U.S. DEPARTMENT OF ENERGY | Nuclear Energy

## Nuclear Energy Enabling Technologies (NEET)

# Advanced Sensors and Instrumentation (ASI) Annual Project Review

## Power Harvesting for Sensor Networks


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# Project Overview

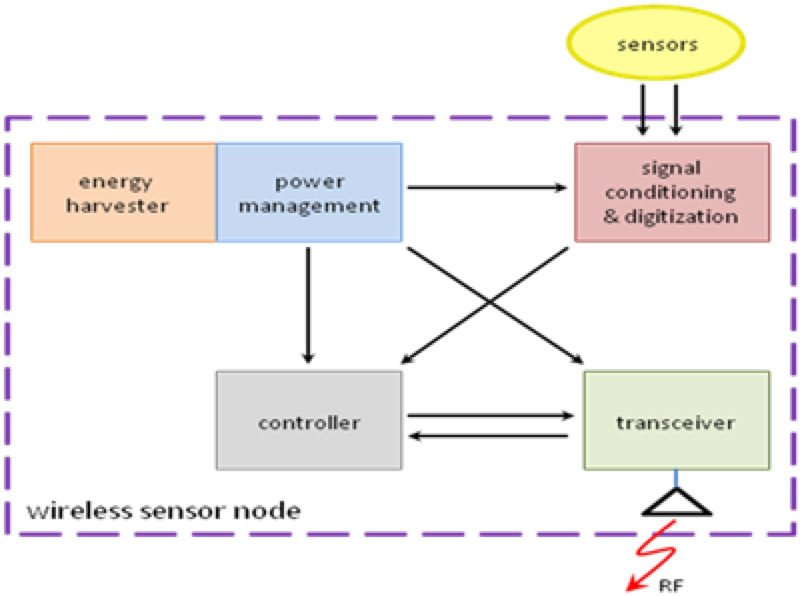
## Goal and Objectives

- The overall goal is to develop and demonstrate an advanced, multi-functional, power-scavenging sensor network system for nuclear power plants.
  - Develop truly wireless sensors (no external power or signal wires)
    - Use ambient energy to power the sensors and electronics
    - Use wireless methods to communicate data from the nodes
  - Enable the cost-effective deployment of larger numbers of sensors that can improve the redundancy, security, and safety of modern reactors
    - The high installation cost of prevents many additional sensors from being deployed
    - The planned self-powered wireless sensor nodes will be easily installed in both new and existing nuclear power plants
  - Wireless sensors addresses part of the physical cable aging issues
- Eventually a Technology Transition plan with the NRC will be needed

# Project Overview (continued – 1)

## Goal and Objectives (continued)

- Determine the most appropriate power harvesting technique to convert ambient energy to electrical energy
- Develop a system where additional sensors can easily be added
- Determine network architecture best suited for NPP environments
- Design the necessary electronics that minimizes power losses
- Design data transmission protocols that are adaptive, robust, and require little power while still maintaining the necessary amount of information flow




Elements of a self-powered wireless sensor node

# Project Overview (continued - 2)

- **Participants**
  - Performed at ORNL using a diverse set of ORNL staff and facilities
    - Principal Investigator – Dwight Clayton
    - Electronics Design – Chuck Britton, Nance Ericson, Dwight Clayton, Andy Andrews, Roberto Lenarduzzi
    - Wireless Communications Design – Steven Killough, Wayne Manges, Dwight Clayton, Roberto Lenarduzzi, Richard Willems
    - Summer Interns as appropriate
- **LWRS, SMR, ARC, and NGNP programs will benefit from this work**
- **The FCRD program could indirectly benefit from this work**

# Technology Impact

- **While power harvesting is starting to be used in some industries, it has not been applied to the nuclear power industry.**
- **Power harvesting sensor networks can help DOE-NE meet its four primary research objectives as identified in the Nuclear Energy Research and Development Roadmap.**
  - Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
  - Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration’s energy security and climate change goals.
  - Develop sustainable fuel cycles.
  - Understand and minimize the risks of nuclear proliferation and terrorism.

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# Technology Impact (continued)

- **Two complementary research areas are being pursued to realize power harvesting sensor networks**
  - Power harvesting methods in a nuclear power plant environment
    - Survey current state of the practice
    - Determine power density of acceptable harvesting techniques
    - Identify gaps in power harvesting
  - Develop highly efficient lower power electronics
    - Design electronics that minimize power losses
    - Design data transmission protocols that are adaptive, robust, and require little power while still maintaining the necessary amount of information flow
- **Successful completion of this R&D will**
  - Provide technologies and solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
  - Improve the affordability of new reactors to enable nuclear energy to help meet the Administration’s energy security and climate change goals.

# Research Plan

- **Description of technical research (tasks) & planned budget**
  - FY2012 - $220 K
    - Determined state of the practice in power harvesting techniques
    - Identified power harvesting techniques applicable to nuclear power generation
    - Determined and documented associated power density
    - Issued ORNL/TM-2012/442 – Power Harvesting Practices and Technology Gaps for Sensor Networks
  - FY2013 - $160 K
    - Determine state of the practice in sensor networks
    - Document communication requirements
    - Develop concept of operation
    - Issue ORNL ORNL/TM-2013/180 – Communication Requirements and Concept of Operation for Sensor Networks
  - FY2014 - $225 K
    - Develop sensor requirements
    - Begin to investigate power loss in required solid-state devices

# Research Plan (continued)

- FY2015 - $250 K
  - Optimize power conversion efficiency
  - Develop methods to minimize power dissipation in solid-state devices
- FY2016 - $250 K
  - Fabricate solid-state device that implements minimized power dissipation
  - Design signal simulator to represent analog signals from sensors
- FY2017 - $675 K
  - Develop data transfer protocols that minimize power consumption
  - Design demonstration system
- FY2018 - $750 K
  - Fabricate demonstration system
  - Evaluate sensors network in a laboratory setting
- FY2019 - $500 K
  - Characterize the performance of a large scale Implementation
  - Draft Technology Transition plan

# FY2012 Accomplishments

- **FY2012 milestones and deliverables**
  - Determine state of the practice for power harvesting
    - Various energy sources were examined
      - Kinetic
        - Vibration
        - Acoustic
        - Mechanical contact force
        - Fluid flow
      - Thermal
        - Thermoelectric – spatial temperature gradients
          - Seebeck effect using bismuth telluride ($Bi_2Te_3$) or silicon nanowires
        - Pyroelectric – temporal temperature gradients
      - Radiant
        - Light
        - Radio-frequency (rf)
  - Identification of power harvesting knowledge gaps
    - Pyroelectric techniques show great promise (5 – 10 times higher energy density of thermoelectric), but additional R&D is needed
    - Some pyroelectric materials operate at 1200°C

# FY2012 Accomplishments (continued – 1)

- Summary of power harvesting practices was delivered in September 2012
  - Wireless sensor networks have proven to be less expensive, more flexible, and more reliable in industrial settings when compared to their wired counterparts
  - NPP facilities are replete with environmental energy sources having potential to power wireless sensor nodes
  - Thermal energy harvesting is an excellent choice for deployment in a NPP environment

| | Energy Source | Power Density |
|---|---|---|
| **Vibration/Motion** | Industry | 100 $\mu W/cm^2$ |
| **Temperature Differential** | Industry | 1–10 $mW/cm^2$ |
| **Radiant Light** | Indoor | 10 $\mu W/cm^2$ |
| | Outdoor | 10 $mW/cm^2$ |
| **Radiant RF** | GSM | 0.1 $\mu W/cm^2$ |
| | Wi-Fi | 0.001 $\mu W/cm^2$ |

# FY-2013 Activities

- **Survey current state of practice in sensor networks**
  - Mesh networks accommodate sensor data where high-reliability and security are important issues
  - Examine commercially available technologies such as “Wireless HART” and ISA100.11a
  - Investigate security at the physical layer and authentication at the MAC layer
  - Consider both passive and active attacks
    - Passive attacks attempts to retrieve vulnerable information
    - Active attacks attempts to disrupt operation (impersonation and spoofing)
  - Many commercially available wireless sensors operate in the unlicensed Industrial, Scientific, and Medical) ISM radio band as defined by the International Telecommunications Union (ITU)

# FY-2013 Activities (continued)

- **Document communication components requirements**
  - Power restrictions
  - Transmission frequency
  - Network architecture including how nodes are added
  - Capabilities required in each node
- **Develop a general concept of operation**
  - Overall architecture
  - Describe various modes of operation
    - "Normal"
    - "Off-normal"
- **Issue ORNLORNL/TM-2013/180 - Communication Requirements and Concept of Operation for Sensor Networks**

# Planned Accomplishments

- **FY2014 milestones and deliverables**
  - Develop sensor requirements
  - Develop simulator to represent analog signals from a variety of sensors
- **FY2015 milestones and deliverables**
  - Development power management strategies so the wireless sensor nodes can be powered via power harvesting
  - Develop methods to minimize power dissipation in solid-state devices
- **FY2016 milestones and deliverables**
  - Fabricate solid-state devices that implements minimized power dissipation
  - Conceptual system design for a fully functional system capable of surviving in the intended environment.

# Planned Accomplishments (continued)

- **FY2017 milestones and deliverables**
  - Develop data transfer protocols that minimize power consumption while maintaining required information flow
  - Develop a robust, bidirectional demonstration system designed for operation in a highly reflective, under-damped RF environment typical of reactor facilities
- **FY2018 milestones and deliverables**
  - Fabricate demonstration system and evaluate in a laboratory environment
  - Verify correct functionality of an integrated system – electronics, sensor for measuring temperature, and communications
- **FY2019 milestones and deliverables**
  - Characterize the performance of a large scale implementation
  - Develop draft Technology Transition plan

# Crosscutting Benefits

- **The Light Water Reactor Sustainability (LWRS) will benefit from this R&D through**
  - Minimizing the need for many power and signal cables to sensors (non-safety systems)
  - Enabling the cost-effective deployment of larger numbers of sensors that can improve the redundancy, security, and safety of modern reactors
  - Easily retrofitted for existing nuclear power plants
  - Helps to address cable aging concerns
  - Self-powered, wireless sensors have the potential to enable monitoring operations, repair, and recovery under a severe accident scenario where local power is lost and human entry is extremely dangerous or not possible.

# Crosscutting Benefits (continued – 1)

- **The Advanced Small Modular Reactor (SMR) Program will benefit from this R&D through**
  - Addressing the I&C cost (a significant portion is cable and cable installation) for smaller electrical output
  - Minimizing the need for many power and signal cables to sensors (non-safety systems)
  - Enabling the cost-effective deployment of larger numbers of sensors that can improve the redundancy, security, and safety of modern reactors (advanced instrumentation and controls)
  - Enable prognostics and diagnostics
  - Self-powered, wireless sensors have the potential to enable monitoring operations, repair, and recovery under a severe accident scenario where local power is lost and human entry is extremely dangerous or not possible.

# Crosscutting Benefits (continued – 2)

- **Advanced Reactor Concepts (ARC) and Next Generation Nuclear Plant (NGNP) programs will benefit from this R&D through**
  - Minimizing the need for many power and signal cables to sensors which will reduce capital costs
  - Measurement of unique parameters such as erosion/corrosion, chemistry/purity of coolant, etc. can be made wirelessly
  - Enabling the cost-effective deployment of larger numbers of sensors that can improve the redundancy, security, and safety of modern reactors
  - Can be easily added to new designs of nuclear power plants
  - Self-powered, wireless sensors have the potential to enable monitoring operations, repair, and recovery under a station blackout scenario

# Crosscutting Benefits (continued – 3)

- **The Fuel Cycle R&D (FCRD) program could indirectly benefit from this R&D**
  - Minimize the need for many of the power cables to various replacement and temporary diagnostic sensors
  - Could be used to “monitor” used nuclear fuel (UNF) and high-level waste (HLW)
  - Could minimize the risks of nuclear proliferation and terrorism
    - During interim storage
    - Recycle processing
    - Long term storage/disposal

# Transition to Competitive Research

- **With just a minimal amount of moving tasks around, this research can be accomplished in two three-year awards.**
  - Design and development of individual wireless sensor nodes and the supporting technologies
  - Development of a demonstration system and development of a Technology Transition plan
- **FY2014-2016, 3 years, $1 M**
  - Develop sensor requirements and sensor simulator
  - Develop, design, and fabricate power efficient solid-state devices
  - Conceptual system design capable of surviving in the intended environment
- **FY2017-2019, 3 years, $1.3 M**
  - Design demonstration system
  - Fabricate demonstration
  - Draft Technology Transition Plan

# Conclusion

- **By successfully implementing power harvesting for sensor networks, advanced sensors and instrumentation can be realized that will enable DOE-NE to**

  - improve the reliability, sustain the safety, and extend the life of current reactors, and
  - develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals.