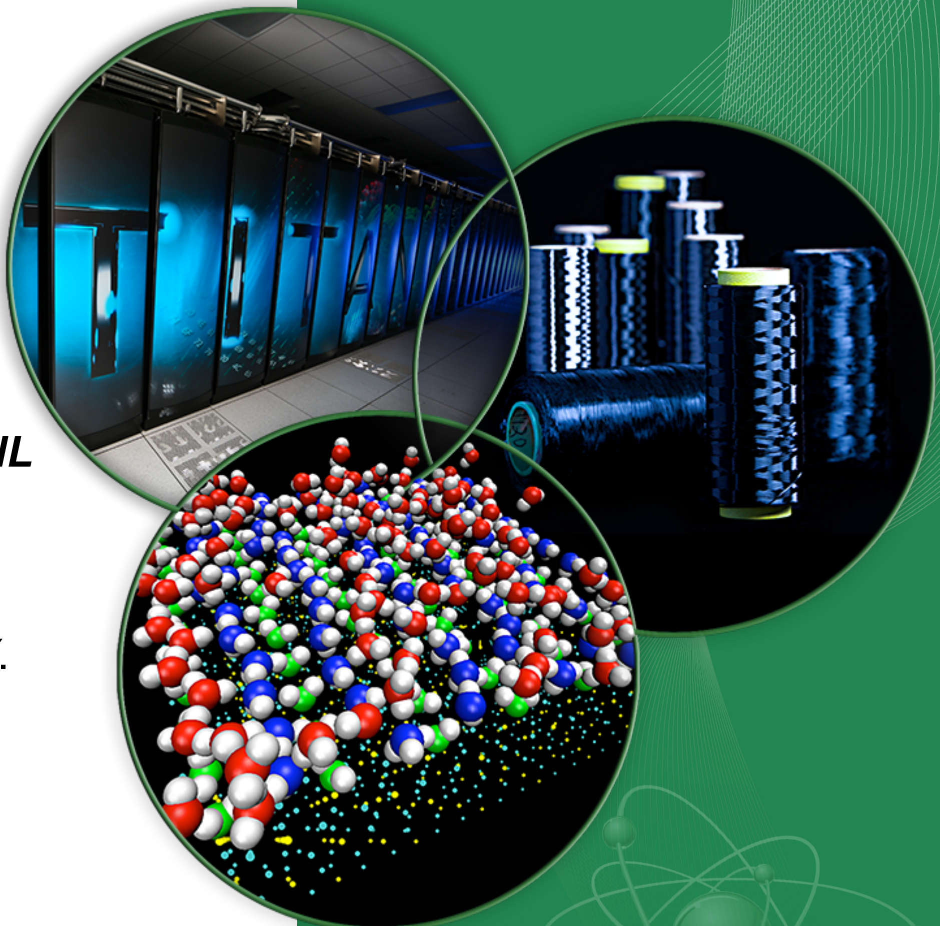
Sensor Technology Assessment for Advanced Reactors



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Sensor Technology Assessment for Advanced Reactors: Project Goals

- Identify gaps in sensor technologies for advanced reactors
- Provide the technical basis for prioritizing research targets within the I&C Technology Area under DOE's Advanced Reactor Technology (ART) program
    - Contributes to the design and implementation of Advanced Reactor (AdvRx) concepts
    - I&C is a power plant's "central nervous system" and therefore a reliable, high performance I&C for advanced reactors provides an important input to support the overall ART mission

How the Sensor Technology Assessment Project Supports the Overall ART Mission

ART PROGRAM

THIS Project

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Other ART projects

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Other ART Projects

Sensor technology target application areas that arise from the this project

- Nuclear and process measurement technologies
- Corrosion monitoring
- Fuel leak detection
- Remote robotic repair and maintenance in containment
- etc., …….

IMPACT OF THIS PROJECT ON AdvRx DESIGN

Map a path for sensor research with objectives including the following:

- Increased safety margins
- Improved reactivity control
- Order of magnitude improvements in detection limit, accuracy, etc.
- Prevention of fuel oxidation and corrosion
- Improved heat transfer and efficiency
- Capability to maintain critical components in a hostile environment
- etc., …..

ART PROGRAM

ART Regulatory Technology Development Plan (ART-RTDP):

- "Links research activities (ART Program) to key regulatory requirements and licensing challenges likely to affect deployment of Advanced Reactors (AdvRx)"

- Facilitates licensing of advanced reactor designs (e.g., reduced calibration intervals, ease of qualification for safety application)
- Supports update and/or development of new standards

Project Scope

- Project Involved three National Laboratories:
  - Oak Ridge National Laboratory
  - Argonne National Laboratory
  - Pacific Northwest National Laboratory
- Scope included high temperature reactors and fast reactors:
- For High Temperature Reactors, scope included:
  - Gen IV reactors whose coolant exit temperatures exceed ~650 °C and are moderated (as opposed to fast reactors).
  - Gas-cooled reactors that have been built and operated throughout the world to date, such as Dragon (UK), AVR (Germany), High Temperature Test Reactor or HTTR (Japan), etc.
  - Molten salt reactors

Project Scope (continued)

- For Fast Reactors, scope included:
  - Gen IV liquid metal cooled reactors whose coolant exit temperatures exceed 500C
  - Sodium Fast Reactors (SFRs), lead-cooled reactors

- The project is not a reactor systems design study, but rather it focuses on the following:
  - sensor performance and experience from high temperature and fast reactors
  - additional measurement needs to support operations, monitoring and maintenance activities
  - identification of the gaps in sensor technology that when closed, will improve the performance of Gen IV plants
  - prioritization of the sensor research needs that will help identify the optimum path to commercial operation of high temperature and fast spectrum reactors

The Sensor Technology Assessment Study Involved Several Tasks

- Assess measurement needs
  - Review operating experience of experimental and demonstration plants
  - Review factors influencing measurement techniques
  - Review Limitations of past measurement techniques
  - Review the State-of-the-Art of Sensor Technologies and technology gaps
  - Identify research to address gaps and measurement needs
  - Collate technology findings

- Prioritize R&D options. Basis for prioritizing may include:
  - Technical feasibility of actually maturing the sensor technology
  - ROM estimate of cost of developing the technology to market
  - The Technology Readiness Level (TRL)
  - Time to maturity: long-term (>5y), medium-term (2-3 y) or short-term (~ 1 y)

FINDINGS OF STUDY: TEMPERATURE MEASUREMENTS

- No temperature sensors currently available to measure the pebble temperature distribution in the core directly in pebble bed reactors.
  - Temperatures of the surrounding graphite structure and the structural metal components are measured using thermocouples.

- The drift in thermocouples is unacceptable at the high (operating) temperature and radiation environment.
  - There is a need for less-drift-prone sensors.
  - Precious metal thermocouples are generally accurate, but tend to have too high a neutron cross-section for use in areas with significant neutron flux.

FINDINGS OF STUDY: TEMPERATURE MEASUREMENTS (2)

- The Johnson Noise Thermometer (JNT) is arguably the "holy grail" of temperature measurement if fully developed, but…
  - currently suffers from significant susceptibility to electromagnetic interference (EMI) because of the minute voltages it produces.
  - To date, Johnson noise thermometry is best employed for online periodic recalibration of mature temperature sensors such as RTDs.

FINDINGS OF STUDY: TEMPERATURE MEASUREMENTS (3)

- Significant issues with implementing ultrasonic-guided wave thermometry include
  - the challenge of transmitting the ultrasonic-guided wave through the primary pressure boundary
  - the fact that it is not immune from drift
    - The high temperatures and high radiation flux of an HTGR will affect the mechanical properties of the waveguide over time and transmute its composition, shifting the recorded temperature.
- Issue with distributed fiber-optic Bragg thermometry is susceptibility to photo-bleaching in high radiation, high temperature environments.

FINDINGS OF STUDY: TEMPERATURE MEASUREMENTS (4)

- Technical challenges associated with the application of optical sensors in advanced reactors include:
  - provision of optical access ports for fiber optics and standoff optical sensors
  - the development of radiation and high temperature tolerant optical materials and fiber optic components for in-vessel devices

FINDINGS OF STUDY FOR PRESSURE MESASUREMENTS

- Reliable pressure sensors are not available for operation in liquid fluoride or chloride salt environments
- Impulse line methods exist but have the potential for salt contamination
- Existing devices are custom made and have exhibited leakage
- There is a need for a long-lived salt-compatible pressure transducer
- Creating a controlled pressure difference at operating temperature between HTGR pressure and a reference pressure is technically challenging because of the high-temperature mechanical property shifts of structural alloys
- An innovative way to develop differential pressure is to use a polymer-derived ceramic (e.g., SiCN) as the differential sensor body
  - A unique characteristic is their formability prior to firing
  - A particular challenge for this type of sensor is wiring the signals back outside the primary circuit. As the ceramic element and electrical wiring pads are directly exposed to the primary fluid, avoiding shorting the electrical leads becomes a significant technical issue

FINDINGS OF STUDY FOR LEVEL MEASUREMENTS

- Several technologies have been adapted for direct measurement of liquid salt levels:
  - e.g., microwave techniques
- Long-term survivability has not been demonstrated for any of the techniques
- SFR technology can benefit greatly from the development of a standoff non-contact technique for real-time measurement of sodium level (non-insertion sensor).
- The sensor should be immune to factors that limit the use of optical sensors (e.g., optical opacity, size, etc.)

FINDINGS OF STUDY FOR FLOW MESASUREMENTS

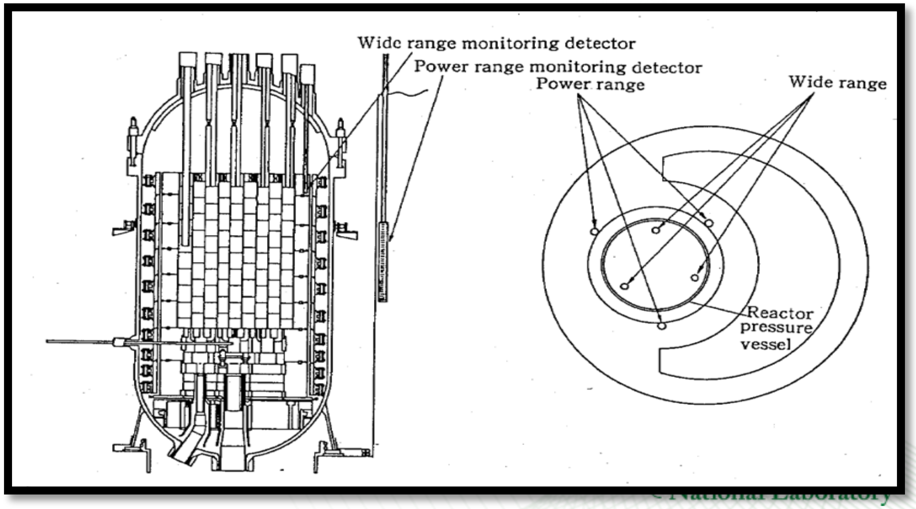
- Work is currently proceeding on ultrasonic, time-of-flight methods for measuring flow velocity.
- High temperature is the challenge from two perspectives:
  - ultrasonic transducers fail at the elevated salt temperatures and therefore must be isolated from the process via waveguides
  - the waveguides act as efficient heat sinks that cool the salt flow piping, which can lead to salt freeze.
- The development of ultrasonic transducers that fully operate at 750 °C and above is needed.

FINDINGS OF STUDY FOR CORROSION AND TRITIUM MESASUREMENTS

- ❑No sensor technology exists for direct corrosion indication or corrosion tracking in a molten salt environment.
- ❑There is a need for in-process, long-term tracking of corrosion *without* the requirement of removing samples or coupons for remote laboratory analysis.
- ❑Tritium measurement historically has been measured using an off-line process.
- ❑A better solution is to deploy an in-process, near real time sensing technology to track tritium production. Such technology is not yet available.

FINDINGS OF STUDY FOR NEUTRON FLUX MEASUREMENTS

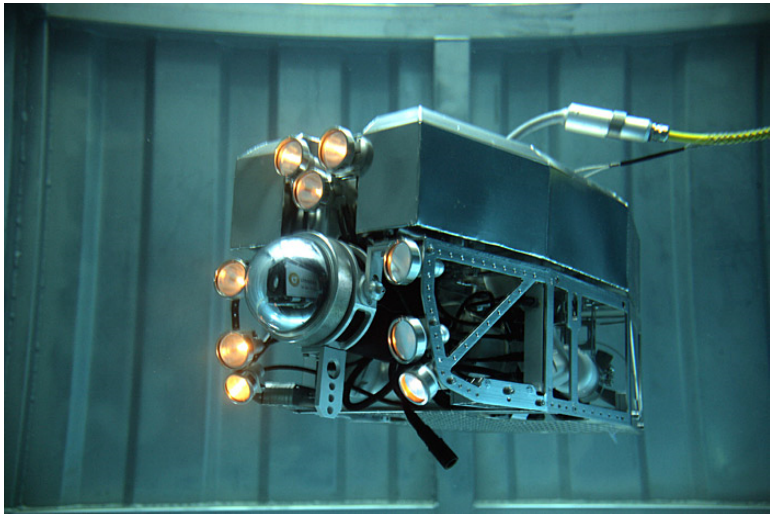
- No suitable in-core neutron flux measurement sensor is commercially available that functions reliably at temperatures above ~550°C.
- Prior HTGR development programs have demonstrated fission chambers that can function up to 800°C
  - Such detectors are not yet commercially available
- The problem with fission chamber performance at elevated temperatures is not from the fundamental processes, since these are not temperature dependent
  - The issue is the metallic deposits, which arise from the evaporation of contaminants from the structural alloy that form across the electrical insulator between the central node and wall shorting out the chamber
- In order to overcome the temperature vulnerability of fission chambers, low-outgassing structural materials and high-temperature-tolerant sealing materials and methods need to be devised.



Neutron detector arrangements in HTTR
Source: LTR/NRC/RES/2010-002, ORNL, 2010

THERE IS A NEED FOR CONTINUED RESEARCH IN NDE FOR PRIMARY SYSTEMS IN ADVANCED REACTORS

- Detection of cracking (especially incipient cracking) in hard-to-access components
- In-situ monitoring to address concerns with hidden cracking in components likely to be of safety significance, where detection may be possible in mid-cycle without shutting the reactor down or draining sodium from the primary system
- The development of radiation and high temperature tolerant sensor materials (acoustic, EM, and optical)
  - Aspects that should be considered include probe design for in-situ monitoring
  - field fabrication techniques (for integrating sensor technology with the component), and calibration to address aging concerns

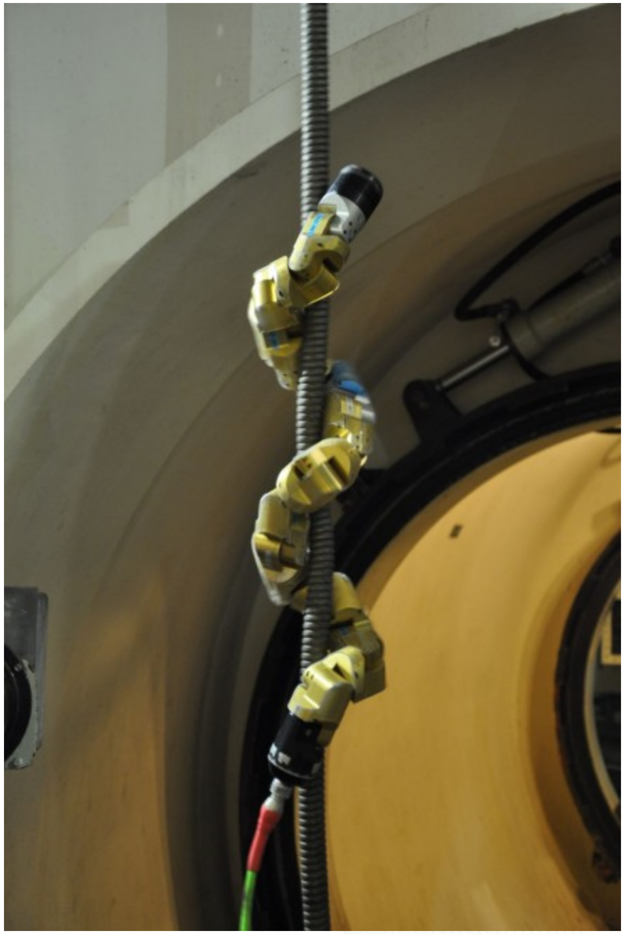


Inspection of reactor primary system using AREVA robot technology
SOURCE: http://www.pennenergy.com/articles/pennenergy/2013/11/susi-robot-used-in-nuclear-reactor-lifetime-extension-project.html

ROBOTICS, VISUALIZATION AND AUGMENTED REALITY TECHNOLOGIES WILL IMPROVE IN-SERVICE INSPECTION IN ADVANCED REACTORS

- Containment environment is hostile to humans
  - Internal atmosphere filled with dry inert gas (Argon or Nitrogen) to minimize oxidation of high temperature components
  - Varying concentrations of toxic gases and dust may also be present
  - Temperatures not suitable for direct human contact
  - High radiation environment, especially during power operation

- Applications to refueling and in-service inspection is regarded as a means to minimize the human error element of maintenance operations
  - speeds up maintenance
  - Contributes to improved capacity factor, safety, and reduced staffing
  - Application of under sodium viewing technology could be an integral component to these technologies



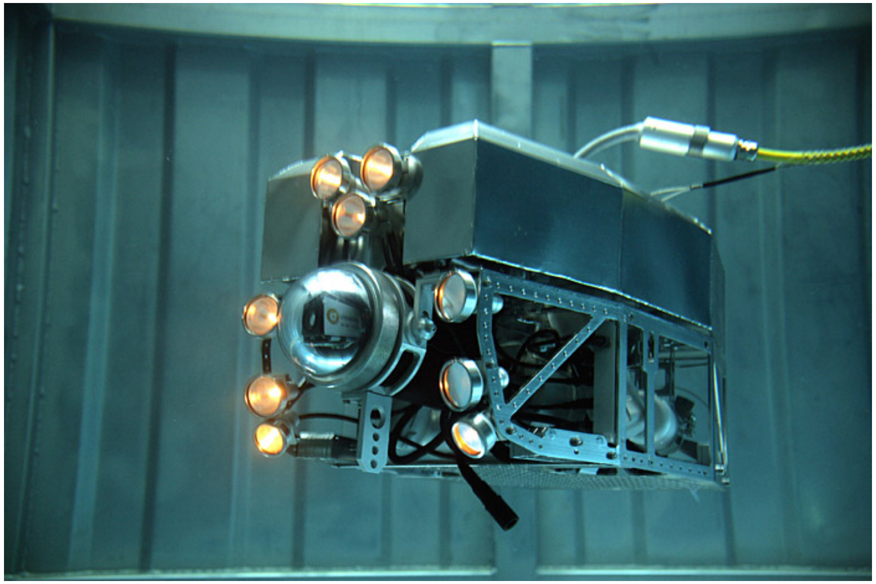
Tests of a modular snake robot in an Austrian nuclear power plant

SOURCE: http://www.wireandtubenews.com/2013/07/10/snake-robot-wends-its-way-through-pipes-vessels-of-nuclear-power-plant/

Oak Ridge National Laboratory

ROBOTS FOR REMOTE INSPECTION, MAINTENANCE AND REPAIR OPERATIONS ARE LIKELY TO BE APPLICATION-SPECIFIC

- It is unlikely that a single tele-operated robotic system design will serve the needs of remote inspection, maintenance and repair
- More likely that division of labor among a team of remote systems – both human operator-controlled and autonomous robotics – will fall into categories corresponding to the functional requirements:
  - Remote inspection
  - Instrument calibration
  - Component replacement-assembly-disassembly
  - Part manipulation
  - Welding/cutting



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CONCLUSIONS: SUMMARY OF PRIORITIZED SENSOR NEEDS

- The study developed tables of specific sensor development needs, each table entry prioritized as high (H), medium (M) or low (L). The prioritized list included the following:
  - In-situ ultrasonic NDE for inspection and monitoring of hard-to-replace components
    - Conventional ISI is challenging (in-coolant) and costly when dealing with hard-to-access components in-vessel. Existing sensors are not compatible with requirements for SFRs
    - Benefit: Increase reliability and inform proactive maintenance, repair, or replacement; passive components are difficult and expensive to replace
  - Sodium flowmeter with high reliability/serviceability
    - Operating experience with EBR-II flowmeters indicated difficulty in servicing creating a reliability problem
    - Benefit: Serviceability and high reliability of primary flowrate

CONCLUSIONS: SUMMARY OF PRIORITIZED SENSOR NEEDS (2)

- Prioritized needs…
  - RF/Optical level sensor
    - Standoff non-contact technique for real-time measurement of sodium level (non-insertion sensor)
    - Benefit: Noncontact, high reliability and accuracy of sodium level
  - In-sodium hydrogen sensor
    - In-situ detection of dissolved hydrogen in sodium of secondary sodium loop
    - Benefit: Detect water/steam leak of SGs before catastrophic SG tubing failure and minimize corrosion and heat transfer surface fouling
  - In-sodium electrochemical oxygen meter
    - Real-time sensing of dissolved oxygen in heat transfer loops
    - Benefit: Detect sodium purity problems before oxygen-induced corrosion and heat transfer surface fouling develop

CONCLUSIONS: SUMMARY OF PRIORITIZED SENSOR NEEDS (3)

- Prioritized needs…
  - Fiber-optic distributed sensor for temperature profiling
    - Conventional sensors such as thermocouples quickly burn out in the harsh in-core environment
    - Benefit: In-core temperature monitoring allows comparison with predictions to identify potential problem areas such as cycle length, peak powers, etc., to satisfy tech spec requirements for safety
  - Ultrasonic guided wave thermometer
    - The ability of transmitting the ultrasonic-guided wave through the primary pressure boundary
    - Benefit: Probe-based ultrasonic thermometry can be deployed in very high temperatures and hostile environments because an electrical insulator is not required and because of its compatibility with refractory alloys
  - Reliable pressure sensor for operation in liquid fluoride or chloride salt environments.