U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Nanostructured Bulk Thermoelectric Generator for Efficient Power Harvesting for Self-powered Sensor Networks

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NEET2

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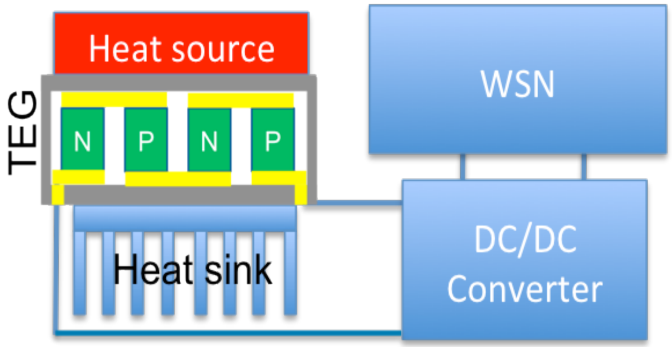
Project Overview

Goal, and Objectives

- Develop high-efficiency and reliable thermoelectric generators (**TEG**s)
- Demonstrate self-powered wireless sensor nodes (**WSN**s)

Participants

- Yanliang Zhang, Boise State University;
- Darryl P. Butt, Boise State University;
- Vivek Agarwal, Idaho National Laboratory;
- Zhifeng Ren, University of Houston.



Schedule 01/2015 - 12/2017

Year 1	• Determine and profile WSN power consumption • Select thermoelectric materials with optimal performance • Study irradiation effect on thermoelectric materials
Year 2	• Develop a TEG and WSN simulator • Design TEG of sufficient power output • Complete analysis of irradiation effect
Year 3	• Fabricate the TEG and test the TEG under irradiation effect • Demonstrate the TEG-powered WSN prototype

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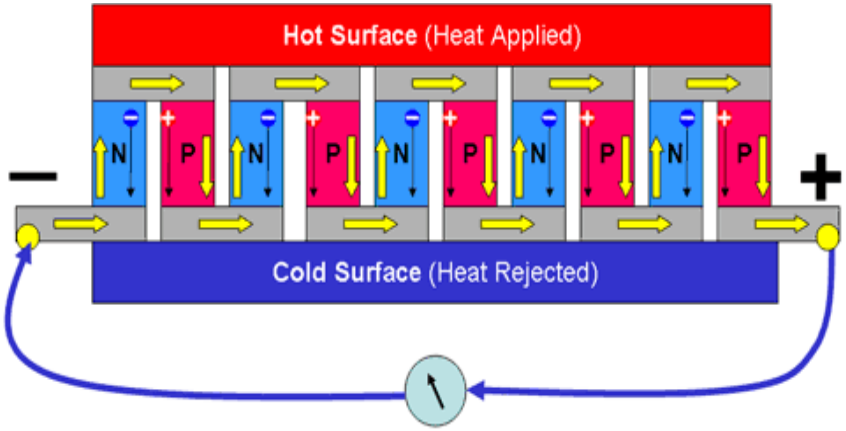
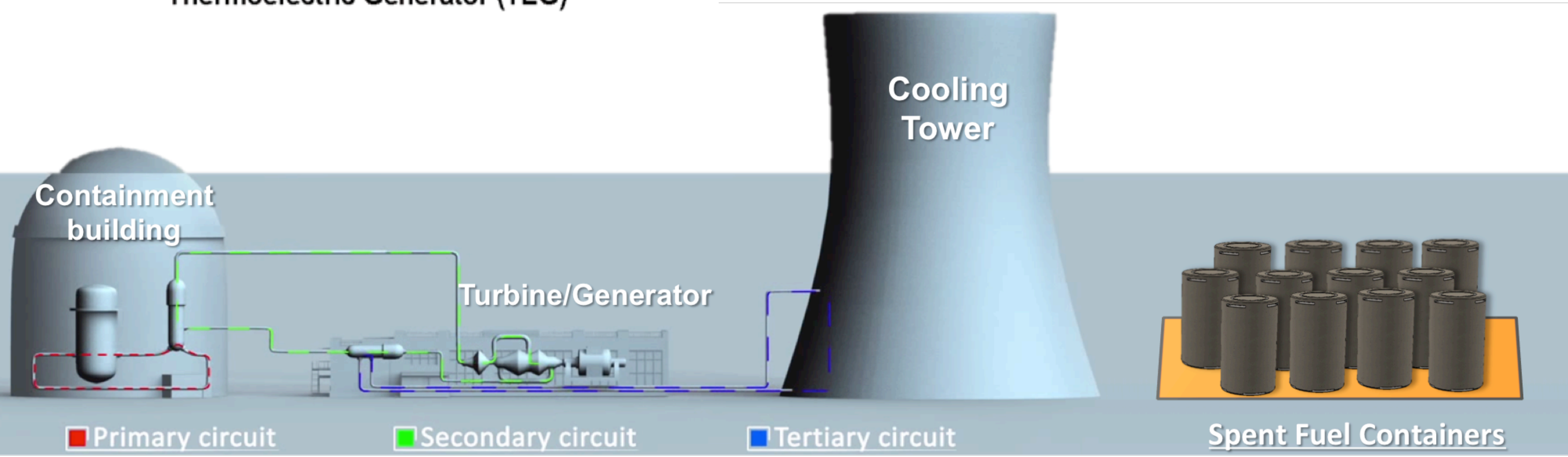
Background and motivation



Thermoelectric Generator (TEG)

- TEG is very compact and reliable
- Heat sources are very abundant in nuclear power plant and fuel cycles
- The efficiency of thermoelectric materials have undergone tremendous improvement in past two decades



Accomplishments

- **The team achieved the following three milestones for FY15**

  - Selected two types of thermoelectric materials with optimal performance
  - Performed initial study of irradiation effect on thermoelectric materials
  - Established wireless sensor node power requirements

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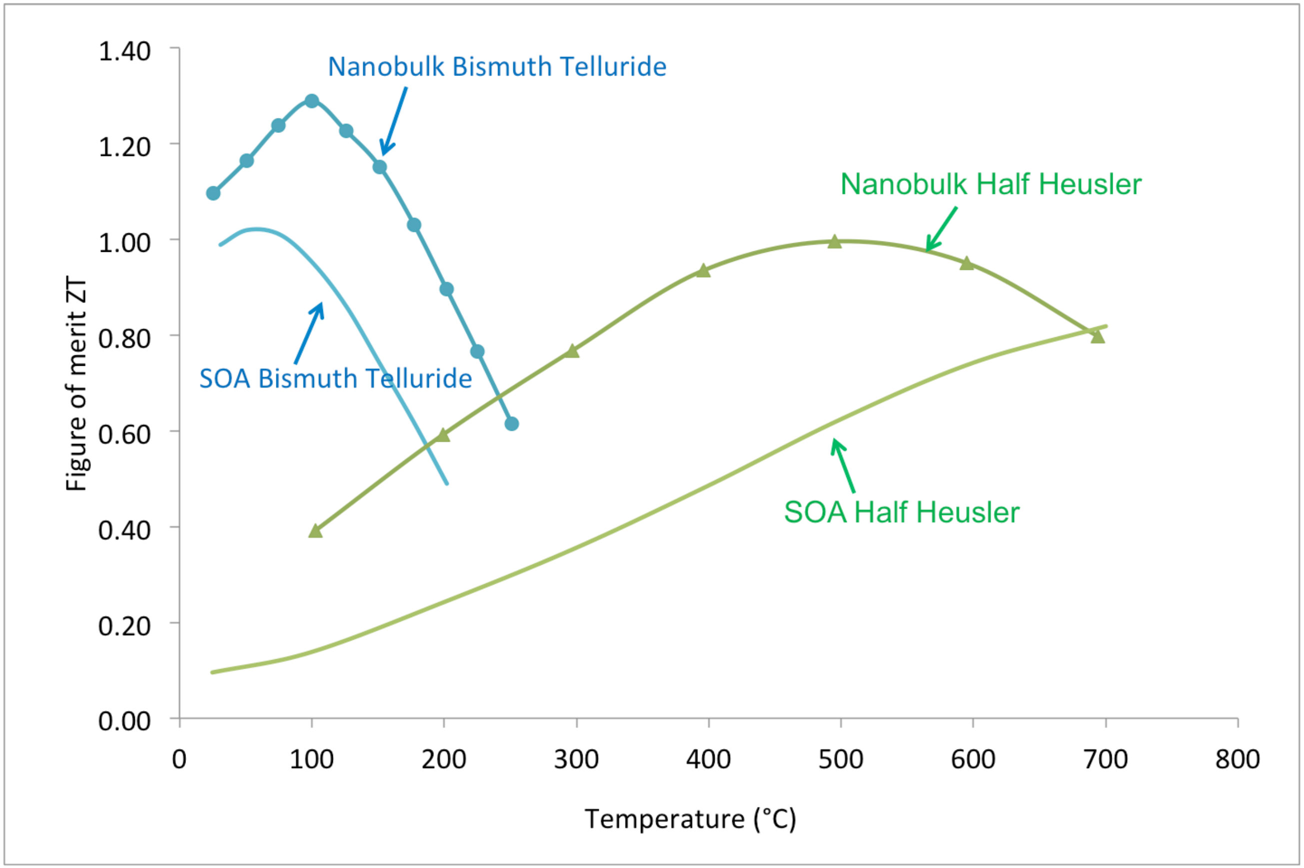
Select thermoelectric materials with optimal performances

Compounds		Bi_2Te_3	PbTe/PbSe	Skutterudites	Half-Heusler	SiGe
Working Temperature		0-200 °C	100-500 °C	100-500 °C	100-700 °C	100-1000 °C
Peak figure of merit ZT	N	1.1	1.3	1.7	1.0	1.3
	P	1.3	2.2	1.0	0.9	1.0
Supply		Te	Te	Rare-earth		Ge
Cost		moderate	moderate	low	Moderate	high
Toxicity		Low	high	Low	low	Low
Mechanical Strength		Moderate	Poor	Moderate	High	High
Thermal Stability		Moderate	Poor	Low	High	High

- Bi_2Te_3 and Half-Heusler are two excellent candidates for power harvesting
- Cover broad application temperature range from room temp to 600 °C
- Combine relatively low cost, high mechanical strength and thermal stability

Enhanced thermoelectric efficiency in nanostructured materials



- Our nanostructured thermoelectric materials have shown 30-50% ZT increases

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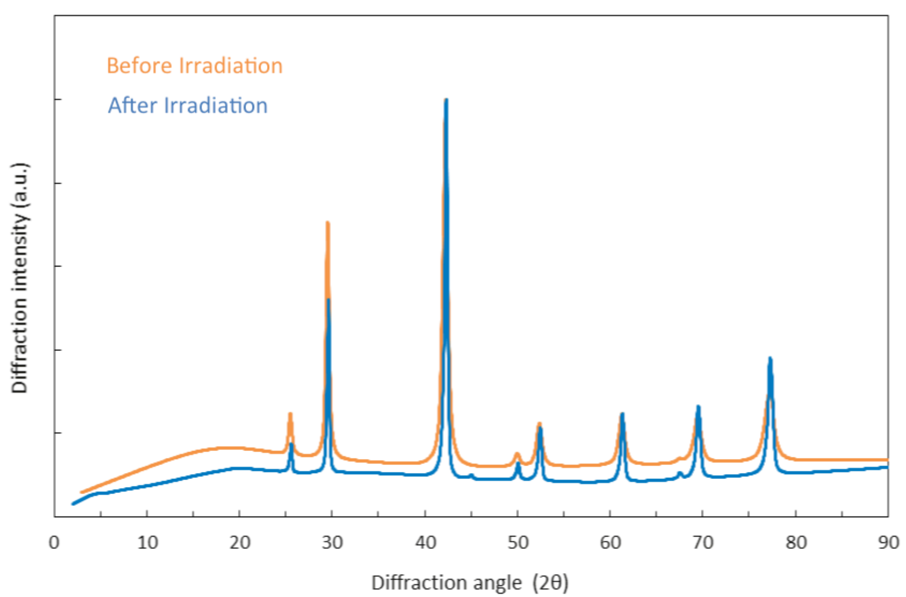
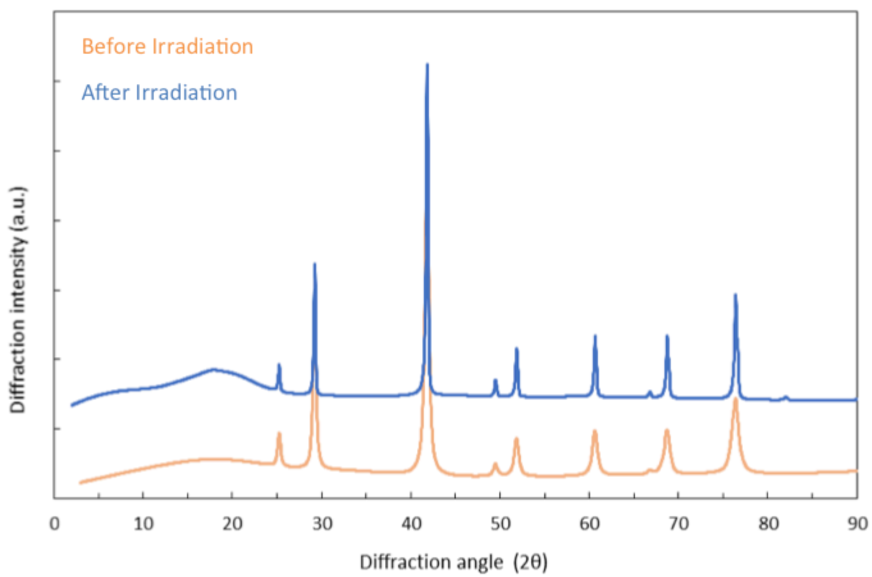
Irradiation effect on nanostructured thermoelectric materials



XRD pattern of the irradiated and non-irradiated *p*-type half-Heusler

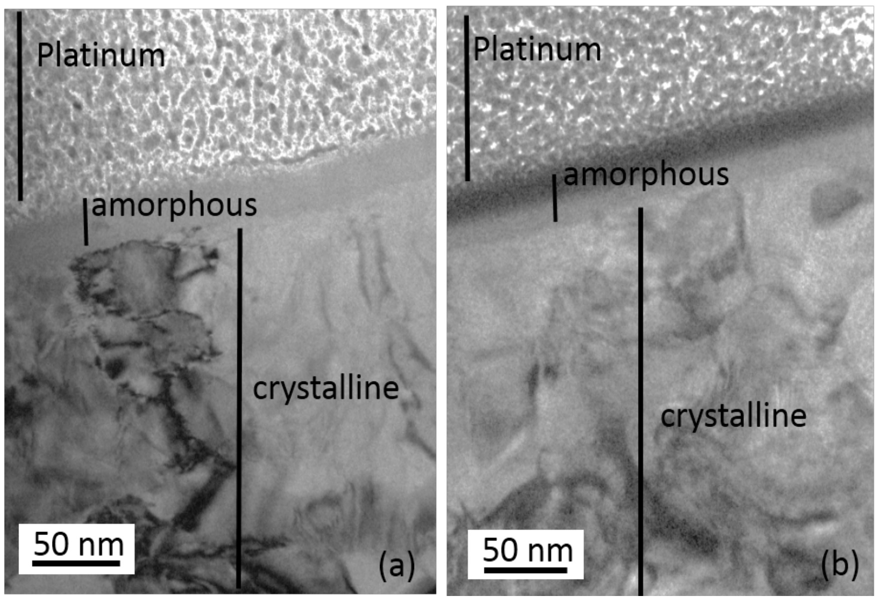


XRD pattern of the irradiated and non-irradiated *n*-type half-Heusler

- XRD reveals similar crystal structure before and after 1 MeV proton irradiation

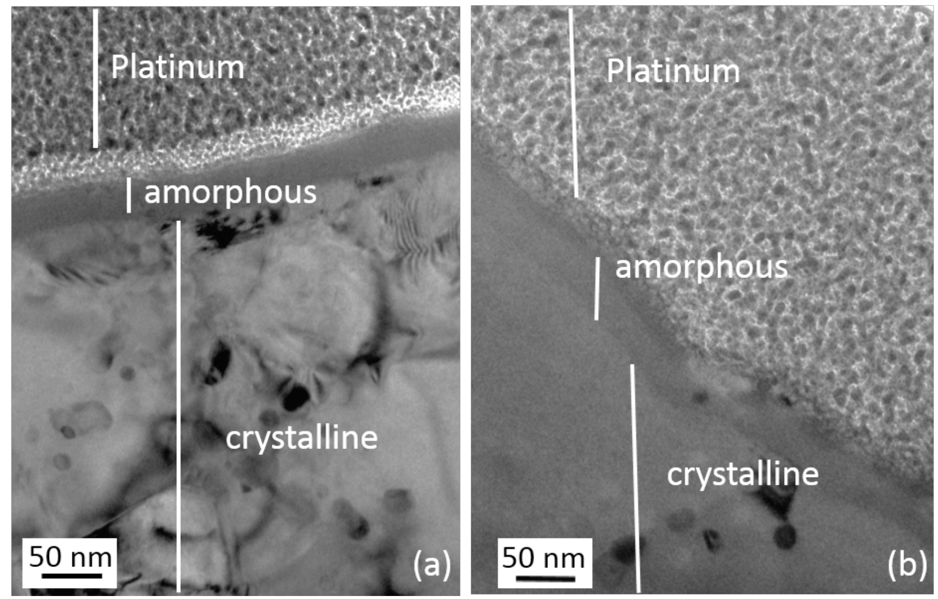
Irradiation effect on nanostructured thermoelectric materials microstructures

Irradiated | Non-irradiated



TEM on irradiated and non-irradiated
p – type half-heusler materials

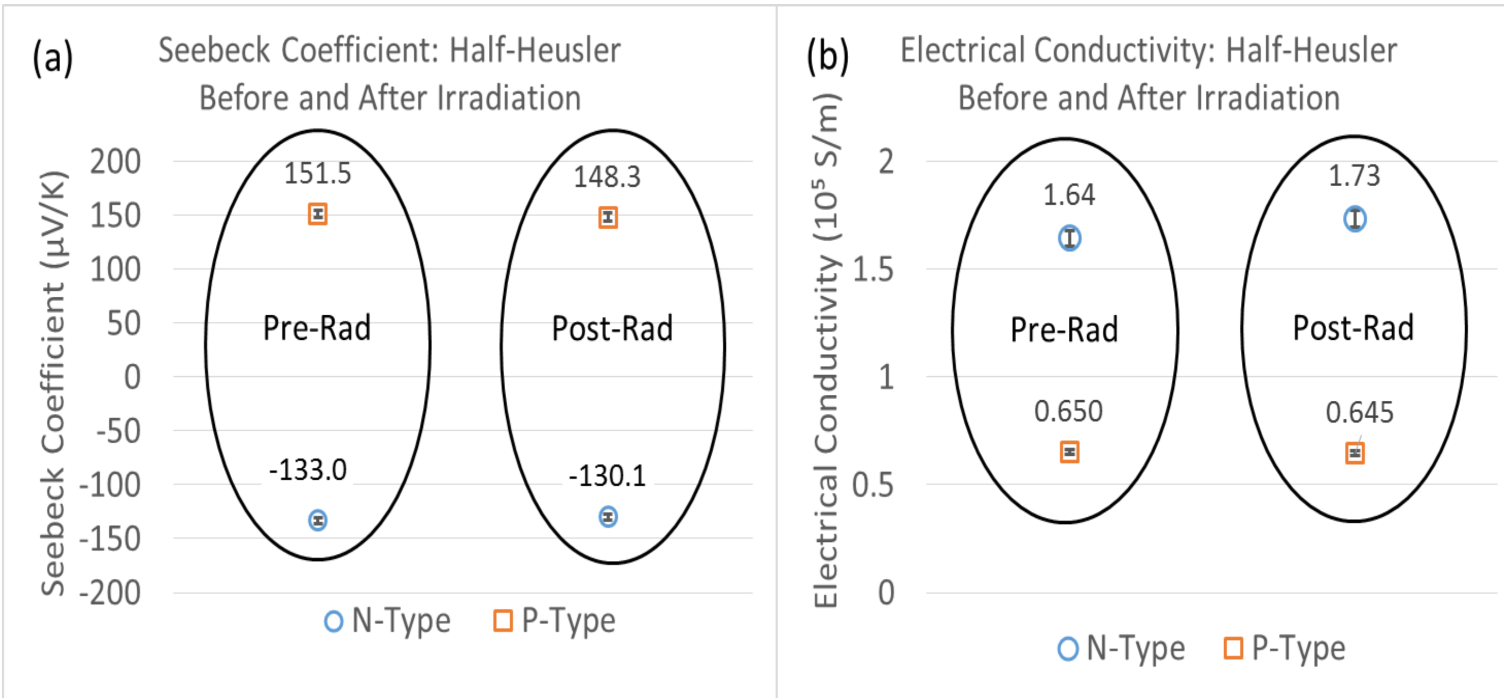
Irradiated | Non-irradiated



TEM on irradiated and non-irradiated
n – type half-heusler materials

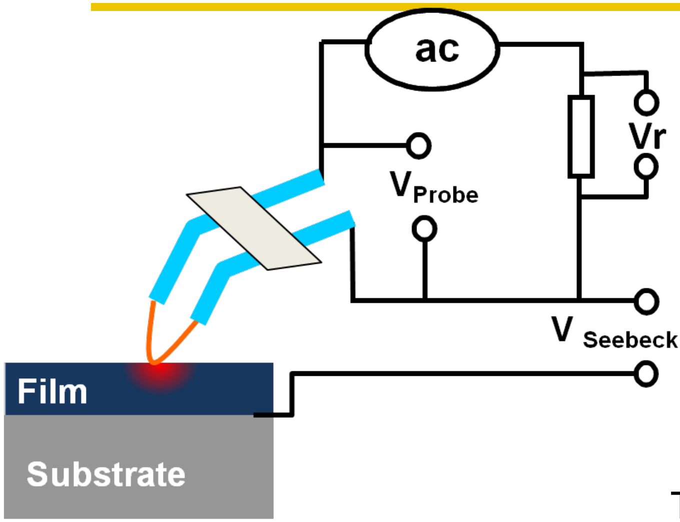
- The similarity of microstructures between irradiated and non-irradiated samples suggest no radiation damage under 1 MeV proton irradiation

Irradiation effect on macroscale thermoelectric materials properties

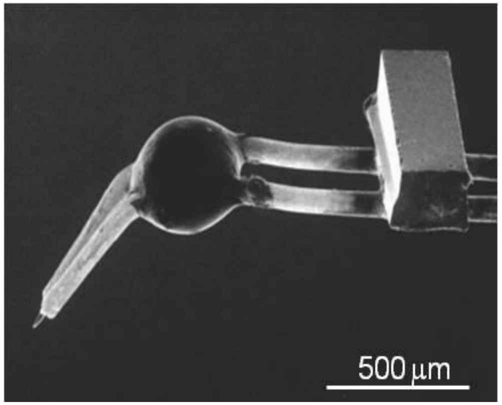


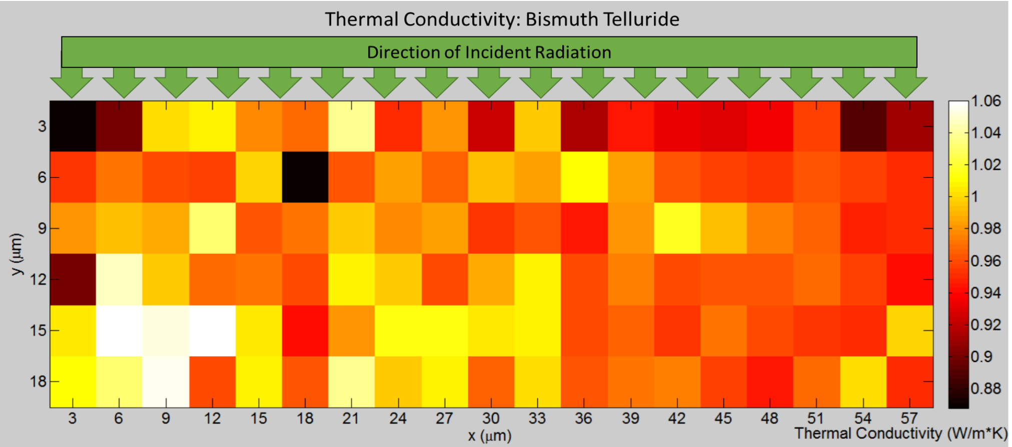
- The Seebeck coefficient and electrical conductivity of half-Heusler materials show negligible changes before and after irradiation.

Irradiation effect on microscale thermoelectric materials properties

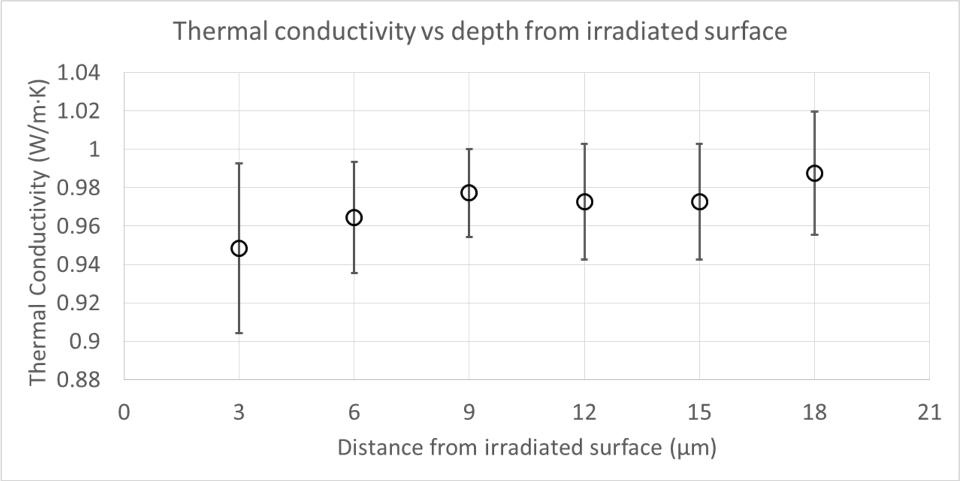


Scan thermal conductivity κ and Seebeck coefficient α simultaneously





Thermal conductivity map of irradiated bismuth telluride cross section



Thermal conductivity remains the same across the irradiated and non-irradiated region

Establish wireless sensor node (WSN) power requirements

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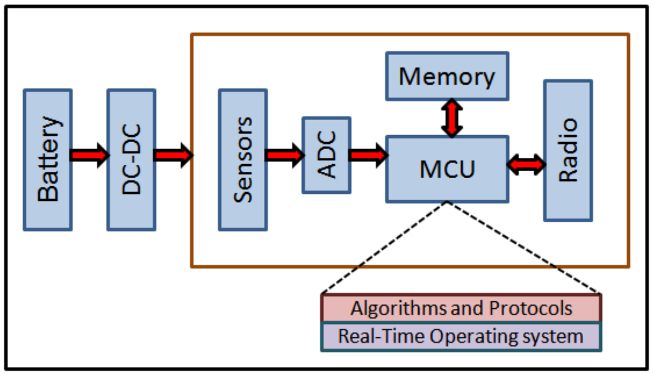
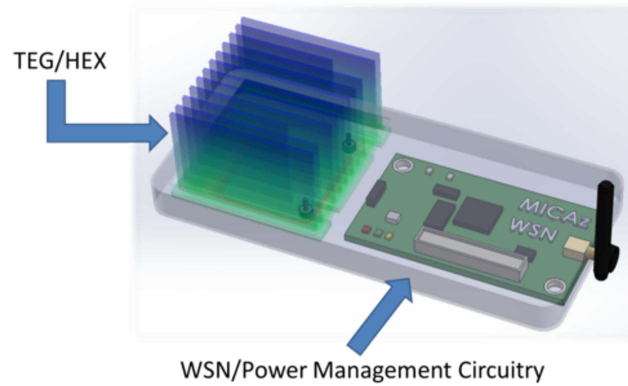
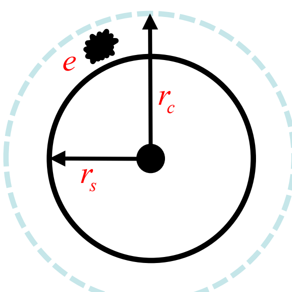
Battery powered WSN

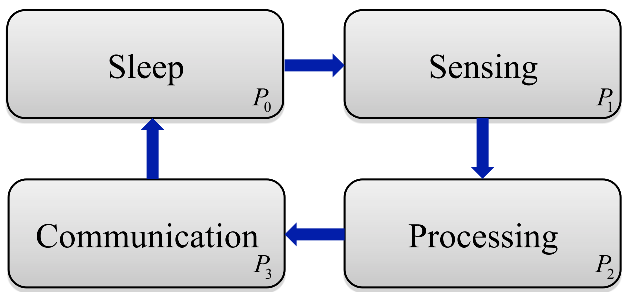


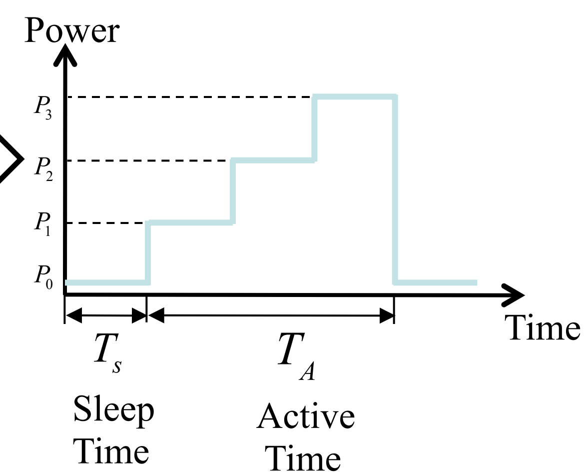
Self-Powered WSN





e : Event
r_s : Sensing radius
r_c : Communication radius





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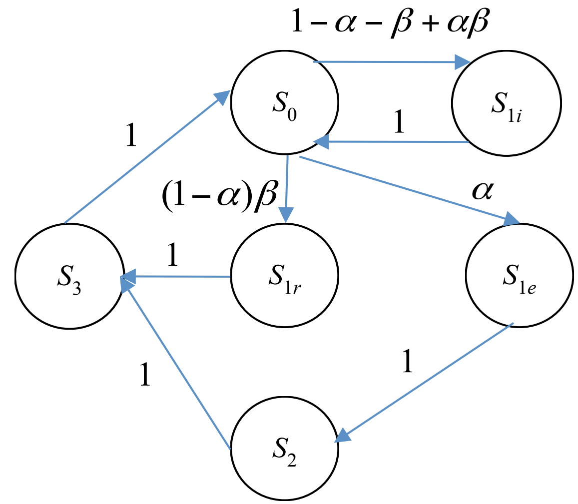
Mathematical Model of WSN Power Consumption

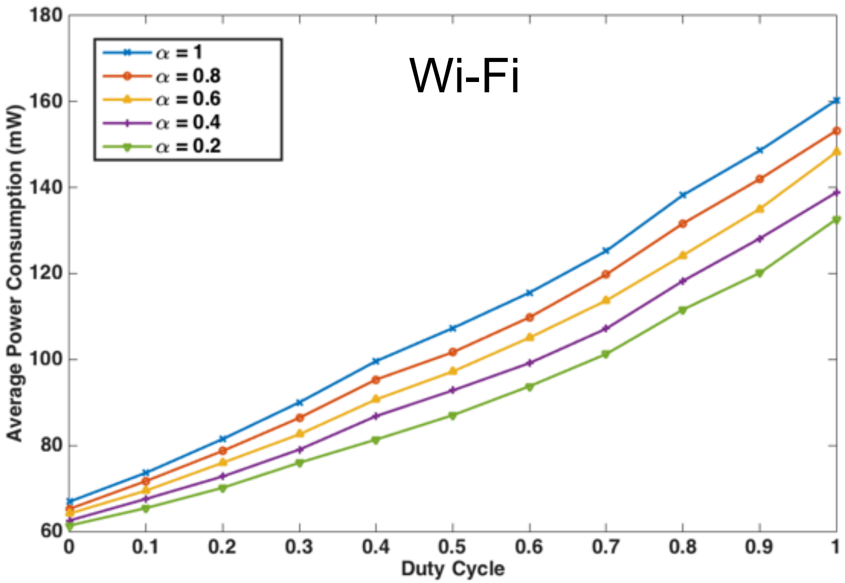
- A rigorous mathematical model based on state transition probabilities and stochastic theory is developed
  - To compute **expected energy consumed** and the **variance of the energy** consumed by a WSN
- The model considers both WSN and network level factors like **packet error rate**, **number of retransmission attempts**, and **latency**

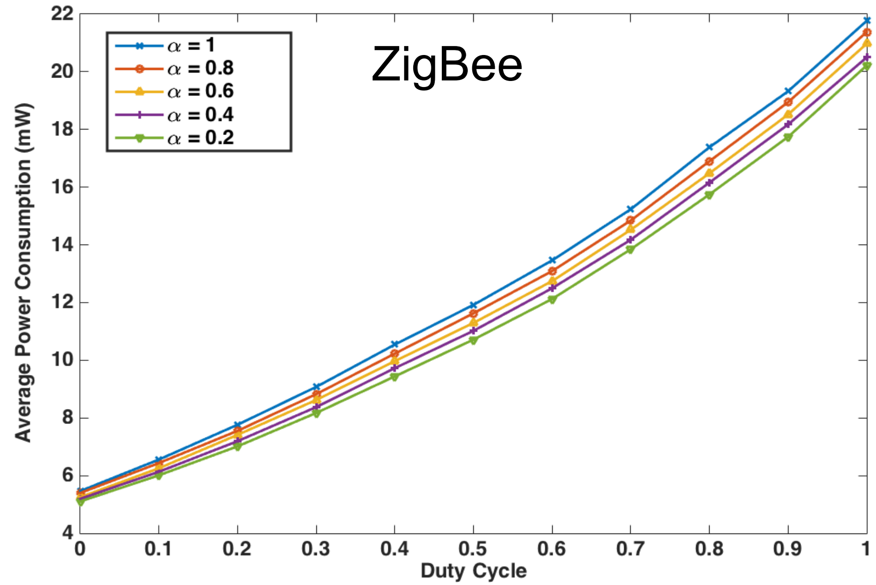


The stochastic operation of a WSN

State	Description
S_0	SLEEP state: No activity
S_{1i}	ACTIVE state: No events
S_{1e}	ACTIVE state: Sensing event alone
S_{1r}	ACTIVE state: Receives relay event alone
S_2	ACTIVE state: Processing of events
S_3	ACTIVE state: Transmission of information

Establish wireless sensor node (WSN) power requirements





We focused on two wireless communication protocols:
IEEE 802.11 – WLAN / Wi-Fi
IEEE 802.15.4 – ZigBee

$$Duty\ Cycle = \frac{T_A}{T_A + T_{S_0}}$$

T_A Active time period during which a wireless sensor node performs sensing, processing, and transmission

T_{S_0} Low energy state time period during which a wireless sensor node remains dormant

α Event occurrence probability

Technology Impact

- ***Impact on overall NE mission and the nuclear industry***

- Address critical technology gaps in monitoring nuclear reactors and fuel cycle.
- Enable self-powered WSNs in multiple nuclear reactor designs as well as spent fuel storage facilities.
- Cost savings by eliminating cable installation and maintenance.
- Significant expansion in remote monitoring of nuclear facilities.
- Significantly improve sensor power reliability and thus safety in nuclear power plants and spent fuel storage facilities.

Conclusion and future work

- Two high-performance thermoelectric materials have been selected for this project.
- Initial radiation analysis on nanostructured thermoelectric materials show no noticeable changes with proton irradiation.
- WSN power consumption has been established based on two wireless communication protocols.
- We will continue studying irradiation effect on thermoelectric materials.
- We will fabricate efficient and robust thermoelectric devices and demonstrate a self-powered WSN.