Oak Ridge National Laboratory

Nuclear Power Generation: Review of the State-of-the-Art and Technology Needs for Passive Wireless Sensors

Sacit M. Cetiner, Ph.D.
Lead for Data Analytics, and I&C (DAIC) Team
Advanced Reactor Engineering (ARE) Group
Reactor and Nuclear Systems Division (RNSD)
Oak Ridge National Laboratory

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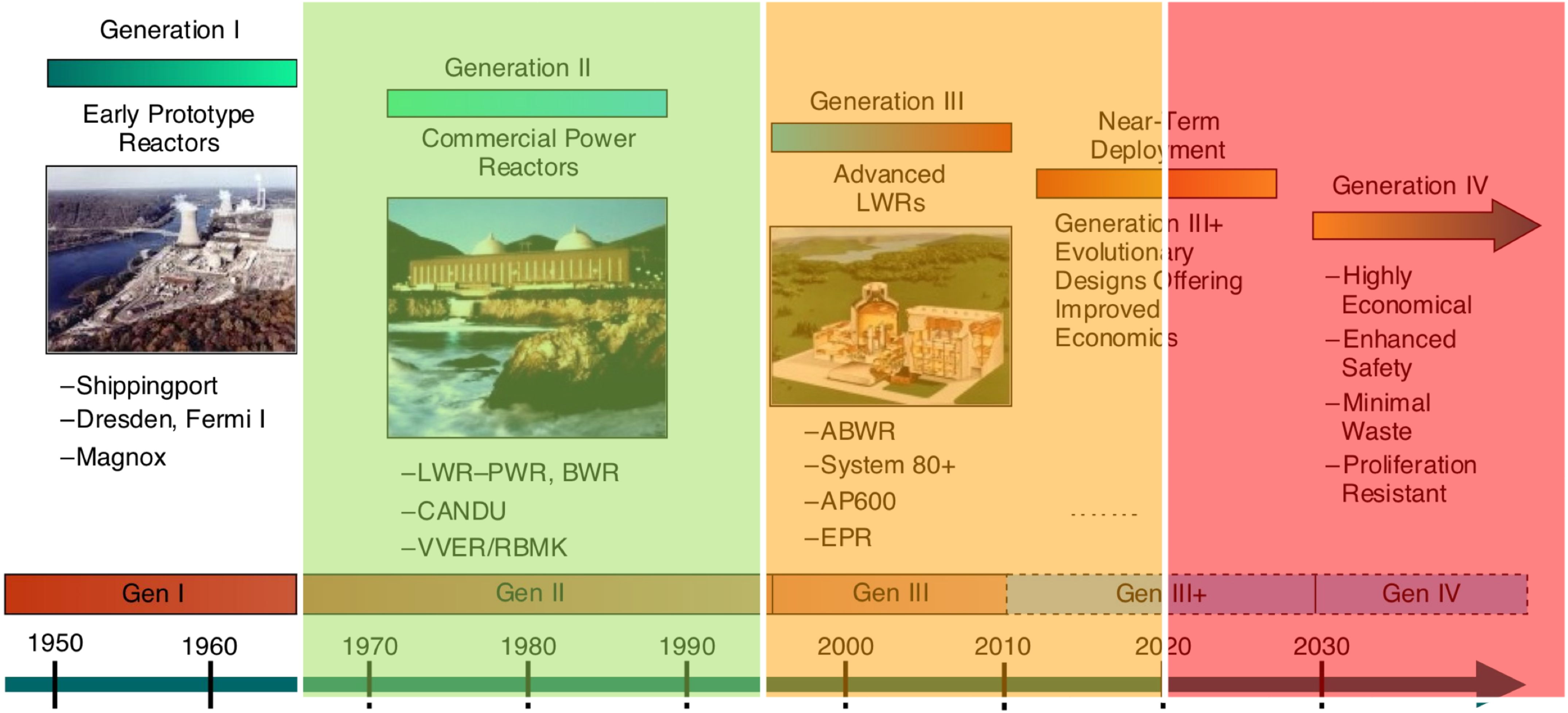
U.S. DEPARTMENT OF ENERGY

Evolution of Nuclear Reactors



Nuclear reactors are considered in two major categories

Light-Water Reactors

- Relies on light water for cooling
  - Pressurized Water Reactors (PWRs)
  - Boiling Water Reactors (BWRs)
- Water also serves as the neutron moderator
- Modest reactor outlet temperatures
  - ~315°C at 15.5 MPa for PWRs
  - ~288°C at 7 MPa for BWRs

Advanced Reactors

- Accepted terminology for *advanced reactors* is non-water-cooled reactors
- Generation-IV reactors are the commonly recognized reactor classes
  - Very-High-Temperature Reactor (VHTR)
  - Molten-Salt Reactor (MSR)
  - Supercritical-Water-Cooled Reactor (SCWR)
  - Gas-Cooled Fast Reactor (GFR)
  - Sodium-Cooled Fast Reactor (SFR)
- A common feature is much higher reactor outlet temperatures
- MSRs have fissile material and fission products dissolved in salt (either fluoride or chloride salt)

Generation-III+ Reactors

Main Features

- Passive safety focus
- Water as the coolant and moderator

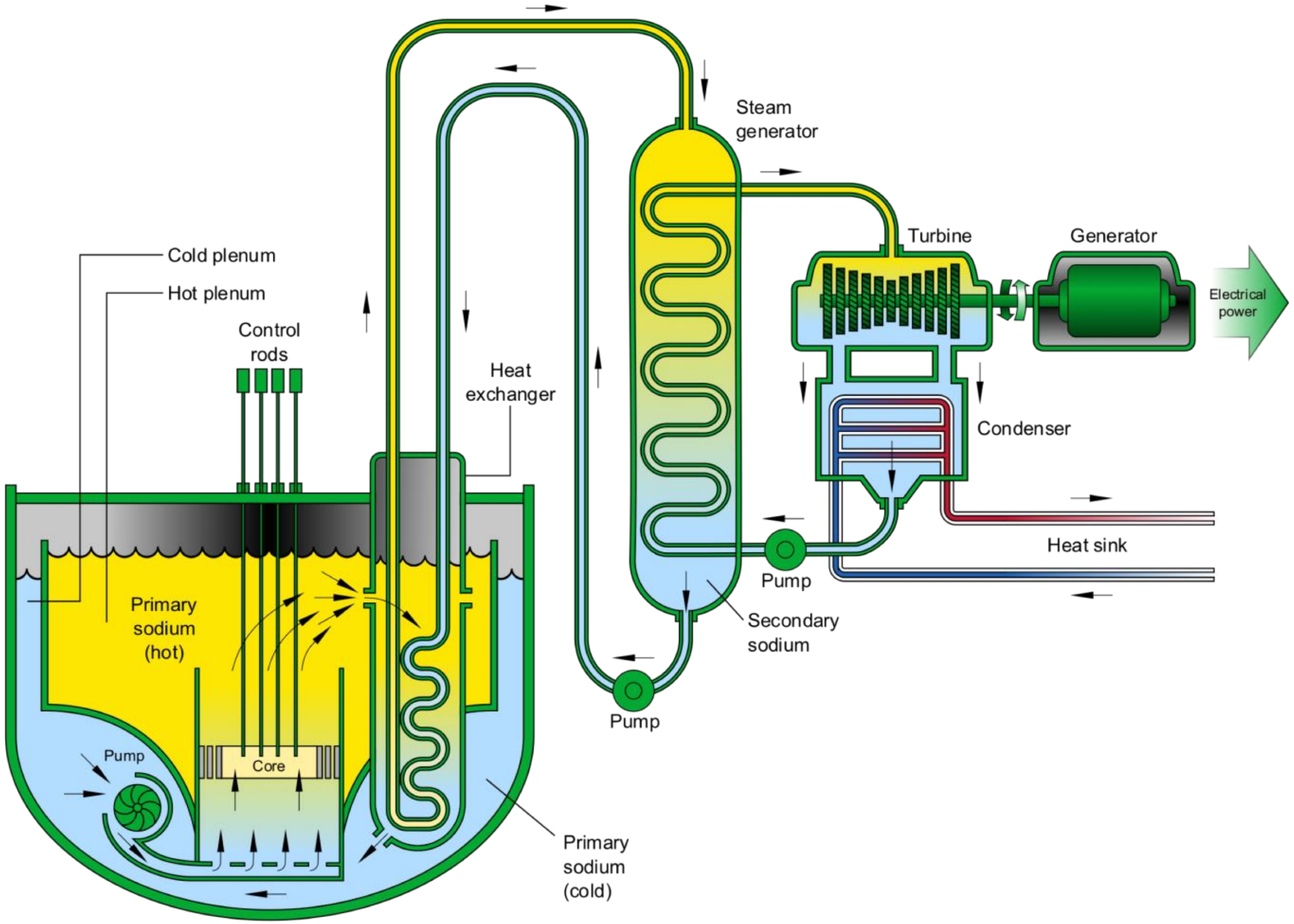
Westinghouse AP-1000
(Source: http://westinghousenuclear.com)

NuScale Power Small Modular Reactor (SMR)
(Source: https://www.nuscalepower.com)

Sodium Fast Reactor (SFR)

Main Features

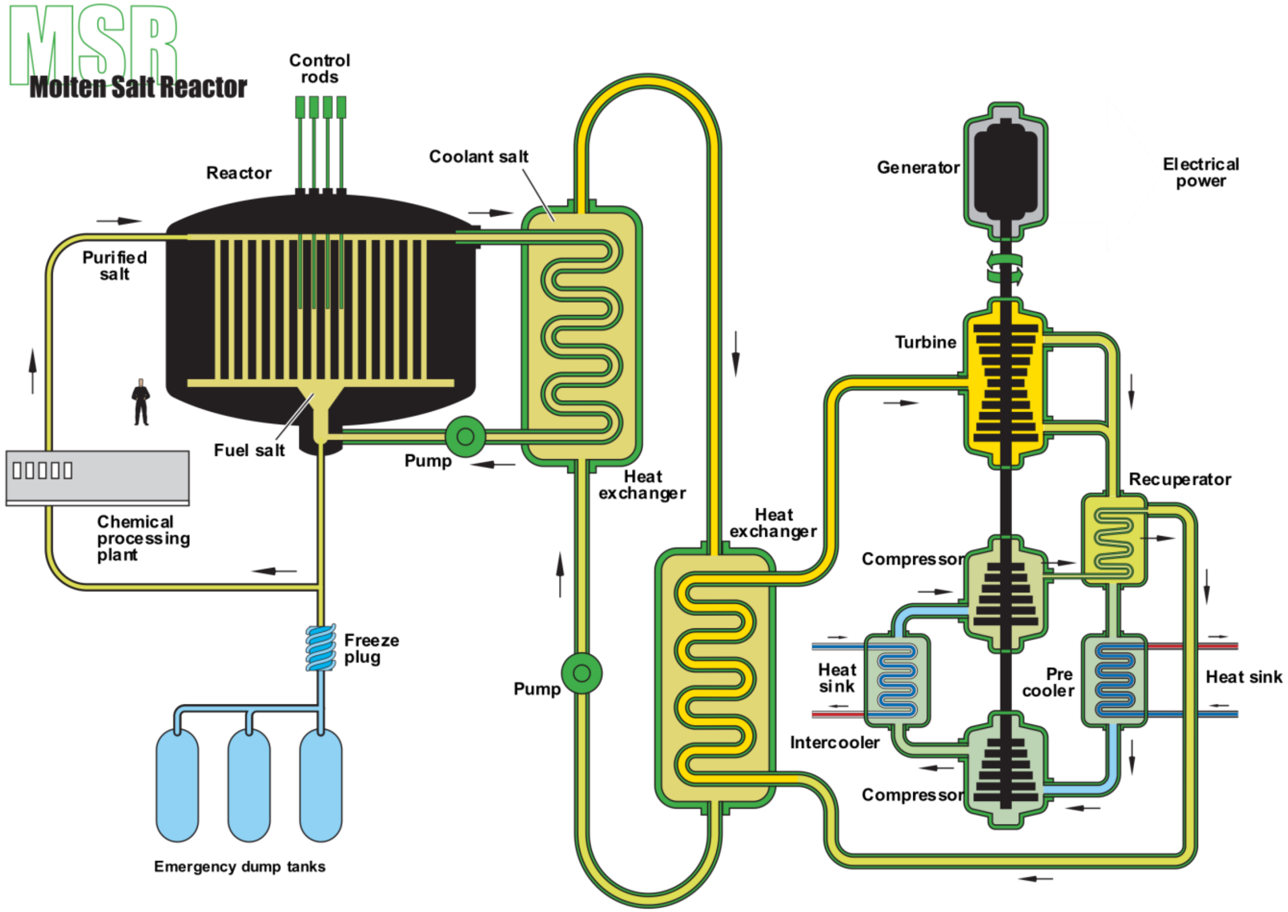
- Fast neutron spectrum
- Near atmospheric pressures
- Liquid sodium coolant (no moderation)
  - Ti ~ 300°C
  - To ~ 500°C
- Typically uses steam cycle
  - >40% thermodynamic efficiency



Molten Salt Reactor (MSR)

Main Features

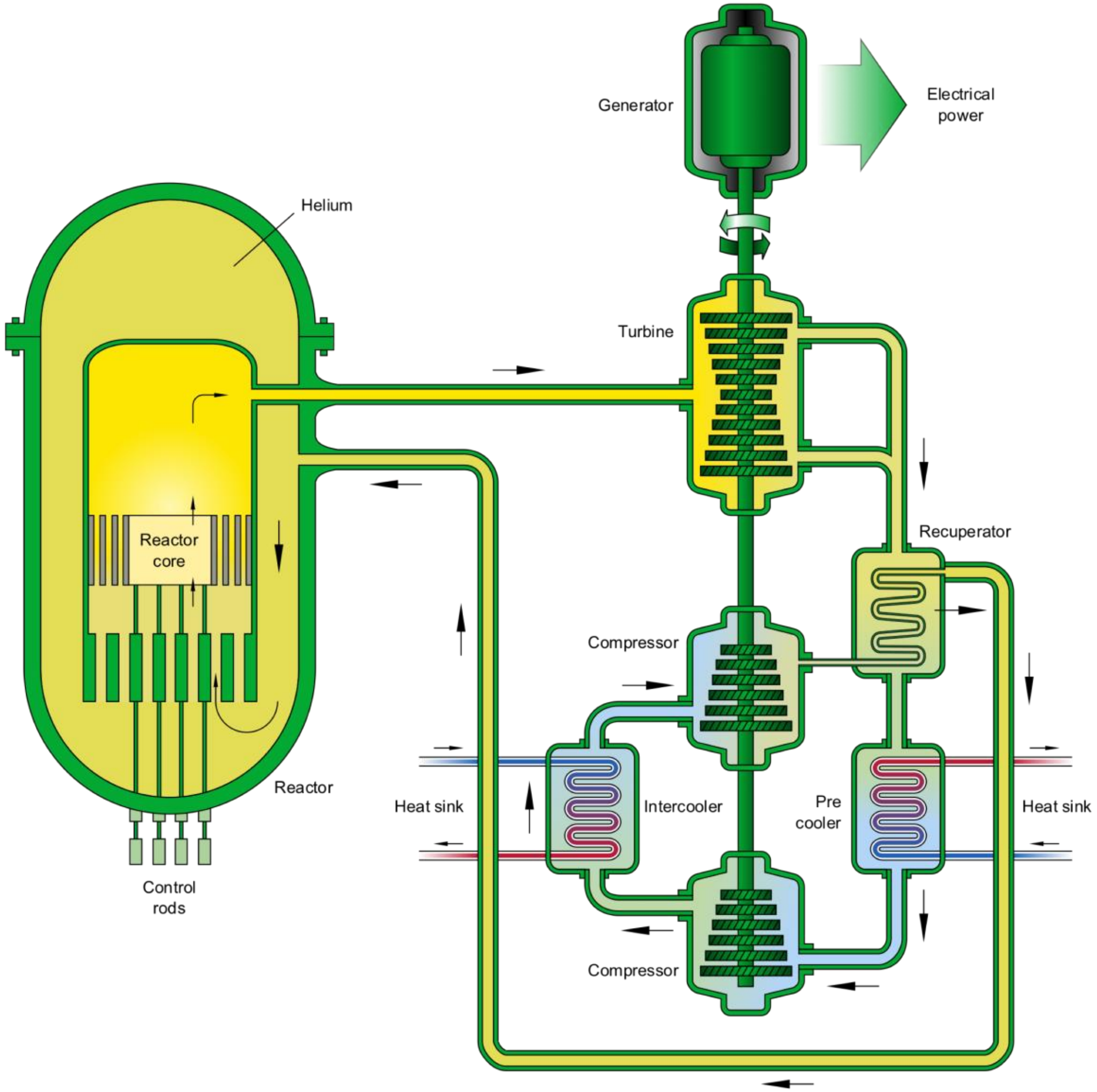
- Thermal spectrum
  - Fast-spectrum variants exist that use chloride salts
- Near atmospheric pressures
- Fissile material is dissolved in fluoride salt
  - Salt is a coolant, heat source and moderator
- High operating temperatures (salts freezes ~454°C)
  - Ti ~650°C
  - To ~700°C



Gas-Cooled Fast Reactor (GFR)

Main Features

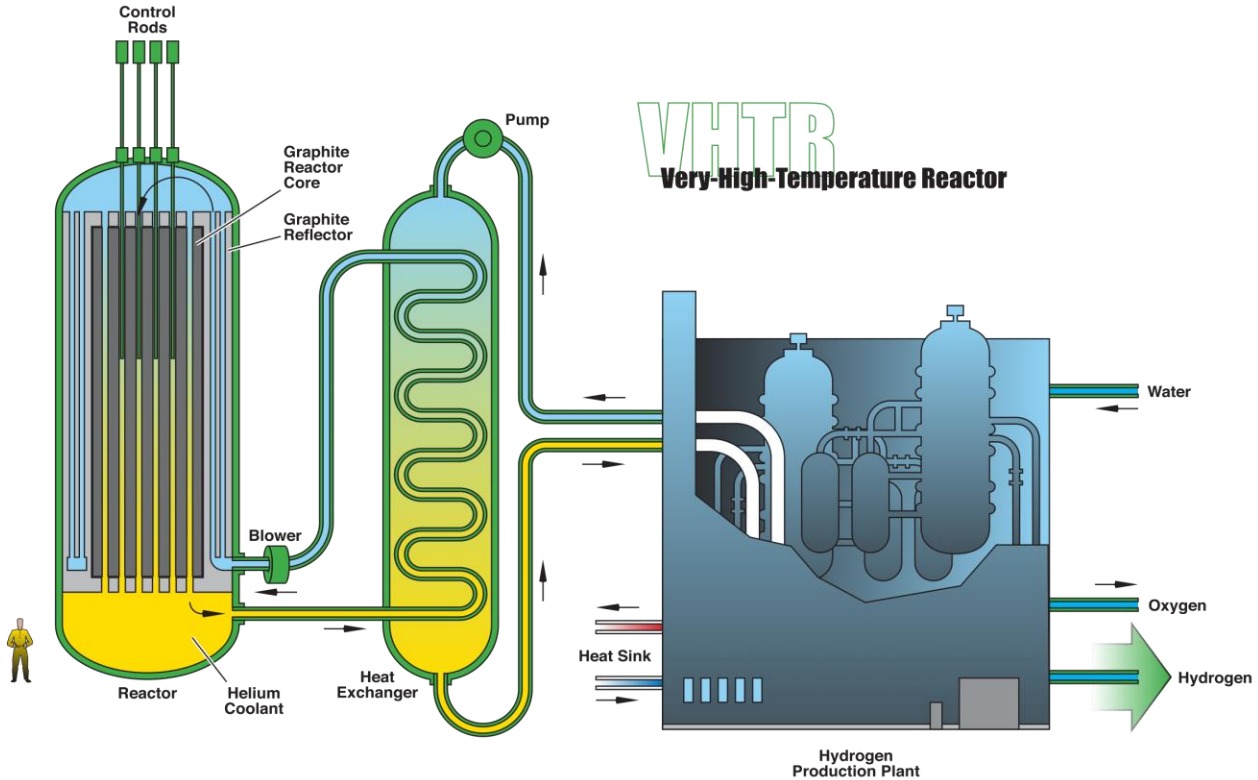
- Fast neutron spectrum
- Coolant is helium
  - To ~850°C
- Typically paired with a Brayton cycle power conversion system



Very-High-Temperature Reactor (VHTR)

Main Features

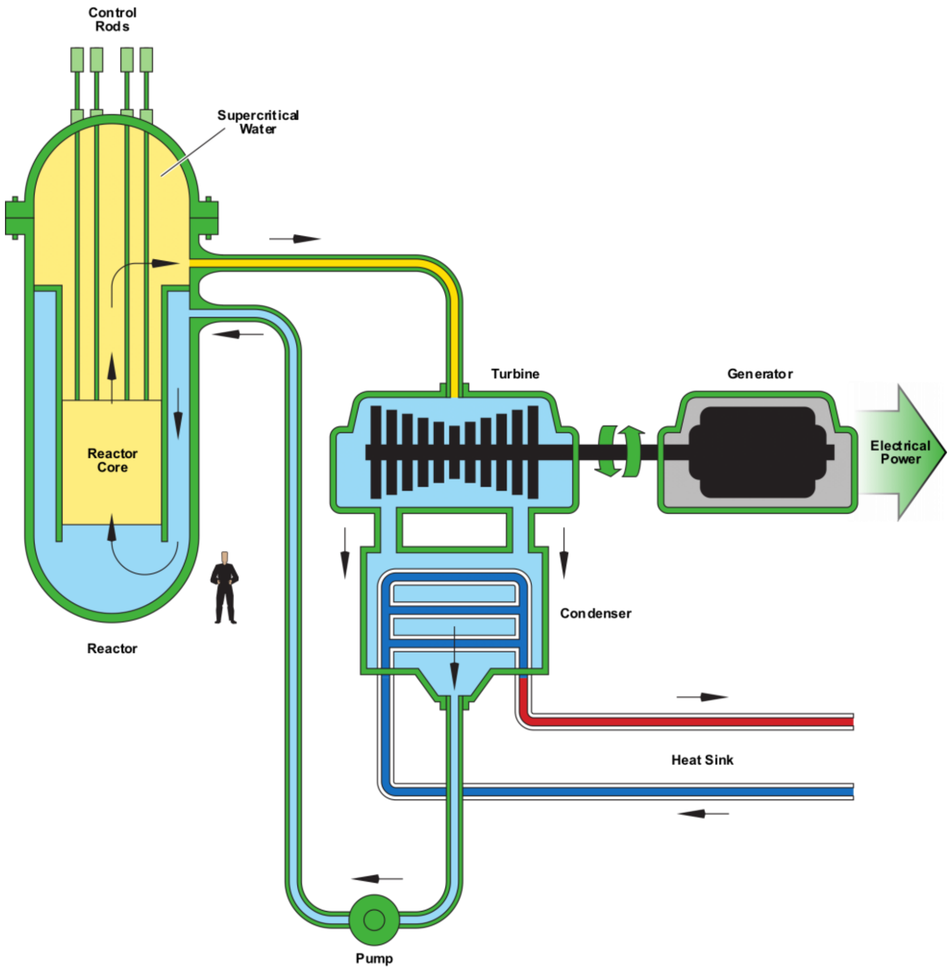
- Thermal-spectrum reactor
- Coolant is helium
  - To ~900°C (target is above 1000°C)
- Neutron moderation is accomplished by large blocks of nuclear-grade graphite
  - Graphite also provides thermal capacitance
- Typically paired with a Brayton cycle power conversion system
- Leading candidate for commercially viable hydrogen production



Supercritical-Water-Cooled Reactor (SCWR)

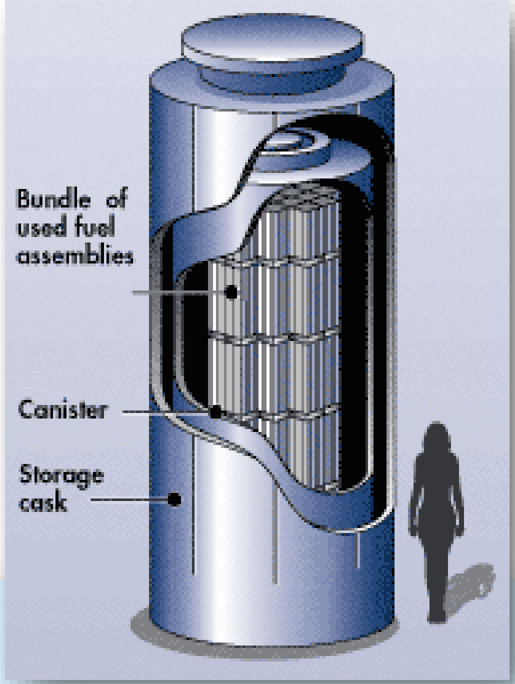
Main Features

- Thermal-spectrum reactor
- Water is coolant and moderator
  - To > 600°C
- Supercritical pressures enable very high thermal efficiency
  - P > 22.1 MPa
  - ~45% efficiency (vs ~33% efficiency in LWRs)



Dry Cask Used Fuel Storage Systems

- Dry cask storage systems offer a temporary solution to storage of used nuclear fuel
- No active cooling is needed
- Fuel assemblies are placed in a stainless steel canister, which is then emplaced in a concrete overpack
- Canister is welded shut after fuel assemblies are placed; no penetrations are allowed
- There is considerable regulatory interest in monitoring canister in-situ conditions to develop confidence in structural integrity



By Nuclear Regulatory Commission – http://www.nrc.gov/reading-rm/photo-gallery/index.cfm?&cat=Nuclear_Reactors, Public Domain, https://commons.wikimedia.org/w/index.php?curid=3429615

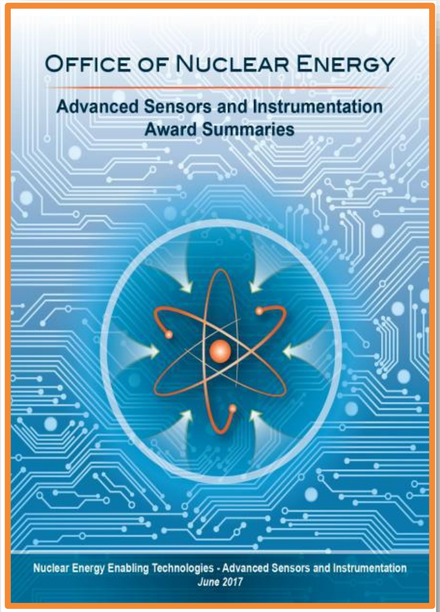
Nuclear Energy Enabling Technologies (NEET): Advanced Sensors and Instrumentation (ASI)

Vision

Develop advanced sensors and instrumentation technologies that address critical technology gaps for monitoring and controlling reactors and fuel cycle facilities

Goals

- Support DOE-NE R&D programmatic needs
  - Fuel and material studies, integral tests
- Provide new capabilities for measurement and control
  - Sensors for harsh environments, advanced control capabilities, fault-tolerant operations
- Address R&D needs for successful deployment
  - Digital technology qualification, advanced operational concepts



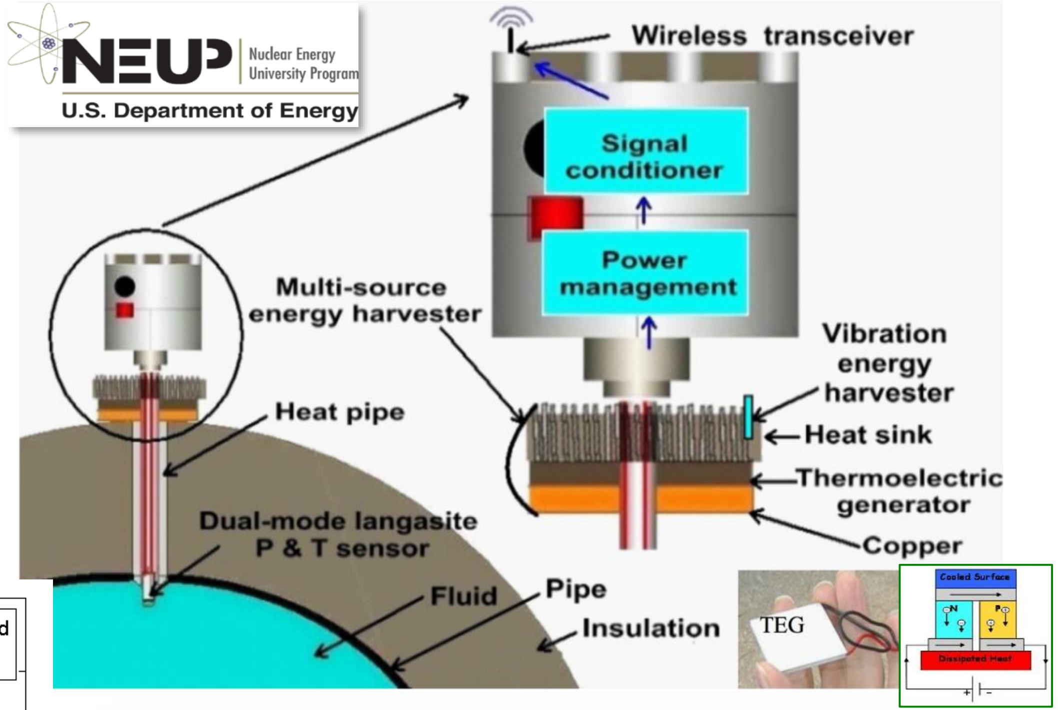
www.energy.gov/ne

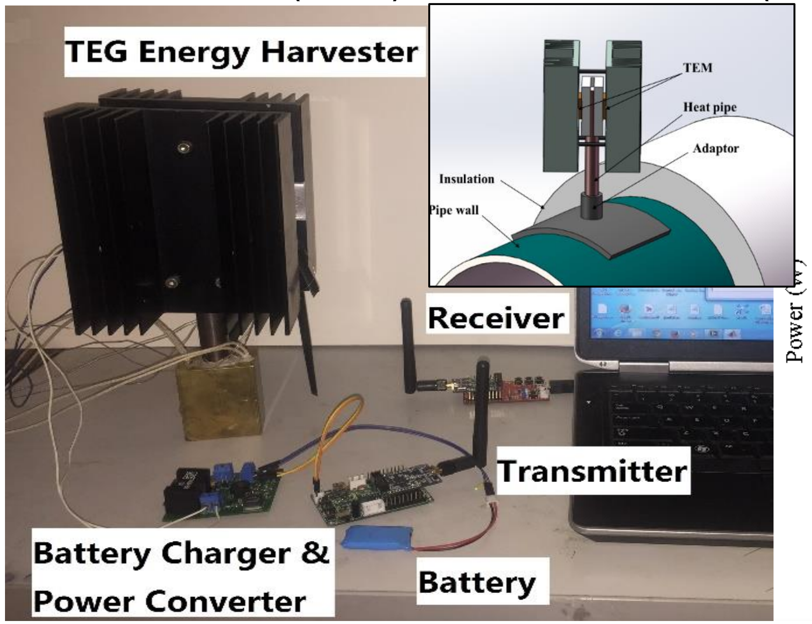
Self-powered Wireless Dual-mode Langasite Sensor for Pressure/Temp. Monitoring of Nuclear Reactors

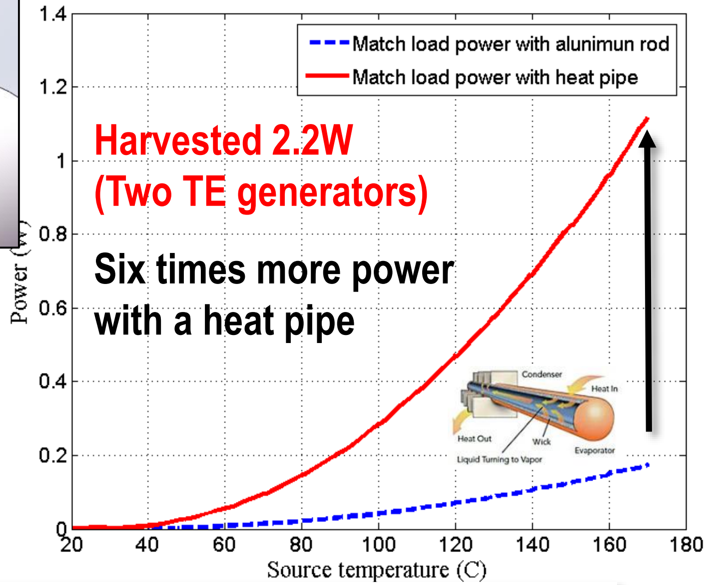
VirginiaTech
Invent the Future

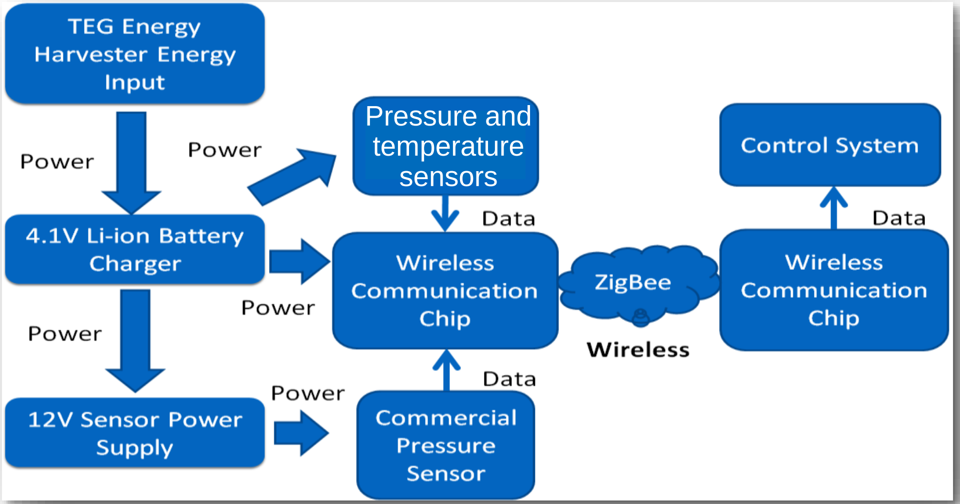
Goal:
Develop a novel **self-powered wireless dual-mode sensor** that can accurately monitor both pressure and temperature using a single device, even in the extreme harsh environments of severe nuclear accidents, without the requirement of external electricity.

2014 NEUP Project:
Lei Zuo (PI, VT), Haifeng Zhang (UNT), Jie Lian (RPI), Shikui Chen (SBU), and Mike Heibel (Westinghouse)









TEG survived above **20MRads** (Radiation test @ Westinghouse)

Self-powered Wireless Through-wall Data Communication for Nuclear Environments

VirginiaTech Invent the Future

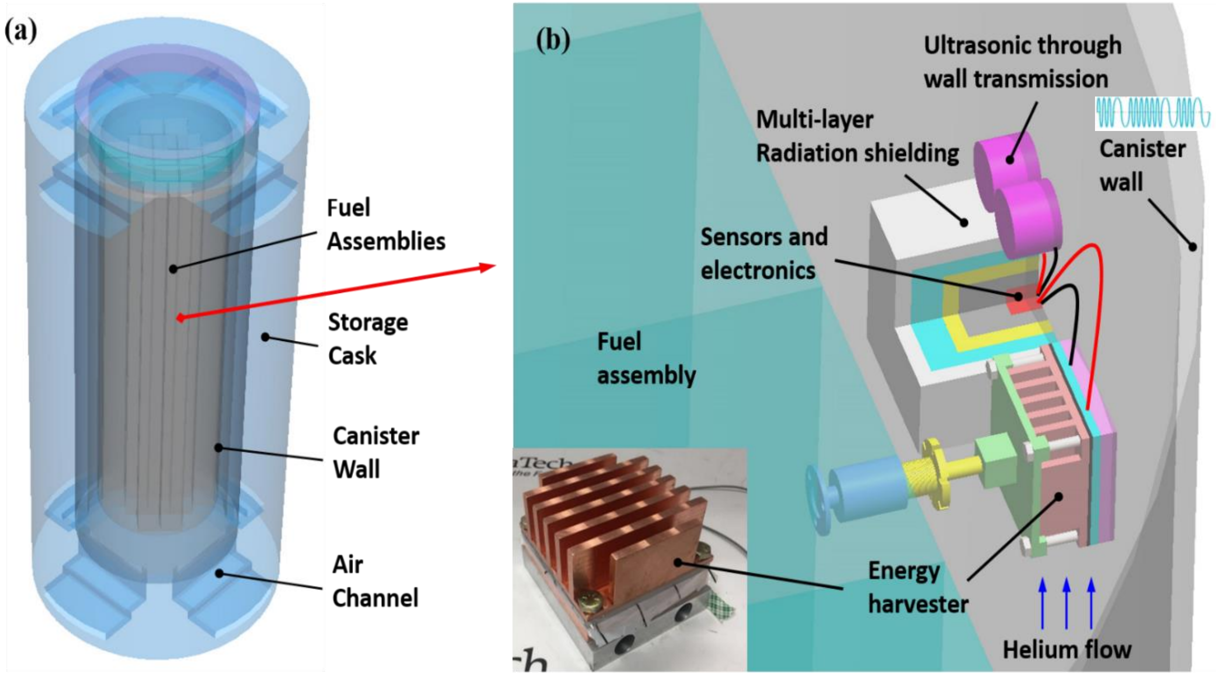
Goal:

Develop novel **energy harvesting** and **wireless data communications** technology for in-situ monitoring of interior conditions in enclosed metal vessels or thick concrete walls as found in dry storage canisters and nuclear reactor vessels.

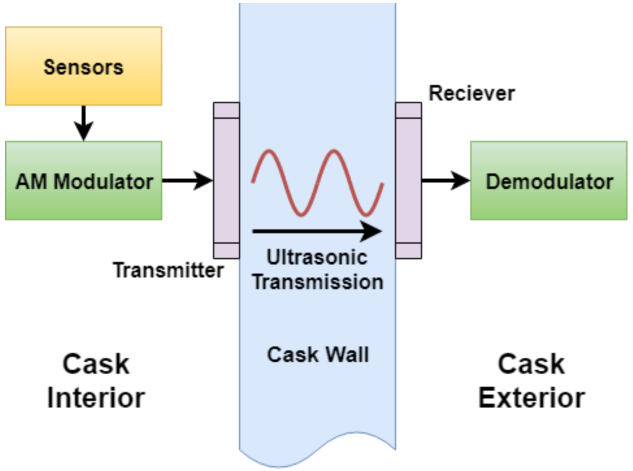
Approach:

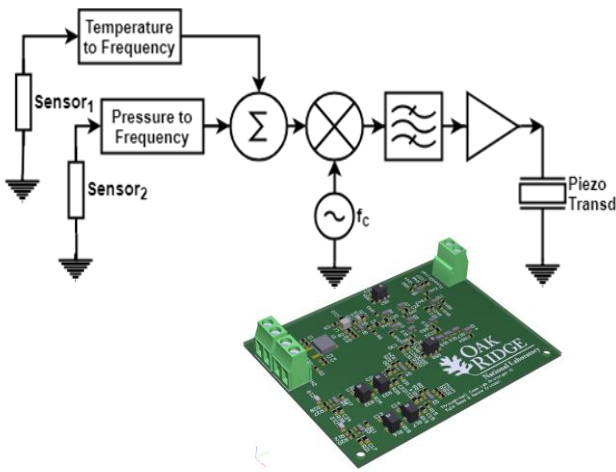
1. Directly harvest electrical energy from the gamma rays using the gamma heating and thermoelectrics
2. Transmit sensory data through the metal wall and thick concrete based on ultrasound communication
3. Design and pack high-temperature electronics circuits with radiation-hardening and/or shielding inside the enclosed nuclear vessels

2016 NEET Project:
Lei Zuo (PI, VT), Haifeng Zhang (UNT), Roger Kisner, Nance Ericson (ONRL), and Mike Heibel (Westinghouse).



Ultrasound through-wall communication





Wireless Reactor Power Distribution Measurement System Utilizing an In-Core Radiation and Temperature Tolerant Wireless Transmitter and a Gamma-Harvesting Power Supply

Goal:
Develop the technology necessary for a wireless reactor power distribution measurement system

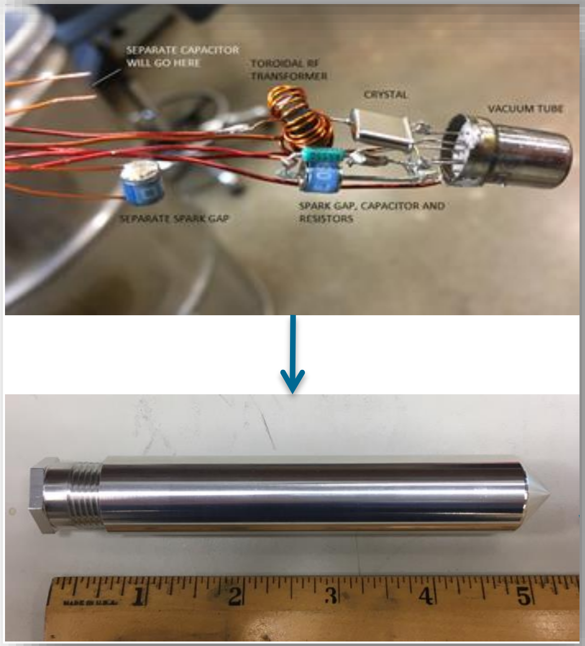
Approach:
Use highly radiation-resistant vacuum micro-electronics (VME) circuit that continuously broadcasts self-powered detector (SPD) and thermocouple signals to an antenna

Results:

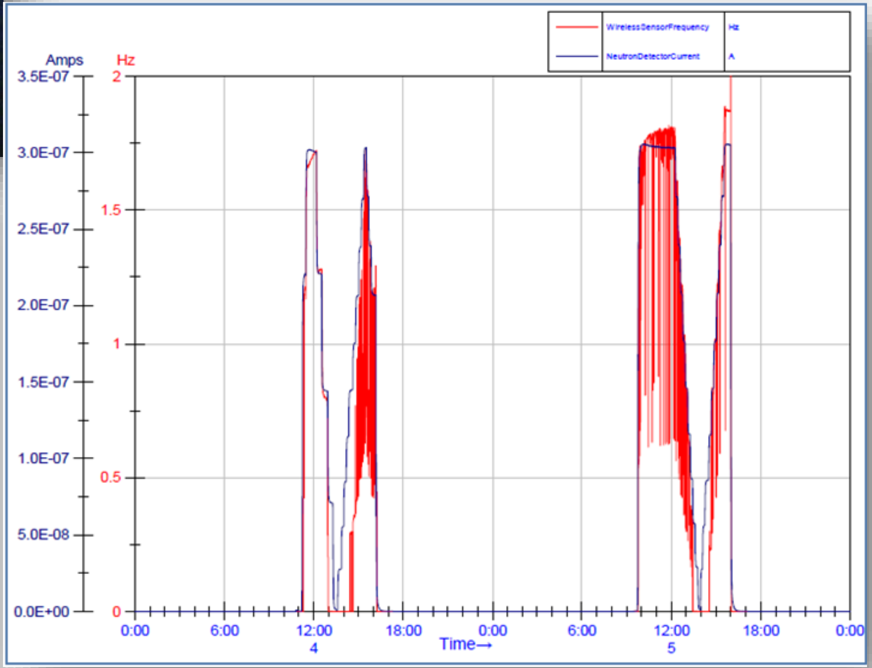
- Total neutron fluence (n/cm^2)
    - Rh SPDs 6.6E+18
    - Capacitors 2.6E+18
    - Transmitters 2.6E+18

2016 NEET Project:
Jorge Carvajal (PI), Mike Heibel (Westinghouse), and Kenan Unlu (Penn State University)

Penn State Breazeale Reactor core during operation



AM transmitter with vacuum micro-electronics*



Experimental measurements obtained at Penn State Breazeale Reactor*

* Used with permission from Westinghouse Co.

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Questions?