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Opportunities for Optical Fiber-Based Sensors in Emergent Small Modular Reactors

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U.S. DEPARTMENT OF
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SMR motivations and needs

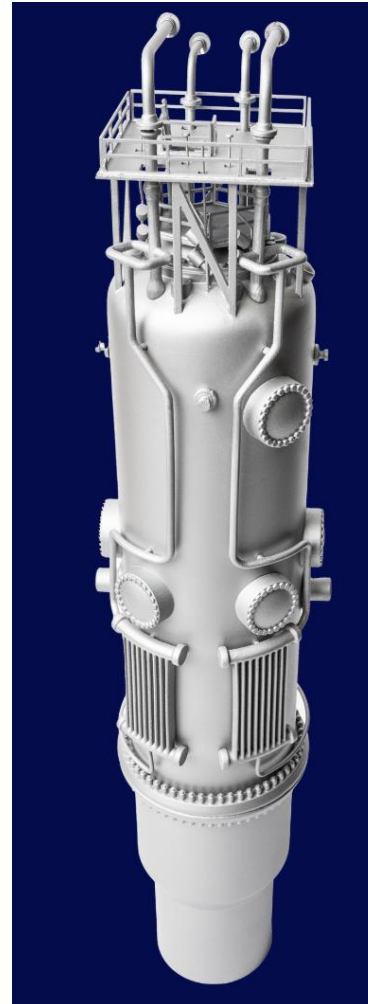
- Motivations

- Lower up-front financial risk
- Factory standardization and scalability
- Inherent passive safety
- Smaller geographic footprint
- High-temperature heat generation for industrial purposes (Gen IV only)

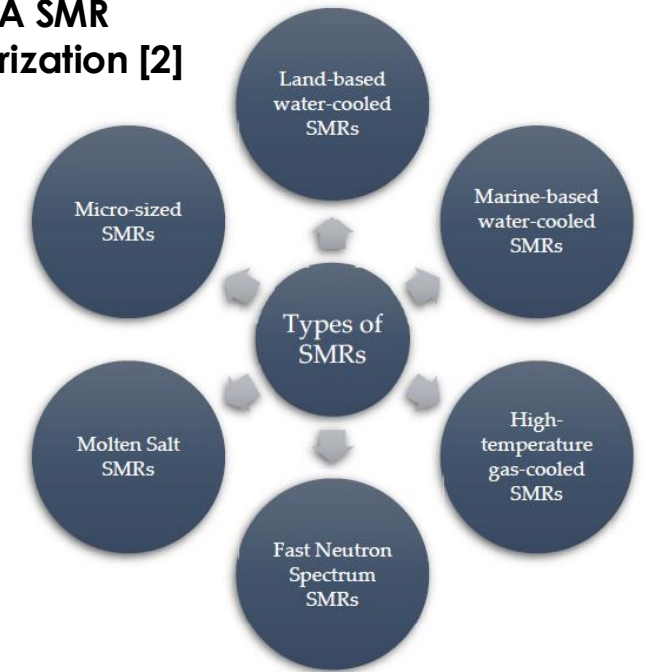
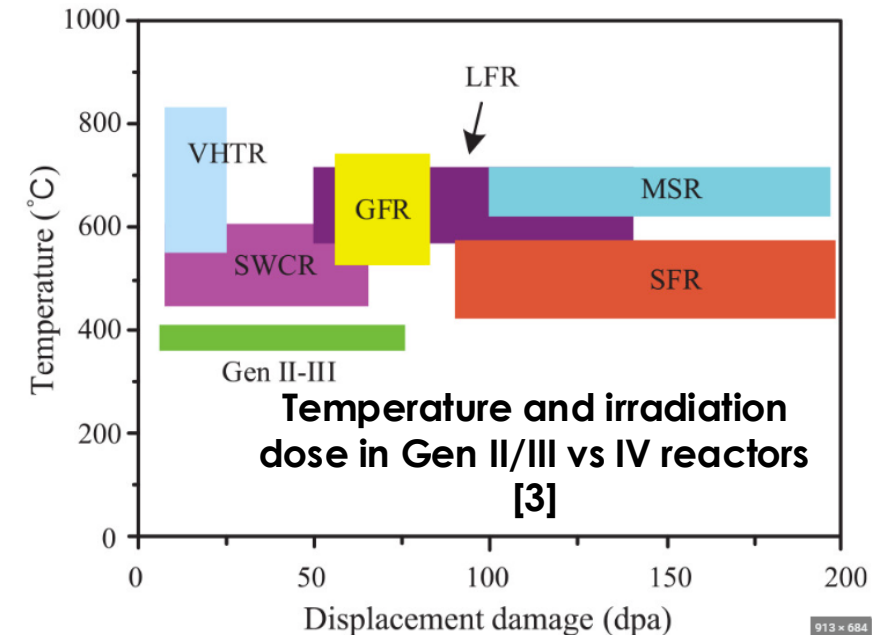
- Needs

- Instrumentation that can support compact layouts
- Autonomous operation and reduced staffing, increased cyber protections
- High-temperature material resilience (Gen IV only)
- Regulatory modernization
- HALEU supply chain (not all designs)

NuScale Power
Module (77MW) [1]



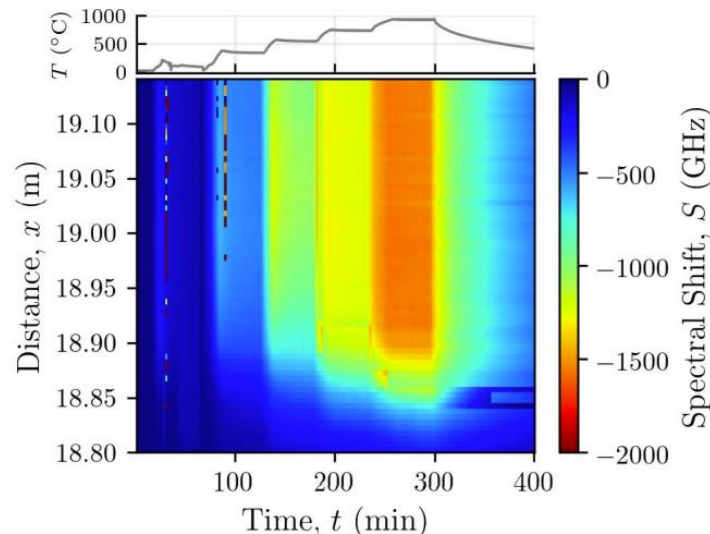
IAEA SMR
categorization [2]



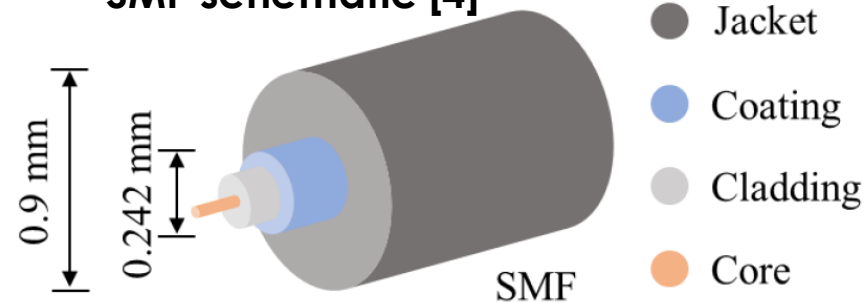
Why optical fibers for SMR sensors?

- Extremely Small
- Capable of distributed sensing
- Can survive temperatures relevant for Gen IV reactors
- Immunity to EM fields
- Demonstrated for measuring several different parameters
- Good resilience to ionizing radiation
- Can be bonded to metallic components for SHM

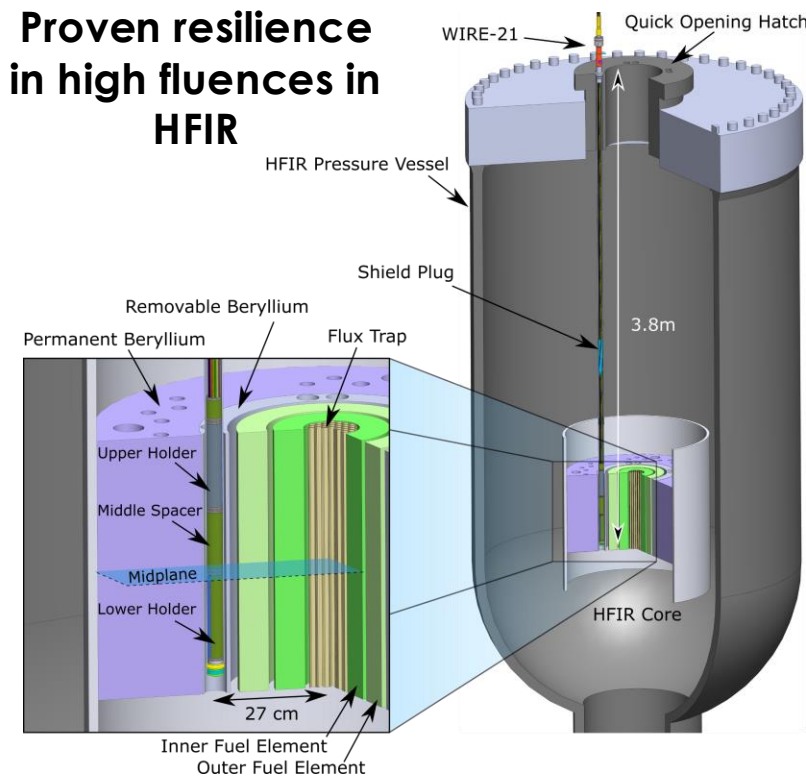
Distributed sensing in extreme temperatures [5]



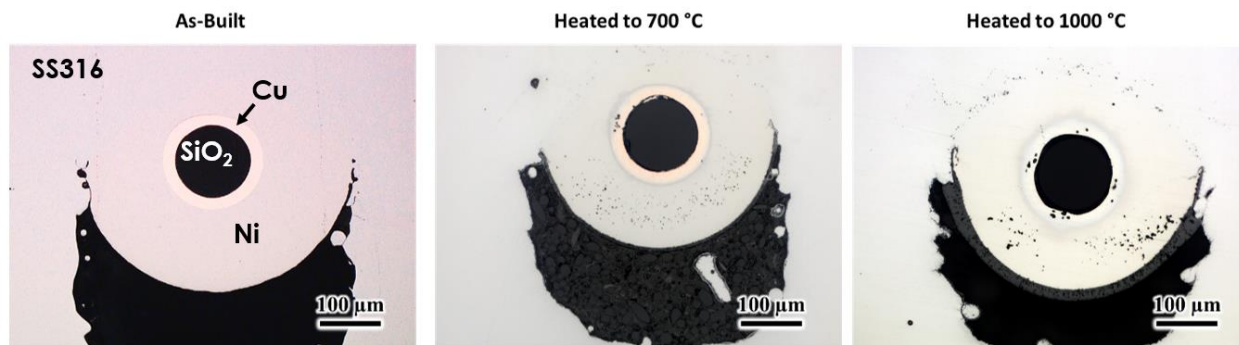
SMF schematic [4]



Proven resilience in high fluences in HFIR

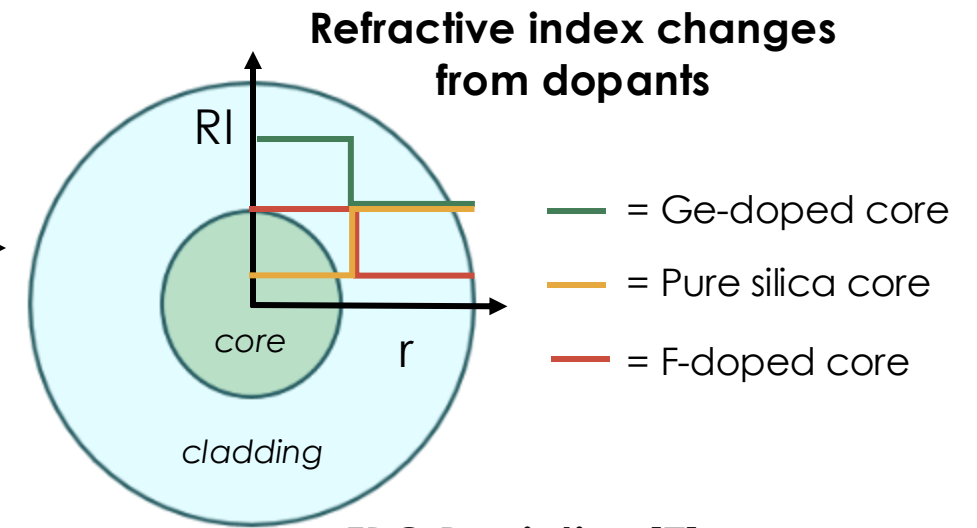


Embedment of metal-coated fibers [6]

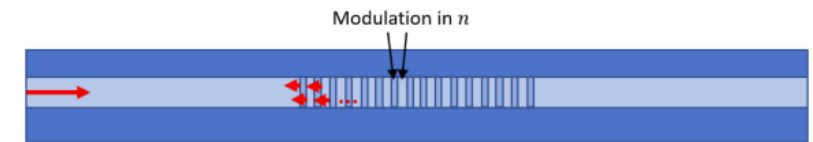


Basics of optical fiber sensors

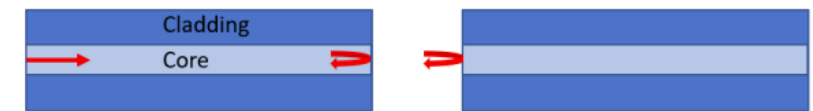
- The most common optical fiber material is amorphous SiO_2
 - Amorphous structure causes random density fluctuations
- Dopants are used to isolate the light via RI differences
- Optical fibers can be used to make point or distributed sensors:
 - Point Sensors
 - Intrinsic reflectors, such as Fiber Bragg Gratings
 - Extrinsic reflectors, such as Fabry Perot Cavities
 - Distributed Sensors
 - Optical frequency domain reflectometry (slow but high spatial fidelity)
 - Optical time domain reflectometry (fast but low spatial fidelity)
- The name of the game for all of these sensors: monitoring shifts in reflected optical frequencies, corresponding to certain measurands**



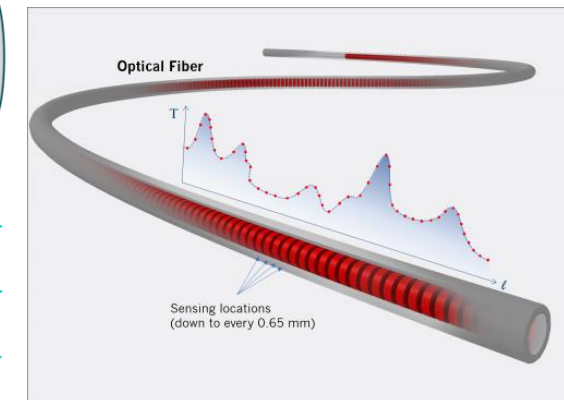
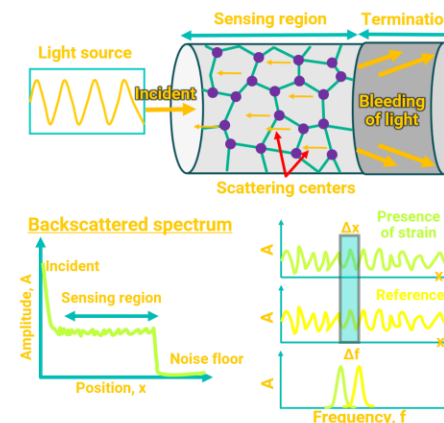
FBG Depiction [7]



FPC Depiction [7]

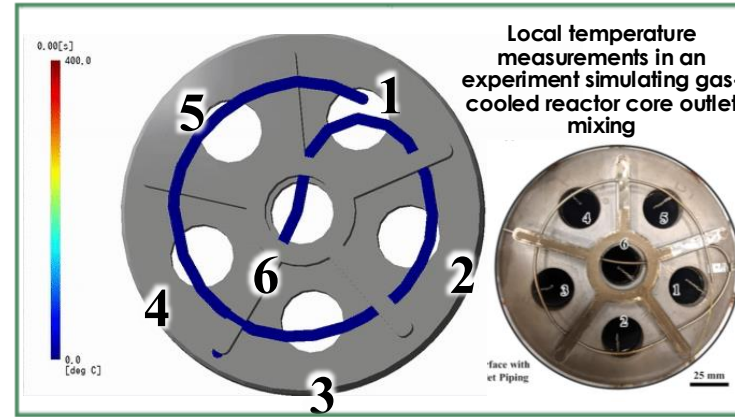
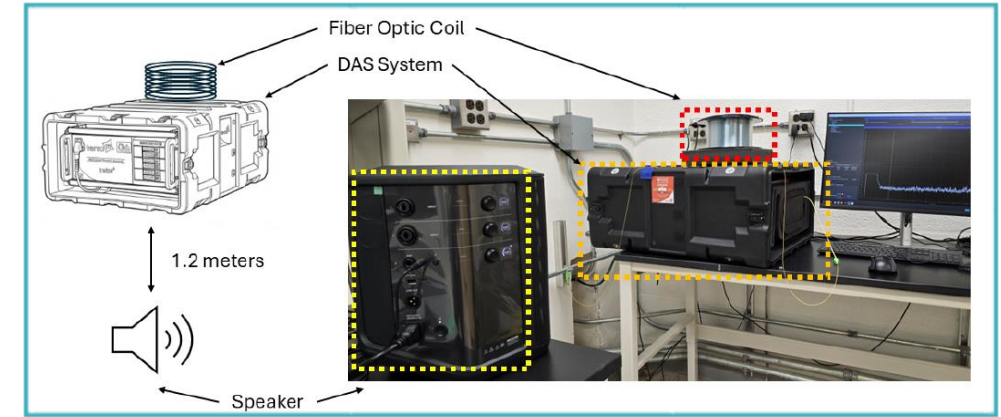
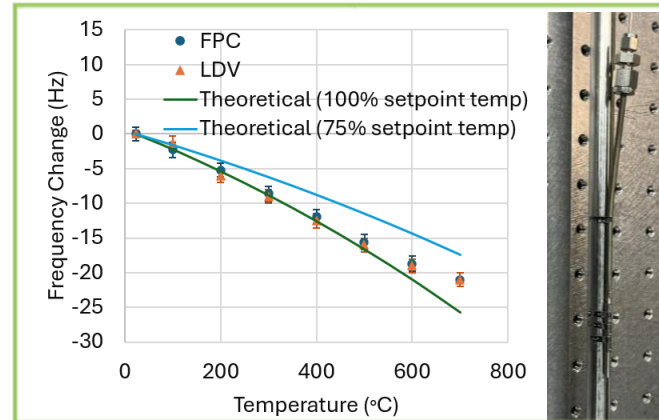
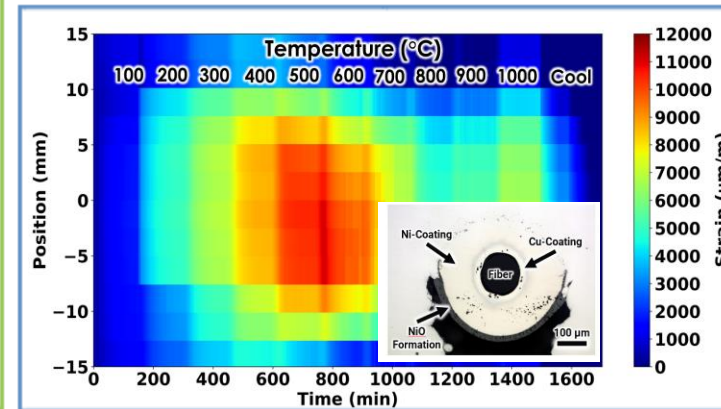
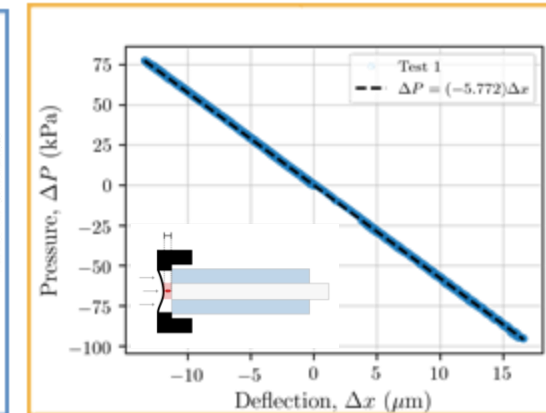
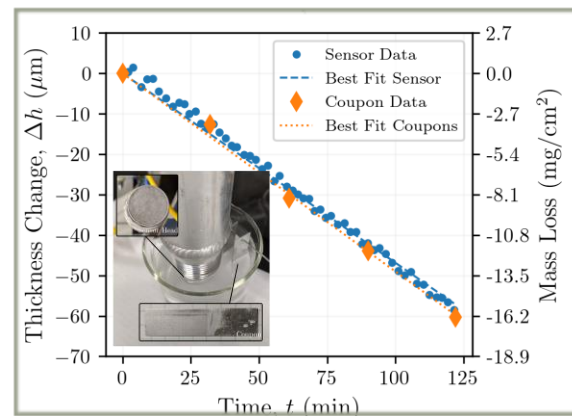
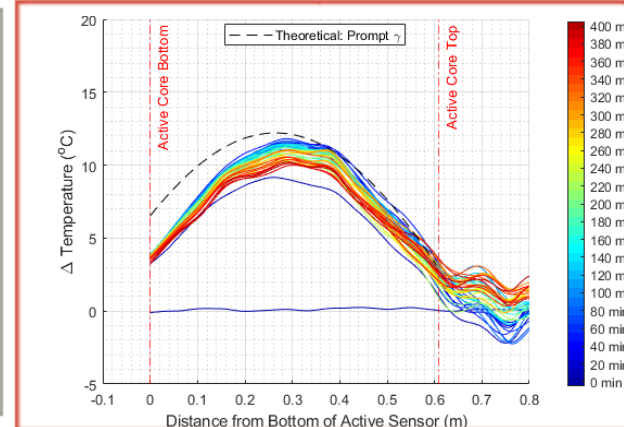
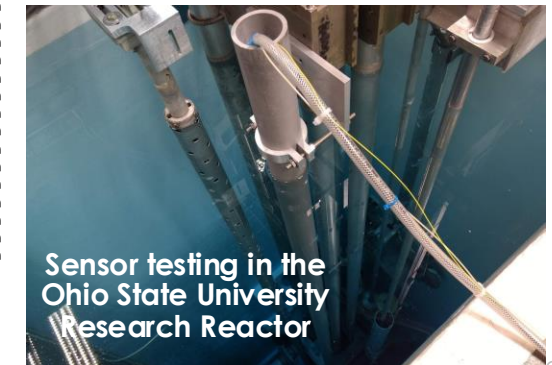


Depiction of OFDR [8]



What can be measured with optical fibers?

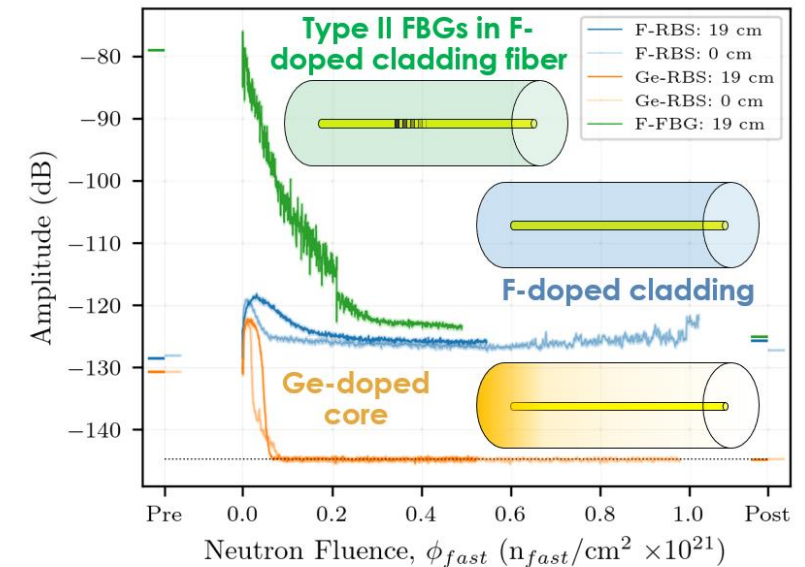
- Temperature [9]
- Acoustic signatures [10]
- Vibration [11]
- Strain [12]
- Pressure [13]
- Corrosion rate [13]
- Dose rate [14]
- The list goes on...



Challenge #1 with optical fiber sensors: RIA

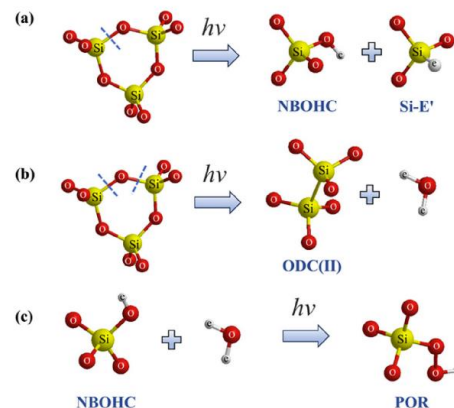
- Radiation induced attenuation (RIA): *the increase in optical signal loss (diminishing of light intensity) that occurs when an optical fiber is exposed to ionizing radiation*
 - For PSC and F-core-doped fibers, this is only an issue in the visible spectrum
 - For Ge-doped cores, this is a broadband issue
- Most optical interrogators operate in the infrared, so RIA can be mitigated with appropriate dopant selection!
 - This is true even for neutron/gamma fluences relevant for long-term reactor operation

HFIR irradiated fibers w/ different dopants [16]

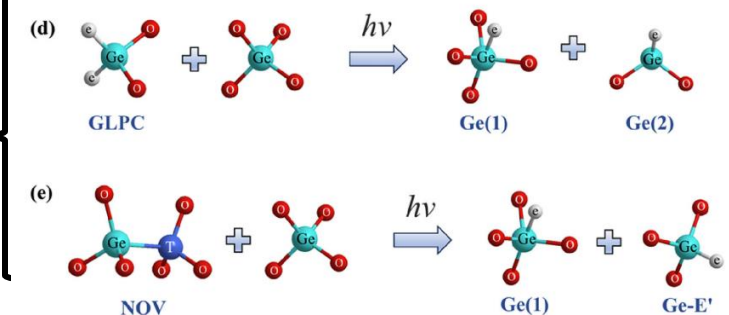


Defects from ionizing radiation in PSC and Ge-doped fibers [15]

Defects in Ge-doped fiber, optically active in NIR



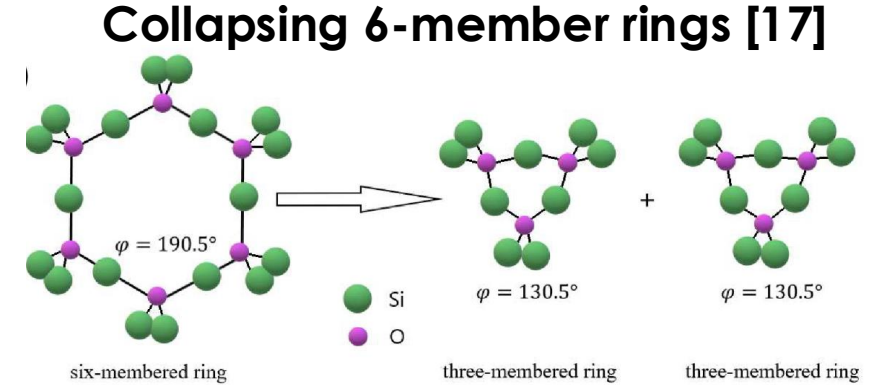
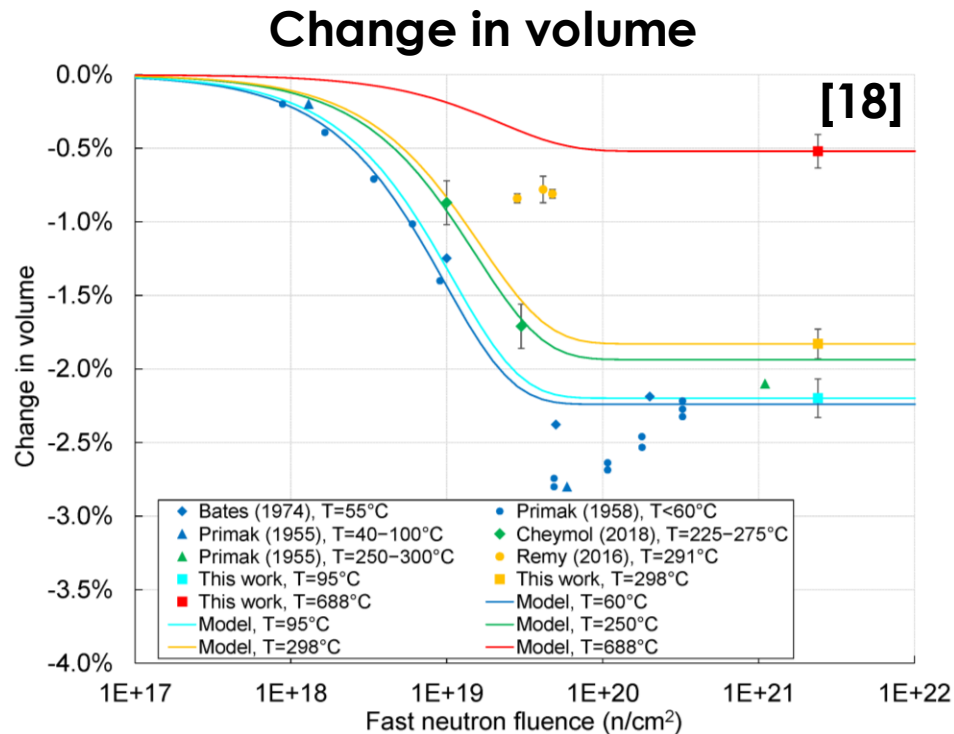
Defects in PSC, optically active in visible spectrum



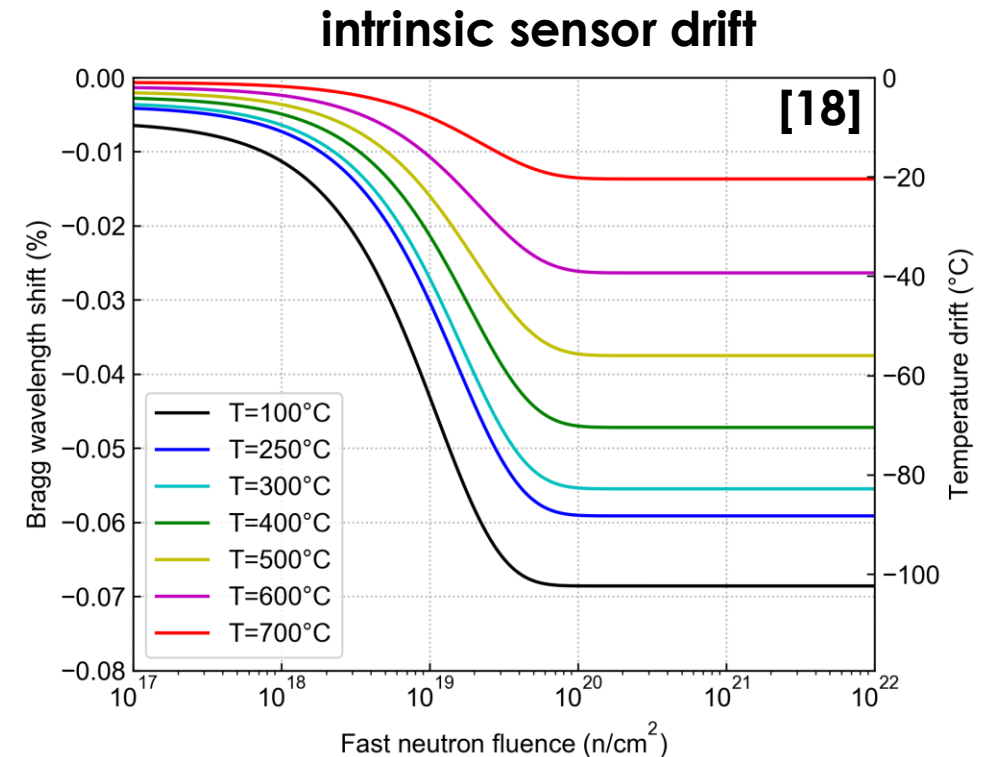
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Challenge #2 with optical fiber sensors: RIC

- Fast neutron bombardment leads to compaction of silica glass
 - Can think of this as a phase change from amorphous to metamict
 - Associated with a reduction in the average bond angle, collapsing of ring-like structures
- Consequence: any sensor that relies on thermal dimensional changes of fiber as a working principle, will drift

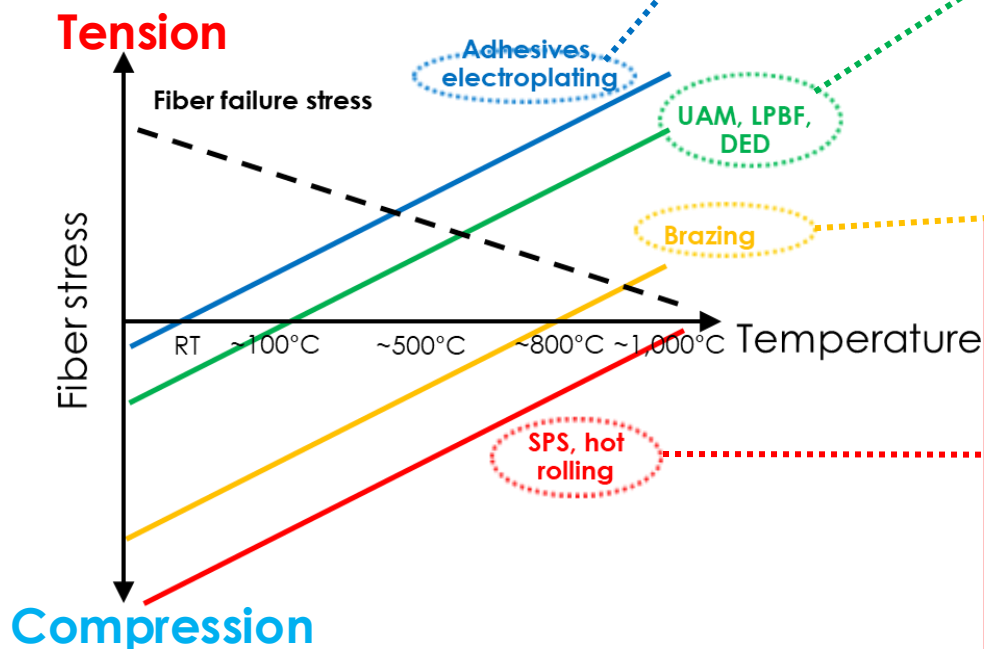
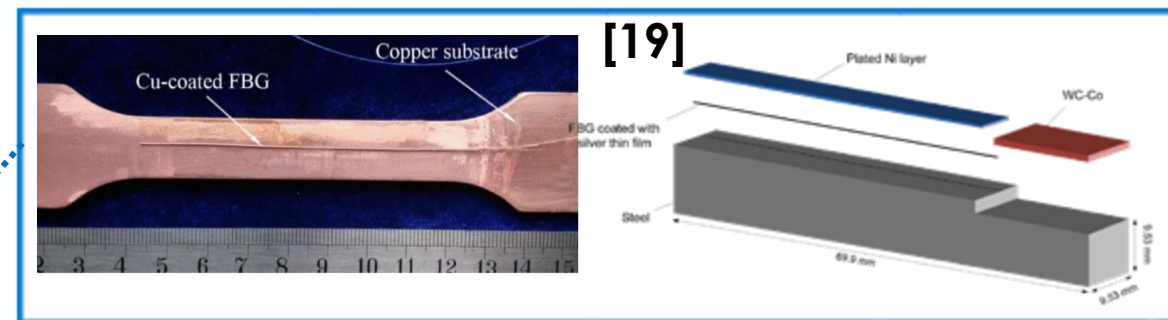
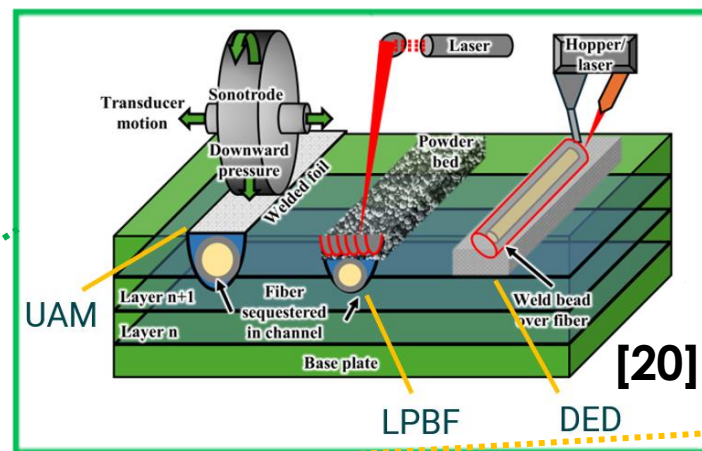
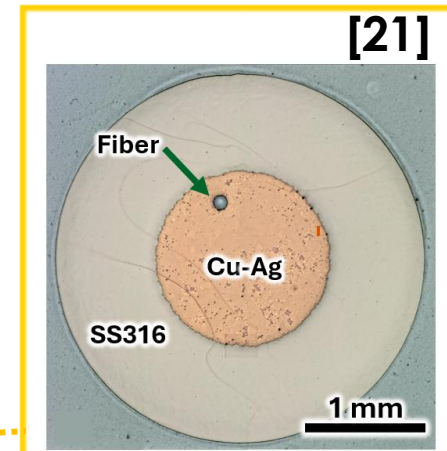
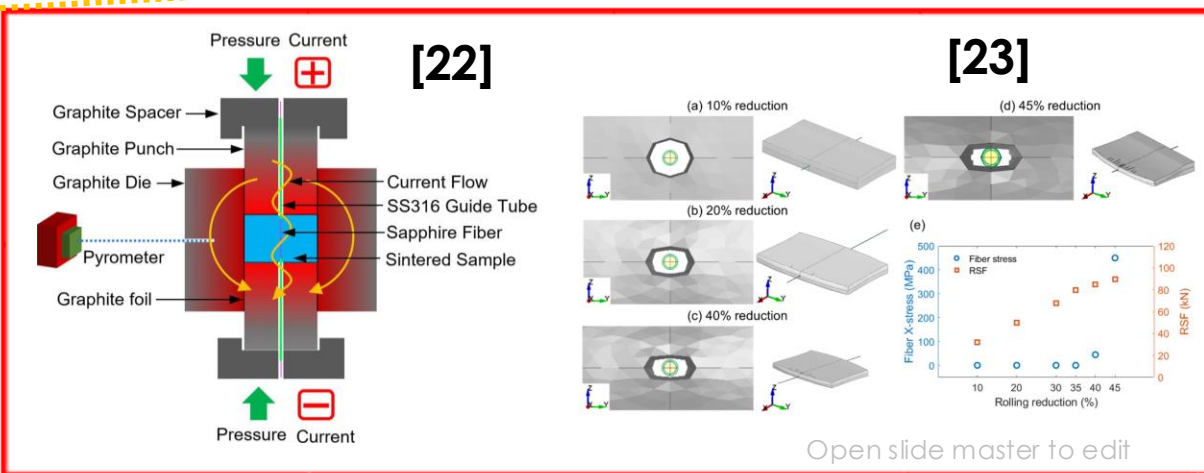


leads to



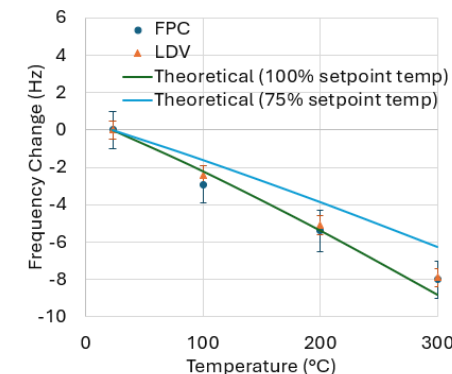
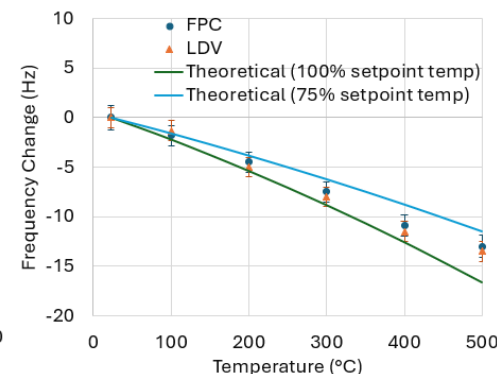
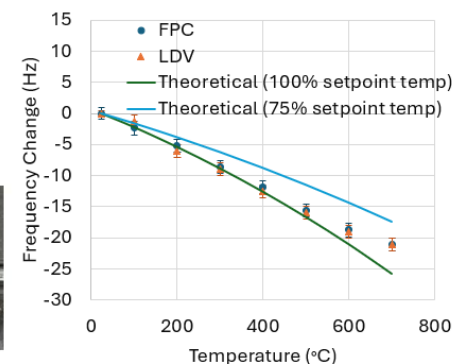
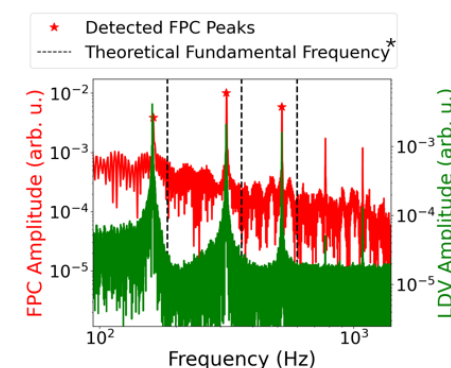
Optical fiber bonding/embedment: a key technology enabler

- To measure static or dynamic strain, an optical fiber must be bonded to the component it is monitoring
- To have a radiation-tolerant bond, embedding techniques with metal-coated fibers are a promising path
 - Lower temperature bonding techniques may work for Gen II/III reactors
 - Higher temperature bonding techniques will be necessary for Gen IV
- Single-point and distributed embedment options are available

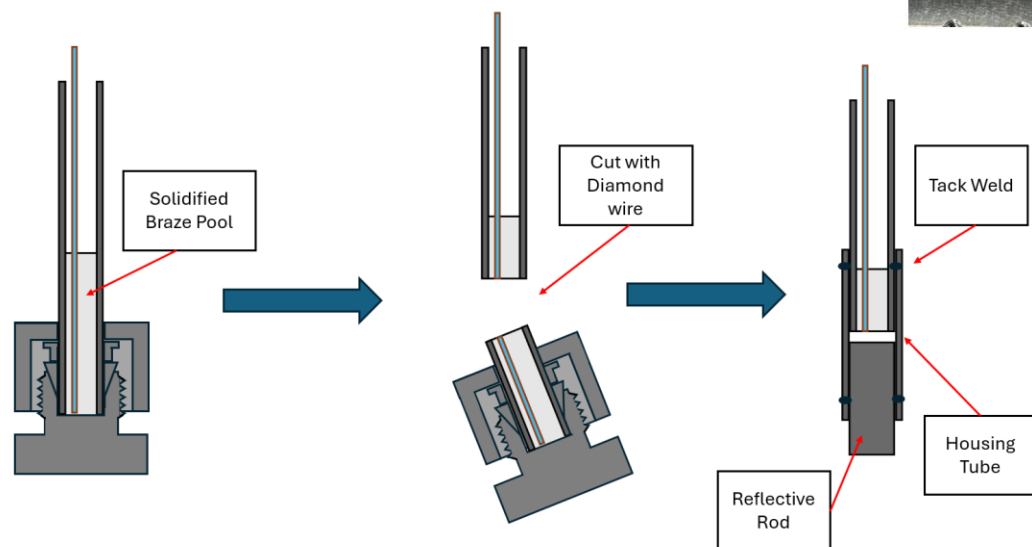
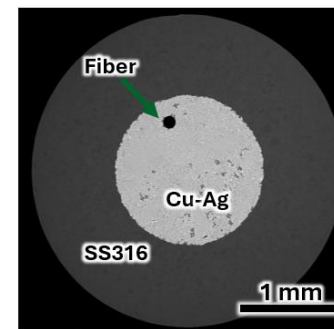
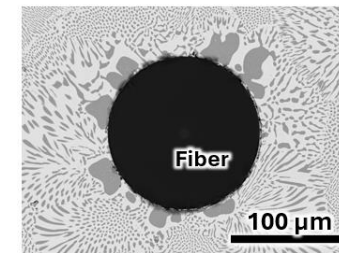
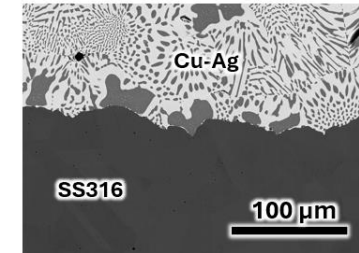


Recent efforts for high temperature bonding

- Recent efforts at ORNL have demonstrated good success with brazing Cu-coated optical fibers [21]
 - Pre-compression of ~ 13000 microstrain measured!
 - Corresponds to zero-strain state of ~ 700 C
- We leveraged this bonding technique to make a brazed FPC
 - Used as a vibration sensor
 - Monitored natural frequencies of a suspended rod up to 700 C
 - Accurate within 1 Hz up to 700 C!

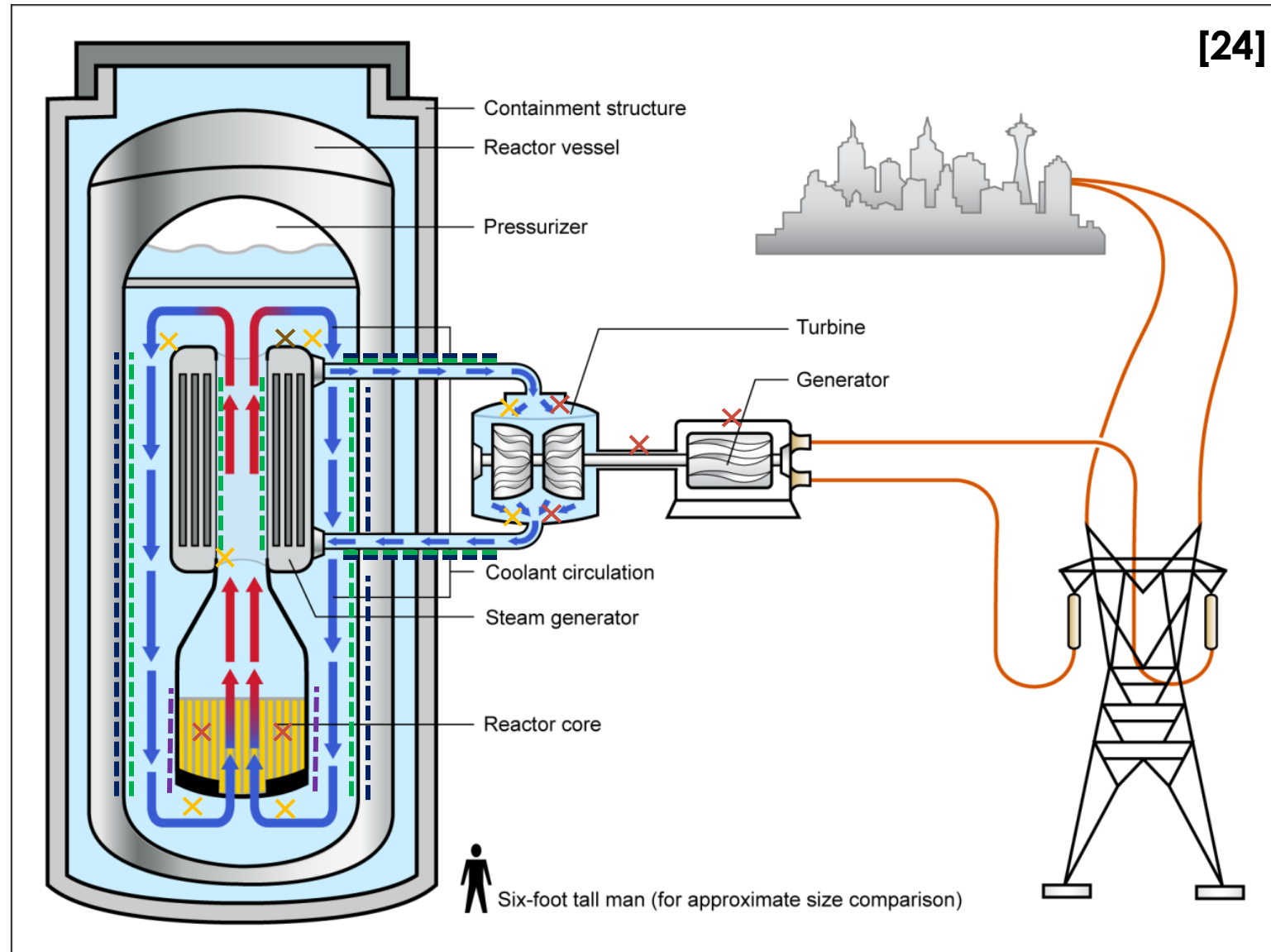


*Calculated at room temperature (22 °C)



Hypothetical Instrumentation Setup in a SMR

- = distributed temperature (OFDR)
- = distributed acoustic signature (DAS)
- = distributed dose rate (OFDR + FBGs)
- ✕ = point pressure (FPC)
- ✕ = point vibration (FPC)
- ✕ = point corrosion (FPC)



Conclusions

- The sensing needs of SMRs differ from large-scale LWRs due to their small size, necessity for autonomous operations, and inclusion of Gen IV reactor designs
- Optical fibers present a promising solution to meet many of the sensing needs for SMRs
 - Small Size
 - Distributed Sensing capabilities
 - High temperature/radiation resilience
- Optical fibers have been utilized to measure several parameters which are relevant to SMRs
- It will be crucial that optical fiber dopants are chosen carefully, to mitigate RIA
- RIC will be the biggest challenge if optical fibers are placed in or near the core
 - Not a concern for dynamic measurements (vibration, acoustics)
- Recent advances in high temperature bonding to metals will enable many SHM applications which were previously impossible due to fiber stresses

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Questions?

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