Module 8: Instrumentation

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MSR Instrumentation Was Developed During the Historic MSBR Program

- Future MSR plants are anticipated to use conceptually similar technologies
  - Flux, temperature, flow, level, pressure, and coolant chemistry remain key process parameters
- Substantially increased automation of maintenance and operations will be a key advance over the historic program
- Tritium monitoring will be especially important for reactors that employ lithium-bearing salts
- Fissile material tracking instrumentation will also be required
- Very high radiation level within containment largely precludes the use of conventional solid state electronics during operation
  - Even following fuel salt draining and flushing dose rates appear prohibitive
  - In-vessel shielding can be employed to decrease dose rate

MSR Characteristics Change Instrumentation Performance Requirements

- Avoiding 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 preclude 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

Presentation Provides an Overview of Specialized MSR Instrumentation

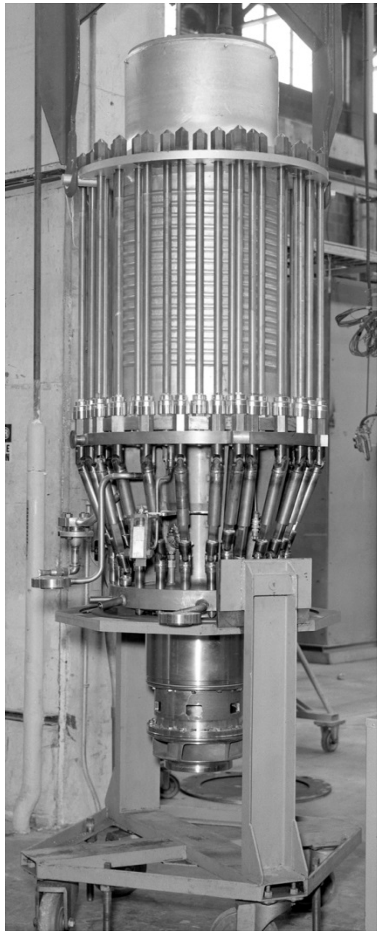
- Temperature
- Flow
- Neutron flux
- Pressure
- Level
- Salt chemistry
- Fissile material tracking
- Fission product tracking
- Tritium tracking

Harsh Environment within Biological Shielding Necessitates Full Automation of Operations and Maintenance

- High radiation environment inside biological shielding prevents human access
  - Containment environment likely to be inert (e.g., 95% dry nitrogen)
- Highly radiation-tolerant operations and maintenance support instrumentation including cameras, motion control, and communications will be required
  - Vessel interior shielding and fuel salt draining and flushing prior to performing maintenance can substantially reduce dose rate
- Some designs are incorporating redundant components to avoid having to perform fuel-salt-wetted component maintenance during the limited vessel system lifetime
  - Additional fuel salt pumps and fuel-to-coolant salt heat exchangers
- Solid state electronics and polymer insulators will have limited lifetimes within biological shielding during outages following fuel draining and flushing
  - Vacuum tube electronics possible within shielding during operation
- Components will include features to facilitate manipulation with long-handled tools (e.g., readily accessible bolts)

Evaluating Remaining Useful Life May Be a Mission for Future I&C Systems

- Advanced reactor designs often rely on replacing rather than developing plant lifetime components
  - Higher temperatures challenge long component lifetimes
  - Avoids requirement for multi-decade qualification
- Improving diagnostic and prognostic technologies
  - Physics-based methods - typically insufficient experience for statistical failure approaches
  - Physics-based methods will require gathering adequate data to develop models
  - Increased sensor coverage to capture additional fault signatures
  - Requires assessing material conditions, e.g., fracture toughness
- Automated maintenance likely to be a key element of component design



MSRE coolant pump with extended bolts enabling remotely controlled replacement

Source: ORNL-TM-2987

No Custom MSR Instrumentation Is Currently Available Commercially

- None of the new MSR designs has yet reached the stage of maturity to develop a complete instrumentation architecture
- Most MSR measurements can be performed with adaptations of known technologies to compensate for environmental stressors
  - High temperature drift
  - Salt compatibility
  - High flow rates
  - High radiation dose tolerance
- MSRs will require some specialized sensors
  - Material control and accountability safeguards instrumentation
  - Salt chemistry monitoring
  - Tritium concentration and location

Temperature Measurement

- Passive safety substantially changes the measurement requirements
  - No known phenomena which would require high speed thermometry
  - Reactor vessel creep and DRACS performance monitoring (e.g., ensuring that the lines haven't frozen due to insulation coming off) are slow phenomena
  - Low uncertainty temperature measurement remains key to determining heat balance
- System design remains a key element of the harsh environment mitigation strategy
  - Integral MSRs have similar measurement access limitations as iPWRs
  - Perform heat balance on coolant salt side of heat exchanger
  - Employ robust thermowells for any inserted thermometers
- At high temperature, nearly all thermometers drift substantially over time
  - High radiation doses exacerbate the issue
- Reliance on first-principles thermometry is anticipated to minimize drift vulnerability for high radiation environment deployment
  - Pyrometry and/or Johnson noise thermometry are based upon invariant phenomena – electronics can still drift

Temperature Measurement (cont'd)

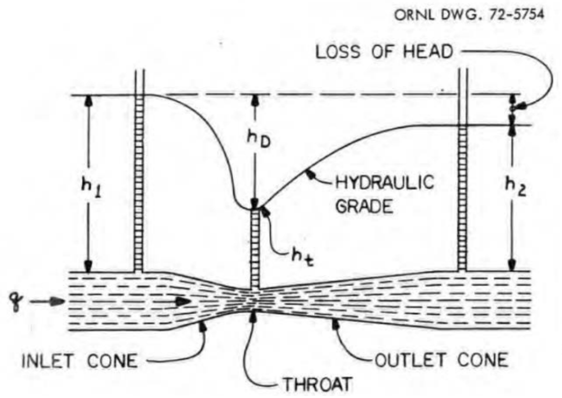
- MSRs will have similar vulnerabilities to flow stratification and unstable flow profiles as PWRs
  - Thermal striping may be an issue requiring additional operating margin to maintain acceptable alloy creep
- Metal-sheathed mineral-insulated thermocouples with insulated (ungrounded) junctions will likely be the workhorse thermometer at MSRs
  - Resistance temperature detectors have higher drifts at MSR temperatures
  - Heat sink compound within thermowells will need to have low neutron cross-section (BN paste is commonly used) for fuel salt measurements
  - Gamma heating of thermocouple leads, thermowell, and sheath need to be accommodated in the design and measurement readout
- Type N thermocouples within high nickel alloy (negative leg) sheaths are the preferred base metal thermocouple type at MSR temperatures in high neutron fluxes
- Au-Pt thermocouples outside of high-flux environment would reduce the measurement drift
- Thermocouple cold junctions may be inside of biological shielding or thermocouple leads (or extension wires) could extend beyond shielding

Flow Measurement

- Fuel salt mass flow measurement is required to establish the power system heat balance
  - Heat balance may be established on coolant salt for systems with inaccessible fuels salt (e.g., fuel salt in tubes)
- Cover gas flow measurement demonstrates lack of line plugging
- Flow measurement in decay heat removal systems assists in demonstration of system availability during normal operations and provides post-accident monitoring
  - Likely based upon observing heat pulse propagation around loop
- Temperature compensation for pipe expansion and coolant density change is key element of minimizing measurement uncertainty
  - Similar issues have arisen in PWR flowmeter uncertainty
- No molten salt flow calibration facilities currently exist

Loop-type Salt Flow Measurements Can Be Implemented Using Venturi Meters

- MSRE employed Venturi flow measurement on coolant salt
  - NaK impulse lines transmitted pressure signal outside of shielding
  - Fuel salt loop flow was inferred from pump speed due to concern about leaking NaK inducing fissile material plate-out
- No current commercial source of supply
  - Technology issue is diaphragm sealing between salt and NaK
- Venturi flowmeters generate small signals for low flow velocities and are vulnerable to throat fouling or corrosion



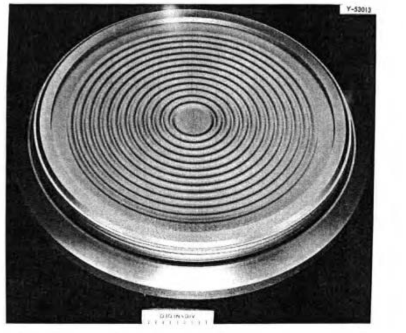
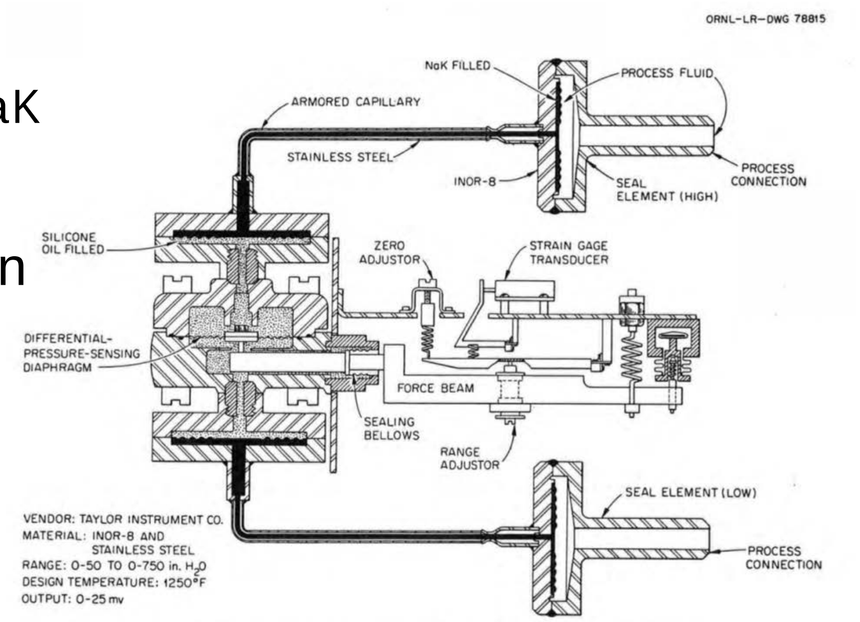
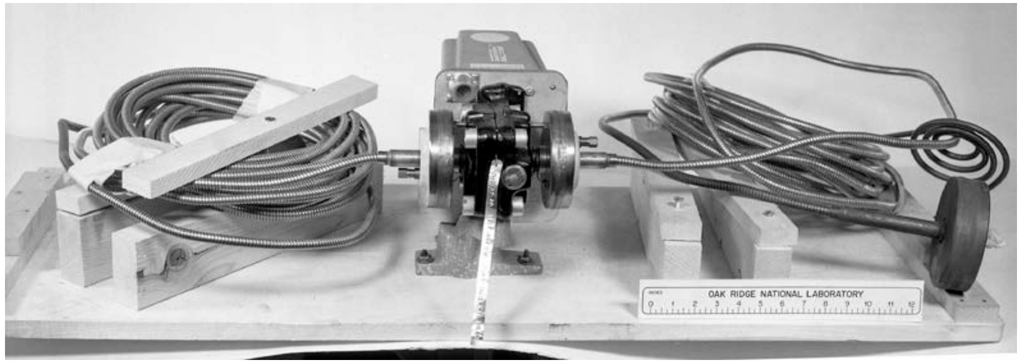


Fig. 6.12.5. Diaphragm seal assembly for NaK-filled differential pressure transmitter.

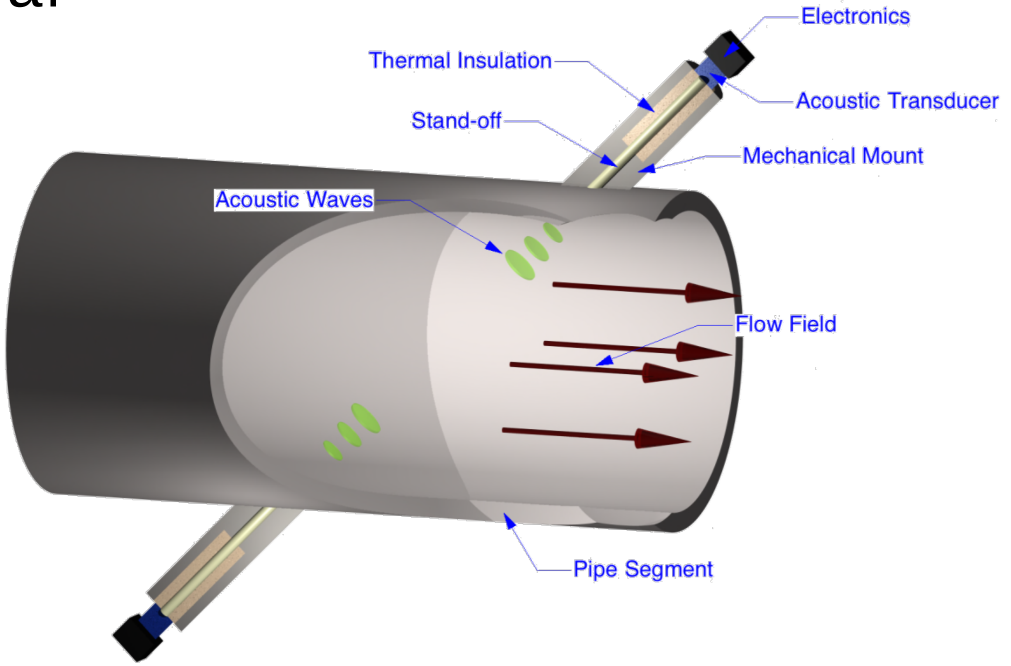
Source: ORNL-TM-729 Part IIB





Clamp-On Ultrasonic Flowmeters Avoid Salt Contact

- Conceptually similar configuration to the configurations employed for power uprates at PWRs
  - Waveguides act as heat fins creating local cold spots
  - Substantial technical challenge in maintaining waveguide alignment over temperature
- Recent development of flowmeters with multiple EMAT (electromagnetic acoustic transducer) around pipe substantially decreasing alignment challenges while increasing signal amplitude



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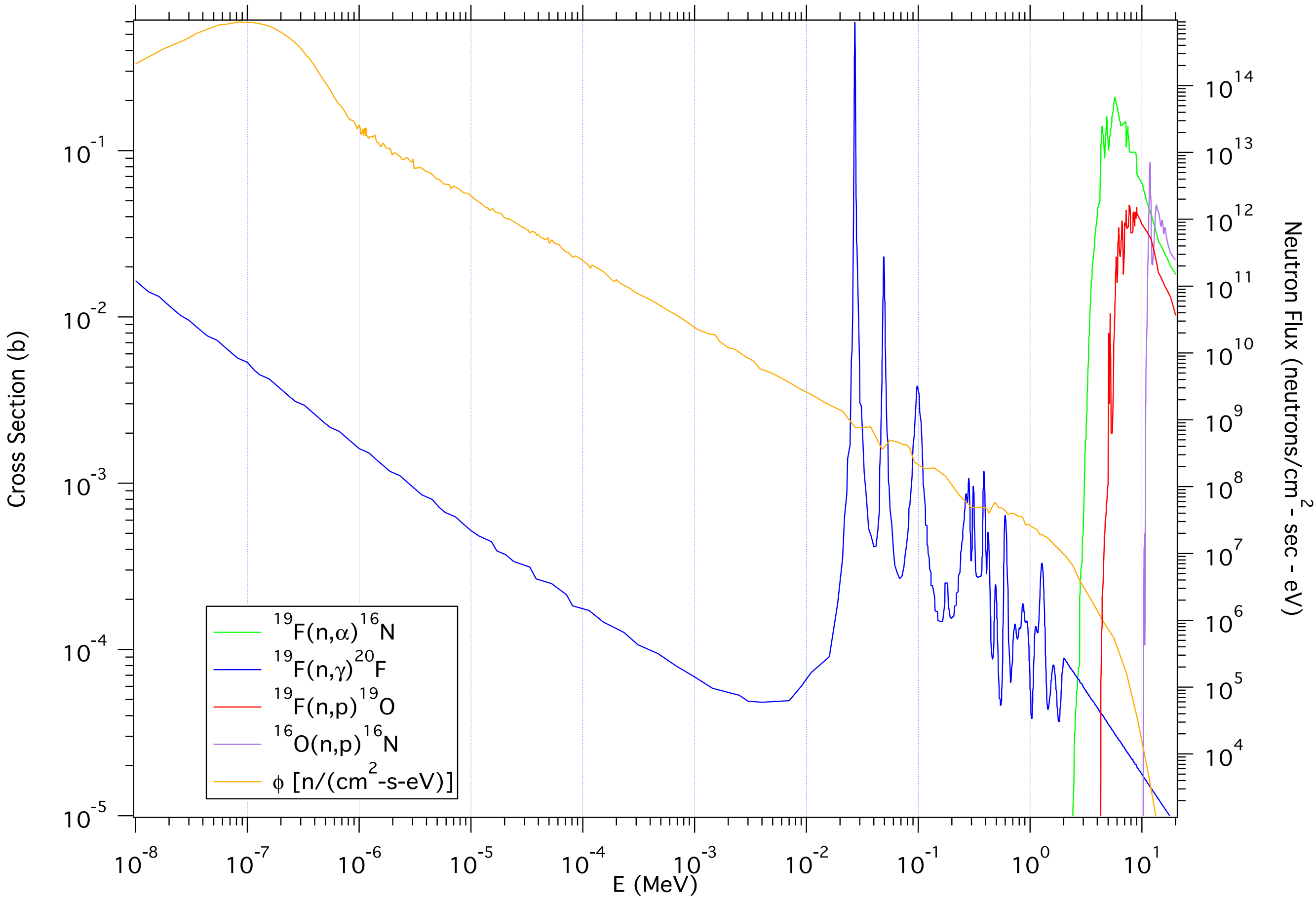
Fluoride Fuel Salt Flow Can Be Measured Using Activation

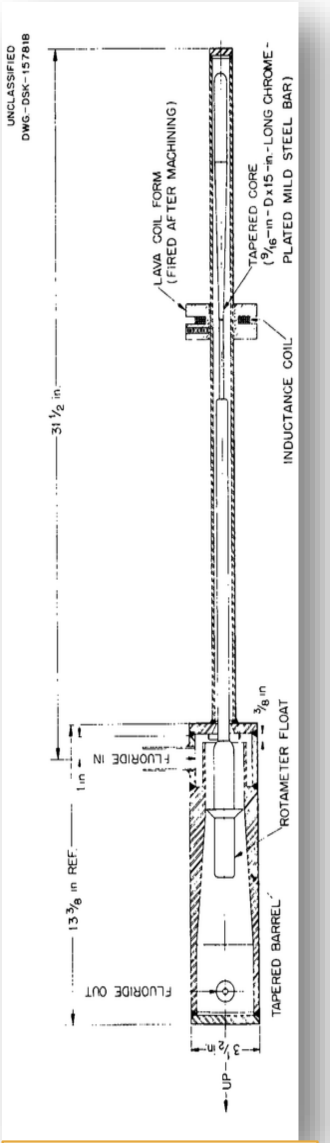
- Activation through delayed neutrons in primary heat exchanger
- ^{19}F has significant (n, α), (n, γ), and (n, p) cross-sections
  - ^{16}N production cross-section for ^{19}F begins at ~2.5 MeV as compared to nearly 10 MeV from ^{16}O
- Similar to nitrogen activation flowmeters used at PWRs
- Different energy gamma rays also enables flow auto-tomography (SPECT – single photon emission computed tomography)



^{16}N — $T_{½}$= 7.1 s; $E_γ$= 6.123 MeV (67%), 7.115 MeV (4%)
^{20}F — $T_{½}$= 11.2 s; $E_γ$= 1.63 MeV (99.99%)
^{19}O — $T_{½}$= 27 s; $E_γ$= 1.36 MeV (50%)

Integral Primary System Fuel Salt Flow

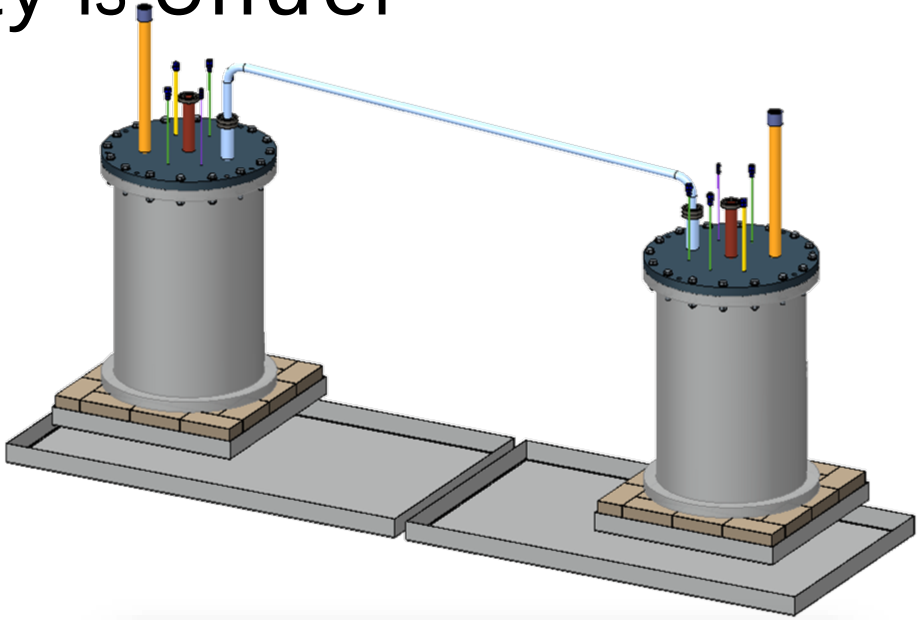
- Significant development challenge
  - No established technologies and a very challenging deployment environment
- Several measurement techniques appear possible
  - Rotameters (variable area flowmeters) were employed for pipe flow for the aircraft reactor experiment
    - Probe type configuration in the downcomer
    - Shaft would extend above salt
  - Neutron noise evaluation
    - Flow-induced vibration of fuel boundary structures will be impressed onto the neutron flux
  - Ultrasonic backscattering
    - Ultrasonic signal may be transmitted through vessel (and shielding, reflector, and/or breeding salt) using an acoustic horn
    - Backscattered signal from fission gas bubbles will be indicative of flow



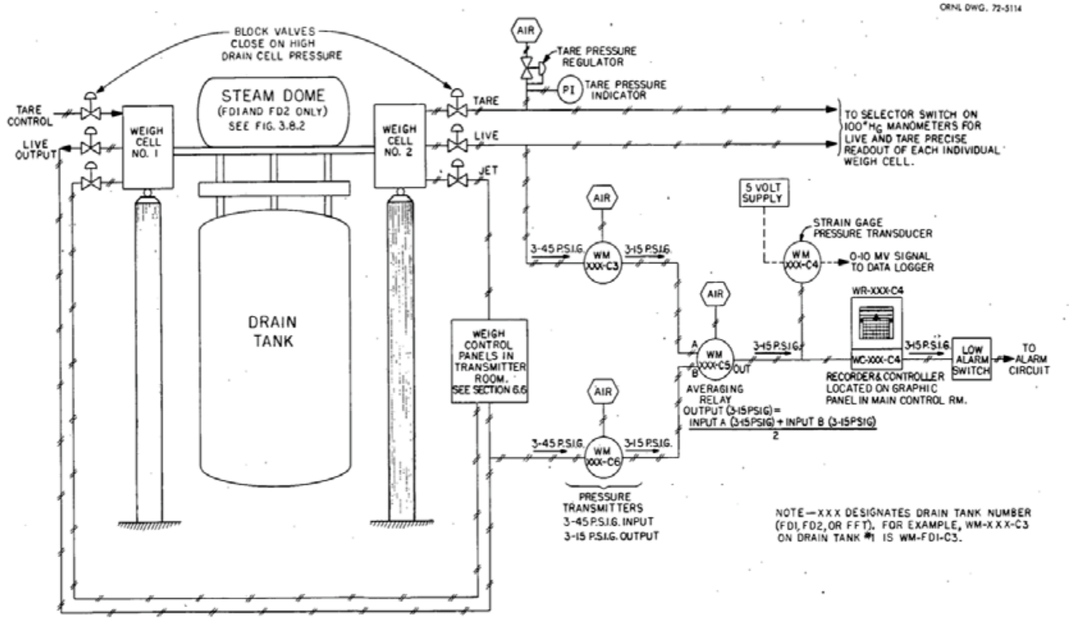
ARE Rotameter

Source: ORNL-2348

Molten Salt Flow Calibration Facility Is Under Development at ORNL



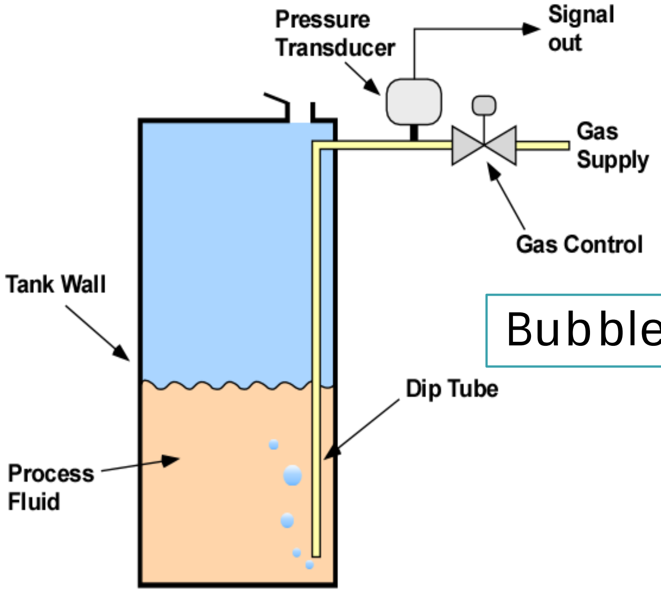
- Two-tank weigh-in-motion type system
  - Employs change in salt weight in tanks as calibration standard
- Weight-based inventory system was used on MSRE drain tanks



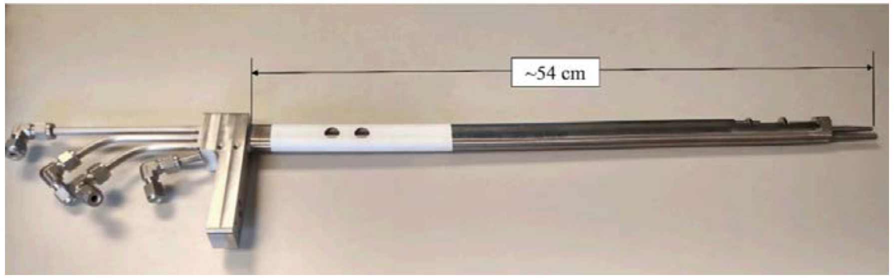
Source: ORNL-TM-729 Part IIB

Bubblers Remain a Viable Level, Pressure, and Surface Tension Measurement Technique

- Small (bubble) inert gas flow is induced in a dip tube
  - Pressure of the gas line is equal to that of the process fluid at the distal end of the dip tube
  - Knowledge of the process fluid density enables level calculation
- Two tubes at different depths enables determining salt density
- Adding third tube of different diameter enables measuring surface tension
- Vulnerable to tube blockage from salt vapor deposition



Bubbler Concept

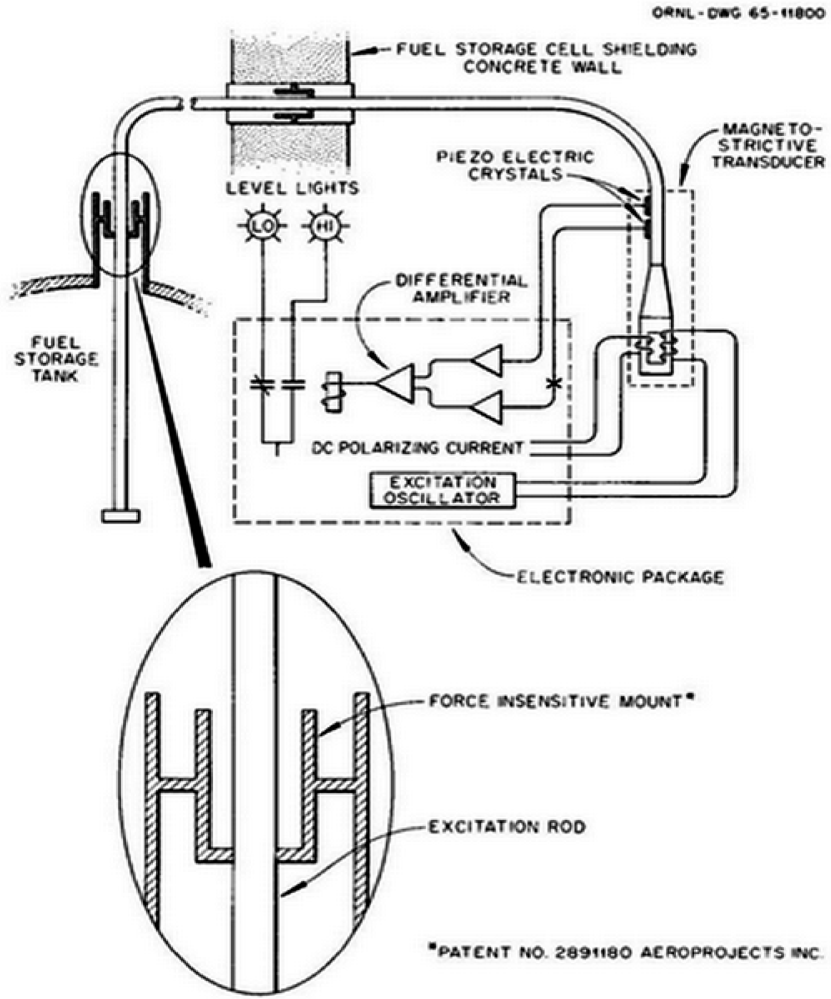


Triple Bubbler

Williams - INL doi:10.1016/j.jiec.2018.02.011

Ultrasonic Level Probes Have Been Employed to Check for Tank Filling

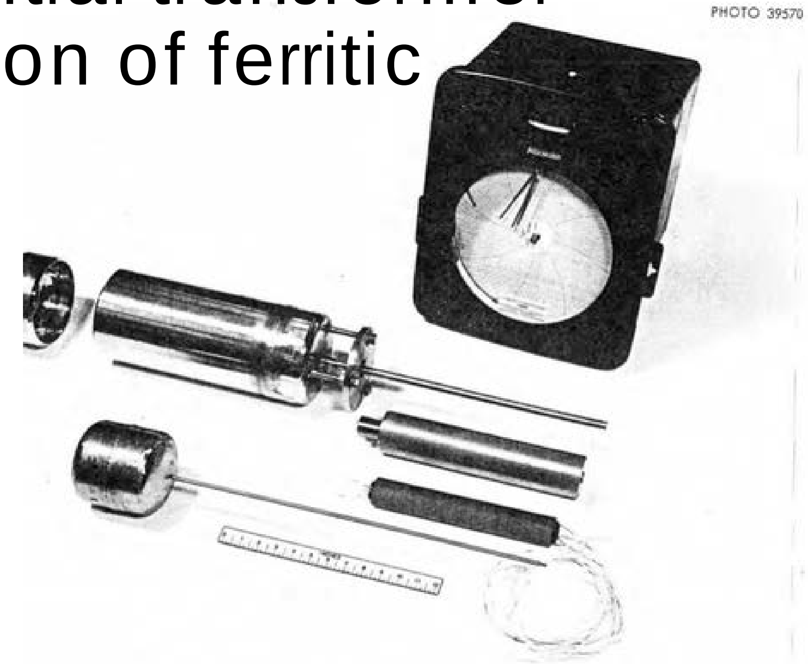
- Based upon transmitting an extensional wave along an ultrasonic waveguide to a plate at its distal end
- Resonance frequency shifts when the plate is immersed in salt
- Requires flexible feedthroughs across all boundaries
- Single point measurement

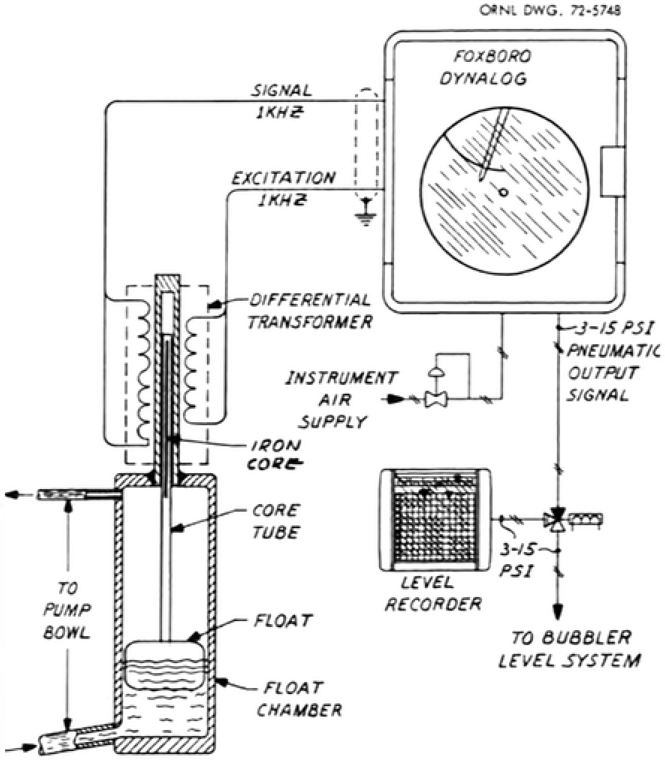


Source: ORNL-3872

Float-Type Level Measurement Was Demonstrated by MSBR Program

- Float connected to a rod extending into standpipe
- Rod upper end includes ferritic material
- Linear variable differential transformer used to measure position of ferritic material

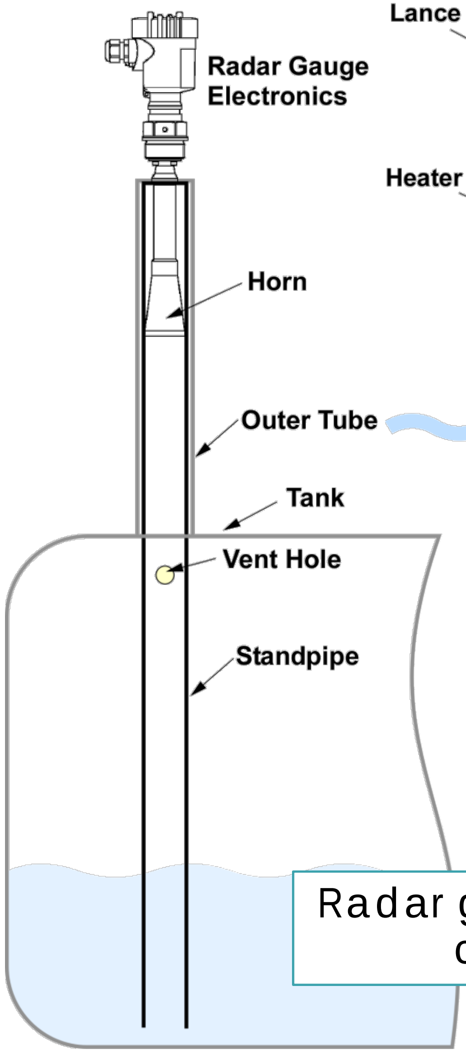




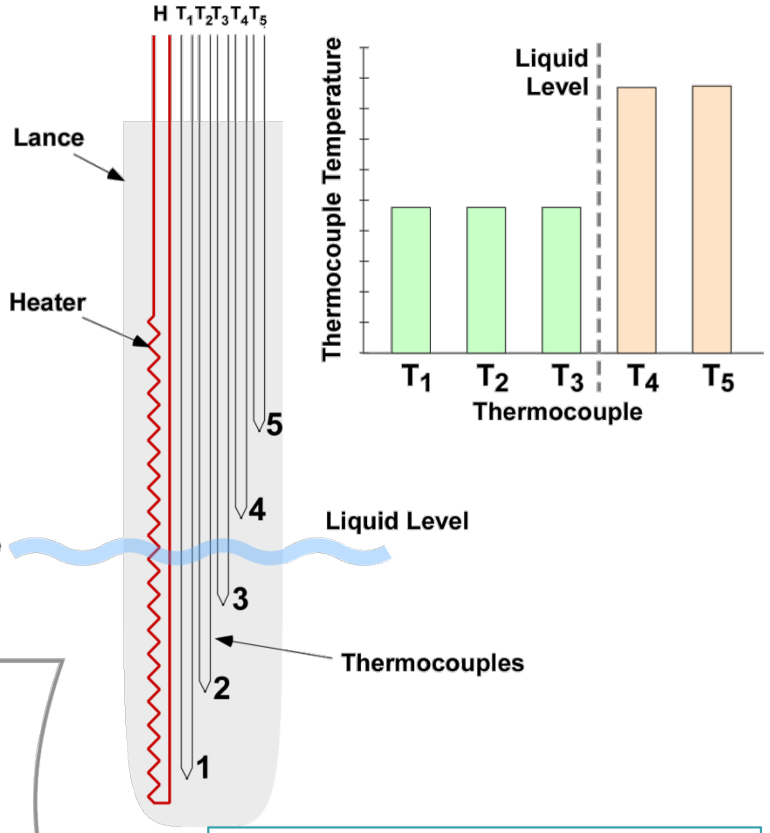
Source: ORNL-TM-729 Part IIB

Level Measurements Can Be Made with Heated Lance or Radar Gauges

- Heated thermocouple lance
  - Based upon difference in heat transfer in cover gas and liquid salt
  - Discretized level values
  - BICOTH (binary coding thermocouples with heater)
    - Multi-junction thermocouples employed to decrease number of wires
- Radar level measurement
  - Noncontact
  - Continuous values
  - Electronics outside of hot zone



Radar gauge deployment configuration



Simplified thermocouple lance configuration

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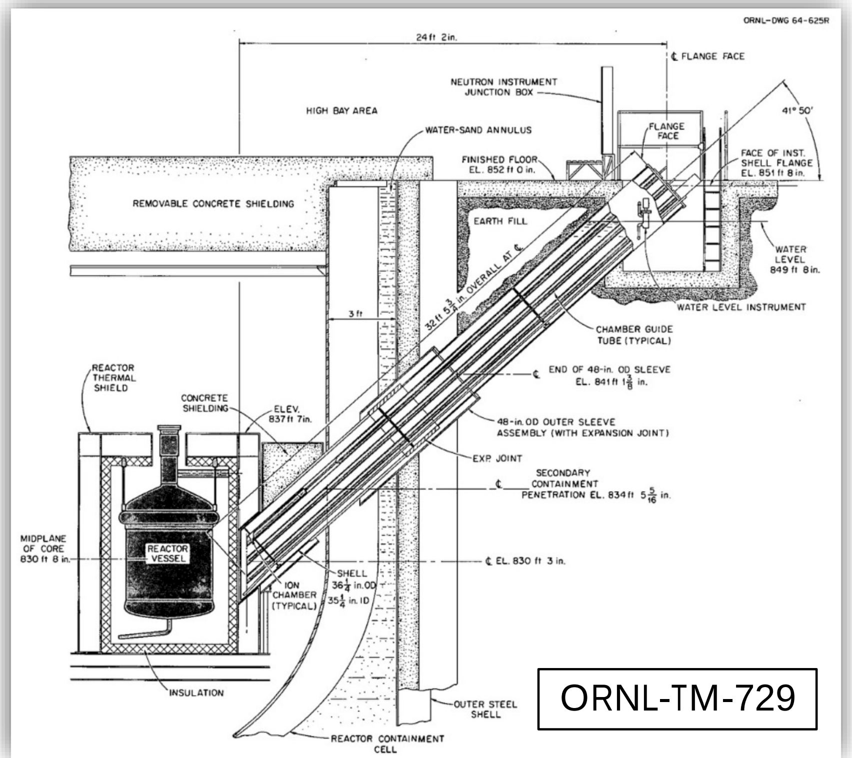
Neutron Flux Monitoring Provides Rapid Indication of Changes in Reactor Power

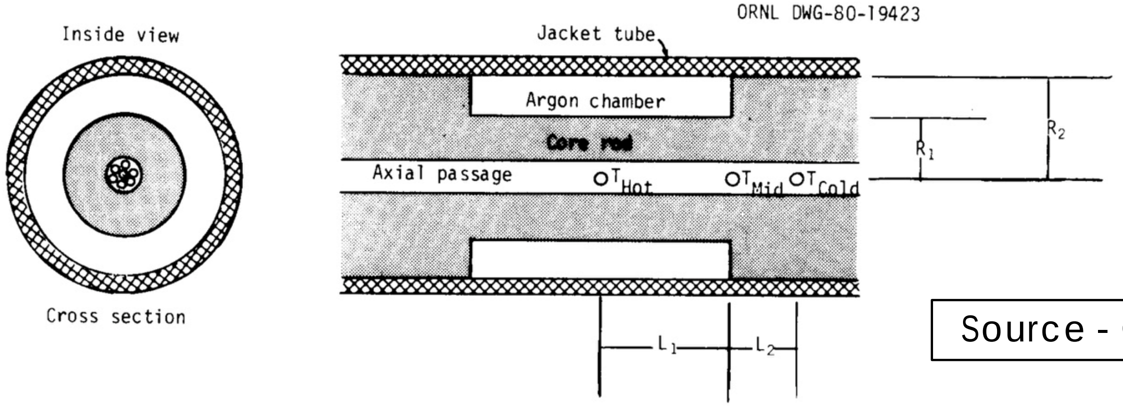
- During power range operations ex-vessel fission chambers can provide strong signals
  - Fission and cover gas bubbles propagating through core were readily detectable on MSRE ex-core ion chambers
- Self-powered neutron detectors (SPNDs) or ion chambers may be used for power profiling
- Initial approach to critical will have smaller signals
  - Start-up source may be dissolved into fuel salt
  - In-core fission chamber would need to function at operating temperature or be actively cooled



MSRE Nuclear Instrumentation Layout

Gamma Thermometers Are a Potential Alternate Local Power Monitor at MSRs

- Materials and structures are similar to thermocouples
  - Have been used at LWRs since 1950s
- Function based upon heating of metal block by local radiation environment and measuring heat dissipation through controlled path
  - Temperature drop is proportional to heat rate
  - Need to be adapted for use above 500 °C due to heat leak across argon gap

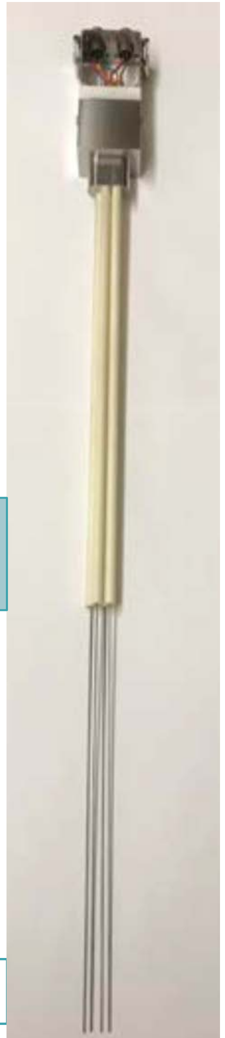


Source - ORNL/TM-7567

Measuring Redox Condition of the Salt Provides Evidence of the Proper Chemical Environment

- Analogous to coolant chemistry monitoring in LWRs
- Electrochemically based measurements are most common technique
- Presence of corrosion products in primary salt indicates that corrosion is occurring
  - Chromium most vulnerable structural material element to oxidation
  - Level of chromium fluoride in salt indicative of corrosion
- Optical absorption potential alternative in clean salts
  - Coolant salts transparent
  - Chromium fluoride is green
  - Optical access from top surface with precious metal mirror in salt

Redox probe fabricated at University of Wisconsin



ANL multielement electroanalytical probe

Source - ML20031D415

Tritium Tracking Is Challenging Due to Low Signal Strength

- Measuring weak beta emission in the presence of a strong gamma background is principal design challenge
  - Flow-through ion chamber and liquid scintillation counting remain standard measurement techniques
  - Direct immersion tritium monitoring for fuel salt is infeasible due to salt self-shielding
  - Inert gas sparging enables disengaging tritium samples from fuel salt for monitoring

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 Is Central to Monitoring Fissile Material Location for Safeguards

- Nuclear material must be accounted for at each stage of operations
  - Material balance measurements and key measurement points are central to safeguards
- Some advanced reactors embed more of the fuel cycle into reactor facility
  - Current safeguards implementations do not address implications of fluid fuel forms
- Additional monitoring likely to be required that doesn't exist today
  - Item counting and visual accountability of fuel may not be possible

Safeguards are the technical means for the IAEA to verify that States are meeting their legally binding undertaking not to use nuclear material or other items for illicit purposes

Safeguards Monitoring Instrumentation Has Not Been Defined

- Key concern is diversion of fissile materials from fuel salt
  - Detecting small quantity, extended duration diversion will set the instrumentation sensitivity requirements
- Cover gas and salt treatment systems are directly coupled to primary salt
  - Filter contents needs to be monitored for fissile content
  - Hold-up (intentional or accidental) of fissile material needs to be monitored
- Used fuel also requires monitoring
  - May be solid providing substantial self-shielding

Fission Product Monitoring Will Chiefly Be through Gamma Detection

- Fission products will be distributed throughout the cover gas handling system
- Conventional gamma detection technology appears directly applicable to MSRs
  - High local radiation environment may require either local shielding radiation tolerant electronics for first stage signal amplification
- Post-accident monitoring environment does not require steam tolerance or significant temperature increases for measurement electronics

MSR Instrumentation Development Is Intertwined with Plant Design and Licensing

ORNL Photo 10-G01432_A

- Significant elements of plant design remain undefined
- Salt thermophysical property measurements will be necessary to verify that the fuel salt composition and properties remain within license limits
  - Likely off-line via laboratory analysis of samples
  - On-line instrumentation would require substantial development
- Planning for multi-decade plant operation largely has yet to be performed
- Instrumentation development appears mostly to be adaptation of conventional process measurement technology
  - Unanticipated implementation hurdles may still exist
- Instrumentation validation and testing largely remains to be performed