Molten Salt Reactor Instrumentation

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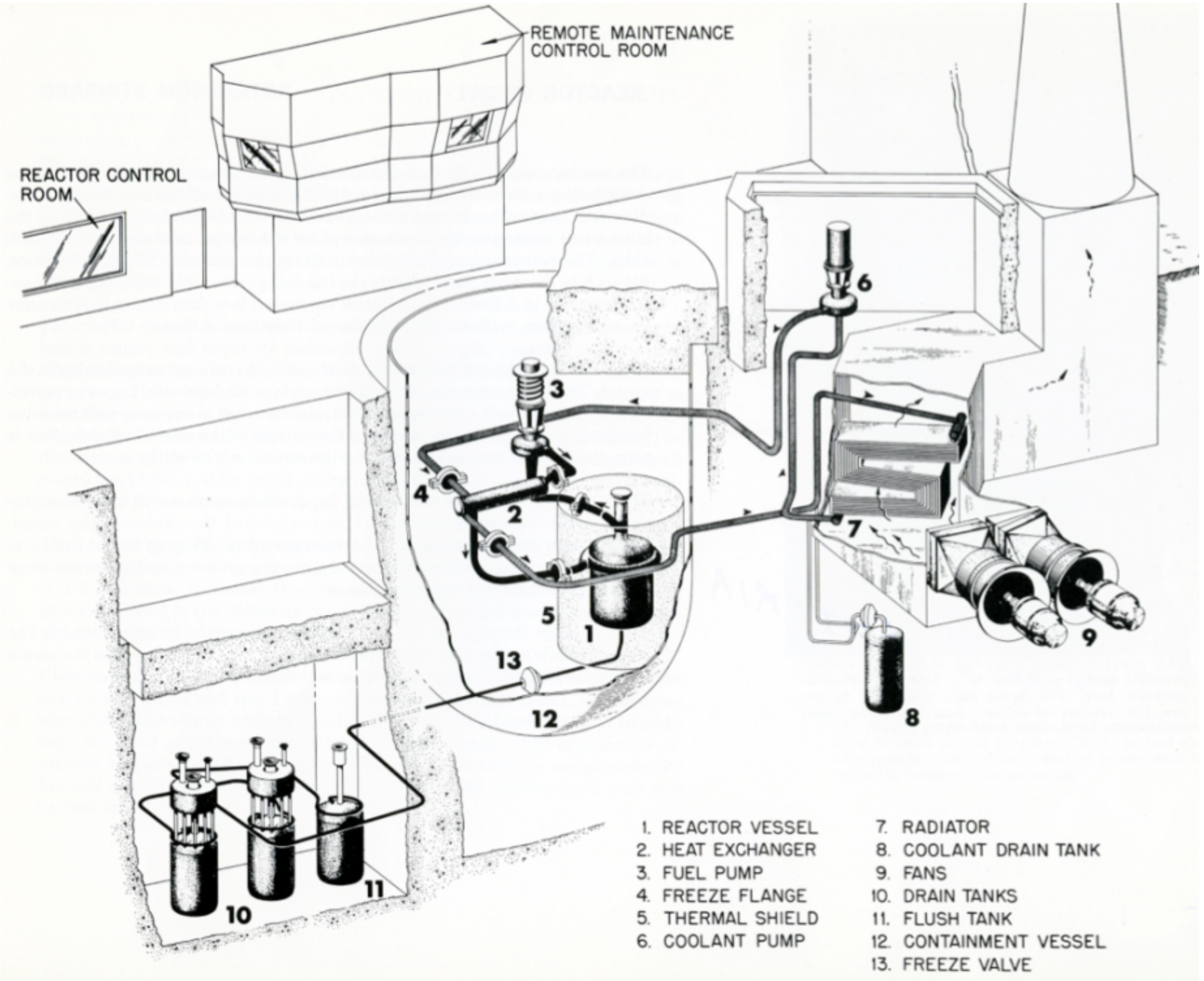
Instrumentation Framework is An Element of MSR Campaign Planning Activities

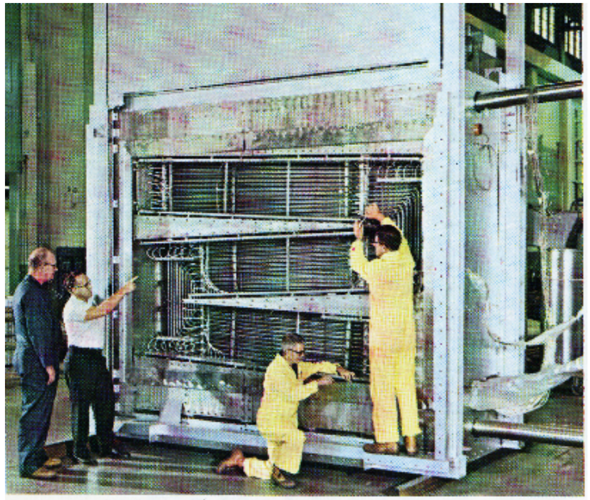
- Framework is available as ORNL/TM-2018/868
  - https://www.osti.gov/biblio/1462848-instrumentation-framework-molten-salt-reactors
  - Similar information for solid-fueled MSRs was generated previously - https://www.osti.gov/biblio/1185752-fhr-process-instruments
- Describes instrumentation's role and performance requirements throughout an MSR's lifecycle,
- Provides a structured MSR instrumentation technology and state-of-the-art reference, and
- Identifies MSR instrumentation technology gaps and recommending RD&D to close the identified gaps.

MSRs are different

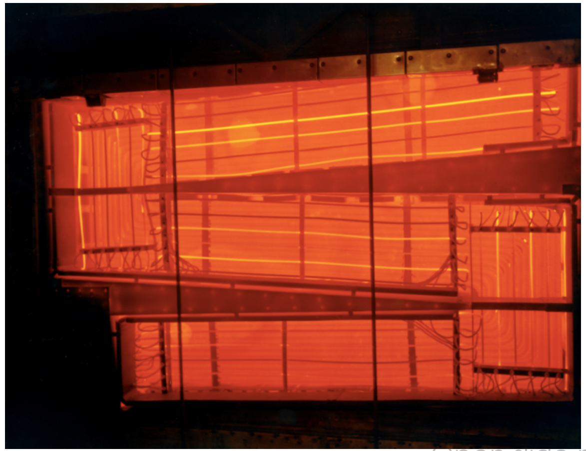
- *High-temperature*, *low-pressure* systems with *chemically inert* fluids
- Improved safety posture
  - *large temperature margins to boiling, no pressure drivers*
  - *Limited excess reactivity in system, fewer safety systems, passive response*
- Can use a range of fuel which changes over short and long time scales

Molten Salt Reactor Experiment demonstrated successful operation

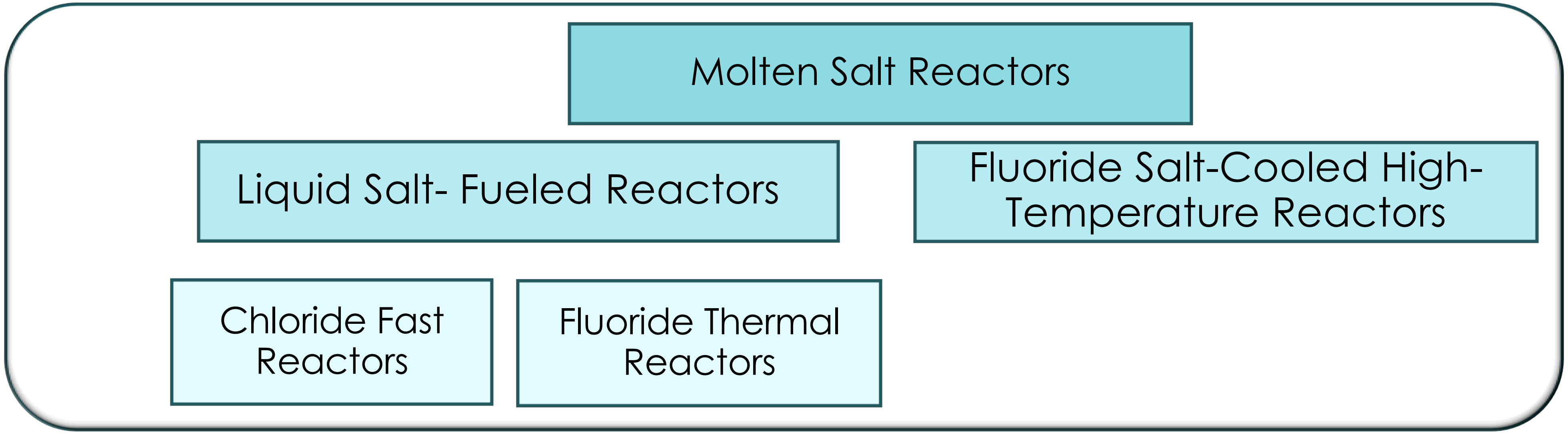




The primary heat exchanger (components seen at right) has a heat-transfer area of nearly 259 square feet. Heat is removed from the coolant-salt mixture in the air-blast radiator (above) and is dissipated through a metal stack to the atmosphere.



MSRs are a broad class of advanced reactors



- **All are derived from the MSRE experience**

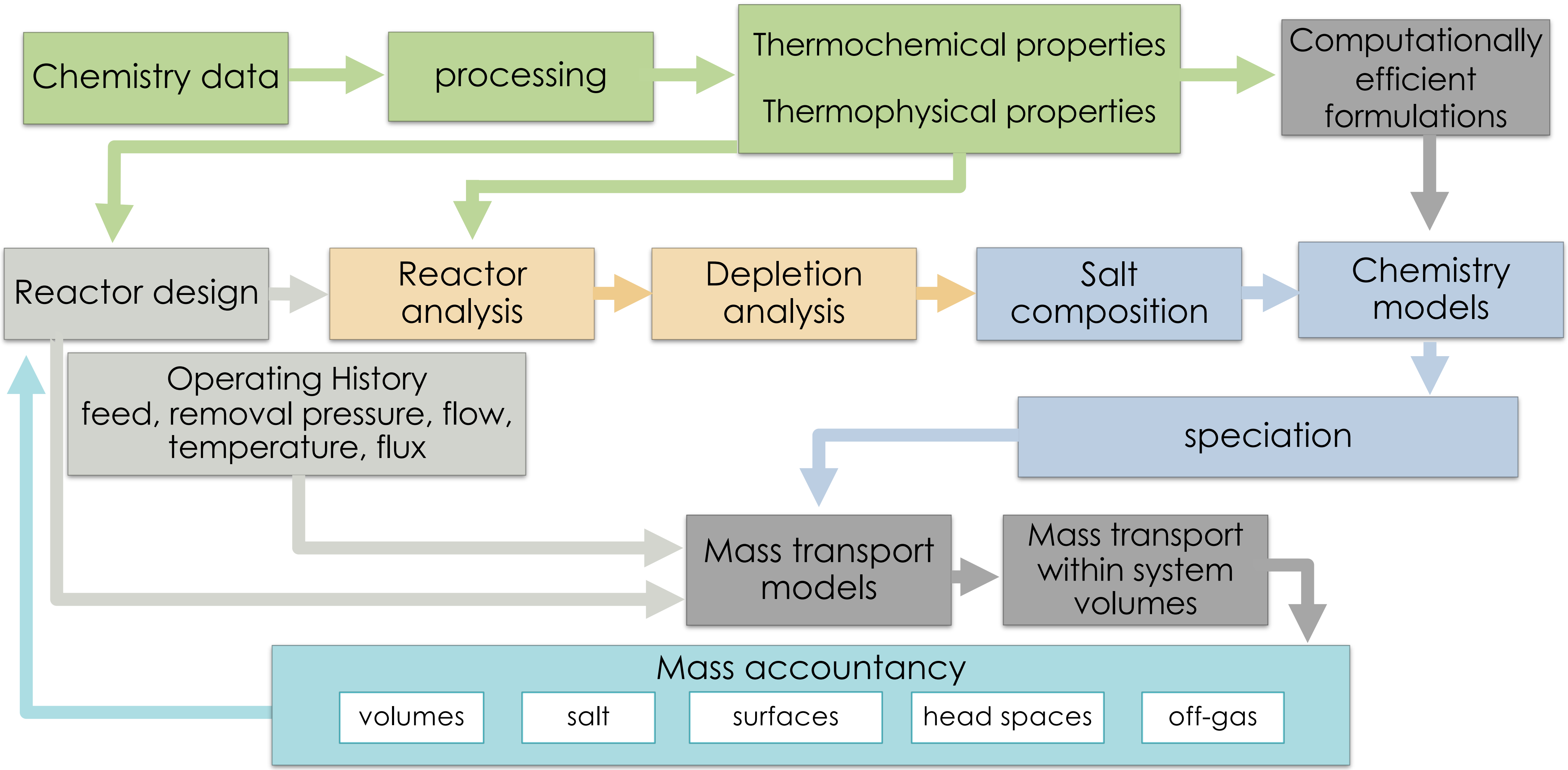
The campaign is addressing MSR challenges

- *salt and materials combinations*
- *salt and reactor performance*
- *regulatory frameworks*
- ***enabling technology***
- *Infrastructure and supply chains*
- *economic competitiveness*

MSR System Development Needs

- Primary system designs come from developers
  - We use the Molten Salt Breeder Reactor as a proxy for development of ancillary system technology
  - Primary system instrumentation (flux, flow, temperature, pressure)
  - Mass accountancy
  - Corrosion monitoring and control
  - Off-gas system
  - Functional containment system
  - Passive decay heat removal
  - Remote systems
  - Salt processing systems

Priority: MSR mass accountancy is essential

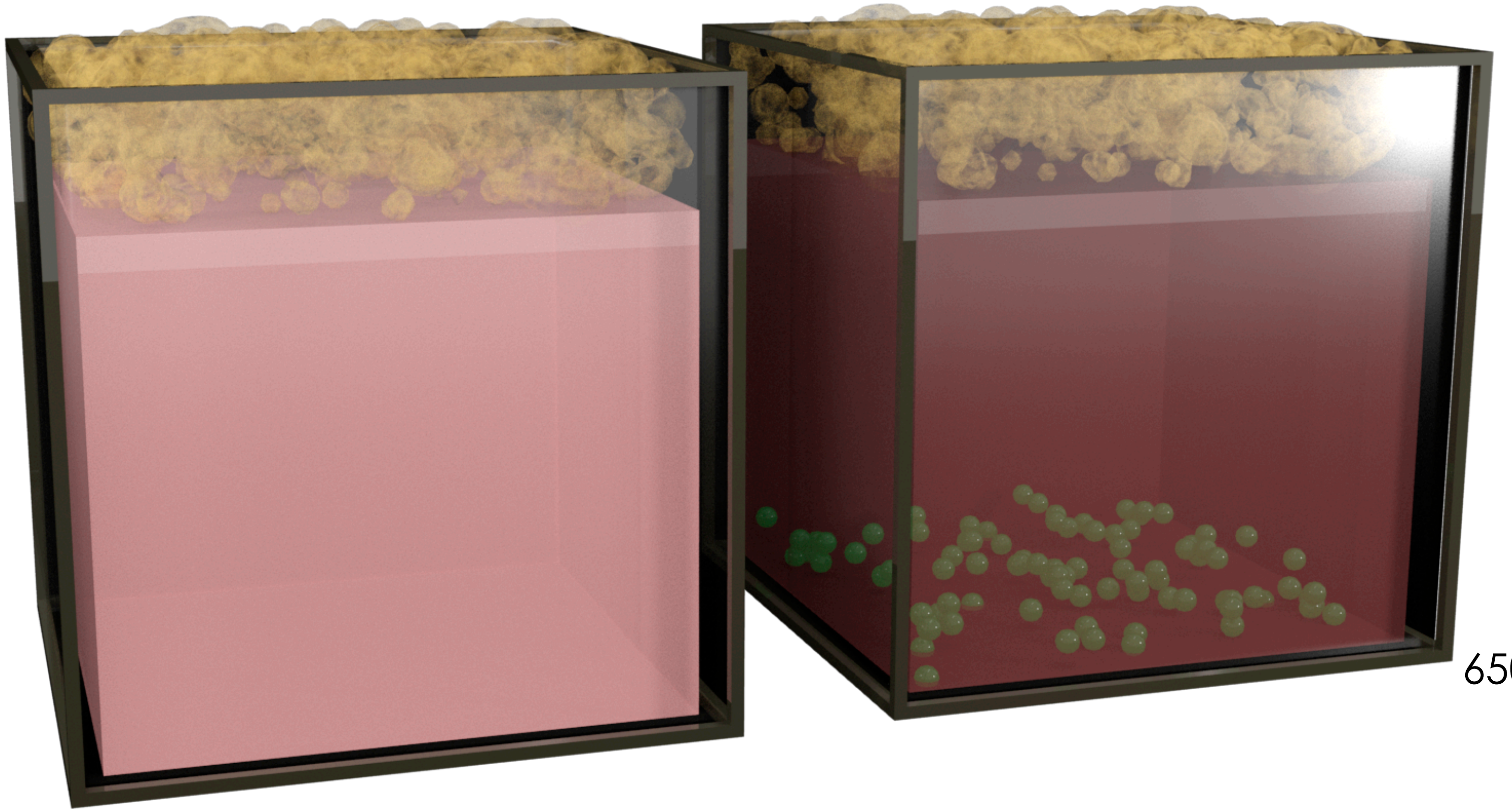


Chemical state modeling for reactor modeling

Significant effort has been devoted to thermodynamic modeling to make calculations like these

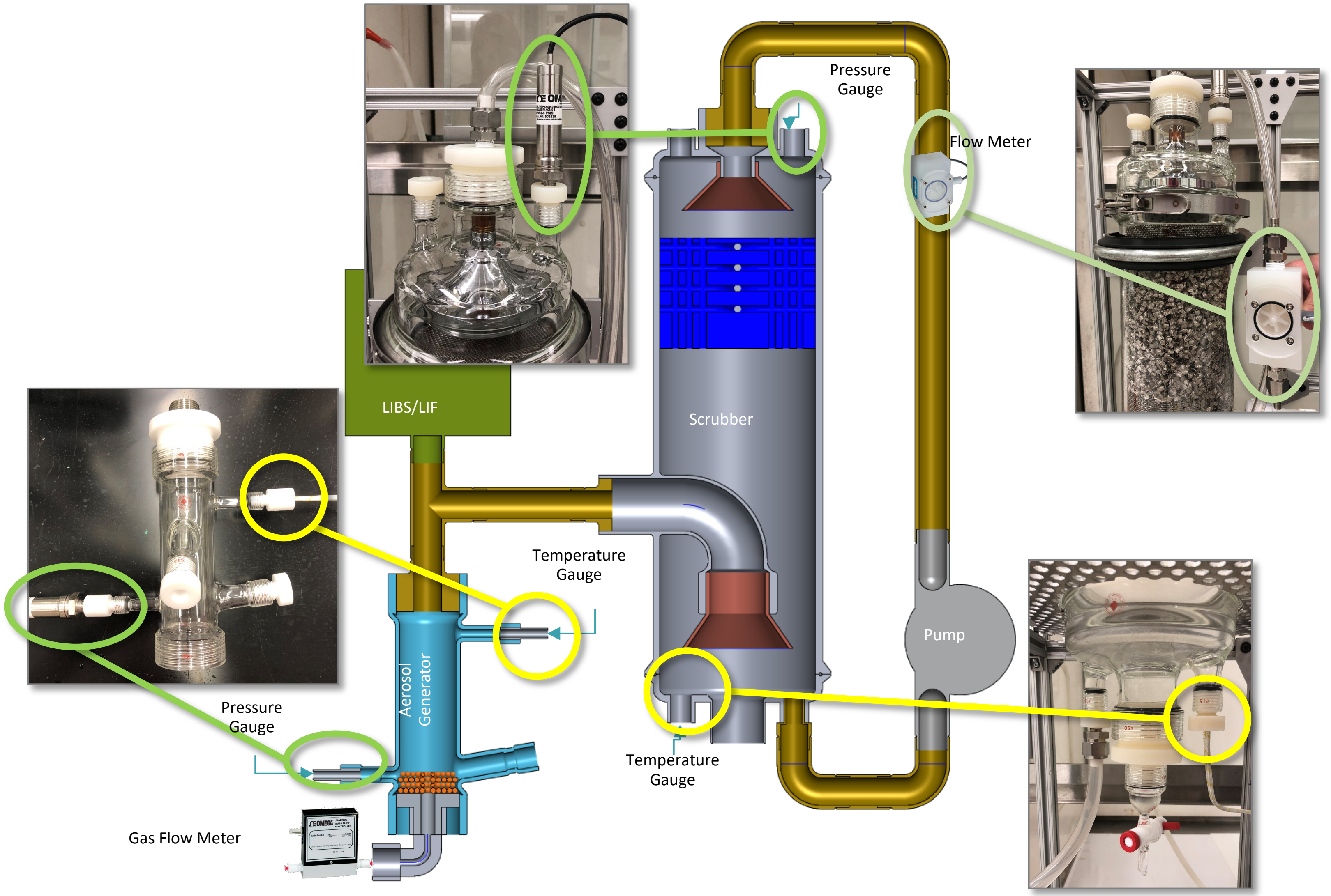
We are extending the models to include additives as well as fission, activation, and corrosion products

750°C
1 mole molten salt



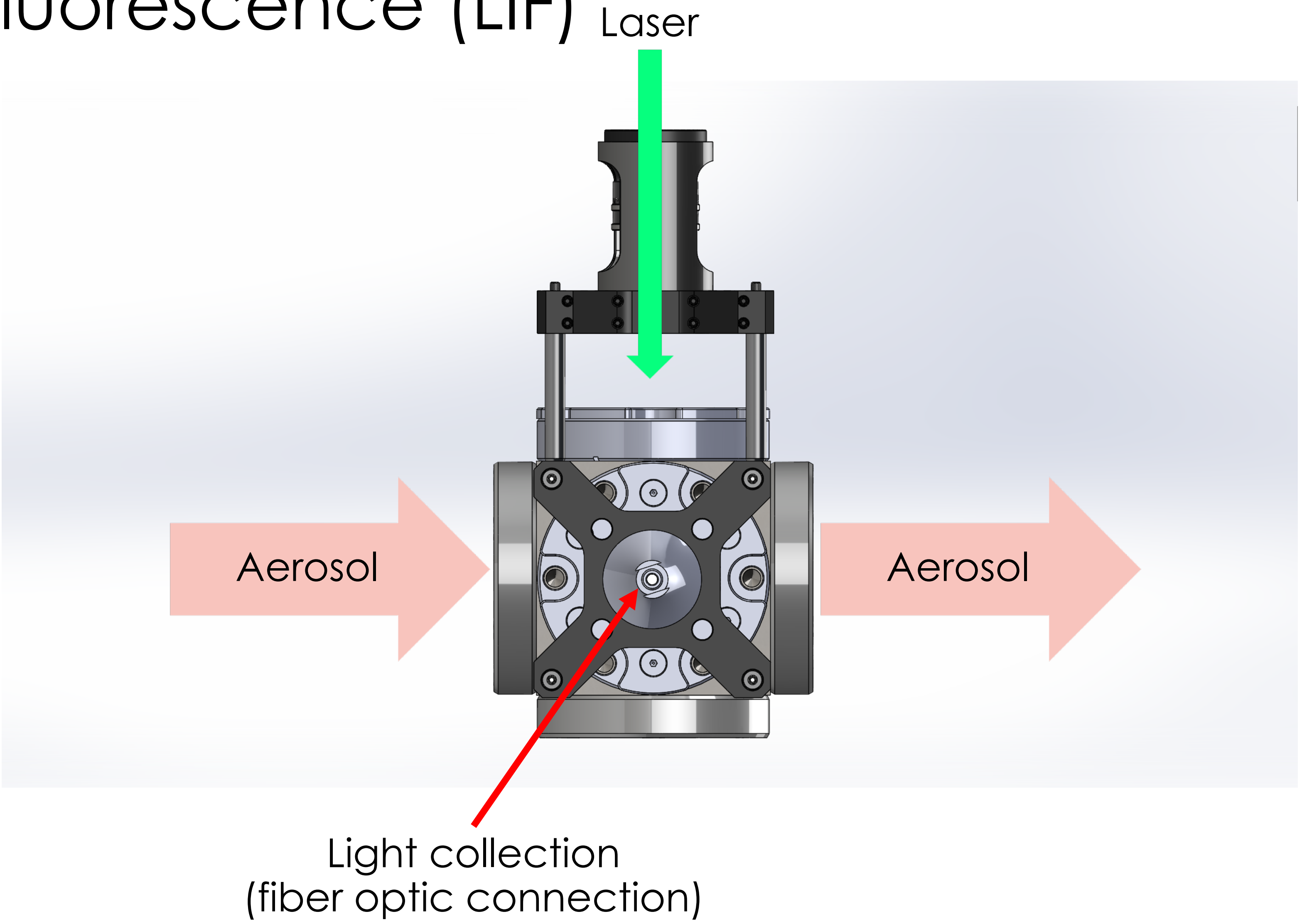
650°C

Scrubber Prototype & Instrumentation



Off Gas System with Instrumentation

Optical sampling geometry for off-gas aerosols/mists using laser induced ablation spectroscopy (LIBS)-laser induced fluorescence (LIF)



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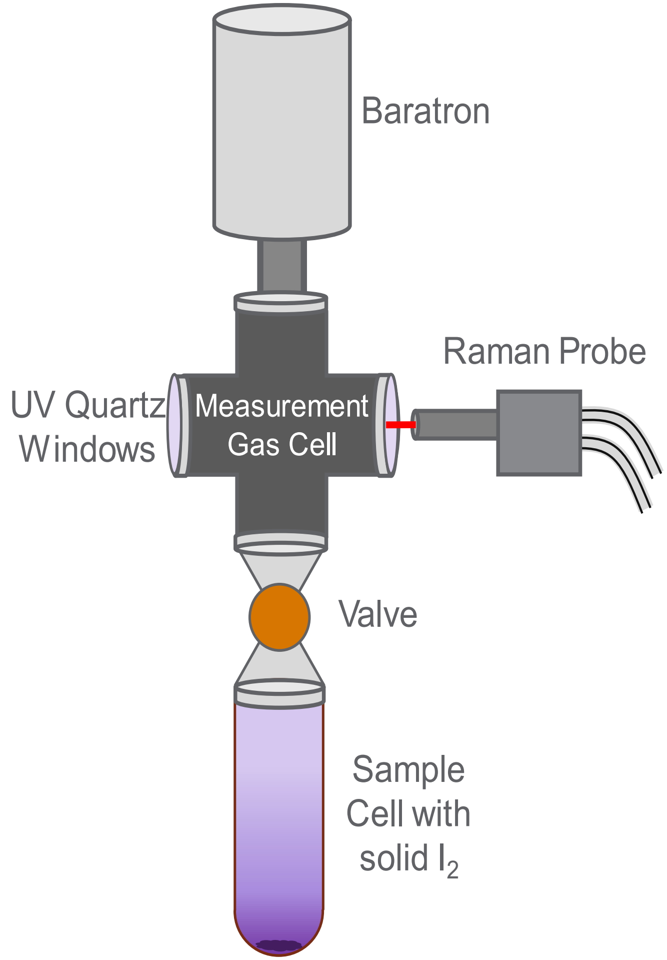
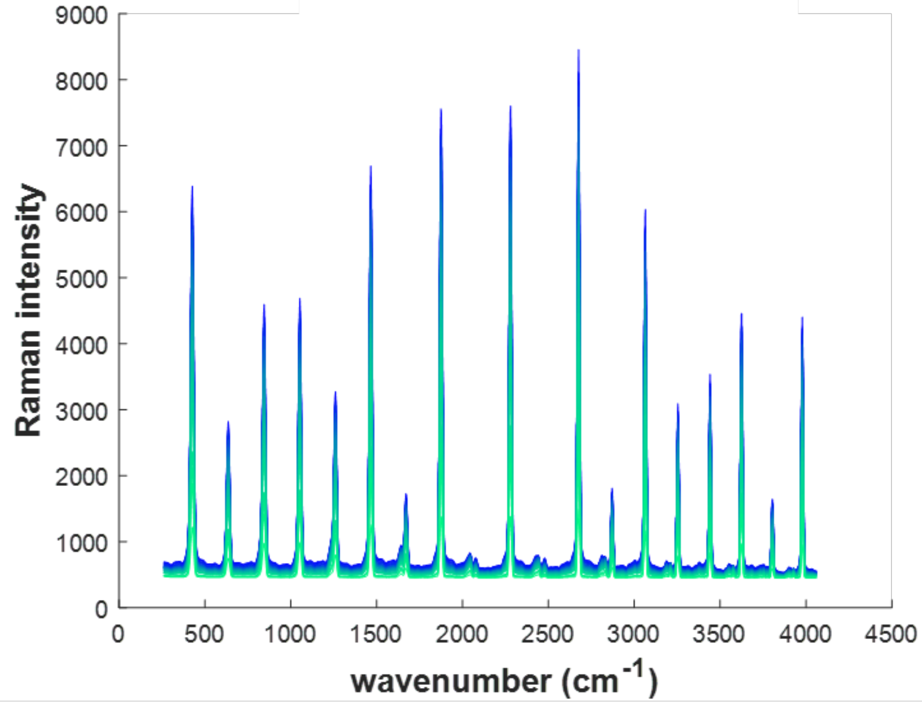
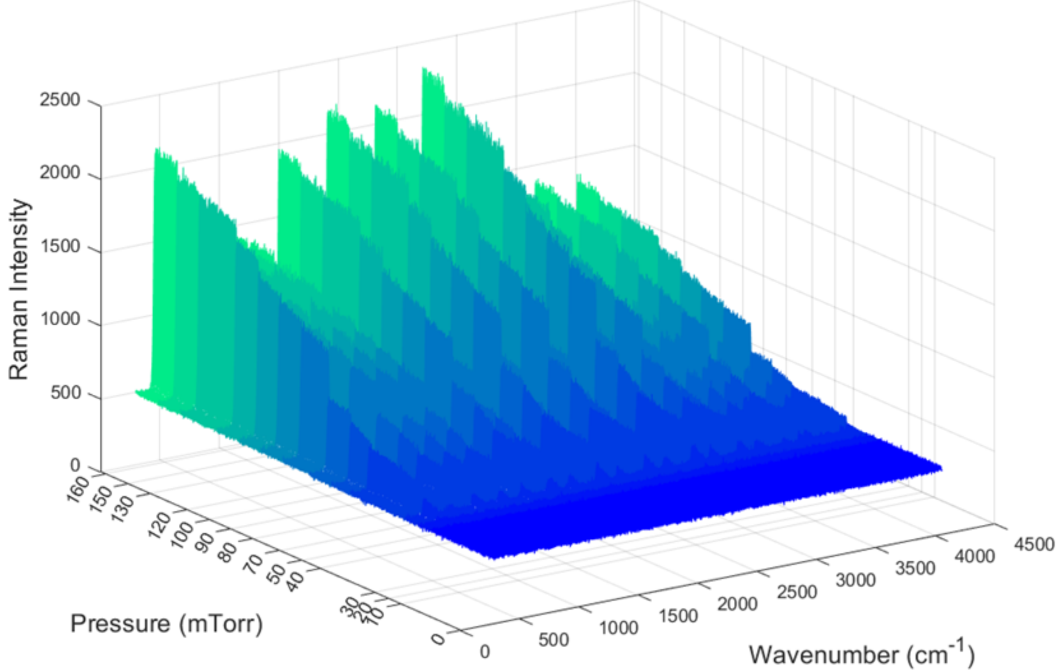
Raman analysis of I_2 and Icl
(Amanda Lines, PNNL)

- Gas cell designed, constructed, commissioned
- Temperature, pressure quantitation of I_2 concentration by Raman
- Chemometric analysis







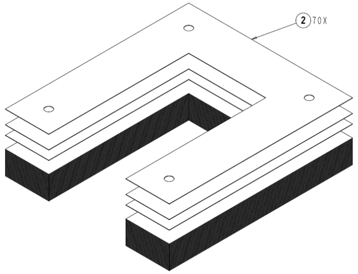
Priority: Corrosion

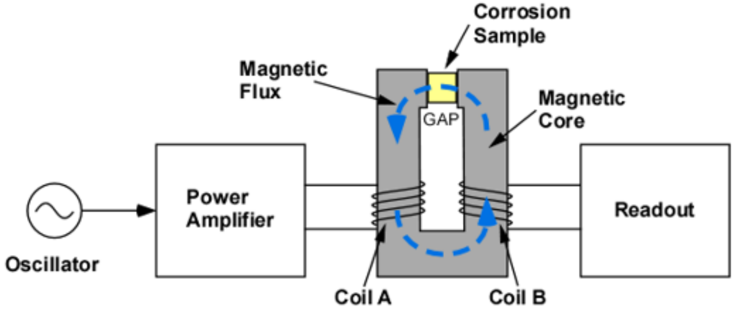
- Potential for corrosion to occur
  - Chemistry modeling
  - Direct measurement within salts (ANL)
- Localized detection of corrosion in structural materials
  - Looking for chromium depletion
- Correction and control of corrosion conditions

High Temperature Corrosion Sensor

- High temperature sensor prototype developed and tested
  - FY18 prototype design converted to a high temperature design through appropriate material selection

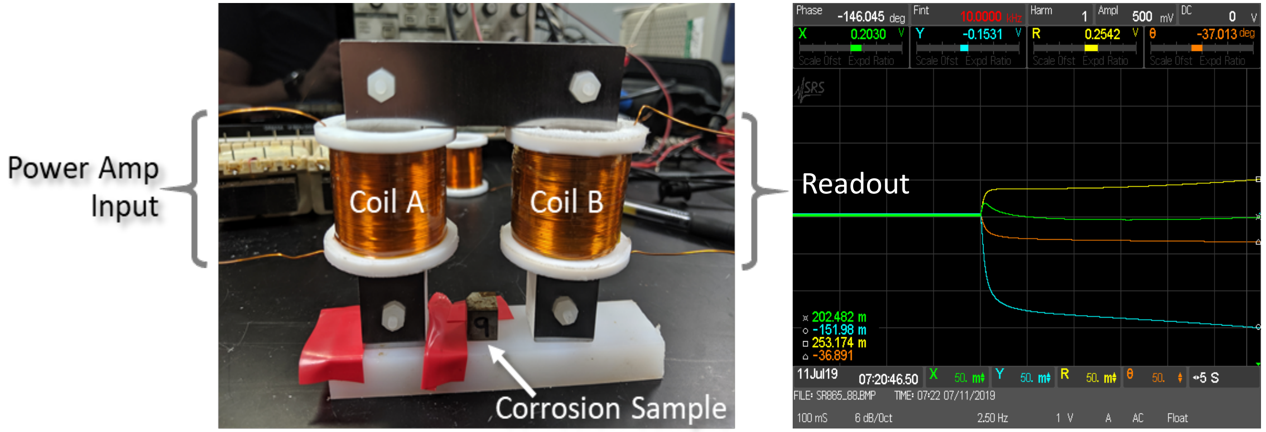
Magnetic core of sensor composed of multiple layers of ferrimagnetic and insulator





*Double test bed uses two sensors driven by two channels on the power amp with outputs measured of separate amplifiers

Illustration of single sensor testbed



Picture of high temperature corrosion sensor and test results

MSR Instrumentation Framework

- Modern MSRs can rely on the instrumentation demonstrated during prior MSR development efforts.
  - No fundamental technology gaps have been identified that would prevent operating or maintaining MSRs
- Improved technology, combined with the integration of modern modeling and simulation, could improve reliability and decrease operating costs.
- Largest potential impact of new instrumentation technologies is in the integration of maintenance automation into reactor design and operations
- Flow measurement has the largest technology hurdles remaining to enable deployment of robust systems.
- Technology for reliable online fuel salt sample acquisition remains at a relatively low TRL.

MSR Characteristics Change Instrumentation Performance Requirements

- Avoid the need for high-speed, safety-grade process monitoring due to the lack of rapidly progressing accidents
  - Lower safety significance of individual MSR plant components decreases in-service inspection requirements
- High dose rates within containment precludes human access for replacement or calibration
- Increasing the need for automated intrusion monitoring to facilitate use of local law-enforcement personnel for plant security
- Adding requirements to inspect/monitor passive safety features to ensure that they continue to be able to perform their functions

Liquid Fuel Necessitates Substantially Different Approach to Fissile Inventory Tracking

- Substantial increase in instrumentation complexity
  - No equivalent of fuel rod counting
- Fissile materials in more locations in more forms
  - Transported with cover gas
  - Plated out ex-core in fuel circuit
  - Plated out onto fuel filters
  - Leaks into guard vessel, DRACS, or coolant loop
  - Used fuel
  - Surfaces of worn out components
  - Fresh fuel
    - Fast reactor fresh fuel will have higher fissile assay
- MSRs are not bulk processing facility as little goes in or out
  - Fissile materials generated inside preventing simple in-out mass balance

Instrumentation Layout Needs to be Included in Early Phase Plant Layout

- Difficult to assess health of large concrete structures without embedded sensors
  - Lesson learned from LWR life extension
- All in-containment maintenance, recalibration, and repair will need to be performed remotely
  - Replacing cabling within containment is difficult and expensive
- Remote access to high radiation environments has been from overhead cranes with long tooling
  - Visual guidance primary sensor

Most Required Instrumentation Does Not Contact Salt

- Heat balance performed on non-radioactive side of primary heat exchanger
- High-degree of passive safety eliminates need for rapidly responding safety-related instruments
  - High-temperature, radiation-tolerant commercial-grade instrumentation from other industrial processes can be widely employed at MSRs

Accommodating Instrument Drift, Recalibration, and Aging Remains Challenging

- MSR designs are intended to operate for years between outages
- Instruments drift over time, and some instruments may fail prematurely
- Online instrumentation replacement and/or recalibration is not mature

Operations and Maintenance Automation Was Not a Focus of the Historic MSR Development Program

- Greatest potential instrumentation enhancement to MSRs is in integrating maintenance automation
  - Modeling and simulation of maintenance and waste handling activities will be especially important to ensure reliable, long-term operations
  - Need for remote maintenance was highlighted in Atomic Energy Commission reviews of MSR technology (WASH-1222 and WASH-1097)

- Instrumentation advancement needs to be focused on technology improvements to enable high-reliability, cost-effective, long-lived, commercial-scale plant operation.

High-Reliability, Low-Uncertainty Flow Measurement is Not Available

- Low uncertainty measurement of coolant flow will be necessary to calculate the heat-balance
- Venturi-meters have been problematic at MSRs
  - NaK impulse lines are not readily available
  - Primary source of error in MSRE power measurement
- Activation-based flowmeter possible for fluoride coolant salts
  - Fluorine-19 has (n; alpha or proton or gamma) cross sections that yield short lived energetic gammas
- Clamp-on ultrasonic flowmeters are difficult to align
  - Standoffs substantially lower signal level

Different MSR Concepts Have Substantial Differences in Instrumentation

- Integral primary systems restrict measurement access
- Chloride and fluoride salts create different chemical environments
- Fast-spectrum reactors tend to have much higher power densities, making in-core instruments more difficult to implement
- Thermal-spectrum MSRs have in-core materials and structures similar to those of high- temperature gas-cooled reactors

Recommended Instrumentation Development Activities

- Integration of maintenance planning and waste handling into reactor point designs to enable support for instrumentation development,
- Online salt and material coupon removal tooling,
- Instrumentation and cabling replacement tooling,
- Tooling for inspection of areas that are not readily observable,
- Online corrosion monitor development,
- High-temperature, salt-compatible gamma-thermometer development,
- Coolant salt ultrasonic flowmeter development,
- Fissile materials tracking planning to enable instrumentation evaluation,
- Fluoride salt activation flowmeter development, and
- Online redox measurement capability development.

MSBR Program Provides Substantial Instrumentation Experience Base

- MSRE only demonstrated limited-term operations.
- Higher speed signal processing for ultrasonic flowmeters or radar level gauges was unavailable in the 1960s.
- MSRE was a small system
  - Decay heat removal will have a higher safety significance in a larger system.
- Fissile materials tracking (safeguards) instrumentation was not specifically considered
- Fast-spectrum MSRs will have significantly higher power densities
- Little or no MSBR residual supply chain remains active.