

Energy Harvesting Opportunities Throughout the Nuclear Power Cycle for Self-Powered Wireless Sensor Nodes

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Abstract

Dedicated sensors are widely used throughout many industries to monitor everyday operations, maintain safety, and report performance characteristics. In order to adopt a more sustainable solution, much research is being applied to self-powered sensing, implementing solutions which harvest wasted ambient energy sources to power these dedicated sensors. The adoption of not only wireless sensor nodes, but also self-powered capabilities in the nuclear energy process is critical as it can address issues in the overall safety and longevity of nuclear power. The removal of wires for data and power transmission can greatly reduce the cost of both installation and upkeep of power plants, while self-powered capabilities can further reduce effort and money spent in replacing batteries, and importantly may enable sensors to work even in losses to power across the plant, increasing plant safety. This thesis outlines three harvesting opportunities in the nuclear energy process from: thermal, vibration, and radiation sources in the main structure of the power plant, and from thermal and radiation energy from spent fuel in dry cask storage. Thermal energy harvesters for the primary and secondary coolant loops are outlined, and experimental analysis done on their longevity in high-radiation environments is discussed. A vibrational energy harvester for large rotating plant machine vibration is designed, prototyped, and tested, and a model is produced to describe its motion and energy output. Finally, an introduction to the design of a gamma radiation and thermal energy harvester for spent nuclear fuel canisters is discussed, and further research steps are suggested.

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General Audience Abstract

In this work multiple energy harvesters are investigated aimed at collecting wasted ambient energy to locally power sensor nodes in nuclear power plants, and in spent nuclear fuel canisters. Locally self-powered, wireless sensors can increase safety and reliability throughout the nuclear process. To address this a thermal energy harvester is tested in a radiation rich environment, and its performance before and after irradiation is analyzed. A vibrational energy harvester designed for use on large rotating machinery is discussed, manufactured, and tested, and a mathematical model describing it is produced. Finally, an introduction to harvesting radiation and heat given off from spent nuclear fuel in dry cask canister storage is investigated. Power capabilities for each design are considered, and the impact of such energy harvesting for wireless sensor nodes on the longevity, safety, and reliability of nuclear power plants is discussed.

To my wonderful parents Douglas and Peggy Klein
Much love to you both

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1 Introduction

1.1 Motivation

Nuclear power accounts for a large portion of the world's energy, being one of the major contributors to the energy market. In 2013 it was estimated to be responsible for 11% of worldwide electricity production, with projections to increase 1 to 2 percent by 2030 [1]. This is important, as a push for cleaner, and more sustainable power sources needs to be made in order to reduce the carbon emissions of our society, and lessen our negative impact on the environment. While sustainable solutions such as solar, wind, and water continue to grow in popularity and usefulness, they still must be supplemented by continuous forms of reliable energy production. Nuclear power is an important player in this energy market, and should continue to be an option well into our energy future. Being cleaner than coal or natural gas power plants while maintaining similar energy outputs, it continues to be a promising alternative.

This said, an important issue intrinsic to nuclear energy applications is the possibility of severe accidents which occur when conditions reach extreme levels causing potential danger to plant workers, surrounding society, and the environment. We have seen multiple disaster scenarios, such as Fukushima or Three Mile Island, since the adoption of nuclear power which have significantly altered the public perception of the safety of nuclear power. An increase in the safety of operations in nuclear power plants is always desired by the industry, and will strengthen public perception of the longevity and reliability of the energy source.

Similarly, used nuclear fuel storage is now starting to become a major issue, as spent fuel rods are beginning to pile up in both wet and dry cask storage. Being a potential danger to the health of the public and workers alike, maintenance and storage of spent fuel should be continually addressed. Dry casks have been able to successfully hold spent fuel for long periods of time while practically eliminating the impact of radiation on workers and surrounding societies, however, the monitoring of these nuclear fuel casks for potential degradation is necessary and can be difficult to accomplish.

To keep nuclear a safe and reliable option for our energy budget, these issues should be, and are being addressed. In order to reduce the possibility of temperature, pressure, and other system health related issues in the main power plant, structural health monitoring sensors have been

implemented throughout nuclear power plants. However, these sensors are mainly dependent on electricity from grid power, diesel back up generators, or short term back up batteries to transmit data to technicians which presents two significant disadvantages. First, during massive loss of power to the plant, which can occur during natural disasters, their backup batteries will be drained quickly as continual sensing will be necessary. Second, current implementation of sensing modules may require the use of lengthy power or data cables, which introduces system unreliability for operation in high-temperature and high-radiation environments [2].

For spent fuel, monitoring of temperature, pressure, radiation, humidity, etc. inside the enclosed vessels is crucial to ensure safe storage and fuel security. However, physical boundaries and radiation levels around these casks make monitoring difficult, and the process can be made easier and further streamlined through wireless sensor transmission.

Energy harvesting for wireless communication provides a promising opportunity to revolutionize sensors and structural health monitoring instrumentation. Through the use of multi-source energy harvesting, utilizing the heat and vibration present around the reactor components, and gamma radiation and heat from spent nuclear fuel, it is possible to power wirelessly transmitting sensing modules in a self-produced manner. Thermal and radiation powered nodes can continue to operate during losses of plant power, and all self-powered nodes will remove the cost and unreliability of the power and data cables, or batteries currently used. Throughout this work, an argument for the use of energy harvesting to help increase the safety of operation throughout the nuclear power process by powering wireless sensor networks is made.

1.2 Thesis Objectives and Impact

The overall objective of this thesis is to investigate and create innovative energy harvesting technologies for self-powered sensing modules which can be used throughout the nuclear power production cycle to increase the safety of operations. The aim is to encourage further research into the topic by showing the potential of the technology. In order to address this, three objectives must be met. First, wasted energy sources must be located and analyzed, second, these sources must provide power for the sensors over the desired operational time frame, and third, the energy harvesting solution must, if possible continue to work in plant shutdown situations, and should survive in the radiation environment. In this work, three forms of energy harvesting will be investigated and discussed for the purpose of powering wirelessly transmitting sensor nodes

specifically for reporting temperature, pressure, humidity, and radiation information throughout the nuclear power plant and in dry casks. A secondary objective is to develop a vibrational energy harvester which can increase the harvesting potential from small amplitude machine vibration. This vibrational energy harvester is designed in a way so it can potentially be used for multiple industries where small amplitude, consistent machine vibration is present. Finally, a way of harvesting gamma radiation is examined, and a harvester is designed which could be placed in any gamma radiation source. The objective of this section is to investigate and inform on the ability to harvest the energy of gamma radiation using material heating to create a local temperature gradient for thermal energy harvesting. The principles used in this design could also be used inside the reactor internals themselves to design a harvester system in order to power wireless sensors within the reactor core. An additional benefit of this study is the development of a comprehensive simulation model of dry cask internals which can be adapted for any dry cask and fuel type being studied.

1.3 Thesis Organization

The motivation and objective for this thesis have been outlined in this chapter. Chapter 2 outlines necessary background information regarding wireless sensing in nuclear power plants, energy harvesting, nuclear power plant operation, and spent nuclear fuel storage. Discussion is made about the location and potential of energy sources including thermal, vibration, and radiation. Chapter 3 gives a brief overview of two thermoelectric based energy harvesters made for the use of thermal energy in the pipelines of nuclear power plants, and experimental results from both the lab bench and a radiation test are given and discussed. Chapter 4 outlines the design, modeling, and experimental results of a vibration energy harvester made to utilize small amplitude vibrational energy from large rotating machinery in the nuclear power plant. Chapter 5 develops a model of dry cask canisters and discusses the potential of a design for gamma radiation and heat harvesting to locally power sensor nodes within dry cask storage of spent nuclear fuel. Finally, chapter 6 gives conclusions of the results, potential applications of the harvesters for other industries, and outlines future steps which should be taken with this project.

2 Background

2.1 Wireless Sensor Nodes and Energy Harvesting

Wireless sensors have been designed, adopted, and deployed over a wide range of commercial infrastructures. This work has included research into their use in nuclear power plants. In a report to the IAEA Hashemian [3] argued for the benefits of machine and condition monitoring within nuclear power plants using wireless sensor networks, saying “Wireless sensors can play a major role in monitoring the condition of the hundreds if not thousands of rotating machines, valves, and mechanical or electromechanical systems in a nuclear power plant.” In a separate article specific to machine and rotating equipment degradation monitoring, Hashemian [4] scoped and implemented a wireless sensor network in the HFIR research reactor at ORNL to monitor various rotating equipment, finding wireless monitoring to be immensely beneficial and effective for checking on key processes and conditions. Separate from nuclear applications, Low et al. [5] discuss wireless sensor networks in industry, concluding that while they are inexpensive, and highly beneficial for providing plant information, their power requirements must be addressed. They discuss the fact that sensors must be placed in order to run wires to them, a difficulty around large infrastructure and a potential failure mode.

To this point, wireless sensor nodes as typically installed require supplied power, either from an external power supply or accompanying batteries in order to transmit data [6]. These necessities are cause for concern, especially when introduced in nuclear environments. Cabling is expensive, can be difficult to install and maintain, and can present reliability problems when placed in high temperature, radiation rich environments as present within a nuclear power plant [2,7], or in the harsh environments in any large industrial plant. Battery powered sensors require frequent replacement, introducing parts and labor costs, and they cause a potential need for plant shutdowns for maintenance, wasting precious time. Finally, sensor nodes powered through the plant or by backup generators can cease to perform during critical operations such as after earthquakes and tsunamis if power is lost both from the plant and from the backup generators. In order to alleviate these critical issues, wireless, self-powered structural health monitoring sensors have been suggested by Clayton et. al. [8], and indeed studied by Hashemian and Kiger [9] who documented the benefits of wireless sensor information transmission within nuclear power plants and

concluded it would be immensely beneficial to the industry. Evidentially, the implementation of self-powered wireless sensors in the nuclear industry, and indeed in any industrial complex, would allow for continuous sensing and data communications, potentially increasing overall safety, while also eliminating the necessity to install and maintain both power/data cables and batteries. Removing these costs alone represents a major improvement, and, more importantly, self-powered sensors can have the ability to operate during major losses of power to the plant which may occur during extreme natural hazards similar to the 2011 Fukushima Daiichi nuclear disaster when current wireless sensors may cease to perform. For these reasons, energy harvesting research specifically targeted for wireless sensor networks in nuclear power plants is necessary.

Energy harvesting has been well discussed in both academic literature and in books, and is the preferred method for power generation in self-powered sensing. Generally speaking, energy harvesting is an area of research applied to the capture and use of wasted, or under utilized environmental energy. This can be a broad range of research as anything from large scale solar, wind, water, or wave energy, to small scale thermal, vibrational, and light energy can be harvested. Uses of the energy are wide reaching as well, considering large solar arrays may power a neighborhood or help supplement a city, while ambient vibrational energy can only typically power small scale electronics. Specific for wireless sensor networks, photovoltaic, vibration, and thermal energy are typically used, especially considering their availability throughout industrial complexes, where wireless sensor networks are often employed. Vibration energy harvesters classically make use of either piezoelectric or electromagnetic transducers, typically utilizing an excitation of energy accumulation or flow in harvesters through the matching of the operational frequency of the device to the frequency present from the vibrational source. More discussion on this form of energy harvesting can be found later in chapter 4. Thermoelectric energy harvesters are also popular, and can generate electrical current when provided a temperature difference across their two sides. An outline of their performance and characteristics is given in chapter 3. These types of small scale energy harvesters are widely studied throughout the literature, and can provide power for small scale electronics such as those in wireless sensor networks.

Regarding this, Davidson and Mo [10] give a nice overview of recent energy harvesting advances for wireless sensors in industrial environments. Many of the devices in their extensive list include both vibrational and thermal energy harvesters. Additionally, Kahn et. al. [11] review recent advances in bridge vibration harvesting, providing valuable discussion on where and how

to implement self-powered wireless sensor nodes on and around bridges, information which can be readily adapted to the energy sector. A wide variety of energy harvesters and their applications can be found in the literature. While much work has been done on general energy harvesting, a surprisingly few number of researchers have investigated energy harvesting within nuclear power plants, though there are a myriad of available sources including: hot piping or vessels, equipment vibration, ventilation and air flow, electromagnetic fields, and room lighting. [6,8]. Most promising of these forms of energy are equipment vibration and hot piping or vessels due to the larger scale of the available energy.

A small number of energy harvesters have been found in the literature specifically targeting nuclear environments. As mentioned earlier, Hunter et. al [6] researched a high-reliability secure wireless communication system using pyroelectric energy conversion technology for self-powered continuous data transmission. Their project showed new research into the capability and application of pyroelectric modules for power harvesting as a competitor to thermoelectric based harvesters. Additionally, Tewolde et al. [12] constructed a thermoelectric harvester to power a sensing system in a small modular reactor and designed an energy management system to regulate the output power for sensing and wireless communication. Finally, work done as a precursor to this thesis is presented by Chen et. al. [13], where an on pipe thermoelectric energy harvester was produced to utilize the temperature difference between nuclear piping and the surrounding air. This previous work is discussed briefly again in chapter 3 of this thesis. This all stated, evidentially the research area of energy harvesting specifically in nuclear environments is rich for potential.

Of course, a discussion on energy harvesting for self powered wireless sensor nodes would be incomplete without an estimate on the power requirement of the node itself. While this thesis is not aimed at electronics or the development of wireless communications, it is worthwhile to briefly discuss the goal for power production of energy harvesters within the nuclear power plant to successfully demonstrate ability to locally power a sensor node. As a baseline for power necessities, a conservative estimate made by Clayton et. al [8] is presented in table 2.1 below. In this consideration they include signal conditioning electronics for thermocouples, a microcontroller, and a radio transceiver which uses twice as much power as the most efficient ZigBee wireless communicator currently on the market. They assume transmission of data every 10 seconds along with relays from other nodes every second.

Table 2.1. Estimated power requirements for a wireless sensor node system [8].

Component	Power Budget Average [mW]
Transceiver including encryption	9
Microcontroller	0.2
Four Channel Thermocouple Cold-Junction Compensation amplification	1
Quad 12-Bit ADC	0.018
Miscellaneous Circuitry	3
Power loss in 85% efficient power conversion/management circuit	2
Total	16

This estimate was made to be representative of most wireless sensor nodes currently utilized for industrial based monitoring. Thus as a conservative estimate on the power requirement for energy harvesters of tens of mW is desired. Of course, for more complicated transmission methods as may be necessary within nuclear power plants or containment vessels, a higher power requirement may be necessary, or a reduced transmission cycle can be used. Additionally, energy harvested can also be stored in batteries for use later by some wireless transmitters.

2.2 Nuclear Power Plant Overview

In order to understand the location and nature of the wasted energy which can be harvested from plant processes, a general outline of nuclear power plants is given here. References throughout this work to components within the nuclear power plant are made to those described in the manual by Testa [14] for the Westinghouse Pressurized Water Reactor (PWR). While this description given below is brief, a more complete understanding of the power plant and its operation can be found in material from Westinghouse [14] or from a multitude of sources online by the USNRC [15]. This outline is simply intended to give the reader enough information to appropriately understand the nature and design of the energy harvesting solutions discussed, and is in no way a complete review of plant operations.

Nuclear power plants contain multiple systems working together for the overall generation of power. In general, heat generated from nuclear reactions in the fuel is responsible for generating steam which is used to turn a generator, creating electrical power. Three main “loops” are present within a PWR: the primary, secondary, and tertiary loops, terms coined for the three different

sections of the plant responsible for various tasks in the production of power. A schematic [14] outlining these sections of the Westinghouse PWR is shown below in figure 2.1.

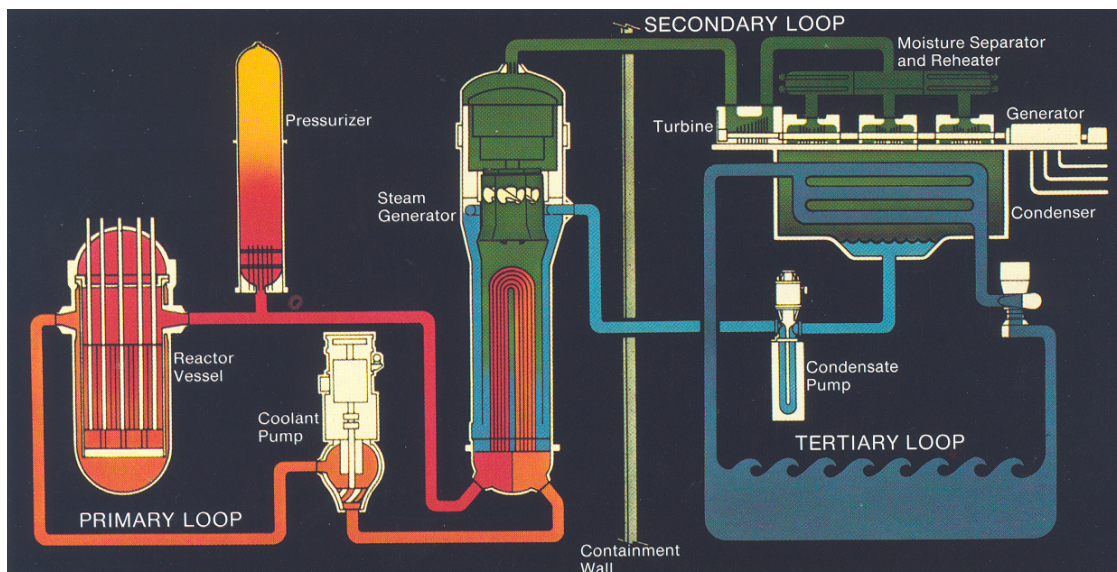


Figure 2.1. Schematic of the Westinghouse Pressurized Water Reactor [14].

First, placed within the primary containment and shielded by a thick concrete wall, the primary loop is responsible for both regulating the temperature of the nuclear fuel, and generating the main power source for the plant. It is made up of the reactor vessel itself, the main coolant pump, a pressurizer, and the steam generator. Connecting each of these components are wide diameter, insulated, stainless steel pipes carrying the pressurized coolant water. According to the Westinghouse manual [14] three different sized plants are available, with two, three, or four primary loops, depending on the necessary power output of the plant. These are each attached independently to the reactor vessel, the main powerhouse of the plant, which houses the nuclear fuel stored in rods. Using the main coolant pump, water in this loop is pumped through the nuclear fuel where it is heated by about 35°C by the thermal output of nuclear fission within the fuel rods, regulating the temperature of the fuel and carrying thermal energy to the rest of the plant. This water is maintained in its liquid form using high pressure produced through the pressurizer attached to the loop, so as not to boil into steam. The use of this pressurized water is the main distinction between a PWR and its counterpart, the boiling water reactor, which allows instead for the water to become steam within the reactor. Heated coolant nearing 325°C is then pumped into the steam generator, where the heat is used to create steam boiled off cool water supplied by the secondary loop. Primary loop coolant water and cool steam generation water do not mix, rather

the coolant water passes through U-shaped heat exchangers and is finally pumped out of the steam generator to be heated again in the reactor vessel.

The secondary loop of the power plant is responsible for the transport of steam for power generation, and its re-condensation. Starting in the steam generator, steam boiled off of cool water by the high temperature coolant, under pressure, is directed by piping to the turbine, generally located in a separate building adjacent to the containment center. The high quality steam is passed over a high pressure turbine, before being re-heated and passed through three low pressure turbines. These spin, ultimately turning the main generator, which creates electrical power to be sent from the power plant into the grid. Once steam is pushed over the blades of the main turbine, it is passed next over the condenser, a large heat exchanger responsible for re-condensing the steam into water to be used again as supply for the steam generator. The condenser is supplied by cool water pumped from an external source, such as a lake or the ocean, which makes up the third and final tertiary loop of the power plant.

2.2.1 Temperature in the Coolant System

When considering places in the plant for the placement of an energy harvester, the coolant loop piping system is an initial attractive potential target due to high temperatures, and thus large potential for wasted heat to harvest. Various parameters of the primary loop are given below in table 2.2.

Table 2.2. Parameters of light water coolant in a Westinghouse PWR [14].

Coolant Parameter	2-Loop Plant	3-Loop Plant	4-Loop Plant
System Pressure (PSI)	2250	2250	2250
Flow Rate (kg/s)	8960	13734	17438
Temperature Prior to Reactor (°C)	287.7	291.7	291.9
Temperature Post Reactor (°C)	324.5	326.6	325.8

Intended to maintain temperature of the coolant each of the pipes has a thick insulation covering, which provides a unique opportunity for energy harvesting. While the pipes remain at a high temperature, due to their insulation the surrounding environment is maintained at relatively normal temperatures. Their temperature introduces an avenue for energy harvesting in the form of a temperature gradient. As will be further outlined in chapter 3, thermoelectric energy harvesters can take advantage of temperature differences when placed across their two surfaces. The larger

the difference, the higher the voltage and current produced by the modules, and thus the more power generated.

It is reported [14] that ambient temperatures in the containment center are predicted to be near or below 60 °C. Thus, as can be seen from the table above given a pipe temperature of 320 °C, a 260 °C temperature difference between primary loop piping and the surrounding air could potentially be utilized. In addition to the primary loop, in the secondary loop post steam generation, steam is kept under pressure, and thus at higher temperatures falling typically between 200 and 275 °C depending on the location. Therefore, in the secondary loop system a temperature difference of between 140 and 215 °C could be utilized. Thus, for sensors near the coolant and steam loop piping, thermoelectric energy harvesters would be ideal for use.

Indeed, there are sensors currently in place within the primary and secondary loop piping to monitor both the temperature and pressure of the liquid flowing in the pipes. This is important to monitor and regulate, as the longevity and safety of the fuel and plant are highly dependent on their temperature. Additionally, considering the PWR relies on pressurized water for heat transport, the system should remain well pressurized. Radiation and humidity within the containment center can be monitored as well to ensure the safety of both workers and the operational equipment, and finally, vibration of rotating machinery can be checked to indicate any potential failure or degradation in the equipment. As discussed above, these sensors can and are being further revolutionized by creating nodes which transmit their information wirelessly. As the next step, energy harvesting capabilities would allow for these nodes to transmit data without the requirement of external power, further enhancing the safety and longevity of the plant.

Important for consideration as well is the longevity of the energy which can be harvested. As discussed in previous sections, wireless sensors attached to either plant power or backup generators can cease to operate if major incidents occur and plant power is lost. Additionally, wireless sensors with batteries may drain quickly post-accident considering consistent monitoring may be needed. On the other hand, even in the event of a shutdown to the main power or back-up generators, the potential thermal energy present in the piping system will be expected to remain for a significant period of time, during which, it would be expected for the temperature gradient to remain [8]. Thus any energy harvester making use of this energy would continue to operate, allowing the wireless sensor to continuously send critical data in accident type situations. This is an incredibly useful

characteristic of thermal energy harvesters, as they can be highly stable, considering large thermal fluctuations take a considerable amount of time. Thus, not only will the temperature gradient be steady and consistent throughout normal operations of the power plant, it would be expected to remain after accidents, making a thermal energy harvester indispensable for a self-powered wireless sensor network.

2.2.2 Vibrating Components

In addition to thermal energy, throughout the process of circulating water and coolant around the plant there are multiple opportunities for vibration to occur, which, in general, is a complete waste of valuable energy. Large equipment such as naturally exhibit vibration during their operation [14,16] and additionally, even piping can vibrate during the process of fluid flow [17,18]. These flow induced vibrations occur many places, including inside the reactor chamber, causing fuel rods to vibrate. Some of this flow vibration has been shown to cause vibration of the containment vessel as flow into and out of the vessel itself can resonate the natural frequency of the structure. Additionally, U-shaped piping within the steam generator can see flow induced flutter due to steam formation. This type of flutter can also occur as steam flows across the condenser section of the tertiary loop. On the other hand, mechanically the largest vibration occurs in the main coolant pump and turbine/generator. The main turbine is isolated from the floor, and thus a large source of vibrational energy [14,16]. Large pumps, however, are the easiest to access, are located near the critical sensors outlined above, and are expected to be routinely checked for damage, and thus seem to provide the best position for an energy harvester.

Pump vibration has been well documented, and much literature is available outlining the operational characteristics of pumps and rotational machinery. As a specific example, as far back as 1997 pump troubleshooting was addressed using vibrational analysis, where Rajesh [19] outlines two case studies of vibration signatures for pumps used in a gas processing complex. More generally, Nelson [20] gives a very nice overview of pump vibration analysis, noting multiple vibration modes associated with operational frequencies which may affect pumps. Additionally, multiple studies have been performed reporting the vibration signatures, and possible failure modes of pumps within nuclear power plants [18,21-24]. Results of these studies show that during operation, pumps exhibit vibration near their operating frequency and at other frequencies dependent on the specific pump and operating characteristics. Many pumps have an operational

frequency between 15 and 60 Hz [16], which is largely dependent on the pump, and environmental characteristics. Naturally, however, these pumps do not have large vibration amplitudes, on the order of 0.0001 ~ 0.001 inches peak to peak [16], meaning harvesting vibration energy can be challenging. While the frequency is high enough, small amplitudes mean small available energies, and amplification of this energy to usable scales is addressed in chapter 4.

Similar to the thermal discussion in the previous section, it is also important to analyze the longevity and condition of vibration throughout the lifetime of the plant and during off normal situations. While thermal energy will remain usable during plant shutdowns, a drawback from using vibrational energy is that once plant operation ceases during an accident or blackout, vibrating machines and fluid flow are both removed. This means that any energy harvester attached to the vibrating source would cease to operate, and continual sensing dependent on vibration would be removed. This said, a benefit for vibrational energy harvesters in the nuclear power plant is the fact that, considering pump and machine maintenance is expected to be performed often, the vibrational source and signature would likely be quite steady during the vast majority of the time when the plant is operational.

2.3 Spent Nuclear Fuel and Dry Cask Storage

Nuclear fuel which has been decommissioned from use within the reactor itself is labeled as spent fuel, and research of this fuel and its storage is of large importance to the nuclear industry as it is still radioactive and quite dangerous to human and environmental interaction [25]. Today, fuel is removed from the reactor typically once being used to a burnup between 35 and 45 GWd/MTU [26]. The trend, however, is to push for higher burnup levels, leading to a need for research into spent fuel storage design and analysis. In fact, thermal analysis of spent nuclear fuel, and the thermal performance of storage containers have been identified as high priority by the DOE Nuclear Energy Division [27] since potential failure mechanisms for the fuel and containments are highly dependent on fuel temperature.

In the industry, upon removal from the reactor, nuclear fuel is first stored in pools of water at least 20 feet deep in order to remove heat from the assemblies and shield workers from gamma radiation left over from the production of radioactive nuclides in power generation [25]. After ~5 years this fuel is then separated and stored in dry storage canisters where it can remain for very long periods of time. According to a report by EPRI [28] (see figure 2.2), there are currently nearly

80,000 MTUs (Metric Tons Uranium) of spent nuclear fuel in storage world wide, with projections to increase to at least 136,600 MTUs by 2060. Currently, approximately 60,000 MTUs of this fuel is stored in wet storage, while 20,000 MTUs are contained within dry cask canisters. Based on these numbers, it is evident that dry storage of nuclear fuel will continue to become increasingly important for consideration by the industry and researchers alike. Canisters which store the fuel should be well designed in order to safely operate for the many years necessary for dry cask storage.

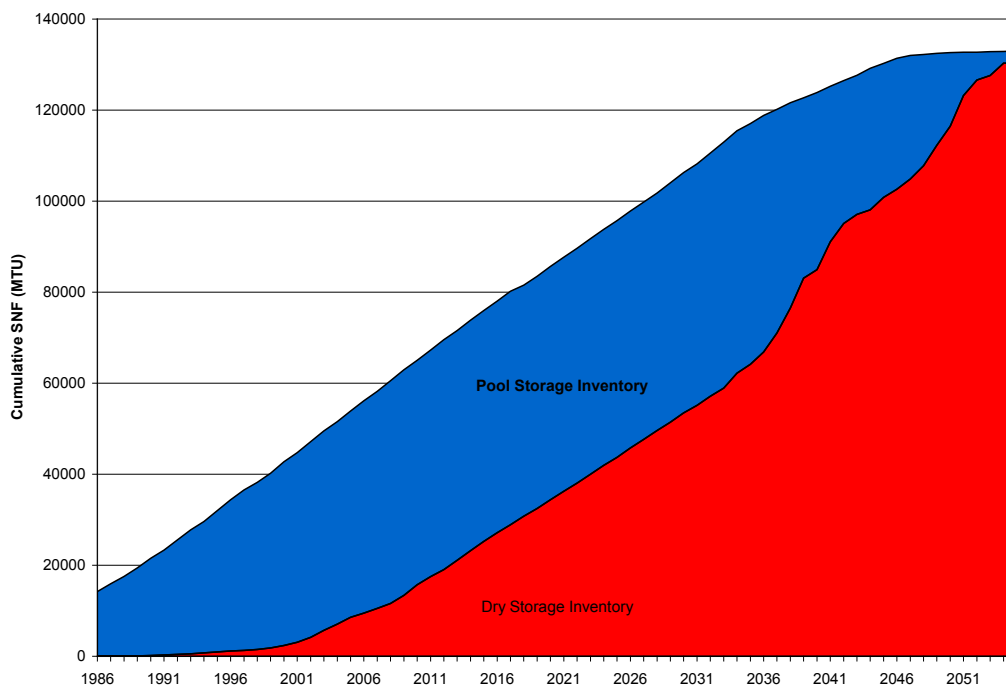


Figure 2.2. Past and future amounts of spent nuclear fuel contained in storage, separated by wet and dry storage [28].

These dry storage canisters are generally made up of two sections, the visible, thick concrete overpack, and the internal, pressurized, steel multi-purpose canister (MPC) housing the fuel itself. The canister considered in this thesis is of a vertical variety, however some models store the fuel in arrays which are distributed horizontally. The MPC in a vertical canister can hold a variety of different fuels and assemblies inside a metal basket, ranging from 24 to 64 assemblies. A fuel assembly is a bundle of fuel rods contained together in a steel housing [14]. The carbon steel inside, and making up the MPC, and the concrete of the overpack are meant to contain the radiation, while

removing heat from the fuel in order to ensure it does not reach a melting point. This work focuses on a specific canister, namely one made by Holtec International [29], depicted in figure 2.3.

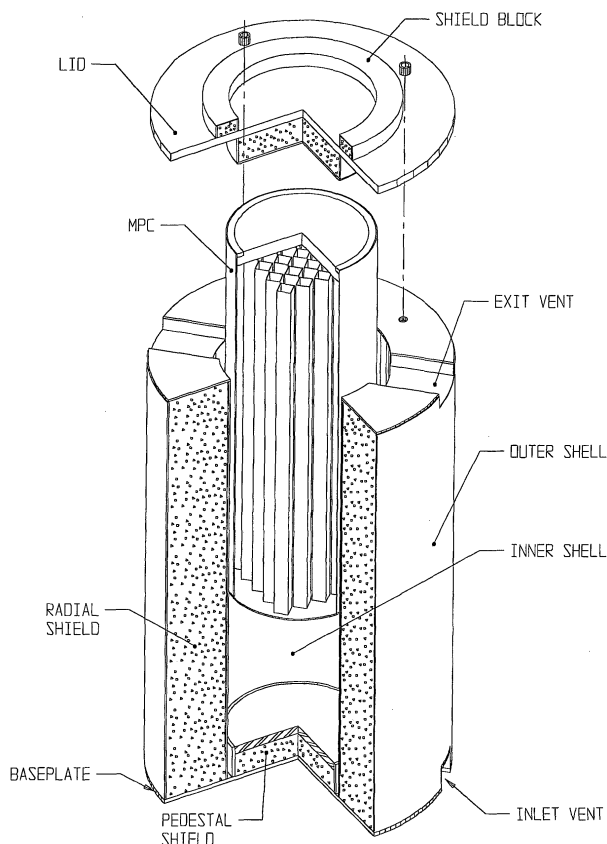


Figure 2.3. Holtec International [29] dry cask canister design. Shown is the overpack, internal MPC, and MPC fuel basket.

Their concrete overpack is made to house the MPC and has inner channels to allow air to flow between the concrete and MPC, cooling the canister. Openings in both the top and bottom of the overpack create a pressure differential, and allow outside air to flow upward through the cask due to the stack effect, (i.e. natural circulation). Inside the MPC, a steel basket holds the assemblies. In this design the steel in the basket is used to conduct heat generated from the fuel outward to the edge of the canister, allowing it to be removed from convection in the aforementioned airflow around the MPC. The canister is also backfilled with helium at 3.3 atm in order to aid in the conduction and convection of heat away from assemblies, and give an inert gas environment.

The Holtec MPC has an outer diameter of 68-3/8 inches, and a height of 190-1/2 inches. The cylinder is approximately 0.5-inch-thick, the inner height top to bottom is approximately 178-5/8

inches, and can hold 24, 32, or 64 fuel assemblies depending on the type of basket and fuel being stored. For typical PWR fuel an MPC-32 is appropriate, which is the basket design is shown below in figure 2.4, and is the design considered by this thesis. The basket walls are 9/32-inch-thick, and each cell is approximately 9.3 x 9.3 inches. The basket has an overall height of 176-1/2 inches, leaving room at the top and bottom of the MPC for helium circulation and support attachments. The concrete overpack is capable of storing any type of MPC as the inner cavity is sized to fit the outside of all three MPC types produced by Holtec. The inner diameter of the overpack shell is 73-1/2 inches, and the height of the inner cavity is 191-1/2 inches. The outer diameter is 132-1/2 inches, and its height is 239-1/2 inches [29].

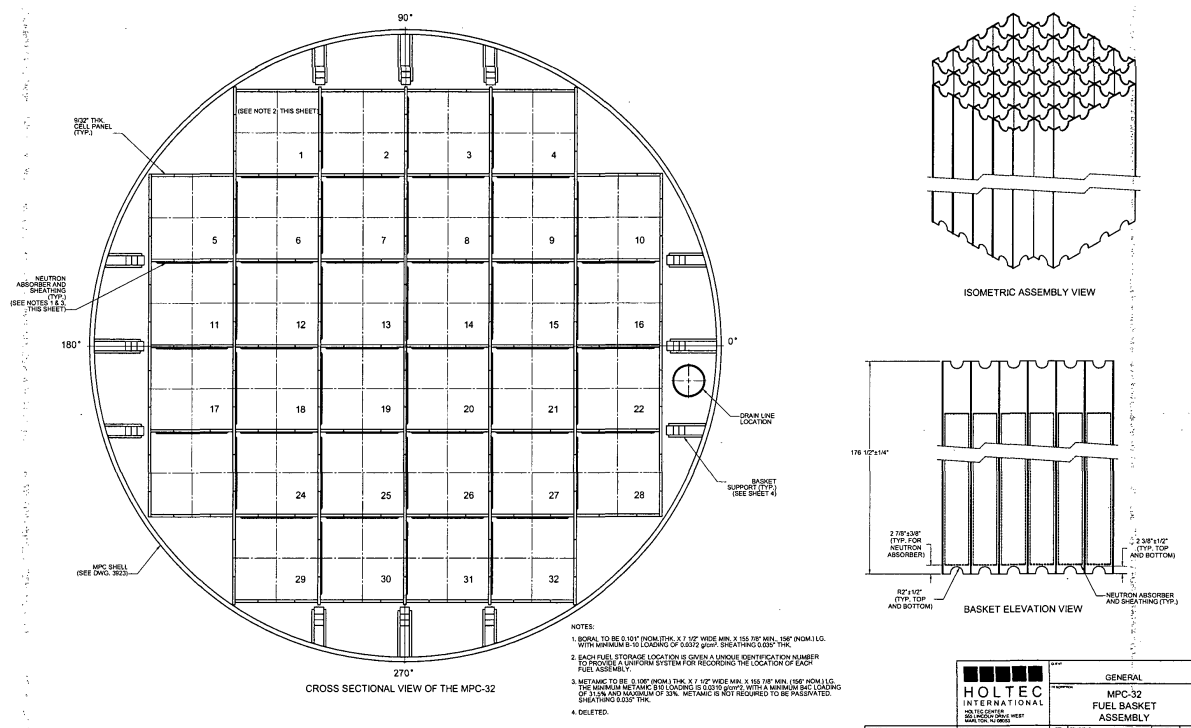


Figure 2.4. Example configuration of an MPC-32 basket to hold PWR fuel assemblies during dry cask storage [29].

Monitoring of conditions within dry casks is of importance, as the temperature of the fuel and humidity within the cask can play an important role in the health of the system, and overall longevity of the storage containers. The USNRC has identified long-term corrosion monitoring, canister integrity, efficiency of radiation absorbers, criticality of fuel control and other conditions as desired monitoring parameters within sealed internals [30]. This offers a unique problem however, as human based monitoring of cask internals can be very difficult, or indeed impossible

due to a real potential for harm from radiation leakage, and for containment rupture. To address this issue, energy harvesting for wireless communication of conditions within canisters is suggested. Wireless communication of data from inside the cask would remove the need for human inspection, and energy harvesting could potentially allow for sensors to run indefinitely. This thesis reports on work done towards the design of a radiation and thermal energy harvester. The main idea is to utilize both the thermal environment along with the gamma radiation present within the dry cask to create a local hot spot in a metal plate through material heating from gamma radiation, and convection from the filling helium for thermal energy harvesting. A hypothesis that gamma heating can be used to power a wireless sensor node is investigated. This is further discussed in chapter 5.

In previous work, Carstens [31] gives a very detailed example of a thermoelectric energy harvester and wireless transmitter for use in a dry cask in his dissertation. In his research a thermal energy harvester was proposed to utilize the temperature gradient between the MPC canister and the airflow around the MPC within the overpack channels. He also outlines a method for wireless transmission of the data outside of the dry cask, and discusses issues with transmitting through concrete. A noted issue with this work however is that it will likely be more useful to monitor information within the MPC, investigating the condition of the fuel itself. In this way conditions directly impacting the spent fuel, and its integrity would be monitored, enabling safety to be ensured. In order to supply energy for a system to work within the MPC, an energy harvesting solution should also be considered for placement within the MPC. Such a system would be able to report, in a self-powered way, information on the fuel and environment within the canister, without the need for operators to endanger themselves to receive the valuable information. Additionally, since it has been shown [32] that any blockage in the air gap could drastically reduce the heat removal performance of the canister, an energy harvester located within the MPC would remove any issues associated with placing materials inside the air gap. Harvesting both thermal and radiation energy from the spent fuel would be ideal for such an energy harvester, considering conditions inside the dry cask.

In regards to the environment within dry casks, much work has already been published regarding their thermal properties. A full list will not be given here, however, recently a few notable works have been done involving CFD analysis of the dry cask studied in this work. Herranz et. al. [32] performed CFD work on a Holtec MPC-32 and overpack system, and provide detailed

analysis of the temperature and flow profiles both within the MPC and in the air gap between the MPC and the overpack. Their main analysis was done on sensitivity of the system to higher or lower heat loads, and blockages within the flow channels. Additionally, Li and Liu [33] have performed CFD analysis on a dry cask canister, and provide much useful information about the temperature and flow distributions within the system. Importantly they also discuss what assumptions have been made in past thermal analyses of canisters, and what assumptions were made by them. Generally, assumptions are made on the total heat load which is present within canisters relying either on old experimental data or estimates based on other simulations, and on the thermal properties of both the helium and fuel.

One of the only reported in-situ experiments done is in a DOE report from 1992 [34] where a performance test was done on a Pacific Sierra nuclear VSC-17 ventilated concrete storage dry cask configured for PWR fuel assemblies. The comprehensive report described details of the fuel assembly type and position, geometry configuration of the cask system, material properties of individual components, and filling gas within the canister. The temperature profiles on the MPC, concrete, air channel surfaces, and fuel canister guide tubes were described in detail, which provided precious data for validation of simulation results. Other experimental work has been done on both full scale and scaled down cask systems with the fuel simulated by electrical heating [35,36]. This said, expansive experimental analysis has not been found to be performed on current installations of dry cask storage with higher burnup, more modern fuel, and much design has relied on simulation results.

Considering much of this simulation work on analysis of dry cask storage has been performed for the purpose of certification, analysis on the radiation from spent fuel is mainly concentrated on the presence and make up of the radiation outside of a dry cask in regards to the dosage which may be received by individuals standing near the overpack. Shultis [37] reported in 2000 on an MCNP calculation of a dry cask with detailed analysis done on the canister and the gamma radiation present outside of the cask. This report, however does not simulate the internals of the canister, opting instead to use experimental analysis taken from reports provided by Transnuclear on their TN-68 cask on the amount of gamma radiation expected to be present from the fuel itself, and generated from neutron activation in the basket and top fittings. Additionally, even very recent works are mainly concerned with providing more appropriate shielding in dry cask storage. As an example from early 2017, Waly et. al. [38] report on work done investigating the impact of

specialty glass use for radiation shielding in a dry cask. In their analysis, they simply assume a uniform cylindrical source of gamma radiation within the MPC, disregarding any attenuation of gamma and neutron radiation by materials within the dry cask itself. Their analysis certainly may be useful for certification purposes as it provides an upper bound on the gamma radiation leakage from the cask, however will not provide more than a rough estimate for the true gamma density and energy distribution at locations within the cask. In fact, the same assumption is made by Carstens [31], who also considers gamma heating of his TEG module and materials used in the design, however, his analysis likely overestimates the gamma heating, as much of the gamma radiation is expected to be absorbed either by the rest of the fuel, or the basket within the dry cask before impinging on a device inside, or outside the MPC. No work has been found specifically addressing gamma radiation density within the dry cask itself, and the effect on other materials in the cask. To address this and other issues listed above along with the need to study a self-powered wireless sensor platform within dry casks, this thesis shows work done investigating both the thermal and radiation environment present within the MPC canister in order to guide the design of an energy harvester and wireless sensor system.

2.4 Summary

A background on the use of wireless sensor nodes within both industrial complexes and nuclear power plants has been given. Many researchers have argued that wirelessly transmitting sensor nodes can increase the reliability and safety of plant operations by allowing for continuous, real time monitoring of critical plant conditions. Furthermore, these sensors can be revolutionized through the use of energy harvesting, enabling them to work without the need for external power, removing power cables and batteries, and giving the potential for operation during off normal events. A brief background on energy harvesting was given, along with the few works found specifically addressing energy harvesting within nuclear environments. Next, an overview of the components and processes present in a nuclear power plant was discussed, and potential places for energy harvesting were investigated, including both thermal and vibrational. Finally, a background on the dry storage of spent nuclear fuel was given, and the design and parameters of a nuclear fuel canister are outlined. Modeling of spent fuel canisters has been performed previously, however, as outlined in this section has been largely used for certification purposes, meaning a more thorough investigation of the environment inside the dry canisters is necessary in order to guide the

development of an energy harvester. From the information given in this section it is intended for this thesis to build an argument and potential solution for the use of energy harvesting throughout the nuclear power process, intended to improve the safety and reliability of nuclear power plants.

3 Thermal Energy Harvesting from Nuclear Power Plant Piping

3.1 Energy Harvester Design

3.1.1 Thermoelectric Modules

Based on the discussion in 2.2 in the previous section, it would be advantageous to use the wasted heat from the high temperature primary and secondary loop pipelines. Considering it is estimated that a temperature difference of up to 260 °C may be present between the piping and the ambient air, a Thermoelectric Generator (TEG) system is ideal for such a use. Thermoelectric Modules (TEMs) as are used in TEGs are solid state devices which generate an electrical current when a temperature difference is applied across the two sides. They are made up of N, and P-Type semiconductor materials which display a property called the Seebeck Effect, named after German scientist Thomas Johann Seebeck who first discovered it in the early 1820's, when he found that two dissimilar metals at different temperatures would deflect a compass, indicating the presence of a current [39]. Due to the atomic lattice structure of the semiconductor materials, a temperature difference causes electrons in the N-Type semiconductors, and holes (absence of electrons) in the P-Type to be driven across the material, effectively creating an electrical current. A TEM is made up of many pairs of N-P legs, shown below in figure 3.1 [40], placed electrically in series and thermally in parallel. The Seebeck coefficient, a parameter describing this effect, is a measure of the voltage potential created across a TEM for a given temperature difference, or $\alpha = \frac{\Delta V}{\Delta T}$. A temperature difference drives a current across the two legs creating a voltage potential difference across conductors placed on either side of the semiconductor material. As is evident from this simple equation, increased temperature differences lead to more power generated. This makes them ideal for application within nuclear power plants because of the large temperature differences between coolant loop piping and the ambient air. Additionally, because of their long lifespan, quiet nature, and ease of use, TEGs are perfect for harvesting wasted thermal energy in low maintenance situations, such as would be desired in a nuclear power plant wireless sensor node arrangement.

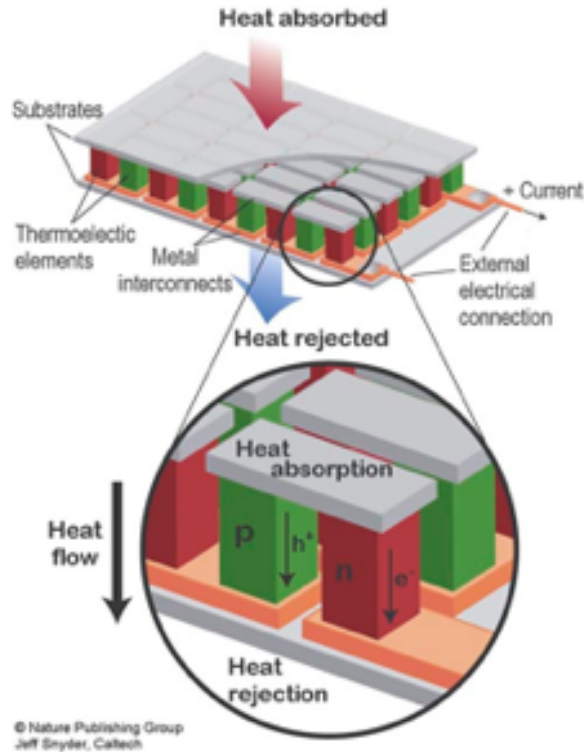


Figure 3.1. P and N-Type semiconductor legs of a TEM [40].

3.1.2 Thermoelectric Generator Design

Two places of significant wasted thermal energy occur within the nuclear power plant coolant loops, each of different temperature, and thus two separate energy harvesters are considered in this chapter. The first harvester is designed for use in the secondary coolant loop responsible for transferring steam to the turbines where temperatures generally fall between ~ 200 °C and ~ 275 °C [14]. Much of the design work for this harvester was performed by Jie Chen in a previous work and is described extensively in his thesis [41] and thus the design will only be outlined here for reference and clarity, and details will be left to his thesis. Based off of this design, a second harvester is made and outlined in section 3.4 in order to be used within the primary coolant loop, where pressurized water is drawn through the fuel and into steam generators. Temperatures here can be much higher, up to ~ 320 °C. For this reason, the first design will from here on be referred to as the lower temperature design, and the second harvester, re-design, as the high temperature design.

The premise of the design for a thermal energy harvester in the power plant piping is shown in figure 3.2, which shows the energy harvester adapted onto a nuclear pipeline. Overall, the lower temperature design uses two thermoelectric modules, two aluminum heat sinks, an adaptor, and a heat pipe.

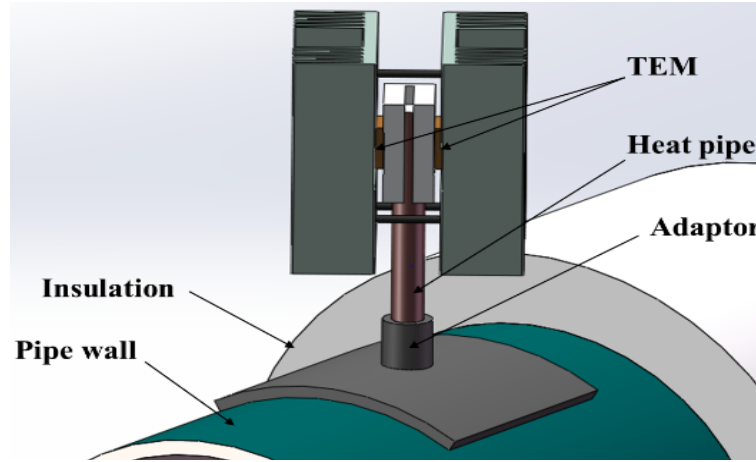


Figure 3.2. Design premise and placement of the thermal energy harvester for high temperature piping.

Considering pipelines have thick insulation layers, as illustrated in Figure 3.2, the system integrates a heat pipe in order to efficiently conduct excess heat from the high temperature pipelines to thermoelectric modules. In such a design, the entire working module can be placed outside the thermal insulation for ease of access and maintenance. Heat pipes contain an operational liquid, which evaporates once heat is applied, causing gas to flow along the pipe to the condenser region. Upon being cooled, the gas condenses back to liquid form, returning to the evaporator region along a wick. Due to the use of the phase change from liquid to vapor during heat transfer it is a very efficient, low resistance method for transferring heat from one location to another. The heat pipe used in this design is a copper wicked heat pipe using water as a working fluid. It has a diameter of 19.05 mm (0.75 inches), a length of 200 mm (7.87 inches), and a designed maximum temperature of 315 °C (600 °F). This maximum temperature, however, is not recommended for sustained use, thus this heat pipe is ideal for the desired lower temperature range of ~250 °C on the secondary loop coolant piping. The TEMs used are two Bi₂Te₃ HZ 2 modules from Hi-Z technologies, each having a surface area of 8.41 cm². They are 0.518 cm thick, and have 97 P/N-type couples. Reported values for the TEMs thermal conductivity and heat flux are 0.024 W/(cm*K) and 9.54 W/cm² respectively during a temperature difference of 200 °C. [42]. To

further utilize the space, the TEMs and heat sinks are integrated symmetrically on both sides of an adaptor which can be self-clamped using three through bolts connected to the two heat sinks. Each heat sink has an overall size of 125 mm (width) $\times$ 150 mm (length) $\times$ 49 mm (height), a fin height of 41 mm, and an average fin space of 5.5 mm. 1/3 of the fins at the center were removed to make room for connection bolts. This prototype, seen in the following figure 3.3 was built and tested in lab, and its performance can be seen below in figure 3.5 in section 3.3. The piping “source” temperature is simulated using a copper heater block which holds a cartridge heater. This can be seen below the harvester with insulation surrounding it, along with thermocouple wires and the PID controller from Omega.

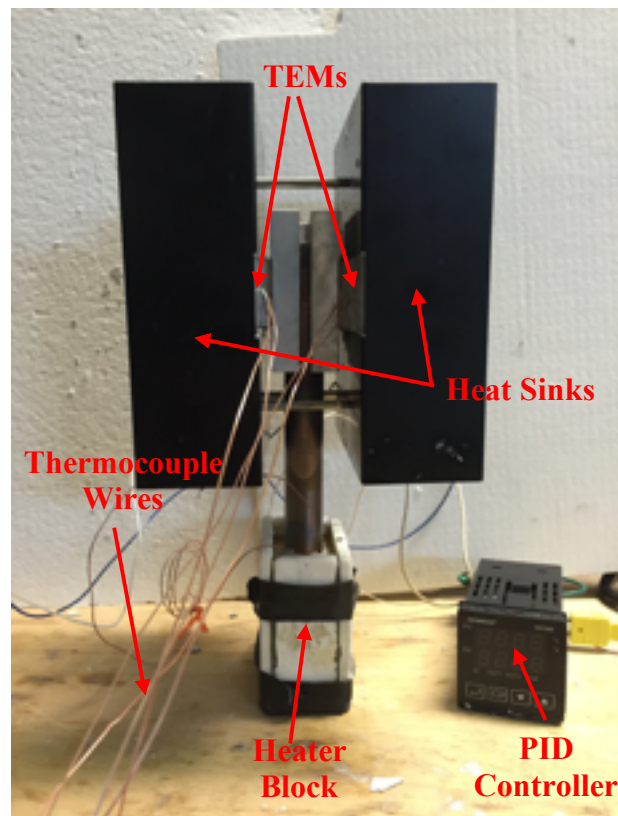


Figure 3.3. Photograph of the lower temperature prototype along with the PID controller and heater.

3.2 Radiation Test

An important consideration for any energy harvester within a nuclear power plant is the level of radiation it will encounter during operation. An effective self-powered wireless sensor must have the ability to operate in an ionizing radiation environment in order to be implemented within a nuclear power plant, considering radiation will be continually present both during normal, and off normal conditions. Table 3.1 below shows an estimate of the dosage levels within both the primary and secondary containment centers as investigated by ORNL [8].

Table 3.1. Estimated radiation data for both the primary and secondary containment centers under various situations [8].

Operation Scenario	Primary Containment		Secondary Containment	
	Gamma Radiation [Gy/h]	Neutron Radiation [$\text{cm}^{-2}\text{s}^{-1}$]	Gamma Radiation [Gy/h]	Neutron Radiation [$\text{cm}^{-2}\text{s}^{-1}$]
Normal Operations	0.2	6.0×10^4	0.02	Low
Shutdown, Pumps Operating	0.2	Low	0.02	Low
Cladding, RPV, and Pipe rupture	2.0×10^5	Low	2.0×10^3	Low
6 month integrated dose after disaster	3.0×10^6	NA	6.0×10^5	NA

It is important that a thermal energy harvester can be functional both during normal operations, but also during off normal situations such as might be present after a natural disaster. Sensing would be of utmost importance during a potential plant containment failure, and in the event of a pressure vessel rupture, gamma and neutron radiation may be abnormally high. As estimated above in table 3.1, an energy harvester with a 20-year lifetime may see between 3.5 and 35 kGy of gamma radiation under normal operations depending on its location in the plant. This dose would be even larger after a disaster type situation. Thus, appropriately, the above energy harvester was tested for its hardening to this level of radiation.

In order to experimentally examine the performance of the TEMs and the overall TEG based energy harvester while in a gamma radiation rich environment, an intense gamma exposure experiment was performed within a radiation test chamber provided by Westinghouse Electric Company in Pittsburgh. The experiment was designed to provide close to 200 kGy radiation, a

long lifetime under normal situations, and the total accumulated dose at 100 hours after a disaster [8]. The lower temperature design was set up to run in the same manner as was done during the initial lab based tests so as to compare results with those seen in the lab. The process was as follows: The harvester was heated periodically by a 200 Watt cartridge heater from OMEGA Engineering controlled through a CN7800 series PID controller also from OMEGA Engineering. Temperature recordings were taken of the hot and cold side of both TEG modules, and the heater source using Type-K thermocouples from OMEGA Engineering. These thermocouple measurements were measured through a Thermocouple Data Acquisition unit from National Instruments and recorded along with the open circuit voltage of the two TEMs using Labview on a laptop computer. Measurements were made every 10 seconds. By setting the source temperature range to oscillate between $\sim 30^{\circ}\text{C}$ and $\sim 250^{\circ}\text{C}$ the performance of the system could be analyzed for differing source temperatures throughout irradiation giving valuable data on the impact of both temperature and radiation on such a device. The source heater was set to increase in 10°C increments every 10 minutes, during which the temperature controller heated to the next step for 8 minutes, and then maintained temperature for 2 minutes. This resulted in an even, slow heating cycle.

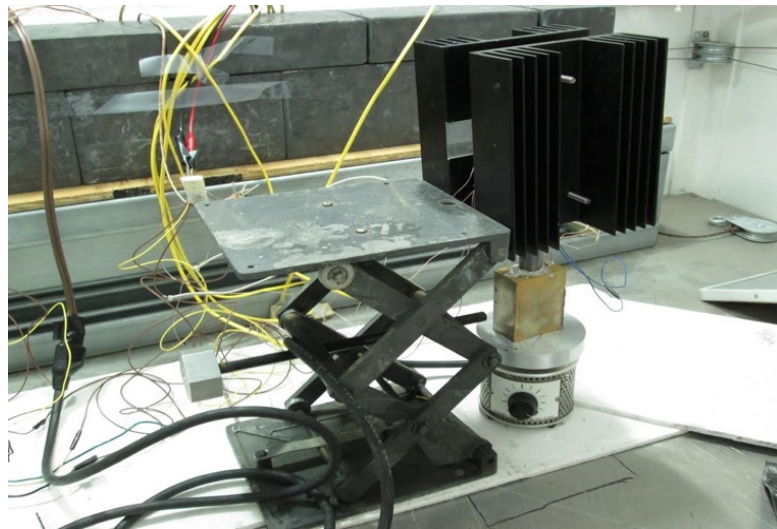


Figure 3.4. Radiation test setup at Westinghouse. A poker chip Co-60 gamma source was placed on the scissor jack to apply gamma radiation to the system.

To apply gamma radiation to the TEG a cylindrical Co-60 gamma radiation source with a diameter of ~ 5 cm was placed on a lifting jack plate adjacent to the generator. The energy harvester prototype was placed at a certain distance from the gamma radiation source as shown in figure 3.4

so that the total accumulated dose after the test would be $200 \text{ kGy} \pm 10\%$. Thermocouple and voltage wires were run through the wall of the containment cell and were connected to the DAQs and a laptop outside the chamber. The TEG setup at the center of the modules saw an average dose rate of $390 \pm 10\% \text{ Gy/hr}$.

It should be noted that after approximately 20 kGy of radiation was applied to the system the cartridge heater designed to apply the source temperature to the system failed. The lab management at Westinghouse removed the system from radiation until another heater could be secured. This heater can be seen in figure 3.4 and was significantly less efficient at heating the system than the designed heat source, and did not heat the system to the same temperature as the original cartridge heater. This can be seen in the results, when the temperature profiles reduce to lower peak temperatures. Even in light of this unfortunate mishap, testing was continued on the system to realize the full 200 kGy of radiation. Results of the experiment are discussed in the following section.

3.3 Harvester Performance During Radiation

As noted above, throughout the radiation experiment both the voltage output of the energy harvester and important temperature readings were measured. The major results of the experiment are shown in figure 3.5 where multiple lines are plotted for a given level of radiation to the system to demonstrate performance throughout the radiation. Shown is the performance before radiation, and then incrementally throughout to just before 200 kGy, thus the performance of the harvester can be tracked. The open circuit voltage of the generator in terms of source temperature is shown in figure 3.5 (a). This represents the voltage performance of the entire system. Figure 3.5 (b) shows the voltage output of both the TEMs in terms of the temperature difference across them, thus the slope of each line is the combined Seebeck coefficient. Figure 3.5 (c) shows the temperature drop across the TEMs as a function of their hot side temperature, which is a representation of the thermal resistance. Finally, Figure 3.5 (d) shows the hot side temperature as a function of the source temperature, demonstrating the performance of the heat pipe throughout irradiation.

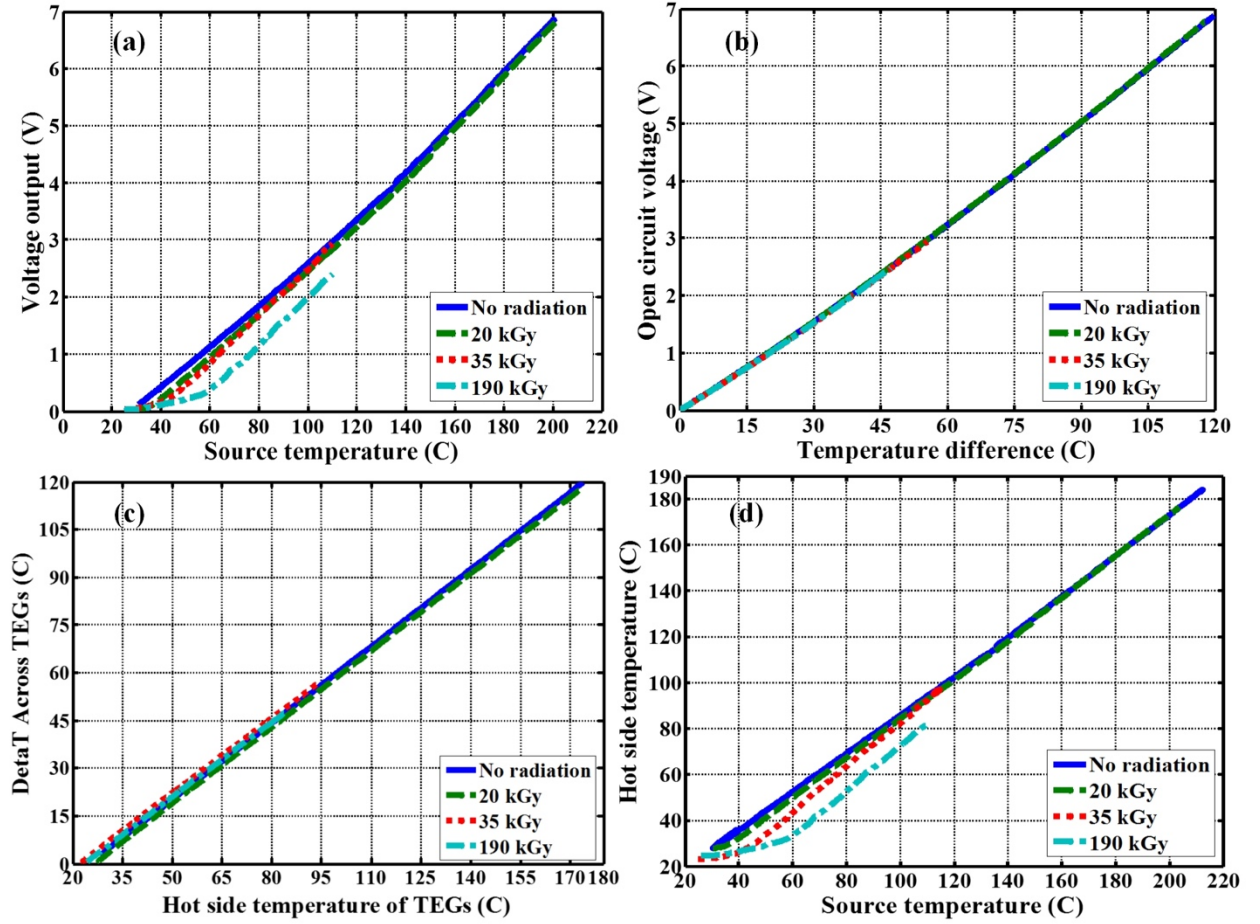


Figure 3.5. System outputs before and during gamma radiation. (a) Overall system performance shown by the open circuit voltage as a function of source temperature. (b) Open circuit voltage as a function of the temperature difference across the TEMs. Slope of each line is the Seebeck coefficient of the TEM. (c) Temperature difference across the TEMs as a function of their hot side temperature which represents TEM thermal resistance. (d) Hot side temperature of the TEMs as a function of source temperature which indicates performance of the heat pipe.

A decreasing trend is seen in figure 3.5 (a), the voltage output (thus the system performance) reduces by up to 20% after 190 kGy of radiation. This means that some aspect of the system was impacted by the gamma radiation. In order to investigate this further, shown in figure 3.5 (b-d) are other system characteristics as mentioned above.

As discussed earlier in 3.1.1, the open circuit voltage of a TEM is created by a material property called the Seebeck coefficient, which measures the potential of an induced voltage in response to a temperature difference across the material. Since thermoelectric modules depend on semiconductor materials which are generally impacted heavily by ionizing radiation, an initial guess for the decrease in overall system performance might be a negative impact on the TEM modules and their Seebeck coefficient. However, the coefficient α , shown graphically in figure 3.5 (b) as the slope of each line, does not change with applied gamma radiation, and as such, it is evident the thermoelectric modules' Seebeck coefficients were not impacted by gamma radiation up to 200 kGy.

Another possible contribution to the loss in output voltage may be an impact to the thermal resistivity of the thermoelectric materials. As TEMs operate under a given temperature difference, any reduction in their thermal resistance would result in a reduction of output voltage as the temperature difference would drop. Evidence [43,44], however, has already shown that gamma radiation has little effect on the thermal resistance of Bi₂Te₃. As a confirmation, shown in figure 3.5 (c) is the temperature difference across the TEGs as a function of the hot side temperature, which reflects the average thermal resistance of both TEMs. As can be seen throughout the test, the thermal resistance changed very little during ionizing radiation.

Thus, by eliminating the possible degradation of the TEG modules as the reason for a reduction in output voltage, the only remaining explanation for the system voltage drop is an impact to the heat pipe performance. To date there is very limited research work looking into the impact of gamma radiation on heat pipes, due in part to varying possibilities of working fluids and wick types. Sanzi et. al [45] found that gamma radiation impacted heat pipes similar to the one used in this system, and states that it was likely caused by radiation separated oxygen and hydrogen. As this occurs, a non-condensable hydrogen gas builds up in the heat pipe condenser section, reducing the heat transfer capability due to reduced condenser surface area. Singh et. al [46] did experiments on heat pipe performance with non-condensable gas present, and found that

it impacted the startup time of their heat pipe when heating from cold creating a hysteresis. This is further confirmed in by Hijikata et. al [47]. A similar outcome is seen in this system, shown in figure 3.5 (d) is the hot side temperature of the TEG compared to the source temperature, which indicates the performance of the heat pipe. Indeed, a temperature hysteresis during cold start much like that outlined by Singh and Hijikata [46,47] is seen, indicating that a similar non-condensable hydrogen gas buildup due to radiolysis has likely occurred. Since the heat pipe supplies heat to the TEG, any reduction in heat transfer capability is expected to negatively impact the overall system performance. Appropriately, the trend seen in the low source-temperature region matches closely that seen in the voltage output in the same region, explaining the reduction in voltage for the system. It is, for these reasons therefore concluded that the reduction in system output voltage is attributed to gamma radiation induced radiolysis of water within the heat pipe leading to the formation of non-condensable hydrogen. This effect is seen to trend directly with larger gamma radiation doses, indicating that system output will further be reduced with increased radiation dosage due to increased impact on the heat pipe. This said, as can be seen at 20 and 35 kGy, the effect is largely reduced once operating temperature is reached. It is hypothesized that this is attributed to the reduction in size of the pocket of hydrogen due to the increased heat and pressure load at higher source temperatures. This would increase the heat transfer capability of the heat pipe allowing for the temperature of the hot side of the TEMs to reach normal temperatures. Thus, it can be reasoned that even after high levels of radiation, the system would only have a degradation in power output during cold starts, which would rarely occur, as plant operation, and fluid flow within the plant is ideally uninterrupted very long periods of time.

Thus, it can be concluded from this test that in general a TEM based TEG system can withstand large integrated doses of ionizing radiation as would be present for such a system operating in a nuclear power plant. This is an important result, as it shows the feasibility of using a TEG and TEM system to power self-powered sensors within nuclear power plants. The level of radiation encountered by this device was representative of the dose after a very long service lifetime within the containment centers of the nuclear power plant, and for days after an accident situation. Such a system then would be an ideal candidate for powering wireless sensors which can operate even during off normal situations when traditional sensors may fail to respond.

3.4 High Temperature Prototype

Based on the promising ability of the lower temperature design in powering wireless sensor nodes, and surviving in a radiation rich environment, it was of interest to change the design to provide an option to implement the device on primary loop pipelines. As discussed earlier in section 2.2.1, the temperature of these pipelines may be as high as 290~330 °C, thus the above design must be changed since the copper-water heat pipe has a designed maximum temperature of 315°C and desired temperature range of ~250°C. Unfortunately, the target temperature range is what is known as the intermediate range for heat pipes and is an area of active research, but few commercially available products. Above approximately 250 °C, the vapor pressure of water based copper heat pipes increases significantly, leading to poor performance, and reduced lifetime of the heat pipe [48]. After approximately 400 °C, the use of Potassium or Sodium as working fluids is widely used, and extremely high temperature heat pipes can make use of liquid metal. A study performed by Anderson [49] suggests the use of mercury and stainless steel for intermediate temperature ranges, however the research has shown that this combination has not yet been found to be stable for extended use, and companies are hesitant to produce such modules because of the danger to the environment posed by mercury. The study also found that research into organic fluids may produce promising results, however adequate experimentation is still lacking. Because of this, the decision was made to investigate moving the TEM to rest directly on the pipe line, and move the heat pipe to integrate directly into the heat sink. This was reasoned due to the temperature seen at the cold side of the TEM modules during tests at operating temperature, which was closer to the 200 °C operational temperature of the heat pipe. As a result of the move of the TEM and increased temperature, a change to the module must also be made, as the previous modules used were designed to work in a lower temperature. PbTe is generally used for higher temperature locations, however, in the event that temperature drops slightly, its efficiency quickly reduces, as has been shown by Minnich et. al [50].

Figure 3.6 below presents this updated design, in which all the components in the first design have remained the same, except the heat pipe is moved to the cold end of the TEM and a higher-temperature PbTe-Bi₂Te₃ module with a size of 5.6 cm × 5.6 cm was placed directly on the heater source (simulation of the primary loop piping) via an adaptor. Such a design allows the same copper-water heat pipe to be used to cool the TEM, maintaining cold side temperature, instead of

increasing the hot side temperature. Additionally, the use of a commercially available hybrid PbTe-Bi₂Te₃ module allows for fluctuation in source temperature to occur without a drop in the generator efficiency leading to a drop in voltage output. In lower temperatures, the Bi₂Te₃ section of the module performs well, and when the temperature is high, as would be expected generally during operation, the PbTe allows for increased voltage output and survivability. By simply moving the position of the heat pipe, the system can be integrated in higher temperature locations throughout the nuclear power plant, such as the primary loop coolant pipeline.

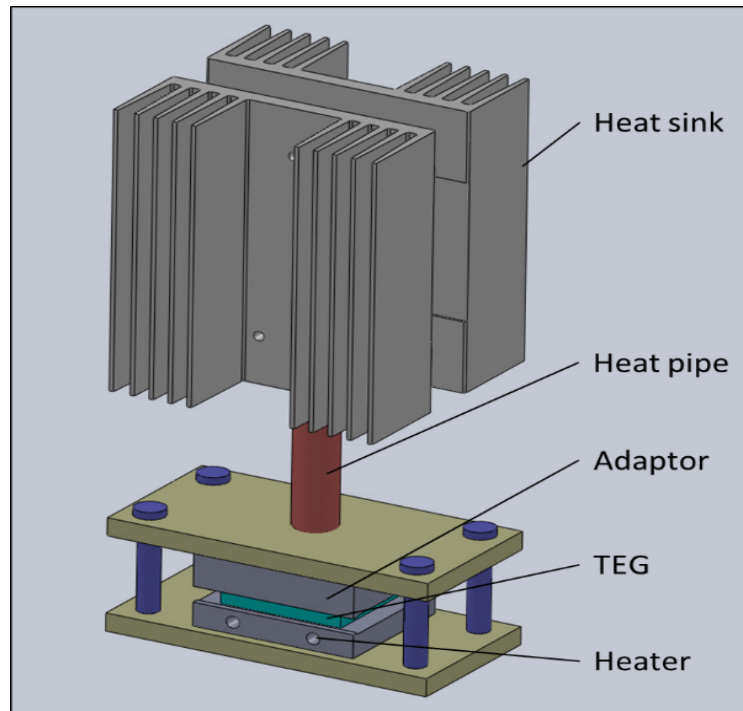


Figure 3.6. CAD design of the higher temperature prototype and test setup. The heater is a simulation of the high temperature pipeline.

3.4.1 Lab Test and Results

Lab based testing was done on the high temperature prototype. The experimental setup and test were exactly the same as used in the lower temperature design. The PbTe and Bi₂Te₃ hybrid TEG module was directly attached to the surface of a copper heat source and the heat pipe integrated heat sink was adapted the cold side of the TEM. Heat was applied to the copper heater in the same fashion as was done with the lower temperature prototype, a 200 Watt cartridge heater was controlled using a PID controller, and temperature was increased by 10°C every 10 minutes up to a maximum source temperature of 340 °C. Temperature recordings were again made of the hot and cold side of the single TEM along with the source temperature, and the voltage output of

the TEM was monitored. All data was collected via DAQs and recorded every 10 seconds using Labview on a laptop computer. For a discussion on the specific components please see section 3.2 above. Shown below in figure 3.7 is the matched load voltage and power output of the harvester over a wide range of source temperatures. The ambient temperature was approximately 20 °C.

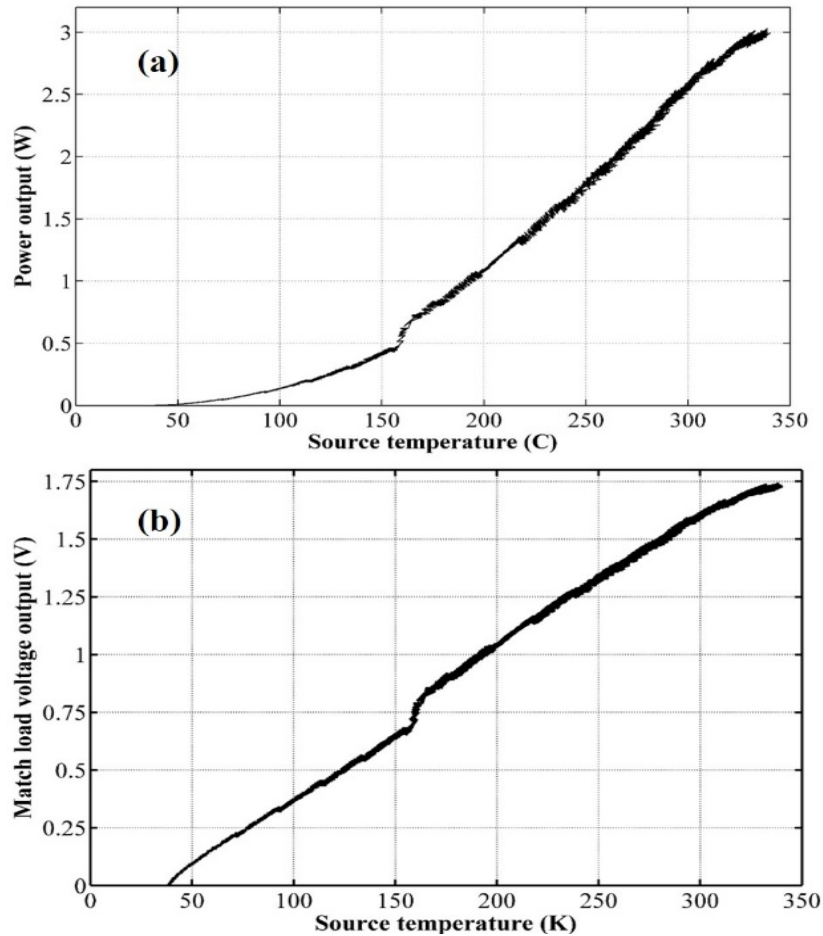


Figure 3.7. Matched load power (a) and voltage (b) of the high temperature prototype harvester.

To provide a matched load, a resistor of 1 ohm was used, which is the same as the internal resistance of the TEM. Voltage drop across the resistor was measured, and the power was calculated from this value and the resistance. As can be seen above, the maximum matched load voltage output and power output of the system was 1.72 V and 3.0 W, respectively at a source temperature of 340 °C. At a working temperature of 320 °C (in the coolant loop, after exiting the reactor), this prototype could output close to 1.7 V and 2.7 Watts at matched load, and at a working temperature of 290 °C (prior to entrance to the reactor), an output of 1.5 V and 2.5 Watts is achievable. It should be noted that these results were taken from an environmental temperature of

20 °C, the actual power output may be lower, as the environmental temperature in the nuclear power plant could be as high as 60 °C.

Evidentially, both the low temperature, and high temperature designs can provide more than enough power to run a wireless sensor node. In fact, considering only approximately 16 mW may be sufficient [8], this energy harvester could additionally charge a battery which can be used for other sensors or actuators at a later time, or may power a wide array of sensors throughout the power plant. A re-design may be considered which removes the use of a heat pipe, considering they have been shown to react negatively to gamma radiation, however, the influence is largely unseen before very large gamma fluences have been applied. As was shown above, even after 200 kGy of gamma radiation from Co-60, equivalent to many years of service, or 100 days after a containment rupture, the heat pipe can still work appropriately well at operational temperatures.

3.5 Summary

The objective of this chapter was to show the feasibility of using a thermoelectric based energy harvester within a nuclear power plant to power wireless sensors near the reactor itself, or within the coolant loop sections. Discussion has been made outlining the reasoning for utilizing a TEG harvester based on the temperature characteristics of the pipeline and the ambient air. A brief outline of a previously designed energy harvester for use on secondary loop piping utilizing a heat pipe, two TEMs, and two heat sinks has been made. Based on the requirement for survivability within a radiation environment, this energy harvester has been tested in a 200 kGy gamma radiation environment and the impact is discussed. The results of the radiation test have shown that while the heat pipe used in the harvester was impacted due to radiolysis, this harvester can survive and continue to operate in up to 200 kGy gamma radiation, equivalent to many years operating in a containment center, and 100 hours after a containment rupture and disaster. Finally, a second energy harvester has been produced and tested which can be used in the primary coolant loop. Higher temperatures in this loop meant a re-design was needed which involved replacing the TEM, moving it to connect directly with the high temperature source, and integrating the heat pipe into the heat sink. Power output of this new device was well over the required range. Based on these results it can be seen on comparing the voltage and power output of these harvesters to the stated power requirement in chapter 2 that energy harvesting for wireless sensor nodes is entirely achievable using heat wasted on the primary and secondary loop piping.

4 Vibration Energy Harvesting from Large Nuclear Power Plant Machinery

4.1 Vibration Signature and Transducer Selection

When considering the multiple available vibration sources within a nuclear power plant as outlined in section 2.3 it was evident that main coolant pump vibration should be targeted for harvesting to supplement the thermal harvester presented in the previous chapter. This is because of its proximity to the sensors which this project is targeting to power, and its size and relative ease of access. Many of the other vibrating sources are located within the internals of either the steam generator or the reactor housing itself, and are difficult to locate and harvest. Additionally, by targeting the pump vibration this design can also be made broad reaching, as such large rotating machinery is present throughout a multitude of industries, not just within nuclear power plants.

As discussed earlier, the signatures of these pumps and of the main turbine block include relatively steady vibration sources, a good choice for a vibration harvester as it's goal is to provide continuous power to either a rechargeable battery or directly to a wireless sensor node itself. Another characteristic is the vibration frequency, which is generally associated with the operational frequency of the pump. These frequencies change depending on the specific pump, however, as was discussed earlier typically lie within the range of 15 ~ 60 Hz for the dominant vibration mode. Lastly, and most importantly, while the machine is large the vibration amplitude can be quite small, on the order of 0.001 inches.

Small amplitude vibration indicates that, while the frequency is high enough to be harvested, the overall vibrational velocity of the machine itself can be quite small since velocity and amplitude are related only by a factor of angular frequency. Harvesters for this type of vibration, and indeed for many machine vibration applications, are usually made of piezoelectric materials. This is likely because of their ease of application and harvester design, classically being used with proof mass and beam bending architectures. One problem with using piezoelectric materials for this application is their inherently high natural frequency. As they are generally quite stiff, their frequency of operation requires a higher source frequency in order to operate at the maximum power potential point. Their uses can be limited as well, as harvester power outputs are generally quite low, in the micro watt range. These issues have recently been addressed using amplification

techniques which not only reduce the natural frequency of the piezo based harvester, but also increase the force or stroke applied to the piezo material, increasing its power output capabilities [51,52]. While these advances are promising, a significant issue remains that piezoelectric materials are quite expensive, and generally do not scale well, meaning they are difficult to use once past a certain size and power threshold. Finally, an issue important to this thesis is their survivability in a radiation rich environment. Gamma radiation, and to some extent, neutron radiation are both present within the nuclear power plant as was discussed in chapter 3. Piezoelectric materials have been shown to be negatively effected by both gamma radiation and neutrons [53-55]. Their crystal structure, and electronic makeup can be shifted, or disorganized by the introduction of ionizing radiation, causing their output voltage to drop due to a change in material properties. As such, a piezoelectric solution was deemed inappropriate for this project.

Another approach to the solution is to utilize an electromagnetic based design. This was the one used because of its ability to perform well in the environmental circumstances. First, the vibration frequency of pumps within the power plant is in a range typically suitable for electromagnetic harvesters. Second, due to their potential for scalability, the power output could be ramped up to suit the needs of a particular project. Finally, the only potential impact to an electromagnetic based design from ionizing radiation could be an influence to the magnetic field strength within the magnet array. It has been shown that the performance of rare earth magnets (as are used in an electromagnetic generator) is not impacted from gamma radiation [56], and is largely resistant to neutron fluences below 10^{18} n/cm² [57], much larger than the expected level in the nuclear power plant even after many years in service, as seen in table 3.1 in the previous chapter.

4.2 Harvester Design

Considering the characteristics of an electromagnetic generator, the vibration signature of the machine vibration was analyzed. It was known that small amplitude vibration would be, and has been difficult to utilize using electromagnetic based designs. This is largely due to the fact that the velocity supplied by small amplitude vibration signatures can be quite small depending on the frequency of operation. This impacts an electromagnetic generator, as their voltage output is directly dependent on the relative velocity of the generator coils and magnet, i.e. $V \propto Blv$ where B is the magnetic field through which a coil of length l moves at a velocity v. Thus, to utilize a small vibration amplitude, and thus small velocity vibration, a harvesting solution must increase

either the magnetic field strength, the length of wire vibrating within that field, or the relative velocity between the magnets and coils.

This design aimed to increase both the magnetic field strength and relative velocity. The approach was to simply and effectively amplify the velocity of the magnet and coil over that which is produced by the vibrating machinery itself, while also maximizing the magnetic field strength across the coils. This was accomplished in two manners. First, a unique electromagnetic generator was fabricated taking into consideration the expected small vibration amplitudes, and the position of the coil within a magnetic field. The generator takes advantage of geometry and magnetic field lines to increase the magnetic field over that from typical architectures. Secondly, to amplify the relative velocity between the coil and magnet array of the generator, a frame is designed which uses both the motion of a proof mass/spring system, and geometry to amplify velocity. This frame is a spring steel compliant mechanism which houses both the electrical generator, and a proof mass. The operating principle rests in both the harmonic motion of the proof mass, induced from base machine vibration and spring/mass/damper dynamics, and the geometry of the frame which translates an amplification in the proof mass motion to the relative motion of the two sides of the generator. To aid in visibility of the working principle and outline of the harvester, figure 4.1 presented below shows the full harvester along with a depiction of it's operation.

A proof mass is affixed to the top mounting bar of the frame using a threaded bolt and a threaded mass. A magnetic array (described below in 4.2.2) is bolted onto one side of the frame, and a coil tube is bolted onto the opposite side which can slide over the magnet sections in the array. Mounting holes for the two halves of the generator are oversized in order to allow for adjustment of the coil and the magnet array position relative to each other. As is known from vibration studies, a system with multiple masses will have multiple natural frequencies. Since the coil tube, 13g, and the magnet array, 85g are not the same mass, it was expected that more than one degree of freedom would be present. To reduce the mismatch in mass of the two sides of the generator, a thin copper mass was manufactured to slide over the mounting block on the coil side and bolt in along with the coil tube. The copper mass, depicted with the harvester in figure 4.1, is 76g and together the mass and coil are 89g. Further discussion of the compliant mechanism frame, operational principle of the harvester, and design of generator is given in the following two subsections.

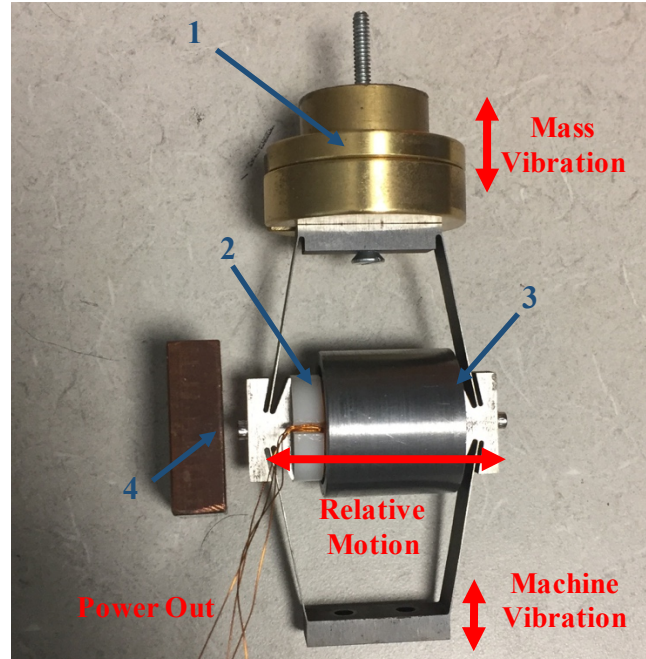


Figure 4.1. Photograph of the combined harvester with a proof mass - 1, coil tube – 2, magnet array – 3, and a copper mass – 4.

4.2.1 Compliant Mechanism Frame

It is typical for vibration harvesting solutions to rely on the harmonic motion of a proof mass excited at its natural frequency with a spring type system. This mass is usually the more massive magnet in an electromagnetic generator design. Operation of the harvester designed in this work is similar with an important addition. Small amplitude base vibration is first amplified in the mass motion through the matching of the natural frequency of the system made of the spring steel frame, proof mass, and electromagnetic generator damper. Secondly, due to the frame and its geometry, the motion of the mass is further amplified in the relative motion of the two sides of the generator. To allow for the desired motion in the frame, four connection beams, which are thin, and very compliant create the amplification geometry. The effect, then, of proof mass motion is a squeezing of the top and bottom of the frame, pushing the two halves of the generator, mounted in the middle of the four compliant beams, apart from each other. This principle is depicted in the simple FEA analysis in figure 4.2b, produced with Inventor CAD software to visualize the movement of the frame. The result is a large amplification in relative velocity seen between the coil and the magnet over what would be using the machine vibration or mass motion alone. As can be seen, small motion in the top of the frame results in larger motion between both sides.

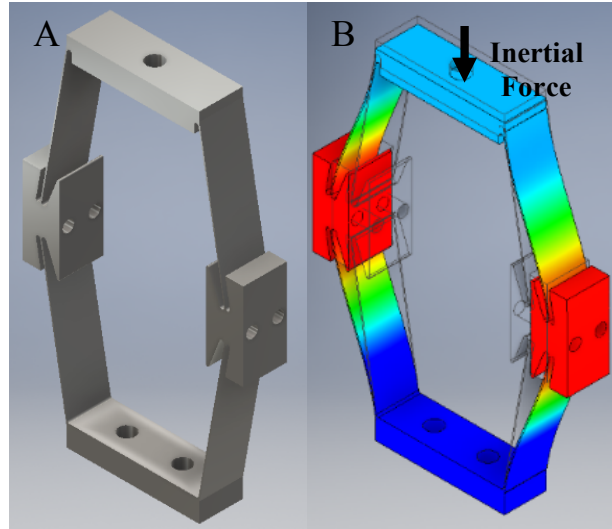


Figure 4.2. CAD representation, A, of the spring steel compliant mechanism frame, and B a simple FEA simulation demonstrating working principle.

Acting as the spring in this system, the frame, depicted in 4.2a, was cut out of a single piece of spring steel using the wire EDM machining method. The frame defines not only the amplification ratio, but also the natural frequency of the system, and is thus vital to the design. In order to design the system to match its natural frequency to the operational frequency of pumps, a number of different parameters on the frame can be adjusted. The main changes are made to adjust parameters on the compliant beams. Changes to their geometric parameters greatly affect the dynamics of the harvester, leading to an important trade off: a low bending stiffness is desired in order to allow for amplified motion of both sides, however, a more compliant beam has a lower natural frequency. Therefore, it is worth discussing the design parameters and choices made.

The length to thickness ratio is important when considering the natural frequency of the compliant beam. Here it was desired to have a very large ratio in order to allow compliance in the direction desired, namely in the plane of the harvester. The length of each of the beams was set to be 35 mm, with a thickness of only 0.3 mm, making a ratio of >100 . The length of the beam largely determines the amplification ratio from the top of the frame to the sides, as can be seen below in the modeling section, and the thickness of the beams allows for compliance in the plane. To maintain stiffness through the plane of the harvester, and reduce motion perpendicular to the desired movement of the generator the beam was designed to be relatively thick, and is here 10 mm. Each of these parameters can be adjusted during the design phase to change the resultant

natural frequency of the system, and the mass can be adjusted after production to slightly shift the frequency as well.

Additionally, as mentioned, the entire premise of the design hinges on geometry of the frame. Here each of the compliant beams are initially 12 degrees from vertical. From purely geometric arguments, the amplification ratio is largest when this angle is near 0 degrees, and reduces as the angle increases. 12 degrees was decided upon based on the desired frequency of operation and previously determined dimensions of the beams. Clearly a frame with a smaller operational angle will have a higher stiffness.

4.2.2 Electromagnetic Generator

In order to create electrical energy, an electromagnetic generator was developed for use within the above described frame. Upon consideration of the type of vibration being targeted by the harvester, the generator was designed with small amplitude motion in mind. Inspiration for the design was adapted from Tang [58] in which magnet geometry creates a larger magnetic field used for an energy harvesting shock absorber. In that work, it was shown that an increase in the magnetic field can be made by placing magnets with poles facing each other. A radial magnetic field can be made using this design principle, and the magnetic field can be appropriately further guided using steel or iron on the inner and outer portions. Using the design principle in that work, here a small generator was made in order to fit between the two sides of the frame described in the previous section. This design was used because it was expected that small motions in the machine would translate to relatively small movements in the coil. This means that designs where a magnet is moved across a coil of wire, using the principle of a changing magnetic flux through the coil, could not be used as the energy density is too low. Instead here a coil of wire was moved through a steady magnetic field, relying on the principle of the Lorentz force stating that motion of a conductor through a steady magnetic field will produce a current proportional to the magnetic field, and length and velocity of the conductor. During the design of the harvester it was hypothesized that the coil wire would largely stay within the magnetic field during its motion, however the velocity would change, inducing a change in current. Thus the use of a strong radial magnetic field through the coils was desired. A photograph depicting the elements of the designed generator, and relative size in inches is shown below in figure 4.3.

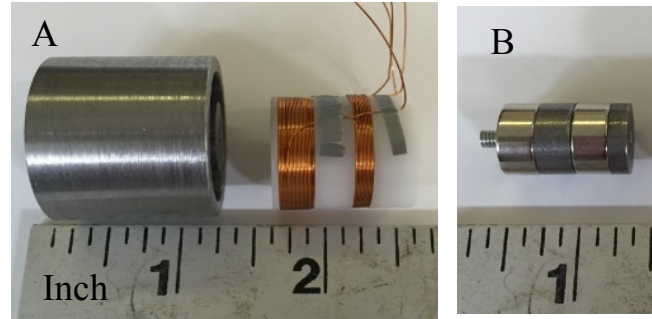


Figure 4.3. Close up photograph of the generator. The steel cylinder, affixed in A, is removed in B to show the inner magnet and steel assembly.

The design is as follows: two axially magnetized neodymium magnets are mounted on an aluminum shaft with similar poles facing each other. Between the two magnets is a disk of 1018 steel in order to focus the magnetic field lines to oppose each other, and radiate radially outward. A 1018 steel threaded end cap threads on the end of the aluminum shaft against the second magnet to complete the magnetic loop and hold the magnet assembly in place on the shaft. Each of these components along with the magnet have an outer diameter of 0.5-inch. A 1018 steel outer cylinder of diameter 1.15-inch is used to guide the magnetic field radially along the generator and complete the loop back into each of the magnets. This outer cylinder threads onto the opposite end of the shaft and sits next to the inner magnet, creating the entire array. Each of the steel sections along with the aluminum shaft were custom made for this application. A depiction of the working principle is shown below in figure 4.4.

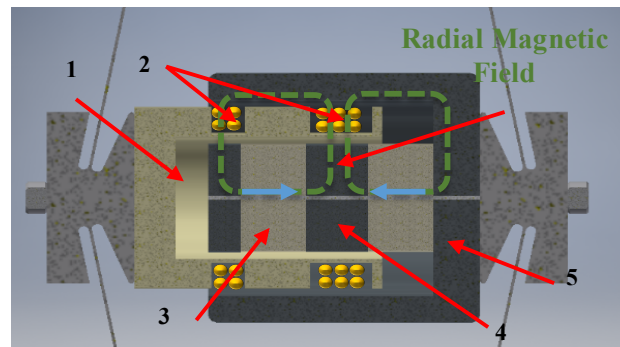


Figure 4.4. CAD cutaway of the harvester to show the working principle. Coil tube – 1, with coil sections – 2, slides over oppositely facing, axially polarized rare earth magnets – 3, which create a strong radial magnetic field through the steel discs – 4, and the steel cylinder – 5.

The entire magnet array has a mass of 85g. Free to slide between the magnet assembly and outer steel tube is a set of copper magnet wire coils wound around a Delrin tube of diameter 0.825-inch. Copper coils wound around the coil tube are positioned directly over the inner steel spacer and the outside steel end cap in order to allow the flux of the magnetic field pass directly through the coils. The total mass of the coil tube is 13g. Together, the generator was found to have a total impedance of 6.58Ω with an angle of 4.03 degrees at 40 Hz as measured by an impedance analyzer. The overall length of the generator is approximately 1.5 inches when both halves are assembled and combined together.

To validate the design principle, a free program called FEMM [59] was used which solves the Maxwell equations for various geometries and materials. The output is a cross section contour plot of the strength of the magnetic field generated within the specified materials. From this plot it is possible to see the effect of changing both materials and geometries in the system. There is also a tool to plot the magnetic field as a function of distance from any point to another point. The materials used in the simulation included Neodymium magnets, pure iron, air, copper, aluminum, and plastic. Once these material properties are set within the geometric array, the system solves the equations and generates a plot of the magnetic field strength. The magnetic field through the coils was predicted by checking the magnetic field strength moving from the inside of the coil to the outside of the coil, and this was plotted for both coils in the generator. Below, figure 4.5 shows the analysis done on the designed harvester showing the predicted magnetic field strength moving through the center coil radially outward from the center steel cylinder edge to the edge of the outermost wind of both coils.

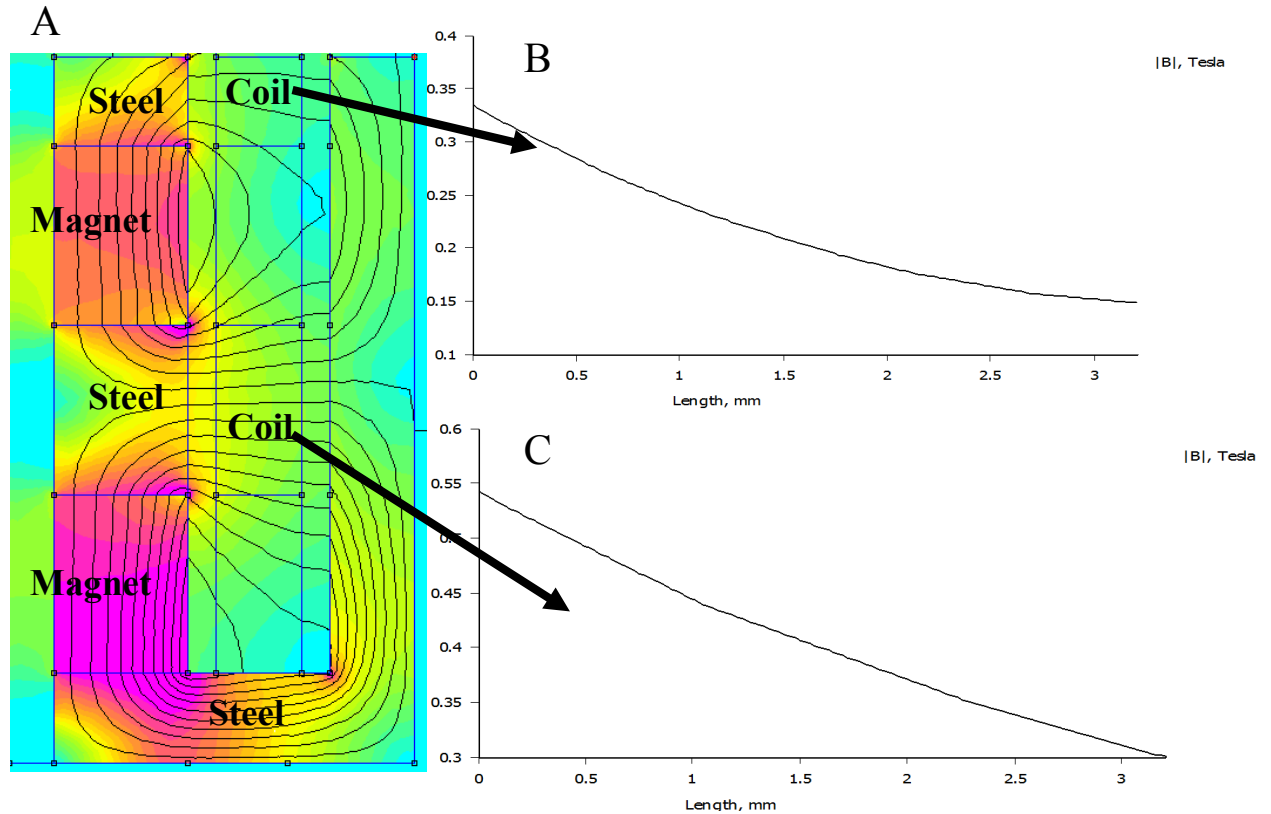


Figure 4.5. FEMM model of the generator, A, and the magnetic field strength radially outward through the top coil, B, and the middle coil, C.

As can be seen in this analysis, the predicted and desired behavior in the magnetic field is generated. Since the two magnets are axially magnetized towards each other, the field lines repel each other radially (left to right in figure 4.5a). Aluminum was used as the shaft of the generator because it has a much lower magnetic permeability than that of steel. This means that as the magnetic field lines are repelled from each other, they tend to be drawn towards the steel, and away from the aluminum shaft, concentrating through the coils as desired. When plotting the magnetic field strength through each of the coils, it was found that it should range from between 0.55 T at its strongest, and 0.15 T at it's weakest, as can be seen in the graphs in 4.5 b and c.

4.3 Dynamic Modeling

Upon investigation into the response of the system to base excitation, and from knowledge of vibration systems it was determined that a 3 degree of freedom model is needed to accurately predict the response of the system. To accomplish this, the following simplified depiction and model is presented in figure 4.6.

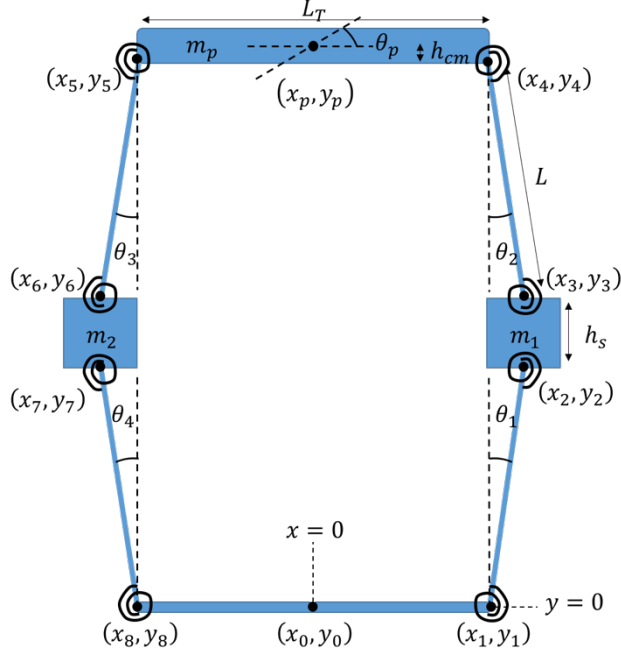


Figure 4.6. Model representation of the frame and harvester system.

Here $(x_0, y_0) - (x_8, y_8)$ represent unique points on the frame system. Both the top and bottom rigid beams are assumed to be of length L_T , both the side masses are assumed to be of height h_s , all four compliant beams are of length L , and the center of mass of the top mass is a height h_{cm} above y_4 and y_5 . The masses m_1 , and m_2 are the mass of the magnet and coil sides respectively including the mass of each part and the mounting beams, and the mass m_p is the proof mass and mass of the top beam. Finally, each of the four compliant beams can make an angle, $\theta_1 - \theta_4$ from horizontal. This angle includes both their original angle, and any displaced angle caused by forces acting on the system. The top mass can rotate about its center of mass under angle θ_p .

The following assumptions are made: the bottom beam is rigidly attached to the host structure, and base motion is in the y-direction solely, meaning y_0 is known, as are y_1 , and y_8 all of which are the base motion. Additionally, the mass of both the harvester sections and the frame are lumped at m_1 and m_2 , and any effects due to the moment arm created by hanging a mass off the end of the frame have been neglected. To begin, each positional variable is derived, and the entire model is constrained through the constraint equations in table 4.1.

Table 4.1. Constraint equations for the model in figure 4.6.

Constraint Equations	
$x_0 = 0$	$x_5 = L \sin \theta_3 + x_7$
$x_1 = \frac{L_T}{2}$	$y_5 = y_6 + L \cos \theta_3$
$y_1 = y_0$	$x_6 = x_7$
$x_2 = L \sin \theta_1 + x_1$	$y_6 = y_7 + h_s$
$y_2 = L \cos \theta_1 + y_1$	$x_7 = -L \sin \theta_4 + x_8$
$x_3 = x_2$	$y_7 = L \cos \theta_4 + y_8$
$y_3 = y_2 + h_s$	$x_8 = -\frac{L_T}{2}$
$x_4 = x_2 - L \sin \theta_2$	$y_8 = y_0$
$y_4 = y_3 + L \cos \theta_2$	$(x_4 - x_5) = L_T \cos \theta_p$
$x_p = \frac{1}{2}(x_4 + x_5)$	$(y_4 - y_5) = L_T \sin \theta_p$
$y_p = \frac{1}{2}(y_4 + y_5) + h_{cm}$	

A dynamic model will now be developed using this system. To begin, the excitation is assumed to be sinusoidal and harmonic, only in the y-direction, and acts on the base of the system. This will induce an inertial acceleration on each of the three masses lumped: between points 2 and 3, at point p, and between points 6 and 7. To find the dynamic system of equations, the Lagrange method was used. An assumed small displacement was made by the acceleration of the base acting on each mass, where $\theta_{\#} \rightarrow \varphi + \delta\theta_{\#}$. $\delta\theta_{\#}$ is a small angle displacement, and φ is the non-deformed angle, which is the same for all four beams. From here, the new displaced $\theta_{\#}$ is plugged into the constraint equations given in table 1. Simplifying using small angle approximations results in the following set of equations (4.1) – (4.8). Note that δx_2 , and δy_2 now denote the change in position of the mass m_1 , δx_7 , and δy_7 , denote the change in position of the mass m_2 , and that all equations are dependent on only $\delta\theta_1$, $\delta\theta_4$, and $\delta\theta_p$, the chosen three unique degrees of freedom.

$$\delta x_2 = L \cos(\varphi) \delta\theta_1 \quad (4.1)$$

$$\delta y_2 = -L \sin(\varphi) \delta\theta_1 \quad (4.2)$$

$$\delta x_7 = -L \cos(\varphi) \delta\theta_4 \quad (4.3)$$

$$\delta y_7 = -L \sin(\varphi) \delta\theta_4 \quad (4.4)$$

$$\delta x_p = L \cos(\varphi) \left(\delta\theta_1 + \delta\theta_p \left(\frac{L_T}{2L \sin \varphi} \right) - \delta\theta_4 \right) \quad (4.5)$$

$$\delta y_p = -L \sin(\varphi) (\delta\theta_1 + \delta\theta_4) \quad (4.6)$$

$$\delta\theta_3 = \delta\theta_p \left(\frac{L_T}{2L \sin \varphi} \right) + \delta\theta_1 \quad (4.7)$$

$$\delta\theta_2 = \delta\theta_4 - \delta\theta_p \left(\frac{L_T}{2L \sin \varphi} \right) \quad (4.8)$$

To take into account the stiffness associated with the frame and beams, a compliant mechanism model is used. Adapted from Howell [60] is a pseudo rigid body formulation for a fixed guided beam used for each of the four compliant beams. To use this model, two important assumptions were made. First, the beams are Euler Bernoulli beams, which is a safe assumption due to an aspect ratio of >100 length to thickness. Second, it was assumed that each of the beams has a fixed, guided behavior. This assumption was made because each of the beams is built into the top or bottom rigid member, and, due to the mounting block for each mass, are largely constrained to move with a fixed curvature at the contact point to the mounting block. The pseudo rigid body model, depicted below in figure 4.7 [60] (adapted from Howell), effectively places rotational springs at the two ends of every compliant beam, with a link in between, meaning there are 8 springs associated with this model. According to the theory put forth by Howell, these springs have a spring constant of

$$K = 2\gamma K_\theta \frac{EI}{L} \quad (4.9)$$

where γ , and K_θ are constants which depend on the geometry of the system, E is the Young's Modulus, $I = \frac{td^3}{12}$ is the area moment of inertia of the beam, where d is the bending thickness, t is the through plane thickness, and L is the length of each compliant beam.

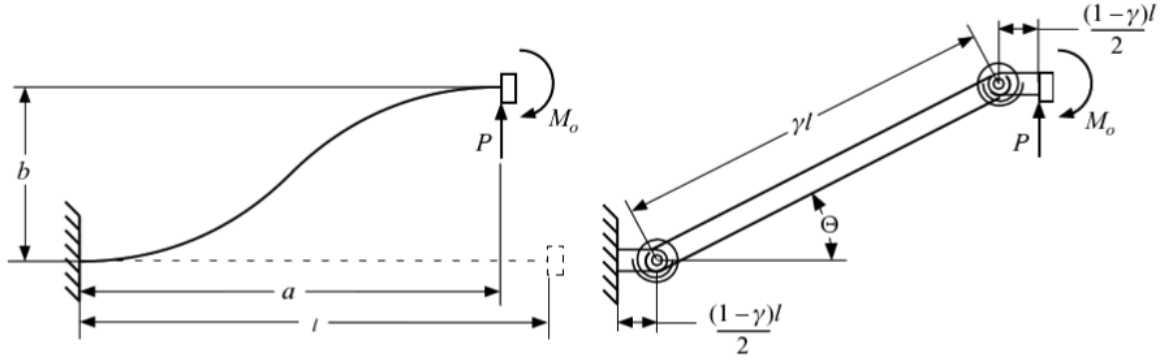


Figure 4.7. Fixed-guided beam model used for the four compliant mechanism beams.
Adapted from Howell for clarity [60].

To formulate the Lagrange equations, the work done on the system is as follows

$$dW = m_1 a \delta y_2 + m_2 a \delta y_7 + m_p a \delta y_p + \kappa_m i (\delta x_7 - \delta x_2) \quad (4.10)$$

where the last term comes from the force created when a voltage is generated during motion of the generator. Here a is the acceleration generated by the base motion, and $\kappa_m = B l_w$ is the motor constant where B is the magnetic field strength, and l_w is the length of wire. i is the current, defined as $i = \frac{V}{R_T}$ where R_T is the total resistance of the coil and external load, and V , the voltage generated from the motion of the coils and magnets, is as follows (Lorenz law)

$$V = \kappa_m (\delta \dot{x}_2 - \delta \dot{x}_7) \quad (4.11)$$

where $\delta \dot{x}_2$, and $\delta \dot{x}_7$, are the x direction velocities of masses m_1 , and m_2 respectively.

As stated above, the inductance of the coil was found to be a small fraction of its total impedance, thus this simpler formulation taking into account only the coil resistance was decided upon. Future work can consider the inductor produced by the coil windings, and incorporate it into this model, for a more comprehensive study.

The total kinetic energy of the system includes x and y motion of all three masses, and is as follows

$$T = \frac{1}{2} m_1 (\delta \dot{x}_2^2 + \delta \dot{y}_2^2) + \frac{1}{2} m_2 (\delta \dot{x}_7^2 + \delta \dot{y}_7^2) + \frac{1}{2} m_p (\delta \dot{x}_p^2 + \delta \dot{y}_p^2) + \frac{1}{2} J_p \delta \dot{\theta}_p^2 \quad (4.12)$$

here a dot denotes a time derivative and J_p is the rotational inertia of the proof mass. Finally, the potential energy associated with all eight springs is

$$U = K(\delta\theta_1^2 + \delta\theta_2^2 + \delta\theta_3^2 + \delta\theta_4^2) \quad (4.13)$$

Plugging equations (4.1) – (4.9) into (4.10) – (4.13), the Lagrange equation can be solved, resulting in a set of differential equations. This results in a three degree of freedom spring-mass-damper system $M\ddot{X} + C\dot{X} + KX = F$ where M, C, K, F and X are the mass, damping, stiffness, force, and displacement matrices as defined in equations (4.14) – (4.18) respectively. These can be solved and plotted with any method desired. In this thesis a Mathematica [61] script was used to define the system and solve these equations using a Laplace transform. Once these equations are acquired, the response of any part of the system can be simulated, and the results are seen in the following section 4.4.

$$M = \begin{bmatrix} L^2(m_p + m_1) & -L^2 m_p \cos 2\varphi & \frac{L}{2} L_T m_p \cos \varphi \cot \varphi \\ -L^2 m_p \cos 2\varphi & L^2(m_p + m_2) & -\frac{L}{2} L_T m_p \cos \varphi \cot \varphi \\ \frac{L}{2} L_T m_p \cos \varphi \cot \varphi & -\frac{L}{2} L_T m_p \cos \varphi \cot \varphi & J_p + \frac{L_T^2}{4} m_p \cot(\varphi)^2 \end{bmatrix} \quad (4.14)$$

$$C = \begin{bmatrix} \frac{L^2}{R_T} \kappa_m^2 \cos \varphi^2 & \frac{L^2}{R_T} \kappa_m^2 \cos \varphi^2 & 0 \\ \frac{L^2}{R_T} \kappa_m^2 \cos \varphi^2 & \frac{L^2}{R_T} \kappa_m^2 \cos \varphi^2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (4.15)$$

$$K = \left(\frac{EI\gamma K_\theta}{L^3} \right) \begin{bmatrix} 8L^2 & 0 & \frac{2LL_T}{\sin \varphi} \\ 0 & 8L^2 & -\frac{2LL_T}{\sin \varphi} \\ \frac{2LL_T}{\sin \varphi} & -\frac{2LL_T}{\sin \varphi} & \frac{2L_T^2}{\sin(\varphi)^2} \end{bmatrix} \quad (4.16)$$

$$F = \begin{bmatrix} -La \sin \varphi (m_p + m_1) \\ -La \sin \varphi (m_p + m_2) \\ 0 \end{bmatrix} \quad (4.17)$$

$$X = \begin{bmatrix} \theta_1 \\ \theta_4 \\ \theta_p \end{bmatrix} \quad (4.18)$$

4.4 Experimental Study and Results

To test the system and verify the performance an experimental study was performed. The harvester was set up on a shaker in the lab, which was placed on a shaker table. This system was used to provide a small amplitude vibration at the base of the harvester to simulate attachment to a pump or other vibrating piece of machinery. The entire setup is shown in figure 4.8 below.

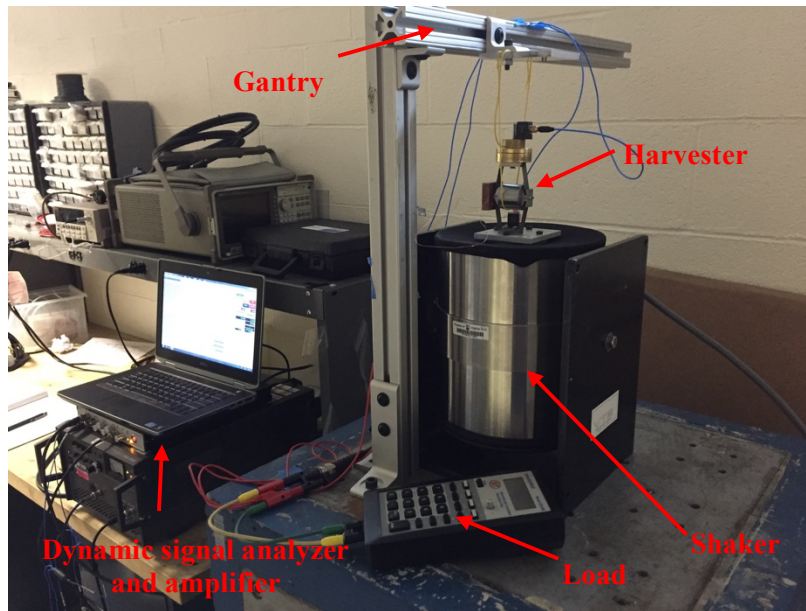


Figure 4.8. Experimental setup with a shaker and dynamic signal analyzer. The computer was used to collect data from the harvester and accelerometers attached to the system.

The harvester is rigidly mounted to the shaker via an aluminum adaptor using two bolts through the mounting bar on the bottom of the frame (see figure 4.2a). It was noted due to the moment arm created by the massive magnet array it's angle with horizontal was not maintained, potentially causing interference between it and the coil tube. To address this, as seen attached to the gantry, a soft rubber band was used during later tests to lightly hold the magnet in position without offering further resistance during vibration. Accompanying the harvester on the shaker is an accelerometer for control of the shaker system. Attached to the harvester, placed across the two leads of the generator is a programmable resistive load. In parallel with the load is a BNC cable

extension for connection to the dynamic signal analyzer used to monitor the voltage output of the system. An accelerometer is attached to either the top or side of the harvester to monitor the dynamics of these two portions with the dynamic signal analyzer. With this setup, the acceleration, and thus velocity, of the top or side of the harvester could be monitored simultaneously with the voltage and compared to the base input. Two separate tests were performed on the harvester. The first was a sweep of frequencies, from which the frequency response function of any part of the system could be taken. From this data the natural frequencies of the system could be determined. These were then used to run the system at its operating natural frequency for a period of time. The shaker was set to maintain this frequency at a desired small amplitude, and the outputs were recorded. In general, when performing tests, the shaker was set to maintain a 0.001-inch amplitude, and approximately 200 grams was used as a proof mass.

Shown below in figure 4.9 is the acceleration frequency response function of both the magnet side and top proof mass of the frame, which was taken by sweeping the system while monitoring the acceleration of both the top and side of the frame simultaneously.

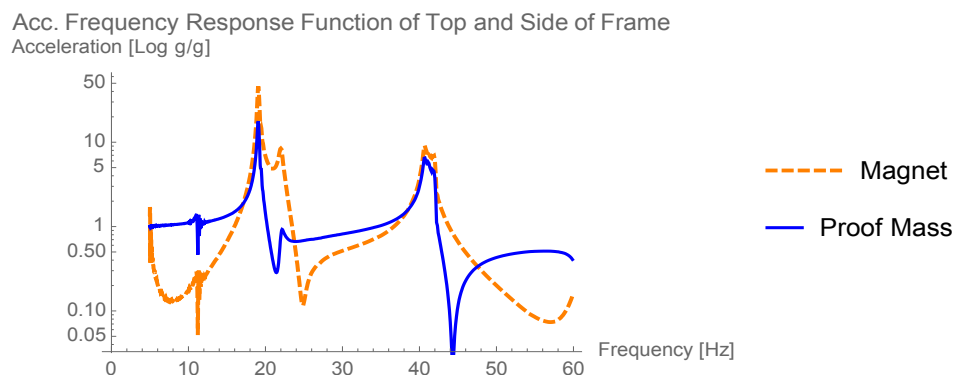


Figure 4.9. Acceleration frequency response function of both the top and side of the frame with the harvester and proof mass attached and no rubber band supporting the magnet. Acceleration is normalized to the base acceleration.

Results from this test are an important and valuable validation of the working principle of the design. The first section of this graph to take note of is the peak near 19.4 Hz. Seen during testing, this is the location of the desired motion of the frame where proof mass motion is greatly amplified through the center of the frame. Attention should be drawn to the peak values in both accelerations at this point. The top of the frame has a peak value of 17.7 g/g, and the side of the frame has a peak value of 46.0 g/g which is a 2.7x increase in acceleration of one side of the frame over the proof mass. Similar results were seen on the opposite side as well, meaning in total, the harvester has a

relative acceleration increase of approximately 5.4x. It is important to note that during harmonic motion at this operating frequency acceleration is related to velocity only by a multiplier of angular frequency, and thus the harvester produces the same amplification in velocity over the proof mass alone, important for the operation of electromagnetic harvesters.

Secondly, note is made about the three main features in the experimental curves. The peak at 19.4 Hz is the designed operational point of the harvester. At this frequency the mass moves periodically up and down, and large side to side motions are induced between the coil and magnet, which are themselves 180 degrees out of phase. The second feature to note is some noise around 23 Hz. It is at this point where a cantilever motion of the magnet array is excited. Finally, at 41 Hz a second peak occurs, where the natural frequency of the coil is excited. At this frequency the coil moves in and out, while the top bar rotates about its center of mass, and the magnet stays largely stationary. The noise seen in this peak comes from collision of the coil with the inside of the magnet array. It is hypothesized that given unlimited room for movement this peak would look very similar to the first at 19.4 Hz, which is seen in the model presented below.

The experimental and modeled open circuit voltage output of the system without modifications are shown in figure 4.10a below.

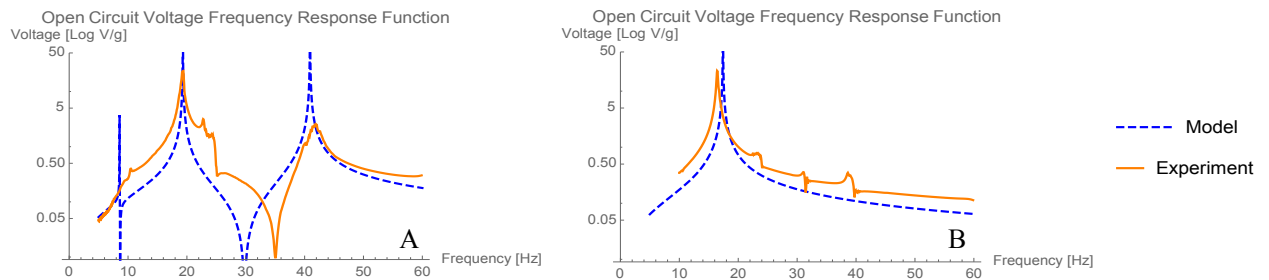


Figure 4.10. Open circuit voltage frequency response functions (A) without additions, and (B) with a mass and rubber band. Results are normalized to base acceleration.

As would be expected, the same frequency characteristics are seen in the voltage output as in the acceleration response. To address these less desirable features in the dynamics, modifications were considered as discussed in the design section. To fix the slight drop of the magnet, a soft rubber band was used to lightly hold the magnet in position, and was anchored to the gantry shown in figure 4.8. Secondly, a copper mass was attached to the coil mounting block to match the mass of both the magnet and coil sides of the frame. As can be seen in the resultant voltage frequency response function of the harvester in figure 4.10b, the three peaks collapse into one defined peak,

and noise is reduced. A frequency downshift is also induced, expected, as mass is added to the entire system.

Important to note from the harvester's performance is its voltage output at the operational frequencies, where the mass and coil are moving apart from each other, and operation is as desired. The peak in the system without modifications (figure 4.10a) has a value of 23.7 V/g, meaning at a base amplitude of 0.001-inch, at 19.4 Hz, the peak voltage output of the harvester is 0.91 V. Alternatively the peak with additions added to the harvester (figure 4.10b) is at 16.4 Hz, an expected downshift in frequency due to the addition of a mass to the coil side of the frame. When operating at this frequency a peak value of 23 V/g was recorded and at 16.4 Hz and 0.001-inch amplitude the voltage output is 0.63 V AC. Both of these voltage values were verified using a dwell at the natural frequency. The drop in voltage output was largely due to the fact that the operating frequency is at a lower value than in the system without additions.

Finally, presented below in figure 4.11 is an example of the power generated by the harvester with additions. Each data point was found as follows: a resistive load was applied across the harvester, and a fine frequency sweep was done about the operational frequency point to find the exact frequency for excitation. A dwell at the natural frequency was then performed with an amplitude of 0.001-inch, and the peak in the voltage drop across the load was recorded. This voltage was then used to calculate the peak power supplied across the load, from which the RMS value could be calculated.

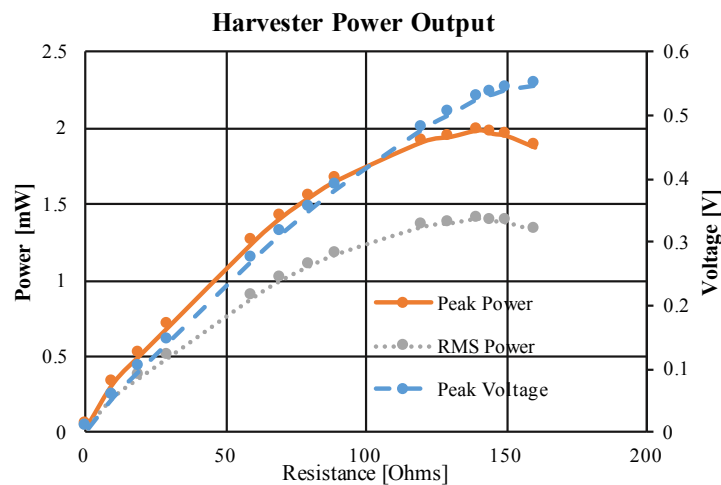


Figure 4.11. Peak voltage, peak power, and RMS power produced by the harvester under resistive loading at natural frequency.

4.5 Discussion of Results

It is important to first note the performance of the simple three degree of freedom model in predicting the natural frequency of the system, frame dynamics, and the voltage output. Using estimations for manufacturing inaccuracies in the system, the natural frequencies were able to be matched quite closely, as was the overall behavior of the system. To show its performance in predicting the frame response as well, the following figure 4.12 is presented with the acceleration frequency response function of the magnet side of the harvester.

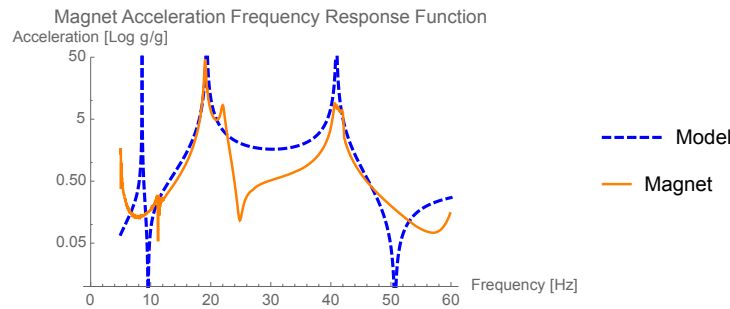


Figure 4.12. Magnet acceleration frequency response comparison between the model and experimental data for the harvester with no side mass or rubber band added.

Three peaks are seen in this figure, and indeed in modeling and experiments in figure 4.10 4.12 above as well. This is as expected from a three degree of freedom system, and they correspond to: 1, the magnet natural frequency, 2 the system natural frequency, and 3 the coil natural frequency. Some notes which should be made when comparing the model and experiment are as follows. The first peak seen in the model is not clearly seen in the experimental data, and it is hypothesized that this is due to the fact that energy at such low frequencies is small, and the inertial force was not large enough to cause significant motion in the experimental system. It is also seen that the peak is very sharp in the model, and thus is expected to be difficult to excite during a sweep of frequencies. Secondly, there is a small downward shift in the voltage model (figure 4.10a) for frequencies lower than ~35 Hz, which is likely due to incomplete modeling of the electrical system, as the inductance was removed from this model for simplification, and the magnetic field and length of wire in the harvester are estimations based on measurements done in the lab. Third, peaks in the model are much more defined, as is expected, considering mechanical damping was not considered, and thus energy in the model can become very sharp at the natural frequency, but cannot during the experiment. Finally, as the model does not include any dynamics of the cantilevered motion of either the magnet or coil, the noise at ~25 Hz is not found by the model.

Thus, in comparing the model to the experimental data, it is evident that the strength of the model is in predicting the natural frequency of the system given mass and frame characteristics. As can be seen in figure 4.10b the model responds appropriately to changes in the mechanical system setup, and can reflect any design changes desired in the design process to guide matching the harvester to a specific rotating machine. It should also be noted the model performs well when investigating non-open circuit situations of the harvester.

Apart from the model, it worth discussing the system with no additions. While the design idea was for operation at the first visible natural frequency, when the proof mass motion induces larger relative motion between the two sides of the harvester, it is possible that operation at the higher natural frequency may also be desired. If a larger stroke were possible, the voltage output at this frequency would be comparable to the designed natural frequency due to the higher frequency, and thus velocity of operation. Design of the system could take this into account, creating a two frequency system capable of dealing with shifts in machine operational frequency, or broad band frequency excitation.

Finally, note is made that this form of energy harvesting produces much lower power than is achievable with the thermal energy harvester presented above. While this harvester design with the frame and generator can significantly increase the potential energy output of the machine vibration using clever geometry, clearly, the power output is less than the desired 16 mW necessary to provide power for the wireless sensor node. These two facts should be considered when placing electronics for the wireless sensor node. An array of these harvesters could be placed on one machine in order to power a node, however, this may be cumbersome. Certainly, the 2 mW of power from one harvester can be used for a sensor with significantly reduced transmission cycles, however it might be more practical to power the sensor mainly through the thermal energy harvesting presented in the previous chapter. Importantly, however the hypothesis that vibrational energy could be harvested from the main coolant pump in a nuclear power plant has been verified, and power in the mW range has been generated, classically difficult for very small amplitude vibrations. The operational idea behind the harvester design has been verified, and can readily be applied to other areas of interest in the energy harvesting field. Additionally, the design is not only useful for nuclear power plants, but may be used in any industrial field with vibrational machinery.

4.6 Summary

This section aimed to show the feasibility of creating an electromagnetic based energy harvester capable of generating usable energy from the extremely low amplitude vibrations present in the main coolant pump of nuclear power plants. A compliant mechanism frame and an electromagnetic generator have been designed and prototyped to amplify vibration velocities, and thus increase harvestable energy density. Experimental study of the frame and generator proved feasibility of the design increasing the relative velocity of a generator approximately 5.4 times over that possible using only proof mass motion. Voltage output of the harvester has shown to be as high as 0.91 V AC, delivering a power of 2 mW at 0.001-inch amplitude base vibration. Additionally, a simple three degree of freedom model has been developed to characterize the harvester, including compliant mechanism analysis and theory, and the model performs well in predicting the dynamics of the system.

From the experimental analysis, it can be seen that approximately 2 mW can be created using this design. This energy could go either to charging a battery for a number of applications, or to powering components in a wireless sensor directly. While the power output is significantly smaller than a thermal energy harvester, this power is still usable. Importantly, the design principle has been proven, as the frame has shown an approximately 2.7 (x2) times increase in velocity over the proof mass during operation at the natural frequency. This is an important addition to the energy harvesting community, as the design principle can be used in various proof mass enabled devices. The use of geometry and a compliant mechanism can also be applied in designs across the field for amplification of output energy over what was previously possible. A parameter optimization could be done and the power output should be expected to be in the tens of mW range, as is the baseline requirement outlined in section 2.1.

5 Radiation and Thermal Harvesting in Dry Cask Storage

5.1 Gamma Heating Principle

As outlined in section 2.5, dry cask storage would benefit from the monitoring of parameters inside the MPC (multi-purpose canister). An energy harvester placed within this section of the cask may be able to harvest energy from both heat flow inside the canister and from gamma and neutron radiation. Considering the high expected temperature and large radiation field from the spent fuel, and noting the promising performance of a TEM in a radiation environment as discussed in chapter 3, it was deemed appropriate to design a thermal energy harvester for use in the dry cask. As also discussed in chapter 3 a temperature gradient is necessary for operation of a TEM, thus this design aims to make a local high temperature spot within the canister. To achieve this, it was hypothesized that a tungsten plate placed within the MPC may be able to gather enough material heating from the fuel to act as a high temperature source for a TEM cooled by the MPC wall.

It is well known that metal, and indeed all materials will absorb heat to a certain degree when placed in ionizing radiation, such as gamma radiation, depending on their material properties. Gamma heating is caused largely by interactions between impinging gamma rays and electrons in the atomic structure of the material, where the energy expended in the collision is ultimately transferred to heat in the material. Thus, certain materials absorb gamma radiation better than others, generally those with higher densities and thus higher atomic cross sections for scattering, a reason lead is used to shield gamma radiation. Specific material absorption characteristics from Compton scattering and the photoelectric effect are well outlined by Hubbel and Seltzer [62] with NIST, and they give a good discussion on the various interaction processes. The idea hypothesized in this section is to use this gamma heating to help create a localized hot spot, aiding the thermal environment already present inside the cask. Tungsten has been chosen as the material for gamma heating because of its high material density, 19.25 g/cm^3 , and high thermal conductivity, $170 \text{ W/(m}\cdot\text{K)}$, making it an ideal candidate to not only absorb large amounts of gamma radiation, but also transfer the generated heat to a TEM placed on its surface. Additionally, any convection and thermal radiation generated in the cask can be taken advantage of, further heating the tungsten plate. The overall idea for the radiation heating portion of the design is presented below in figure

5.1. Depicted along with the energy harvester is a section for conditioning electronics, and through wall transmission electronics to send sensor data to wireless transmitters outside of the MPC.

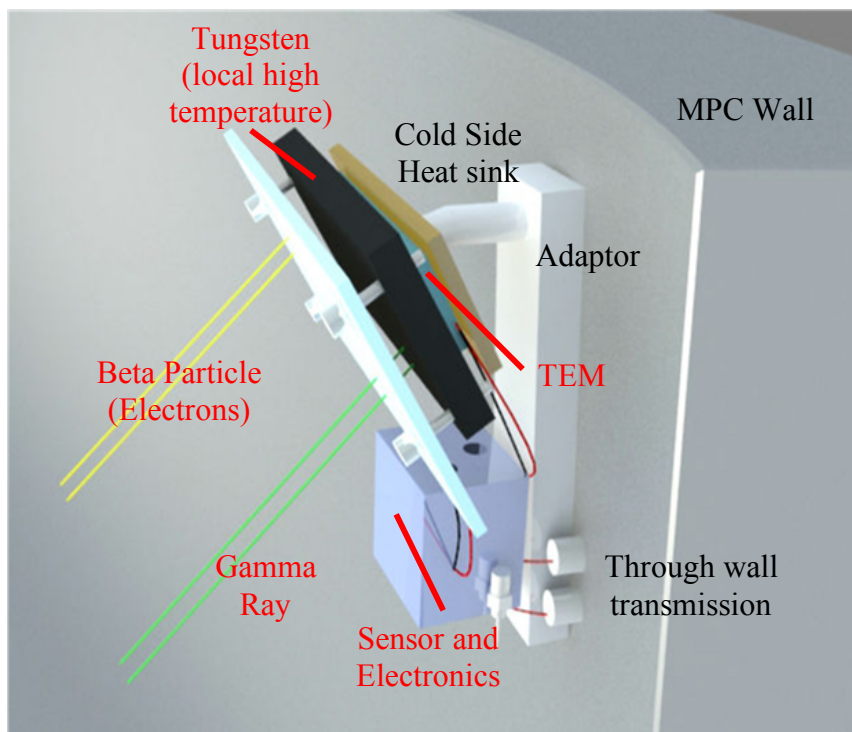


Figure 5.1. Dry storage energy harvester, sensor, and through wall communication idea representation.

In order to investigate and hopefully guide the development of such an energy harvester, the thermal and radiation environment within the cask must be thoroughly analyzed, and as outlined in section 2.5 detailed analysis on radiation densities and absorption characteristics inside the MPC are largely missing from the literature found. Thus a simulation of the decay heat, nuclide make up, gamma and neutron spectrums, and potential gamma induced material heating is made in the following section 5.2. In this section SCALE is first used to calculate the decay heat, and gamma and neutron spectrums emitted from the fuel in certain years during storage. This information is then used to build a simulation in MCNP6, a Monte Carlo based particle transport simulation which takes into account the tungsten plate, dry cask geometry, and material make-up, providing the material heating in the tungsten for various years. Finally, a CFD analysis is presented which provides information on where best to place the energy harvester within the dry cask to take advantage of the thermal environment. Based on the analysis made two energy harvesters are outlined in section 5.3 along with discussion about their effectiveness.

5.2 Environment in the Dry Cask

5.2.1 ORIGAMI Modeling of Spent Nuclear Fuel

ORIGAMI, a part of the SCALE Code System [63] from ORNL is widely used in the nuclear industry in order to calculate the isotopes present after various conditions are applied to a type of nuclear fuel. The software can accurately give an estimation of the expected radiation and decay heat left from fuel which has been used to certain burnup levels, allowing the user to perform isotopic depletion and decay calculations for a wide range of fuel assemblies. Here, the software was used to calculate the decay heat, nuclide makeup, and gamma and neutron emission spectrums for the fuel under consideration from the time it left the reactor, to 50 years in dry cask storage (55 years since removal). In this way the decay heat in the CFD analysis, and radiation levels for material heating estimations, can both be tailored to the specific fuel and time frame desired for simulation.

The fuel employed for the simulation was a Westinghouse 17x17 assembly, with a total cask MTU of 15 spread over 32 assemblies (see discussion in section 2.3), an enrichment weight percentage of U-235 of 4%, a burnup of 45 GWd/MTU, 3 runs per fuel assembly, and an average power of 40 MW/MTU. This fuel configuration approximates an average assembly being removed from a reactor, as typical fuel now has a U-235 enrichment between 3 and 5%, and is used up to, and in the future past, 45 GWd/MTU [26]. For calculation of the number of MTUs stored in the canister, it is assumed the PWR reactor contained 90 MTUs and the fuel is evenly distributed among 193 fuel assemblies [14]. Based on this, the MTU per assembly can be determined [31]. Using this average fuel allows one to receive data which can be expected to be a representation of what will typically be present in dry storage canisters in the upcoming years. Of course, fuel make up, burnup levels, and run times can change from assembly to assembly, which will cause the data to fluctuate some, however, without a specific fuel type in mind, this “average” fuel was selected for use for this design process. A more accurate representation of an actual fuel assembly can be made by inputting the data taken from a reactor history if desired, however as this data is highly specific to the reactor and fuel assembly, a general route was taken for this work in order to show the process, and to find the characteristics of an average set of fuel, which can be used to guide an energy harvester and wireless transmission node design.

ORIGAMI offers an “Express form” [64] which was used in this work, and allows one to quickly perform decay calculations on typical assembly and fuel types given limited knowledge of the fuel and its usage inside the reactor. A more rigorous analysis can be done if actual data from a reactor is retrieved, and the results are desired. In this simulation, the software was given the initial conditions and fuel parameters listed above, and various cooling times were input to simulate decay in both wet and dry storage. The input file generated for this work is shown in the Appendix section. The cooling time given in the line “cycle{ down=1825 }” was changed to reflect the desired cooling year, in days since removal from the reactor. The total decay production for 55 years after removal from the reactor (5-years wet storage, and 50-years dry storage) is shown graphically below in figure 5.2, one of the available outputs of the ORIGAMI simulation. From this, one can get a feeling for the total radiation which would be generated within the dry cask, and which isotopes provide a majority of the decay for various years throughout the storage lifetime.

Additionally, the code was updated to give the total number of both gamma particles and neutrons generated by the decay of the spent fuel in a second, for a given year, along with their spectrum placed into energy bins which can be chosen by the user. Shown below in table 5.1 is the total decay heat, gamma intensity in number/second, and neutron intensity in number/second generated by the fuel for years 5 – 55 after removal from the reactor, i.e. 50-years in dry cask storage. Finally, a file containing the entire material make up of the spent fuel at the decay year is also generated. Each of these radiation and materials files was also formatted to provide input into an MCNP simulation. While the ORIGAMI analysis was able to provide total gamma, neutron, decay heat, and material lists for every year, this simplified modeling is not able to provide detailed information on where the gamma density is strongest within the dry cask, and its effect on and from other materials in the cask. For more detailed modeling containing specific information on the dry cask studied, an MCNP calculation was created using the data produced from the ORIGAMI analysis, as is discussed in the next subsection.

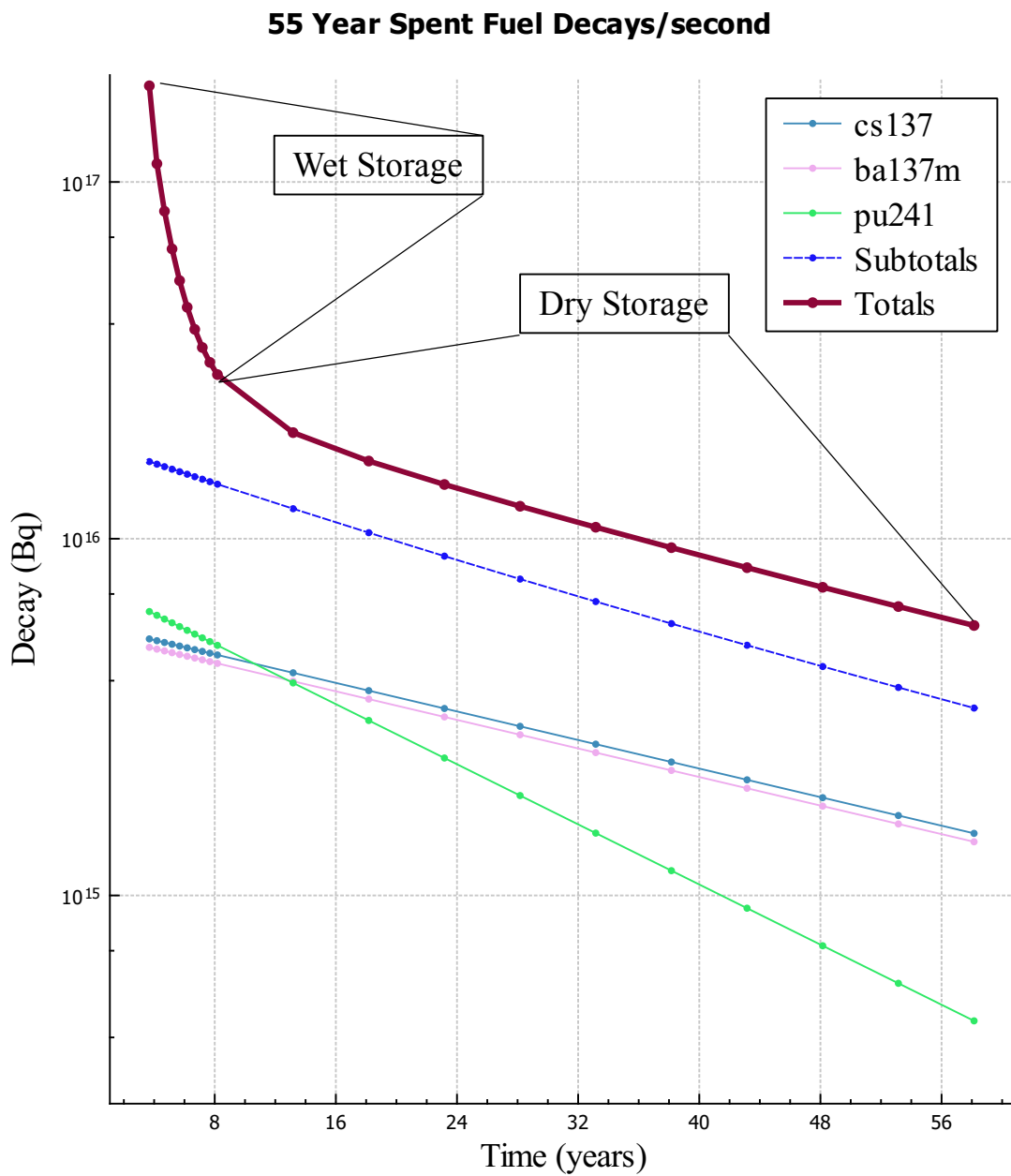


Figure 5.2. 1 MTU spent fuel decay from removal from reactor to 50-years dry storage. A subtotal is given for the three most active isotopes.

Table 5.1. Decay heat, gamma spectrum, and neutron spectrum from the 15 MTUs of spent fuel for 50 years of dry cask storage.

Year (Since removal)	Decay Heat (kW)	Gamma Intensity (#/s)	Neutron Intensity (#/s)
5	38.44	2.64×10^{17}	1.02×10^{10}
10	24.52	1.47×10^{17}	8.4×10^9
15	21.07	1.20×10^{17}	7.0×10^9
20	19.00	1.04×10^{17}	5.9×10^9
25	17.31	9.2×10^{16}	4.9×10^9
30	15.85	8.2×10^{16}	4.1×10^9
35	14.56	7.3×10^{16}	3.4×10^9
40	13.42	6.5×10^{16}	2.9×10^9
45	12.40	5.8×10^{16}	2.4×10^9
50	11.49	5.1×10^{16}	2.0×10^9
55	10.67	4.6×10^{16}	1.7×10^9

5.2.2 MCNP6 Model and Gamma Heating

In order to study the heating effect when placing tungsten within the MPC canister, an MCNP6 [65] simulation of the dry cask was created. MCNP is a Monte Carlo based software created by LANL and distributed by ORNL which has been used to simulate particle transport in nuclear problems for many years. Generally, it is used to study the effect of radiation on a wide range of materials and structures as desired by the user. In this project MCNP was used to simulate the material heating which would be expected to be generated in a tungsten plate placed within the dry cask. The simulation was run using the gamma particle and neutron spectrums along with the material list produced by the SCALE analysis outlined in the previous section for 50 years in dry cask storage. Varying the storage time allows for the design to take into account changes in radiation over the lifetime of the energy harvester and sensor during its operation in the dry cask. An example of the simulations made for this project is depicted in the following figures 5.3 and 5.4 showing cross sections of the dry cask.

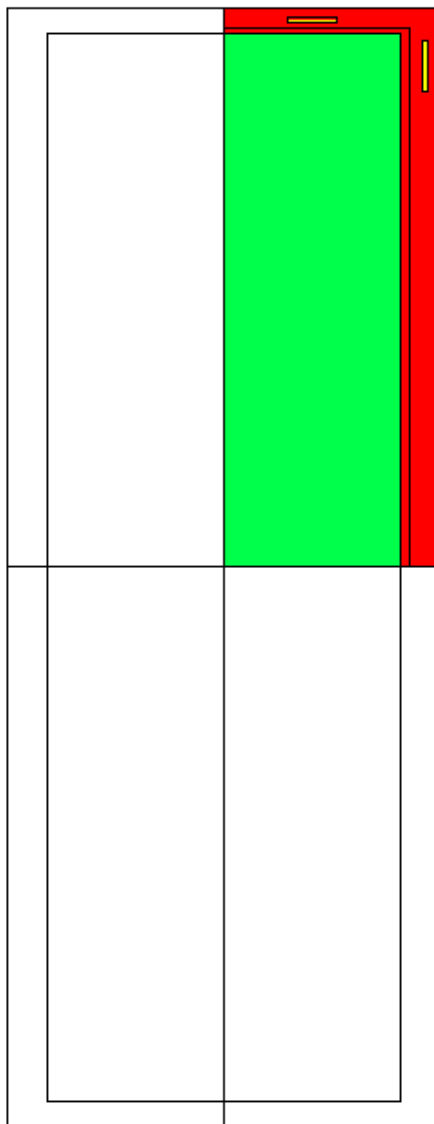


Figure 5.3. Vertical Cross section of the MPC simulated in MCNP6. Green: Stainless Steel Basket, Red: Helium, Yellow: Tungsten.

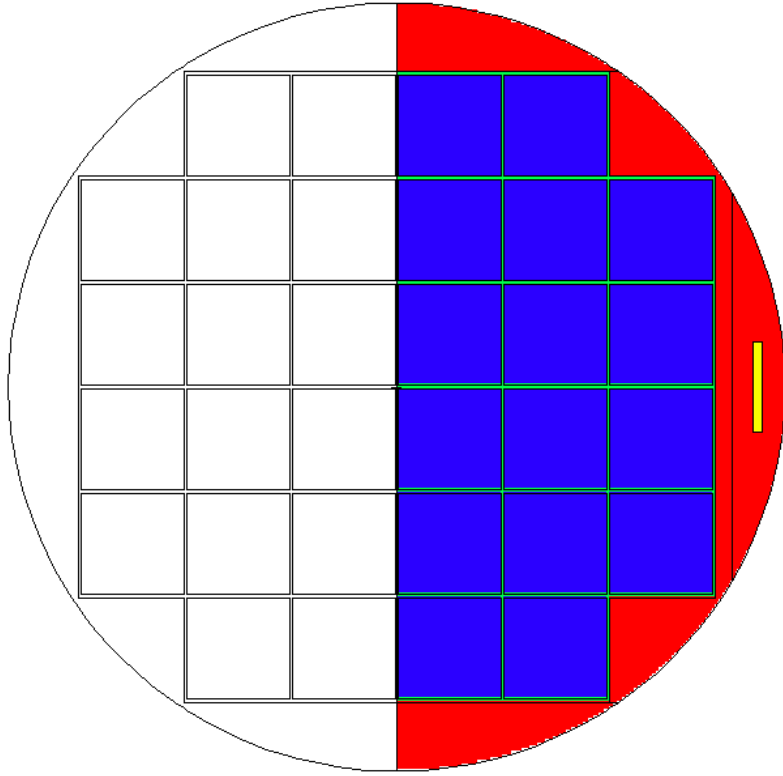


Figure 5.4. Horizontal Cross section of the MPC simulated in MCNP6. Blue: Fuel Materials, Green: Stainless Steel Basket, Red: Helium, Yellow: Tungsten.

In these figures, color sections represent places where the simulation tracks particles that are generated in the fuel, while white sections represent void, where the simulation releases particles from memory, thus a quarter cask model was used. Discussion on why a quarter model is used is made later in this section. Dimensions used in this simulation are those listed in section 2.3 for the design of a Holtec dry cask system [29]. In these figures, first, the blue sections are locations where the fuel is stored. An assumption and simplification has been made here in which material in these sections is a homogeneous mixture of all the elements present in the fuel during the year being simulated. It was decided to remove detailed representations of the fuel assemblies to reduce computational time and effort, and considering the majority of material filling these sections is accounted for by the ORIGAMI output. A full list of the materials generated by ORIGAMI will not be given here as it is quite long, however the reader can find an example of the full simulation run for year 5 in the appendix of this thesis. This assumption for homogenized fuel assemblies seems a safe one to make considering much of the fuel assembly sections are filled with material, and the purpose for simulation was to give an estimation of material heating in the tungsten plate

taking into account gamma absorption by other materials in the cask. Secondly, green sections represent the stainless steel basket. A material comprised of 85% iron, 10% chromium, and 5% nickel to simulate the stainless steel was applied to these sections acting as the basket. Third, red sections indicate helium gas where the density of the helium is estimated from the ideal gas law with a temperature of 100 °C and pressure of 3.3 atm. Finally, two tungsten plates were placed in the cask to see effects of material heating on the side of the cask and on the top, above the fuel assemblies. These tungsten slabs are depicted in yellow, their cross section is 20 x 20 cm², with a thickness of 2 cm.

To simulate gamma generation in the fuel a gamma source term was applied to start gamma radiation anywhere in the blue sections, representing the fuel assemblies. This gamma radiation was spread evenly throughout the fuel assemblies with equal probability to start anywhere in the fuel assemblies. Gamma particles were assigned a starting energy anywhere between 0.01 – 20 MeV with a probability given from the output of SCALE for the year desired to be simulated. These gammas were then allowed to propagate outward from their starting position in any direction with equal probability. MCNP also allows users to “tally” certain statistical properties of the system, one of them being the material heating. Thus a material heating tally taking into account all photons, neutrons, and electrons was assigned for both tungsten slabs. The units of this tally were assigned by MCNP to be in Jerks/(g*particle) where 1 Jerk = 10⁹ Joules, and the gram is referring to the mass of the cell being tallied. Therefore, output of the tally was normalized to the mass of the cell and number of particles being generated. The simulation was run until all statistical checks were well passed by the MCNP6 software and error was around 5%, in this case it took 2.85 x 10⁶ gamma particles being transported.

It is worthwhile here to discuss the error analysis in MCNP and the methods used in this simulation to reduce error. This section is intended to provide insight into the simulation performed in this task, however, should the reader be interested in further discussion, he/she is directed to a very good MCNP primer by Shultis [66] which discusses error and error reduction in great detail. In general, for every problem run, a 10 parameter statistical check is made by MCNP to tell the user how well the simulation behaved. These include: 1. a check for random behavior, 2. a three-part check on the relative error, which includes the value, a check ensuring the value decreases with particle number, and a check on the decrease rate, 3. a three-part check on the variance of the variance including all three parameters as in 2, 4. two checks on an internally calculated figure of

merit, and finally, 5. a check on the slope of the calculated PDF (Probability Distribution Function). The relative error and variance of the variance are both desired to be less than 0.1, or 10%, and the slope of the PDF should be larger than 3. If all statistical checks are passed, the simulation can be believed to be very precise. The accuracy is of course determined by the assumptions made in the simulation, and any simplifications from real geometry and behavior.

The simplest method for decreasing error in the simulation is to allow more particles to run. This, however, can be the most time consuming, as complicated simulations as done in this analysis may take many hours to run, thus other methods were also used to increase precision. The first used here was to simulate only a quarter of the full dry cask to enable more particles to be run in a smaller amount of time. This simplification is reasonable, as it is assumed that the vast majority of gammas generated in the other three sections of the cask would contribute very little to energy deposition in the two tungsten slabs. To check this assumption, one simulation was run with the full cask being simulated, and thus the full gamma source, and a second simulation was run with the quarter model, and thus a quarter of the gamma source. To appropriately compare the two results, heat generation tally results from the quarter cask were divided by 4, as the tally is normalized to the source particle number, and only a quarter of the total gammas are simulated in the quarter model. A comparison of the two tallies is given below in figure 5.5, where the heat generation tally result is plotted for an increasing number of particles run along with error of each result. As can be seen, both models appear to converge on the same result, however the quarter model converges much faster, and the error is much smaller, ~4%, as compared to >10% in the full cask simulation. Thus, considering even after 2.8 million particles the full cask had not converged, and all statistical checks were not passed, it was reasoned that a quarter model would provide better results, with less simulation time required.

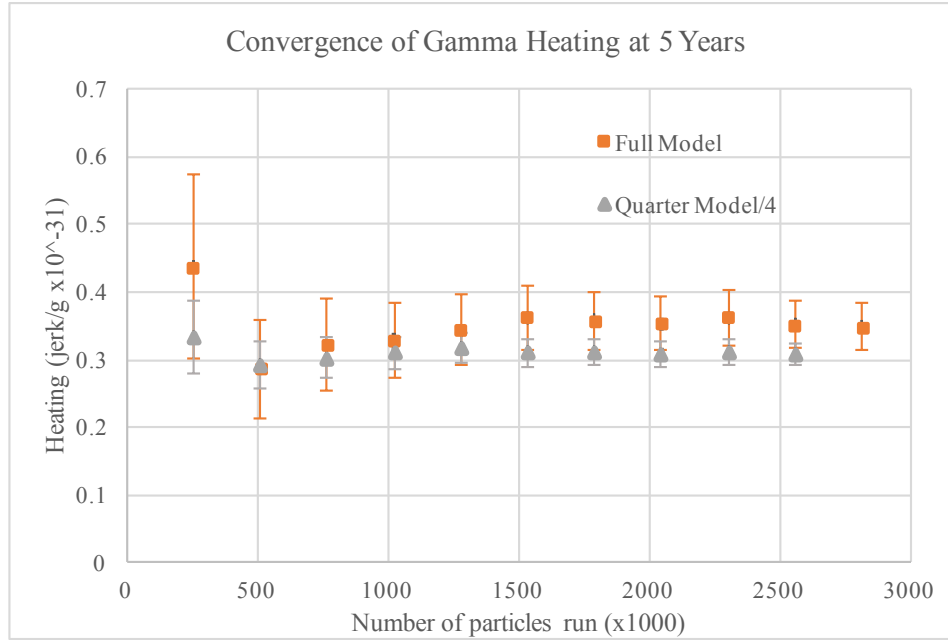


Figure 5.5. Comparison between the heating tally results of both a full cask and a quarter cask model.

Secondly, a method called geometry splitting was used. To use this method, geometries in the system are split into sections, and each section is assigned an increasing cell importance for the particle being transported and tallied. A particle leaving a cell of lower importance to higher importance has an increased probability to split into multiple particles, thus appropriate geometry splitting creates a cascade of particles being “pushed” towards the region of interest. To compensate for the addition of particles into the system, the overall computational weight of each of the split particles is also reduced accordingly to maintain statistical acceptance. In this way many particles can be transported through a section of high cell importance without the need to run a large number of overall simulated particles. In this simulation cell importance is increased moving from the fuel to the basket, and again from the basket to the helium which is itself split into two sections. This geometry split can be seen in figures 5.3 and 5.4 as a line through the red helium sections. Importance is again increased in the outer helium section, and finally increased once more in each of the tungsten sections. In this way many particle histories are tracked in each of the tungsten slabs, however the same number of source particles are run, allowing for better statistical performance in the heating tally while also keeping the simulation time reasonably low.

Results of the heating simulation were tabulated and analyzed using an excel spreadsheet. In order to calculate the heat generation rate in each of the tungsten slabs, the following calculation was used.

$$\text{Energy Generation} = (10^9)(H)(M)(N)$$

Where H is the heating result from the tally in Jerks/(g particle), M is the mass of the tungsten slab being heated in grams, N is the total number of gammas per second, and the factor of 10^9 is used to transfer units from Jerks to Joules. Thus energy generation has a unit of Watts. The simulation and calculation were both run for a total of 11 cases, every 5 years from year 5 (start of dry storage) to year 55 (50 years of dry storage) to see the heating effect and trend throughout the life of the dry cask and energy harvester. Shown below in figure 5.6 are the results for energy generation due to gamma radiation in a $20 \times 20 \times 2 \text{ cm}^3$ slab of tungsten both at the top of the fuel assembly basket, and to the side, both depicted in figure 5.3. As can be seen, approximately 2 W is generated in the tungsten slab above the fuel assemblies, and 1.25 W is generated in the slab beside the assemblies in the first year of storage. This heat generation drops quickly in the next 5 years, and eventually at 50 years in dry storage there is 200 and 300 mW generated in the side and top slabs respectively.

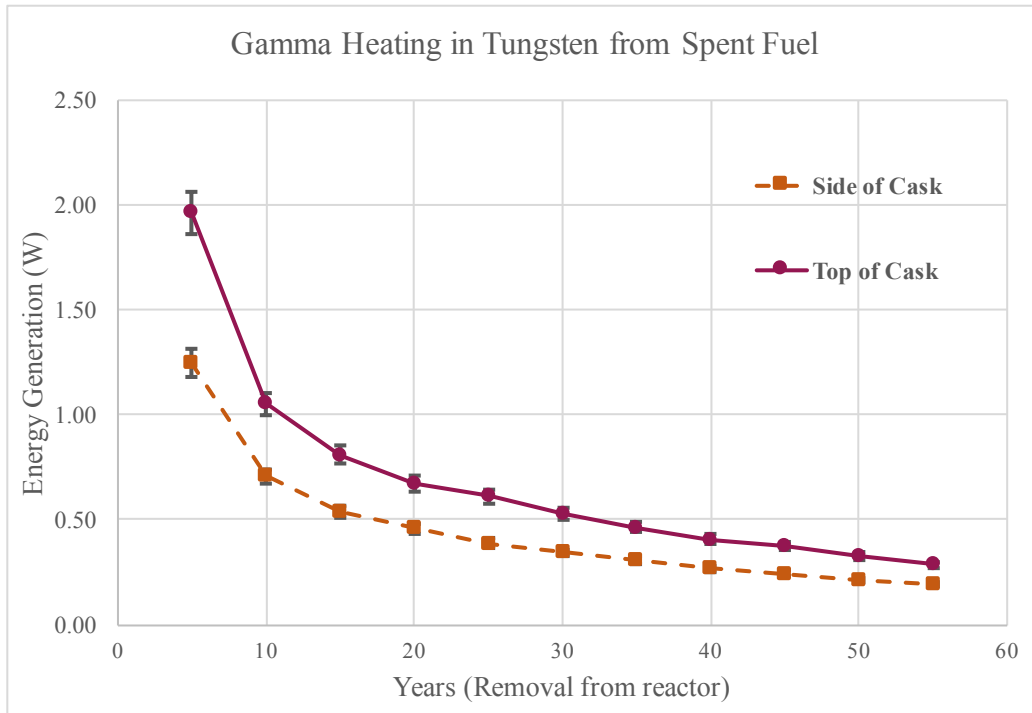


Figure 5.6. Energy generation in tungsten at the top and side of the MPC canister for 50 years of dry cask storage.

Other simulations were run as well, moving the tungsten plate around within the canister. Appropriately, tungsten placed closer to the basket wall absorbed more gamma radiation than did slabs placed closer to the canister wall. In general, for each case, the energy generation followed the same trend seen above, dropping by about one order of magnitude over the course of 50 years.

Effects from neutron generation in the fuel were also considered and a simulation was run for the first year of dry cask storage (year 5 since removal from the reactor). The results for heating in the tungsten for this year were only approximately 1 micro watt in both top and side plates, and thus further simulation of neutron transport for other years was not performed, as the result does not contribute significantly to the heat generation. This is largely due to the fact that the total number of neutrons generated by the fuel is seven orders of magnitude less than gammas. In fact, the heating tally normalized to the particle number was actually found to be one to two orders of magnitude larger for neutron transport rather than gamma transport, however, due to the fact that millions more gammas are generated each second, their effect in material heating is much more pronounced. Certainly, however, in areas where there are more neutrons present, such as in the reactor itself, heating due to neutron interactions would be expected to contribute much more to material heating.

Evidentially material heating is less significant than originally hypothesized, at least within a dry canister. This is largely due to the fact that much of the gamma radiation produced in the fuel is absorbed by the surrounding fuel, and basket. In order to utilize this heat source the plate and harvester must be very well insulated, such that a significant temperature rise in the plate is generated. Were such a plate placed inside a different nuclear canister, such as in the reactor vessel itself, a much larger heat generation would certainly be present. In order to investigate placement of an energy harvester, and other possible forms of energy for harvesting, the thermal environment within the cask was also simulated using the above SCALE analysis results.

5.2.3 Thermal Modeling of Dry Casks

In order to provide a better understanding of the thermal environment in the MPC and guide placement of the energy harvester for optimum production of a temperature difference, a CFD analysis was done by Yongjia Wu, a collaborator on this project. His simulation took into account a dry cask from Holtec international with dimensions as described earlier, as well as all of the known material properties of both the fuel and the helium. Heat generation in the fuel was forced

to follow the same profile as has been widely used and found in past literature [32,33], with the full decay energy equaling that produced by the SCALE analysis done in 5.2.1 and presented in table 5.1. Additionally, appropriate values for the thermal conductivity of the fuel, as taken from experimental analysis literature [33], were used, and convection and thermal radiation were considered in both the helium within the MPC, and the air in the air gap between the MPC and the concrete overpack. Additionally, when examining the Reynolds number of the flow in the air gap between the MPC and concrete overpack, the flow was found to be in a transitional phase between laminar and turbulent. Thus two turbulence models were considered in his analysis. The two models used were a standard $k-\epsilon$ model and a modified SST $k-\omega$ model. Generally, the standard $k-\epsilon$ model works well for fully developed flows away from wall regions, however, as much of the analysis in this research is done near wall areas, the SST $k-\omega$ model was also used, which is the most general turbulence model, and works reasonably well for many turbulence flows. Again, the simulation was done for multiple years of dry cask storage to see the change in properties over the lifetime of the dry cask. Overall temperature results for the simulation at the beginning of dry cask storage are presented below in figure 5.7, and flow velocity is shown in figure 5.8.

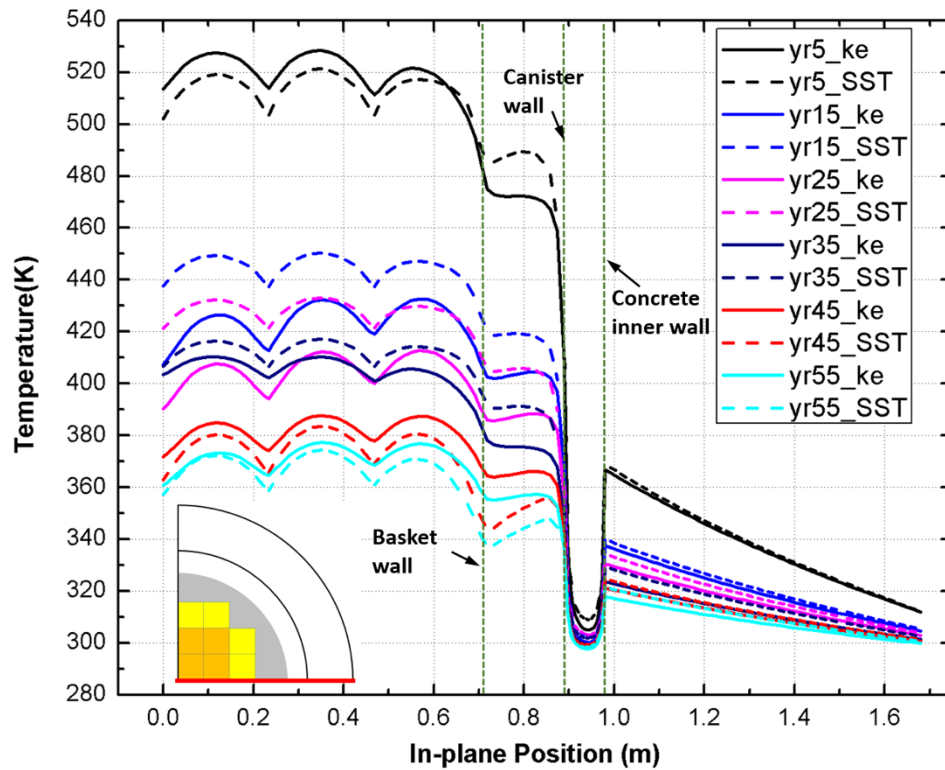


Figure 5.7. Temperature profile radially along the center of the cask for 50 years of dry cask storage. Both the standard $k-\epsilon$ and SST $k-\omega$ models are presented.

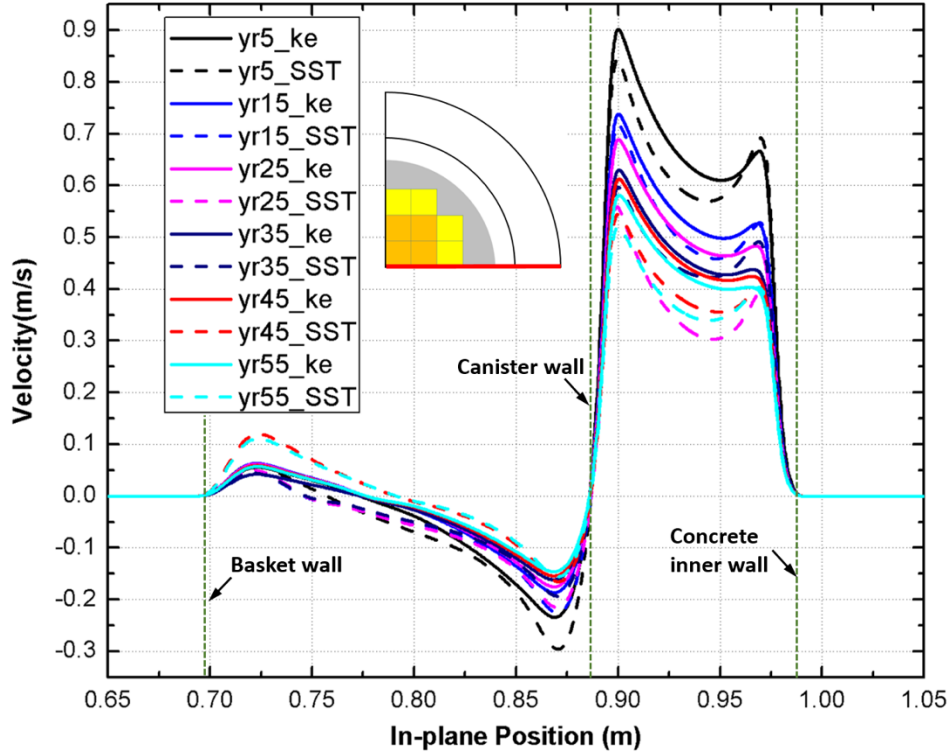


Figure 5.8. Flow velocity profile radially along the center of the cask for 50 years of dry cask storage. Both the standard $k-\epsilon$ and SST $k-\omega$ models are presented.

As can be seen in figures 5.7 and 5.8 characteristics of the environment within the dry cask change throughout its service lifetime due to the reduction in total decay heat output of the stored fuel. Considering all of the above characteristics of the dry cask MPC, designs for two energy harvesters are made in the following section, one attempting to make full use of the material heating principle, and one using the thermal environment within the canister.

5.3 Harvester Design

To guide the design of both energy harvesters for a dry cask canister, the temperature and flow velocity within the canister should be well analyzed over the lifetime of the cask. Shown below in figure 5.9 are the temperature and flow velocity profiles for years 5 and 55 (50-years dry cask storage) superimposed on each other. These are taken along the radial direction at the center (axially) of the cask, the line of which is shown above in figures 5.7 and 5.8. As can be seen, there is: one, an enduring temperature gradient present between the fuel, helium gap, and MPC wall; and two, an enduring helium circulation flow along both the wall of the fuel basket, and the wall of the MPC canister generated from convection in the helium. Using these results as a guideline,

two energy harvesters are designed for placement between the basket and canister walls along the side of the MPC. One takes advantage of only the gamma radiation present within the canister through material heating of a tungsten plate and is a proof of concept in order to inform future designs of harvesters which utilize ionizing radiation. A second, more applicable design takes advantage of the thermal environment and gradients within the dry cask.

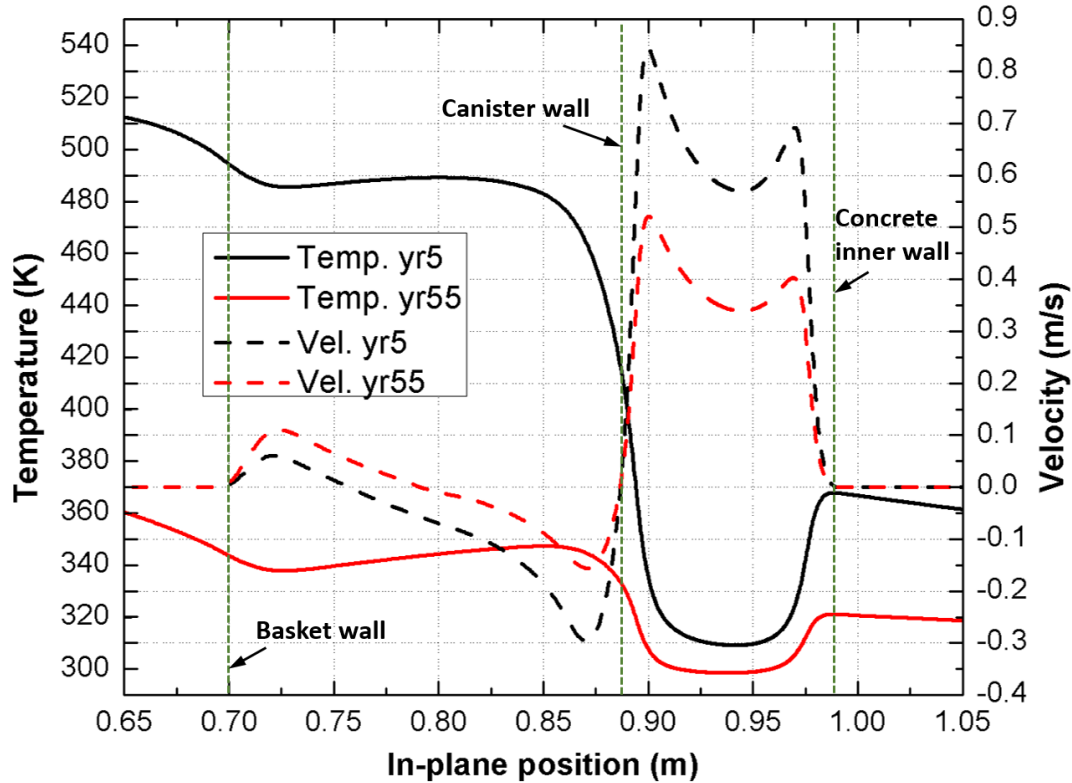


Figure 5.9. Temperature and flow velocity profiles radially along the center of the canister. Given are results for year 5 and year 55 since removal from the reactor.

5.3.1 Gamma Heating Energy Harvester

In regards to the hypothesis presented in section 5.1, it is worthwhile to examine the potential of an energy harvester utilizing only gamma radiation, if only to show the difficulty in using such a solution. As discussed earlier in section 5.2, a tungsten plate of $20 \times 20 \times 2 \text{ cm}^3$ placed near the side or top of the basket within the MPC would only be expected to gather between 1 and 2 Watts of energy accumulation in the first year of storage. This can be considered as an energy generation term within the tungsten and, once realizing this along with the fact that convection or conduction to the environment would remove any additional benefit gained from material heating, it is reasoned that such an energy harvester would need to be very well insulated from its environment.

Additionally, it was found during MCNP simulations that the closer the plate is located to the basket the higher the energy of gamma radiation it would absorb. Given these two facts, the following design has been considered, as depicted below in figure 5.10.

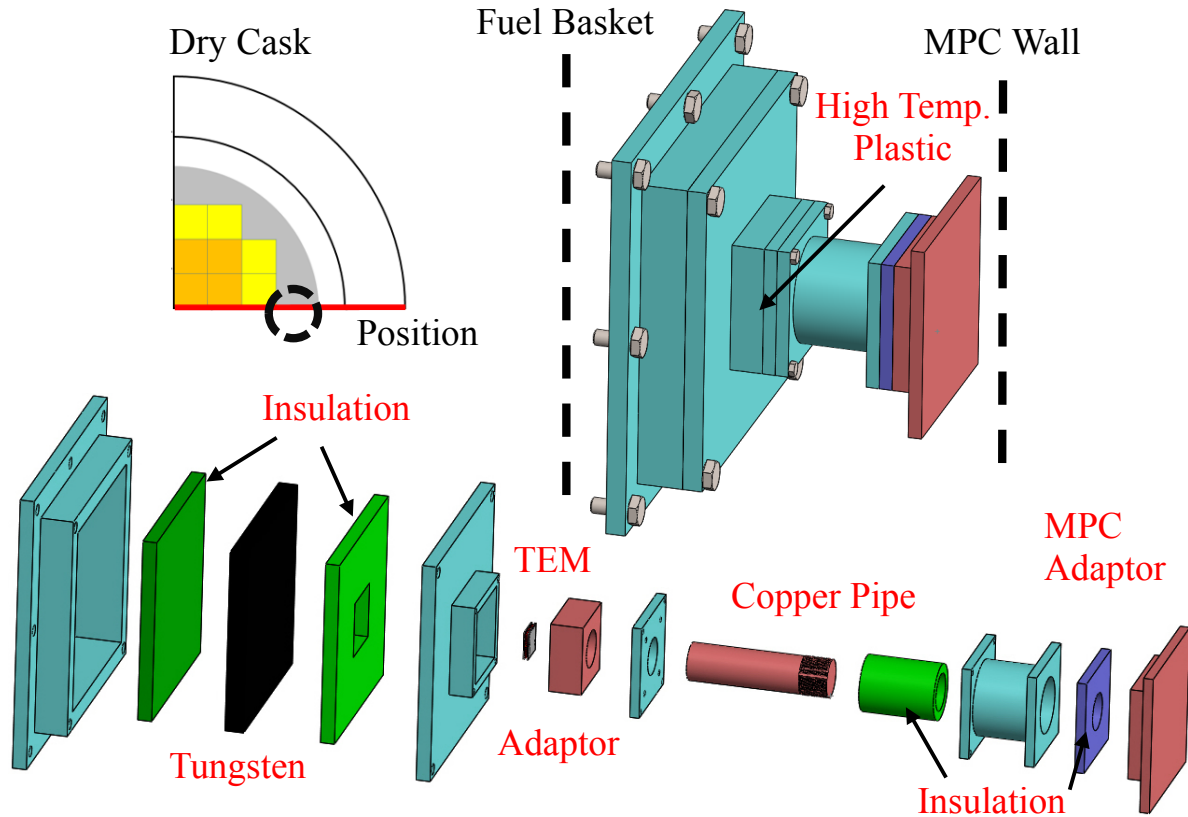


Figure 5.10. CAD representation of the Gamma Heating energy harvester.

Here the tungsten plate has been encased by high temperature plastic to aid in thermal isolation, and is bolted to the wall of the basket. In running various MCNP6 simulations, it was found that material added prior to the tungsten would cause significant scattering of the gamma particles, reducing the energy level of those absorbed and resulting in a reduction in material heating. Thus, considering fiberglass insulation is very porous, it was reasoned this would likely be a suitable solution to insulate the tungsten closest to the basket. An MCNP6 simulation was run both with and without a simulated layer of fiberglass in front of the tungsten slab, and it was found that 2.58 Watts was absorbed without insulation, and 1.07 Watts with, at the beginning of dry cask storage (year 5). To use the small increase in temperature in the tungsten plate, a TEM made of Bi₂Te₃ is mounted to the back of the plate using a copper adaptor and surrounded as well with insulating plastic. Only one TEM is used based on the fact that such a design has limited heat flux,

and the addition of more TE modules would certainly reduce the temperature difference across any one module, reducing the overall power output [13,41]. To sink the heat from the back of the TEM, ensuring a temperature drop, the back of the mounting block is attached to the MPC wall via a backward threaded rod system. The rod is free to rotate in the adaptor, and will tighten against the MPC wall. A compressible layer of insulation between the MPC wall adaptor and plastic tube allows for the threaded rod to clamp or unclamp the system from the MPC wall. In this way the TEM is thermally connected to the cooler MPC wall without the need to mount to the canister.

A COMSOL simulation was performed on this harvester to estimate the expected voltage output for the first year of dry storage (year 5). The tungsten plate, surrounded by insulating material was provided an internal energy generation term of 1.5 Watts. Assuming the rest of the system is insulated as well, the cold side of the MPC adaptor was set to be 410 K (136.85 °C) per results from the CFD simulation. Results are shown below in figure 5.11. As can be seen 0.298 V can be generated at year 5 from a temperature difference across the TEM of 7 °C. Using the reported value of 4 Ω for the internal resistance of the TEM [42], the power across a matched load is 5.55 mW, much lower than the stated necessary 16 mW in chapter 2.

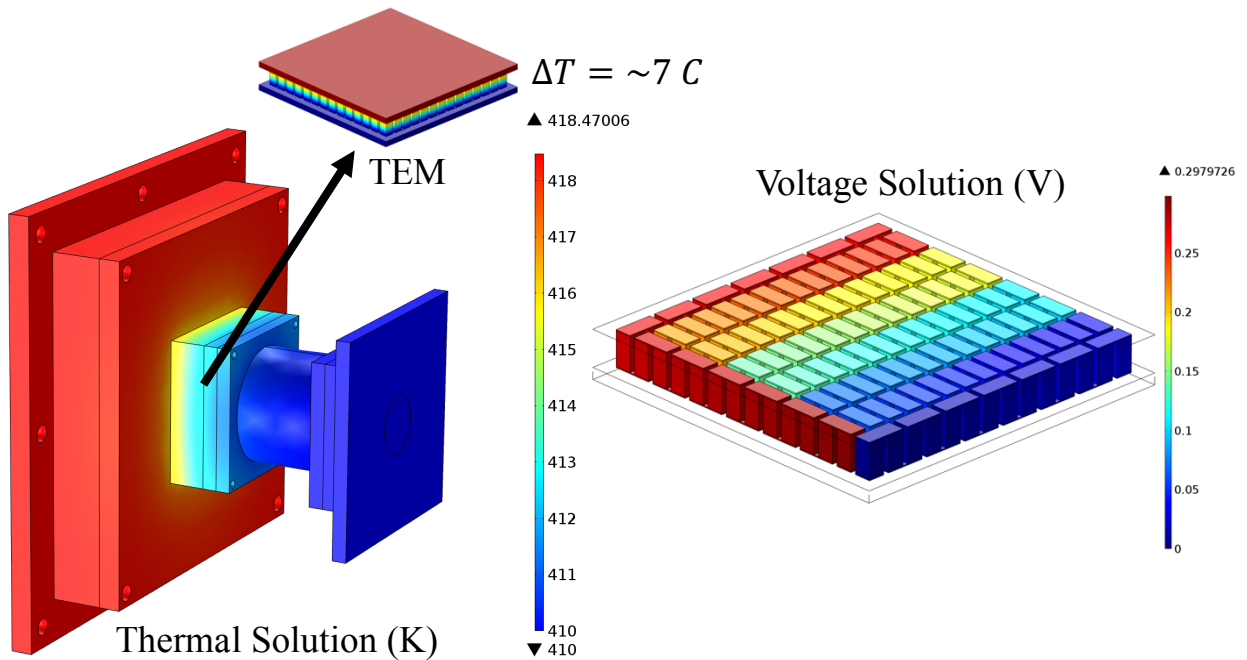


Figure 5.11. COMSOL simulation of the Radiation Heating energy harvester depicting the tungsten plate and TEM, along with temperature and voltage results.

Of course, more heat could be supplied to the tungsten plate, and thus the TEM by simply removing the insulation on the front of the slab and allowing conduction to occur from the high temperature basket wall. As a rough estimation, considering the thermal resistance of the TEM is large, if the tungsten plate was allowed to sit on the high temperature basket, looking at figure 5.9, it would be expected that a temperature drop on the TEM of around 70 °C might be achievable in the first year of storage, and 10 °C in the 50th year of storage. Based on the data sheet for the assumed Hi-Z 2 module [42], this would correspond to a power output near 500 mW in the first year, and close to 6 mW in the 50th year of storage. This rough estimation indicates that the use of the thermal environment to heat the tungsten is close to 100 times more effective than using gamma heating alone. However, the design presented above is intended simply to provide information regarding the hypothesis that gamma radiation can be harvested using material heating.

5.3.2 Discussion on Radiation Harvesting

At this point it is worthwhile to discuss the drawbacks from using radiation for a power source within the dry cask canister. It should first be noted that the tungsten plate alone in the radiation harvester would be close to 26 kg, very heavy and cumbersome for a simple, low power output energy harvester. A plate this large, while being necessary to gather a significant amount of gamma radiation, is additionally prohibitively expensive, making the premise unattractive. As addressed in chapter 2, all literature found discussing radiation from a dry cask canister did not take into account absorption by the basket or fuel itself. Thus the hypothesis made using these past results simply overestimated the amount of energy available for harvesting from gamma radiation. Once absorption of gammas by the fuel and the stainless steel basket is taken into account, the actual predicted material heating according to MCNP6 is very low. Even after surrounding the plate with very thick insulation, the predicted energy output for the one usable TEM is quite small as shown above, especially when considering the overall size of the harvester. Considering as well that more than 20 mW may be necessary for complex electronics involved in through wall transmission, it is evident that harvesting gamma radiation does not offer a suitable solution. This said, the premise has been validated, and may be shown to be possible if given better circumstances. Were the harvester placed in a different nuclear canister, such as the main containment vessel in the nuclear power plant where both gamma and neutron radiation are expected to be many orders of magnitude larger, this may be an acceptable form of energy harvesting.

5.3.3 Convective Flow Energy Harvester

Considering the power output of the radiation based energy harvester is much lower than expected and needed, a secondary, more applicable energy harvester is therefore designed. When examining both the flow and temperature profiles in figure 5.9, two characteristics are evident. First, there is a large temperature drop at the wall of the canister due to the air current outside the MPC. This makes the wall a convenient location to place a heat sink for a TEG device, as the temperature is significantly lower than in the helium closer to the fuel basket. Secondly, it is noted there is a persistent convective flow close to both the basket and canister walls, the larger of which being at the MPC wall. Taking these two characteristics into consideration, it is evident that a convective flow based energy harvester would be quite effective. Shown below in figure 5.12 is the initial design for such an energy harvester, which is intended to be oriented for placement along the MPC wall, such that the convective flow velocity is a maximum through the fins.

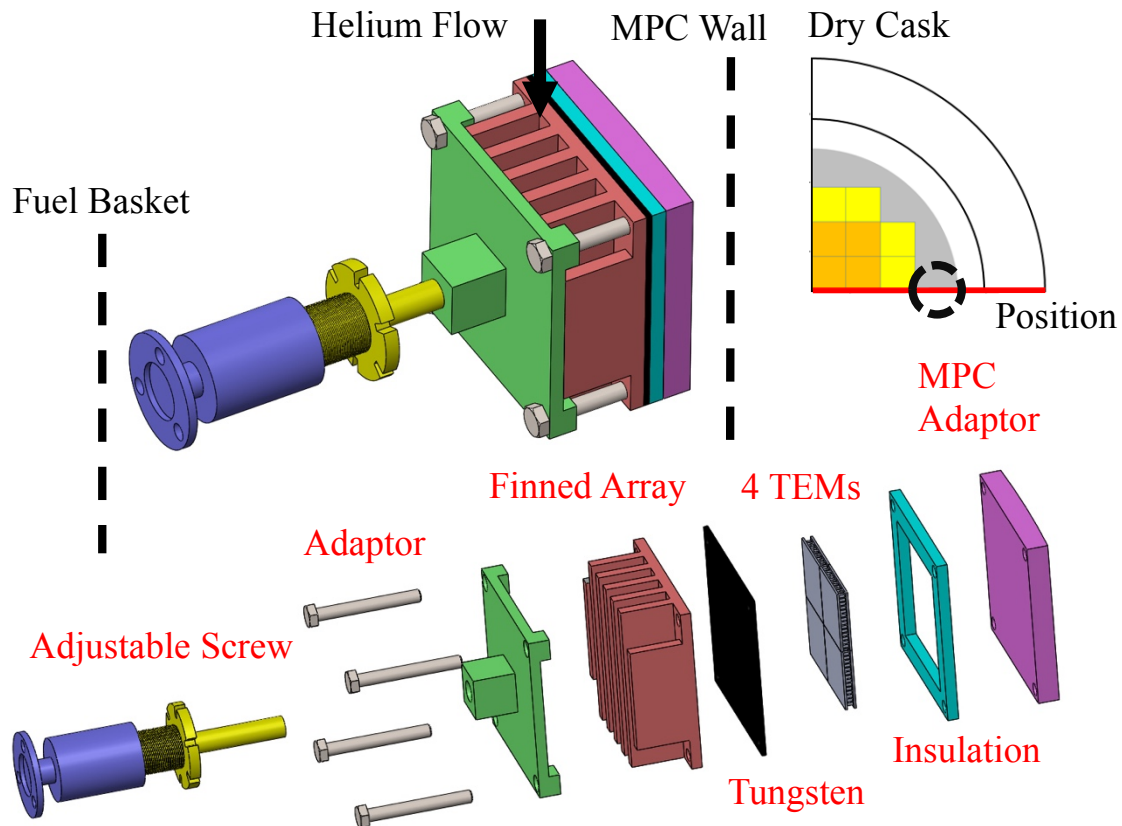


Figure 5.12. A CAD schematic representation of an energy harvester taking advantage of the convective flow within the MPC canister.

Here a copper fin array is used to improve the heat flow to the hot side of four Bi₂Te₃ TEMs. These are assumed to be HZ-2 modules from Hi-Z technologies [42] of size 3 x 3 x 0.518 cm³, and are attached to the back of a tungsten plate employed to help shield from gamma radiation. A copper heat sink adaptor is mounted to the back of the TEMs to thermally attach them to the cooler canister wall. To make best use of the space while constraining the device to be relatively small the following dimensions were used: the fin array base has a length and width of 8 cm to accommodate the four TEMs, the height of each of the fins is 2.5 cm in order to penetrate the flow, and their thickness is constrained to be 5 mm to aid with machining. The copper cold side heat sink adaptor is curved to fit the contour of the MPC wall, and is thin enough such that the entire package has a height of 6 cm, making full use of the convective flow along the wall seen in figure 5.9. Finally, it was reasoned that mounting to the MPC wall would be undesirable, considering the potential for containment rupture, thus a mounting rod is positioned, free to rotate, off the end of the finned array which can be screwed into and out of a base attached to the basket wall. In this way, the harvester can be “clamped” to the MPC canister wall, without the need for mounting to the canister itself, making the design modular, and easy to install. Thin sheets of pliable graphite will be placed between the adaptor and the canister wall to minimize surface roughness issues.

The finned array was optimized for the conditions of the cask based on the flow along the wall. The parameter chosen to optimize was the fin number, thus the dimensions of the baseplate, fin height, and fin thickness were taken to be constant, and the fin spacing was varied. It was reasoned that the flow along the canister wall could be considered a forced convective flow, and in light of this, optimization was performed accordingly as outlined below.

First, as theorized by Bejan in his work from 1992 [67] about optimized fin arrays in a forced convective flow, and adapted for use more recently by Wang et. al [68], two approximations exist for the heat transfer rate to/from a finned array in a forced convective flow. The first, appropriate for arrays with narrow channels between successive fins, is as follows

$$\frac{Q_{nc}}{\Delta T} = C_P \left(\frac{\rho W_{hs} H_f}{1 + \frac{\tau_f}{S_f}} \right) \left(\frac{S_f^2}{12\mu} \right) \left(\frac{P}{L_{hs}} \right) \quad (5.1)$$

where C_P is the specific heat at constant pressure for helium calculated at 3.3 atm, ρ is the density of helium calculated at 3.3 atm, W_{hs} , and L_{hs} are the width and length of the heat sink (finned

surface), τ_f , S_f , and H_f are the thickness, spacing, and height of the fins respectively, and P is the pressure drop across the finned surface, as calculated below in equation (5.3).

Secondly, an approximation appropriate for arrays with wide channels is given by

$$\frac{Q_{wc}}{\Delta T} = 1.208 \left(\frac{k_f W_{hs} H_f}{1 + \frac{\tau_f}{S_f}} \right) \left(\frac{\text{Pr} L_{hs} P}{\rho v^2 S_f^2} \right)^{\frac{1}{3}} \quad (5.2)$$

where Pr is the Prandtl number, and k_f , and v are the thermal conductivity and kinematic viscosity of helium respectively. The pressure drop P in equations (5.1) and (5.2) is given below in equation (5.3). It was first theorized by Bejan [67], and then well outlined and condensed in an online publication by Simons [69].

$$P = \left(K_c + \frac{4 F_{app} L_{hs}}{D_H} + K_e \right) \left(\frac{\rho U_{inf}}{2} \right) \quad (5.3)$$

Here K_c and K_e are parameters based on the finned surface structure and can be found in the Simons publication online [69]. D_H is the hydraulic diameter for the flow, in this case being $2S_f$, U_{inf} is the velocity of the flow assumed to be constant, and F_{app} is given by the following formula, again from Simons [69]

$$F_{app} = \frac{\sqrt{\frac{11.8336}{L_{st}} + (f Re_{Dh})^2}}{Re_{Dh}} \quad (5.4)$$

where Re_{Dh} is the Reynolds number based on the hydraulic diameter, $L_{st} = \frac{L_{hs}}{D_H Re_{Dh}}$, and f is a polynomial function based on dimensions of the finned structure, and can be found approximated by Bejan [67] or Simons [69].

It is reasoned by Bejan that an approximate solution to the optimum fin spacing is given by the intersection of the above two heat transfer rates. Inputting parameters for the design dimensions and flow pattern given above, along with properties of the helium fluid surrounding the finned surface the following plot was generated in Mathematica, shown in figure 5.12. Fin number was calculated using the given fin thickness of 5 mm, and assuming the fins fill the base surface. As can be seen, the two approximations for heat transfer rate are plotted for varying fin number and

flow velocity. Evidentially, according to this analysis the crossing point and thus the approximate optimal fin number is between 7 and 8, and does not vary significantly with decreasing flow velocity, important considering as time progresses in the dry cask the flow velocity generated by helium circulation diminishes, as is seen in figures 5.8 and 5.9.

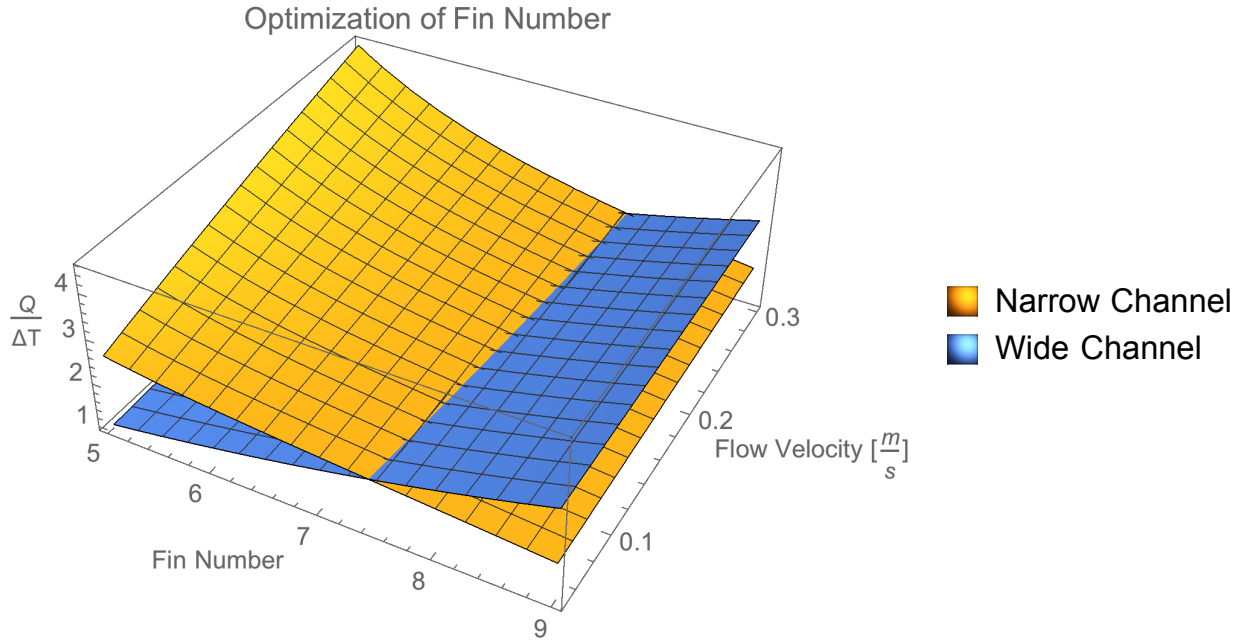


Figure 5.12. Optimization of fin number for a finned surface placed in the convective helium flow near the MPC wall.

It is hypothesized, however, that considering the geometry of this system is quite small the narrow channel might be a better approximation. In order to further address the issue, Bejan [67] also presents numerical analysis verifying this approximation. The ultimate conclusion of the paper is the finding that, for optimally spaced finned arrays, the following parameter (here coined the “Bejan Parameter”) should be close to 3 for flows with a Prandtl number below 0.72.

$$Bejan\ Parameter = \left(\frac{S_f}{L_{hs}} \right) \left(\frac{P L_{hs}^2}{\alpha \mu} \right)^{\frac{1}{4}} \quad (5.5)$$

Thus, considering the Prandtl number in the canister is 0.66, the following plot was made to find the optimal fin number. Shown in figure 5.13 below is the optimal fin number given the dimensions of the harvester plotted against various flow velocities, assuming the Bejan Parameter is equal to 3. As can be clearly seen, 7 fins give the optimal fin spacing for this flow, a confirmation

of the hypothesis that indeed the narrow channel result is more accurate. Important to note as well is the fact that this optimal fin spacing is relatively constant with decreasing flow velocity as would be expected throughout the life of the canister. Thus 7 fins were chosen to be used in the design.

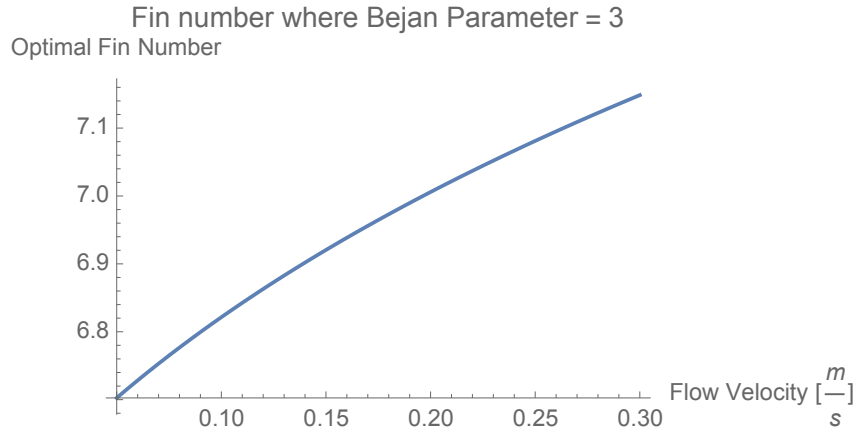


Figure 5.13. Optimal fin number when the Bejan Parameter is equal to 3.

Given the above work, a COMSOL simulation was performed for this harvester given initial conditions from both year 5, at the beginning of dry cask storage, and year 55, after 50 years of dry cask storage. In the first case at year 5, an ambient temperature of 480 K (206.85 °C) was applied, and the temperature of the heat sink on the MPC wall was taken to be 410 K (136.85 °C), both based on the CFD simulation in figure 5.9. Similarly, for the second case at year 55, a temperature of 346 K (72.85 °C) was given for ambient, and 333 K (59.85 °C) was applied to the MPC wall. A convective coefficient was also applied to the finned surface in both cases, and the coefficient was approximated using the work by Bejan [67], where the average convection coefficient is determined by the formula given below in equation (5.6).

$$\bar{h} = \frac{0.62(\rho P)^{\frac{1}{2}}}{Pr^{\frac{1}{2}}}(L_{hs}C_p) \quad (5.6)$$

Here the parameters are the same as given above, and thus the average convective coefficient is dependent on the pressure drop, which is dependent on both the flow velocity and the number of fins. Giving 7 fins and the expected flow velocity for both year 5 and 55 as approximated by figure 5.9, coefficients of 145 W/m²*K and 130 W/m²*K were found for both years respectively, and input into the simulation. It should be noted that this formula is stated as being the theoretical maximum, and thus results of the simulation are the upper limit on the performance which can be

expected by the system. Finally, four Bi₂Te₃ modules were attached to the back of the finned surface. The temperature and voltage results of year 5 are shown below in figure 5.14.

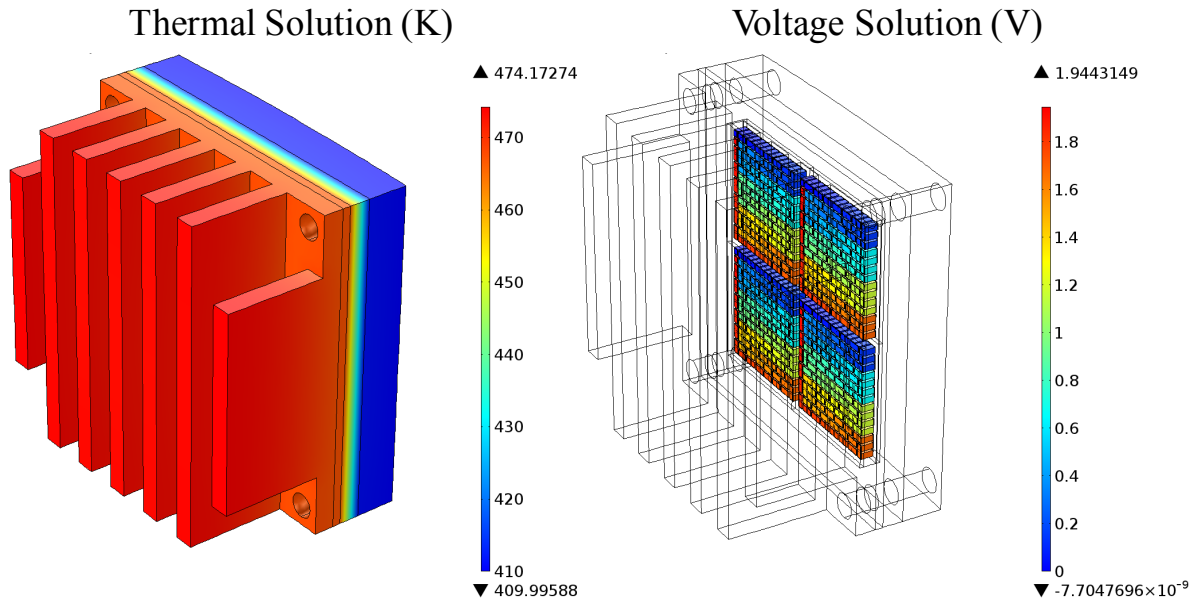


Figure 5.14. COMSOL simulation of the Convective Flow energy harvester depicting the finned surface, TEMs, and heat sink, along with temperature and voltage results for year 5.

A simulation was also run for the year 55 case, and major results of both simulations are given below in table 5.2. Based on these results, it is relatively straightforward to estimate the power output of the device. Given four TEMs placed electrically in series, one can show that the expected power supplied across an external resistor is

$$Power = \frac{16 R_L V_{OC}^2}{(4R + R_L)^2} \quad (5.7)$$

where R_L is the load resistance, V_{OC} is the open circuit voltage of one TEM, and R is the internal resistance of one TEM. Maximizing this equation with respect to load resistance, as is well known, gives a value of R_L equal to that of the total internal resistance. Thus, using the reported resistance value of 4 Ω per TEM [42], the matched load power of the device across a 16 Ω resistor is given as well in table 5.2. As can be seen, even after 50 years of storage, the use of thermal properties in the canister allows for enough power to be produced to run a wireless sensor, as estimated in chapter 2, and the power output is two to three orders of magnitude larger than the radiation energy harvester.

Table 5.2. Major results of COMSOL simulations on the Convective Flow energy harvester.

Year (Since Removal)	ΔT (K)	Voltage per TEM (V)	Matched Load Power of TEG (mW)
5	64.17	1.94	944.8
55	11.73	0.33	28.1

5.4 Summary

The objective of this chapter was to first come to a better understanding of conditions inside a dry cask storage canister for spent nuclear fuel, and then use the information to guide the design of an energy harvester for a wireless sensor within the canister. A SCALE analysis was performed given typical fuel being removed from reactors for storage in canisters. This gave decay heat along with gamma and neutron spectrums generated by the fuel for 50 years of dry cask storage. Using these results and the design of a Holtec canister shown in chapter 2, an MCNP6 simulation was created in order to study the distribution of gamma radiation in the canister, as well as the level of heating expected to occur in a tungsten slab placed within the MPC. Finally, a CFD analysis was performed and analyzed, resulting in both temperature and flow velocity profiles within the canister. Based on the results from the above comprehensive simulation two energy harvesters were designed, one as a proof of concept and guide for gamma heating energy harvesting, and a second more applicable design using the thermal environment. The gamma heating energy harvester employs a well insulated tungsten slab mounted on the basket wall, and simulation results show that only 5.55 mW can be harvested at the beginning of dry cask storage. Considering this harvester is quite large, heavy, and results in a small amount of harvested energy, the second energy harvester was designed to employ the convective current running along the wall of the MPC canister. A finned surface is utilized to create a local hot spot for four TE modules, which are then sunked to the canister wall. Results of a COMSOL simulation estimate that 944 mW of energy can be harvested at year 5, the beginning of dry cask storage, which drops to 28 mW after 50 years of storage. According to the work done in this chapter, it was found that the hypothesis originally presented in chapter 2, and again in 5.1 that significant energy can be harvested from gamma radiation is largely untrue. While a harvester can be designed, it seems to be rather impractical for use in a dry cask canister. If placed in locations with much higher gamma and neutron fluxes, the design may be of more use.

6 Conclusions and Future Work

6.1 Future Work

Based on the work done in this thesis, the following contributions can and should still be made to this work.

A thermal energy harvester for nuclear power plant piping has been designed, and the principle validated. Using this design, it has been shown to work continuously in a gamma radiation environment. This said, more experimental work should be done in neutron rich environments to see its response to neutron radiation. This is important because at points throughout the nuclear power plant high energy neutrons can be present. If there is any degradation to the system from neutron fluences, a study on the shielding of the harvester and its associated electronics should be made. Finally, a more comprehensive test should be performed where the harvester attached directly to a test reactor piping to see its performance and test the ability to power a wireless transmitter. This could be first accomplished by placing the system on a similar pipe in the coal plant located on campus at Virginia Tech, and then taken to a test reactor.

A vibrational harvester prototype was made which demonstrates a new way to increase the velocity of vibration, and potentially extract more energy from vibrating machines. While the design has proven to be feasible, from here a more concerted effort should be made to optimize the frame and harvester designs for a specific application. This could be done by selecting a specific machine, and designing a similar system for its operational frequency. In addition, a re-design should be considered to include a linear guide for the mechanism to ensure both the coil and magnet are well aligned. This would remove the need to have external attachments to align the two, and may increase the energy harvesting potential as interference and the induced friction could be minimized. The design would also benefit from deliberate matching of the masses for both the coil and magnet array. This would allow for the dynamics of the system to match the desired one peak output. The model can be further updated to take into account the coil inductance, cantilevered motion of the magnet and coil, and a more accurate estimation of the generator characteristics for full prediction of the voltage and power output. Finally, the system should be tested within a radiation chamber to show survivability in the harsh environments present within nuclear power plants, and can be extended to be adapted to a wide range of vibrating machinery.

Lastly, the two designs for the thermal energy harvesters within the dry canister should be machined and tested. Tests should include both a lab based proof of concept test, and a more realistic test, perhaps in an in-situ research oriented dry cask canister. Once the energy harvester has been proven, power conditioning, and sensor electronics should be made and tested as well for their survivability in the environment. The package should be well shielded and insulated, and can be tested as well in an intense radiation and thermal environment to show operational feasibility.

6.2 Conclusions

In this work two thermoelectric based energy harvesters, and an electromagnetic based energy harvester have been discussed. Building off a previous design for use in the nuclear power plant coolant system piping, a study has been performed on the impact of gamma radiation on the thermoelectric and heat pipe sections of the harvester. The system was taken to Westinghouse to be tested in a radiation chamber, where 200 kGy gamma radiation was applied, the expected amount encountered during a lifetime operation, or at 100 days after containment rupture. The performance of the harvester was monitored throughout the irradiation, indicating any effects on the system made by the radiation. Based on the results, it was found that there was little to no effect on the TEMs, while the heat pipe experienced drop in performance during cold start. This had an effect on the harvester, reducing the voltage output as well, however the total voltage output remained well above the needed voltage and power for charging batteries, or powering wireless sensor nodes, and the impact is expected to only be important during cold starts. Expanding this work to incorporate the design on higher temperature pipelines as are present in the primary coolant loop, a second energy harvester was created which places a hybrid TEM directly on the pipeline, and cools the system using a heat pipe integrated into a finned heat sink. 1.72 V and 3.0 W, respectively can be generated by this harvester at a source temperature of 340 °C. Results of this study show the feasibility of using such a system anywhere within a PWR nuclear power plant, and its survivability within ionizing radiation. Important to note as well is the ability for this design to continue power production during off-normal situations. Since thermal energy present within the coolant system will be expected to remain after an accidental shutdown of the plant, and the harvester has proven to remain operational even after enduring gamma fluxes expected during weeks after containment rupture, this form of energy harvesting could potentially provide a sensor

enough energy to transmit information during the most critical times after an event, increasing overall plant safety.

Secondly, a vibrational energy harvester was designed in order to amplify the velocity of a small amplitude base vibration for a coil and magnet array of an electromagnetic generator. Experimental results show an approximately 5.6x increase in velocity over the proof mass alone. Approximately 2 mW peak power was able to be produced using the harvester with 0.001-inch amplitude base vibration. While the power output is smaller than the required 10s of mW, the harvester demonstrates an important step in the energy harvesting community, as the vibration of a small vibration amplitude source was successfully amplified for use by an electromagnetic energy harvester. An optimization of the design for a specific machine could be made, which should increase the power output significantly. To help with this, a model was created which can predict the natural frequencies of sections of the system, along with approximate voltage output. This model can further be used for the design of a system similar to this, given parameters of the beam and generator. The electromagnetic energy harvester is hypothesized to be largely resistant to both gamma and neutron radiation, as past research has shown neodymium magnets are entirely unaffected by gamma radiation, and only affected by neutron radiation well above the dose expected to be seen at vibrating pumps within nuclear power plants. This system is not only useful for nuclear power plants, but the design can be put to use for a wide array of vibrating machinery used across the industry. Important to note, however, is that this form of vibrational harvester requires plant power, as vibration sources are completely lost if the plant has been shut down, meaning this harvester would be removed from operation during off-normal situations.

Lastly, analysis was done on the potential for harvesting both gamma radiation, and thermal energy from within nuclear containments. A dry cask was investigated in order to demonstrate the potential for using energy harvesting to power wireless sensors placed within dry storage containers of spent nuclear fuel. A model of the dry cask internals was made using both SCALE and MCNP6 software in order to find the decay heat, gamma and neutron generation, and potential radiation heating of a tungsten plate for harvesting energy. This work was then combined with CFD analysis done on the dry cask in order to design an energy harvesting system. Using the results of this simulation, two energy harvesters are designed, one to use gamma radiation heating alone, and a second using the thermal environment within the dry cask. Both harvesters employ TE modules to harvest the temperature gradients produced by the environment the canister wall.

It is hypothesized using simulations that 5.55 mW of energy can be harvested from the spent fuel radiation alone, and 944 mW can be harvested using the thermal gradients present within the cask itself, both at the beginning of dry cask storage. Considering the small amount of energy available by the radiation energy harvester and its large size, the original hypothesis for utilizing material heating in a dry cask environment was disproved. The second thermal energy harvester was then considered in order to give an appropriate solution to the problem allowing wireless sensor transmission from within the MPC itself. This energy can be used to transmit sensor data out of the fuel canister using state of the art through wall communication. Additionally, considering work done in chapter 3 on TEM survivability in gamma radiation environments, the TEMs used in this work should survive well, especially since each of the modules is shielded by the tungsten plates as well. This form of energy harvesting can also be expected to perform over a very long lifetime of the dry cask.

Ultimately this thesis has worked to show the feasibility of the use of energy harvesting throughout the nuclear process for the powering of wireless sensor nodes. Not only are a myriad of wasted energy sources available for scavenging, but they may be put to use powering critical wireless sensor networks, as has been shown in the analysis above. It has been the aim of this thesis to encourage further work on energy harvesting technologies specifically targeting nuclear environments, and to this extent it has been shown that multiple technologies can be tailored for use in the nuclear process, ultimately providing an avenue to increase safety across the industry through the use of self-powered wireless sensor nodes.

References

- [1] International Energy Agency 2015 Energy and Climate Change: World Energy Outlook Special Report
- [2] Clayton D 2015 Design Considerations for Wireless Sensor Networks in Nuclear Power Applications. Lecture presented at *Future of Instrumentation and Internet Workshop*
- [3] Hashemian H M What you need to know about sensor reliability before and after an accident *IAEA TWG NPPIC Meeting. Vienna: IAEA Nuclear Power Engineering Section Division of Nuclear Power Wagramer Strasser 5*
- [4] Hashemian H M Wireless sensors for predictive maintenance of rotating equipment in research reactors *Annals of Nuclear Energy* **38** 665-680
- [5] Low K S, Win W N and Er M J 2005 Wireless sensor networks for industrial environments *Proc. International Conference on Computational Intelligence for Modelling, Control and Automation, and International Conference on Intelligent Agents, Web Technologies and Internet Commerce*
- [6] Hunter S, Lavrik N, Datskos P and Clayton D 2014 Pyroelectric energy scavenging techniques for self-powered nuclear reactor wireless sensor networks *Nuclear Technology* **188** 172-184
- [7] Hashemian H M 2010 Aging management of instrumentation & control sensors in nuclear power plants *Nuclear Engineering and Design* **240** 3781-3790
- [8] Clayton D, Andrews Jr W and Lenarduzzi R 2012 Power harvesting practices and technology gaps for sensor networks
- [9] Hashemian H M, Kiger J C, Morton G W and Shumaker B D 2011 Wireless sensor applications in nuclear power plants *Nuclear Technology* **173** 8-16
- [10] Davidson J and Mo C 2014 Recent advances in energy harvesting technologies for structural health monitoring applications *Smart Materials Research*
- [11] Kahn F U and Ahmad I 2016 Review of energy harvesters utilizing bridge vibrations *Shock and Vibration*
- [12] Tewolde et al 2014 Sensors for small modular reactors powered by thermoelectric generators in *Proc. ASME Small Modular Reactors Symp* V001T02A007
- [13] Chen J, Zuo L, Wu Y and Klein J 2016 Modeling, experiments and optimization of an on-pipe thermoelectric *Energ. Convers. Manage* **122** 298–309
- [14] Testa D and Kunkle A 1984 The westinghouse pressurized water reactor nuclear power plant *Westinghouse Electr. Corp., Water Reactor Div.* (Pittsburgh, PA, USA)
- [15] USNRC. (2017, February 28). Power Reactors. Retrieved from <https://www.nrc.gov/reactors/power.html>
- [16] Brown D N Machine-condition monitoring using vibration analysis, a case study from a nuclear power-plant *Bruel & Kjaer Application Notes*

- [17] Pettigrew M J, Taylor C E, Fisher N J, Yetisir M and Smith B A W 1998 Flow-induced vibration: recent findings and open questions *Nuclear Engineering and Design* **185** 249-276
- [18] Paidoussis M P 2006 Real-life experiences with flow-induced vibration *Journal of Fluids and Structures* **22** 741-755
- [19] Rajesh R S 1997 Pump troubleshooting through vibration analysis *World Pumps* October 1997 14-18
- [20] Nelson W E Pump vibration analysis for the amateur *Proc. of the Fourth International Pump Symposium* 109-119
- [21] Sinha J K and Balla C B N S Vibration-based diagnosis for ageing management of rotating machinery: a summary of cases *Insight* **48**(8) 481-485
- [22] Sinha J K Vibration-based diagnosis techniques used in nuclear power plants: an overview of experiences *Nuclear Engineering and Design* **238** 2439-2452
- [23] Koo I S and Kim W W 2000 The development of reactor coolant pump vibration monitoring and a diagnostic system in the nuclear power plant *ISA Transactions* **39** 309-316
- [24] Runkel J, Stegemann D and Vortriede A 1998 Operating experience with an on-line vibration control system for PWR main coolant pumps *Nuclear Engineering and Design* **183** 157-167
- [25] Storage of Spent Nuclear Fuel. (2016, October 12). Retrieved from <https://www.nrc.gov/waste/spent-fuel-storage.html>
- [26] Bruno J and Ewing R C 2006 Spent nuclear fuel *Elements* **2** 343-349
- [27] Adkins H E 2012 Modeling used fuel storage temperatures, Lecture presented at *Nuclear Waste Technical Review Board* (Idaho Falls)
- [28] EPRI 2012 *Impacts Associated with Transfer of Spent Nuclear Fuel from Spent Fuel Storage Pools to Dry Storage After Five Years of Cooling* Final Report No. 1025206
- [29] Holtec International 2010 *HI-STORM 100 Final safety analysis report* Holtec Report No. HI-2002444, Rev. 8.
- [30] Easton E Dry cask storage of nuclear spent fuel, Lecture for *U.S. Nuclear Regulatory Commission*
- [31] Carstens T A 2013 Thermoelectric powered wireless sensors for dry-cask storage, Doctoral dissertation at University of Wisconsin-Madison
- [32] Herranz L E, Penalva J and Fera F 2015 CFD analysis of a cask for spent fuel dry storage: model fundamentals and sensitivity studies *Ann. Nucl. Energy* **76** 54-62.
- [33] Li J Liu Y Y 2016 Thermal modeling of a vertical dry storage cask for used nuclear fuel *Nucl. Eng. Des.* **301** 74-88
- [34] McKinnon M, Dodge R, Schmitt R, Eslinger L and Dineen G 1992 Performance testing and analyses of the VSC-17 ventilated concrete cask *EPRI*

- [35] Wataru M, Takeda H, Shirai K and Saegusa T 2008 Thermal hydraulic analysis compared with tests of full-scale concrete casks *Nucl. Eng. Des.* **238** 1213-1219.
- [36] Takeda H, Wataru M, Shirai K and Saegusa T 2008 Heat removal verification tests using concrete casks under normal condition *Nucl. Eng. Des.* **238** 1196-1205.
- [37] Shultis J K 2000 Radiation analysis of a spent-fuel storage cask Rep. No. 290 (Manhattan, KS: Kansas State University)
- [38] Waly E A, Fusco M A and Bourham M A 2017 Impact of specialty glass and concrete on gamma shielding in multi-layered PWR dry casks *Progress in Nuclear Energy* **94** 64-70
- [39] Caltech Materials Science 2015 Brief history of thermoelectrics, Retrieved November 30, 2015, from <http://thermoelectrics.caltech.edu/thermoelectrics/history.html>
- [40] Snyder G J and Toberer E S 2008 Complex thermoelectric materials *Nature Materials* **7**(2) 105-114
- [41] Chen J 2015 Design and analysis of a thermoelectric energy harvesting system for powering sensing nodes in nuclear power plant, Master's thesis at Virginia Polytechnic Institute and State University
- [42] Hi-Z Technology Hz-2 datasheet <http://www.hi-z.com/uploads/2/3/0/9/23090410/hz-2.pdf>.
- [43] Kilp G and Mitchell P 1961 Radiation effects on thermoelectric materials *Westinghouse Electr. Corp., Atomic Power Dept.* (Pittsburgh, PA, USA)
- [44] Idnurm M and Landecker K 1967 Changes produced in thermoelectric materials by thermal-neutron irradiation *Brit. J. Appl. Phys.* **18**(8) 1209
- [45] Sanzi J, Jaworske D and Goodenow D 2012 Titanium-water thermosyphon gamma radiation exposure and results *Proc. 10th Int. Energy Convers. Eng. Conf.* 4078
- [46] Singh R, Akbarzadeh A and Mochizuki M 2010 Operational characteristics of the miniature loop heat pipe with non-condensable gases *Int. J. Heat Mass Transf.* **53**(17-18) 3471-3482
- [47] Hijikata K, Chen S and Tien C 1984 Non-condensable gas effect on condensation in a two-phase closed thermosyphon *Int. J. Heat Mass Transf.* **27**(8) 1319-1325
- [48] Intermediate Temp Heat Pipes 2015 Retrieved November 30, 2015, from <http://www.1-act.com/advanced-technologies/heat-pipes/intermediate-temp-heat-pipes/>
- [49] Anderson W 2007 Intermediate temperature fluids for heat pipes and loop heat pipes *5th International Energy Conversion Engineering Conference and Exhibit (IECEC)*
- [50] Minnich A, Dresselhaus M, Ren Z and Chen G 2009 Bulk nanostructured thermoelectric materials: Current research and future prospects *Energy & Environmental Science* (2) 466-479.
- [51] Ma X, Wilson A, Rahn C D and Trolier-McKinstry S 2016 Efficient energy harvesting using piezoelectric compliant mechanisms: theory and experiment *Journal of Vibration and Acoustics* **138**

- [52] Wang L, Chen S, Zhou W, Xu T and Zuo L 2016 Piezoelectric vibration energy harvester with two-stage force amplification *JIMSS*
- [53] Broomfield G H 1980 The effect of low-fluence neutron irradiation on silver-electroded lead–zirconate–titanate piezoelectric ceramics *J. Nucl. Mater.* **91**(1) 23–34
- [54] Broomfield G H 1985 The effects of temperature and irradiation on piezoelectric acoustic transducers and materials *Harwell, U.K., UKAEA Rep. AERE-R 11 942*
- [55] Holbert K E, Sankaranarayanan S and McCready S S 2005 Response of lead metaniobate acoustic emission sensors to gamma irradiation *IEEE Transactions on Nuclear Science* **52**(6)
- [56] Luna H B et. al. 1989 Bremsstrahlung radiation effects in rare earth permanent magnets *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **285**(1-2) 349-354
- [57] Cost J R, Brown R D, Giorgi A L and Stanley J T 1987 Radiation effects in rare-earth permanent magnets *MRS Proc* **96**
- [58] Tang X, Lin T and Zuo L 2014 Design and optimization of a tubular liner electromagnetic vibration energy harvester *IEEE/ASME Transactions on Mechatronics* **19**(2) 615-622
- [59] Meeker D 2014 Finite Element Method Magnetics (Version 4.2) [Computer software]
- [60] Howell L 2001 *Compliant Mechanisms* (Wiley, New York)
- [61] Wolfram Research, Inc. 2017 Mathematica, Version 11.1 (Champaign, IL)
- [62] Hubbell J H and Seltzer S M 2004 X-Ray mass attenuation coefficients, Retrieved from <https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients>
- [63] Rearden B T and Jessee M A 2016 SCALE Code System (Version 6.2.1) [Program documentation] *RNSD of ORNL*
- [64] Williams M L, Skutnik S E, Gauld I C, Wieselquist W A and Lefebvre R A 2015 ORIGAMI: A code for computing assembly isotopic with origen
- [65] Goorley T et al 2012 Initial MCNP6 Release Overview *Nuclear Technology* **180** 298-315
- [66] Shultis J K and Faw R E 2011 An MCNP primer (Manhattan, KS: Kansas State University)
- [67] Bejan A and Sciubba E 1992 The optimal spacing of parallel plates cooled by forced convection *International Journal of Heat and Mass Transfer* **35**(12) 3259-3264
- [68] Wang C, Hung C and Chen W 2012 Design of heat sink for improving the performance of thermoelectric generator using two-stage optimization *Energy* **39**(1) 236-245
- [69] Simons R E 2016 Estimating parallel plate-fin heat sink pressure drop, Retrieved April 07, 2017, from <https://www.electronics-cooling.com/2003/05/estimating-parallel-plate-fin-heat-sink-pressure-drop/>

Appendix

A. SCALE Code

Below is the code which was used to simulate the dry cask decay heat. It was run using the SCALE 6.2.1 system, obtained through Oak Ridge National Labs. To change the length of time which the fuel is allowed to cool, and enable study of fuel at various years during dry cask storage, the 1825 in the line “cycle{ down=1825 }” can be changed to reflect the number of days desired for cooling time. It should be noted that this code also gives the gamma and neutron spectrums for various energy levels at the desired cooling year.

=origami

title=”TypicalDryCaskConditions”

options{ mtu=15.0 ft71=all stdcomp=yes decayheat=yes mcnp=yes }

libs=[“w17x17”]

fuelcomp{ uox(fuel) { enrich=4 } mix(1) { comps=[fuel=100] } }

modz=[0.7332]

pz =[1.0]

hist[

 cycle{ power=40 burn= 375.00 nlib=4 down=18.75 }

 cycle{ power=40 burn= 375.00 nlib=4 down=18.75 }

 cycle{ power=40 burn= 375.00 nlib=4 down=0 }

 cycle{ down=1825 }]

ggrp=[2e6 1.5e6 1.25e6 1e6 0.8e6 0.6e6 0.5e6 0.4e6 0.3e6 0.2e6 0.15e6 0.1e6 0.08e6 0.06e6
0.05e6 0.04e6 0.03e6 0.02e6 0.015e6 0.01e6 0.001e6]

ngrp=[20e6 15e6 10e6 5e6 4e6 3e6 2e6 1.5e6 1.25e6 1e6 0.75e6 0.5e6 0.25e6 0.1e6 0.05e6
0.01e6 0.001e6 0.0001e6]

srcopt{ sublib=all brem_medium=uo2 alphan_medium=case print=yes }

end

B. MCNP6 Code

Results from the ORIGAMI study were input into a MCNP6.1 simulation. The input file is given below. Source information is from year 5 (beginning of dry storage), and is the gamma spectrum. This source was varied depending on the year and output of ORIGAMI, as was the material list for the fuel. The full material list was chosen to be omitted due to the large number of lines. Different sizes and placements of the two tungsten plates were investigated as well.

Full Dry Cask with Basket and Assemblies estimation - Quarter Model

```
C *****CELL CARDS*****
C
C
C *****Four sections of fuel assemblies*****
11 1 -2.4 -19 23 24 3 4 5 6 7 8 9 10 12 13 14 16 18
12 0   -19 -23 24 1 2 3 6 7 8 9 10 11 13 14 15 17
13 0   -19 -23 -24 1 2 3 6 7 8 9 10 11 13 14 15 17
14 0   -19 23 -24 3 4 5 6 7 8 9 10 12 13 14 16 18
C
C *****Four sections of the basket*****
21 2 -7.8 (-3:-4:-5:-6:-7:-8:-9:-10:-12:-13:-14) 23 24
22 0   (-1:-2:-3:-6:-7:-8:-9:-10:-11:-13:-14) -23 24
23 0   (-1:-2:-3:-6:-7:-8:-9:-10:-11:-13:-14) -23 -24
24 0   (-3:-4:-5:-6:-7:-8:-9:-10:-12:-13:-14) 23 -24
C
C *****Two tungsten slabs*****
3 3 -19.25 -20
4 3 -19.25 -21
C
C *****Helium filled MPC canister*****
C *****Geometry split near tungsten***
511 4 -0.0004316 -22 23 24 -25 #11 #21 $Quadrant 1
512 4 -0.0004316 -22 23 24 25 #3 #4 $Quadrant 1
C *****Rest of canister*****
52 0   -22 -23 24 #12 #22 $Quadrant 2
53 0   -22 -23 -24 #13 #23 $Quadrant 3
54 0   -22 23 -24 #14 #24 $Quadrant 4
6 0    22

C *****SURFACE CARDS*****
C
C
C *****Inner 16 basket sections*****
1 RPP -47 -46.29 -70.3225 70.3225 -216 216
2 RPP -23.6775 -22.9675 -70.3225 70.3225 -216 216
3 RPP -0.355 0.355 -70.3225 70.3225 -216 216
4 RPP 22.9675 23.6775 -70.3225 70.3225 -216 216
5 RPP 46.29 47 -70.3225 70.3225 -216 216
6 RPP -70.3225 70.3225 46.29 47 -216 216
```

7 RPP -70.3225 70.3225 22.9675 23.6775 -216 216
 8 RPP -70.3225 70.3225 -0.355 0.355 -216 216
 9 RPP -70.3225 70.3225 -23.6775 -22.9675 -216 216
 10 RPP -70.3225 70.3225 -47 -46.29 -216 216
 C
 C *****Outer 16 basket sections*****
 11 RPP -70.3225 -69.6125 -47 47 -216 216
 12 RPP 69.6125 70.3225 -47 47 -216 216
 13 RPP -47 47 69.6125 70.3225 -216 216
 14 RPP -47 47 -70.3225 -69.6125 -216 216
 15 RPP -70.3225 -47 -70.3225 -47 -216 216
 16 RPP 47 70.3225 -70.3225 -47 -216 216
 17 RPP -70.3225 -47 47 70.3225 -216 216
 18 RPP 47 70.3225 47 70.3225 -216 216
 C
 C *****Bounding box for fuel assemblies*****
 19 RPP -70.3225 70.3225 -70.3225 70.3225 -216 216
 C
 C *****Tungsten Slabs*****
 20 RPP 78.7 80.7 -10 10 192.5 212.5 \$Side
 21 RPP 25 45 -10 10 220 222 \$top
 C
 C *****Outer MPC*****
 22 RCC 0 0 -226 0 0 452 85.7
 C
 C *****Geometry Split*****
 23 PX 0
 24 PZ 0
 25 RPP 0 74 -70.3225 70.3225 0 218

 C *****DATA CARDS*****
 C
 C
 PHYS:P
 PHYS:E 100 0 0 1
 PHYS:N
 MODE P E N
 C *****Increase importance towards tungsten*****
 IMP:P 1 0 0 0 6 0 0 0 300 300 12 60 0 0 0 0
 IMP:N 1 0 0 0 6 0 0 0 300 300 12 60 0 0 0 0
 IMP:E 1 0 0 0 6 0 0 0 300 300 12 60 0 0 0 0
 PRINT 10 30 110
 C *****Start gammas in the fuel assemblies*****
 SDEF PAR=P ERG=D101 X=D1 Y=D2 Z=D3 CEL=11
 SI1 0 70.3225
 SP1 0 1
 SI2 -70.3225 70.3225
 SP2 0 1
 SI3 0 216
 SP3 0 1
 C *****Source information from ORIGAMI*****

SI101 H 1.0000E-03 1.0000E-02 1.5000E-02 2.0000E-02 &
 3.0000E-02 4.0000E-02 5.0000E-02 6.0000E-02 &
 6.9530E-02 8.0000E-02 1.0000E-01 1.5000E-01 &
 2.0000E-01 3.0000E-01 4.0000E-01 5.0000E-01 &
 6.0000E-01 8.0000E-01 1.0000E+00 1.2500E+00 &
 1.5000E+00 2.0000E+00
 SP101 D 0.0 1.3409E-01 6.2001E-02 3.9196E-02 5.1372E-02 &
 5.1581E-02 2.7969E-02 1.3562E-02 1.3894E-02 &
 1.2061E-02 1.8937E-02 3.4050E-02 1.4996E-02 &
 1.4305E-02 9.2774E-03 9.6035E-03 3.7107E-02 &
 4.2525E-01 1.4063E-02 7.5026E-03 8.5458E-03 &
 6.3275E-04
 C *****Tallies*****
 F2:P 20.2 21.6
 E2 1.0000E-03 1.0000E-02 1.5000E-02 2.0000E-02 &
 3.0000E-02 4.0000E-02 5.0000E-02 6.0000E-02 &
 6.9530E-02 8.0000E-02 1.0000E-01 1.5000E-01 &
 2.0000E-01 3.0000E-01 4.0000E-01 5.0000E-01 &
 6.0000E-01 8.0000E-01 1.0000E+00 1.2500E+00 &
 1.5000E+00 2.0000E+00
 *F6:P,N,E 3 4 21
 +F16 3 4 21
 C *****Fuel makeup from ORIGAMI*****
 m1 FULL MATERIAL LIST OMITTED DUE TO LARGE NUMBER OF LINES
 C *****Stainless Steel Basket*****
 M2 26056 -0.85 24052 -0.1 28058 -0.05
 C *****Tungsten*****
 M3 74000 1
 C *****Helium Gas at 3.3 atm*****
 M4 2004 1 GAS=1
 NPS 2820000
 CTME 150