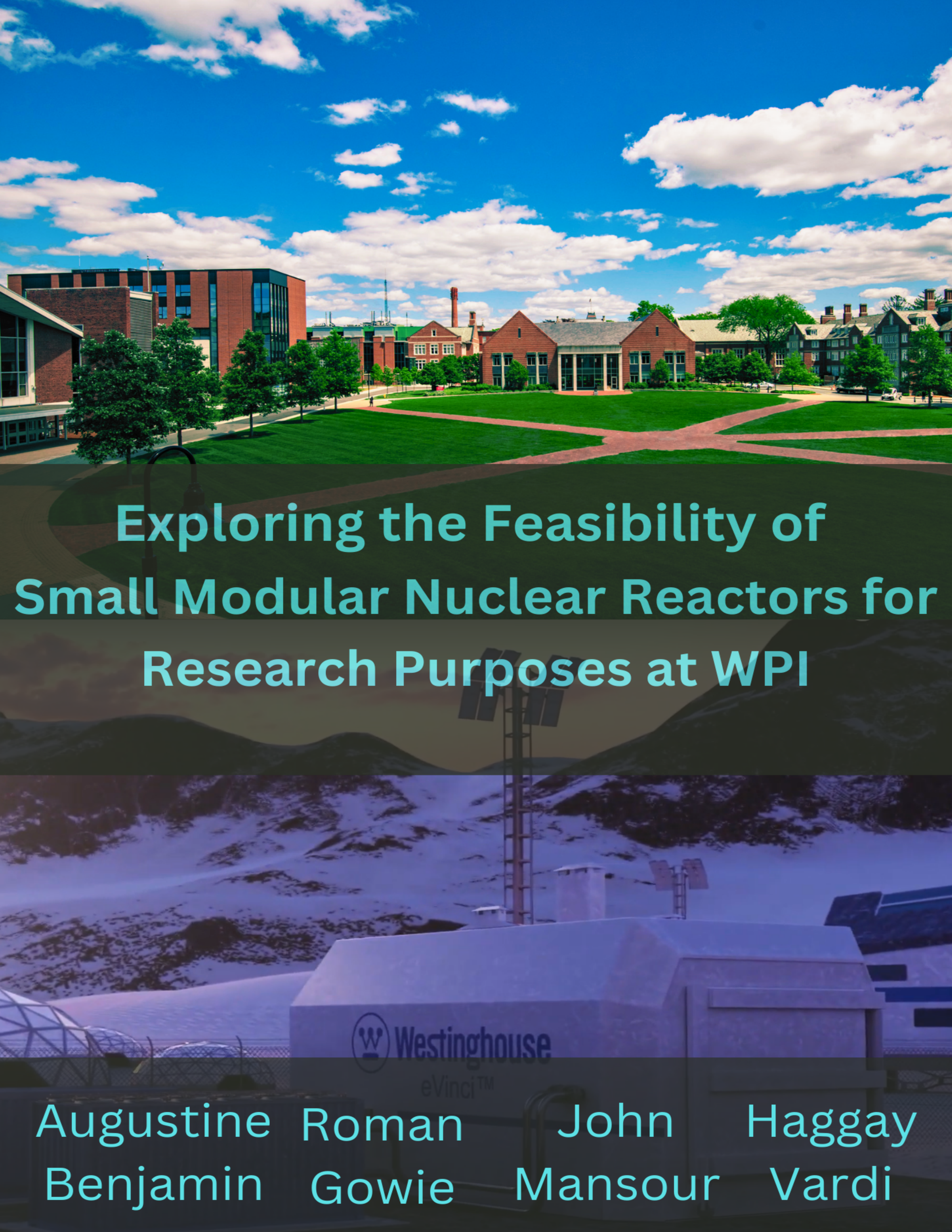

Exploring the Feasibility of Small Modular Nuclear Reactors for Research Purposes at WPI

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Abstract

The goal of this study was to assess the feasibility of implementing a Westinghouse eVinci™ Generation IV microreactor as a university research reactor at WPI. The eVinci, which can produce both 13MW of thermal power and 5MW of electrical power, can be a game-changing tool in the world of university research reactors (URRs) as its power capabilities are notably larger than any existing URR. Additionally, it could potentially act as a hybrid power-research reactor due to its unique attributes. To determine the feasibility of such an implementation, we explored different reactor-based nuclear research programs in other universities, spoke with numerous nuclear science experts, and read regulations and licensing protocols in collaboration with the Nuclear Regulatory Commission (NRC). We concluded that the eVinci would be best used for nuclear medicine, materials science, and sustainability research applications as they are competitive nuclear research fields that allow collaborations with the industrial sector. Additionally, we found that WPI could pursue a Class 104 research license, which allows for the university to conduct the research programs mentioned, as well as produce energy with the limitation of up to 50% of the cost of the reactor maintenance and operations. All and all, this study demonstrates that the Westinghouse eVinci could be a powerful research tool for WPI.

Executive Summary

Since the decommissioning of the Generation I Leslie C. Wilbur reactor in 2011, WPI's nuclear engineering program has been in decline, currently only offering a minimal graduate nuclear engineering certificate. The eVinci microreactor, a Generation IV reactor from Westinghouse LLC, could bring WPI back to the forefront of nuclear research and sustainability. Through this report, we discuss the research programs and industrial collaborations WPI could implement, while investigating the eVinci 's safety and security characteristics in addition to regulation-related challenges regarding hybrid research and energy usage of the eVinci.

Objectives

Our primary goal is to investigate how an eVinci microreactor could be implemented for research and hybrid energy-research usage at WPI. To accomplish this goal, we identified six target objectives:

1. Understand nuclear research methods
2. Understand how research could be conducted in the eVinci microreactor
3. Investigate existing nuclear research programs
4. Outline specific research program possibilities at WPI based on local academic expertise
5. Investigate instrumental research opportunities
6. Outline the processes for a hybrid research-power microreactor at WPI

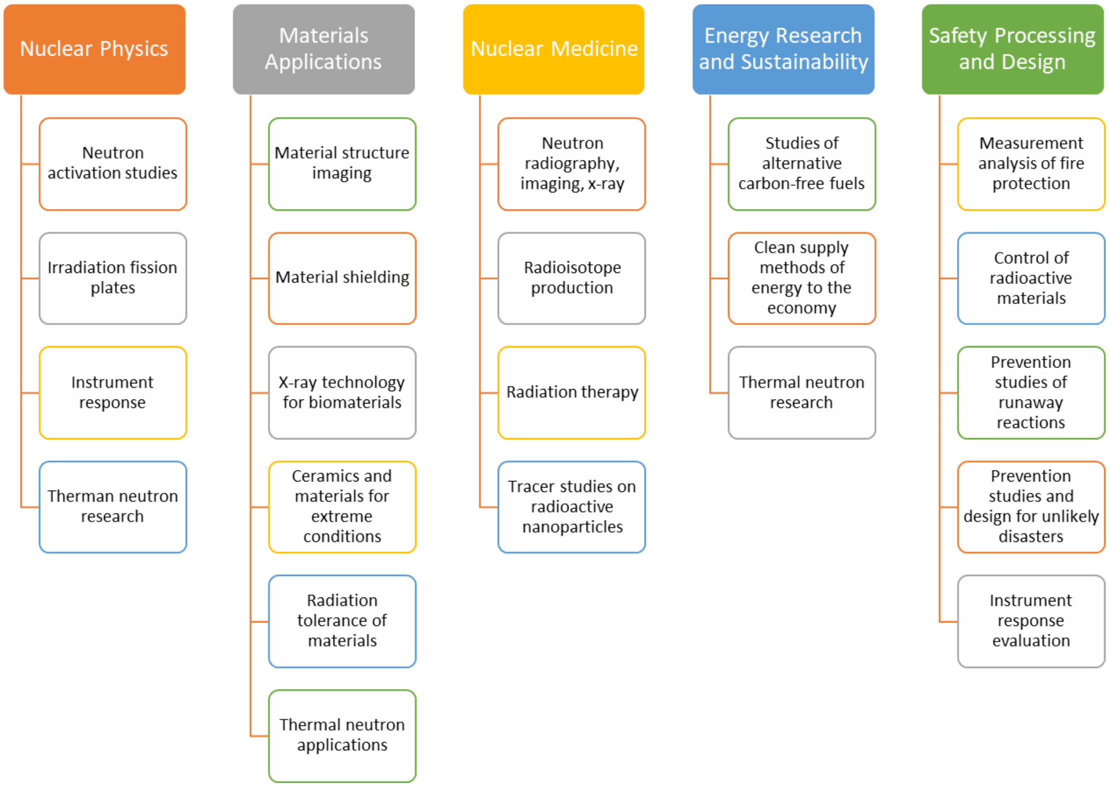
Methods

To better understand the research potential of Generation IV microreactors and the federal regulations surrounding their implementation, we interviewed several nuclear research experts, related-field researchers, and an NRC representative. Additionally, we interviewed WPI's radiation officer, who shared his experienced recommendations on the topic and allowed us to establish a direct line of continuity between the decommissioning of the Leslie C. Wilbur Reactor and the implementation of a future microreactor on campus. In addition to these interviews, we analyzed multiple NRC regulations that describe the licensing processes of reactors towards either research or energy purposes. Due to a lack of specific regulations for Generation IV reactors, the SHINE Technologies's licensing process was used as a case study to what an eVinci 's licensing process might look like for WPI, as SHINE recently received permission to construct an advanced research reactor from the NRC. Finally, additional scientific literature was reviewed in support of what we learned in our interviews, helping us assemble a well rounded repository of information regarding the eVinci and its potential future as a research reactor.

Key Findings

Research Programs and Industrial Collaborations

Possible research topics in the eVinci and their applications



WPI could use the eVinci to perform research in a range of scientific fields. The reactor's characteristics and power output allow the application of multiple research techniques. This sets the eVinci apart from current university research reactors as it can sustain a more versatile nuclear research program, even in medium-sized schools such as WPI. Although any of the fields discussed in this study could act as a research focus for the school, we concluded that sustainability, materials science, and nuclear medicine would likely best serve the school's interests and capabilities. Sustainability is a central topic on campus that would attract great attention if WPI became one of the first institutions to operate a Generation IV microreactor. It could also attract additional federal grants from the Department of Energy and the Nuclear Regulatory Commission, similar to those received by WPI in the past for energy-related achievements. Materials science and nuclear medicine would be good research focuses for the school as they also provide great industrial collaboration opportunities. Allowing WPI to focus on a small number of research fields would enable it to become a more recognized leader in these areas. Additionally, the continuous maintenance of a relationship between academic research and industrial collaborations would further support WPI's expertise in the mentioned topics.

Student Involvement

WPI could expand its usage of the eVinci through various projects and class labs. WPI's senior year project, the MQP, allows undergraduate students to gain an extensive hands-on experience in the field of their major. Therefore, the reactor could be used for MQP projects by students with relevant fields of interest. WPI has had MQPs involving radioisotope development in the past as well as current MQPs focused on the eVinci. Future MQPs that use the reactor could be developed for fields such as physics, materials science, biology, chemistry, environmental studies, and chemical engineering. Labs for certain classes would also be viable options for undergraduate students, notably for WPI's Chemical Engineering Department. The eVinci can integrate with their current labs in thermodynamics, heat transfer, and safety processes. Professors would also be likely to find a way to integrate the reactor into their current research, or create a new project that could incorporate the reactor into their research. These programs would help graduate students who are looking for a thesis topic. Both graduate and undergraduate students could also partake in possible training programs and become licensed and certified for reactor usage. Involvement through these training, project, and research programs could also present numerous advantages for employment in the nuclear industry.

Safety and Security

The various safety features of the eVinci, combined with its small size and the fact that it uses so little fuel means that our primary concerns are keeping it from contaminating the surrounding area and securing it from external threats are all focused on maintaining control of the reactor itself. The fuel cannot be removed non-destructively, so stealing the fuel for radioisotopes would require displacement of the entire reactor, an operation that will involve the deconstruction of the building and carrying the reactor out of the city. Since this scenario is unlikely due to the complexity of its operation, most safety risks would therefore derive either from damage, mismanagement or incorrect usage of the reactor. This means that WPI can focus its efforts on securing access to the reactor: who can get to the reactor, who can use the reactor, and whether we are able to ensure that those groups of people match the group of people authorized to do so. With these addressed, WPI would be better equipped to license the reactor and manage it safely.

Microreactor Power-Generation Capabilities

WPI's use of electricity has increased by about 4 million kWh over the past three years (Office of Sustainability, 2022). Much of this electricity usage is dedicated towards heating and cooling the campus. The eVinci's immense heat generation capacities, which reach about 13 MWth, could be applied towards campus heating and fully meet WPI's heat-related power usage. The rest of the university's electric power usage could be supported by the eVinci's electric generation capacities, which reach about 5 MWe. By taking advantage of the eVinci's complementing power generation capabilities, WPI could effectively reduce its yearly spendings (Baker et al., 2022). Additionally, by relying on nuclear energy to produce heat and electricity, WPI would take a significant step towards achieving its Greenhouse Gas Reduction and Sustainability Plans.

Implementing the Reactor at WPI

In order for WPI to incorporate the eVinci into the campus, the university would have to apply for a construction permit and operations license, then proceed with the construction of the reactor facility. This is a process that takes multiple years and would require careful cooperation with Westinghouse and the NRC. WPI would be able to use the eVinci for research with a Class 104 license, a license that designates a reactor for the use of research and medical therapy. This license also allows WPI to meet some of its sustainability needs, as one of the Class 104 license clauses allows the reactor to be used for energy. This, however, is a limited clause, as revenue from energy production must not exceed 50% of the reactor's cost of maintenance and operation.

Recommendations

1. Recommendation 1: WPI should advocate for updated microreactor regulations to the NRC and pursue a hybrid reactor. If implemented, these suggestions would help WPI use the eVinci with its maximum potential in combined research and energy applications.
2. Examine collaboration opportunities with Westinghouse to reduce reactor costs. WPI could use its ties with Westinghouse to receive an early model of the eVinci at significantly lower costs in exchange for studies of the reactor's performance.
3. Determine a location for a hybrid reactor. Due to the requirements of the construction permit, WPI would have to scout desirable locations for the eVinci. The location would be chosen based on the reactor's design, environmental impacts, and the safety of surrounding communities.
4. Explore cost forecasts for implementing the eVinci. The eVinci is likely to cost a large amount of money to construct, with smaller ongoing costs in operations, and maintenance. WPI should determine

whether the eVinci aligns with WPI's financial agenda by assessing the possible revenue streams from research grants, industrial collaborations, and energy savings against the costs mentioned.

5. WPI's eVinci-based nuclear research program should concentrate on Material Science, Nuclear Medicine, and Energy and Sustainability applications. Although the eVinci could support a wider variety of fields, we believe that the three subjects mentioned would act as the best application of the eVinci considering WPI's interests and expertise.

6. Provide the WPI community with an extensive, informative campaign regarding the implementation of a microreactor on campus. A campaign could provide the WPI community with a basis of knowledge and garner feedback with a potential survey. Websites, posters, and other forms of media could be used to spread awareness.

7. Survey the interest of professional groups to collaborate with a university. Industrial collaborations can act as a significant revenue stream to support WPI's nuclear research operations. Identifying potential partners early on would allow WPI to minimize reactor implementation costs and maximize collaboration-based revenue.

8. Investigate local researchers' willingness to collaborate with WPI. In a similar fashion to industrial collaboration, WPI should explore collaboration opportunities with local institutions that have nuclear programs. Such collaborations could enhance WPI's research capabilities and or act as an additional revenue source.

9. Further investigate the necessary lab requirement for an eVinci-based research facility. Certain spaces will need to be created for each beam port. These spaces could be divided between the research program and energy production sites.

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Introduction

The first self-sustaining nuclear reactor, the Chicago Pile 1, was introduced to the world in 1942. Although it was established to be a part of the U.S. Army's efforts to actualize the Manhattan Project, this achievement was able to confirm what the Military Application of Uranium Detonation Committee had already thoroughly conceptualized(MAUD). In 1940 - the neutron collision of Uranium-235 can produce immense amounts of energy in a highly effective manner (World Nuclear Association, 2020). The dusk of WWII and the dawn of the Cold War incentivized the U.S. to further explore this energy potential, leading to the rapid development and distribution of Generation I nuclear reactors throughout the 1950's and 1960's for both civilian and military purposes (Goldberg & Rosner, 2011). During this period, WPI instituted the Leslie C. Wilbur Nuclear Reactor Facility which was established in 1959 and operated at 10kWth until finally being decommissioned in 2011 (Federal Register, n.d.).

Throughout the years, academic research performed using nuclear reactors has led to the development of many important technological advances and techniques. Examples include material doping for semiconductors (*Neutron Transmutation Doping of Silicon at Research Reactors*, 2016), radioisotope production for pharmaceutical purposes (*Radioisotope Production in Research Reactors | IAEA*, 2016), and much more. Unfortunately, many of these fields require relatively high neutron flux and reactor power in comparison to what is available with today's reactors, resulting in limited access to these technologies and difficulty in promoting further discoveries.

Recent international factors such as climate change and energy crises have reinvigorated incentives to invest in nuclear power, which has been relatively dormant since the mass distribution of Generation II reactors in the 1980's. Combined with significant technological breakthroughs, this investment led to the design of Generation IV reactors that are expected to be much smaller and more powerful than their predecessors and could potentially begin their commercial deployment as soon as mid to late 2020's. This forecast was recently confirmed with the NRC's first certification of a Generation IV Small Modular Reactor–a major breakthrough in the advancement of this technology (*NRC Certifies First U.S. Small Modular Reactor Design*, 2023). The focus of Generation IV reactors on energy raises an important question–will this new reactor technology be able to sufficiently support nuclear research, and if so, what would be its best use in an academic setting? As WPI recently received a grant from the Nuclear Regulatory Committee for the purpose of searching for opportunities to combine carbon-free energy with unique research facilities on campus, this study aims to determine what academic programs may be feasible in light of a Westinghouse eVinci microreactor. Specifically, this project planned to determine whether the capabilities of the eVinci can host an academic nuclear research program and increase the awareness of emerging Generation IV reactor technology.

Chapter 1: Background

1.1. Research Reactors

Research reactors are a category of nuclear reactors that are designed to provide a neutron source for research and other applications that include education and training (NRC, 2020). There are numerous types of research reactor technologies, with the most common in use being pool reactors with plate fuel (*Nuclear Reactor - Research Reactors,* n.d.). Currently, there are about 220 operating research reactors throughout 53 different countries. Russia has the most research reactors with 52, while the United States has slightly fewer, with 50 active reactors (WNA, 2021).

An overwhelming majority of research reactors are located at universities. Universities, including WPI, began building reactors in the 1950s and 1960s to conduct research on applications used in different fields and industries. They were also used for learning and training through programs such as nuclear engineering, physics, chemistry, and biology (NRC, 2020). Today, almost all of the active research reactors at universities are Generation II reactors that were established between 1965-1996 (Goldberg and Rosner, 2011).

1.1.1. Understanding Nuclear Energy

The purpose of a nuclear reactor is to contain and control nuclear chain reactions that produce heat through fission. Fission is a process in which the nucleus, or the core, of an atom splits into multiple nuclei while releasing energy (Office of Nuclear Energy, 2021). The nucleus of an atom is made out of protons and neutrons. When a neutron collides with another atom's nucleus, the nucleus will split and any excess neutrons from the reaction will collide and split surrounding atoms in a similar manner. Each of these collisions result in a release of energy through heat and radiation, and as the chain reaction expands, the amount of energy released grows significantly (Galindo, 2021). The measure of intensity of these neutrons during fission is the neutron flux. The flux can be measured based on the rate of flow of the neutrons during fission. Higher neutron fluxes allow for more intense research to be conducted. In nuclear reactors, uranium-235 is used for fuel assemblies since it is easily split apart in fission (U.S. Energy Information Administration, 2020). Nuclear fission occurs in both research and power reactors. In research reactors nuclear fission serves as a neutron source, while in power reactors it is used as a source of heat to create steam.

1.1.2. Research Reactors Versus Power Reactors

Unlike power reactors that are used in providing energy, a typical research reactor is a net consumer of power (WNA, 2021). Research reactors are also simpler to operate, as they are smaller, operate at lower temperatures, require less fuel, and create less waste. Power reactors are designed to produce massive amounts of energy and are rated at an average of 3,000 MWth. Research reactors in comparison are rated at 0.10 to 20 MWth. Research reactors do not need to run high-energy reactions the way power reactors do, as they are focused on research projects, which are less intensive than power generation for commercial use (WNA, 2021). A positive aspect of the lower, required power levels is that they need minimal to no cooling for short periods after a reactor shutdown. Research reactors do, however, require higher uranium enrichment percentages when compared to power reactors. Usually, research reactors operate at around 20% enrichment, more than three times the 3-6% seen in power reactors. The reactor that WPI is considering, Westinghouse's eVinci, is marketed as a power reactor, but it has the potential to be the first reactor to be used for both tasks.

1.1.3. Research Reactor Variants

Among all of the University Research Reactors (URRs), there are distinguishable features that separate one reactor design from another. Features that make certain research reactors unique include: the moderator and reflector material, reactor design, and fuel type. The moderator is a material that slows down the neutrons that create nuclear reactions. Examples of moderator materials include water (H2O), heavy water (D2O), polyethylene, and graphite (WNA, 2021). A reflector is a layer of material surrounding the core of the reactor that reflects the neutrons that escape during the reaction process. These reflected neutrons create more fissions and an improved neutron economy. Typical reflector materials include graphite, beryllium, water, and natural uranium.

In terms of reactor designs, the most common include the pool-type, tank-type, and tank-in-pool-type. The designs all incorporate Generation II technology, reactor technology typically seen in reactors installed in the late 1960s to late 1990s (Goldberg and Rosner, 2011). These designs all utilize water as a moderator and most contain either beryllium or graphite as a reflector. The key components of each design are identified in this IAEA statement: “In a pool-type reactor the core is a cluster of fuel elements sitting in a large open pool of water. In a tank-type reactor the core is contained in a vessel, as it is in nuclear power plants. In tank-in-pool type reactors the core is located in a pool, but enclosed in a tank through which the coolant is pumped.” (IAEA, 2016).

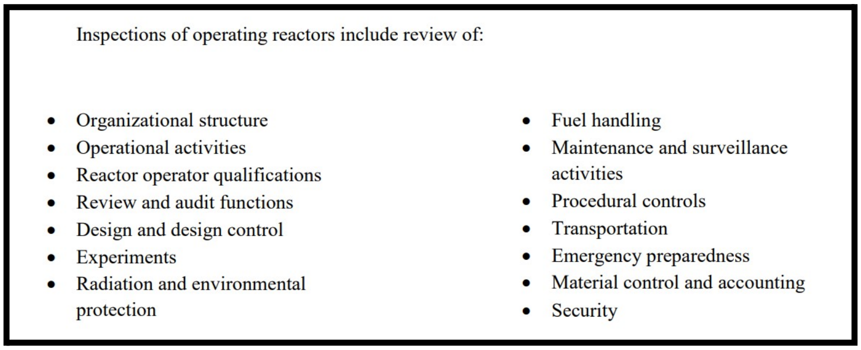
Research reactors can also be distinguished by the fuel it uses. TRIGA (Training, Research, Isotopes, General Atomics) fuel, which is a common version of the pool-type reactor which uses hydrogen as a moderator (WNA, 2021). There are other less common designs for research reactors that use heavy water and graphite as a moderator. Examples of this would be fast reactors. Fast reactors require no moderator and can run on a mixture of uranium and plutonium as fuel (WNA, 2021). This design, along with others, have yet to be incorporated en masse by universities that are operating research reactors.

1.1.4. Licensing and Security

Every university research reactor in the United States requires a license from the United States Nuclear Regulatory Commission to legally authorize reactor operation and the use and possession of radioactive material (NRC, 2021). The NRC performs inspections of the reactor's facilities to ensure their safety and security standards. If the reactor is licensed to operate at power levels of 2 MW or above, then these inspections are performed annually. Reactors that are licensed to operate below 2 MW of power are inspected every 2 years. Reactors that are shut down, but not decommissioned are given abbreviated inspections every 3 years. Each of these inspections use a graded approach that looks at aspects seen in the figure below.

Figure 1

Metrics that are graded by the NRC when inspecting reactors looking to be licensed (NRC 2021)



Inspections of operating reactors include review of:

- Organizational structure
- Operational activities
- Reactor operator qualifications
- Review and audit functions
- Design and design control
- Experiments
- Radiation and environmental protection
- Fuel handling
- Maintenance and surveillance activities
- Procedural controls
- Transportation
- Emergency preparedness
- Material control and accounting
- Security

The NRC also provides a comprehensive written exam and a hands-on operating test to reactor operators. These tests assess the operator's knowledge and abilities to control a reactor during routine and emergency operations. If these examinations are passed, the operator is granted a license that lasts 6 years. This license, however, is restricted to the reactor the operator controls. The managers of the reactors must also certify their operators for license requalification to the NRC by testing their operators with a written test and a manual operations test every 2 years. This allows the operator to refresh their knowledge on skills and information they already knew, as well as learn any new developments, procedures, or modified systems. The assessment of the operator given by the reactor management gets sent to the NRC if the operator is seeking a renewal of their 6 year license (NRC, 2021).

Security concerns have been prevalent since the 1970s due to their high enrichment percentages. Material theft has been the biggest concern, as exposure to the nuclear radiation can lead to health and safety problems for the general public. Concerns were magnified after the events of 9/11, as the NRC strengthened their rules for security in response. These enhancements included screening of personnel, observation of the facility's activities, alarms and devices to detect intrusion, vehicle and package searches, and much more. The NRC conducts regular inspections to see if a reactor meets their health, safety, and security measures using a graded approach similar to the licensing procedure. These results are then reported to the Federal Bureau of Investigation (FBI) and Department of Homeland Security for assessment. The NRC keeps regular communications with these organizations to mitigate any potential threats (NRC, 2021).

Universities have struggled to either maintain their reactors to regulatory standards, or to justify the overwhelming cost of operation against dwindling financial support. These points coincide with the downward trend of active URRs. Continued reactor aging, lower interest levels, increased regulations, along with other concerns have plagued the research reactor's status in recent years (IAEA, 2016).

1.2 The Decline of Older Generation Research Reactors

1.2.1 Early Uses for URRs

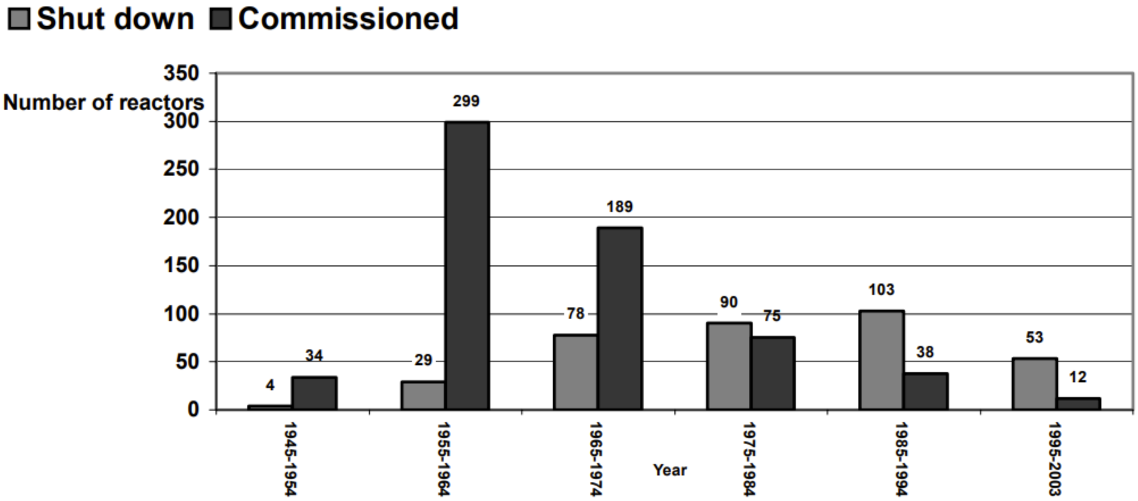
A majority of the early research reactors were supported through government funding. These early reactors were used for research in nuclear physics, nuclear medicine, military submarines, and materials analysis (MIT NRL, 2023). Early research reactors were Generation I reactors with power capabilities ranging from 1 kWth to 1 MWth, with most being in the middle-to low range of that spectrum (Goldberg and Rosner, 2011). In comparison, most of today's Generation II URRs are capable of generating 1 MWth - 10 MWth, a capacity which averages being 11 times greater than the mean power capabilities of previous reactors (*NEUP - University Reactors,* 2022,). At that time, most research applications did not require a high neutron source intensity, as nuclear science was a new field in its early stages. The transition to Generation II coincided with the increase in neutron flux demands, resulting in older generation reactors becoming less applicable to modern research requirements.

1.2.2 Reasons for URR Decommissioning in earlier decades

Studies in the earlier decades of URRs examine the possibilities of fewer URRs being commissioned and the number of shutdowns increasing. One of these research reactor studies during the earlier decades shown in Figure 2 addresses the impracticability of managing spent fuel (IAEA, 2022). The NRC reached the conclusion stating, URRs raise concerns about storage and disposal of enriched fuel.

Figure 2

Number of research reactors commissioned and shut down, 1945-2003



From "Overview of the status of research reactors worldwide," P. Adelfang and I. G. Ritchie, 2003, *International Meeting on Reduced Enrichment for Research and Test Reactors.* Copyright 2003 by the International Atomic Energy Agency.

Concerns with URRs arose from the individuals residing near the research facilities that were experimenting with neutron intensities; meanwhile university administration, user community and the government had concerns over the cost and safety of URRs (OSTI, 1988). The main challenge of research reactors is to maintain them up to the licensing standards of the NRC which can be technically and economically draining for institutions (IAEA, 2016). Different universities had individual reasons for decommissioning their research reactors: the reactors may have produced a significant amount of waste inside of the reactor room, or perhaps the university failed to meet the NRC guidelines of maintaining the reactor overtime due to financial burden. The financial burden of maintenance to the NRC's standards was likely caused by lack of funding for research. This occurs when the energy produced by the reactor is too weak for energy intensive research. The need for more energy is especially strong in recent forms of nuclear research. Without the ability to conduct enough research to justify the cost of renewing the license, the university administration is likely to decommission the reactor as a cost cutting measure (Adams, personal communication, 2023).

1.2.3 WPI’s Leslie C. Wilbur Nuclear Reactor Facility

In 1959, Worcester Polytechnic Institute integrated the first research reactor in New England providing 10-kilowatts of power (WPI, 2022). The primary usage of that reactor, known as the Leslie C. Wilbur Nuclear Research Facility (LCWNRF), was to support the Nuclear Engineering focused laboratory activities and student projects. The students were under close supervision and able to gain reactor operating experience as well as nuclear engineering experimental practice (NRC, 2010). The reactor was also contracted by the navy in Groton, Connecticut to certify and train their nuclear engineers on topics pertaining to radiological safety (D. Adams, personal communication, February 8, 2023). The reactor, however, saw a decline in use, as the reactor’s 10-kilowatts of power did not meet the needs of the professors involved. According to the official order of its decommissioning, the LCWNRF was shut down due to “finding no significant impact” for its operation (Govinfo, n.d.), hinting on the inability of small reactors to host significant research after the rapid growth in understanding nuclear fission. The reactor ceased operations in 2007, and was finally decommissioned in 2011 due to low power of the Generation I reactor, high cost of operation and maintenance, and a decrease in student research involvement. (D. Adams, personal communication, February 8, 2023). The decommission program of the LCWNRF cost 3 million dollars and required thorough decontamination to protect the environment from radiation exposure (NRC, 2010).

1.3 Generation IV Reactors

1.3.1 Technology

In response to the world's growing need for more efficient and sustainable energy sources, the Generation IV International Forum (GIF) has set a target to develop a new generation of nuclear systems. The Forum, composed of 13 countries working in collaboration, has identified eight goals that will define a generation IV nuclear system: 1. Provide long-term sustainable energy generation; 2. Minimize and reduce the long term burden of nuclear waste; 3. Clear cost advantage over other sources; 4. Achieve comparable financial risk to other energy projects; 5. Develop excellent safety capabilities; 6. Design resilience to core damage; 7. Eliminate the need for off site emergency response; and 8. Ensure the inability to be modified and used as a weapon (Generation IV Goals, n.d.). As of 2023, the GIF has been able to develop six technologies that satisfy these goals and could potentially be introduced to the commercial market by 2030. An elaboration of these technologies is available in Table 1.

Table 1

Overview of Generation IV Systems (GIF Portal - Technology Systems, n.d.)

System	Neutron Spectrum	Coolant	Outlet Temperature °C	Fuel Cycle	Size (MW_e)
VHTR (Very-high-temperature reactor)	Thermal	Helium	900-1000	Open	250-300
SFR (Sodium-cooled fast reactor)	Fast	Sodium	500-550	Closed	50-150 300-1500 600-1500
SCWR (Supercritical-water-cooled reactor)	Thermal/fast	Water	510-625	Open/closed	300-700 1000-1500
GFR (Gas-cooled fast reactor)	Fast	Helium	850	Closed	1200
LFR (Lead-cooled fast reactor)	Fast	Lead	480-570	Closed	20-180 300-1200 600-1000
MSR (Molten salt reactor)	Thermal/fast	Fluoride salts	700-800	Closed	1000

Adapted from "Generation IV Nuclear Reactors" by *World Nuclear Association.* Copyright 2020 by World Nuclear Association.

Generation IV systems are often summed into two types of nuclear reactors: Small Modular Reactors (SMRs) and Microreactors. These reactor designs are replacing the Generation II designs mentioned in Section 1.1, and succeeding the technology of the unreleased Generation III and III+ SMR and Microreactor designs (Goldberg and Rosner, 2011). According to the International Atomic Energy Agency (IAEA), a Small Modular Reactor is defined as a Generation IV reactor that has a power capacity of up to 300MWe (Liou, 2021). Some advantages of SMRs include their ability to be manufactured in separate plants and assembled on site, their small footprint which allows more flexible site selection, and their ability to be installed off-grid which makes them a crucial power solution for rural areas and remote communities. Additionally, as per GIFs goals 5-7, SMRs are expected to be self-regulating and require no human intervention in order to shut down their systems, thus significantly lowering the potential release of radioactivity to the environment and making them much safer than any existing reactors. Lastly, SMR designs allow for reduced fueling requirements, resulting in a need to refuel only every 3-7 years in comparison to 1-2 years in current plants (Office of Nuclear Energy, 2010).

The second type, which takes on the modular approach of SMRs and enhances their versatility, is Microreactors. According to the IAEA, a microreactor is categorized as a Generation IV reactor that can generate up to 10MWe (Liou, 2021). Although microreactors hold many of the same benefits as SMRs, they have a clear advantage in their versatile application. In design, microreactors are small enough to fit on a truck (What Is a Nuclear Microreactor?, 2021). Thus, microreactors become an ideal power solution in emergency responses and in industries or communities that are constrained by inaccessibility (Zhang et al., 2022). Their simplistic design and expected high market demand makes them a common Generation IV system flagship choice for most developers.

1.3.2 The eVinci Microreactor

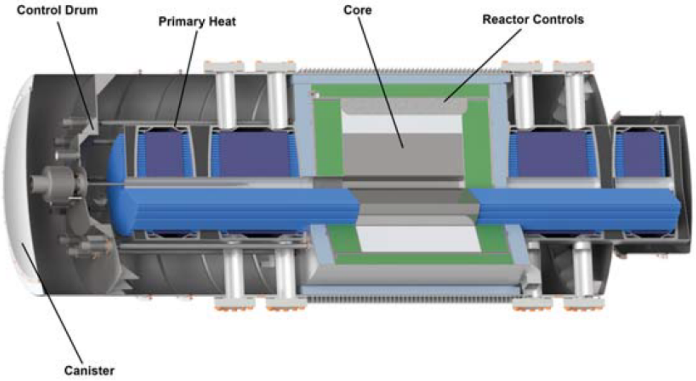
WPI has partnered with the Westinghouse Electric Corporation to investigate the feasibility of the Westinghouse eVinci microreactor for the purpose of conducting research. This work was partially supported by the U.S. Nuclear Regulatory Commission Research and Development Grant Award #31310021M0046 (D. Medich, personal communication, February 21, 2023). The eVinci reactor is a high temperature heat pipe reactor. This is a technology that is derived from the VHTR technology described in Table 1 and combined with heat pipe technology that has already been successfully developed by the Los Alamos National Laboratory (LANL). The eVinci reactor holds a number of benefits when considering an optimal nuclear reactor for an academic institution. The first lies in its safety features. The eVinci microreactor contains no moving mechanical parts beyond the reactivity drums in its monolithic block (Arafat, 2019). These drums ensure that the reactor is completely self-regulatory through chemical reactions and natural forces. These reactions maintain the temperature inside the reactor and prevent the possibility of any potential failures or need for outside intervention. Additionally, the lack of mechanical systems within the reactor prevent any failures due to mechanical wear.

The second major advantage of the eVinci is its power generation capabilities. According to Westinghouse, the eVinci can generate up to 5MWe and 13MWth (*Westinghouse Nuclear > Energy Systems > eVinciTM Micro Reactor*, n.d.). These large values could meet most of WPI's power needs with the exception of its peak heat usage in the winter (Baker et al, 2022). It can fit on a small truck and occupies less than 0.06 acres in an outdoors operational site (Arafat, 2019). The eVinci's capability to be installed independently of commercial power is another great benefit under the scope of power generation. That means that WPI could have more flexibility in its choice of reactor site as well as more independence in its power generation control. Potentially, during the slower months, WPI could also make use of the eVinci's power generation capabilities by selling excess electricity and allocating the resulting funds towards academic resources and other needs.

While its power generation potential seems promising, one problem that remains unsolved is the eVinci's potential in research applications. Since no microreactors currently exist, there is no available data that could directly answer this question. For this reason, this study focuses on collecting and analyzing evidence to investigate this potential. As discussed in Section 1.1, nuclear research is often performed at the core of a reactor, relying on fission to obtain a strong enough neutron flux. The neutron flux signifies the intensity of the neutrons during fission. In the case of the eVinci, the core is not designed to be accessed. It is made out of a solid block that is surrounded by a set of mechanical control drums, a thick layer of neutron shielding, followed by a gamma shield (Arafat, 2019). Damaging these protections to access the core would be unwise. However, the design of the neutron shielding around the core suggests that the outward flow of neutrons (neutron flux) immediately outside the core may be particularly uniform. This uniform neutron flux means that researchers would not need direct core access to eVinci in order to get a sufficiently large and consistent level of irradiation for samples. If researchers can access portions of the reactor merely near the core, the research uses of the eVinci expand significantly. The results of our investigation into this possibility are reported in Chapter 4.

Figure 3:

A cut view of the eVinci's monolithic core (Arafat, 2019).



From "Our Next Disruptive Technology" by Y. Arafat and J. V. Wyk, 2019. *Nuclear Plant Journal.* Copyright 2019 by Westinghouse Electric Company LLC.

1.4 Research Applications for Nuclear Reactors

Modern research reactors possess a variety of uses in disparate fields of research and industry. We can enumerate a few of these uses under the categories of neutron radiography, radioisotope transmutation, neutron transmutation doping, and neutron bombardment. All of these take advantage of the strong neutron flux provided by a reactor's core, but in different ways.

1.4.1 Neutron Radiography

Neutron radiography takes the undirected flow of neutrons out of the reactor core, collimates it into a beam, and uses this beam to measure the useful properties of some sample. This process is unique because neutrons can penetrate a sample deeply, giving us a 3D image of its inside without altering or destroying it. It is also precise, able to resolve even microscopic flaws in the structure of a material (IAEA, 2015). Neutron radiography is especially useful when tracking the water content of an otherwise dry material, or when trying to find contamination by hydrogen-containing chemicals (Zhou et al., 2020; Borges, 2020). Recent research using this facet of a research reactor's capabilities includes an examination of the uptake of water in brick-cement masonry under various weather conditions and how the geometry of the brick-cement boundary can improve waterproofing (Zhou et al., 2020), stress and corrosion analysis in machine parts (IAEA, 2015), and the development of radiography techniques with even more powerful penetration (Li et al., 2022). However, even dedicated radiography research facilities have difficulty taking advantage of the full neutron output of a research reactor (Von Der Hardt & Röttger, 1981), so any prospective research reactor proposal would need to have additional projects to avoid wasting valuable irradiation time.

1.4.2 Radioisotope Transmutation

Radioisotope transmutation is both a process with a commercially viable end product, and a subject of research. The process starts by selecting a sample of an element with the correct nuclear properties (most often exactly one fewer proton than the target isotope) and bombarding it with neutrons. This transmutes its component atoms into a radioisotope that decays quickly to the final radioisotope you originally desired (Behzad et al., 2014). The process benefits from not being time-gated around a specific experiment and can be done during the reactor's free time between experiments. Radioisotope transmutation as a field of research is based around improving this method of production (Leung et al., 2018), and finding better nuclear reactions. This enables us to make currently useful radioisotopes more efficiently, and to make new radioisotopes that may find some future use: either in industry or for other research. Radioisotope production is currently dominated by research reactors (Mushtaq, 2010), and demand for radioisotopes far outstrips the amount research reactors are capable of producing (Luo et al., 2016), so this field is quite active, and we can expect it to remain so for some time.

1.4.3 Neutron Transmutation Doping

Neutron Transmutation Doping (NTD) is similar to radioisotope transmutation, but the materials bombarded and end goals are different. NTD involves a sample of some material not expected to transmute significantly upon bombardment, pre-doped with a radioisotope chosen to transmute to the desired dopant upon neutron bombardment. The most common uses of NTD are all ways of doping Silicon (Si) wafers to make semiconductors, though substances like gallium and gallium arsenide are treated similarly, used for their distinct electrical properties (*Neutron Transmutation Doping of Silicon at Research Reactors*, 2016). Neutron transmutation doping benefits from being a non-chemical method of introducing contaminants to the Si wafer, and can therefore circumvent any inconvenient chemical properties of the base material or dopant by instead originally doping with a more convenient chemical. Methods of construction such as chemical vapor deposition that are more fraught when working with a pre-contaminated material are easier to handle when the dopant can be introduced after the sample is made (Yamada et al., 2007).

1.4.4 Neutron Bombardment

Neutron bombardment is a simple process: take a sample, and place it near the reactor under a strong neutron flux, irradiating it heavily. Then remove the sample and see how it has been altered by the irradiation. Some current research that takes advantage of this process includes making radiation-resistant heat sinks that neither embrittle nor lose conductivity when irradiated (Si et al., 2020), research on the embrittlement of steel and what elements are transmuted into the steel when it is degraded by radiation (Wakai et al., 2005; Zhang et al., 2019), and the testing of reactor part designs, ensuring that they are capable of handling the extreme environment inside a nuclear reactor core (IAEA, 2015). Neutron radiography is also useful for these projects, as the results of irradiation can penetrate deep into the material, and neutron radiography's non-destructive nature and high penetration make it an excellent fit for observing these alterations.

1.5 WPI's Current Nuclear Program

Currently, WPI offers an extremely limited nuclear engineering program. The program includes five nuclear engineering-related courses and grants its participants a Graduate Certificate in Nuclear Science and Engineering (NSE). According to WPI's Graduate Catalog (2022), the program covers topics such as "nuclear power, radioactivity, chain reaction physics, nuclear reactor safety, power plant design and operation, and case studies of nuclear accidents". As implied by this course selection and its leading professors' background with nearby reactors such as the University of Massachusetts Lowell reactor, the program is heavily inclined towards reactor-related work.

1.6 Environmental Impacts

1.6.1 WPI's Environmental Goals

In 2017, WPI developed the Greenhouse Gas Reduction Plan, which aims to decrease the school's net contribution to climate change. This plan recommends that we reduce our yearly gross greenhouse gas (GHG) production down to 80% of our 2014 GHG production by 2025. This GHG production is divided into those produced indirectly via energy consumption, and those produced more directly via combustion of natural gas for heating, campus vehicles, or on-campus power equipment. (WPI, 2017). Some ways in which the school hopes to achieve this goal is through thermal and electric energy efficiency upgrades, implementation of "Green Labs" for sustainability education, and the performance of an engineering study of further energy reduction in information technology equipment (WPI, 2017). In addition to the Greenhouse Gas Reduction Plan, WPI also developed a Sustainability plan in 2020, which addresses WPI's sustainability goals from 2020 to 2025. According to that plan, WPI is hoping to reduce its electricity consumption by 10% while increasing its renewable energy production by 25% by the same date, and construct all new infrastructure to be LEED-certified (Office of Sustainability, 2020). WPI's most recent *Annual Sustainability Report* demonstrates the university's success so far in implementing these goals, with electricity usage reduced by 12% and GHG emissions reduced by 13% since 2018 (Office of Sustainability, 2022).

1.6.2 WPI and Harrison Street Partnership

In 2023, WPI agreed to terms with Harrison Street, a Chicago-based investment management firm, establishing a 40-year partnership that seeks to achieve WPI's sustainability agenda. With the agreement, Harrison Street becomes the exclusive energy provider for the university. Harrison Street and WPI have begun implementing their multi-phased energy conservation approach, with goals of new windows and LED lights in campus buildings, solar panels, and increased efficiency of the heating and cooling systems. Through this partnership, WPI looks to eventually transition into carbon neutrality (WPI, 2023). With nuclear energy being a carbon neutral energy source, the eVinci could be a viable option for the partnership's sustainability initiatives.

1.6.3 Environmental Concerns and Uncertainties

As mentioned above, microreactors are generally considered "green" energy sources. However, a recent Stanford University-sponsored study concerning the waste production of microreactors has suggested that microreactors incorporation as a main energy source will increase nuclear waste production by a factor of up to 35 (Krall et al. 2022). While nuclear waste produces far smaller waste volumes than CO2 waste, any waste contribution should be taken seriously and thoroughly analyzed. Since much of the technical information regarding the eVinci is currently confidential, there are still uncertainties regarding the eVinci's impact on the environment from the standpoint of waste. One aspect that can be confirmed, though, is that no nuclear waste will remain on WPI's campus, as Westinghouse will handle all eVinci waste production (N. Hugger, personal communication, February 2, 2023).

In its impact on WPI's environmental goals described in Section 1.6.1, a 2022 WPI Interactive Qualifying Project (IQP) group estimated that the eVinci is capable of lowering WPI's emissions by 84% (Baker et al, 2022), far surpassing the school's initial goals. Additional research regarding the energy applications of the eVinci is also being conducted in parallel to this study in hopes of shedding additional light on the eVinci's impact on the environment. Despite some questions remaining regarding its exact waste volumes, the eVinci stands out as a promising contributor to WPI's plans on achieving its Greenhouse Gas Reduction Plan and Sustainability Plan target threshold.

Chapter 2: Objectives

This study's goal was to evaluate the potential of a Generation IV microreactor in general, and an eVinci microreactor in particular, for research at WPI. To achieve this goal, the team developed three main subgoals to guide the research:

1. Determine whether the eVinci microreactor can act as a research reactor.
2. Explore the feasibility of specific research fields that could be utilized in a research microreactor at WPI.
3. Outline the processes needed to establish a hybrid research-power microreactor at WPI.

We addressed the first of these by consulting with our advisor, Professor David Medich, PhD, and his graduate student, Norbert Hugger, who have extensive technical expertise in the subject and familiarity with Westinghouse's work. By confirming that microreactors could sustain research operations, we established a need for further research in the topic of microreactor applications as URRs, and opened the door for a more technical focus for this study. The rest of this chapter aims to elaborate on these more technical objectives and provide the reader with reasons for their importance.

Objective 1: Understand nuclear research methods

Exploring universities with functioning research reactors helped us understand how a reactor could operate at WPI. The main points included the personnel required, hours of operation, refueling process, safety and security measures, and usage trends. We used the University of Missouri Research Reactor (MURR) and the UMass Lowell Research Reactor (UMLRR) as case study models due to their decades of operation experience. Even though the reactors we researched were Generation II pool reactors instead of Generation IV eVinci microreactor, these universities provided knowledge on what

WPI could expect from daily reactor usage. By achieving this objective, we were able to generate Finding 1.

Objective 2: Understand how research could be conducted in the eVinci microreactor

Once we established an understanding of how other reactors are used for research, we needed to know how the eVinci would be used for similar purposes. In particular, we needed to know how we might use it for those purposes we identified as likely: neutron radiography, radioisotope production, elemental transmutation, and materials testing. We spoke with researchers here at WPI who are well-informed on the eVinci's capabilities, as well as Dr. William Miller at MURR and Dr. Tries at UMass Lowell. After talking with them, we had the knowledge necessary to determine what objects and structures we may need to add to the reactor for it to be able to provide useful research. Our ideas for this are described in Finding 1.

Objective 3: Investigate existing nuclear research programs

For WPI to establish a nuclear research program, certain scientific focuses must serve as the program's concentration. As discussed in Section 1.6.2, WPI's current program is focused on nuclear physics applications. While nuclear physics is a strong subject of focus in a nuclear engineering program, nuclear science includes a wide variety of topics, some of which may serve as stronger candidates for reactor-based research programs. To understand what focuses a reactor-based nuclear research program could include, we identified two notable research reactors. The first was MURR, which is similar in its power capacity to that of the eVinci, and the second was the UMLRR, which is located nearby and can reflect on the local academic interests in nuclear research. Examining both programs provided inspiration for feasible research focuses as described in Findings 2, 3, 4, 5, and Recommendation 5.

Objective 4: Outline specific research program possibilities at WPI based on local academic expertise

Potential research programs are not useful unless there are students and professors interested in pursuing them. With this in mind, we interviewed WPI professors to gauge their potential interest in using a microreactor for research. These interviews guided our ideas on potential uses for the reactor, and ensured that the research additions to the reactor beam ports, irradiation chambers, etc.–that we will propose are well-suited to the uses WPI is likely to apply to them. We also used the information we obtained while pursuing this objective to narrow our research focus to particular practices that professors here at WPI are likely to be interested in. An elaboration on these speculations is available in Findings 2, 3, 4 ,5, and Recommendation 5.

Objective 5: Investigate instrumental research opportunities

An interesting anecdote we came across while conducting our background research is that as of 2023, there is little to no research regarding the technical potential of microreactors as manufacturing and academic instruments. Most of the current theoretical research aims to address only the safety characteristics and potential effects on sustainability of different Generation IV technologies. From this, we concluded that reactor manufacturers release such little data to the public regarding the technical potential of their products, that it would be impossible to explore the true potential of microreactors until they are produced and in use. Therefore, we recognized that if WPI implements a microreactor on campus, the university may want to explore instrumental research opportunities and how they could be sponsored and conducted. This objective is addressed by Finding 2 and Recommendation 2.

Objective 6: Outline the processes for the integration of a hybrid research-power microreactor at WPI

The eVinci microreactor would ideally serve two simultaneous purposes on WPI's campus: nuclear research and energy production. It needs to be ensured that these purposes would not conflict with one another. The energy production could affect how the research is done, which would make it more difficult for WPI to conduct research while providing electricity or heat to the campus. In order to identify potential conflicts and constraints, our team collaborated with another IQP team that was focused on energy production. Interviews were conducted with NRC personnel to investigate licensing constraints when pursuing implementation of a microreactor that is focused on research and energy. The energy team's data suggested that there is no clear directive from the NRC that the reactor can provide energy in the form of electricity and direct research simultaneously. In anticipation of this, there are types of research that can interfere with energy production. The research team investigated current regulations that would allow WPI to have a license to operate a reactor meant for hybrid usage. Through comparison of this data, optimal locations for a hybrid reactor in the local WPI campus area were revealed. With the data collected by both teams, an outline of how the eVinci may simultaneously operate both its research purpose and its power purpose without creating a need-based conflict was created. The main impediment to using the reactor for research purposes is further discussed in Finding 13.

Chapter 3: Methods and Analysis

To achieve the objectives set in Chapter 2, our team established three main methods for data collection, focusing on gathering information from people of interest, reviewing federal laws and regulations that may limit or affect our findings, and evaluating related literature for further information in related topics. We used a combined approach to collect and use data from these different sources. Then, we reviewed and analyzed this data by performing qualitative coding, which involved categorizing the data collected by the different topics discussed, concerns raised, and then recognizing trends between interviews.

3.1. Interviews

We developed an interview protocol based on R. Pawson's approach in 1996 *Theorizing the Interview,* which focuses on creating a situation in which the "theoretical postulates/conceptual structures under investigation are open for inspection in a way that allows the respondent to make an informed and critical account of them". In our application of this method, our interviewees were fully informed of our study's purposes in the beginning of the interview, and were encouraged to question our investigation and speculations. To formulate effective questions, our team divided our interviewees into categories and constructed a list of general questions for each category. Then, the team performed research on the interviewee's background and adjusted the existing questions to match the information we wanted to learn from the interviewee. In the team's effort to apply its findings to WPI's community, several WPI faculty members were also interviewed and school protocols were reviewed. Our interview protocols and questions are available in Appendices A and B. The data collected was then processed using qualitative coding techniques as described in Section 3.1.4 to derive concise findings and results. After a preliminary analysis was performed, additional contact was established with some of our interviewees through email and verbal communications. These communications were used to clarify misunderstood data and ask for additional opinions and information regarding specific topics within these persons' expertise.

3.1.1. Interviews with Nuclear Science Experts

To understand typical reactor practices and programs, we interviewed various nuclear science experts at WPI and other universities. The first person we interviewed was Norbert Hugger. Norbert is a physics PhD candidate at WPI whose research is focused on designing a Generation IV URR that has the ability to provide a zero-emission source of energy to campus. Norbert's research, which is funded by the Nuclear Regulatory Commission and is focused on modeling the radiation created by the eVinci, served as a strong foundation for this project and is closely connected to it through our advisors and NRC funding. Due to his ongoing collaboration with Westinghouse's engineering team, Norbert's in-depth knowledge of the eVinci's design and capabilities served as significant contributions to many of our findings. Specifically, Sections 4.1, 4.2, 4.3, and 4.5 heavily relied on information derived from his interview, and allowed us to achieve Objectives 4 and 5.

Outside of WPI, the nearest university research reactor in Massachusetts is the University of Massachusetts Lowell Research Reactor (UMLRR). To gain a good understanding of common research practices, research program potentials, and local academic interest and application opportunities, we contacted Dr. Mark Tries, a physics professor at UMass Lowell with an expertise in radiological sciences and protection. Although the UMLRR's power output is much lower than the eVinci's, Dr. Tries' years-long experience with nuclear research provided us with a detailed insight to UML's academic and industrial applications of the reactor. Reflecting on our project, Dr. Tries was also able to provide us with technical suggestions for similar applications given an eVinci microreactor. Furthermore, Professor Tries' expertise extended to common reactor operations, such as training programs for students as well as safety and security measures. Overall, the interview with Dr. Tries allowed us to gain a meaningful insight to the local practices and potential of next generation URRs, and effectively achieve Objectives 1, 2 and 3. This information contributed to the generation of the findings in Sections 4.1, 4.2, 4.3, and 4.4.

To understand the potential of the eVinci as a research reactor, we had to investigate the research program of a reactor that is comparable in its power capabilities. Currently, the most comparable research reactor in the United States is the University of Missouri Research Reactor (MURR), which operates at 10MWth, making it the highest-power URR in the US (*MU Research Reactor - About,* n.d.). To identify the best person to interview, we emailed the reactor's interim director, Mr. Matt Sanford, who then put us in contact with Professor Emeritus Dr. William H. Miller. Professor Miller is a recognized expert in the field of Nuclear Engineering, and has worked in MURR for over 39 years, publishing over 125 technical papers on issues concerning energy, radiation and nuclear power. Professor Miller is also a registered Professional Engineer in the State of Missouri and a Certified Health Physicist. Professor Miller's mastery of nuclear sciences and reactor operations provided us with generous data regarding possible academic and industrial applications of the eVinci, as well as an insight to how these practices can help fund the program. Professor Miller also provided a detailed presentation regarding MURR and its facilities, allowing us to understand what a similarly-capable reactor could achieve. Overall, Professor Miller's knowledge of reactor usage and research programs at MURR helped us achieve Objectives 1, 2, and 3. It also helped produce the findings found in Sections 4.1, 4.2, 4.3, and 4.5.

3.1.2. Interviews with WPI Professors

Our interview with Norbert Hugger allowed us to identify departments at WPI that may be interested in using the microreactor in their projects and relevant faculty members. These departments were: the department of mechanical and materials engineering, the department of chemical engineering, and the department of biochemistry. Then, we began reading professors' biographies on the WPI Faculty Directory website. Some tools that helped us focus our research towards specific faculty members was our personal knowledge of these members and recommendations from other faculty members. Once members were identified, they were emailed, provided with some background information on this study, and asked if they would be willing to be interviewed. Not all members responded, and some refused. Eventually, three faculty members, Professor David Adams, PhD of the Biochemistry Department, Professor Stephen J. Kmiotek, PhD of the Chemical Engineering Department, and an anonymous faculty member of the Mechanical and Materials Engineering Department, agreed to participate in this study.

Professor David S. Adams' name was the first name that came up when we began our research for relevant members. Professor Adams serves as WPI's radiation officer, and is one of WPI's last active faculty members who worked on the Leslie C. Wilbur Nuclear Reactor, and even oversaw the reactor's decommissioning in 2011. Besides his knowledge in radioactive sciences, Professor Adams has a PhD and a Postdoc in Molecular Biology, making him a local expert in nuclear medicine applications. Due to his extensive scientific background and immense experience in its applications towards nuclear sciences, Professor Adams' interview helped us establish a strong foundation for Objectives 1, 2, 3, and 4. Data collected from Professor Adams' interview serves as one of the cornerstones for this study's findings, specifically those in Sections 4.1, 4.2, 4.3, 4.4, and 4.6.

Professor Stephen J. Kmiotek was recognized as a viable source for this study due to his extensive background in chemical and environmental industries. Specifically, his experience and interest in Chemical Process Safety and Air Polluting Engineering helped us achieve Objectives 1, 2, and 4, and served as the main knowledge basis for Objective 5. Professor Kmiotek's unique background in environmental studies also helped us recognize potential research fields that we did not consider before, including Energy and Sustainability and Safety Processing and Design. Therefore, Kmiotek's valuable contribution to this study helped us generate the findings in Sections 4.1, 4.3, and 4.4.

The last WPI faculty member we interviewed asked to remain anonymous. Therefore, specifics of their credentials and circumstances of their choice as an interviewee were not reported. However, it can be shared that their extensive background in Mechanical and Materials engineering played a central role in our achievement of Objectives 2 and 4 and helped us to generate the findings under Sections 4.1 and 4.2.

3.1.3. Interview with an NRC Representative

In order to understand the process of licensing, as well as the regulations involved in the security and implementation of a reactor, we conducted an interview with a representative from the Nuclear Regulatory Commision (NRC). The NRC acts as the United States' regulating organization of nuclear energy, and is therefore the most reliable source for information regarding licensing and law-related constraints. The NRC representative's background and identity were kept confidential as requested. In addition to answering our questions, the NRC representative provided additional regulatory documents. These answers and documents contributed to Objective 6 and our findings in Sections 4.5 and 4.6.

3.1.4. Interview Analysis

We based our interview data analysis on a qualitative coding technique described in Saldana's 2009 *The Coding Manual for Qualitative Researchers*. First, we generated each interview's transcript and read them individually, looking for topics that arose repeatedly across interviews and concerns that were common to different individuals. We constructed a small collection of topics and concerns from this first reading: capabilities, industrial collaboration, implementation, safety and security, student involvement, and research programs. Then we reviewed the transcripts a second time, each of us with our own subject in mind, and collected the information we found on each subject in a central document, each part attributed to its original source. We took this document, and discussed it as a group, going over each section in turn and relating what we found to our objectives and the other sections. It is this portion of the analysis that we made into our findings and recommendations. The contents of the transcripts and citation thereof were generated in accord with the preferences we were given in the consent form, which is in Appendix C.

3.2. Document Analysis

3.2.1. Policies, Guidelines, and Regulations

Much of the data collected here is derived from government policies and regulations. Expanding on Section 3.1.3., the Nuclear Regulatory Commission (NRC) is the federal agency tasked with regulating “commercial nuclear power plants and other uses of nuclear materials, such as in nuclear medicine, through licensing, inspection and enforcement of its requirements” (Nuclear Regulatory Commission, 2022). The policies and regulations we based our findings on were suggested by the NRC representative we interviewed. Additional policies that were reviewed are WPI sustainability plans, specifically the Greenhouse Gas Reduction Plan, which helped us review the technical information we obtained on the eVinci microreactor in light of WPI’s carbon-emission goals. Additionally, the plan helped us establish a base for the necessity of this study as described in Chapter 1.

The documents provided by the NRC representative pertained to the licensing process, safety and security concerns, and regulations regarding hybrid usage for research and energy. The NRC’s

CFR Part 10 Section 50 and Reactor Archive, the Atomic Energy Act, Abilene Christian University's "Preliminary Safety Analysis Report and Environmental Report" submitted to the NRC for a construction permit, and SHINE Technologies' website provided context towards the key points of licensing, safety, and security. The NRC's CFR Part 10 Section 50 and the Atomic Energy Act details licensing regulations for different reactor classifications. The classifications we read focused on research reactor licenses and hybrid reactor clauses. Also, the NRC's documentation on its risk-assessment process enabled us to make inferences about which security and safety concerns are most relevant. Abilene Christian University's "Preliminary Safety Analysis Report and Environmental Report" provided us with an approved example of criteria set by the NRC for a reactor construction permit. SHINE Technologies' website and the NRC's Federal Archive provided an estimated timeline for permit and license application and approval, as well as construction of a facility for the SHINE Technologies reactor.

In addition to government regulations, WPI policies were also reviewed to better understand campus needs and potential constraints. One particular such policy was WPI's Greenhouse Gas Reduction Plan (2017). The plan, which helped establish the need for this study, elaborates WPI's plan to "achieve a 20% reduction in… Greenhouse Gas emissions by FY25" (*Greenhouse Gas Reduction Plan*, 2017) and is supported by WPI's Sustainability Plan 2020-2025. Mainly, it aided our team in examining potential financial constraints and university motives that could help establish the need for a hybrid research-power microreactor on campus. Additional WPI construction plans and policies were reviewed by this project's parallel study, *Exploring the Feasibility of Nuclear Reactors for Energy at WPI 22-23* by Burns et al. as a part of their ambition to determine a feasible location for a hybrid microreactor on campus.

3.2.2. Additional Research and Literature

Scientific literature served as a main source for background information on the topics discussed in this study as well as supporting pillars to statements given in our interviews. To ensure reliability, most of the scientific literature we reviewed was found through WPI's Gordon C. Library databases. Some of the main databases used include Engineering Village, ScienceDirect, and Google Scholar. Oftentimes, multiple articles discussing a singular topic were reviewed to ensure the consistency and legitimacy of the information found. Additional supporting data was found on official organizations' websites. An example would be the International Atomic Energy Agency's website, which includes numerous articles that can be assumed legitimate due to IAEA's practice as a regulating agency. Similarly, many university websites are referenced in this study based on the same assumption of reliability and truthfulness. Through these websites, we were able to find basic supporting information that the reader is often assumed to know when reading advanced academic literature. Beyond supporting our statements, the sources mentioned above allowed us to deliver to this report's readers simplified information in the hopes of delivering this study's complex, technical basis in an interesting manner.

3.3. Limitations

The main limitation we encountered was not knowing the NRC's future licensing intentions in regards to universities using Generation IV technology. One of this study's objectives was to "outline the processes for the integration of a hybrid research-power microreactor at WPI" (Objective 6). During our conversations with the NRC, the NRC representative had mentioned that the NRC was producing a new regulation within the NRC's Ten Title Code of Regulations (10 CFR) called "Section 53" for Generation IV reactors. Unfortunately, this document is still in its early drafting stages, and most of the information it may contain is currently confidential. The representative did not mention if the most recent draft of Section 53 contained regulations on usage for research or hybrid purposes, but explained it will contain streamlining measures for regulations of newer reactor technologies (NRC Representative, personal communication, March 21, 2023). Whilst we determined a possible, limited method for hybrid use through the current Class 104 research license regulations, we could not determine whether the NRC would take future considerations to updating their regulations so Generation IV reactors could be used for complete hybrid power-research purposes.

Another limitation we encountered was the lack of available, in-depth information regarding the eVinci. Since the eVinci is still under development, much of its design elements are confidential and not shared with the public by Westinghouse. While some important aspects such as its power capabilities and major core components are released, important points such as the dimensions and cost are not finalized. This limits our ability to make complete judgements pertaining to WPI's potential implementation of the eVinci. With that being said, our conversations with experts suggest that the design is suitable for current research and energy needs.

Chapter 4: Findings

As a result of the analysis discussed in Section 3.1.4, we identified six major categories to better describe our thirteen findings: research programs, industrial collaborations, student involvement, safety and security, microreactor capabilities, and reactor implementation. These categories line up with this study's objectives and frame the results of our data collection and analysis. The findings included in each of these categories are meant to summarize our results and provide some preliminary recommendations.

4.1. Research Programs

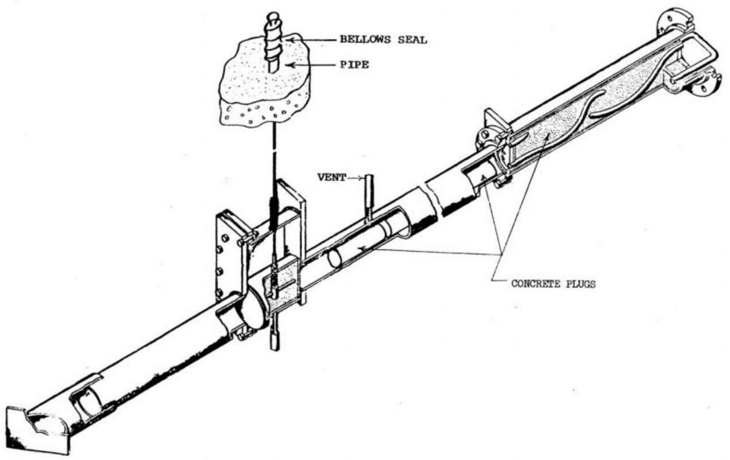
Objectives 1 and 2 aimed to investigate research fields that may be optimal for an eVinci-based program at WPI. Based on several of our interviews, we identified multiple research techniques that could be used towards academic research, and understand how these techniques would be applied in the eVinci. Building on this knowledge, the team used the information gathered to determine five potential research fields that the reactor would be effective in supporting. The following findings describe in more detail how research, and practically in what areas of focus, would be conducted with a WPI-operated eVinci microreactor.

Finding 1: Multiple beam ports allow for concurrent research programs

Following our conversations with Dr. Mark Tries and Professor William Miller, we learned that research in pool reactors is usually conducted through "beam ports" (M. Tries, personal communication, February 20, 2023; W. Miller, personal communication, February 13, 2023). These beam ports are long, hollow tubes that penetrate the reactor's shielding and serve as direct access points to the reactor's core. Through these ports, radiative beams such as neutrons or gamma rays can travel from the core to the point of experimental investigation in a controlled manner (Penn State Breazeale Reactor Achieves First Simultaneous Neutron Beam Operations (Penn State University, 2022). Typically, reactors have multiple ports to allow simultaneous research on the reactor using different radiative environments. Based on data collected from MIT, MURR, Penn State, and the University of Wisconsin, research reactors typically have between four to six beam ports (University of Wisconsin, 2023; MIT Nuclear Reactor Laboratory, 2023; Penn State University, 2022; W. Miller, personal communication, February 13, 2023).

Figure 4

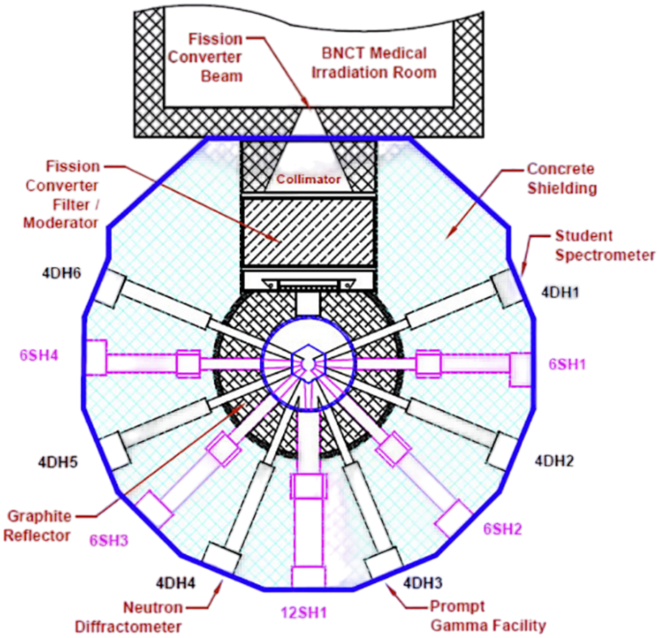
An illustration of a beam port by the University of Wisconsin (*Beam Ports*, n.d.)



From “Beam Ports,” *University of Wisconsin Nuclear Reactor*. Copyright 2023 by Board of Regents University of Wisconsin.

Figure 5

An overview of the MIT reactor beam port configuration (*Neutron Beam Ports | MIT Nuclear Reactor Laboratory*, n.d.)

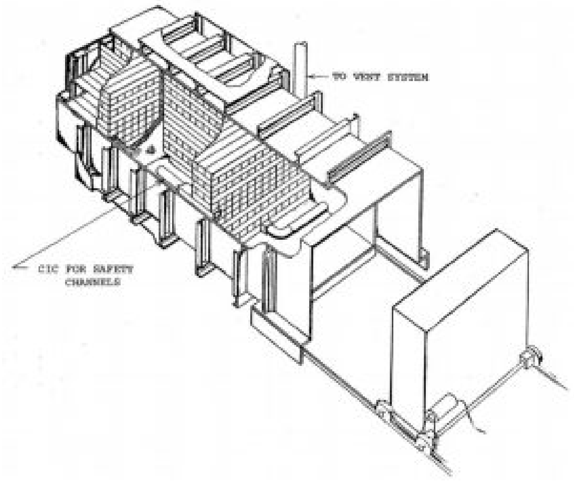


From “Neutron Beam Ports,” by *Massachusetts Institute of Technology Nuclear Reactor Laboratory.* Copyright 2023 by MIT NRL.

An additional feature in the reactor’s shielding is the thermal column. The thermal column is a “graphite-filled horizontal penetration through the biological shield” which provides neutrons in an appropriate energy range for irradiation experiments (University of Wisconsin Nuclear Reactor | *Thermal Column*, n.d.). Unlike the beam ports, the thermal column provides protection to reactor operators and researchers through a dense concrete door which closes the column at the reactor shield. Thus, gamma radiation does not travel in a direct line from the core towards operators, and allows for a safer experimental space.

Figure 6

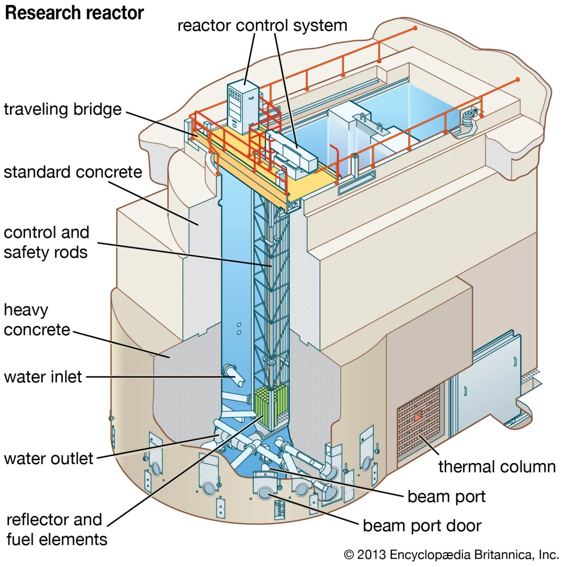
Schematic of the University of Wisconsin Nuclear Reactor thermal column (University of Wisconsin Nuclear Reactor | *Thermal Column*, n.d.).



From "Thermal Column," *University of Wisconsin Nuclear Reactor*. Copyright 2023 by Board of Regents University of Wisconsin.

Figure 7

A labeled schematic of a pool research reactor (Encyclopedia Britannica, 2013)



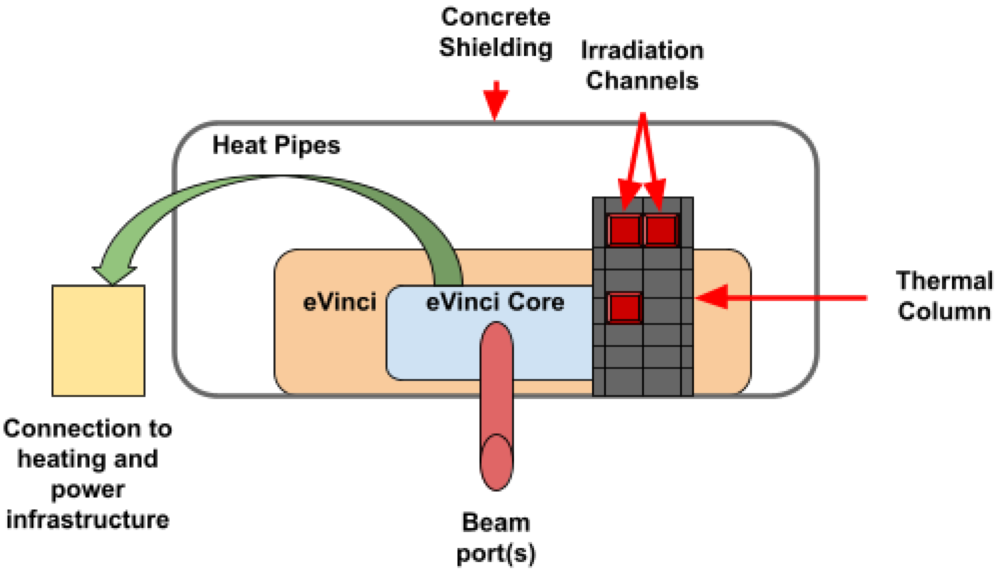
From "Research Reactors: Water cooled, plate-fuel reactors," by *Britannica*. Copyright 2013 by Encyclopædia Britannica, Inc.

Similarly to current research pool reactors, the eVinci could be adjusted to support a multi-beam port system. There are multiple ways in which beam ports can be configured. For example, placing the reactor in the middle of the lab space rather than its corner would allow for the installation of additional beam ports, thus maximizing the eVinci's potential towards research. See MIT's configuration in Figure 5 above for reference. In this case, the beam port configuration would allow the usage of different applications such as thermal beams, fission spectrum, and gamma rays all at the same time (M. Tries, personal communication, February 20, 2023).

According to Norbert Hugger, Westinghouse would provide in-core sample irradiation facilities as a base for the ports, and WPI would construct the beam ports into the building or concrete shielding during the reactor's installation period at the university (N. Hugger, personal communication, February 2, 2023). To elaborate on construction requirements, the eVinci would need to be submerged in concrete, and have a thermal column installed near the location of its core as illustrated by Figure 8 below. At the moment, it is not clear how these additions will affect the finances of the construction. In addition, we do not know the maximum number of beams that could be installed on the eVinci. However, we can confirm and speculate that the number of ports will be greater than one and likely not greater than four. This confirms that the eVinci will allow for multiple research operations to run simultaneously. According to Dr. Mark Tries, it is recommended that one beam port in the reactor would be configured towards a thermal beam (M. Tries, personal communication, February 20, 2023). A thermal beam allows for the exploration of how thermal neutrons interact with certain materials. For example, boron composites, which are used for radiation shielding applications, could undergo thermal neutron bombardment to test their radiation resistance capabilities (Harrison et al. 2008; Huang et al., 2022). By doing so, WPI could introduce a greater variety of nuclear manufacturing and operations methods to its arsenal. Since most nuclear research is done in beam ports, the finding that the eVinci is able to support multiple beam ports verifies the eVinci's capability to sustain any sort of research, and thus holds great importance in this project's development.

Figure 8

A side view of the eVinci with a single beam port configuration (N. Hugger, personal communication, February 2, 2023).



Finding 2: The eVinci microreactor could support research in materials science, nuclear physics, nuclear medicine, energy and sustainability, and safety processing and design.

The eVinci microreactor also can support numerous nuclear research techniques, which will allow researchers to perform studies in a wide variety of fields. According to Norbert Hugger, the eVinci could effectively perform Neutron Activation Analysis (NAA), Prompt Gamma Neutron Activation Analysis (PGNAA), Neutron Radiography, and Small Angle Neutron Scattering (SANS) (N. Hugger, personal communication, February 2, 2023). These techniques take advantage of the eVinci's high uniform neutron flux, and are essential to any research in the reactor. By using these techniques, the reactor would enable new research programs in nuclear physics, materials science, nuclear medicine, energy research and sustainability, and safety processing and design.

To perform studies in nuclear physics, researchers will likely rely on NAA. According to Dr. Tries, NAA could be used in the study of soils. Additional possible concentrations within nuclear physics include irradiation fission plates, nuclear excited states of fission nuclei, and evaluation of the neutron response versus the gamma response for instruments (M. Tries, personal communication, February 20, 2023). If thermal neutrons are used, Dr. Tries recommends pursuing material science applications that study interaction between thermal neutrons and certain materials.

NAA and SANS could also be incorporated in material science applications. According to the interviewed WPI Mechanical and Materials Engineering professor, NAA and SANS create finer contrast on materials in comparison to electrons and x-rays so can be used to identify crystal structures and characteristics in materials. This technique could also be used towards x-ray technologies and biomaterials (WPI Materials Science Professor, personal communication, February 16, 2023). This professor also discussed how neutron diffraction could support material shielding. They recommended using the reactor towards the development of ceramics for extreme conditions. Tries, in agreement with their suggestions, also recommended using the reactor in the study of the radiation tolerance of materials.

In the field of nuclear medicine, the eVinci microreactor could be used for neutron radiography, imaging, and x-ray. Neutron radiography is an imaging technique that generates images by directing a neutron beam towards an object. The nuclei within the object obstruct the neutrons to greater or lesser degrees depending on the mass of those nuclei and how densely they are packed, essentially casting a shadow in the neutron beam. This beam then shines on a neutron scintillator, which takes the neutrons falling upon it and converts them into visible light. Finally, this light is captured by a digital camera, creating the desired image. While results may look visually similar to an x-ray image, neutron radiography can identify in detail objects that are often invisible to x-ray radiography (L'annunziata, 2007). Due to the high, uniform neutron flux in the eVinci, neutron radiography could be easily performed using the reactor's beam ports. As discussed in Finding 1, beam ports are used to channel radiation rays and minimize their spread. Therefore, channeling neutron beams from a neutron flux source should be a basic functional application of the reactor's characteristics.

In addition to radiography, the eVinci could be used for a variety of medical applications that are high in demand, thus helping WPI establish a strong relationship with hospitals in the Worcester area. According to Dr. Tries, a beam from the reactor can be used in radiation therapy such as boron neutron capture therapy (BNCT). BNCT therapy is a radiation science that is used as an emerging tool to kill superficial tumors by "selectively concentrating boron compounds in tumor cells and then subjecting the tumor cells to epithermal neutron beam radiation" (Nedunchezhian et al., 2016). Since BNCT is not a widely available treatment (Huifang et al., 2021), having a facility that can supply it to local patients would allow WPI to stand out as an impactful local academic contributor. Another major contribution of the eVinci to nuclear medicine would be the production of radioisotopes. Important isotopes such as Molybdenum 99 and Lutetium 177 are currently being produced by other research reactors such as MURR (W. Miller, personal communication, February 13, 2023), and could provide WPI with a financial and academic opportunity that is both ethically helpful and professionally advancing.

Beyond research topics that are based on classical sciences, the eVinci microreactor also allows for research in energy innovation and sustainability and safety processing and design. As the world is searching for alternative carbon-free energy sources, research in energy innovation and sustainability will allow WPI to become a green energy leader in New England. Professor Stephen Kmiotek, professor David Adams, and Norbert Hugger have all echoed the potential of such a program in our interviews with them. Some specific topics that were mentioned include the exploration of alternative fuels and clean energy supply methods to the economy (S. Kmiotek, personal communication, February 15, 2023). Exploring sustainability-and-clean-energy related topics could potentially allow for additional financial support from the Department of Energy as it will fall under the topic of the current grant that the school is using for the exploration of carbon-free energy (D. Medich, personal communication, March 2, 2023).

The eVinci will also be able to host instrumental research in topics such as safety processing and design. According to professor Kmiotek, a microreactor could benefit the Fire Protection department by allowing measurement analysis of fire protection during emergencies–a topic WPI students already have some experience in (S. Kmiotek, personal communication, February 15, 2023)–and could also expand knowledge on fire safety processing. Additional areas of study suggested by professor Kmiotek include the control of radioactive materials, the study of the reactor to understand and prevent runaway reactions, and instrument response evaluation in terms of neutron vs. gamma response. Additionally, Dr. Kmiotek emphasized the benefit a microreactor would have in allowing chemical engineering students to study the reactor's safety mechanisms for processing design. Such studies would allow WPI students to design for unlikely scenarios such as the East Palestine, OH disaster (Dance, 2023) and thus prevent and avoid similar events in the future.

Table 2

Possible research topics in the eVinci and their applications

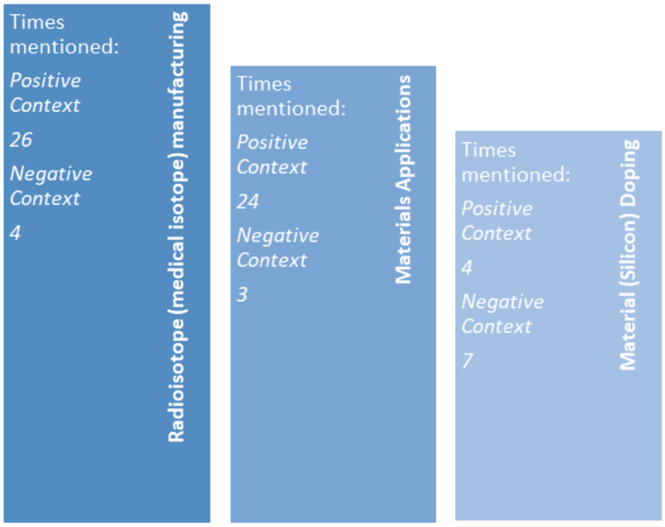
Nuclear Physics	Materials Applications	Nuclear Medicine	Energy Research and Sustainability	Safety Processing and Design
Neutron activation studies	Material structure imaging	Neutron radiography, imaging, x-ray	Studies of alternative carbon-free fuels	Measurement analysis of fire protection
Irradiation fission plates	Material shielding	Radioisotope production	Clean supply methods of energy to the economy	Control of radioactive materials
Instrument response	X-ray technology for biomaterials	Radiation therapy	Thermal neutron research	Prevention studies of runaway reactions
Therman neutron research	Ceramics and materials for extreme conditions	Tracer studies on radioactive nanoparticles		Prevention studies and design for unlikely disasters
	Radiation tolerance of materials			Instrument response evaluation
	Thermal neutron applications			

4.2. Industrial Collaborations

Finding 3: A microreactor could be used to manufacture medical isotopes

Figure 9

Industrial applications of nuclear research based on coding analysis from interviews conducted



As seen in Figure 9 above, one of the most consistently echoed applications of research reactors throughout our discussions with experts and review of analytical reports was medical isotope manufacturing. Although the production of radioisotopes can be very time-consuming and expensive (*Production Methods | NIDC: National Isotope Development Center*, n.d.; *National Research Council (US) Committee on Medical Isotope Production Without Highly Enriched Uranium*, 2009), its impactful industrial demand could bring stable financial income to WPI that would likely fully support the nuclear program's operations and still produce revenue. A market size and competitive landscape report by Market Research Guru valued the global Medical Isotope market size at USD 715.4 million at 2021, with the expectation for its increase to USD 1064.67 million by 2027 (*Global Medical Isotopes Industry Research Report Competitive Landscape Market - Industry Reports*., 2022). In our conversations with Professor Miller (and Dr. David Medich of WPI), it was revealed that MURR funds most of its operations by producing Molybdenum Tc-99m for medical imaging (W. Miller, personal communication, February 13, 2023; N. Hugger, personal communication, February 2, 2023; D. Medich, personal communication, March 30, 2023).

According to professor David S. Adams and given the eVinci microreactor's capabilities, WPI could produce between 15-20 variations of isotopes (D. Adams, personal communication, February 8, 2023). Dr. Mark Tries emphasized one radioisotope in particular, Lutetium 177, which is in high demand in the industry and low in facilities that can produce it due to the significant power required to do so (M. Tries, personal communication, February 20, 2023). Based on this information, it is recommended that WPI should seriously consider this option, as it would enter the market at a favorable time and should experience market growth and additional revenue benefits.

In terms of applications, radioisotopes are mainly used in the pharmaceutical industry and as metabolic tracers in other biomedical applications (D. Adams, personal communication, February 8, 2023). However, they can also be used in agriculture and other nuclear research applications (*Radioisotope Production in Research Reactors | IAEA*, 2016). This wide range of applications makes radioisotopes a popular nuclear product within the industry. At WPI, experts such as Dr. Tries and Adams have recognized that radioisotope manufacturing could develop a strong relationship between the university and hospitals in the Worcester area, resulting in WPI dominating the region's radioisotope supply chain (M. Tries, personal communication, February 20, 2023). Specifically the reactor's capabilities could be used towards radio-chemical facility purposes and treatments such as Boron Neutron Capture Therapy (BNCT).

Table 3

A list of some common radioactive isotopes and their applications (*Radiation Emergency Preparedness and Response - Common Radioactive Isotopes | Occupational Safety and Health Administration*, n.d.)

Isotope	**Type of radiation**	**Half-life**	**Where the isotope is commonly found**	**For more information**
Americium-241 (Am 241)	Alpha particles; weak gamma radiation	432.2 years	Medical diagnostic devices; industrial devices that measure density and thickness; household and business smoke detectors	CDC Radioisotope Brief
Cesium-137 (Cs-137)	Beta particles and gamma radiation	30.17 years	Medical radiation therapy devices; calibrating radiation detection equipment; industrial devices that measure density and thickness; as a byproduct of nuclear fission processes in nuclear reactors (e.g., power plants)	CDC Radioisotope Brief
Cobalt-60 (Co-60)	Beta particles and gamma radiation	5.27 years	Medical radiation therapy (implants or external radiation sources); food irradiation	CDC Radioisotope Brief
Iodine-131 (I-131)	Beta particles and gamma radiation	8.06 days	Medical diagnostic and radiation therapy	CDC Radioisotope Brief
Iridium-192 (Ir-192)	Beta particles and gamma radiation	73.83 days	Industrial gauges for inspecting welding seams; medicines to treat certain cancers	CDC Radioisotope Brief
Plutonium-238 (Pu-238)	Alpha particles	87.7 years	Heat and power source for satellites	CDC Radioisotope Brief
Plutonium-239 (Pu-239)		24,110 years	Nuclear weapons; byproduct of nuclear reactor operations and nuclear detonations	
Plutonium-240 (Pu-240)		6,564 years	Byproduct of nuclear reactor operations and nuclear detonations	
Polonium-210 (Po-210)	Alpha particles	138 days	Naturally occurring and found in small amounts in the environment, including in food, water, and the air	CDC Clinical Guidance for Polonium Exposure
Strontium-90 (Sr-90)	Beta particles	29.1 years	Power source for space vehicles, remote weather stations, and navigational beacons; industrial gauges; medical radiation therapy	CDC Radioisotope Brief
Uranium-235 (U-235)	Alpha particles	700 million years	Concentrated (i.e., enriched) for use as nuclear power plant or other reactor fuel; nuclear weapons; as naturally occurring material	CDC Radioisotope Brief
Uranium-238 (U-238)		4.47 billion years	Radiation shielding (only weakly radioactive, much denser than lead); as naturally occurring material	

From “Common radioactive isotopes,” *Occupational Safety and Health Administration. Copyright 2023 by United States Department of Labor.*

Finding 4: A microreactor could be used to analyze materials through neutron diffraction and neutron scattering

As discussed in Finding 2, the eVinci's significant power capabilities allow it to use powerful research techniques such as neutron diffraction and neutron scattering (SANS). These techniques are especially useful when discussing the applications of nuclear research towards materials. In Finding 2, we discussed how neutrons create a far finer contrast on materials in comparison to electrons, the more common technique used in the industry. According to professor Miller of MURR, if the reactor is powerful enough, it can be effectively used towards material analysis and development by large companies and other industry representatives. In MURR, Miller discussed how General Motors used their reactor to analyze newly developed materials' properties for their engines. Similarly, Miller has expressed the potential of the eVinci microreactor in similar applications in the automotive and aerospace industries (W. Miller, personal communication, February 13, 2023).

Other aerospace material applications were similarly echoed by Dr. Tries and the materials professor. Examples include shielding techniques using neutron diffraction (WPI Materials Science Professor, personal communication, February 16, 2023), and radiation tolerances for space environment applications (M. Tries, personal communication, February 20, 2023). As many large aerospace manufacturers are located in Connecticut, New Hampshire, and Vermont, WPI could establish itself as a powerful industrial research facility in the region.

Finding 5: A microreactor is not well-suited to be an effective tool for silicon doping

The eVinci is a high temperature heat reactor, making it a poor choice for silicon doping (N. Hugger, personal communication, February 2, 2023). This conflict was initially voiced by Norbert

Hugger, and then further elaborated upon by professor Miller of MURR. The main reason that both experts recommend to refrain from attempting any material doping in the reactor is that material doping requires low temperatures. This conflicts with the reactor's habitually very high temperatures (Arafat, 2019). Therefore, its operations are unfavorable for the task. In addition, since most existing research reactors are low temperature reactors, material doping is a widely available and very popular nuclear technology application. Locally, MIT uses its reactor to conduct neutron transmutation doping of silicon (*Neutron Transmutation Doping of Silicon | MIT Nuclear Reactor Laboratory*, n.d.). Hence, entering this market would be a poor use of WPI's resources and would likely consume much effort while producing very little reward. According to professor Miller, even MURR, which was one of the first reactors to use this technique in the world, has stopped working on silicon doping and moved on to radioisotope production due to the decrease in demand for the first and increase in demand for the latter (W. Miller, personal communication, February 13, 2023).

4.3. Student Involvement

Finding 6: The microreactor would provide opportunities to undergraduate students through new projects and labs

When WPI had the Leslie C. Wilbur Reactor, numerous professors would use it for multiple MQP topics. The biology department performed MQPs that used the reactors in the development of radioisotopes for biological imaging and therapy. In addition, learning how to use the reactor, enabled students to develop their knowledge of the major, as well as gain skills in the field of nuclear engineering (D. Adams, personal communication, February 8, 2023). After the decommissioning of the Leslie C. Wilbur Reactor, the MQPs focused on nuclear energy are generally done by physics students. There are currently MQPs for undergraduates in physics related to medical physics, particularly neutron radiography (N. Hugger, personal communication, February 2, 2023). A microreactor at WPI could provide students local access to research facilities, rather than relying on external sources for data. Professor Kmiotek believes that his current MQPs in safety processing and design could greatly benefit from having a reactor. One of his research projects revolves around reducing improbable failure events from occurring. His research, sponsored by Honeywell, looks into the improbable energy capture events for powerful materials that are used in packaged systems. These materials are designed to resist leak or rupture. The goal of this MQP is to further decrease the probability of combustion due to exposure and capture of high energy. The eVinci could be used for energy capture projects involving radiation exposure, and finding ways to improve the material's radiation tolerance (S. Kmiotek, personal communication, February 15, 2023).

The microreactor would also provide opportunities for project based learning in labs for chemical engineering classes. Professor Kmiotek mentioned that undergraduates students in his chemical engineering classes could make use of the reactor through lab experiments involving advanced measurements and heat exchangers. These labs could familiarize WPI's undergraduate body with the reactor technology more quickly, as well as provide an experience more aligned with WPI's "hands-on" curriculum (S. Kmiotek, personal communication, February 15, 2023). A likely challenge that would arise is the requirement of training, as well as access to the reactor. In order for students to use the reactor, they would need to have some form of reactor training to abide by the reactor's safety standards (M. Tries, personal communication, 2023). Such training typically takes about 6 months, meaning the reactor's use in a lab setting is going to be an optional feature. Access for experiments using the reactors would be another difficulty, as WPI has a scheduling website for various forms of laboratory and research equipment (WPI Materials Science Professor, personal communication, February 16, 2023). Most likely, students and professors would have to schedule a time slot and be placed in a queue. The possibility of prioritization of access is present, which means that certain projects would have some precedent over other ones. This is something WPI would have to consider if the reactor were a part of the campus.

Finding 7: Graduate students would also benefit from these additional research programs

As mentioned in Section 4.1, graduate students could research various fields while using the reactor. Typically, reactor-based research is sponsored by academic funds and grants that professors receive for their proposals (W. Miller, personal communication, February 13, 2023; M. Tries, personal communication, February 20, 2023). These grants are crucial to paying for equipment, as well as maintaining the reactor for the students to adequately conduct their research. The UMLRR has received numerous grants for various styles of research such as feasibility studies, pilot studies, and pure research (M. Tries, personal communication, February 20, 2023). WPI graduate students in the physics department also rely on grants to help fund their research activity (N. Hugger, personal communication, February, 2, 2023). As mentioned in Section 4.2, if a microreactor were to be implemented, WPI could see many organizations and companies express demand for these neutrons. Likewise, many professors would like to find a way to use the new, powerful reactor, as it could be a way to develop their research programs with grants from these organizations and companies (WPI Materials Science Professor, personal communication, February 16, 2023). This demand for research will provide more opportunities for students to gain research experience, as well as nuclear science experience.

Finding 8: Students can be provided training for certifications relevant to the nuclear sector

Having the eVinci at WPI would provide students the opportunity to participate in training sessions and obtain reactor certifications. These are opportunities for students who are interested in learning more about reactors and how to use them, as the reactor's facilities would not be accessible to students who lack training and certification. Students would first be certified as student operators with at least 6 months of training, and with further experience and training, could become a licensed reactor operator (M. Tries, personal communication, February 20, 2023). Working with the reactor could provide real world skills in the nuclear industry, as the work experience in a university reactor is extremely similar to that of a professional one. In an industry that seeks experienced reactor operators, such positions would provide the students with a clear advantage in the job market. WPI's old reactor also had training programs for students to obtain certifications. The training program also extended to nuclear-related industries, with ties to the naval program in Groton, Connecticut (D. Adams, personal communication, February 8, 2023). The technology of WPI's Leslie C Wilbur Generation I reactor was eventually outdated, and students were not able to apply the gained operation skills to modern industry anymore. If WPI were to initiate a research reactor program, the eVinci would not see this problem. The Generation IV technology is the latest technology for reactors today, meaning that students that work on the reactor could see more relevant skills when compared to the Generation II university research reactors.

4.4. Safety and Security

Finding 9: The primary safety concern for a closed reactor like the eVinci is preventing unskilled or malicious use of the reactor. Other concerns are mitigated by the design of the reactor, or by correct installation.

The eVinci brings with it certain security and safety concerns. WPI and the surrounding community want to be sure that nothing done with the reactor will put them in danger. To this end, the NRC regulates the operations and implementation of research reactors, and uses a three-stage risk assessment process as part of determining if a reactor is safe enough to use. They consider risks to the reactor core itself, the risk of emitting radioactive materials and radioactivity into the environment, and assuming that radiation was emitted from the reactor, the risk to the surrounding community and environment (NRC, 2020). A typical pool reactor, similar to the one previously used by WPI, can emit radioactivity into the surrounding environment without damage to the reactor core–via mismanagement of the fuel or pool water–and reactor activity is not self-regulating (D. Adams, personal communication, February 08, 2023; S. Kmiotek, personal communication, February 16, 2023). Preventing this requires constant assays of all material in proximity of the reactor (pool water, walls of the reactor pool, groundwater in the area), and active controls are necessary to ensure that the reactor retains stable critical activity (D. Adams, personal communications, February 8, 2023). The design of the eVinci mitigates some of these concerns, making these risks more improbable, and diminishing the risks that need to be monitored.

WPI would not need a similarly complex system for monitoring the eVinci. The eVinci is a closed system that uses solid heat pipes for cooling, and does not get refueled during its lifetime. Therefore no flowing, radioactive hot solvents need to be monitored (Westinghouse, 2023), and individual fuel rods or components both do not need to be accessed for operations and cannot be accessed without cutting open the reactor (D. Adams, personal communication, February 8, 2023; WPI Materials Science Professor, personal communication, February 16, 2023). The eVinci therefore only presents a risk of environmental contamination if it is damaged. The eVinci is also self-regulating to some degree, as it reacts less efficiently the hotter it gets, preventing a positive feedback loop and consequent meltdown (D. Adams, personal communication, February 8, 2023). Therefore, the primary safety concerns come from incorrect operation and maintenance of the reactor, as by default the reactor is not only safe but entirely inactive.

Finding 10: The eVinci's primary security requirement is ensuring that it is not removed from the premises.

We can divide the security concerns mentioned during our interviews into two broad groups: authorization and authentication, and resisting terrorism or sabotage. The former is mandatory for any reactor, to ensure that WPI knows who is interacting with it, how they are interacting with it, and whether they are permitted to interact with it that way (D. Adams, personal communications, February 8, 2023). The eVinci is unlikely to be different in this respect, and the NRC demands that WPI keep track of that information. What will be different is the latter category. The eVinci is a closed system, not designed to be altered or opened up after installation. The fuel it is made with is the only fuel it will have (Westinghouse, 2023). This makes it much more difficult to capture fuel from the reactor and use in a bomb, or unauthorized nuclear testing, etc. This means that the security plans for similar open reactors are more than sufficient, as the eVinci's fuel and components are straightforwardly more difficult to appropriate. If someone wants the fuel from inside the eVinci, they have to take the whole reactor. If someone wants to try and abuse or break the eVinci in a spectacular way, they must first gain access to it and subvert the authorization process (M. Tries, personal communication, February

20, 2023). Therefore, this authorization process should be the focus of WPI's security plan for the eVinci.

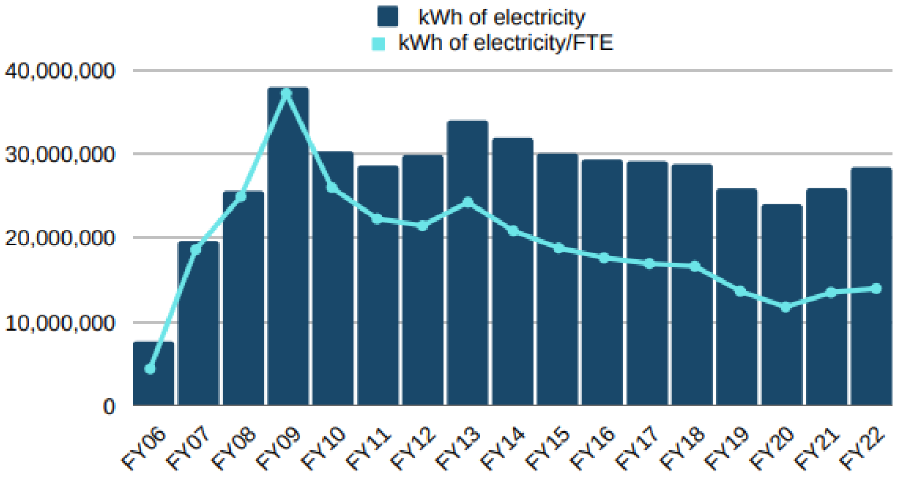
4.5. Microreactor Power-Generation Capabilities

Finding 11: Generation IV microreactors offer enough power to meet energy and novel research needs simultaneously

The eVinci's ability to produce large quantities of electricity and heat would meet much of WPI's power demands and reduce carbon emissions. According to WPI's sustainability reports, WPI's power consumption in 2021 was 25 million kWh. In 2022, electricity usage had risen to 30 million kWh (WPI Office of Sustainability, 2023). These data suggest that the energy demands of WPI have increased within the past few years and we should expect further increases in the upcoming years. Thanks to its electrical capacity of 5MWe, the eVinci can produce enough electrical power to meet WPI's upcoming energy needs (Baker et al, 2022; N. Hugger, personal communication, February 2, 2023).

Figure 10

Historical Electricity Usage of WPI (FY10 - FY22*)*



*Fiscal year (FY) is from July 1st - June 30th. FTE = full-time equivalent student

From "Annual Sustainability Report 2021- 2022 Academic Year," by the *WPI Office of Sustainability*. Copyright 2023 by Worcester Polytechnic Institute.

The eVinci does not only produce electricity, it also produces a lot of neutrons, which are carrying a portion of the thermal energy that the eVinci creates. As discussed in Section 4.1, these neutrons can be used for research; and the more thermal power a reactor delivers, the more research its neutrons are capable of doing. The thermal energy produced by the eVinci can also be used for heating purposes (W. Miller, personal communication, February 13, 2023). WPI currently uses a power house for heating and air conditioning across campus. Moving in the direction of sustainability energy design, WPI has investigated different ways to reduce natural gas dependency. By taking advantage of the eVinci's heat generation capabilities, WPI could fully heat its campus through a sustainable power source. Thus, providing heat to WPI's buildings, complementing its electricity power production capabilities, and further supporting WPI's Greenhouse Gas Reduction and Sustainability Plans (D. Adams, personal communication, February 8, 2023).

4.6. Implementing the Reactor in WPI

Finding 12: Obtaining a nuclear reactor license is a multiyear long process

In order to implement the eVinci for research, WPI would have to obtain a reactor operations license and construction permit, followed by the overall construction process. The process of getting the permit and license, combined with the time spent on the construction of the reactor space, can take multiple years. An example of this process can be seen with SHINE Technologies Reactor. SHINE Technologies is an isotope manufacturing company based in Wisconsin. Their work revolves around using nuclear fusion to manufacture radioisotopes to diagnose or treat heart diseases and cancer. The SHINE Medical Technologies Reactor, is a medical isotope manufacturing reactor that has recently obtained its permits, and is currently in the construction process (NRC Representative, personal communication, February 21, 2023). The figure below details the timeline of the reactor.

Figure 11

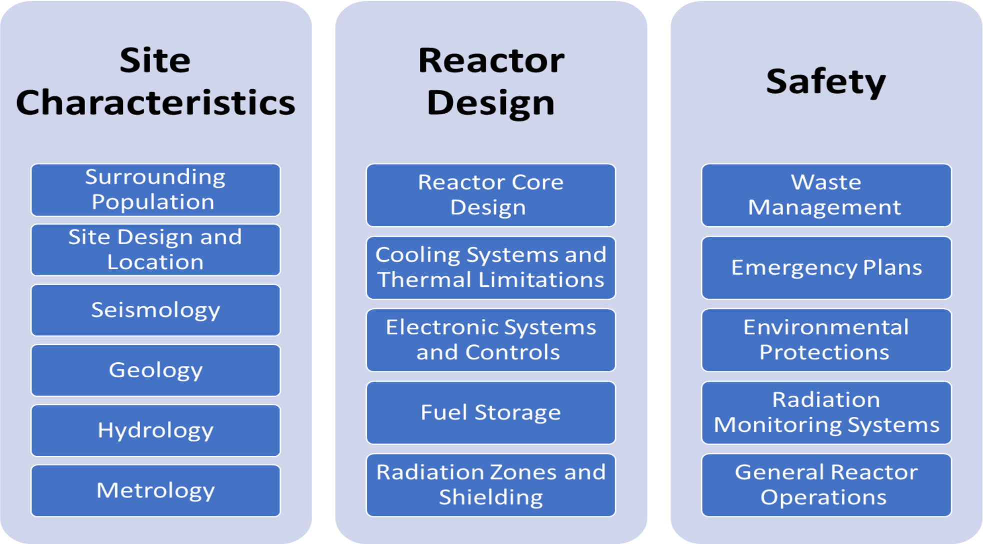
Timeline of the SHINE Technologies Reactor Implementation Process (*In the Matter of SHINE Medical Technologies, LLC; SHINE Medical Isotope Production Facility*, NRC Federal Register Archive, December 2022; *SHINE Medical Technologies, LLC*, NRC, March 2, 2023)

The ongoing construction process has encountered numerous supply chain issues due to the COVID-19 pandemic, delaying the project's completion from December 31, 2022 to December 31, 2025 (NRC CFR Archive). WPI would have to consider such issues if the university were to move forward with construction.

As demonstrated by Figure 11, the construction permit is the first necessary step in the process of implementing any nuclear reactor. According to SHINE, the construction permit took about four years of cooperation with the NRC to obtain, with two years dedicated to environmental data collection, and the other two towards safety and environmental reviews (SHINE Technologies, February, 2016). In order to receive the construction permit, WPI would have to submit a construction permit application, as well as a "Preliminary Safety Analysis Report and Environmental Report". Abilene Christian University is a recent example of this application. An overview of the content in Abilene Christian's "Preliminary Safety Analysis Report and Environmental Report" can be seen in Table 4 below.

Table 4

Construction Permit "Preliminary Safety Analysis and Environmental Report" Topics (NRC CFR Part 50, 2022)



Site Characteristics	Reactor Design	Safety
Surrounding Population	Reactor Core Design	Waste Management
Site Design and Location	Cooling Systems and Thermal Limitations	Emergency Plans
Seismology	Electronic Systems and Controls	Environmental Protections
Geology	Fuel Storage	Radiation Monitoring Systems
Hydrology	Radiation Zones and Shielding	General Reactor Operations
Metrology		

Adapted from "Preliminary Safety Analysis and Environmental Report," Copyright 2022 by the United States Nuclear Regulatory Commission.

WPI will need to obtain the eVinci reactor design information from Westinghouse to complete their own report. WPI will also have to develop criteria for reactor locations that ensure the safety of the nearby population, the efficacy of the reactor in that location, as well as generate a financial qualifications report that determines if WPI can handle the costs of constructing the reactor.

The next step is obtaining the reactor class license that details the use case of the reactor. There are two classes of licenses that the NRC provides: the Class 104 and Class 103 permits. Class 103 licenses are found in commercial and industrial reactors which are commonly used in energy production. These licenses are typically more difficult to obtain due to the larger amount of energy produced, which results in a greater amount of regulations when compared to the Class 104 license (NRC CFR Part 50, 2022). Class 104 licenses are typically obtained for university research reactor programs. In the NRC's Ten Title Code of Regulations (10 CFR), Part 50.21, the NRC details the Class 104 requiring that the applicant use the reactor and facility for medical therapy and research activity. These are representative of the research programs detailed in Section 4.1. These research programs must be detailed in the license application for review by the NRC. The license would require WPI to detail a test and utilization facility in which the university will conduct its research (NRC CFR Part 50, 2022). This must abide by NRC CFR Part 50.2 (c) which states "an application has been filed for a license authorizing operation at: (1) A thermal power level in excess of 10 MWth; or (2) A thermal power level in excess of 1 MWth, if the reactor is to contain: (i) A circulating loop through the core in which the applicant proposes to conduct fuel experiments; or (ii) A liquid fuel loading; or (iii) An experimental facility in the core in excess of 16 square inches in cross-section." (NRC CFR Part 50, 2022). In order to implement a research program that involves a reactor, the ideal license for WPI to pursue would be the Class 104 license.

Finding 13: The possibility of a hybrid research-energy reactor at WPI

As mentioned in Finding 1, the eVinci, through its beam ports, can be configured for different purposes. One purpose we explored is assigning ports for hybrid use of the reactor. Hybrid use would entail WPI being able to use the eVinci for research and energy at the same time. Even though the eVinci is capable of hybrid usage, the regulations help detail the legal boundaries of doing such activities. The first likely path would revolve around the class of the license. Finding 12 defined that a Class 104 license would be ideal for the purposes of research, and it would also be the best path in terms of a hybrid reactor (NRC Representative, personal communication, February 21, 2023). The main reason is the conditions that the license has in terms of energy production through section 31 of the Atomic Energy Act and Regulation 50.22 of the NRC's 10 CFR. Section 31 of the Atomic Energy Act states "The Commission is authorized to issue licenses under this section for utilization facilities useful in the conduct of research and development activities of the types specified in section 31 in which the licensee sells research and testing services and energy to others, subject to the condition that the licensee shall recover not more than 75 percent of the annual costs to the licensee of owning and operating the facility through sales of non energy services, energy, or both…" That means the reactor's sales of non-energy and energy services must not exceed 75% of the operations and maintenance. Regulation 50.22 of the NRC's 10 CFR goes on to clarify "... That in the case of a production or utilization facility which is useful in the conduct of research and development activities… such facility is deemed to be for industrial or commercial purposes if the facility is to be used so that more than 50 percent of the annual cost of owning and operating the facility is devoted to the production of materials, products, or energy for sale or commercial distribution, or to the sale of services, other than research and development or education or training." These regulations make it clear that in order to have a Class 104 research reactor, the energy sales must not cross 50% of the 75% sales threshold. This impacts the hybrid reactor since electricity would be considered energy for sale or commercial distribution, which would result in the reactor requiring the Class 103 license discussed in the previous finding (NRC Representative, personal communication, February 21, 2023). As mentioned in Section 1.1.2 of the background, power reactors produce far more energy than research reactors, meaning the likelihood of surpassing the 50% threshold is high. This would cause the reactor to be classified as a commercial reactor. Heating, however, does not fall into this category, meaning that WPI could use a hybrid reactor to produce heat and remain outside of the threshold (NRC AEA Sec. 103, December 2022). This would require one of the reactor ports mentioned in Finding 1 to be reserved for this use case, with the remaining ports being reserved for the research programs. Through this, WPI can use eVinci to meet its sustainability goals, and to bolster its research programs.

Chapter 5: Recommendations and Conclusions

5.1. Recommendations for WPI administration

Recommendation 1: WPI should advocate for updated microreactor regulations to the NRC and pursue a hybrid reactor

The eVinci has the ability to conduct both research and energy output due to its 13 MWth power capacity and multiple beam ports. We determined that new regulations and a new license class for hybrid use would be beneficial for WPI and other universities that are looking to implement Generation IV microreactors. Current regulations under the Class 104 research license caps the amount of energy produced by the reactor to 50% of the reactor's operations and maintenance cost. With Generation II still being the prevalent reactor generation for university research reactors, we believe that the current NRC regulations are still better suited to Generation II. With Generation IV reactors being discussed as a possible successor to the current research reactors, the NRC should look into how universities can use the reactor to better their campus. This can be achieved by writing regulations that make space for hybrid uses, as research and sustainability are both goals that any university would desire. These new regulations could be included in the Class 104 license for Generation IV reactors in universities. The NRC could also find it beneficial to develop a new form of license for hybrid uses. This “hybrid license” would remove or amend the “below 50% of the cost of operations and maintenance” constraint while still requiring research, and allow for universities to use the Generation IV technology to its full power capabilities.

Recommendation 2: Examine collaboration opportunities with Westinghouse to reduce reactor costs

One concern that we were not able to investigate directly is the expense of purchasing and implementing a nuclear microreactor. While no source was able to accurately estimate these costs, all of our interviewees agreed that such processes can cost WPI hundreds of thousands to millions of dollars. To effectively reduce these costs, WPI could use its ties with Westinghouse to receive an early model of the eVinci at significantly lower costs in exchange for studies of the reactor's performance. This is a common practice in industry (N. Hugger, personal communication, February 2, 2023) that could benefit both WPI's vision and Westinghouse's industrial aspirations. On WPI's side, it would receive a low-cost microreactor and both students and faculty members would be able to perform instrumental research on it. On Westinghouse's end, they would be able to take their first steps towards commercialized microreactors in academic institutions and verify its performance at no cost to themselves.

Limitations that must be recognized in this recommendation include: the need to secure this opportunity quickly, and the possibility that the instrumental research performed on the reactor may have to remain confidential. As an increasing number of universities begin investigating the potential of Generation IV reactors, the eVinci stands as a favorable option for many academic necessities. If WPI wishes to act upon this recommendation, it will have to secure its ties with Westinghouse soon or else other institutions might take its place as an experimental host. Another issue is that any information gained from the instrumental research on the eVinci would likely be confidential. While this may not be a major issue to many, this may limit WPI's ability to perform and publish sustainability and safety processes studies on the reactor as discussed in Finding 2. Depending on any

NDAs, this may also limit WPI’s ability to perform industrial collaborations as discussed in Findings 3, 4, and 5.

Recommendation 3: Determine a location for a hybrid reactor

The process of licensing a reactor takes years. If WPI would like the eVinci to be part of their sustainability plans, they should start the process as soon as possible. The location WPI selects for the reactor affects its connection to campus heating, ease of access for faculty, and the space they have available for testing apparatuses. Location is an important factor to consider in terms of cost and research focus, and a short list of potential locations should be generated before attempting to address these concerns. The most advantageous location would be on the main campus, in a building or portion of a building made for the reactor, but this possibility must be filtered through the relevant cost considerations.

Recommendation 4: Explore cost forecasts for implementing the eVinci

Licenses and permits require financial verification of WPI’s ability to fund constructing and maintaining operations. WPI should explore how the eVinci could fit into their financial plans. WPI’s administration would need to report to the NRC the cost of constructing a facility in the application for a construction permit, as well as a financial report determining if the university has the funding to perform research and the possibility of energy generation. We believe that while implementing the eVinci would likely require high up front costs, its potential for long term financial benefits should also be considered. This would include grants for research programs from organizations, industrial collaborations, and the savings on electricity and heating bills.

Recommendation 5: WPI's eVinci-based nuclear research program should concentrate on Materials Science, Nuclear Medicine, and Energy and Sustainability applications

As discussed in Finding 2, WPI could use the eVinci to perform research in a wide range of scientific fields using a variety of research techniques such as NAA, PGNAA, SANS, and Neutron Radiography. This versatility sets the eVinci apart from current university research reactors as it can sustain a broader nuclear research program, even at a medium-sized school such as WPI. Although any of the fields discussed in this study could act as research focuses for the school, we recognize that sustainability, materials science, and nuclear medicine would serve the school's interests and capabilities best. Sustainability is a topic that is valued by many faculty, staff, and students on campus, and serves as one of WPI's central goals. Initiating a sustainability and energy reactor-based research program would attract a great deal of attention from WPI's body, external academic community, and the general public. It could also attract additional federal funding from the Department of Energy and the Nuclear Regulatory Committee, similar to the funding of this study. Materials science and nuclear medicine would be good research focuses for the school as they also provide great industrial collaboration opportunities. Allowing WPI to focus on a select number of research fields would allow it to become a more recognized leader in these areas. Additionally, constantly connecting academic research to industrial applications would ensure that WPI retains its expertise in the aforementioned topics.

5.2. Recommendations for future research

There are multiple IQPs studying the feasibility of bringing new sources of heating and electricity to campus via a microreactor. Microreactors such as the eVinci are an ideal fit for a college campus since the main focus of the reactor would be to provide the opportunity to conduct research to graduate students as well as professors. The reactor could serve as a new hub to study nuclear medicine and material science while simultaneously imparting a new source of sustainable energy to the campus. WPI is looking to change how it consumes energy and build partnerships with local institutions focused on sustainability and support from the Nuclear Regulatory Commission; future research could address this by creating a strategy around developing awareness of the strengths of a microreactor on campus.

Recommendation 6: Provide the WPI community with an extensive, informative campaign regarding the implementation of a microreactor on campus

To ensure that the WPI community is aware of the eVinci's use cases, we recommend future efforts to develop and deploy an informative campaign. The campaign would inform the WPI community on the potential benefits to students, faculty, and administration. The information presented would also address any concerns or common misconceptions the community has towards nuclear energy. These benefits range from the research capabilities to the advancement of energy sustainability. Examples of the campaign would include a website, videos, and posters of flyers. These posters would provide the information the research groups found regarding the effects of the eVinci on the WPI community. Attaching a link or QR code to a survey by the research groups would also be a useful campaign strategy. The survey allows for the community's voice to be heard, and can be used as a measurement of their views regarding the attached information on the eVinci.

Recommendation 7: Survey the interest of professional groups to collaborate with a university

As this study found, industrial collaborations can act as a significant cash flow to support nuclear research operations. With this in mind, further research may be needed to recognize potential local partners and construct a quantitative evaluation of the financial benefits of such opportunities.

Our team recommends this research to be a two step evaluation. First, a feasibility study of industrial collaborations that would begin with local hospitals, institutions, and companies and later expand to the bigger industrial leaders in Massachusetts, Southern New Hampshire, Connecticut, and Vermont. This study could be done by a student group such as an IQP. Once a map of potential partners has been established, a study of revenue potential could be conducted. This study would likely require professional financial analysts. Using the information gathered in both studies, WPI administration could thoroughly assess the costs and benefits of working with industrial partners and their implications for WPI's nuclear research aspirations.

Recommendation 8: Investigate local researchers' willingness to collaborate with WPI

WPI should explore the potential of collaborating with other nuclear researchers in New England. Such an initiative would support WPI's ambitions of establishing itself as a local nuclear engineering leader. One nearby university that should be considered for such a collaboration opportunity is the University of Massachusetts Lowell, as it already has a stable nuclear engineering program. WPI should reach out to researchers at UMass Lowell in regards to their recent nuclear research initiatives and examine methods which could support a mutually-beneficial reactor program. To further investigate what such a program could look like, student-led research groups at WPI could conduct a series of interviews with research faculty at UMass Lowell on the subject of a nuclear research partnership. Faculty and researchers that are directly involved with nuclear systems modeling and similar practices could also open a partnership with WPI to design the research reactor facility. While this recommendation uses a partnership between UMass Lowell and WPI as an example due to an existing relationship between the institutions, we believe that other local institutions should also be surveyed for their willingness to work with WPI on research opportunities.

Recommendation 9: Further investigate the necessary lab requirements for an eVinci-based research facility

There are a couple benefits to installing the reactor on campus: getting students to and from the reactor is easy as they are already close by, and the reactor is well-placed to serve electricity to the campus in the future. We could siphon heat from the reactor and into rooms on campus, since those rooms would be close by. To best take advantage of these benefits, we need to ensure that any on-campus location selected is capable of executing these functions well. For example: this location must allow space for beam ports of various sizes, it must allow the reactor to be integrated into the existing heating system with minimal installation modifications, and we must also be able to fit in an apparatus for putting samples near the reactor body without completely shutting down the reactor. All of these requirements will affect the way the reactor is installed in the location selected, and should be accounted for as choices are reviewed.

5.3. Conclusion

Our work strongly supports the feasibility of implementing an eVinci microreactor for research purposes at WPI. Evidence from our findings shows that the eVinci's characteristics, specifically its core and neutron flux, are well-suited for research applications. Furthermore, despite its size, the eVinci can host multiple beam ports, which allow it to effectively support numerous simultaneous research programs, student projects and training, as well as industrial work. In addition, its power capabilities, which are higher than any existing URR's, will allow WPI to perform ground-breaking nuclear research, thus effectively becoming a leading nuclear institution in New England and a notable pioneer in the United States. This study also echoes Westinghouse's claims regarding the eVinci's safety features, showing that its closed system build prevents environmental contaminations and unwanted public radioactive exposure. These same features also greatly contribute to its security, as the eVinci’s core and fuel cannot be accessed from the outside, and must be completely removed from site in order to extract any endangering materials.

Moving forward, WPI must consider the timeframe of incorporating the NRC licensing process in its infrastructure plan with Harrison Street, as both processes are years-long projects that will likely require significant financial investment. Since Generation IV reactors will likely soon become the new standard for nuclear reactors, WPI must also voice the need for Generation IV-oriented licenses to the NRC, specifically considering microreactors for hybrid purposes. As this study determines that the eVinci microreactor holds great potential in its applications for research, we strongly believe that WPI should take initiatives for its implementation on campus as soon as possible, using the knowledge obtained from this study on the eVinci and the energy and sustainability study’s findings to its advantage.

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Appendices

Appendix A: Interview Protocol

Roman Gowie coordinated interviews via email, and each interviewee was provided and did sign a consent form before meeting us. This informed them of the purpose of the interview, what was going to happen during the interview, that the interview was going to be recorded, their right to terminate consent to be interviewed at any time and what was going to be done with the interview recordings. If an interviewee asked to remain anonymous, we removed identifying information from the interview transcript and referred to them as an anonymous source, instead of citing them by name. Prior to the interview, we reiterated the subject of the interview to ensure that the interviewee understood what we were going to talk about, and what we were going to do with their words.

The interviews were conducted over Zoom. We chose Zoom for its recording capabilities, which aided in making accurate transcripts. If they preferred to meet in person we met them in person, and recorded their voice using a smartphone. All four of us, Augustine Benjamin, Roman Gowie, John Mansour, and Haggay Vardi, were present for each interview, with Vardi leading the interview and asking most of the pre-written questions, and others interjecting for clarification or to ensure that nothing is missed.

Appendix B: Interview Questions

Norbert Hugger

Start with eVinci background so the interviewee is made aware of the prospect of SMRs at WPI for research

1. What type of research do you conduct? (does it involve nuclear reactions?)
2. Does your research involve using nuclear reactors?
3. Currently, there is not a research reactor at WPI. Does this impact how you make research decisions? Do you use other institutions' reactors in your research? If so, how does that look in terms of coordinating with that institute?
4. Can you specify practically how your research is done? (# of people involved, what part of the reactor you target, etc.)
5. How do you currently conduct your research? (Outside institution reactor?)
6. Are you familiar with the Westinghouse eVinci reactor?
7. Do you feel the eVinci would be able to meet your research needs? If so, how?
8. Do you believe your research methods will change with an eVinci? If so, how?
9. What are some challenges you believe you may face given a Gen IV eVinci for your research purposes?

Non-WPI Interviewees - General Questions

1. (if professor) What sort of research do you conduct?
2. (if professor) Of these research topics, which of them do you conduct using the research reactor?
3. What sort of research does your institution's reactor specialize in?
4. What is involved in keeping the research reactor running on a day to day basis? (assigning research time, operation time, staff required, etc.)?
5. Do you currently face any problems with the gen 2 reactor?
6. Where do you see the current Gen 2 reactor going in the future?
7. How familiar are you with Gen IV reactors and their capabilities?
8. How would Gen 2 compare to the eVinci in terms of your research? (how would this change affect your research)
9. Have there been any thoughts of using Gen 4 reactors on your campus?
10. (If familiar with Gen 4 technology) What are some problems that you expect to face if you were to transition to a Gen 4 reactor for research purposes?
11. Neutron irradiation is a method that yields I-131 that pharmaceuticals can use as radioactive medicine. What other sort of contributions can you see happening in terms of working with isotopes?

Professor Mark Tries

1. Primary experience with the UML reactor?
    a. Is current research conducted using the reactor? How?
2. Pros and cons of the reactor (1MWth)? Limitations?

   a. I'd like to get comments on neutron fluxes and how elaborate the collimation needs to be for this reactor and the research they prefer to do. (augustine)

3. Considering adding GenIV?
4. Student integration in nuclear work and reactor in particular?
   a. What sort of experience do they get?
   b. How involved can they be?
   c. Undergrad opportunities?
5. How does UML approach the matter of safety/security of the reactor?
6. Operation training? Tooling? Staffing?
7. What sort of research are you (and your grad students) currently conducting?
8. What sort of experience do you have using nuclear reactors for research purposes?
9. Do you believe that eVinci could benefit your research program in any way?
10. What type of research in your field could come from having the eVinci?
11. Is there research that you would like to do, but have chosen not to due to lack of access to a different reactor/neutron source?
12. Could the difference in power of the eVinci(GenIV) compared to current research reactors lead to the discovery of new imaging techniques using radioactive tracers, ones that are more cost effective and enhance the imaging process overall?
13. Where do you see your research going in the next five years? Would the eVinci be applicable/helpful in those domains? Would having it here change your current plans and direction

Professor William H. Miller (Bill)

1. Given your experience with MURR throughout the years, what sort of advantages did having 10 MW of power give you in comparison to other reactors?
2. What is the most meaningful, in your opinion, use of such a powerful reactor? In what field do you see the most significant impact?
3. How did the radiochemists added to MU in the 2000s make use of the reactor? Were there alterations you had to make to the reactor or lab surrounding the reactor to make it more useful to them?
4. I can see that you've used neutron scattering to find light elements inside samples of otherwise heavy atoms–is this the primary use case of neutron scattering analysis?
5. Detecting water damage is a clear case where it is useful to be able to detect light atoms–are there other circumstances where materials scientists and other engineers would want to be able to detect hydrogen (or other light atoms) for their research?
6. Do you think that the field of neutron spectrography is expanding, contracting, or shifting in some other fashion?
7. Are you familiar with microreactors? (if not, explain)
8. What are some limitations that you are expecting from Gen. IV microreactors?
9. What are some advantages that you are expecting in research using microreactors?
10. How would a Gen IV reactor affect your past and current research?
11. What are some problems that you expect to face if you were to transition to a gen IV reactor?
12. Considering MURR's past flexibility and increase in power capabilities, do you expect MURR to upgrade to a Gen IV reactor?
    a. Why or why not?

13. What sort of unique programs does MURR offer and how do they differ than other schools? Why?
14. How involved do students get in MURR - undergrad and grad?
15. (if involved) how does their experience in MURR affect their career?
16. MURR must produce lots of waste - How does it handle removing?
17. Security wise - how do you secure your facility?

Westinghouse

***The interview with Westinghouse was scrapped after we consulted with Norbert Hugger

1. Do you feel that the eVinci is well suited for all forms of nuclear research? (maybe some, or none? If none ask why that is (maybe the design)
2. How do you feel an eVinci would operate if WPI were to use it for research? (Staff, run time, maintenance, core access, etc)
3. We heard there were ‘ports’ of some kind on the outside of the eVinci–how accessible are these?
4. Could they be opened and accessed while the eVinci is in operation?
5. What is the predicted neutron flux outside of the eVinci itself, in its immediate surroundings?
6. Are you familiar with elemental transmutation? (if not, explain the process quickly)
7. We would like to use the excess neutrons thrown off by the reactor to irradiate elemental samples and transmute them to convenient radioisotopes. Would the ports be useful for this activity?
8. Are there good alternatives to inserting objects in the reactor ports for elemental transmutation?

WPI Professors - General Questions

1. What sort of research are you (and your grad students) currently conducting?
2. What sort of experience do you have using nuclear reactors for research purposes?
3. Do you believe that eVinci could benefit your research program in any way?
4. What type of research in your field could come from having the eVinci?
5. Is there research that you would like to do, but have chosen not to due to lack of access to a reactor/neutron source?
6. Where do you see your research going in the next five years? Would the eVinci be applicable/helpful in those domains? Would having it here change your current plans and direction

Materials Science Professor

1. What sort of research are you (and your grad students) currently conducting?
2. What sort of experience do you have using nuclear reactors for research purposes?
3. Do you believe that eVinci could benefit your research program in any way?
4. What type of research in your field could come from having the eVinci?
5. Is there research that you would like to do, but have chosen not to due to lack of access to a reactor/neutron source?
6. Where do you see your research going in the next five years? Would the eVinci be applicable/helpful in those domains? Would having it here change your current plans and direction?
7. Microreactors(e.g. eVinci) are smaller and have less heat generation compared to large reactors; they also contain advanced materials that are corrosive resistant. What kind of materials are capable of achieving this level of operation?

8. Why was it so difficult to have students work on the reactor in the past?
9. How do you see the reactor being implemented into MQPs for the department?
10. How do you think the department will adapt to a reactor (New concentrations? Labs?)

Professor Stephen J. Kmiotek

Introduce our objective to them, provide background on the eVinci's capabilities

1. What sort of research are you (and your grad students) currently conducting?
2. What sort of experience do you have using nuclear reactors for research purposes?
3. Do you believe that eVinci could benefit your research program in any way?
4. What type of research in your field could come from having the eVinci?
5. Is there research that you would like to do, but have chosen not to due to lack of access to a reactor/neutron source?
6. Where do you see your research going in the next five years? Would the eVinci be applicable/helpful in those domains? Would having it here change your current plans and direction?
7. Neutron irradiation is a method that yields I-131 that pharmaceuticals can use as radioactive medicine. What other sort of contributions can you see happening in terms of working with isotopes?
8. Why was it so difficult to have students work on the reactor in the past?

Professor David S. Adams

1. Are you familiar with WPI's work to potentially bring a genIV microreactor for research purposes on campus? Are you familiar with such reactors and their potential?
    a. If not -> explain
2. What sort of research did you conduct with the old reactor? What techniques did you use for this type of research?
3. What sort of future do you see for this topic of research?
4. Given a 10 MW reactor, what type of research would you conduct?
    a. (If familiar with microreactors) How would a microreactor benefit your work?
    b. Was there some sort of research that you would have wanted to do but couldn't due to lack of reactor-related sources?
5. What were some issues with the old reactor?
    a. What led to the old reactor's disassembly?
    b. What are some problems that must be addressed if a new reactor would be brought to campus?
    c. What about safety risks, in particular?
    d. Who are the people we should try to convince?
    e. Have any tips for us?
6. What are some differences in how radiation risks should be managed today, with the eVinci, compared to how we managed them in the past, with the old reactor?
7. What did the old lab look like? How many people operated the reactor at the same time? How much research was conducted simultaneously?

NRC Representative:

1. Have you done any work/studies on Gen 4 reactors?
2. Do you envision Gen 4 reactors being integral to the advancement of nuclear research? (Or just the future of nuclear research in general)
3. How is the NRC anticipating the future changes in the nuclear reactor field?
4. Is there work being done currently to enable the installation and usage of hybrid reactors(simultaneous energy and research usage)?
5. (If not) Is such work necessary?
6. (If not) Could WPI participate in initiating such work?
7. (If so) Would such work be positioned to enable WPI to install a hybrid reactor?
8. (If so) What considerations are the NRC taking under consideration for a hybrid reactor? Conflicts? Simplifications?
9. (If so) How would the licensing and evaluations for a hybrid reactor be different compared to a regular research reactor or power reactor?*******
10. What does it take to approve a research reactor in terms of licensing, etc?
11. How would Gen 4 licensing be different from Gen 2? (What are the key differences?)
12. What does it take to approve a Gen IV reactor installation?
13. If installed, what would the NRC need to do (yearly, monthly, bi-annually) to uphold the licensing of the reactor
14. How would the security regulations of a microreactor be different to that of a Gen 2 reactor?
15. What are the main safety concerns of the NRC with a Gen 4 reactor?
16. What would the timetable look like for licensing?

Appendix C: Consent Form

Informed Consent Agreement for Participation in an IQP Interview

Primary Investigator: Derren Rosbach

Contact Information: Tel: 508-831-5000 / Email: drosbach@wpi.edu

Title of Research Study: Exploring the Feasibility of Small Modular Nuclear Reactors for Research

Introduction:

You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study:

We are conducting this study to determine whether the eVinci modular nuclear microreactor is viable as a research reactor for Worcester Polytechnic Institute, with an eye towards combined research/energy production usage.

Participation:

Participation in this interview is voluntary. You are free to answer questions to whatever extent you are willing. You are free to withdraw from the interview and withdraw your responses from the study at any time before publication. Refusal to participate will not result in any penalty to you.

Benefits and risks to study participants:

No direct benefit to you is expected due to this interview. You may expose yourself to some potential risk to your employment based on how you respond to the interview questions, but this is unlikely for the questions that we are going to ask you.

Record keeping and confidentiality:

The interview, if it is held over Zoom, will be recorded. This recording will be used to write a transcript, which will be published in the final IQP report. After this, the recording will be destroyed. If the interview is held in person, the audio will be recorded using the interviewer's smart phone, and this recording will be used to write a transcript, which will be published in the final IQP report. After this, the recording will be destroyed. In both cases, the recording will only be shared with interviewers, the person writing the transcript, and project advisors. You may ask not to be recorded, in which case we will write a transcript in real-time. You may also ask that the transcript not be published, and/or that your identity be kept anonymous. In the former case we will not publish your transcript, and it will be used only for writing the report, and in the latter case we will not cite you by name as the source of your comments and refer to you only as an anonymous source.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact professor Derren Rosbach by email or telephone, both of which are listed at the top of the page. You may also choose to contact the IRB Manager Ruth McKeogh: Tel. 508 831-6699, Email: irb@wpi.edu, or the Human Protection Administrator Gabriel Johnson: Tel. 508-831-4989, Email: gjohnson@wpi.edu.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

Do you consent to having your interview recorded, as outlined above?

yes/no:___________________

Do you consent to having the transcript of your interview published?

yes/no:___________________

Do you wish for your identity to remain anonymous in the final report?

yes/no:___________________

______________________________________ Date: ____________________

Study Participant Signature

____

Study Participant Name (Please print)

_____________________________________ Date: ____________________

Signature of Person who explained this study