produce a minimum of seven times less waste than conventional light water reactors, furthering the argument that enhanced focus on nuclear developments should not be discounted [34].

Other SMR opponents argue that the long timeline for SMR development and implementation makes the technology irrelevant to the energy technology landscape, as renewable technologies are expected to be both cheaper and more environmentally friendly by the time that SMR technology can be widely implemented [22]. Again, while this argument *may* have implications for future large scale SMR implementation and use, it provides no reason to avoid investigating the feasibility of implementing a particular SMR model in the university setting.

4.3 Mass Manufacturing

One of the key advantages of SMR technology put forth by advocates is the fact that the smaller nature of the reactor allows for assembly-line module construction and transport of almost fully constructed nuclear reactors to the intended location. This limits the amount of on-site construction that must take place, resulting in a safer and more streamlined construction process. Despite these benefits, SMR opponents point out that mass manufacturing is more likely to lead to catastrophic manufacturing errors. Preventing such errors would thus require much more rigorous oversight and quality control checks, requiring more funding [20]. However, the oversight of the production process in the nuclear energy industry is more rigorous than almost any other industry in the US. Therefore, the same rigorous oversight should and would be applied to the manufacturing and siting of SMRs. Whether maintaining this level of oversight would require more funds is another issue, and does not affect the overall feasibility being discussed in this paper.

Opponents also argue that the assembly-line production would pose severe challenges associated with potential defects and subsequent recalls. However, because of rigorous testing, any potential defects in manufacturing should be noted online, allowing for correction before distribution. If a reactor has already been distributed when a defect is found, procedures for implementing corrections in response to such an unlikely event would take place.

4.4 Waste

Another issue that SMR challengers point out concerns the number of reactors that would ultimately be constructed and the associated complications with waste. They argue that smaller reactors would result in an increased number being constructed compared to construction projections for conventional reactors, resulting in a waste stream that is more difficult to monitor and control. This waste problem ultimately results in greater expenses associated with SMRs and serves as a further argument against the positive economic benefits of SMR technology. Additionally, opponents argue that the underground set up of most SMR models, a design feature that promotes enhanced safety and security, would make waste more difficult to deal with [28].

Ideally, the reactor chosen for implementation in the proposed setting would possess a very long refuel cycle. Many of the models currently being developed are designed such that the core lifetime is greater than five years, some as long as thirty years. The longer the refuel cycle, the less often spent fuel will have to be removed from the reactor. Extremely long refuel cycles make up for any added complications associated with removing the spent fuel from below ground and reduce the complexity of waste monitoring associated with a potential greater number of total reactors. Therefore, as it pertains to the scope of this study, this waste argument serves as no barrier to the feasibility of implementing an SMR in a university setting.

4.5 Summary of Criticisms

While some noteworthy arguments against the widespread development and implementation of SMR technology exist, most (assuming their validity) serve as reasons to limit large scale implementation of such technology. They do not serve as effective reasons to avoid investigating the potential of implementing a single reactor in the university setting proposed. If the goal of this study was to determine whether SMR technology should be pursued as a large scale nationwide energy source, these arguments would be more relevant. However, since the purpose of this paper is to determine the feasibility of implementing an SMR in an urban setting, none of the above arguments serve as particular limitations.

5. Design Assessment

Given the above considerations and subsequent design requirements, several SMR models were selected for potential implementation in the proposed urban environment. The considered models include SVBR-100, TWR-P, and EM^2. These models, having met the above base guidelines, will, in the following sections, be further evaluated to determine whether they can feasibly be implemented in an urban setting. The models will also be compared and, if applicable, the most promising model will then be identified.

Table 2: *Overview of Considered Models*

	SVBR-100	TWR-P	EM^2
Company	AKME Engineering (Russian Federation)	TerraPower (United States)	General Atomics (United States)

Electrical Capacity (MWe)	101	500-600[2]	240
Thermal Capacity (MWth)	280	1475	500
Type of Coolant	liquid Lead Bismuth	liquid Sodium	Helium
Coolant Circulation	Natural	Forced	Forced
Fuel Type	UO_2	U-235 + U-238 from existing depleted Uranium waste	Used PWR fuel + depleted Uranium + low enriched U-235
Fuel Enrichment	<16.4%	15.75%	11.4%
Thermodynamic Cycle	Indirect Rankine cycle	Rankine steam cycle with super heat	Direct Brayton cycle
Efficiency	36%	38.5%	48%
Deployment Schedule	Planned deployment for 2021	Operational by early 2020s	TBA
Refuel Cycle (Core Life) (years)	7-8	60	30
Safety Features	Passive	Passive	Passive
Vessel Diameter (m)	9.2	13.3	4.7
Vessel Height (m)	19.4	17.65	10.6

[2] *The fact that this output lies outside the range of SMR typical outputs will be discussed in following sections.*

Service Lifetime (years)	60	60	30

5.1 Potential Light Water Reactors

While many light water SMR designs are currently being developed, none of the more promising models meet the basic guidelines for electrical output and refuel cycle. Therefore, no light water reactors are considered for potential implementation in the university setting described in this paper. While this is unfortunate given the prominence of large-scale LWRs and subsequent experience gained from the widespread operation of this type of reactor, a long refuel cycle is of high priority for this scenario. A brief overview of what LWR designs were considered is included in section 5.4.

5.2 Potential Liquid Metal Cooled (Fast Breeder) Reactors

5.2.1 SVBR-100

5.2.1a General Information

The SVBR-100 model is a type of fast reactor with lead-bismuth coolant that is being developed by AKME Engineering of the Russian Federation. This lead-bismuth cooled (LBC) reactor technology has a history in the Russian Federation, where it has been used in eight different nuclear submarines (alpha class) over the past fifty years [33], [38].

SVBR-100 is in the advanced stages of development. As of September 2012, siting license works were underway and work was begun on pilot plant specifications and reactor core research and development [32]. This research and development program includes approximately 20 test facilities (existing, modernized, and new) and involves six different Russian research institutes [33]. A complete reactor and power plant design was expected to be completed in conjunction with a preliminary safety report by 2013. By this time, a construction license was also anticipated to be obtained [32]. According to AKME Engineering, this license was issued by Federal Service for Ecological, Technological and Nuclear Supervision in May 2013 [33]. The trial unit is expected to be commissioned by 2017 [32]. The World Nuclear Association lists the SVBR-100 model as a “reactor for near term deployment” and describes the deployment as “well advanced” [29].

5.2.1b Technology Specifics

The electrical and thermal capacity of the SVBR-100 are 101 MW(e) and 280 MW(th) respectively. As mentioned previously, this model is a type of fast reactor that utilizes a chemically inert lead-bismuth coolant and the standard fuel material, UO_2, which is enriched to less than 16.4 percent. The core operates without any partial refueling and is anticipated to require replacement every seven to eight years, which corresponds to a lifetime duration of about 53,000 full power hours. This is desirable for the proposed setting, especially given the favorable deployment timeline. Additionally, the plant is said to achieve 36 percent efficiency [33].

SVBR-100 includes a fast neutron reactor core that operates without any partial refueling [38], [32]. When refueling is required, fresh fuel is loaded as a single cartridge [32]. A notable advantage of the SVBR-100 core design is its fuel universality [33]. The design of the reactor allows it to operate using different fuel types (UO_2, MOX, etc) and in different fuel cycles without changing the design and deteriorating safety characteristics. The lack of partial refueling makes it possible to change the core content at each refueling by using the type of fuel that is most economically effective at the current stage of nuclear power development. The adaptability of the SVBR-100 reactor relative to fuel type results in the possibility to realize a timely and graduate changeover to the closed nuclear fuel complex (NFC) that will be economically justified. Additionally, during the 60-year lifetime of SVBR-100, the consumption of natural uranium calculated for 1 GW(e) is forty percent less than the consumption by reactor WWER-1000 for the same time [39].

The enriched uranium oxide is loaded into the reactor for the first and second lifetimes. The fuel for the third lifetime is formed from the first lifetime spent nuclear fuel (SNF) during the second lifetime, after the SNF has been cooled and reprocessed. Some enriched uranium oxide is added to compensate for the mass of heavy atoms required for loading. Therefore, the fuel for the third lifetime is a mixture of three components: (1) extracted plutonium along with minor actinides built up during the first lifetime, (2) extracted uranium and enriched in U by 10.8%, and (3) added enriched uranium oxide. The second component is distributed uniformly over the core. The fourth lifetime fuel is formed from the second lifetime SNF, the fifth lifetime fuel from the third lifetime SNF, and so on [39].

As with most SMR designs, the entire primary equipment circuit of the SVBR-100 model is contained within a robust single reactor vessel [32]. This integral design is a common feature of SMR technology that enhances simplicity by eliminating the necessity of large external primary piping. This eradicates the risk of a loss of coolant accident (LOCA) caused by a large break [25]. The reactor monoblock contains the core, the whole equipment of the primary circuit and the steam generator modules. The basket containing the core and Control and Protection System (CPS) rods is located in the central part of the reactor monoblock. The basket is then surrounded by in-vessel radiation shielding with the steam generator and reactor coolant pump (RCP) modules arranged within. A protective plug is placed above the core [38]. The reactor monoblock with backup containment vessel is placed in the tank of a passive heat removal system, where the reactor monoblock is secured. The water filled tank also acts as a neutron shield [38].

The mass and overall dimensions of the monoblock are such that it can be manufactured in a factory setting and then delivered to the plant site by utilizing many possible modes of transportation, including sea, car, or rail [38]. The monoblock is 4.5 meters in diameter and 7.86 meters in height. The core itself is approximately 1.64 meters in diameter and 0.9 meters in height [39].

Figure 3: ***Single SVBR Module in its Containment*** [33]

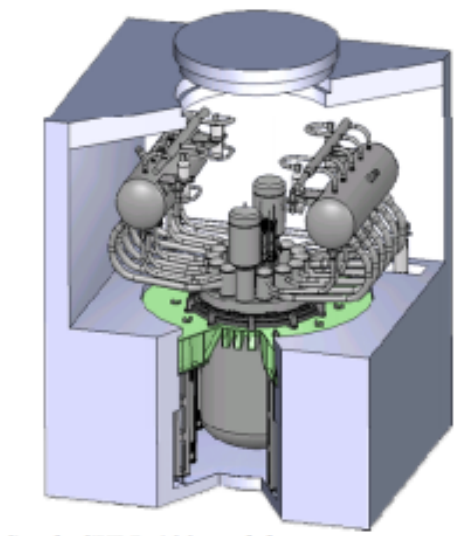
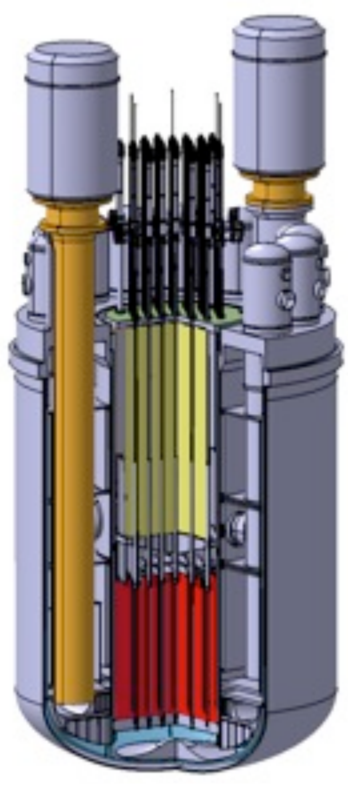


Figure 4: ***The SVBR-100 Reactor*** [38]



The SVBR-100 model utilizes a lead bismuth coolant, a eutectic alloy of lead and bismuth [38]. The pipelines for this coolant are all external [32]. The reactor passes heat to a two-circuit removal system and steam generator with a multiple circulation, secondary coolant system. The natural circulation of the coolant in the reactor heat removal circuit is sufficient to passively cool down the reactor and prevent hazardous superheating of the core [32].

5.2.1c Available Cost Information

As with all SMR designs, some cost reductions exist for the SVBR-100 design (compared to large lead bismuth cooled reactors) as a result of the smaller size, integral design and the resulting ability to exclude many safety systems [32]. However, other economic benefits exist that are specific to the particular SVBR-100 design. The lack of partial refueling makes it possible to change the core content at each refueling by using the fuel type that is most economical at that point in time [39]. Therefore, some savings can be realized through prudent fuel selection, when applicable. Additionally, with the existing low costs associated with uranium and enrichment of uranium, the use of oxide uranium fuel with postponed reprocessing and storage of spent fuel on plant site is economically justified for SVBR-100 [39]. However, the lead bismuth coolant is more expensive than other liquid coolants, which should also be considered when determining whether to implement the SVBR-100 model [38].

5.2.1d Safety Features

Like all SMR designs, the low power potential of the SVBR-100 design contributes to its enhanced inherent safety compared to large conventional reactors [38]. Also like all SMR designs, the SVBR-100 employs an integral arrangement of primary circuit equipment within a single vessel that operates at approximately atmospheric pressure. This integral design allows for the exclusion of many safety systems required for traditional reactors and results in a lack of high pressure in the primary circuit [32]. This lack of high pressure means that, in the event of the failure of all cooling systems and a subsequent blackout, no core melting occurs and the integrity of the monoblock is provided passively as a result of heat accumulation by the in-vessel structures and coolant. Additionally, the absence of pipelines and primary circuit valves outside the reactor monoblock results in design simplification, prevents accidents from a loss of coolant, and prevents blockage of coolant circulation through the core [33].

Passive safety is also achieved by use of the chemically inert lead bismuth coolant (LBC). In contrast to the inertness of LBC, sodium (utilized in many other reactors) is explosive in contact with air and water [38]. This, in conjunction with the very high boiling temperatures of LBC (1670 °C), significantly reduces, if not eliminates, the risk of chemical explosions and internally caused fires. The high boiling point also improves the reliability of heat transfer from the core and thus enhances safety by eliminating the potential for a heat removal crisis [38]. Any radiological emergency possible for the SVBR-100 reactor could not lead to high-pressure radioactive emissions into the atmosphere [33]. The risk of these and other specific potential accidents is prevented or eliminated through various design features, which are summarized in Table 3 [33].

Table 3: ***SVBR-100 Accident Prevention Design Features***

Accident	Mitigation Through Design
Loss of flow	Natural LBC circulation mode
Loss of coolant	Double vessel structure
Transient over power	Passive safety systems
Local blockage	Wrappless fuel sub assemblies

The reactor also includes an emergency shutdown system, which involves six emergency protection rods in dry channels that are equipped with springs and electromagnetic locks. The rods are inserted into the core in response to signals arrived from the control system or in case of loss of power, and also during emergency overheating due to gravitation forces owing to the fusible locks. Additionally, thirteen reactivity compensating rods (RCR) are equipped with the springs and electromagnet locks. These rods are inserted into the core by the control system signals or in case of loss of power, and are fitted with the weight increasing materials of tungsten or uranium to prevent their lifting in LBC. This setup makes it possible to consider the RCR system as the second system of emergency protection [38].

Finally, the transportation of fuel in the reactor monoblock with solidified lead bismuth coolant eliminates the risk of nuclear radiation accidents during shipment [38].

5.2.1e Security Features

Many of the design features of the SVBR-100 model result in a very low risk of proliferation, including those features associated with SMRs in general, such as below grade placement. Additionally, Uranium is enriched to less than twenty percent, approximately 16.4 percent, when using uranium oxide fuel initially [32]. The design also possesses an absence of breeding blankets, where weapons grade plutonium can be accumulated [33]. Additionally, the long lifetime of the core contributes to a lower possibility of fuel access. While the seven to eight yearlong core lifetime does limit the accessibility of fuel, it represents the shortest refuel cycle of the three reactors being considered. When fuel is transported, it is done so in the reactor monoblock with the solidified lead bismuth coolant. This creates an additional technical barrier to the theft of fuel [38]. Finally, proliferation risk is minimized during reprocessing, as two percent of fission products and actinides accumulated in the spent fuel remain in the re-fabricated fuel.

5.2.1f Waste Disposal Methods

As mentioned previously, the SVBR-100 spent nuclear fuel is unloaded cassette by cassette [32]. After being extracted from the reactor, the spent fuel assembly is placed in a container with lead that is preheated in an electric furnace to a temperature above its melting point. The container is then sealed and transported to a dry storage site with natural air cooling, as the lead in the container solidifies. This system results in four barriers that prevent any radionuclides from escaping into the environment: the fuel matrix, fuel element cladding, solidified lead, container housing. Additionally, the solid lead in contact with the steel cladding of the fuel element prevents corrosion [38].

5.2.2 TWR-P

5.2.2a General Information

The TWR-P, traveling wave reactor prototype, model is a type of traveling wave reactor that employs a sodium cooled breed-and-burn (B&B) concept and is being developed by TerraPower. While the concept of traveling wave technology is a more recent development, many other features of the TWR-P model are based on technologies present in current systems. For example, the helical coil steam generator design is based largely on the design developed for the Advanced Liquid Metal Reactor (ALMR) program [13]. Many of the components of the TWR-P safety systems, in particular, are based on current technologies and will be discussed in section 5.2.2d.

Traveling wave reactors in general are a class of reactors that are uniquely designed to operate indefinitely after a startup period using only natural or depleted uranium. The waves that breed and deeply burn fissile nuclides in-situ travel relative to the fuel and provide the possibility for a very long core life, which is extremely favorable for the desired setting. Such a long core life, in turn, allows for significantly higher fuel utilization, up to thirty times greater than LWRs. Traveling wave reactors (TWRs) also involve a high breeding ratio, meaning the core produces enough extra fuel to start other TWRs without requiring any additional fuel enrichment. As a result, subsequent generations of TWRs can be started with discharged fuel from previous generations. TWRs require no chemical reprocessing capabilities with element separation, which eventually eliminates the need for enrichment. Thus, widespread use of TWR technology would result in a reduction in the number of required reprocessing and enrichment plants. As a result, an expansion of nuclear energy can be achieved without the expansion of the fuel cycle infrastructure associated with producing weapons materials [13].

Predictably, the many significant benefits associated with TWR technology are accompanied by their own set of challenges. These include the Positive Coolant Temperature Coefficient (PCTC) Challenge, the High Peak Discharge Burnup Challenge, the High Cladding and Duct Fluence Challenge, and the TWR Design Challenge. Innovative features of different TWR models are being pursued to combat these design challenges and the overall development is seen as promising [13].

Despite the ability to combat many of these challenges through design innovations, the technical challenges associated with TWR-P result in a less favorable deployment schedule. TWR-P is currently not listed on the World Nuclear Association's "Small Nuclear Power Reactors" website, which lists current SMR designs according to their current stage of development. TWR-P is excluded even from "reactor designs at earlier stages," implying that the feasible implementation of TWR-P in a setting similar to the one proposed in this conceptual design is much farther off [29]. However, TerraPower describes TWR-P as "near term deployable" and argues that TWR-P could be deployed by the 2020s, suggesting more favorable expectations concerning the model's deployment [13].

5.2.2b Technology Specifics

The electrical and thermal capacity of the TWR-P model are 500-600 MW(e) and 1475 MW(th) respectively. As the electrical capacity of this model lies beyond the range established for SMRs, TWR-P cannot technically be classified as an SMR. It is included in this conceptual design because it, like SMRs in general, represents a type of novel nuclear reactor. Additionally, the ability to scale the output down to the required demand of the potential university that implements this model, serves as further justification for its inclusion in this analysis. Finally, the lack of potential for feasible implementation of all prominent SMR designs other than SVBR-100 and EM^2 in addition to the many potential benefits of TWR-P warrant the inclusion of an additional possibility, despite its non-SMR classification.

As mentioned previously, the model is a type of traveling wave reactor that utilizes a sodium cooled breed-and-burn concept. It utilizes U-235 enriched to less than sixteen percent and U-238 from existing depleted Uranium waste. However, the general ability of TWRs to utilize their own used fuel as well as used fuel from LWRs eliminates the need for enrichment in the longer term. The core operates without any partial refueling for the entire design lifetime of 60 years. This is the most favorable refuel cycle of any of the reactors being considered. The fast neutron spectrum allows for up to a thirty-fold gain in fuel utilization efficiency when compared to conventional LWRs utilizing enriched fuel. Additionally, the use of a liquid metal coolant allows for a greater thermal efficiency than possible with other coolants. While TWR-P does not specifically employ integral configuration, the core sits near the bottom of the reactor vessel, which is enclosed within a guard vessel [13].

Figure 5: *TWR-P Single Module* [13]

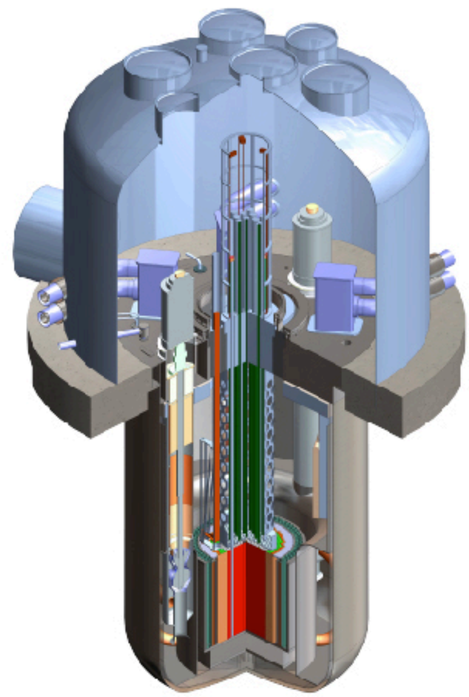


Figure 6: *TWR-P Schematic; one of two total loops* [13]

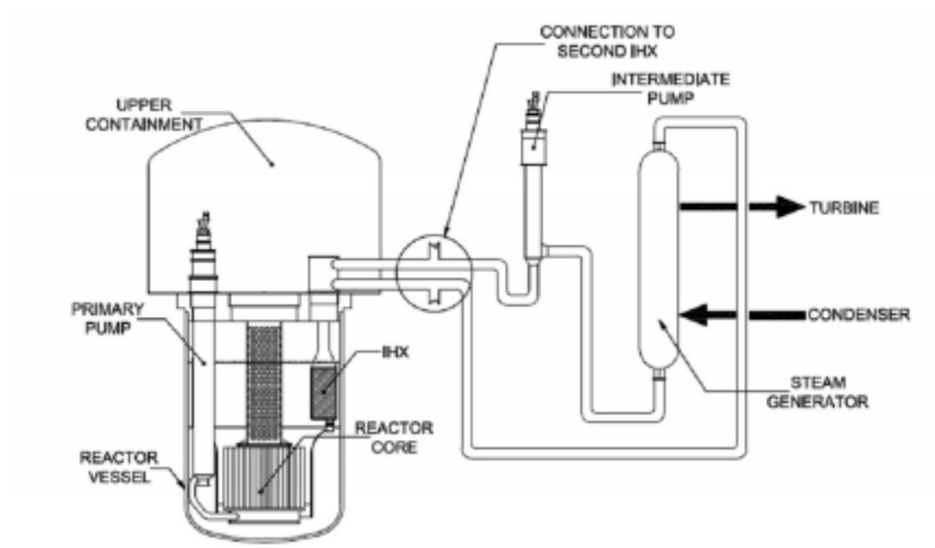


Figure 7: ***TWR-P Core Map*** [13]

	Assembly Type	Quantity
	Driver Assemblies	126
	Feed Assemblies	132
	Control and Safety Assemblies	15
	Lead Test Assemblies I	12
	Lead Test Assemblies II	9
	Open Test Assembly	1
	Reflector Assemblies	138
	Shield Assemblies	78
	Total	**511**

5.2.2c Available Cost Information

According to TerraPower, TWRs represent "the lowest cost alternative to enjoy the energy security benefits of an advanced nuclear fuel cycle without the associated proliferation concerns of chemical reprocessing" when compared to other fast reactors [13]. Additionally, TerraPower claims that the TWR-P is expected to save approximately two billion dollars in fuel costs compared to current LWRs, over the life of the plant [6]. Additionally, similar to SVBR-100, a lack of partial refueling allows for the most cost effective fuel to be utilized when refueling take place.

5.2.2d Safety Features

As no radial piping penetrations exist through either vessel (reactor vessel or guard vessel) the risk of loss of coolant accidents is eliminated. Additionally, the large volume of sodium acts as a huge heat sink, meaning transients are much slower and operators have much more time to respond to unexpected events. Thus, the overall safety of the plant is significantly enhanced when compared to currently operating LWRs [13].

The TWR-P model is also better equipped to deal with risks associated with potential earthquakes. Both the primary control and safety rod assemblies contain 19 sodium-bonded and vented B4C pins in an inner round duct. The round shape of the inner duct in combination with rod pin array geometry provides faster scram time and is less susceptible to jamming during seismic events. The helical coil steam generator also contributes to the safety of TWR-P specific to earthquake risk mitigation. A significant benefit of the generator is that a long tube length can be accommodated in a relatively short overall steam generator package. This short steam generator results in a reduction in the height of the steam generator building, and also leads to reduced loads associated with seismic events [13].

The generator design is also based largely on the design developed for the Advanced Liquid Metal Reactor (ALMR) program, a design that was essentially completed and subjected to extensive sodium testing. The planned changes associated with the implementation of TWR-P design include appropriate scaling, as the design heat load for the TWR-P unit is slightly lower than for the ALMR units [13].

Despite the fact that the design and operation requirements for the steam generators are quite stringent, the potential for a small leak in a tube cannot be eliminated completely. If a small leak is detected quickly so that the appropriate action can be taken to prevent failure, a small amount of leakage can be tolerated. To maximize detection potential, the TWR-P design incorporates both hydrogen detectors and an acoustic leak detection system. The former has been utilized successfully in many previous plants and while the latter is relatively new, much work has gone into its development and testing [13].

Also of considerable importance from a safety perspective is the reactor's decay heat removal system. The TWR-P heat removal is achieved using the same equipment used for normal power operation - pumped sodium flow in the reactor main heat transport system (RMHTS), steam generation in the steam generators, and heat removal via the steam condenser and its normal heat rejection system. A seven-day supply of deionized make-up, emergency feedwater pumps, and power operated relief valves that dump steam to the atmosphere, collectively serve as a back up to this system. The backup system is highly reliable, as it includes redundant equipment, is powered by on-site Diesel generators, and is seismically qualified; however, it is not designated as a safety system. Safety grade heat removal is achieved through four redundant and passive direct reactor auxiliary cooling system (DRACS) loops, each of which consists of a sodium-to-NaK heat exchanger located in the reactor vessel, a natural circulation NaK loop, and a natural convection NaK-to-air heat exchanger. Each DRACS loop, submerged in the sodium pool at a temperature of 360 ºC, is designed to remove 3.1 MW(t) of heat. With two loops in operation, the reactor sodium pool temperature is expected to reach a peak of 540 ºC, which is sufficient to prevent economic damage to the plant. Even with only one DRACS loop in operation, the peak temperature is only expected to reach 700 ºC, which is still sufficient to assure public health and safety [13].

Overall, the safety analysis using the SAS4A/SASSYS1 code showed that the TWR-P design has desirable safety characteristics. This includes a lack of sodium boiling in Anticipated Transients Without Scram (ATWS) due to the inherent reactivity feedback. During protected transients, the fuel-clad integrity is preserved, as the redundant reactor shutdown systems ensure a safe shutdown of the reactor [13].

5.2.2e Security Features

Though TWR-P is not technically considered an SMR, it is designed to be placed below ground, meaning it benefits from the associated security enhancements. Additionally, the use of discharged fuel from previous generations or depleted uranium is less favorable for nuclear weapons materials than enriched uranium. Additionally, as TWR technology does not require any reprocessing plants and eventually no enrichment plants, the risks from the two most proliferation prone parts of the fuel cycle can be eliminated through widespread use of TWRs [13].

5.2.2f Waste Disposal Methods

Another significant benefit associated with the TWR-P model is its contribution to waste reduction. The ability to utilize waste fuel from other reactors results in an overall reduction in nuclear waste production, with a minimum of seven times less overall waste. Additionally, less uranium ore needs to be mined since depleted uranium can be used directly as a fuel. TWR-P thus significantly reduces the overall societal waste burden by utilizing waste produced from other reactors and producing less waste itself by requiring less uranium ore and utilizing its own waste materials [13].

Since TWR-P operates with no partial refueling, the spent fuel will be removed during a single event, after the 60-year core lifetime. The fact that waste disposal must only take place once over such a long period of time is extremely favorable for the given setting.

5.3 Potential Gas Cooled Reactors

5.3.1 Energy Multiplier Module (EM²)

5.3.1a General Information

EM² is the abbreviation for the Energy Multiplier Module, a design being developed by General Atomics. It was designed as a modification of an earlier, high-temperature helium cooled reactor and represents an attempt to utilize used nuclear fuel without conventional reprocessing [32]. General Atomics sees this breeding and burning of the reactor's own fuel as a potential solution to the nuclear waste problem, which has been enhanced by the Yucca Mountain repository cancellation [10]. The core is designed to operate without reprocessing for approximately 30 years [32]. Despite the attractive nature of the model's ability to reduce spent fuel inventories and the long core lifetime, the deployment timeline for EM^2 is less favorable. The design status of this model is listed as "conceptual design," indicating that no prediction has been made concerning the eventual deployment of EM^2 [32]. The World Nuclear Association describes EM^2 as a "reactor design in earlier stages" [29].

Despite a more long-term deployment timeline, the technology appears promising. The Generation IV International Forum explored and evaluated fourth generation reactor concepts, including the high temperature gas cooled reactor, which rated well and was established as the most developed candidate. A preliminary design was completed in 2003 and component testing is currently in progress in Russia [26].

The goals of the EM^2 model are as follows: To reduce capital investment and power cost by thirty percent compared to advanced light water reactors (ALWRs), to consume and reduce used nuclear fuel inventory and subsequently minimize the need for long term repositories, to reduce the need for uranium enrichment and eliminate conventional fuel reprocessing, (thus reducing proliferation risks), and to advance electrification through site flexibility and process heat application [26].

Figure 8: ***EM^2 Reactor System*** [5]

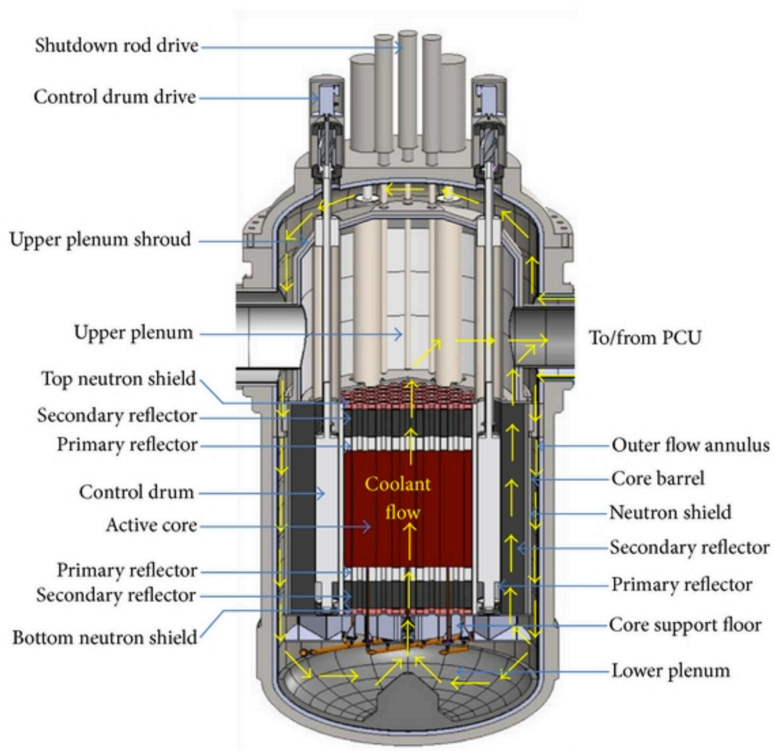
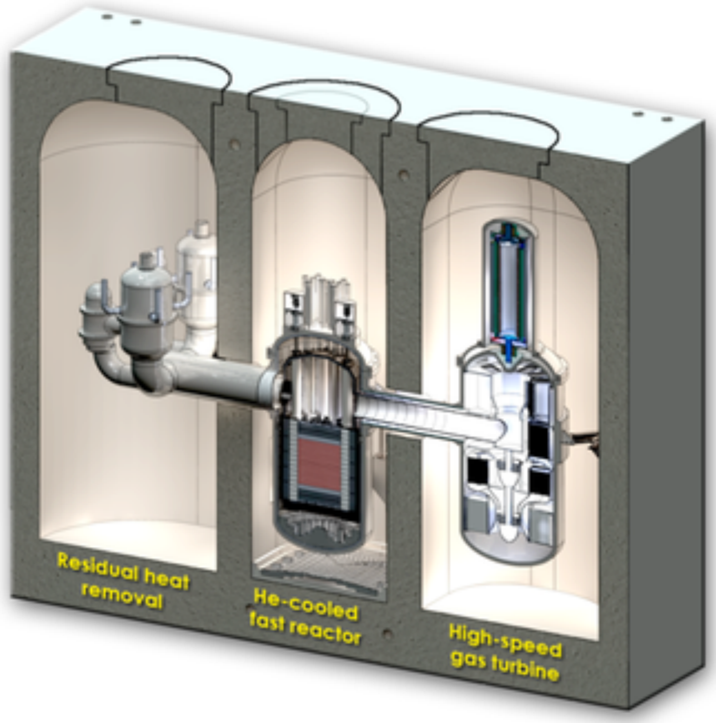


Figure 9: ***Single EM² Module*** [32]



5.3.1b Technology Specifics

Based on a closed cycle gas turbine, the EM² model is designed to produce 240 MW(e) and 500 MW(th) through the utilization of used nuclear fuel [32]. The core is anticipated to last 30 years without the need for refueling or reshuffling, about twenty times as long as light-water reactors [10]. As a result, the lifetime of the model is also listed at 30 years. This lengthy core lifetime is extremely favorable for the potential setting discussed in this paper.

The basic design approach of EM² is to create very good neutron economy in a small core size with the objective being to maximize the neutrons going to fission and conversion. EM² is an all-ceramic core gas cooled fast reactor with fast neutron spectrum, very low absorption structural materials (SiC), very high U loading (UC fuel), and very effective reflector (BeO-graphite) [26]. The result is that 97% of neutrons produce fission (conversion of U238 → Pu239) and higher actinides at beginning of life. Energy is extracted from fuels with high fission product content, including used LWR fuel and recycled EM² fuel. AIROX is utilized to convert used nuclear fuel (UNF) to EM² fuel feedstock, with no separation of heavy metals or solid fission products.

The reactor uses carbide fuel, a composite of silicon carbide as cladding material and beryllium carbide and graphite as neutron reflector material. The core contains SiC–SiC clad porous UC plates arranged in a SiC–SiC assembly frame making a fuel assembly (FA). There are 21 FAs creating each layer and 17 layers stacked on top of each other, surrounded by a BeO layer, then a graphite reflector layer, and finally a B4C layer, all sitting in the core barrel. The core is made up of starter fuel of uranium enriched to an average of 11.4% U-235 with axial blankets of depleted uranium. In a first generation plant, the fuel consists of about 22.2 t of low enriched uranium (LEU) starter and about 20.4 t of used nuclear fuel. The used nuclear fuel is roughly 1% U-235, 1% Pu and mixed actinides (MA), and 3% fission products; the rest is U-238. The U-235 of the initial fuel loading dominates the fission rate for the first 10 years of operation. After about 10 years, enough Pu-239 has been bred in the blanket for it to start dominating the fission rate. At the end of core life after about 32 years, approximately 23% of the initial heavy metal loading has been consumed (~14% fissioned and ~9% converted) and the fuel is discharged and can be used to manufacture starter fuel for additional EM^2 units. The peak discharge burnup of the starter fuel is ~300 MWd/kg. While it is not a pure breed and burn (B&B) system in its once-through version, the EM^2 can be said to utilize the B&B principle. If a subsequent core starter fuel loading can be manufactured without chemical reprocessing directly from the discharged fuel of an EM^2 module, the total family of EM^2 reactors can be said to be operating collectively in a B&B mode [26], [32].

General Atomics claims that there is no need for uranium enrichment after the first generation reactor, as the discharge from the preceding generation is used for the succeeding generation. Out of each discharge, about 38.5 t is used in the succeeding generation while about 4 t of fission products are removed [32].

EM^2 operates using a closed cycle gas turbine. The core lifetime is listed as 30 years without refueling or reprocessing [32].

EM^2 is cooled by helium gas with a core outlet temperature of 850°C. When compared to other coolants such as sodium, the helium coolant is inert, single phase, nonradioactive, and chemically stable against water, and no intermediate loop is required for thermal-to-electric energy conversion [5]. The reactor unit is coupled to a closed cycle helium turbine, which is claimed to achieve 48% efficiency [32]. High temperature gas reactors in general have the unique ability to use the direct Brayton cycle, which is able to achieve such efficiency. Additionally, a directly coupled Power Conversion Unit offers many advantages, including vertical orientation, short interconnect, a single shaft with flexible coupling, an integrated generator, electromagnetic bearings, and a recuperator and intercooler [26].

5.3.1c Available Cost Information

Given the long-term nature of the deployment schedule for this particular model, no specific cost data is available regarding the construction of the EM^2 model. The utilization of analogous technology in large-scale breeder reactors has so far proved uneconomical. It is the modularity of the EM^2 design that makes it more economically viable to utilize technology that uses nuclear fuel without conventional preprocessing

[10]. However, for the purposes of this scheme, only one module would be implemented, perhaps limiting the economic viability achieved through staggered construction of multiple modules.

However, early results show EM² can achieve a cost advantage. A reduced initial capital investment, approximately 3 billion, is anticipated, as opposed to about 5 billion for a 1.2 GW(e) ALWR [26]. Additionally, as with both previous models, some minor cost benefits are achieved through the fact that a lack of partial refueling allows for the most cost effective fuel to be utilized at each refuel event.

5.3.1d Safety Features

The entire containment is designed to be sealed below grade for the entire 30-year core period, contributing to the safety benefits associated with SMRs in general discussed previously. Additionally, the graphite core provides high temperature stability. The use of helium coolant also reduces risk as it is an inert gas that does not react dangerously with water. The EM² design also allows heat to be removed passively during potential loss of coolant events, due to a low power density, low power rating, and negative temperature coefficient [26].

The reactor core includes shutdown systems that are independently and adequately activated to rapidly shut down the reactor core under postulated accident conditions. The static and dynamic reactivity worth of the shutdown system shall be sufficient to terminate the reactivity and power transient following a reactor trip in response to a reactivity excursion accident such as a loss of coolant [5].

5.3.1e Security Features

Like other SMRs, the EM² model benefits from its underground placement. As mentioned previously, this below grade location provides significantly enhanced proliferation resistance when compared to large-scale reactors. Additionally, the long refuel cycle provides heightened security by limiting the exposure of the core.

5.3.1f Waste Disposal Methods

The EM² spent fuel cladding is first removed and the fuel pulverized and processed using the AIROX dry process to remove fission products. The fuel burned in the reactor is recycled upon discharge [32]. All heavy metal is recycled. Therefore, the waste stream contains only fission products and that discharged heavy metal could be utilized in new EM² reactors, effectively closing the nuclear fuel cycle [8], [26].

5.4 Explanation of Exclusion of Other Potential Models

While the three designs described above represent the SMR models most feasible for implementation in the described setup, many other models were considered. Table 4 depicts the reasoning behind the exclusion of other theoretically potential models.

Table 4: *Excluded Designs* [32]

Model	Company	Country	Type	Reason
Westinghouse SMR	Westinghouse	US	LWR	Short refuel cycle
mPower	Babcock & Wilcox	US	LWR	Short refuel cycle
NuScale	NuScale Power Inc.	US	LWR	Short refuel cycle; low electrical capacity
IRIS	Westinghouse	US	LWR	Short refuel cycle
SMART	KAERI	Republic of Korea	LWR	Short refuel cycle
UNITHERM	RDIPE	Russian Federation	LWR	Low electrical capacity
PRISM	GE Hitachi	US	LMFBR	Short refuel cycle
Gen4	Gen4 Energy (formerly Hyperion Power Generation, Inc.)	US	LMFBR	Short refuel cycle; low electrical capacity
4S	Toshiba	US	LMFBR	Low electrical capacity
PBMR	National Project Management Corp	US	HTR	Short refuel cycle
GT-MHR	General Atomics	US	HTR	Short refuel cycle
HTR-PM	Chinergy	People's Republic of China	HTR	Short (continuous) refueling; above grade

Westinghouse SMR, mPower, NuScale, IRIS, SMART, PRISM, Gen4, PBMR, GTMHR, and HTR-PM represent potential models with a refuel cycle that is too short for feasible implementation in the university setting. While many of these models possess other promising features, they have refuel periods shorter than four years, which is unreasonable for the setting described in this conceptual design. Other potential models, UNITHERM and Gen4, possess an electrical capacity that is too low for the amount required by the university system. While the modular nature of these designs makes the implementation of multiple units possible, it is preferable to implement one unit whose electrical capacity meets the demand of the university.

6. Discussion

Based on the analysis of the considerations relevant to SMR implementation in an urban setting and the analysis of each specific reactor model, it is reasonable to conclude that the implementation of an SMR in the described university setting is technically feasible. Economic considerations may limit some universities from feasibly being able to complete such implementation, but based on all other considerations, operating an SMR on a university campus is realistically achievable. The question then becomes, out of the three models considered (which represent the most promising SMR designs for the discussed setting), which model is the most suitable for implementation, if such a distinction can be made.

While each model possesses different means of achieving the determined requirements - level of safety and security, output, refuel cycle, etc. – all three do in fact meet those requirements. However, as each model also possesses its own specific benefits over the other two, one could theoretically be isolated as the most suitable design. While it may not be prudent for this analysis to distinguish one model as the most promising universally, a ranking system can be constructed such that a university could choose a model based on its own values or specific site characteristics.

This ranking system is depicted in Table 5 and includes the model features that are most quantitatively comparable as well as the rank of each model for each specific feature. A rank of 3 represents the most favorable model for that feature and 1 represents the least. Comparable features include those for which some degree of quantitative comparison can take place i.e. features that can be fully represented as a raw number (refuel cycle) or features that include various aspects that are quantitatively represented (fuel enrichment). Preliminary weights are assigned to each feature to distinguish some semblance of relative significance. Any university attempting to determine the most suitable SMR model could then adjust these weights based on their personal university needs and values. The most suitable model is then the one with the highest overall score.

Table 5: *Model Scores for Relevant Features*

Feature	Preliminary Weight	SVBR-100 Relative Score	TWR-P Relative Score	EM^2 Relative Score
Refuel Cycle	2	1	3	2
Deployment Schedule	1	3	2	1
Size	1	2	1	3
Fuel	1	1	2	3
Total Score		**8**	**11**	**11**

6.1 Justification for Model Ranks

6.1.1 Refuel Cycle

The refuel cycle represents one of the most easily comparable features, as it is directly quantifiable. The model with the longest refuel cycle, TWR-P, is thus given a 3, while EM^2 receives a 2, and SVBR-100, with the shortest refuel cycle, receives the 1.

6.1.2 Deployment Schedule

Deployment schedule is another fairly easily quantifiable feature. Deployment schedules for SVBR-100 and TWR-P are fairly comparable (both claimed to be deployed by early 2020s). However, the World Nuclear Association lists SVBR-100 deployment expectations for 2012 specifically, without addressing expectations for TWR-P. TerraPower describes the associated expected deployment timeline as the "early 2020s." EM^2 has a much less definitive deployment schedule expectation. Therefore, SVBR-100 receives the 3, TWR-P the 2, and EM^2 the 1.

6.1.3 Size

Size rankings are determined by overall vessel size. EM^2 is the smallest, with dimensions 4.7 m diameter and 10.6 m height, thus granting it the 3. TWR-P is the largest with a 13.3 m diameter and a 17.65 m height, resulting in a rank of 1. The SVBR-100 vessel is 9.2 m in diameter and 19.4 m in height, resulting in a rank of 2.

6.1.4 Fuel

Comparing fuel is slightly less quantitative. TWR-P and EM^2 are both more favorable than SVBR-100 in terms of fuel utilization in that they both utilize large portions of spent fuel initially. EM^2 is given the 3 since the LEU it does utilize is enriched to a lower percentage (11.4%) that the LEU utilized by TWR-P (15.75%).

6.2 Justification for Initial Weights

Refuel cycle is the feature possessing the highest preliminary weight. As this feature contributes the most to risk minimization of the nuclear reactor given the proposed setting, it follows that it should be identified as the most significant comparison feature. It is identified as a 2, suggesting it is twice as significant to model choice than other included features. It is arguably reasonable to assign an even higher weight, such as 3, but the more modest weight is given for preliminary purposes. All other features are given a weight of 1 as they are both equally significant and less crucial than refuel cycle. A university with severe space limitations could surely increase the weight of size to a 2, and thus, also increase the rank of refuel cycle to a 3 to maintain its position as the most significant feature. Based on this very basic framework, any university considering the implementation an SMR could manipulate the weights to determine which of these three very promising models is the most suitable for their particular setting and goals.

7. Conclusions

The purpose of this conceptual design was to determine whether it would be feasible to implement an SMR in a university environment, using the University of North Carolina at Chapel Hill as a basic model, and if so, to identify the best model for potential implementation. All relevant issues associated with such implementation were considered and the required features for any potential models were established based on those considerations. Given these baseline requirements, three SMR models were identified as potentially feasible to implement in the described setting: SVBR-100, TWR-P, and EM^2. Each was evaluated more thoroughly to confirm its potential feasibility, as well as to determine the most appropriate model given the urban environment and the associated considerations.

Overall, implementation according to the described scenario should be feasible, as all three of the selected models meet the baseline requirements and possess features that improve their suitability beyond that basic level. Based on the developed rudimentary ranking system, TWR-P and EM^2 appear to be the most suitable, as SVBR-100 suffers from a lack of lengthy refuel period relative to the other two models. The weights within the ranking system can be adjusted slightly according to the needs and/or values of any university pursuing implementation of an SMR.

The apparent feasibility of such implantation has promising implications for nuclear development in general, as well as for energy sustainability in the US university setting. Implementing an SMR would provide an individual university with the ability to transition to a more environmentally sustainable fuel source that also offers energy independence from utility companies. Additionally, the successful widespread utilization of this technology on university campuses [3] could ultimately contribute to improved US attitudes toward nuclear energy in general, and thus, to a shift away from fossil fuel use to greater nuclear energy production.

[3] *Specifically, universities that fit the description of the urban environment presented in this analysis.*

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