

Project No. 12-3331

# Thermoelectric-Driven Sustainable Sensing and Actuation Systems for Fault-Tolerant Nuclear Incidents

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## Reactor Concepts

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# **Final Report**

**NEUP Award 12-3331**

## **Thermoelectric-Driven Sustainable Sensing and Actuation Systems for Fault-Tolerant Nuclear Incidents**

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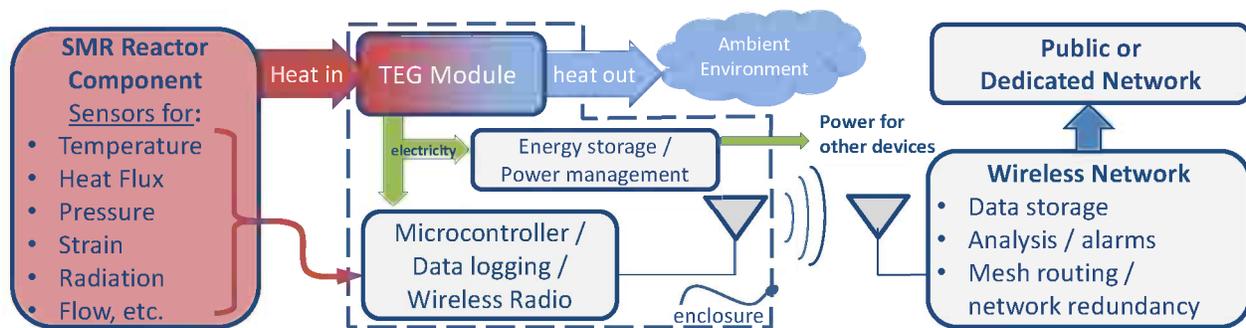
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## 1 Introduction and Executive Overview

The Fukushima Daiichi nuclear incident in March 2011 represented an unprecedented stress test on the safety and backup systems of a nuclear power plant. The lack of reliable information from key components due station blackout was a serious setback, leaving sensing, actuation, and reporting systems unable to communicate, and safety was compromised. Although there were several independent backup power sources for required safety function on site, ultimately the batteries were drained and the systems stopped working. If, however, key system components were instrumented with *self-powered sensing and actuation packages* that could report indefinitely on the status of the system, then critical system information could be obtained while providing core actuation and control during off-normal status for as long as needed.

This research project focused on the development of such a self-powered sensing and actuation system. The electrical power is derived from intrinsic heat in the reactor components, which is both reliable and plentiful. The key concept was based around using *thermoelectric generators* that can be integrated directly onto key nuclear components, including pipes, pump housings, heat exchangers, reactor vessels, and shielding structures, as well as secondary-side components. Thermoelectric generators are solid-state devices capable of converting heat directly into electricity. They are, commercially available technology. They are compact, have no moving parts, are silent, and have excellent reliability. The key components to the sensor package include a thermoelectric generator (TEG), microcontroller, signal processing, and a wireless radio package, environmental hardening to survive radiation, flooding, vibration, mechanical shock (explosions), corrosion, and excessive temperature. The energy harvested from the intrinsic heat of reactor components can be then made available to power sensors, provide bi-directional communication, recharge batteries for other safety systems, etc. Such an approach is intrinsically fault tolerant: in the event that system temperatures increase, the amount of available energy will *increase*, which will make more power available for applications. The system can also be used during normal conditions to provide enhanced monitoring of key system components. A schematic of the concept is shown in the figure below.



**Figure 1 –Key components of the thermoelectric (TEG)-driven monitoring system. TEG converts heat from hot reactor component to electricity, which powers a microcontroller and rechargeable battery or super-capacitor. Data relayed wirelessly to external permanent or temporary network.**

Importantly, an emphasis on cost and the use of mature, commercially available technology was made throughout the project, with the intent that the resulting developments would be economically viable as well as technically viable.

In the balance of this report, the individual tasks associated with the project are discussed in detail, including relevant results and accomplishments, challenges, and recommendations for future work. A summary of relevant publications and contributions to the scientific literature is also presented, and a final summary of actual scheduled tasks presented.

## 2 Program Objectives

The following list summarizes the program objectives for this project. Each is discussed in its own section in the following.

1. Requirements Review and Feasibility Study of Optimal Locations to Place TEGs
2. Initial Design and Analysis of TEG Devices
3. Fabrication and Testing of Thermoelectric Generator Prototype
4. Sensor Integration and Real-Time Monitoring of Vital System Component Parameters
5. Energy Storage and Power Management
6. Actuation Integration and Feasibility Study
7. Demonstration of Packaging and Environmental Protection
8. Keeping Abreast of Emerging Thermoelectric Technologies
9. Reporting and Project Management

### 2.1 Requirements Review and Feasibility Study of Optimal Locations to Place TEGs

The project proposes attaching thermoelectric generators to nuclear components. In order to be as effective as possible, candidate locations sites and their associated temperatures are required in order to assess the landscape of potential installation sites. An initial review of state of small modular reactors (SMR) was thus conducted at the start of the project.

Several different SMR designs types are currently being developed. One major classification method for SMRs is based on the type of coolant they use. There are three major classes: *light water reactors* (LWR), *gas-cooled reactors* (GCR) and *fast neutron reactors* (FNR). FNRs use liquid metal as coolant and have the highest process temperatures. The development state of different SMRs in each class made by different manufactures have also been reviewed and identified. The main items of interest are the physical size of the reactor, its capacity and process temperatures.

Key candidate locations considered are the core temperatures and the steam generator (both on the primary side and the secondary side) and feed water heaters. These locations represent reasonably high temperature and heat availability to maximize the power output from the TEG. Expected operating temperatures for these locations along with ambient conditions were also tabulated.

In addition to the surveys of a variety of different nuclear facilities for candidate sites at the beginning of the project, PIs Longtin, Zuo, and Hwang reviewed the candidate sites with U. Pitt and Westinghouse representatives. Different candidate locations for the TEG device on SMRs were discussed at length. It was determined that a promising potential configuration would be to have long heat pipes (15 to 20 feet in length) extending radially outward from the outer container of the SMR. The heat pipes would be oriented horizontally, and terminate in a small annular tunnel surrounding the SMR for access and maintenance. Issues such as radiation exposure to the TEG and related electronics were discussed, with preventative

measures including placing strategic bends in heat pipe to avoid direct line-of-sight to the reactor core, and using appropriate shielding.

A summary of representative temperatures was also compiled from literature reports to determine expected operating temperatures that would be available for the TEG.

## 2.2 Initial Design and Analysis of TEG Devices

### 2.2.1 Thermal Analysis of Thermoelectric Devices

Complete numerical and mathematical models<sup>3,4</sup> were proposed to model the performance of thermoelectric devices (as indicated in Fig. 2), taking into account all competing phenomena: thermal and electrical contact resistances between the thermoelectric materials and junctions, convective boundary conditions on the cold- and hot-side junctions as well as the sides of the thermoelectric materials, Fourier heat conduction; Joule heat; the Peltier and Thomson effects; and the temperature-dependent properties. This was done to provide the most accurate description of device performance under any potential operating condition the device would be exposed.

Although the majority of these studies focused on using the current highest-performing low-grade waste-heat materials, bismuth telluride, they are easily adaptable to using any material selected for testing, for example, silicon-germanium, lead-telluride, etc. This provided a valuable evaluation tool for any selected material and device configuration, allowing for a complete and accurate description (i.e., power output, developed voltage and current, heat input and output, experienced temperature difference) of the device as per selected installation location. These preliminary studies allow the evaluation of device performance based upon the location of installation and operating conditions.

The results of the study indicate the following trends: 1.) an increase in electrical and thermal contact resistances non-linearly decreases the temperature difference across the thermoelectric material, the heat input and subsequently the power output and efficiency of the device, and 2.) increasing the convective heat transfer coefficients on the cold- and hot-side interconnectors up to a value of  $10^5 \text{ W-m}^{-2}\text{K}^{-1}$  increases in the power output and efficiency, and thereafter, there is no change in device performance.

The integrated thermoelectric device enables the implementation of thermoelectric devices waste heat recovery within fluid streams, allowing for the capture and conversion of more waste heat into electricity. This expands the application and scale of the thermoelectric device to efficiently provide more electrical

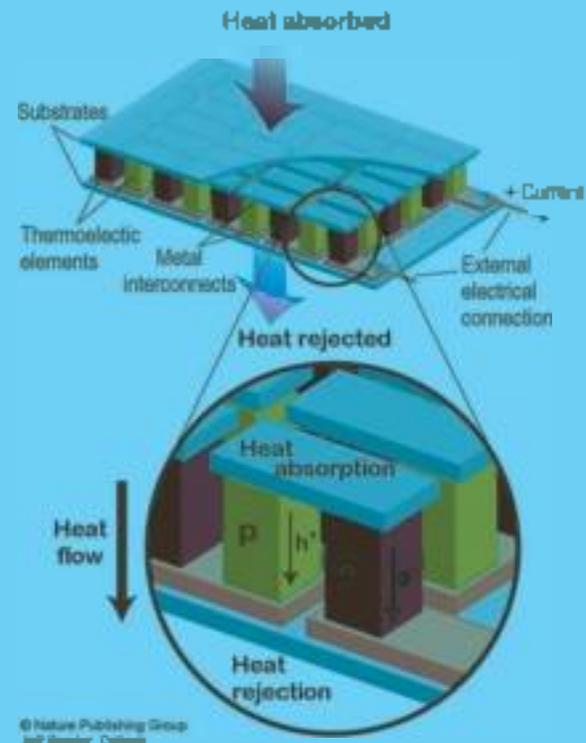


Figure 2: A conventional thermoelectric device. Image provide by Caltec Materials Science department.

power, whether it is used to power sensors, charge batteries or be used for mechanical actuation. Thus, the number of locations that can be selected for thermoelectric device installation can be increased.

### 2.2.2 System Designs to Extract Heat from Reactor

Locations to install thermoelectric devices to convert wasted thermal heat energy into electricity were analyzed. Locations where high levels of potential radiation interaction could occur were omitted from the list of installation locations, due to the degradation of thermoelectric material performance over time due to radiation exposure. Therefore, locations of interest that are easily accessible, experience no radiation, provide sufficient waste heat to provide power on the kilowatt scale and that do not disrupt activity and/or reduce the thermal efficiency of the plant were reduced to post-low-pressure turbine before the condensing unit (cooling tower or heat exchanger). Using the Westinghouse AP1000 as an example, the cooling tower rejects the low-grade waste heat post-turbine and pre-pump at a rate of 7.5 giga-BTU/hr. Thus, capturing a portion of this waste heat and converting it into electricity would be sufficient for small-scale power generation (orders of kilowatts) to run emergency sensors, and has the potential for mid-scale power generation (order of hundreds to thousands of kilowatts) during normal operating conditions and many post-accident operating scenarios where the decay heat is still being dissipated through the secondary/tertiary loop. This device design could be implemented near and/or around the steam generator, outside the containment vessel to be used during potential loss of coolant accidents.

Therefore, studies on small-scale integrated thermoelectric devices were pursued to demonstrate proof-of-concept, as well as characterize the performance of said devices<sup>3-4</sup>. From these studies, work on building, testing and characterizing physical prototypes followed.

#### References:

1. Reddy, B. V. K., Barry, M., Li, J., & Chyu, M. K. (2013). Mathematical modeling and numerical characterization of composite thermoelectric devices. *International Journal of Thermal Sciences*, 67, 53-63.
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3. Reddy, B. V. K., Barry, M., Li, J., & Chyu, M. K. (2013). Thermoelectric performance of novel composite and integrated devices applied to waste heat recovery. *Journal of Heat Transfer*, 135(3), 031706.
4. Reddy, B. V. K., Barry, M., Li, J., & Chyu, M. (2013). Enhancement of Thermoelectric Device Performance through Integrated Flow Channels. *Frontiers in Heat and Mass Transfer (FHMT)*, 4(2).

### 2.2.3 Thermal Analysis of Thermoelectric Design

Experimental validation and characterization of the integrated thermoelectric device proposed under the first year of study were conducted as to determine the feasibility of implementing the design within a nuclear reactor environment<sup>1-2</sup>. These studies characterized the performance of small-scale integrated thermoelectric devices in terms of power output per heat input (i.e., inlet temperature and flow rate of a working fluid) and were accompanied by numerical simulations<sup>3</sup>.

Two prototypes were constructed: a single-stage module with two p-n junctions as to demonstrate the proof-of-concept, and a multi-stage pin-fin integrated thermoelectric device with 35 p-n junctions to demonstrate a new device design and the scalability of the integrated thermoelectric device. The single stage integrated thermoelectric device is depicted in Fig. 3a, whereas the pin-fin integrated thermoelectric device is depicted in Fig. 3b.

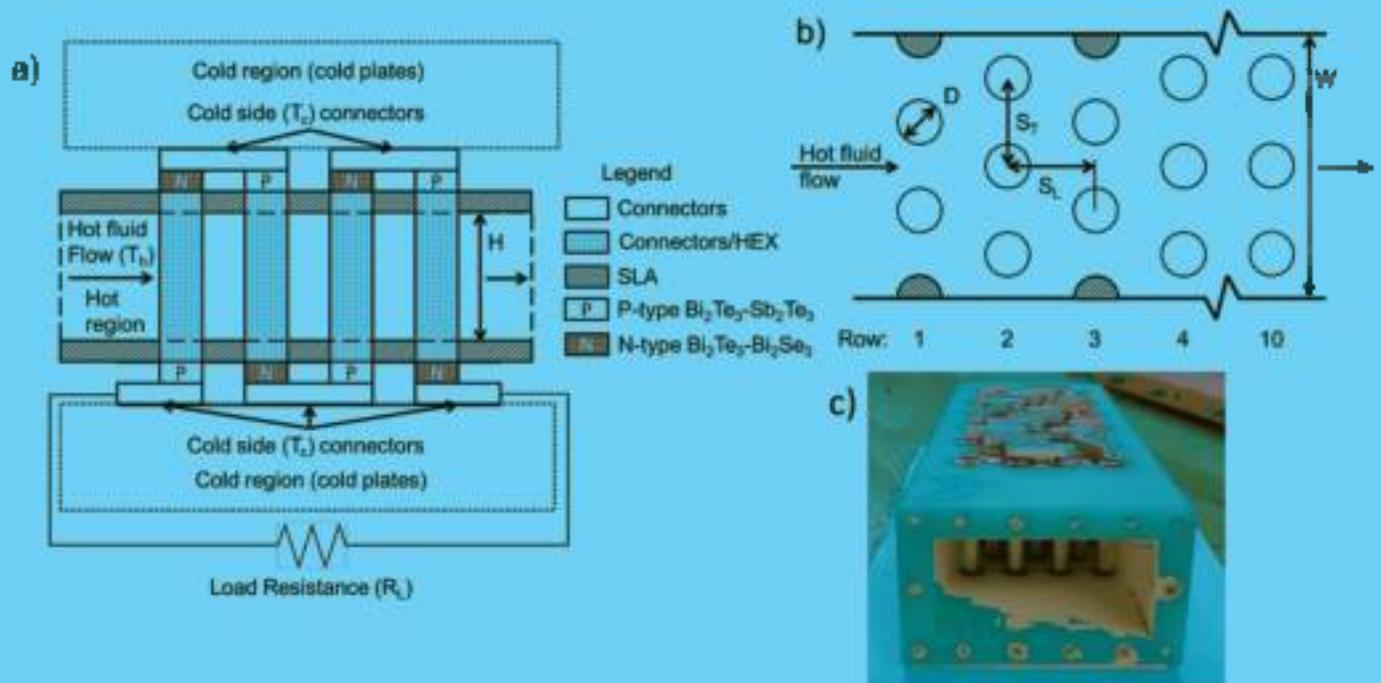


Figure 3: a) Schematic of a pin-fin integrated thermoelectric device with b) top-down view illustrating the pin-fin arrangement (i.e., hot-side heat exchanger exposed to working fluid) and c) pin-fin integrated thermoelectric prototype.

From these prototypes, the performance characteristics were determined. The working fluid used was air with inlet temperatures varying between 50 and 150 °C and flow rates (as characterized by the Reynolds number) varying between 3,000 and 9,000. The results are summarized as follows: 1.) an increase in fluid inlet temperature (i.e., working fluid temperature) has a greater effect on increasing power output and device efficiency as compared to an increased in flow rate; 2.) Heat input into the device increases near-linearly with an increase in fluid inlet temperature and flow rate, however flow rate has a greater effect due to an increase in the convective heat transfer coefficient; and 3.) The efficiency of the device increases with an increase in inlet temperature, however, it also decreases with an increase in flow rate.

The integrated thermoelectric device is able to extract a larger quantity of waste heat and impose a larger  $\Delta T$  across the thermoelectric materials, thus yielding a larger power output in comparison to a conventional thermoelectric device design. Therefore, future work is recommended to focus on incorporating the integrated thermoelectric design into the secondary loop post-low-pressure turbine.

### 2.2.4 Maximizing Thermoelectric Efficiency

Conventional commercial thermoelectric devices rely on geometries that are simple to fabricate. This usually results in the cross-sectional area and length of the n- and p-type materials to be the same, as illustrated in Fig. 2 above. Advances in additive manufacturing coupled with mass-production of simple parts has allowed for the fabrication of modules containing thermoelectric materials of differing geometries, which allows for an increase in device performance in terms of power output, and also reduces the amount of material used, reducing cost. A complete mathematical model was developed to optimize the geometry (cross-sectional area and length) of both n- and p-type materials of a thermoelectric junction based upon temperature-dependent properties, independent thermal and electrical contact resistances as well as cold- and hot-side temperatures of the junctions.

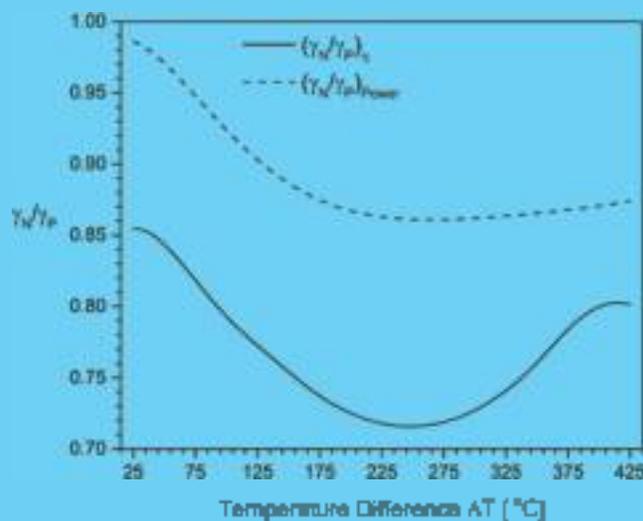


Figure 4: Ratio of cross-sectional area of n- to p-type materials to maximize thermal efficiency or power output of a p-n junction using co-optimization process.

The results of this study indicate that co-optimization of length and cross-sectional area can reduce material usage by over 27% and increase power output and efficiency by 10% in comparison to conventional construction. Figure 4 illustrates the effect of temperature difference across the thermoelectric material and the resulting ratio of cross-sectional areas of the n- to p-type material (in this case, bismuth telluride) through a co-optimization process.

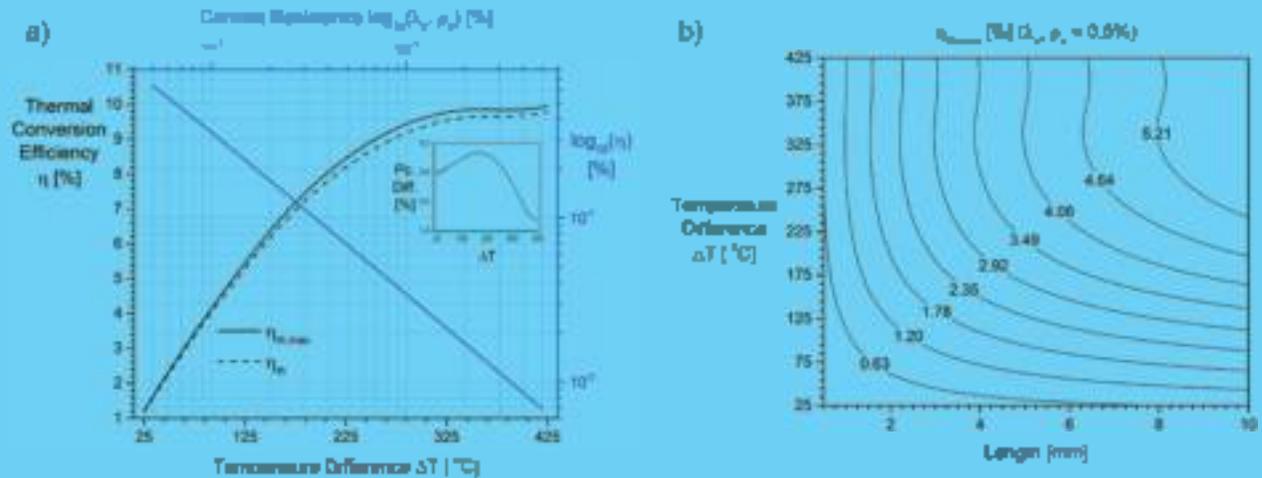


Figure 5. a) Thermal conversion efficiency versus temperature difference and thermal and electrical contact resistance (as a function of percentage of respective material internal resistance) and b) maximum thermal conversion efficiency versus length and temperature difference for a given thermal and electrical contact resistance (0.5%).

Additionally, the effect of contact resistances, both thermal and electrical, on the power output and thermal conversion efficiency were addressed. These studies provided reasonable predictions on the power output and thermal conversion efficiencies for co-optimized geometries, aiding in the design and location development of thermoelectric devices within the nuclear environment. Figures 5 and 6 illustrate the effect of the thermal and electrical contact resistances, as well as temperature difference across the thermoelectric junction, on thermal conversion efficiency and power output, respectively. It is evident when designing multiple thermoelectric junctions within a device that it is necessary to minimize thermal and electrical contact resistances associated with brazing/soldering, as well as to allow the device to operate in the temperature difference range (i.e. difference of hot- and cold-side temperatures across the thermoelectric materials rather than the hot- and cold-sides of the device). From this information, proper device design, configuration and fabrication were pursued to develop an integrated thermoelectric device applied to low-grade waste heat recovery, as well as to aid in the analysis of commercially available thermoelectric devices.

To build upon the geometric optimization of thermoelectric materials, a materials synthesis study was conducted to determine how to maximize the thermoelectric efficiency of the bismuth telluride as opposed to thermoelectric device design. Since the device design underwent an optimization procedure, the next step was to enhance the materials to provide a larger power output as per given operating condition, i.e. the efficiency of the material. A parametric study to determine the processing conditions to increase the figure of merit (ZT), expressed as the ratio of the Seebeck coefficient squared times the electrical conductivity over the thermal conductivity, of n-type bismuth telluride was pursued by the method of cold-isostatic pressing followed by sintering and annealing. The process of cold isostatic pressing provided the means to produce a highly textured material, i.e. control the direction of the crystals, which influence the electrical and thermal properties. Sintering and annealing provided the means to solidify, strengthen and reduce the electrical resistivity of the material while enhancing the texture. Additionally, studying the effects of operating temperature on texture and performance were pursued to provide insight into material behavior in harsh conditions.

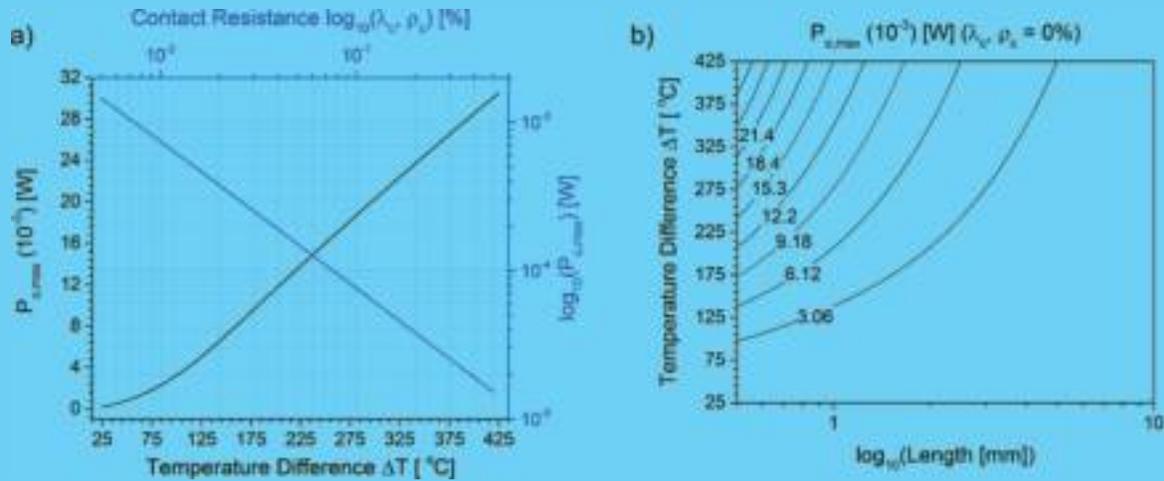


Figure 6: a) Maximum power output of a single p-n bismuth telluride junction versus temperature difference and thermal and electrical contact resistance (as a function of percentage of respective material internal resistance) and b) maximum power output versus length and temperature difference for a given thermal and electrical contact resistance (0%).

Figure 7 illustrates the effect of compaction pressure on texture of the bismuth telluride sample in terms of the Lotgering factor, which is a metric of the degree of preferred orientation within the sample, as well as the effect of sintering temperature. With an increase in preferred crystallographic orientation, there will be a change in the thermal and electrical characteristics of the material, thus the thermal-to-electrical conversion efficiency. With bismuth telluride, an increase in the  $\{001\}$  family results in a reduction of the thermal conductivity. Furthermore, with a reduction of crystal size and an increase in coherency of said crystals, the thermal conductivity is decreased without an increase in the electrical resistivity.

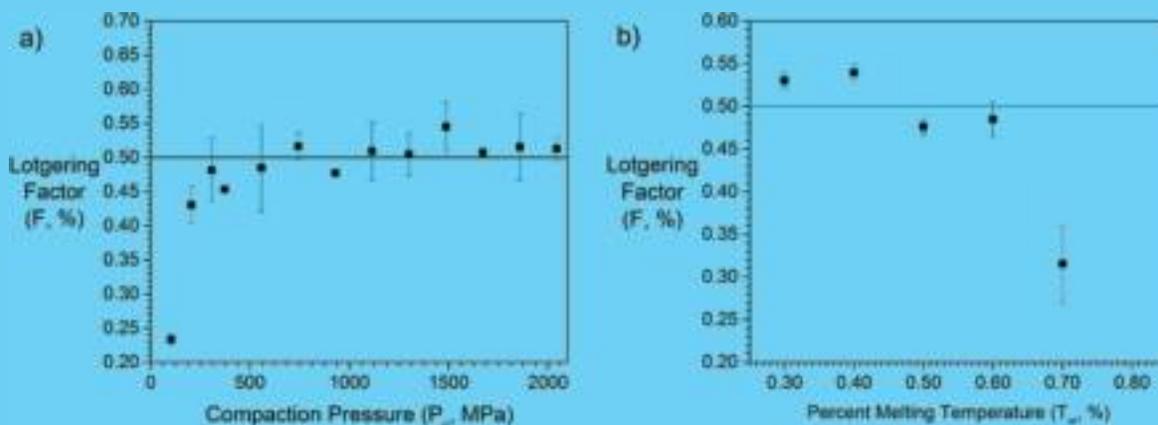


Figure 7: Effect of a) compaction pressure on preferred crystallographic orientation of bismuth telluride and b) effect of annealing temperature on texture of bismuth telluride.

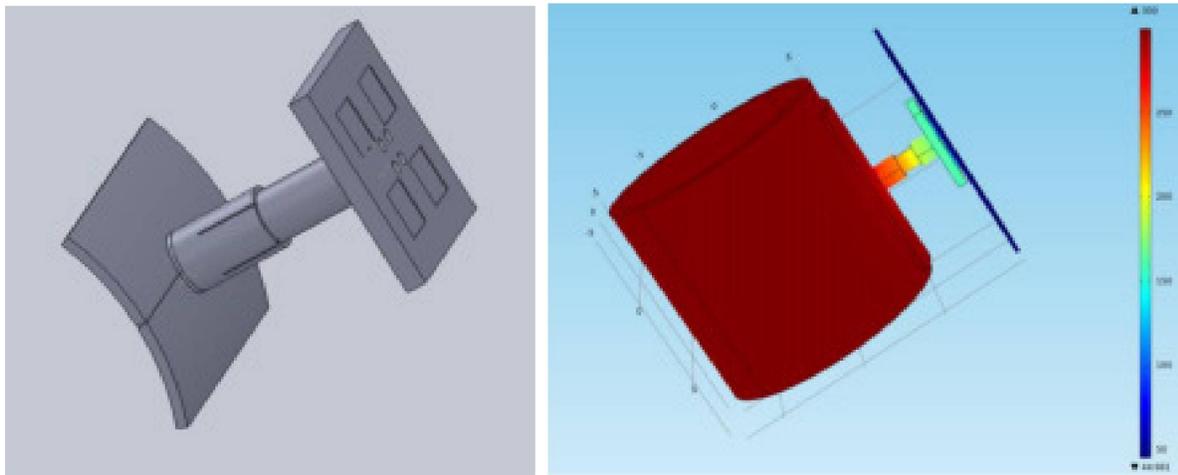
The effect of annealing temperature on texture (Fig. 7b) has profound insight into the performance of thermoelectric materials for waste heat recovery during normal and post-accident conditions within the nuclear industry. If the material is heated above 50% of its melting temperature, the physically induced

texture of the material is destroyed, and subsequently the performance will degrade. Under worse-case scenario conditions, this results in reduced power output.

Future work is recommended to quantify the performance (ZT) of these materials and characterize their performance under normal and post-accident conditions when being used within conventional and integrated thermoelectric designs.

### 2.2.5 First Prototype Thermal and TEG Analysis

The design and analysis cycle of the first-generation thermoelectric generator (TEG) for a typical SMR was based on the expected temperatures of the locations where the TEGs will be placed. The design includes the attachment of the TEG to a hot pipe and the heat sink. For the TEG attachment, a model was developed and analyzed to find the temperature distributions and heat fluxes. The attachment consists of a single solid aluminum rod to draw heat from the hot pipe to a heat spreader that holds the hot side of the TEG (Fig. 8).



*Figure 8: (left) CAD model of first-generation design. (right) thermal analysis of temperature profile in operation using COMSOL.*

On the cooling side, a passive cooling system based on extended surfaces (fins) was used for simplicity and reliability. This includes analysis of natural convection from a curved surface and various types of fin types and configurations to find the optimal passive cooling system. Considerable effort was spent on the fin analysis during this reporting period. The fins represent the heat transfer to the cold-side temperature, which is typically ambient air. COMSOL finite-element software was used to model the temperature distribution and heat flow through the TEG, the companion mounting assemblies, and the heat sink exposed to the ambient air. A key design decision has been made to attempt to avoid the use of a cooling fan in order to improve heat sink performance. Although a fan will reduce the TEG cold-side temperature and improve electrical output, it presents a liability concern as the fan represents a potential failure point. Furthermore if the cooling is not sufficient when the fan fails, the device will cease to function and possibly even become permanently damaged due to heat overload. Since a core design goal of this project is reliability under extreme conditions, a fan-less heat sink configuration has been chosen. One of the most favorable configuration is a series of vertical fins made in aluminum and the TEG device mounted on the side of the device.

This prototype was installed at the local power plant on campus, as discussed in Section 2.3 below. A full thermal analysis of the heat conduction and convection through the prototype were performed using COMSOL. The material choice and prototype dimensions were chosen to provide hot- and cold-side temperatures on the TEG devices of 230 C and 75 C, respectively. The design consists of a curved aluminum heat collector designed to straddle a 12.75" diameter, Schedule-80 steam supply line. A 1.5" aluminum "pillar" protrudes 5" radially outward, to which the TEG devices are attached mounted on a flat plate and a 12" x 12" heat sink. Four 1.5" x 1.5" TEG modules connected in series will provide the electrical power to drive the sensor and wireless radio electronics package. The predicted power produced for a 600 F pipe temperature is 1.2-1.4W, while the electrical consumption for the sensorless and wireless package will be 400-500 mW.

### 2.2.6 Second-Generation Prototype Analysis

The first-generation prototype was suitable for components with relatively high (300+°C) temperatures. This afforded a simple, reliable design used simple conduction through a thick, high thermal conductivity material such as copper. Unfortunately, this approach is not well suited for components that may have a lower average temperature. In this case the thermal conduction through the aluminum post alone does not provide enough heat to run the TEGs effectively.

A second-generation design was thus undertaken in which heat pipes are used in order to move the heat from the SMR component to the TEGs. Heat pipes are an attractive option for heat transfer from hot nuclear pipe elements to the TEG element because they have very high effective heat transfer rates with no electrical power consumption. They also have flexibility in working fluid for different temperature ranges and are completely sealed with no maintenance requirement.

The design process for the second prototype was similarly done using COMSOL to assess the expected temperatures and heat flow through the system. The design was otherwise similar to the first prototype, however in this version a heat pipe is used to transfer the heat from the steam pipe to the thermoelectric generator. In addition to being part of the proposed work scope, the heat pipe provides exceptional heat transfer, which was deemed necessary for the lower pipe temperature of 200 °C (350°F).

To simulate the heat pipes in COMSOL, a rod with an effective thermal conductivity of 10,000 W/m·K was used, rather than simulating the internal workings of the heat pipe. The assumption is made that no heat pipe operating limits are reached. To ensure this, the actual heat pipes used in the prototype (Section 2.3) have been oversized to ensure that no operating limits are reached in the as-tested configuration.

As with the first prototype, a finned heat sink to the ambient was found to be sufficient to provide the heat removal and produce enough temperature drop across the thermoelectric generator. The output voltage was estimated to be approximately 60% of that for the higher temperature pipe on the first prototype, which was deemed enough to drive the electronics.

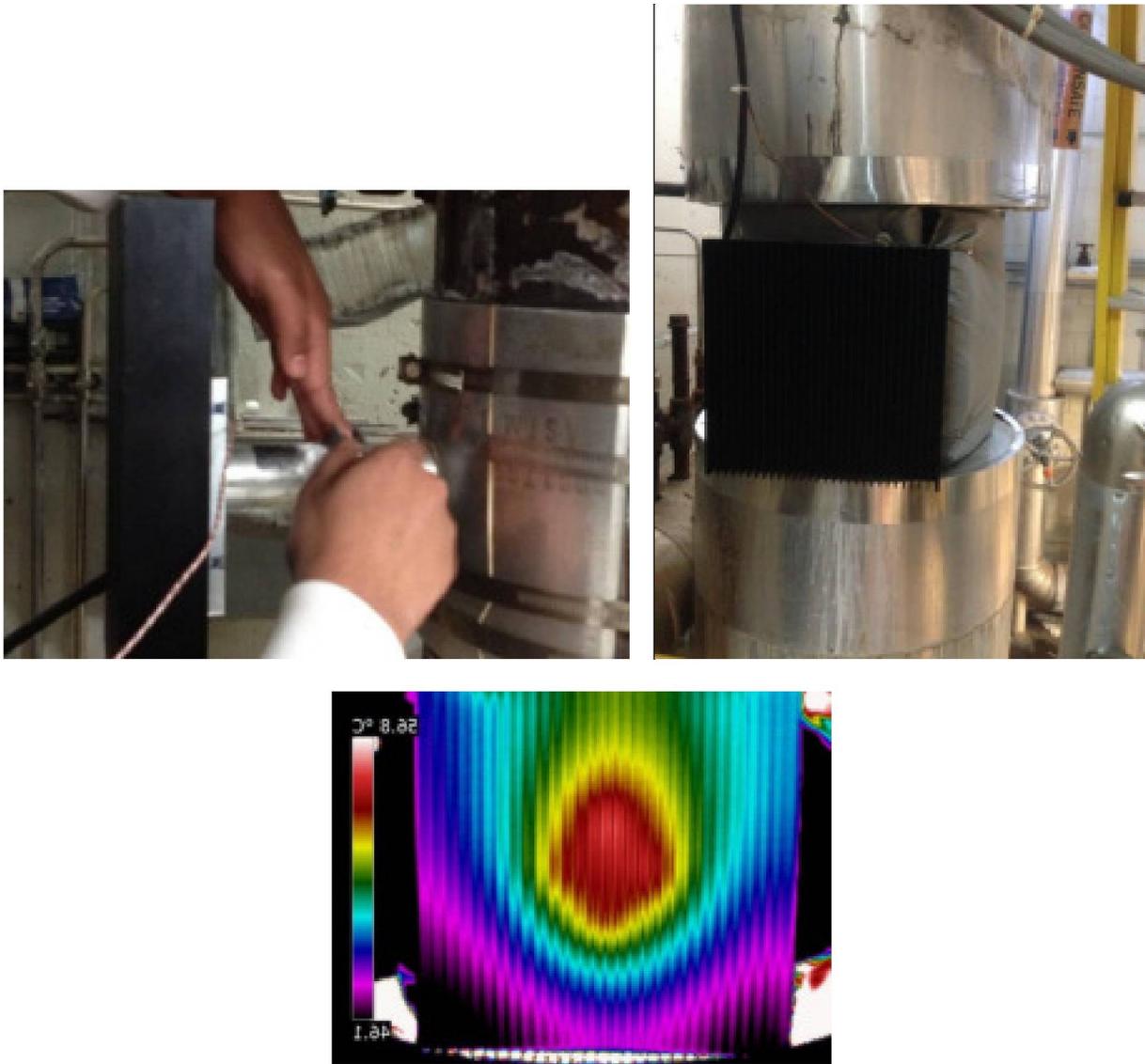
## 2.3 Fabrication and Testing of Thermoelectric Generator Prototype

### 2.3.1 First-Generation Prototype

The completion of a first-generation prototype energy harvester, sensing, and wireless platform was completed in Year 2. The prototype was based on a BiTe thermoelectric generator (TEG) commercially availa-

ble from *Hi-Z* technologies. Four individual TEG modules were integrated into a thermal/structural platform to provide electricity to a custom-designed electronics package. The TEG modules were arranged electrically in series to produce 7 – 9 VDC at up to approximately 1 watt of electrical power, depending on the operating temperature. The thermoelectric modules were thermally connected to a curved mounting component designed to fit a schedule 80, 12 inch steam pipe. A large heat sink (with no fans) served as the cold reference for the TEGs. We have a co-generation plant on campus in which a gas turbine generates 45 MW of electrical power, and the turbine exhaust is used to provide steam for heating to the entire campus. The management of this facility, run by Calpine, graciously allowed us to install the prototype on the main steam line that provides steam to the entire campus within their facility. The nominal conditions of the steam in the pipe are 650°F and 600 PSI. The pipe outside diameter is 12.75 inches for which the coupler was designed accordingly (Figure 8, above).

The entire prototype was attached to the pipe using large circular clamps and a custom insulation jacket was fabricated and fitted around the assembly to simulate an actual nuclear component that would natively have insulation on it. The prototype installation is shown in the figure below.



*Figure 9: (top left) First-generation prototype installation on main steam line at Stony Brook University Calpine Power Plant. (top right) Complete device, in operation. (bottom) thermal image of heat sink from previous picture. The red hot spot in the center is above the thick aluminum post in Fig. 1 that delivers heat to the TEG modules.*

The plant exhibited a planned shutdown for maintenance in May 2014, and the prototype accurately captured both the shutdown event (decrease pipe temperature) and the subsequent restart several days later. The first-generation prototype did not have a separate electrical power reserve on board, such as a battery or super-capacitor, so the device stopped working once the pipe temperature dropped below about 200 °F. This has been addressed with the separate power backup, as discussed in Section 2.5 in which the electronics design incorporates a power reserve so that measurements can continue to be made for several days if the component temperature drops (or the TEG power system fails).

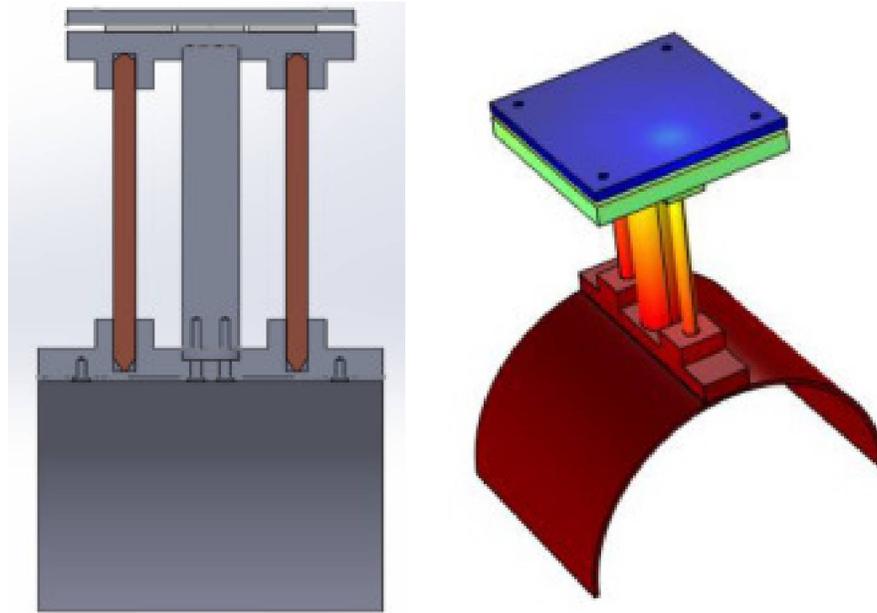
### 2.3.2 Second-Generation Prototype

In Year 2 the second-generation prototype fabrication was begun. This design is for a lower- temperature application, and was designed to be installed the backup steam facility on the Stony Brook campus (figure below).



*Figure 10: Target location of steam pipe for second-generation prototype at Stony Brook backup steam facility. Pipe is 8" in diameter and has a typical temperature of 350 °F.*

The target pipe temperature for the pipe to be used in this application is only 350°F. As such, thermal management becomes more critical. The second-generation design, shown in the figure below, incorporates heat pipes (brown objects in figure) to dramatically enhance the heat flow from the pipe surface to the thermoelectric modules. In addition, higher-performance thermoelectric modules were used, and aggressive power management implemented in the electronics to make the most use of power that is actually produced. The device was designed for the pipe shown in the figure above.



*Figure 11: (left) Second-generation prototype design. Steam pipe is on bottom, and TEG modules are at top. Brown objects are heat pipes to enhance heat transfer (right) thermal analysis of CAD model at left. Analysis shows uniform heat delivery at top section (blue) so that all four thermoelectric modules will see nearly the same temperature for operation*

Scheduling complications and upgrade projects precluded the installation of the second-generation prototype on the actual steam plant, so this device was tested in the laboratory instead using an 18" long section of 8" Schedule 40 steel tubing and a quartz heater to simulate the heated pipe. In retrospect, this proved to be a beneficial choice, because a variety of pipe temperatures could be selected, allowing the ability to characterize the prototype performance across a range of temperatures.

#### 2.4 Sensor Integration and Real-Time Monitoring of Vital System Component Parameters

The power generated from the TEG module is used to drive a custom-built electronics package, which includes power management and conditioning, a microcontroller for overall system management and control, and dedicated hardware for the sensors. In general any electronic sensor can be used, provided its power and data collection requirements can be met. In this project, we chose to monitor temperatures using industry-standard type-K thermocouples. The thermocouples were used to measure (1) the steam pipe temperature itself, and (2) the hot side temperature of the thermoelectric module.

The circuit was designed in-house. The circuit board was fabricated from a commercial PCB house, with the component installation and testing done in house as well. The board has provisions for four thermocouples, an optional pressure transducer, and a voltage monitoring capability. Another key feature of the of the electronics is an aggressive sleep mode to save energy: a master clock will power the electronics and sensors down for a pre-determined interval then wake the electronics up and report a measurement. The system will return to sleep mode after the transmission.

The printed circuit board that is used to collect and transmit the data from the prototype unit is shown in Fig. 13. A buck-boost DC/DC converter with a 3V to 15V input range was designed to maintain both stable 3.3V and 5V supply for the circuit. Two Maxim *Max31855* temperature-conditioning chips, an ATMEL

ATMega64 microcontroller ( $\mu\text{C}$ ) and a Digi International Inc. XBee Pro radio module for wireless communication are all included in the board design. The board is equipped 2 10-bit analog-to-digital converters (ADC) for additional sensor inputs required. The decision was also made to incorporate a battery charging and management chip, both for operation of the electronics themselves as well as charging larger storage batteries for actuation. This is discussed in further detail in Section 2.5.

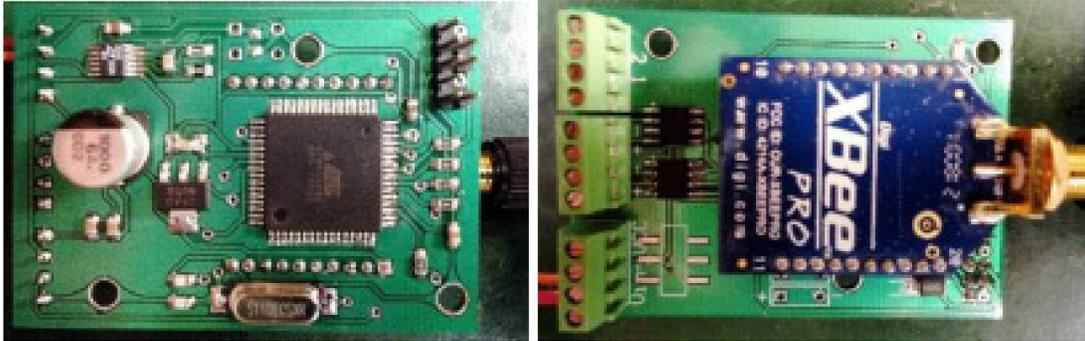


Figure 12: Printed circuit board for prototype

The total power consumption of the board is 330-390mW under 3V stable lab power supply, including an onboard status LED. All the data collected was transmitted via the wireless radio to a notebook with a LabVIEW<sup>®</sup> interface.

The electronics package records the two thermocouple temperatures as well as the temperature of the electronics package itself from an onboard sensor, and reports all three readings wirelessly to a separate commercially available notebook computer that is located within 30 m of the transmitter. The notebook, in turn, is connected to the internet, and the data is transmitted back to a server in the PI's research laboratory for processing, display and storage. The data there is used to generate a webpage that provides real-time status updates of the pipe temperature. The electronics package and radio are shown in the figure below.

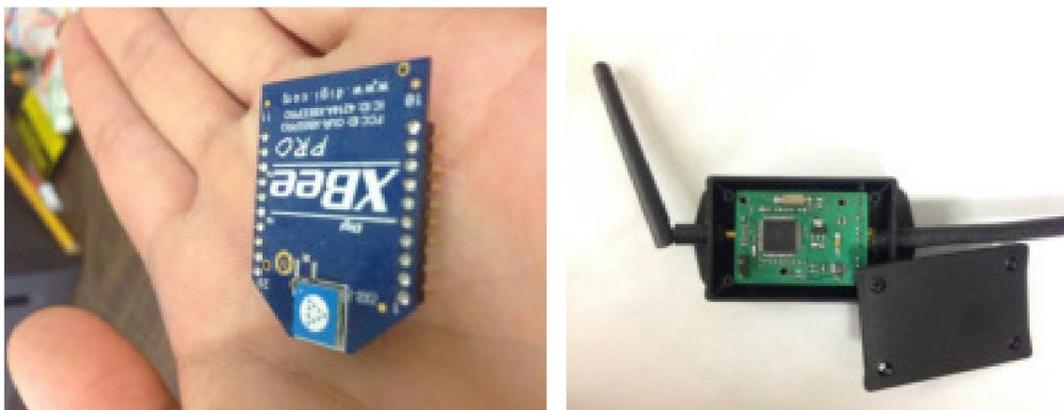


Figure 13: (left) Wireless radio module used for Zigbee communication (right) complete module as installed in power plant.

### 2.4.1 Radiation Considerations

The design and testing of the prototype addresses all the expected challenges present in a nuclear power plant with the exception of radiation exposure. Different electronic components can handle varying degrees of radiation exposure and different locations and operating conditions result in different levels of radiation. To protect these components, two approaches can be taken. First, radiation-hardened and radiation-tolerant components can be used in the system when available. The rated tolerance is based on the expected radiation levels inside the plant during normal and off-normal conditions. A second and preferred approach is to use an enclosure that can withstand high levels of radiation. The electronics package can be placed in the center of an environmental protection enclosure made from different layers that protect from different types of radiation.

Although radiation can cause negative effects in electronic circuits, nuclear radiation exposure is not necessarily undesirable for TEGs. A study performed using neutron radiation by Westinghouse found the Seebeck coefficient to actually improve after exposure. Lead telluride ( $p$ -PbTe) was exposed to a total neutron dosage of  $\sim 10^{19}$  neutrons/cm<sup>2</sup>. Measurements made after irradiation found that the electrical resistivity increased nearly four times and Seebeck coefficient increased by 2 to 3 percent. The ZT was somewhat reduced, but the offsetting effects of the Seebeck coefficient and the thermal conductivity limited the net change in ZT.

## 2.5 Energy Storage and Power Management

Although the TEG device will nominally provide continuous DC power in the presence of a heat source, it was felt that for additional reliability and redundancy that a secondary power supply be made available for the sensing and wireless systems. If the TEG module were to fail or otherwise become detached from the component, for example from an impact or explosion, it would no longer be able to provide the required electrical power for the sensors and wireless radio. This task thus focused on providing a secondary energy storage capability.

Both batteries and super capacitors were explored as the energy storage devices (ESD). The ESD is then stored with surplus electricity available from the thermoelectric module during nominal operation.

An important design consideration is maximizing the runtime for the sensor system in the event that the primary TEG becomes unavailable. This required focusing on several aspects of the entire sensor package design, including the following:

1. *Low power design.* By keeping the electronics package electrical consumption to a minimum, every life is maximized. Fortunately the advent of cell phones and other portable devices has resulted in substantial advances in commercially available circuit technology that employs low-power capabilities. One possible, these components were used in the sensor design.
2. *Aggressive sleep mode.* The microprocessor used for the sensor package was programmed to go into an aggressive sleep mode in between sensor reporting periods for example a typical protocol would be for the microprocessor to be in a deep-sleep state for some period of time, say 30 seconds. The microprocessor is then woken up by an interrupt-driven signal from a low-power real-time clock, where it proceeds to interrogate the sensors, process the data, wake the radio

and send the data out on the network, and then go back to sleep again. By adopting such an approach, the duty cycle (period of time where the circuitry is actually working) can be reduced to one part in 10,000 to one part of 100,000, resulting in substantially increased energy savings.

3. *Automatic switchover to backup power without manual intervention.* A small but important point is that the power supply should not be interrupted in the event of the TEG failure. As such a dedicated power management system was used in the final circuit design that automatically manages and monitors the primary power source. If it falls below a threshold voltage the secondary power is brought in immediately, without any interruption in power to the electronics and sensing circuit

In the final design, a Li-ion battery was used as the backup power source. The Li-ion based rechargeable energy storage system was tested on the bench by using a DC power supply to simulate the thermoelectric power output. An electronic battery management chip was incorporated into the prototype that managed tasks include (i) battery charging, (ii) switching over to battery power when the primary power drops out, (iii) reducing the charge current to trickle charge the battery once the battery has fully charged. By incorporating the battery management chip, the rest of the electronics in the sensor package become “power blind” in that they are unaware of the source of power (either from the thermoelectric module or the battery). Transitions to and from battery power also happen fast enough so that the electronics are not interrupted.

## 2.6 Actuation Integration and Feasibility Study

in addition to providing monitoring sensing capabilities, the wireless network proposed as part of this project is also capable of sending commands and requests back to the plant. This provides for the ability to control devices within the plant through the same network. For example valves could be opened, tanks drained, pumps operated, etc. Actuation in general requires a significantly larger amounts of energy than would normally be available through the TEG devices. This task explored how the required energy for actuation would best be obtained.

Our initial round of thinking involved utilizing banks of rechargeable batteries, such as lead-acid or lithium-ion battery banks. The banks could be initially charged when installed, and then the electricity from the TEG devices could be used to trickle charge the batteries to maintain their charge. This approach is attractive at first glance, for it solves the problem of having large amounts of power available when needed for a short period of time, while being able to take advantage of surplus electricity that the TEG generates over longer periods of time. After additional analysis, several issues arose in terms of an electronic approach. In particular, all battery technologies tend to degrade over a period of several years. The concern would be that a battery remains fully charged and otherwise unused, then when needed, it would have little to no actual capacity, rendering it useless for actuation tasks. Additional concerns such as corrosion, protection of the batteries, reduce performance at high temperatures, and the complexity of the electrical switching circuitry all also present additional potential failure points for such a system.

Batteries remain potential technology to use for actuation, and are not ruled out completely, however it is recommended now that *pneumatic actuators*, rather than stored-electricity, be used for emergency actuation. Examples include using actuators to open emergency cooling water valves or shut down valves of a damage pipe loop in nuclear power plants. The benefits of using a pneumatic actuator are its small

electrical energy consumption (0-20 mA and 6 VDC), easy-maintenance, and long-term gas/liquid storage capably needed only. By contrast, the motor in and electrical actuator needs a large electrical energy store that usually is measured in the hundreds or thousands of watts.

Pneumatic controls appear to be the most promising choice for long-term reliability and ease of storing the required energy. Compressed carbon dioxide cylinders are one possible source for energy actuation. The cylinders are commercially available in small formats, provide a large volume of CO<sub>2</sub> (0.5 to 1.0 kg, or 250 to 500 L of CO<sub>2</sub> respectively), and at attractive pressures (600 to 1000 psi). The benefits of using a pneumatic actuator are its small electrical energy consumption (0-20 mA and 6 VDC), easy-maintenance, and long-term gas/liquid storage capably needed only. One potential issue is that CO<sub>2</sub> tanks are typically inspected every five years because the gas is mildly corrosive under pressure. This, however, could be incorporated into part of the maintenance cycle, in which the cylinders are exchanged at five-year periods and the rest of the system inspected for operation.

Another option is R134a, which is the refrigerant used in many home and automotive air conditioning systems. R134a does not present a corrosion hazard and thus the tanks can be in service much longer (15+ years) without a maintenance cycle. R134a is a greenhouse gas (much more so than CO<sub>2</sub>), however the total amount released would be miniscule (ideally zero) in the global picture. R134a also has a moderate working pressure, which is useful. One concern is that the pressure may drop significantly in very cold climates, which may limit the energy available for actuation. This issue would be plant-specific, based on the location and historical weather data for the site.

Although an actual actuation prototype was not fabricated in this project, the technology review resulted in pneumatic controls as the most attractive means to store large amounts of energy for actuation, while being available 24/7 on a moment's notice, and being able to reliably provide this capability for decades.

Other alternative candidate energy storage mechanisms evaluated, in addition to compressed gas and batteries included: (1) mechanical energy storage (linear and coiled springs), (2) gravity-based systems in which a weight was allowed to fall to effect actuation, (3) hydrostatic head (elevated tank with water or hydraulic oil), and (4) chemical-based systems. All of these alternative approaches were found to be inferior in one or more ways when compared to the pneumatic actuation suggested in this work.

A follow-on NEUP project would be well suited to explore these options in detail, including a more extensive cost/benefit analysis of the various powering options, detailed models of aging and reliability, prototype testing, and accelerated aging to assess long-term reliability.

## 2.7 Demonstration of Packaging and Environmental Protection

Work is continuing on package designs, and recommendations for shielding options for the TEG devices. The main emphasis in enclosure design is neutron bombardment. Shielding for neutrons is not as easy as for gamma-rays since they are heavier and more energy dependent. The designing of neutron radiation enclosures consists of 1) Slowing down fast high-energy neutrons; 2) Absorbing these slowed neutrons; and 3) attenuating the incident gamma radiation created during the activation. To slow down the fast high-energy neutrons, neutrons should collide with particles that have similar mass so that its energy loss can be maximized, so hydrocarbons are suitable for this purpose. To absorb the slowed down thermal neutrons, materials should have higher probability to form cross sections to interact with neutrons. Boron,

cadmium and polyethylene have high absorption cross sections are good options. However, low density materials can emit gamma rays when interacting with neutrons, therefore it is more effective to incorporate both high and low atomic number elements.

In this project, given that the radiation is intense in a nuclear power plant, an incorporated design for both gamma and neutron radiation design is recommended. This would consist of multilayer shielding as suggested above: the outer layer with low-Z material to slow down neutrons; the middle layer with good absorption cross section to absorb neutrons; and an inner layer with high-Z material to absorb gamma radiation and the incident radiation produced in neutron interaction. Additional layers or structure such as mechanical support and a sealing layer will need to be added as well for protection from traditional environmental threats including explosion flooding, fire, and crushing.

### 2.7.1 Radiation Testing

During the project, the performance of the thermoelectric modules, the electronics package, and the wireless device as a result of being exposed to both gamma and neutron radiation were characterized. A gamma ray source at Brookhaven National Laboratory, which is 30 minutes from Stony Brook University. This is a cesium-60 source the currently can produce about 1000 rad of gamma radiation. The electronics, sensors, and thermoelectric devices were exposed to this radiation source for a variety of different time periods to accumulate dosage.

Initially thermoelectric materials were tested. The N-type material is iodine-doped  $\text{Bi}_2\text{Te}_{2.5}\text{Se}_{0.5}$  and the P-type material is lead doped  $\text{Sb}_2\text{Se}_3$ . The dopant in both cases amounts to much less than 1% of the thermoelectric material  $\text{Bi}_2\text{Te}_3$ . The sample size is thermal conductivity sample 12.7 mm in diameter and 2 mm thick. The Hall Effect sample size is 10 mm square with a thickness of 1 mm.

Gamma radiation from the BNL 60-Co source with 1M and 10M Rad dose was delivered on  $\text{Bi}_2\text{Te}_3$  N type and  $\text{Sb}_2\text{Te}_3$  P type material. Thermal conductivity, electrical conductivity resistivity including the carrier concentration or mobility and Seebeck coefficient were then characterized. The thermal conductivity measurement is done using a *TA Instruments* flash instrument in the Advanced Energy Center at Stony Brook University.

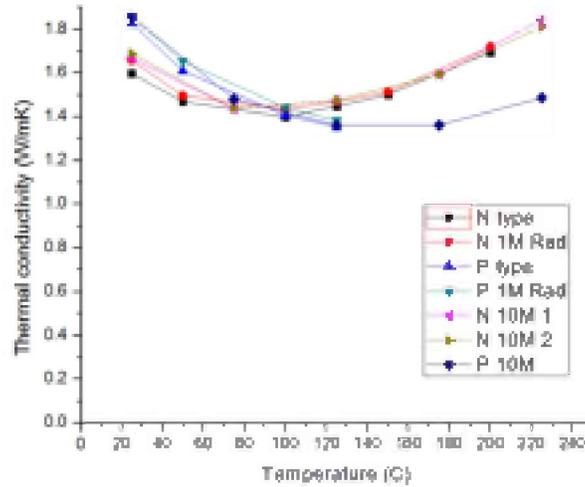


Figure 14: Thermal conductivity of N,P type material before and after gamma radiation.

As shown in figure above, the thermal conductivity of both types of material before radiation (N type, P type) do not change much after 1M or 10M Rad of gamma radiation. The difference is within the measurement error of the equipment. This is typical of previous measurements made in the literature.

Table 1: Electrical properties of N, P type material before and after radiation

sample	mobility (cm <sup>2</sup> /V*s)	sc (E19/cm <sup>3</sup> )	resistivity (E-5ohm m)
N1	180	1.45	2.38
N2	167	1.41	2.65
N1r	180	1.34	2.6
N2r	172	1.42	2.54
N2r	170	1.40	2.54
P1	230.5	2.5	1.13
P2	230.8	2.54	1.11
P1r10	222	2.5	1.12
P2r10	229	2.46	1.1
P_neutron_radiation1	222	2.48	1.13
P_neutron_radiation2	221	2.46	1.1

Table 1 shows up to 10M Rad of gamma radiation the electrical properties do not change significantly. Furthermore, the carrier concentration and mobility of both materials has been characterize using an HMS4800 Hall Effect Measurement system. The change noted is again negligible.

The sample has also been irradiate with neutrons at up to 10<sup>14</sup>/cm<sup>2</sup> at Penn State, as shown in Table 1. After this neutron irradiation the electrical properties also do not change significantly. Again, this is not unexpected: from the literature, it is suggested that dose on the order of 10<sup>19</sup>/cm<sup>2</sup> or more is required to effect a noticeable change in device properties. From our perspective, the results are encouraging in that a well-designed enclosure should be able to keep the gamma and neutron radiation fluxes well below

these values, hence standard, commercial off-the-shelf components should be useable without issue in an eventual implementation.

## 2.8 Keeping Abreast of Emerging Thermoelectric Technologies

During the course of this project, the major trends in thermoelectric device fabrication were reviewed periodically to determine if any significant innovations occurred that would be of interest or benefit to the project. Somewhat not surprisingly, the thermoelectric landscape has largely remained the same over the duration of the project. Although the quest for high-performance (high ZT) materials continues to be an active and vibrant research area, in terms of practical devices suited for actual applications (and that are cost-effective), traditional Bismuth-Telluride devices remain the device of choice. Although thermoelectric devices with a higher electrical power output would certainly be welcome, the technological advances being made are deemed not significant enough to warrant any deviation from the Bismuth-Telluride thermoelectric devices. At the same time, thermoelectric devices based on new materials present additional complications in terms of survivability and long-term reliability. For these reasons, it is recommended that adoptions or further development of the thermoelectric-driven sensing packages for nuclear facilities adopt industry-standard, proven bismuth-telluride technologies.

## 2.9 Reporting and Project Management

As of this writing, all quarterly project reports and annual reports have been submitted. This final report constitutes the completion of reporting requirements for the project. In terms of project management, the program remained on-schedule and on-budget, with no significant scope or budget deviations occurring.

# 3 Publications Produced from this Project

A summary of all presentations to date on the project are included below.

## 3.1 In preparation

Two manuscripts are now in prepared for publication based on the work above. The tentative titles and candidate journal for each are indicated below. Although the actual journal cannot be guaranteed at this point, the title and list of authors will not change substantially, should the reader wish to search for these publications once they appear in the literature.

1. Tewolde, M., Tao, H., Chen, H., Zhang, T., Hwang, D., Zuo, L., and Longtin, J.P., "Design and Fabrication of Thermoelectric-Generator-Based Sensors for Small Modular Reactors," to be submitted to the *ASME Journal of Nuclear Engineering and Radiation Science*.
2. Chen, H., He, T., Tewolde, M., Hwang, D., and Longtin, J.P., "Low-Temperature Heat-Pipe-Assisted Thermoelectric Generator System for Wireless Sensors," to be submitted to *Applied Thermal Engineering*.

The expected completion and submission timeframe for both articles is the summer of 2016.

## 3.2 Published

The following publications and presentations have resulted from this project.

3. Tewolde, M., Seo, D., Kim, K., Zhang, T., Hwang, D., and Longtin, J. P., 2015, “Integrated additive manufacturing and laser micromachining to fabricate thermoelectric generators directly onto waste-heat components” presented at the *ASTFE First Thermal and Fluids Engineering Summer Conference*, New York, NY, Aug. 9–12, 2015.
4. Fu, G., Zuo, L., Lian, J., Wang, Y., Chen, J., Longtin, J.P., and Xiao, Z., 2015, “Ion Beam Irradiation Effect on Thermoelectric Properties of Bi<sub>2</sub>Te<sub>3</sub> and Sb<sub>2</sub>Te<sub>3</sub> Thin Films” *Nuclear Instruments and Methods in Physics Research B*, Vol. 358, pp. 229–235.
5. Tewolde, M., Lin, C.C., Chen, H., Tao, H., Fu, G., Liu, D., Zhang, T., Nie, C., Zheng, W., Benjamin, D., Liu, F., Zuo, L., Hwang, D., and Longtin, J.P., 2013, “Thermoelectrically Powered Sensing for Nuclear Power Plants,” *ANS Winter National Meeting*, Nov. 13–14, 2013, Washington, DC.
6. Tewolde, M., Lin, C.C., Chen, H., Tao, H., Fu, G., Liu, D., Zhang, T., Benjamin, D., Liu, F., Zuo, L., Hwang, D., and Longtin, 2014, Sensors for Small Modular Reactors Powered by Thermoelectric Generators, “presented at the ASME Small Modular Reactor Symposium, Apr. 15–17, 2014, Washington, DC.
7. Lin, C.C., Chen, H., Tewolde, M., Fu, G., Liu, D., Zhang, t., Tao, H., Chao, N., Zheng, W., Liu, F., Zuo, L., Hwang, D., and Longtin, J.P., 2013, “Thermoelectrically Powered Sensing for Small Modular Reactors” presented at the 2013 ASME Heat Transfer Conference, Minnesota, MN.
8. Poster session at the 2013 Advanced Energy Conference in New York City on April 30, 2013. Poster entitled “Thermoelectric-Driven Sustainable Sensing and Actuation Systems for Fault-Tolerant Nuclear Incidents”. The poster won 1<sup>st</sup> Prize in the poster competition, receiving a \$250 cash award.

## 4 Schedule / Gantt chart

The duration of this project was three years (36 months), spanning the dates Oct. 1, 2012 through Sep. 30, 2015. The tasks discussed in Section 2 above were performed according to the schedule below.

Table 2 – Project Performance Schedule

Task	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
<b>Task 1: Requirements review &amp; feasibility study of TEG locations</b>	◊	◊										
<b>Task 2: Initial design and analysis of TEG devices</b>	◊	◊	◊	◊								
<b>Task 3: Fabrication and testing of TEG prototype</b>		◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
<b>Task 4: Sensor integration / real-time monitoring of components</b>			◊	◊	◊	◊	◊	◊	◊	◊	◊	◊
<b>Task 5: Batteries and power management</b>		◊	◊	◊	◊	◊	◊	◊	◊	◊		
<b>Task 6: Actuation integration and feasibility study</b>	◊			◊	◊			◊	◊	◊	◊	◊
<b>Task 7: Demonstration of packaging and environmental protection</b>						◊	◊	◊	◊	◊		
<b>Task 8: Keeping abreast of emerging thermoelectric technologies</b>		◊		◊		◊		◊		◊		◊
<b>Task 9: Reporting and project management</b>	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊	◊

## 5 Conclusions and Future Recommendations

This project explored the concept of using thermoelectric (TEG) modules to power wireless, autonomous sensor systems for modular SMR reactors. The study included the design, analysis, and experimental validation of two thermoelectric-driven sensor prototypes. The first prototype used a simple aluminum bar for heat transfer and is suitable for higher temperature applications. The second prototype used heat pipes to substantially improve the heat transfer from the SMR component to the TEG, and is suitable for

lower-temperature components, thus extending the potential temperature range for this solution. Data were collected in both laboratory and field testing, with results in good agreement with predicted values. The technology appears to be promising to provide additional safety and redundancy to next-generation SMR reactors. It is recommended that future funding be considered to further develop this technology.