PNNL-SA-149883

Pacific Northwest
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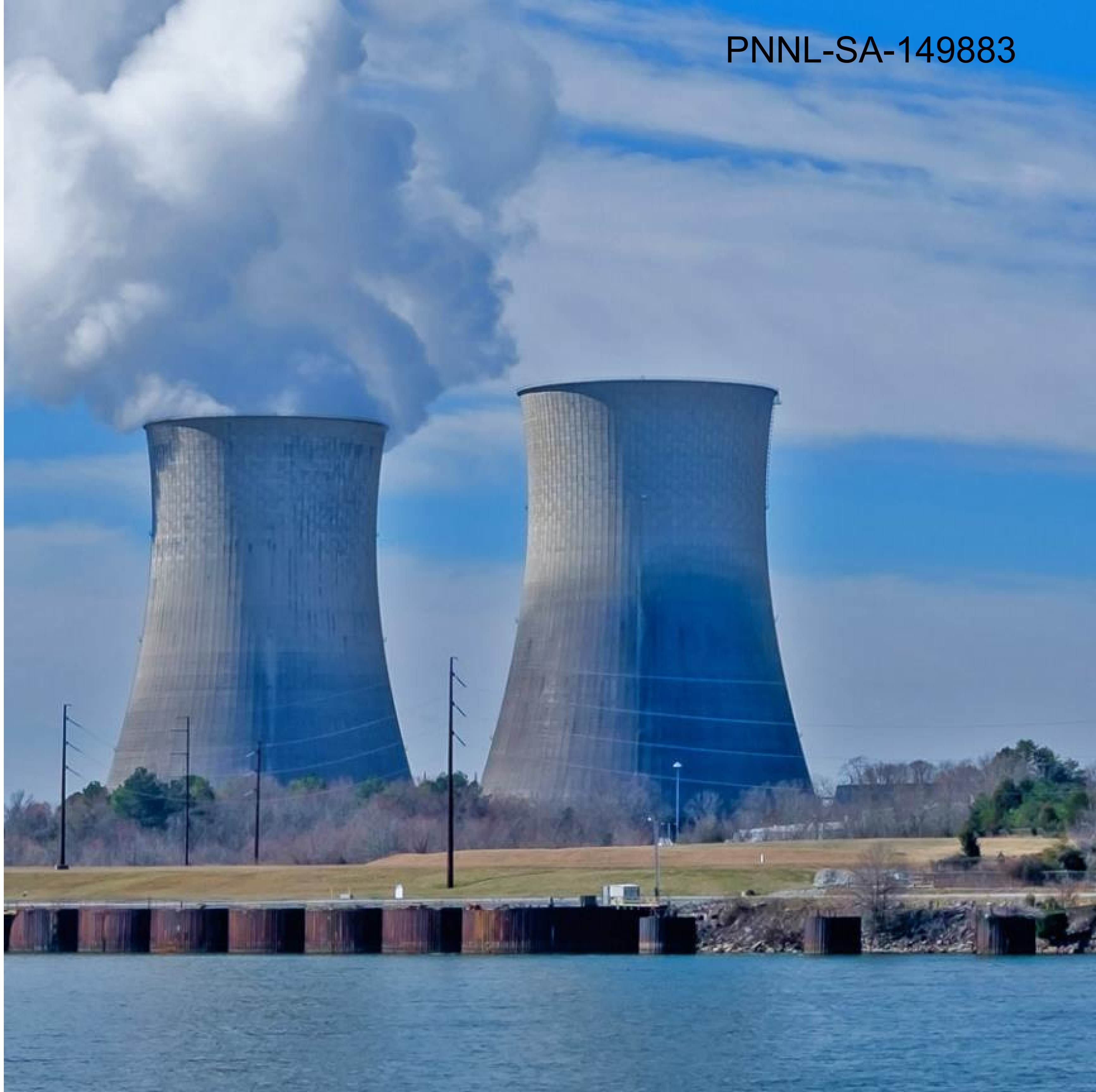
Progress Toward Bridging Harsh Environment Online Monitoring Gaps for Advanced Reactors

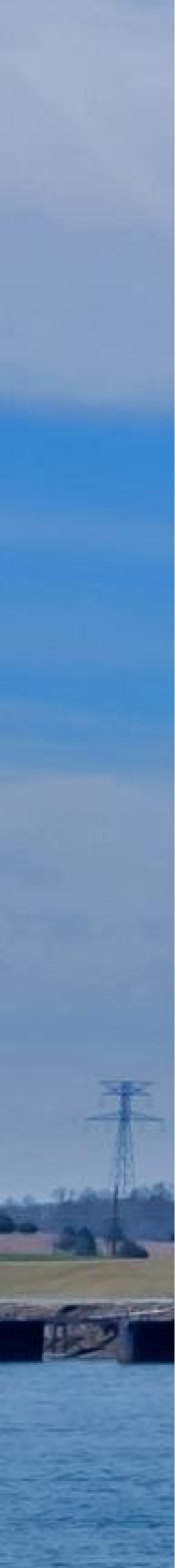
December 2019

S. W. Glass



U.S. DEPARTMENT OF ENERGY BATTELLE

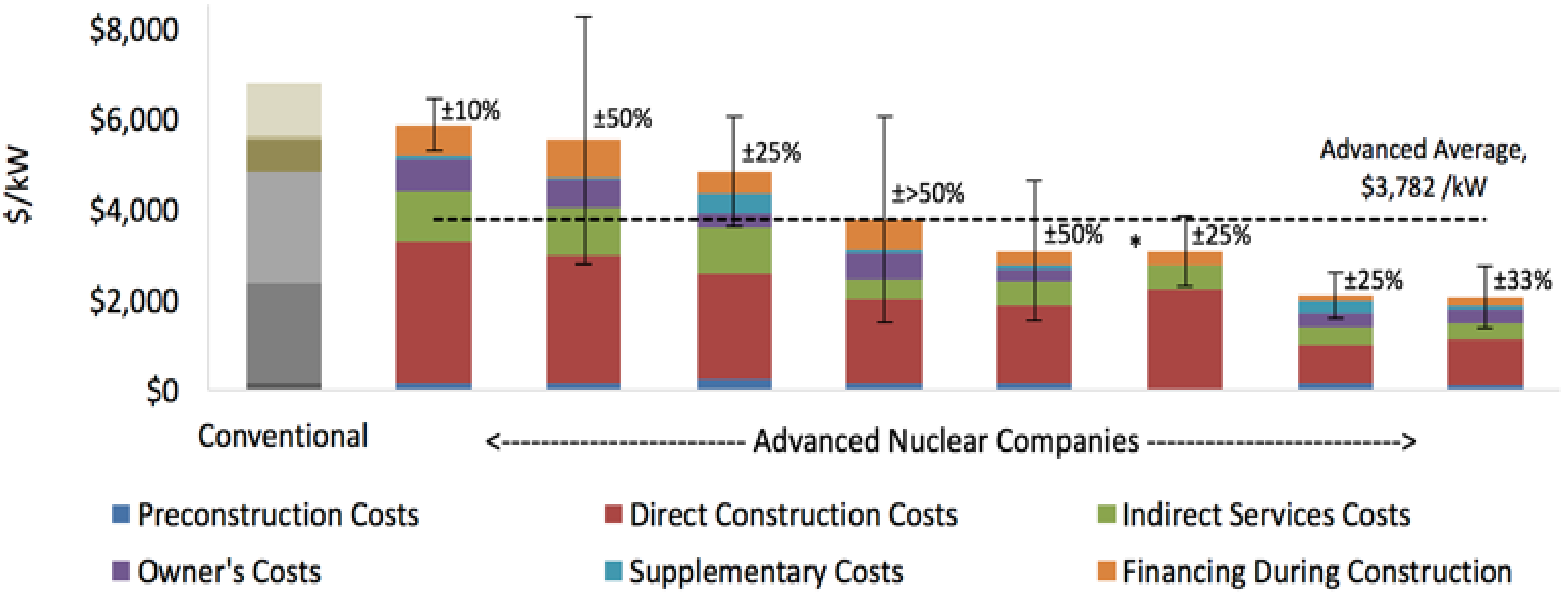
PNNL is operated by Battelle for the U.S. Department of Energy



Presentation Outline

- Why advanced reactors?
- Designs, operating history, and gaps
- PNNL initiatives
  - Sensors for High Temperature & Radiation
  - Cold Spray Magnetostrictive High-Temperature Technology
  - Optical Sensors for Imaging, Motion, Flow, Material Identification, …
  - High-Temperature On-line Heat Exchanger Tube Monitoring
  - Sensor Website and Database
  - Code Involvement
- Conclusions

Why Advanced Reactors? It's the MONEY!



From EIRP; WHAT WILL ADVANCED NUCLEAR POWER PLANTS COST? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development (2018)

First Generation of MSRs Plan to Rely on Known Component Technology

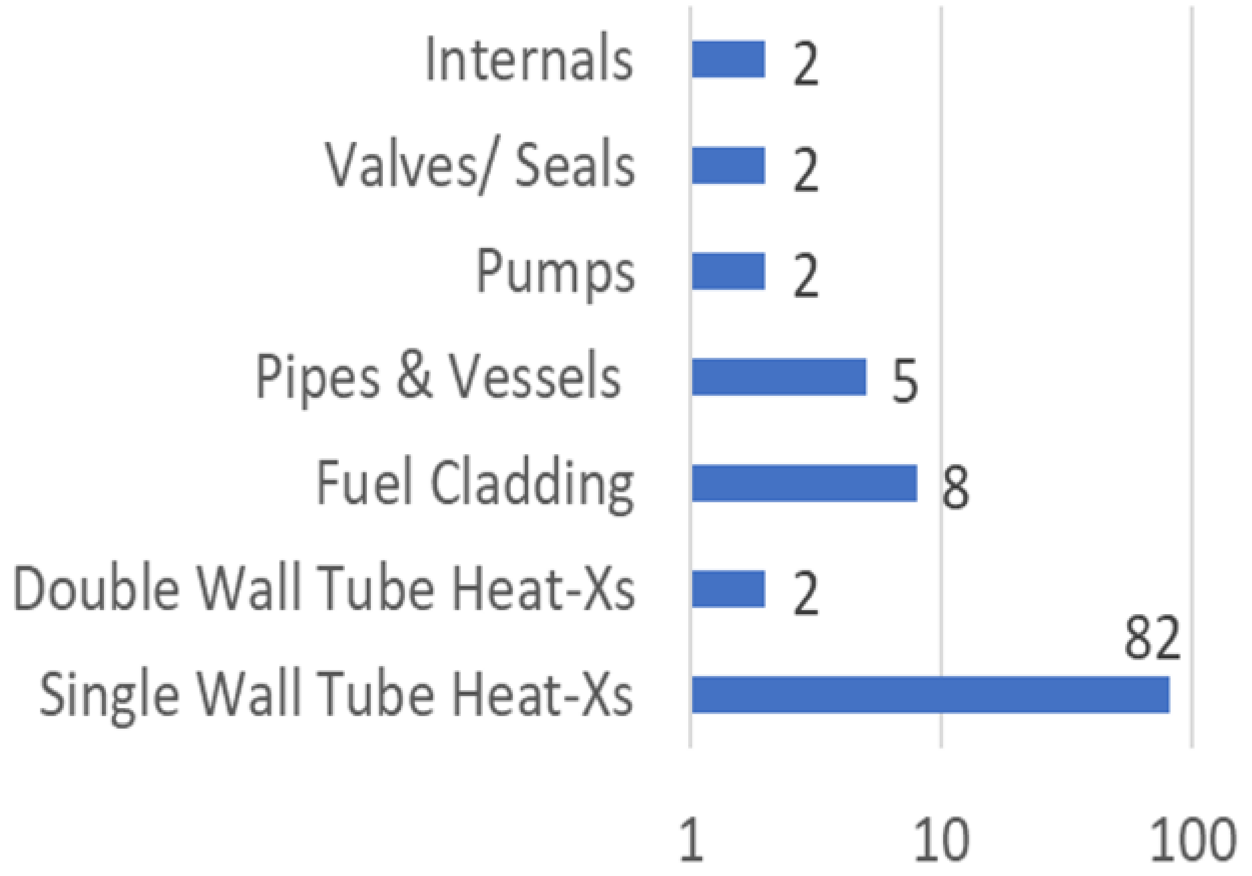
(from ORNL Module 2: Overview of MSR) Technology and Concepts

- Pumps
- Vertical shaft, cantilever-style similar to those used with sodium fast reactors
- May require pressurization of fuel system to avoid pump cavitation
- Could be coupled with spray ring to evolve fission gases and tritium
- Heat exchangers
- Tube and shell remains leading candidate technology
- Tube vibration and flow-accelerated corrosion present the most significant power density limits
- Double wall possible/considered for tritium release mitigation
- Many designs have dual-stage to isolate high-pressure steam from fuel
- Vessel and piping
- Either clad ASME BPVC code-qualified material or modified Alloy N used under a limited-term code case
- Interior shielding to minimize radiation damage is planned by multiple vendors

Operating Experience Related to Materials and Component Integrity for Advanced Non-LWR Rxs

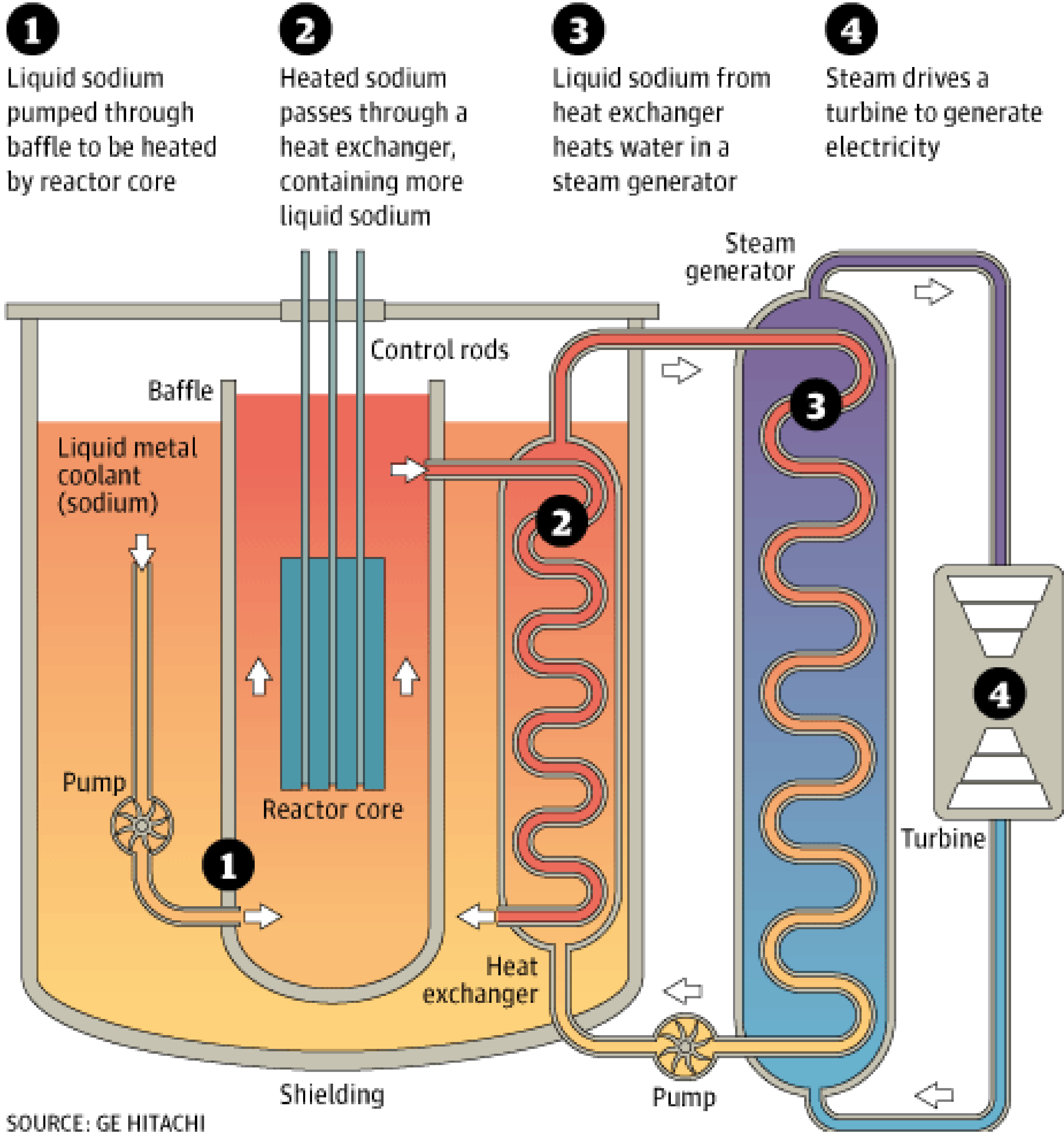
- MSR experience is limited. ORNL's MSRE 1965-69 used Hastelloy N but concluded "mechanical properties...are not sufficient for long-term operation…"
- The report focused on SFRs profiting from decades of OE. Distribution of events are summarized in chart.
- Recommendation: Accurate detection methods of corrosion and leaks are necessary… The design phase should consider sensor placement and reliability under operating conditions.

Summary of NRC TLR-RES/DE/CIB-2019-01 Advanced Non-Light-Water Reactors Material and Operational Experience (SFRs only)

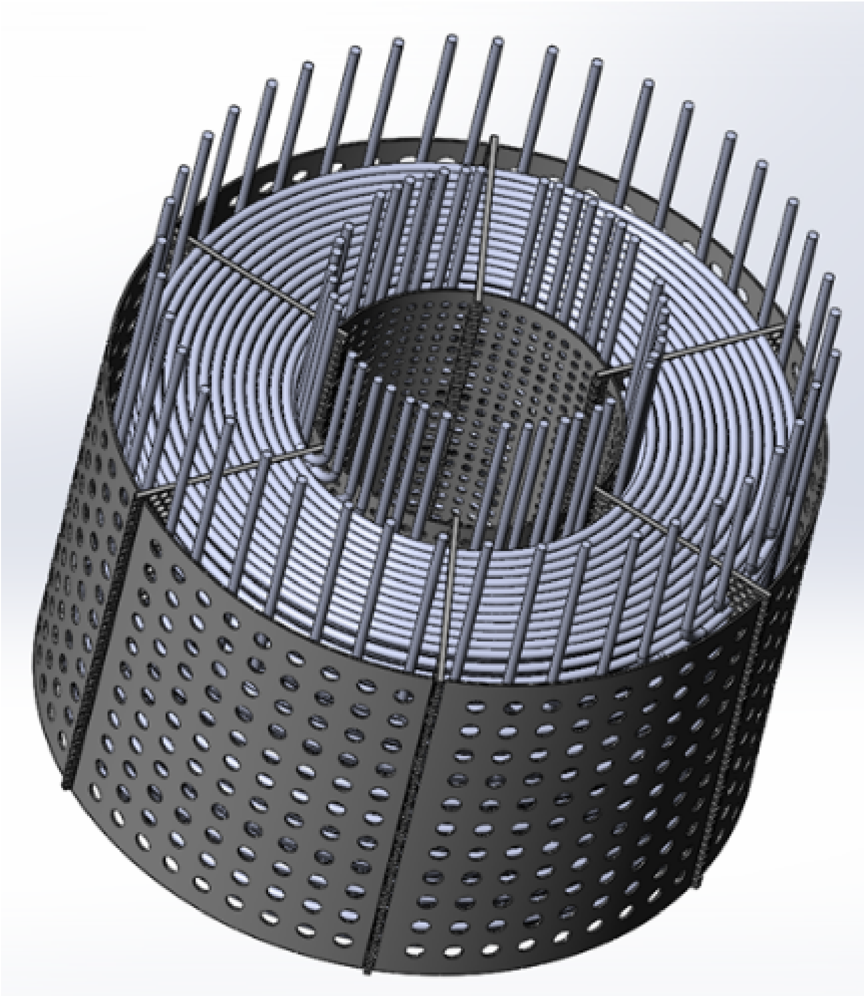


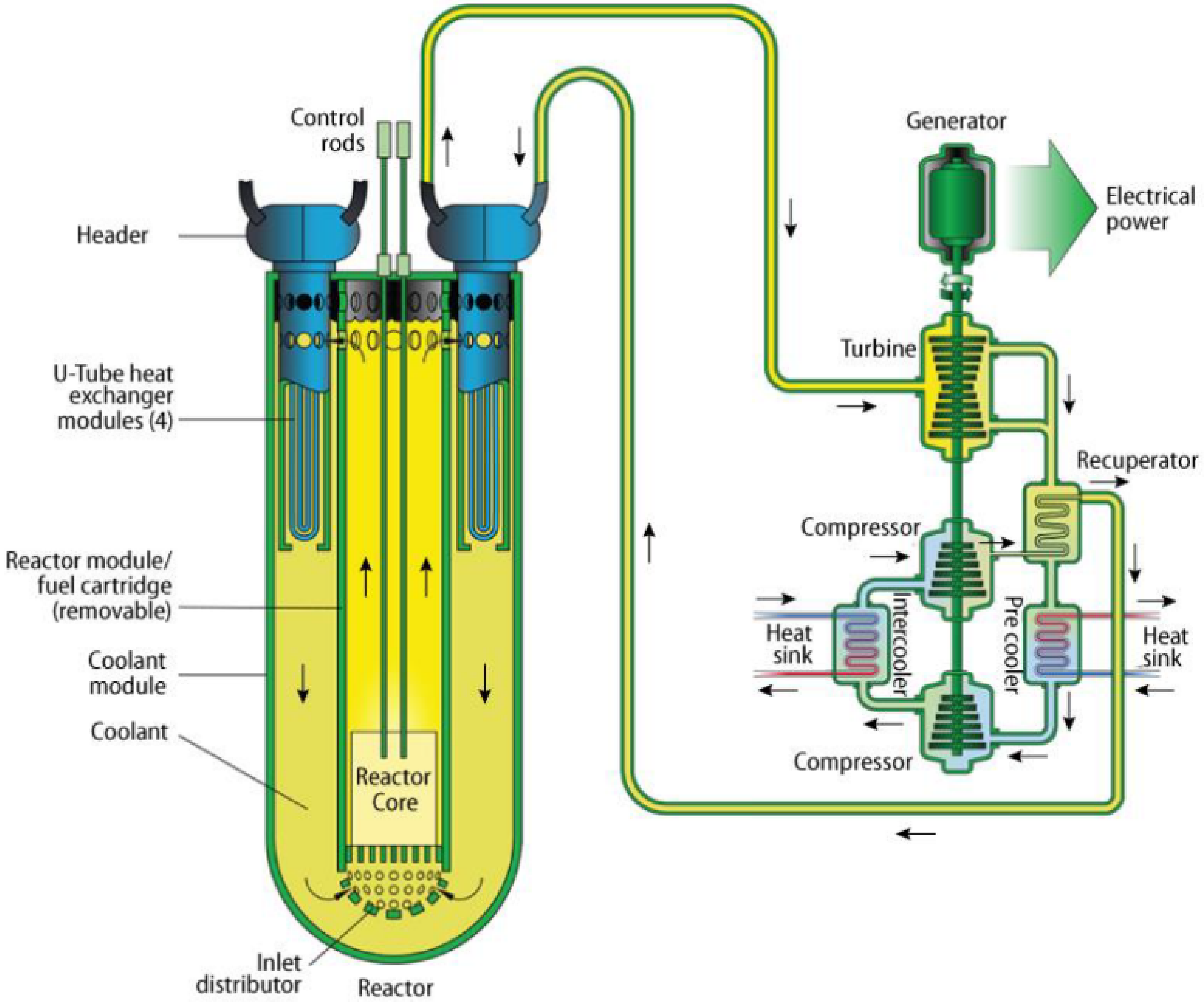
Typical layout of SFR (Super Phenix [France], BN-600/800 [Russia], FFTR [US], Monju [Japan], EFR [China], PRISM [US];TWR [US]

- Na – Na Primary Heat-X loop inside shielding vessel - <2 atm pressure
- Pump on Heat-X cold leg
- Na-Water/Steam on secondary loop
- Pump on Heat-X cold leg
- 360-600^{o}C

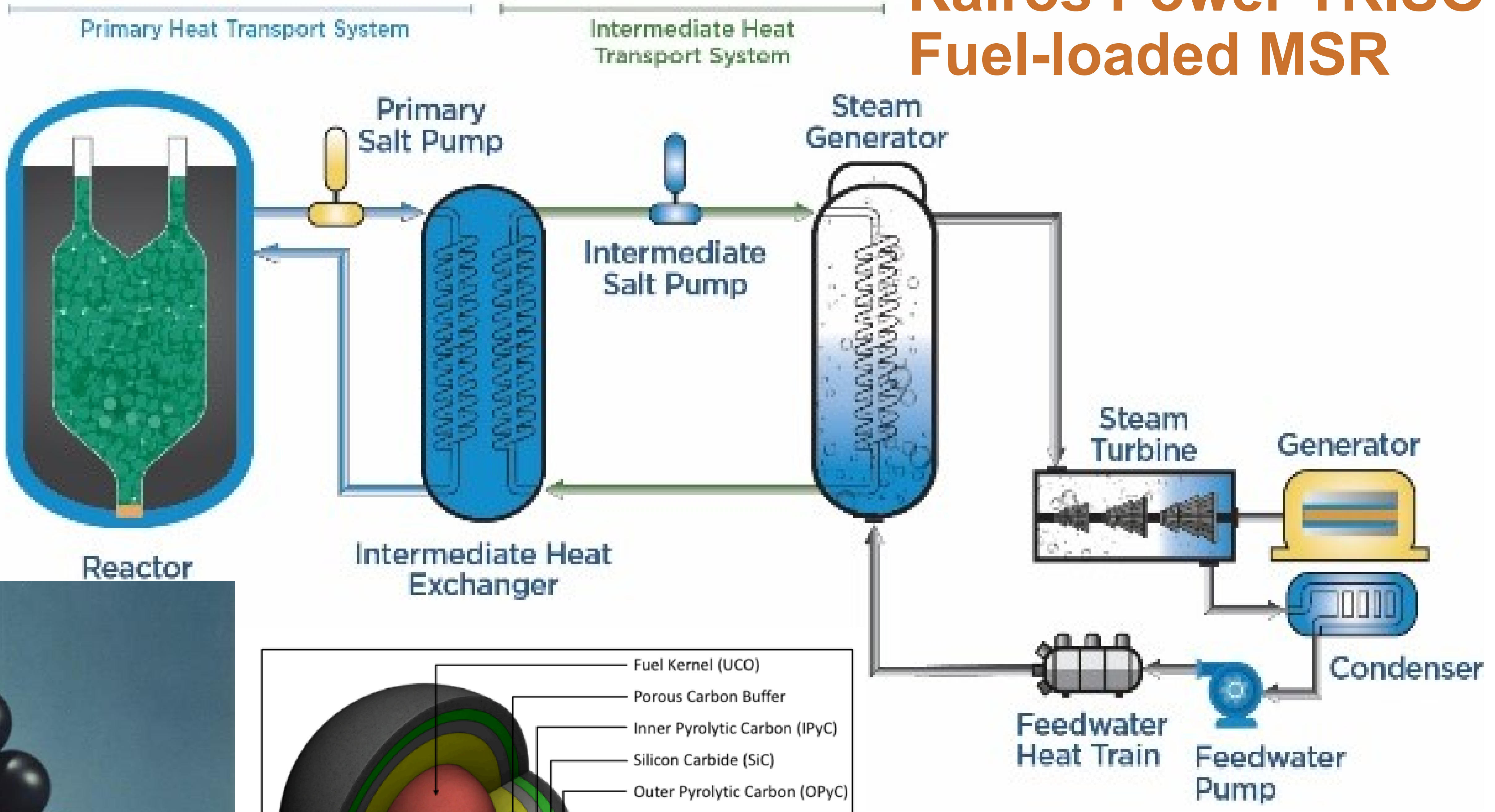


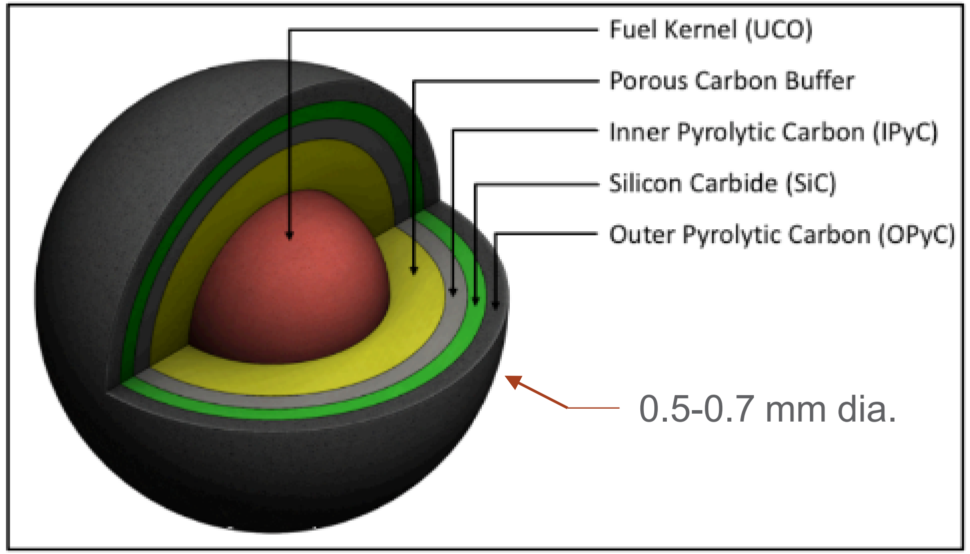
Hydromine Lead Reactor and Single-Stage Spiral Heat-X



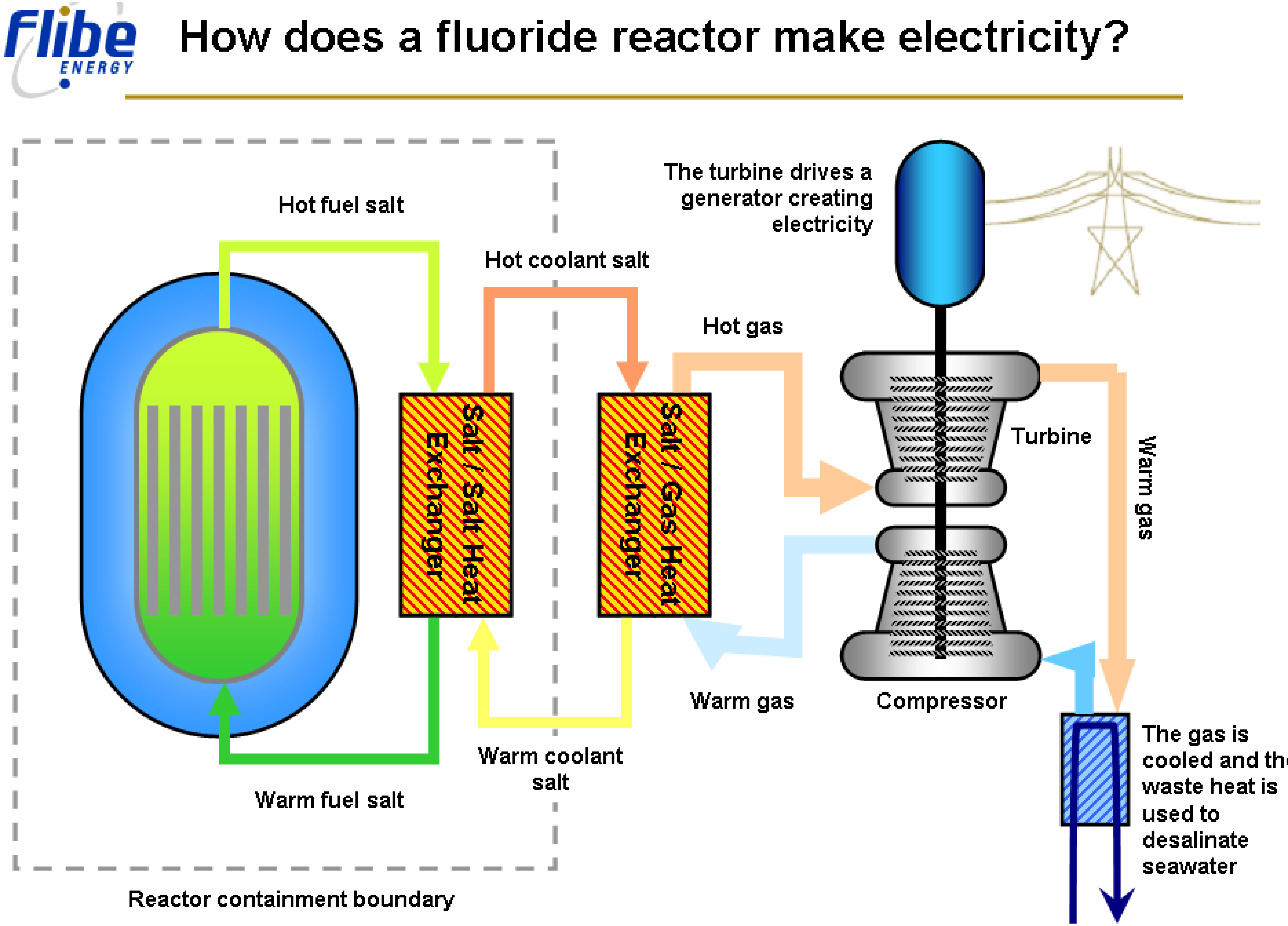


Kairos Power TRISO Fuel-loaded MSR





Flibe Dissolved Fuel MSR with Hot Gas Heat-X and Turbine



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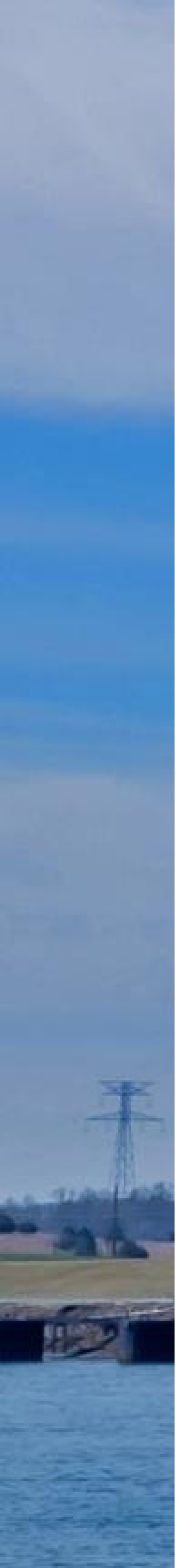
Reactor Operating Parameter Comparison

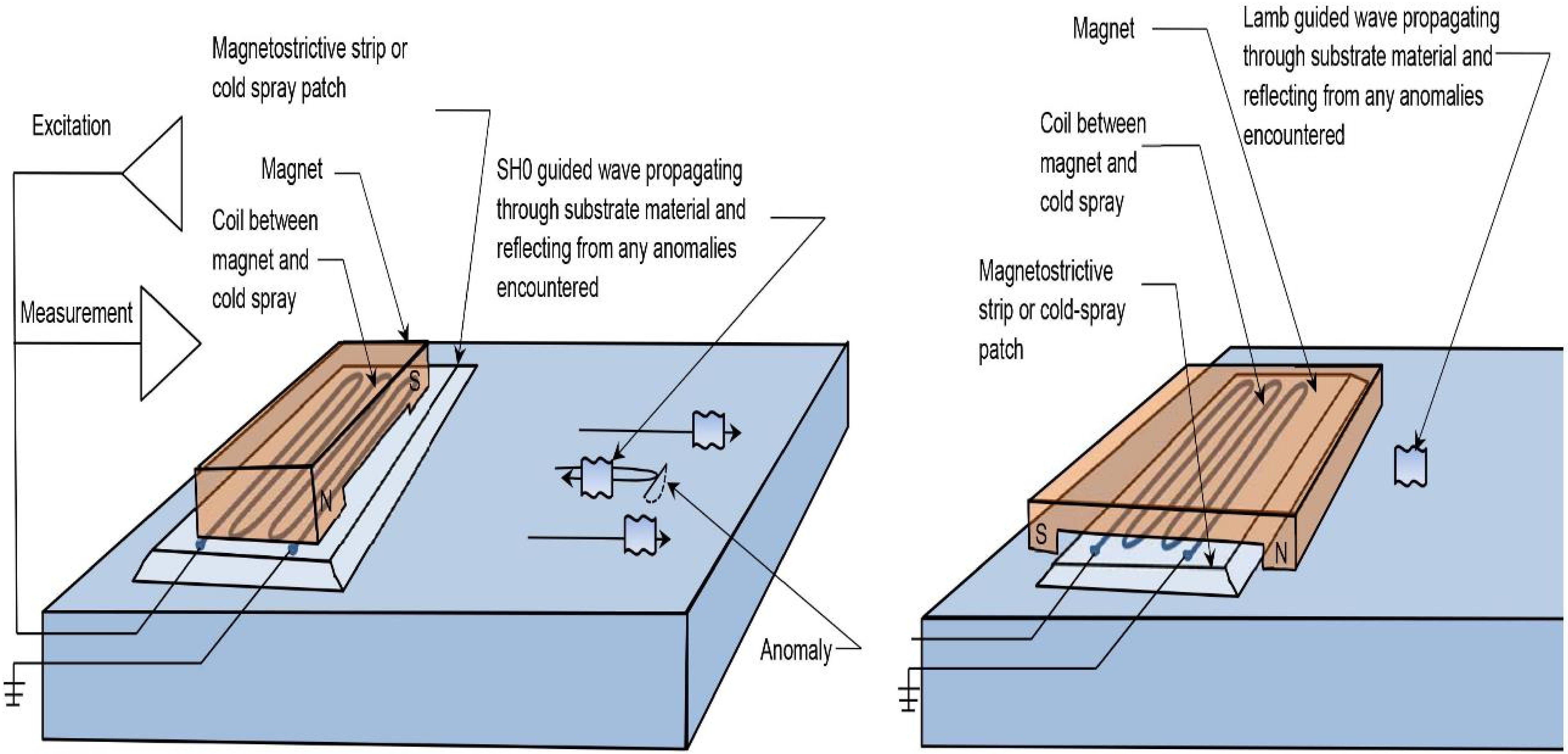
	MSBR – Single Fluid	MSFR	AP1000	S-PRISM	IMSR
Inlet temperature (°C)	566	675	280	363	625–660
Outlet temperature (°C)	705	775	322	510	670–700
Primary coolant flowrate (kg/s)	11,820	18,920	14,300	2,992	5,400
Thermal power (MW)	2,250	3,000	3,400	1,000	400
Core power density (MW/m^3)	22.2	330	110	120	9–14
Reactor pressure (MPa)	~0.1 (cover gas)	~0.1 (cover gas)	15.5 (pressurizer)	~0.1 (cover gas)	~0.1 (cover gas)
Core structure volume (%)	63–87	0	~50	~63	70–95



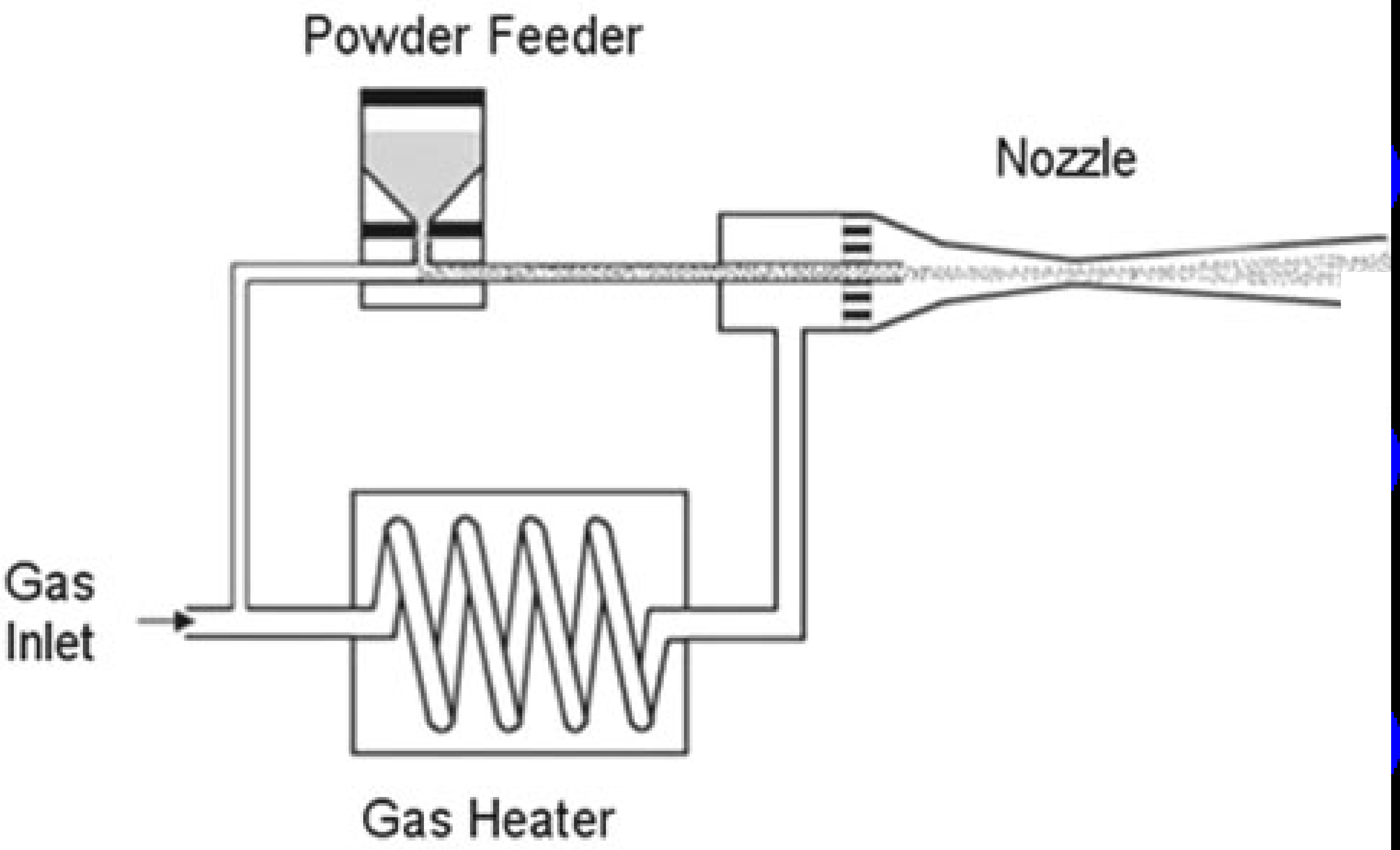
PNNL Initiatives

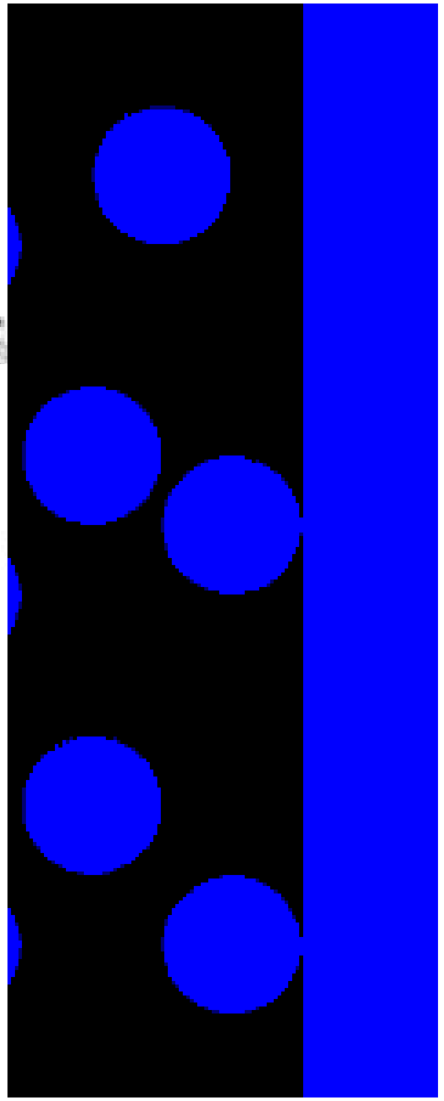
- High-Temperature Cold Spray Magnetostrictive EMAT
  - Guided-wave flaw detection
  - Non-invasive flow meter
- Acoustic Emission
- High-Temperature Piezoelectrics for On-line Heat Exchanger Monitoring
- Multi-Modal Optical Sensors
- Multi-Modal SAW Sensors (NEET)
- Molten Salt Chemistry/Corrosion Science Focus
- Advanced Rx Sensor Website/Database
- ASME Code Involvement

Magnetostrictive Cold Spray Sensor Sends SH-0 Waves Perpendicular to Magnet N-S Axis and Lamb Waves Parallel to Magnet N-S Axis



Conceptual Representation of a Cold Spray System





Typical Field-portable Manual Application System

Image courtesy of VRC Metal Systems

Candidate Materials for MS Sensors

Material	MS Coeff. (3/2) $\lambda s \times 10^{-6}$	Curie Temp.	Notes (mostly related to cold spray)
Nickel (Ni)	–50	354°C	Corrosion-resistant; commonly cold-sprayed
Cobalt (Co)	–93	1120°C	Can be cold-sprayed; may need environmental control
Iron (Fe)	–14	770°C	Can be cold-sprayed; corrosion-susceptible
Ferrous Cobalt (FeCo)	87	500°C	Standard for adhesive strip alloyed 50%/50%
Galfenol	>200	670°C	No cold-spray history
Met-Glass	60	370°C	No cold-spray history but similar to ceramics that have been sprayed

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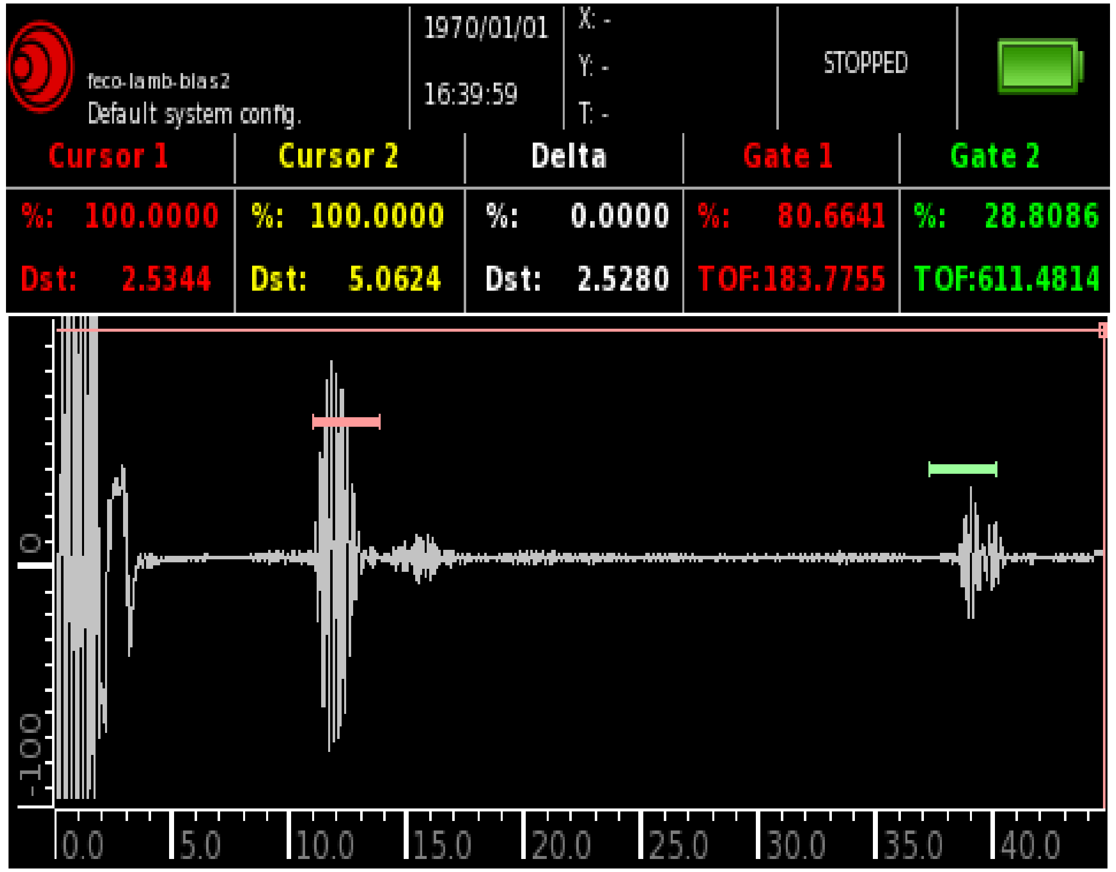
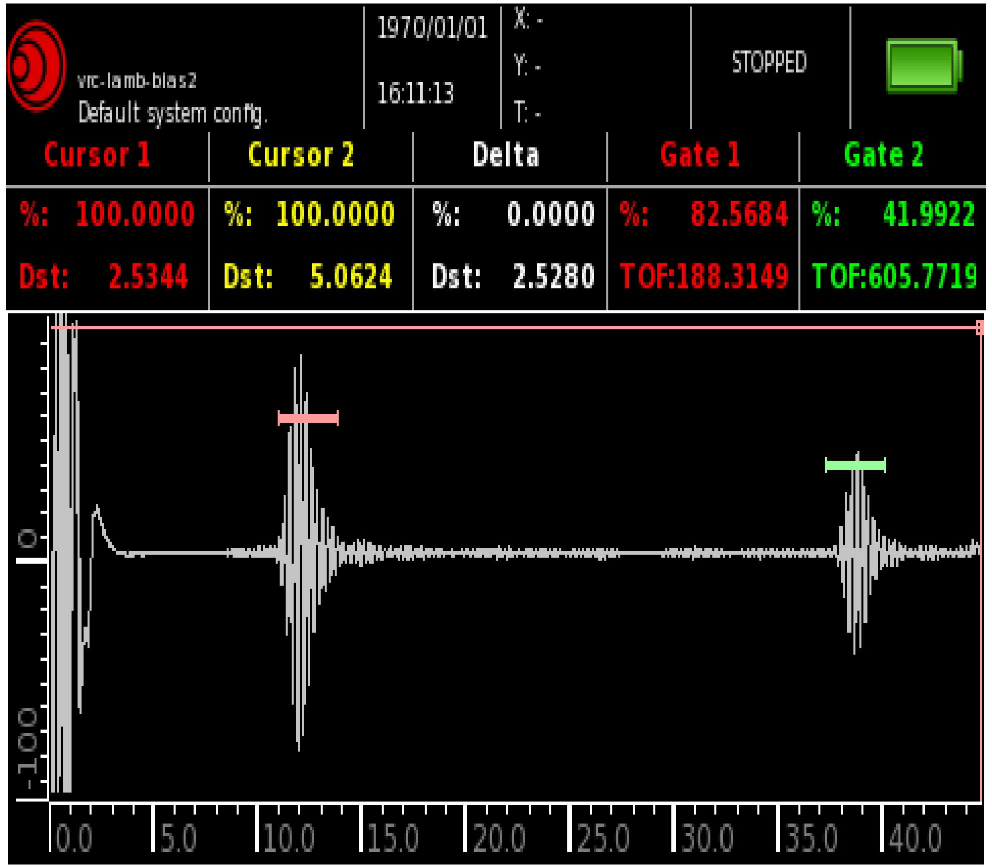
Round 2 Lamb Wave Response on ¼" SS Plate; FeCo Strip Compared to CPNi Patch CPNi

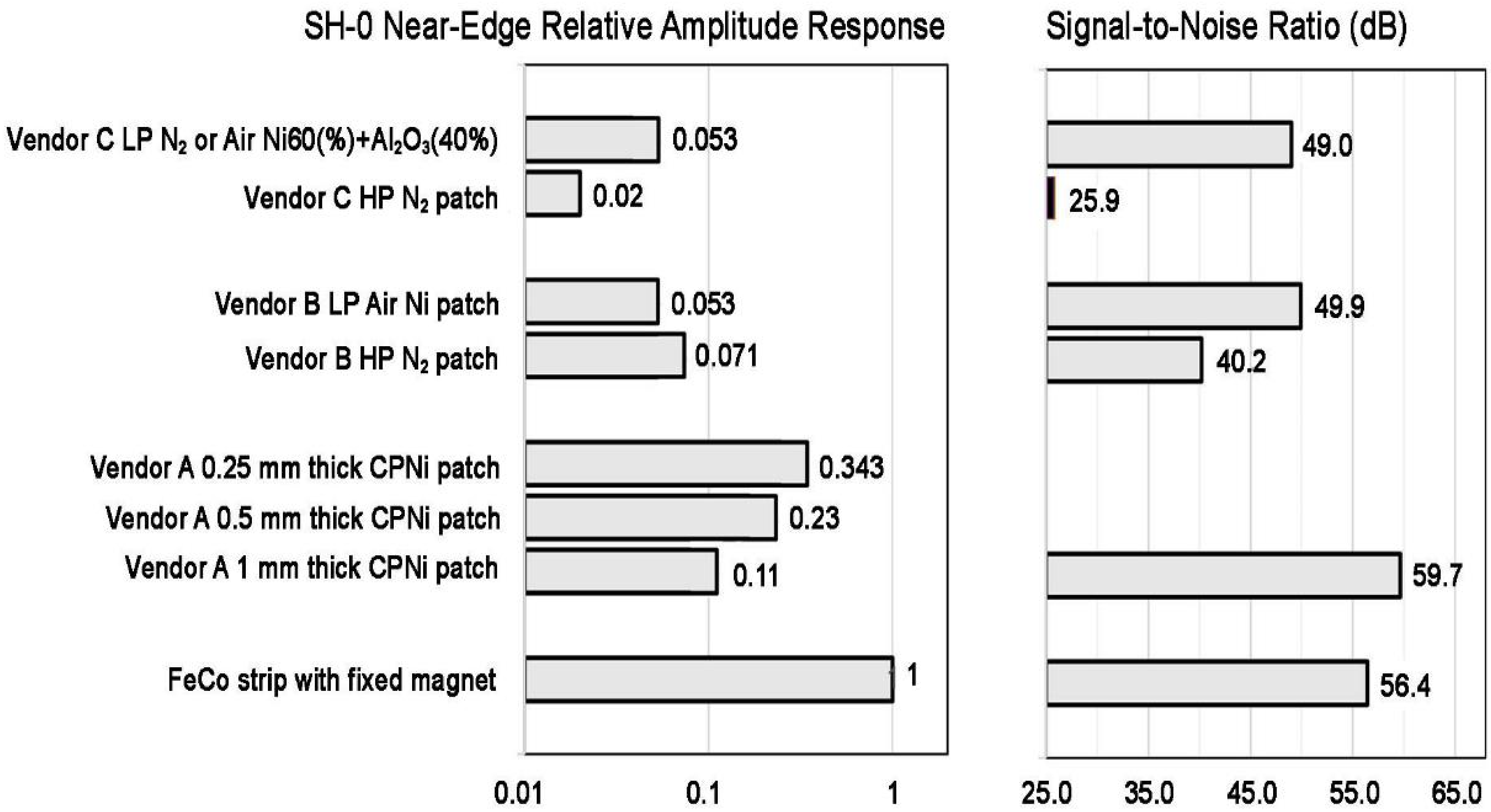


¼ in. S.S. plate with coil over FeCo strip and stationary permanent magnet

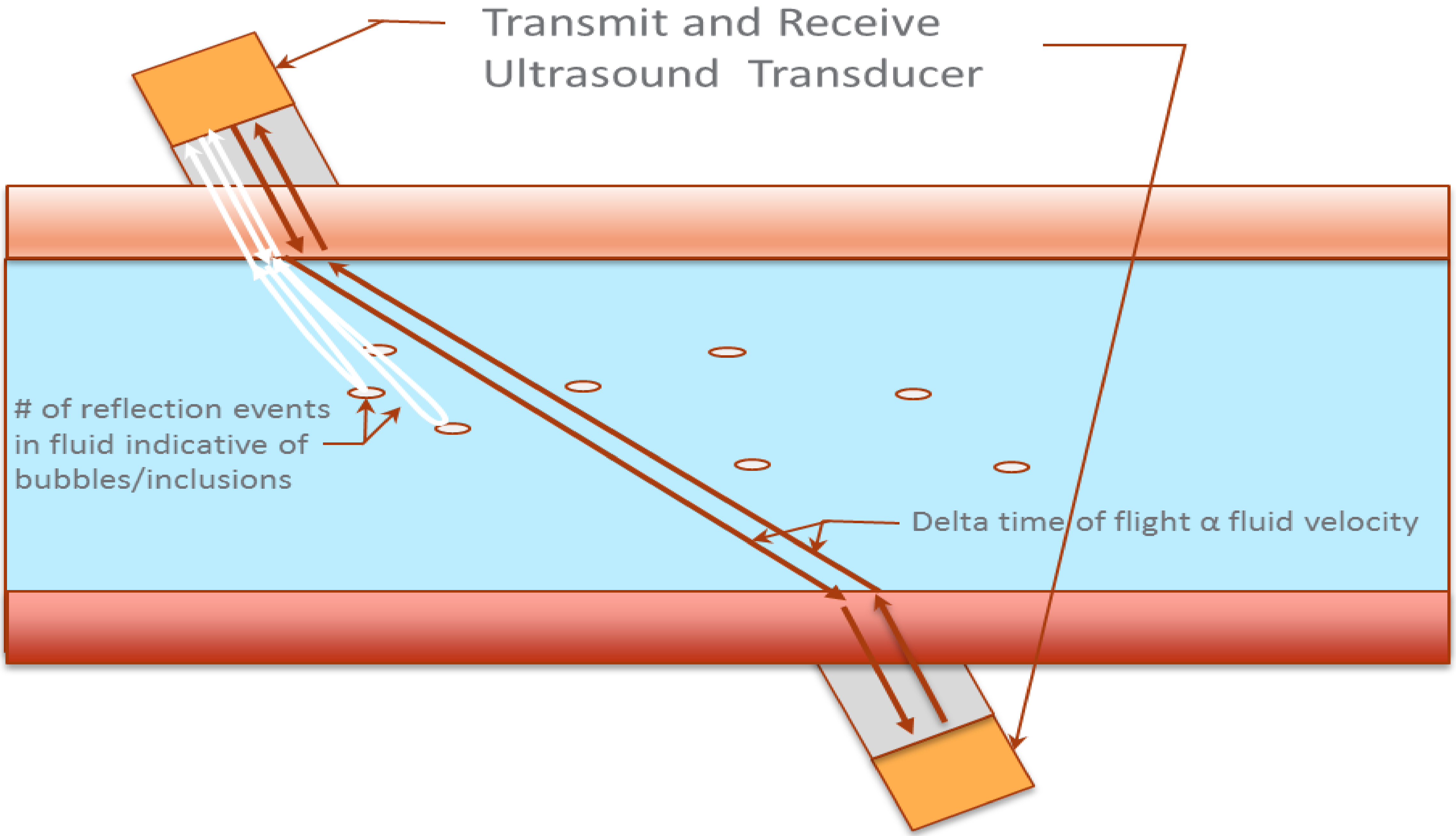


¼ in. S.S. plate; 0.5 mm CPNi patch and stationary permanent magnet

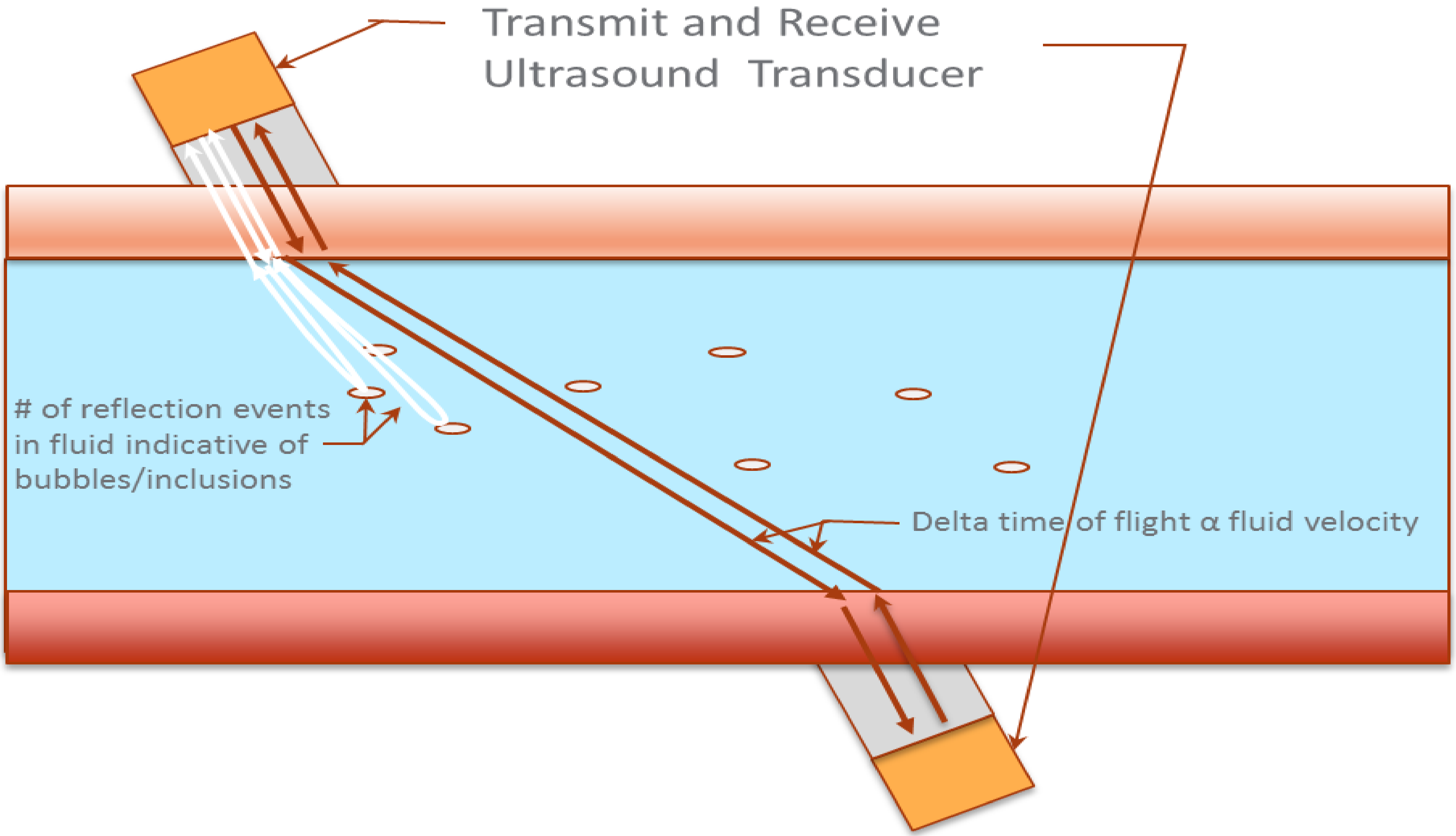
SH-0 Response to Various Cold-Spray Patch Configurations Relative to FeCo Strip



The MS Sensor in the Lamb Wave Mode Could Be Extended to Measure Flow, Inclusions, and Temperature



Alternatively Piezoelectric Sensors Can Be Evaluated for Flow, Temperature, and Reflections of Inclusions



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Acknowledgments

- Magnetostrictive EMAT is an established way to perform guided-wave inspections.
- BUT the current state of the art uses adhesives or pressure coupling that are difficult for many advanced reactor configurations.
- Magnetostrictive Ni tests indicate that the cold-spray patch sensors can be used for SH-0 and/or Lamb-wave inspections. Other materials may work even better.
- Thanks to a TCF award and a follow-up DOE SBIR, this technology has been licensed and is being exploited commercially.

Department of Energy's Technology Commercialization Fund.

Innerspec High-performance NDT solutions

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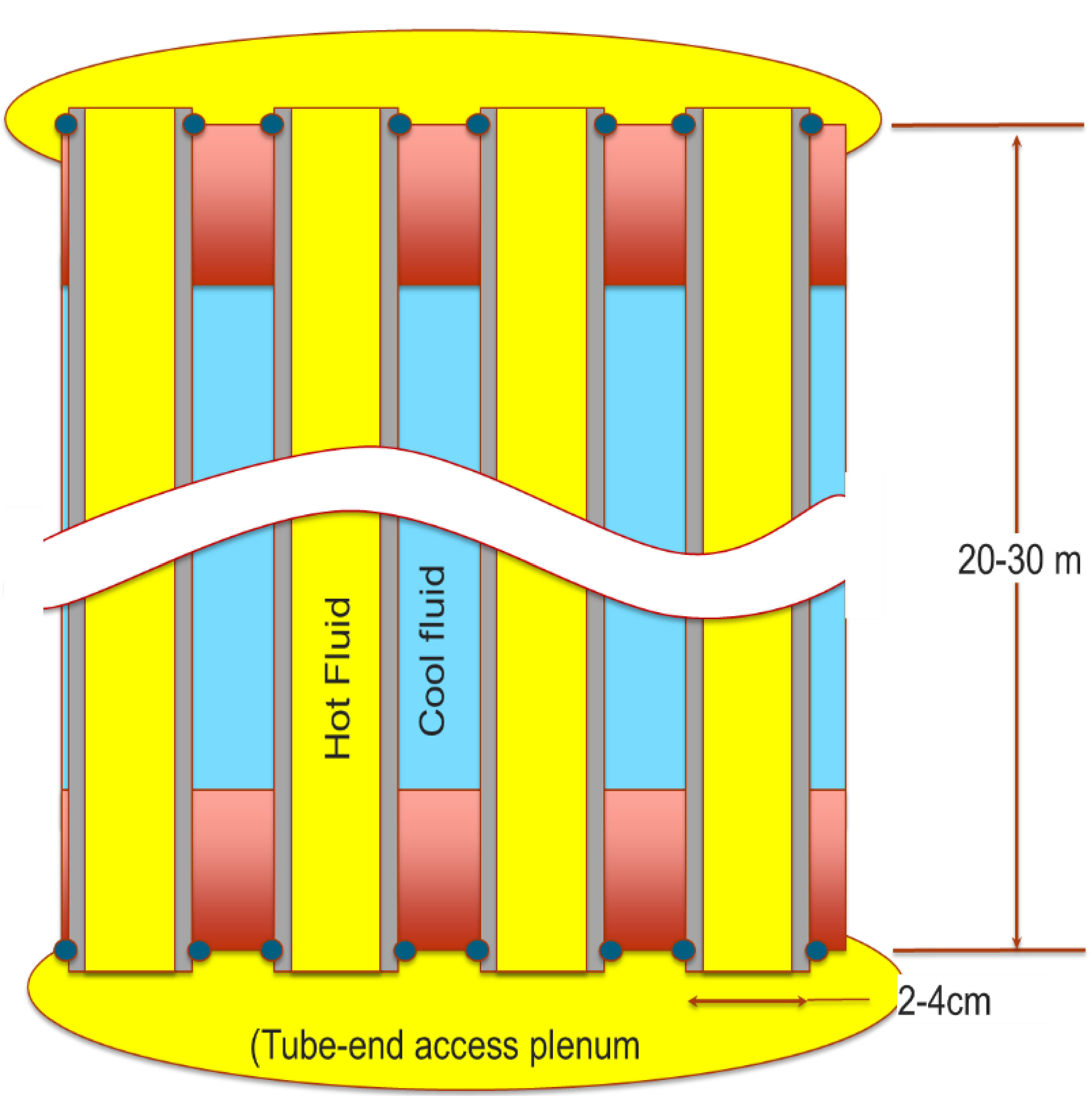
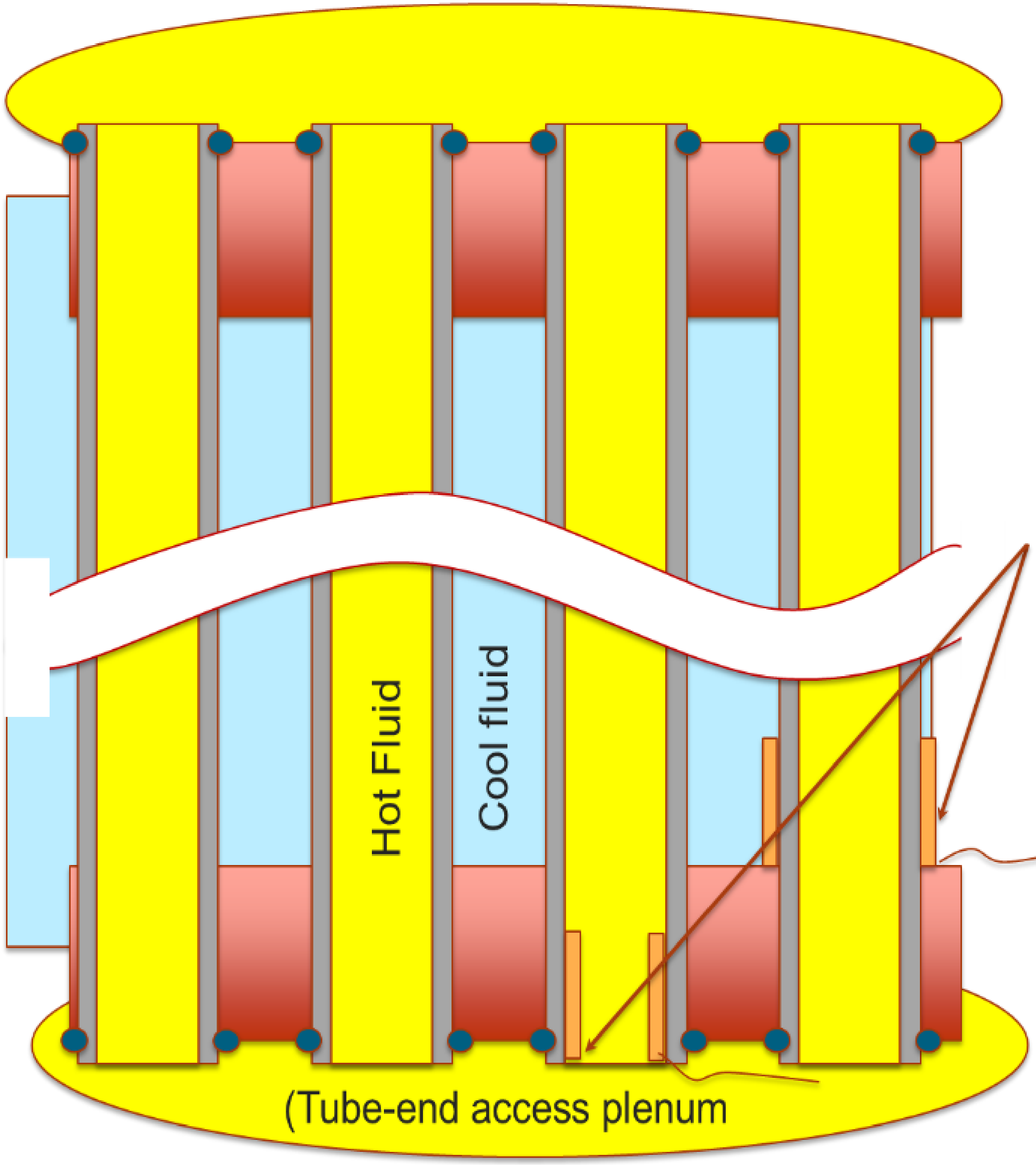
Typical power plant tube bundle shell-and-tube heat exchanger configuration



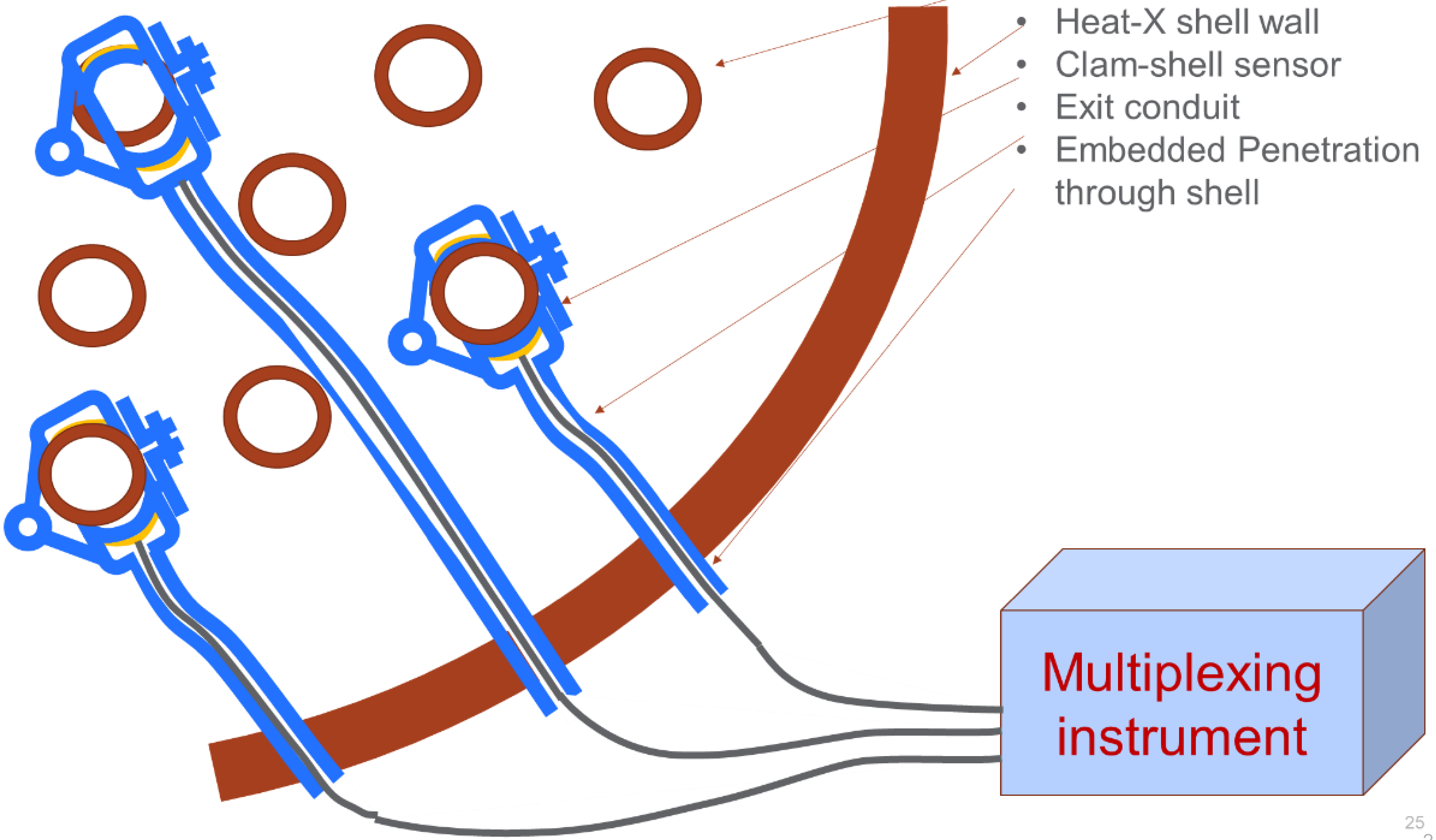
Primary ID sensors would be subject to high flow forces. Secondary OD sensors are protected from high flow forces and also are held at lower temperatures than the primary tube ID fluid.



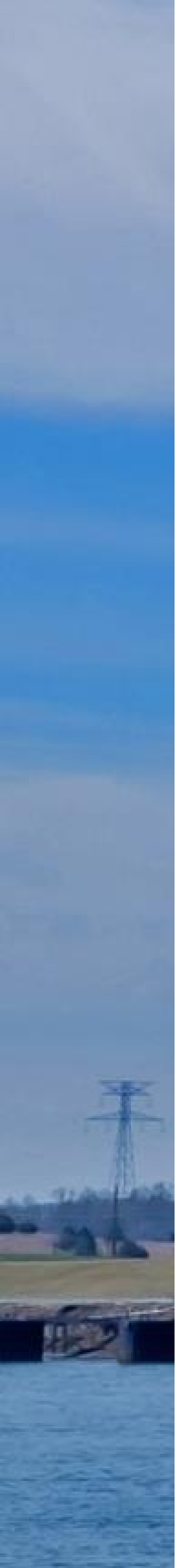
GW Transducer (Piezo or EMAT) – must withstand environment and wire must be brought to instrument. Likely only practical on bundle periphery and probably only practical on secondary (OD) side (right) – not with primary (ID) side (left)

System In-Situ

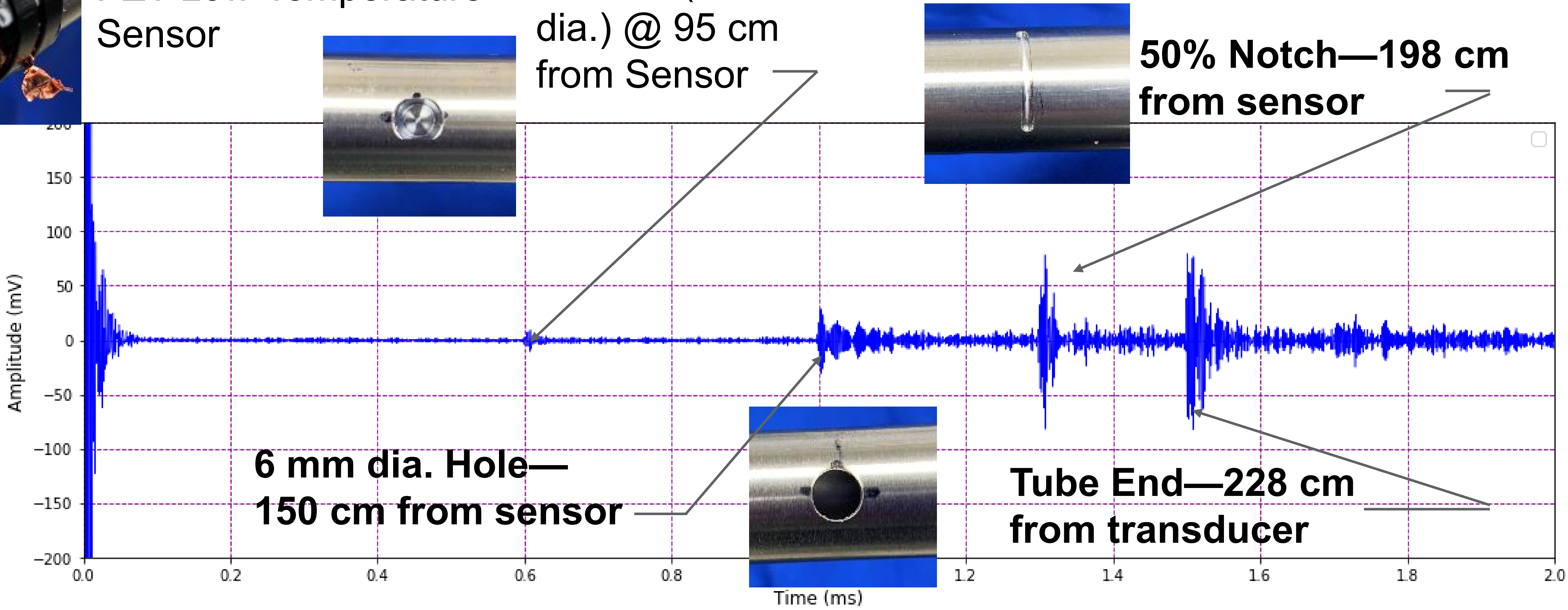
- Heat-X tubes
- Heat-X shell wall
- Clam-shell sensor
- Exit conduit
- Embedded Penetration through shell



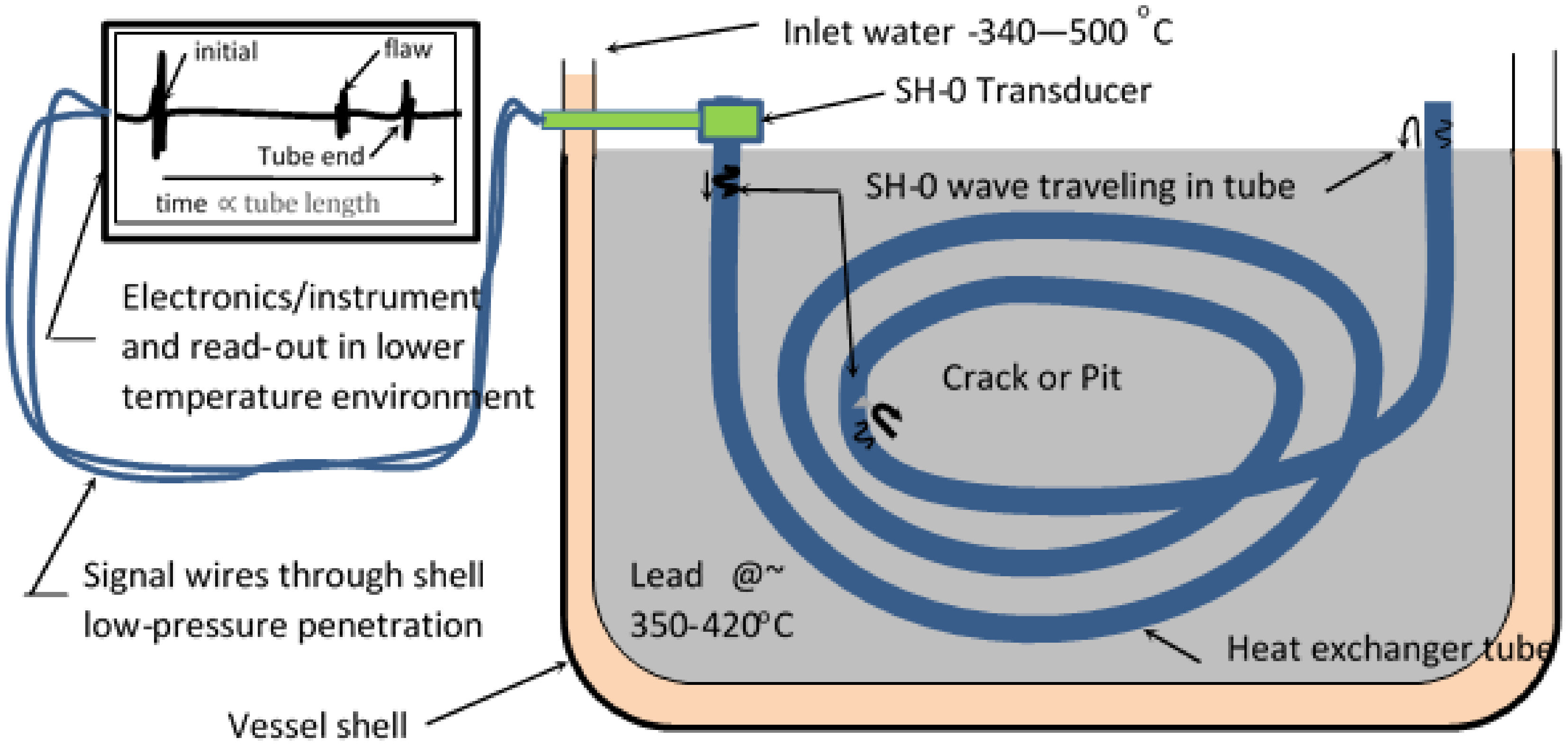
Progress Toward Feasibility Assessment of On-line Heat Exchanger Tube Monitor

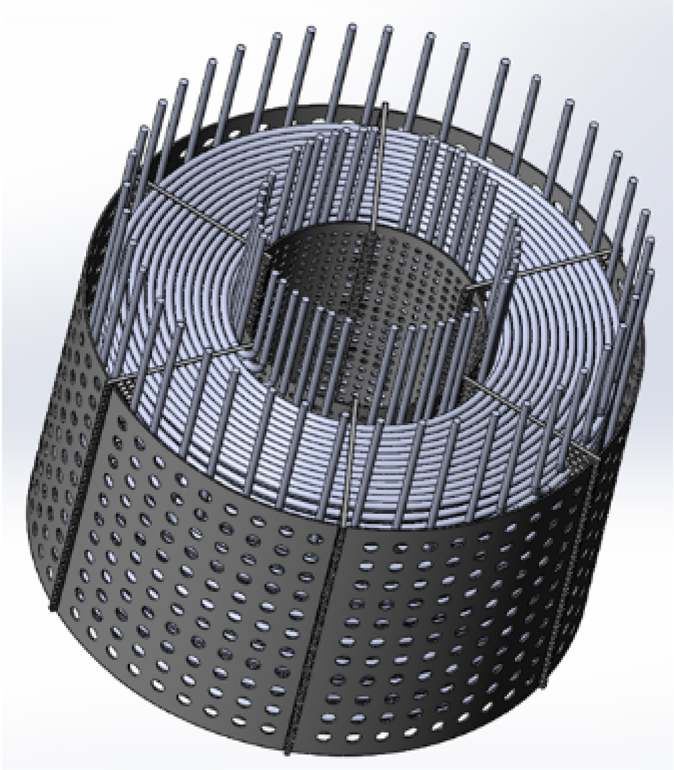


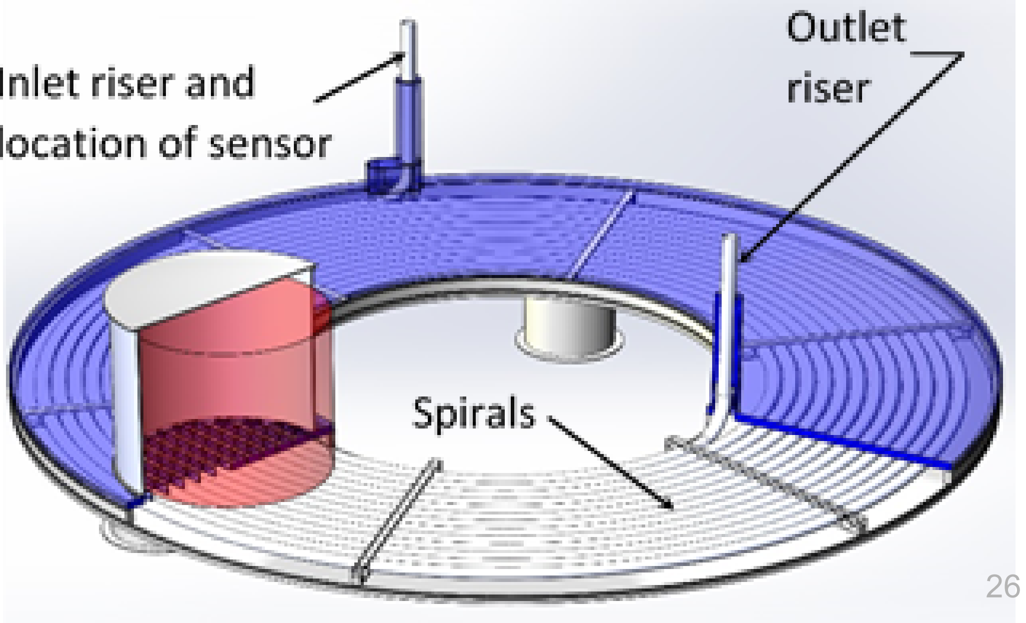
Torsional SH-0 Wave PZT Low-Temperature Sensor



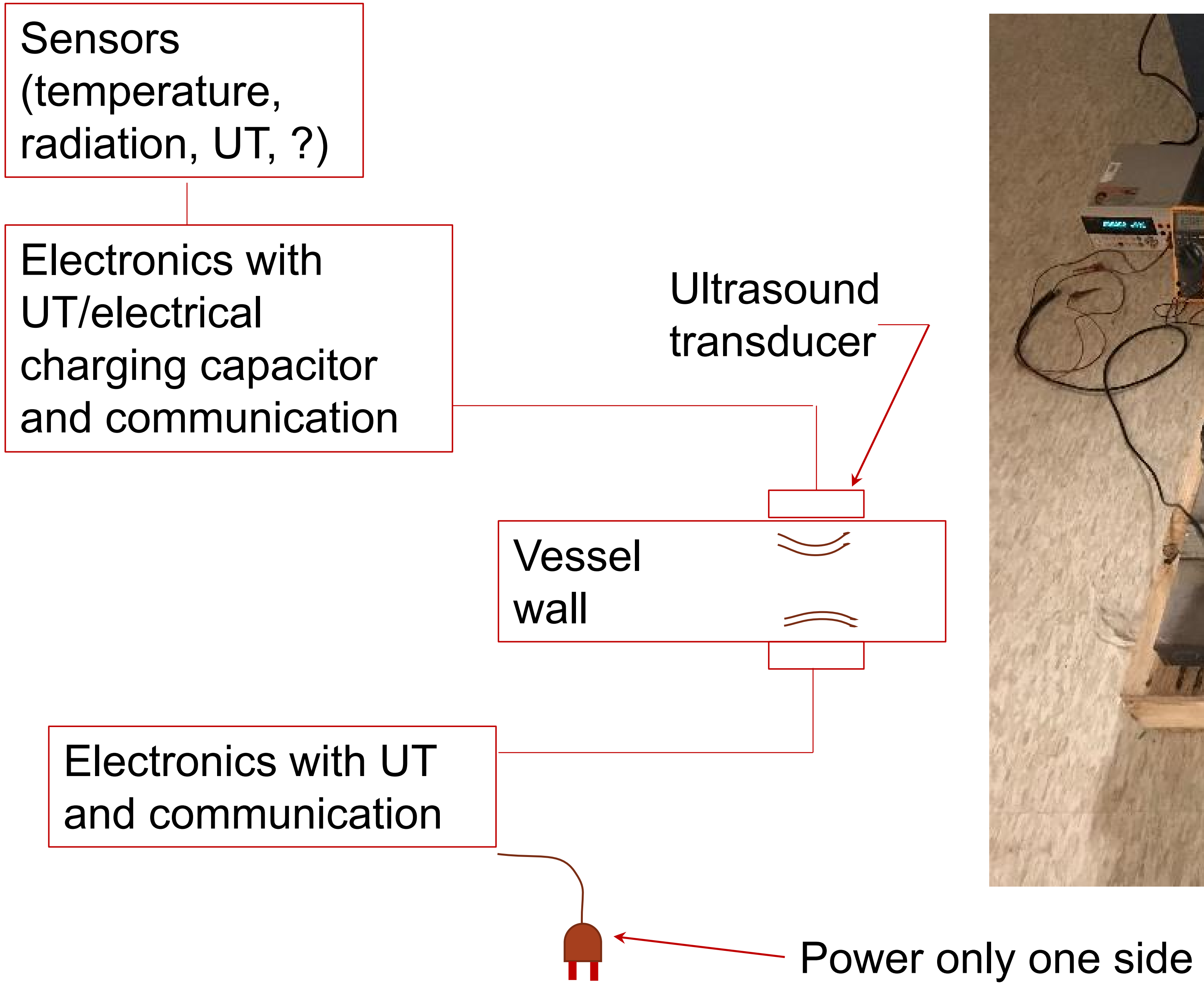
Initial Target for On-line Heat-X Monitoring in Molten Lead Reactor





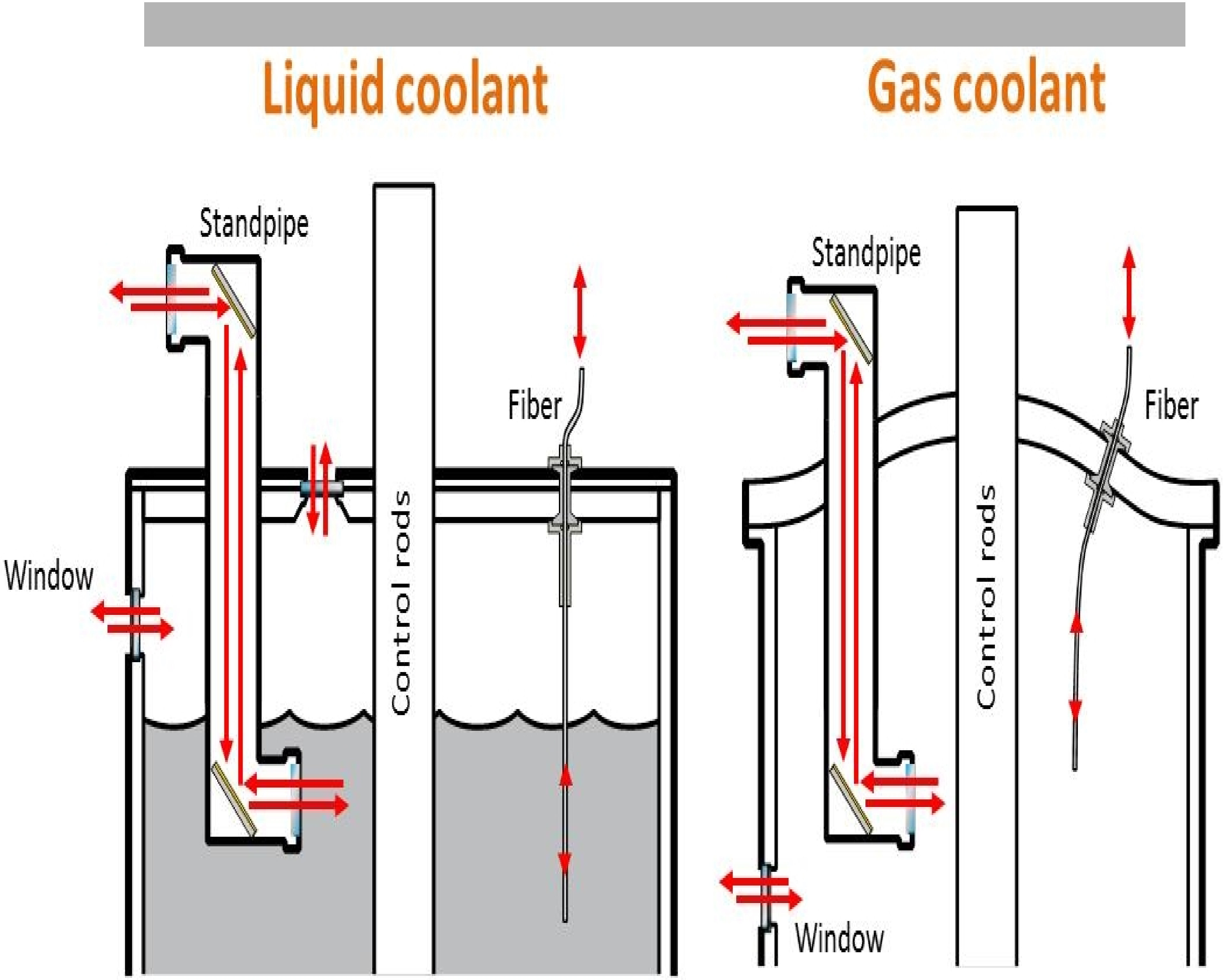


Ultrasonic Power & Communication – Virtual Penetrations

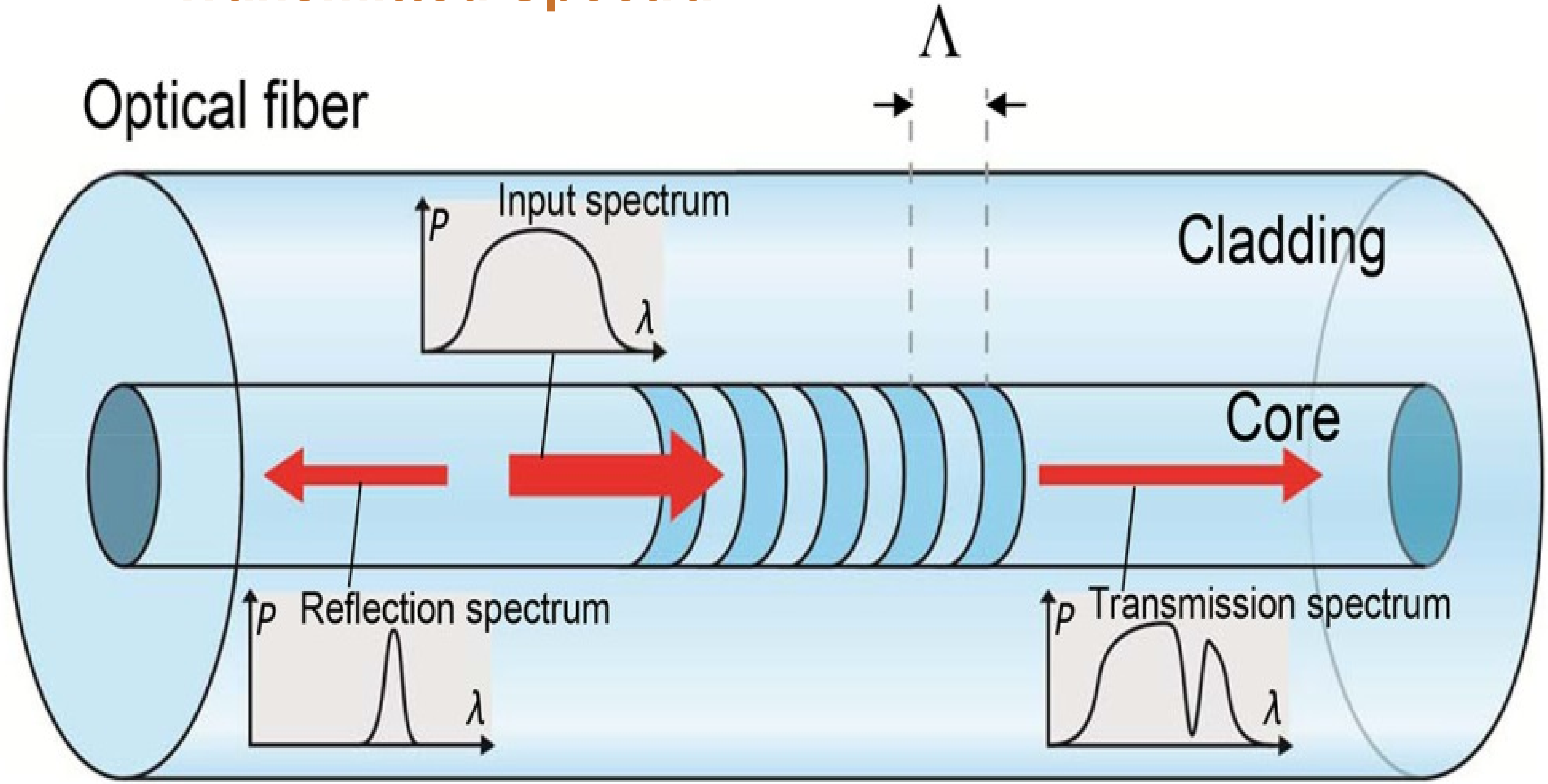


Upper Regions of a Liquid-Cooled (left) and Gas-Cooled (right) Reactor, Showing Optical Access Concepts.

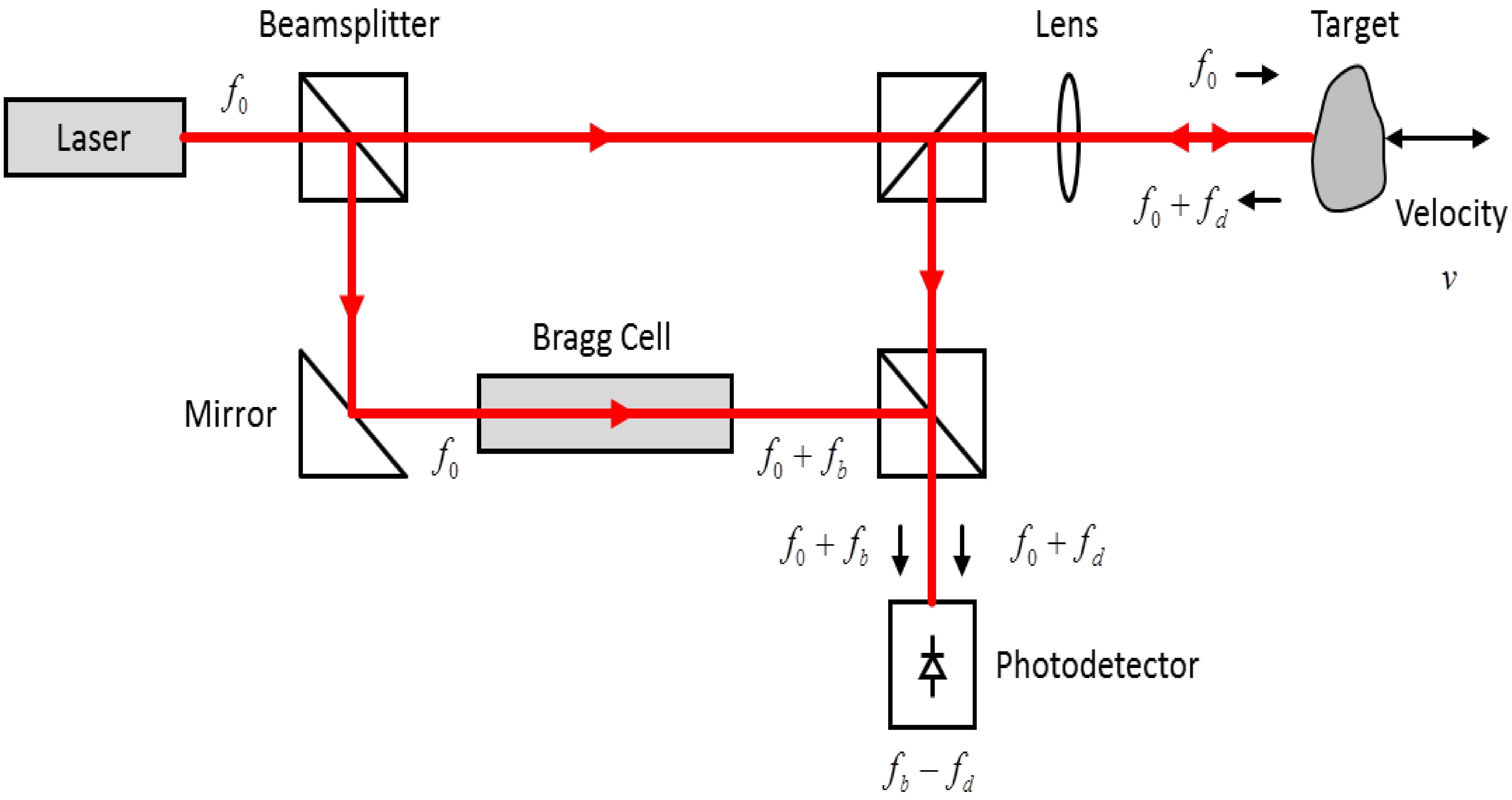
- Optical access through the containment vessel also may be required.

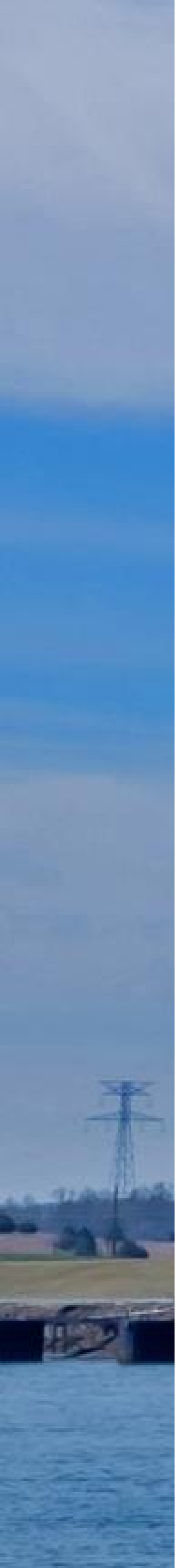


Basic Optical Fiber Sensor, Showing How the Incident Light is Separated into Reflected and Transmitted Spectra



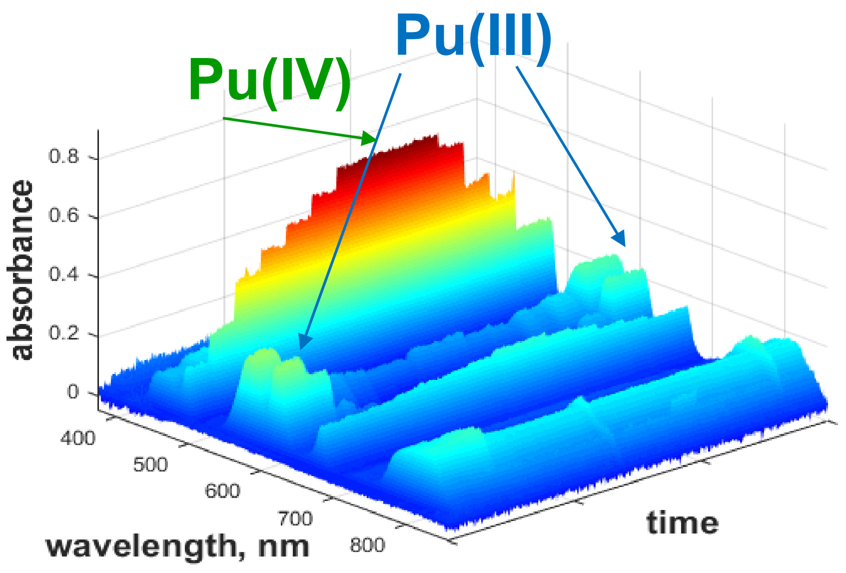
Heterodyne Laser Vibrometer

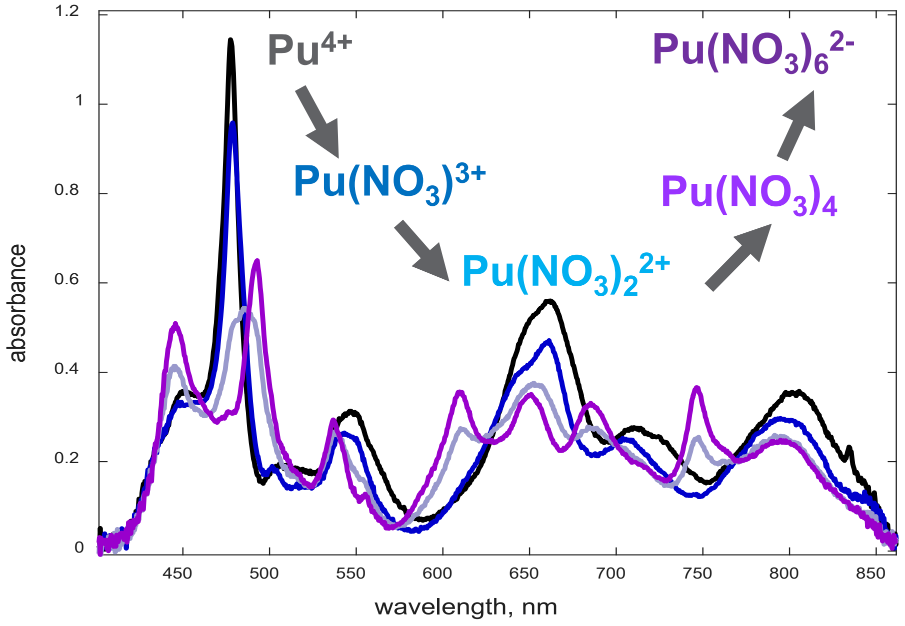




Chemical Characterization: Optical Spectroscopy

- Provides chemical information
  - Identification and quantification
  - Oxidation state
    - ✓ Essential information for control of systems
  - Molecular and elemental species
    - ✓ Essential information to understand/control separation efficiency or general system behavior
- Fast
- Robust
- Versatile





U(III)

U(IV)

U(VI)

Pu(III)

Pu(IV)

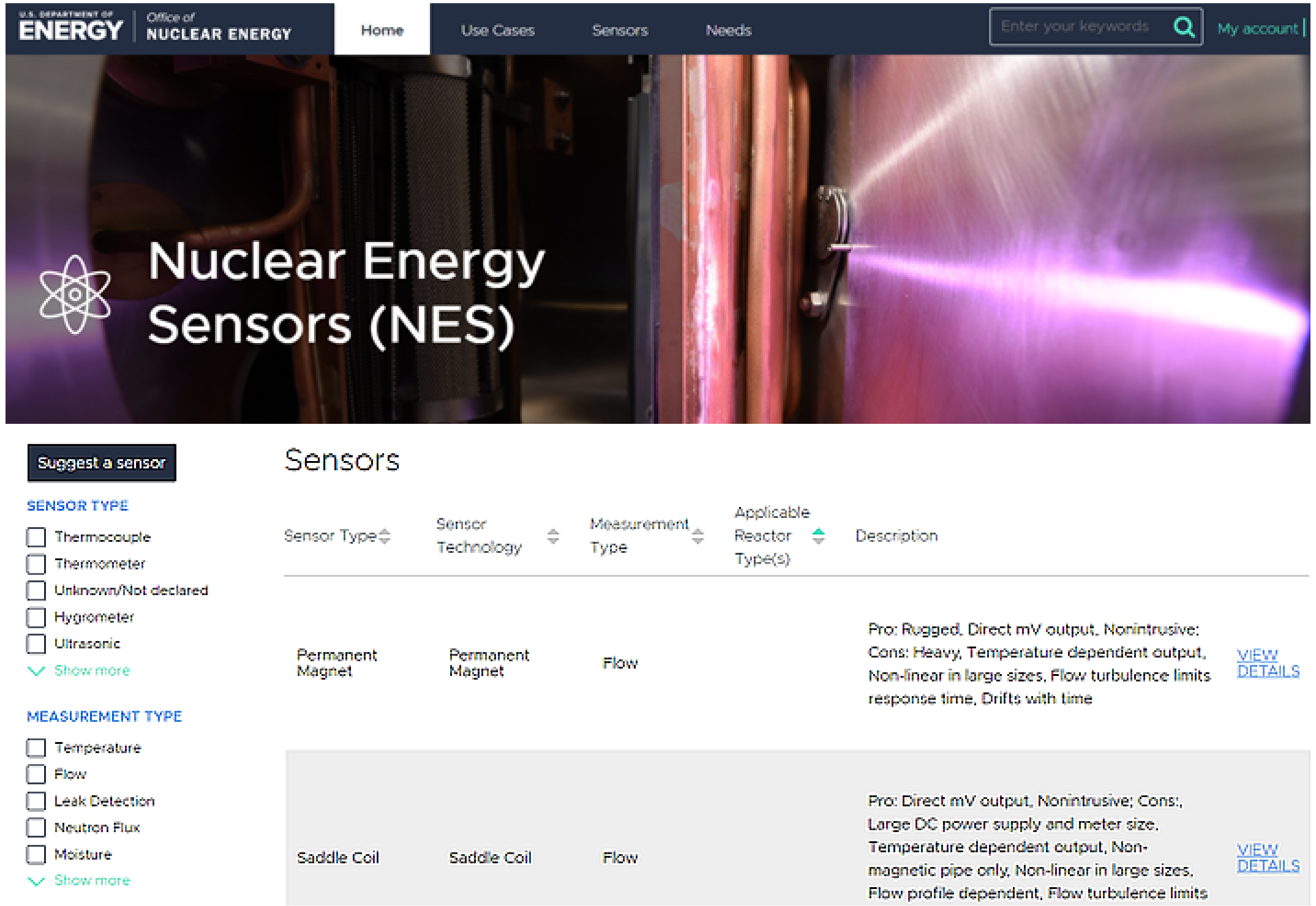
Np

Cr

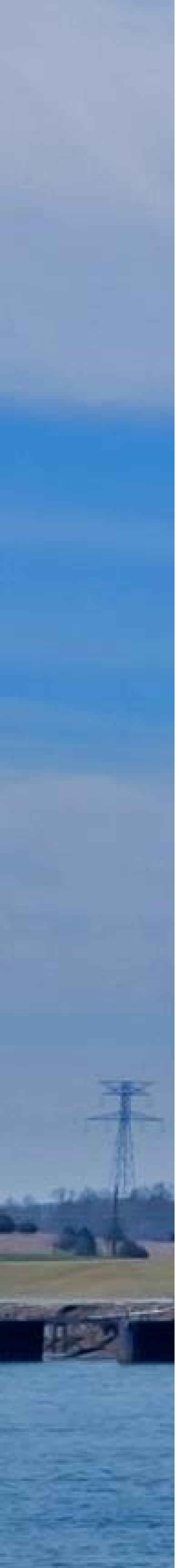
Lns

Nuclear Energy Sensor Database

- Purpose: Collect, store, and maintain nuclear power plant sensor technology information for nuclear energy applications. Provide the nuclear industry with the ability to browse and search sensor data.
- Initial Content: ORNL/TM-2016 “Assessment of Sensor Technologies for Advanced Reactors.”
  - Nuclear energy sensors
  - Sensor use cases
  - Sensor needs and gaps



Status: The website is currently going through a soft launch and looking for subject matter experts interested in providing or reviewing content.



ASME CODE Section XI Division 2 - Requirements for Reliability and Integrity Management (RIM)

- Published July 1, 2019, after 15 years of development
- Addresses the entire life cycle (design through decommissioning) of all types of NPPs
- Sets Reliability Targets for each passive structure, system & component (SSC)
- Because advanced NPP designs do not exist and there is no operational experience, RIM details a process to achieve Reliability Targets
- RIM utilizes expert panels to guide the RIM program development
- PNNL has supported the development of RIM and will continue as the code evolves considering both regulatory and industrial parties

Conclusions

- Advanced reactor technology promises lower cost, safe, and sustainable energy.
- BUT there are serious technology gaps that must be bridged before we can realize this goal.
- PNNL and DOE have several initiatives to help bridge these gaps. I have mentioned:
  - High-temperature ultrasound sensors for structural integrity, flow, and temperature
  - Magnetostrictive cold spray as a high-temperature sensor
  - On-line heat exchanger tube monitoring
  - Acoustic power and modem for virtual penetrations
  - Fiber and optical guides for motion, temperature, and material identification
  - An advanced reactor sensor website and database
  - ASME code evolutions to guide the industry as new technology emerges

Thank you