AM for Strategic Sensor Integration and In Situ Monitoring

Chris Petrie

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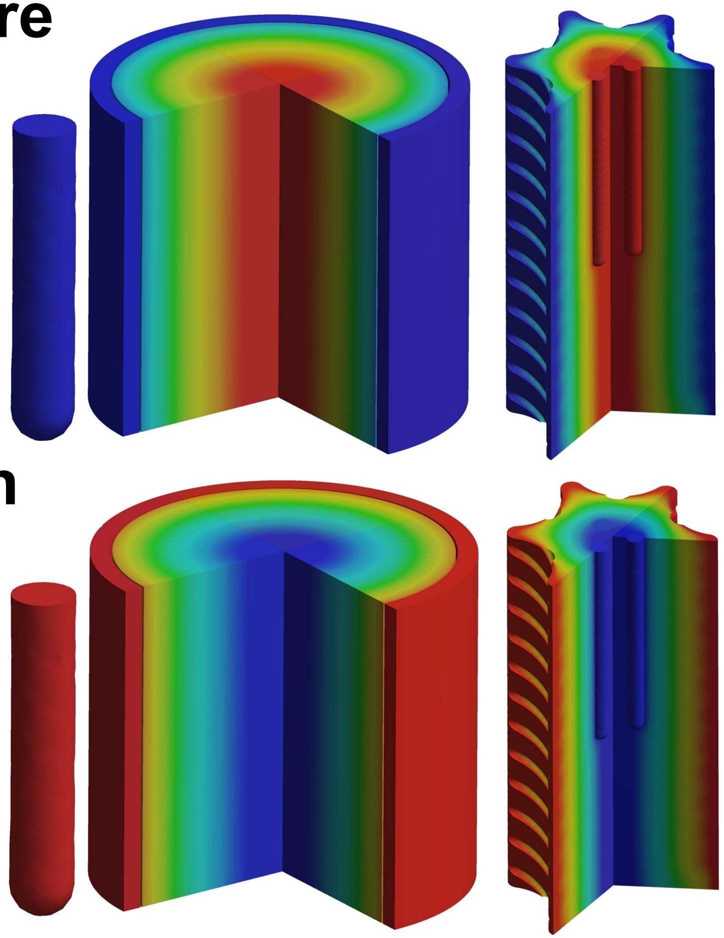
Contributions from:
H. Hyer, D. Sweeney, A. Schrell, D. Richardson,
G. Vasudevamurthy

Embedded sensors for nuclear applications

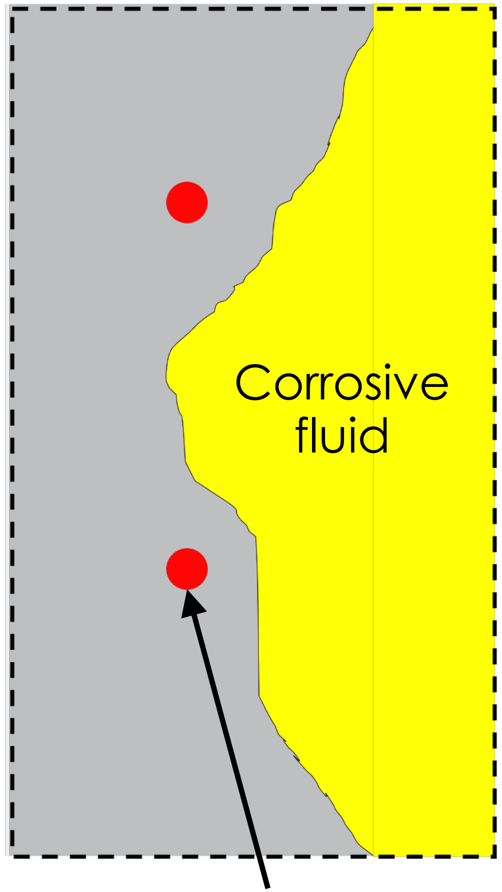
Traditional | Embedded sensors

Temperature

Neutron flux

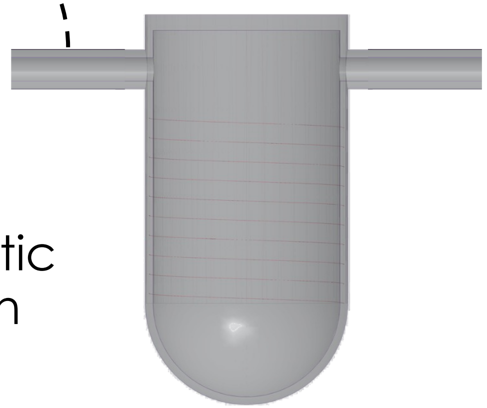


Integration of sensors during manufacturing in locations that would otherwise be inaccessible



Spatially-distributed fiber optic strain sensors embedded in coolant piping

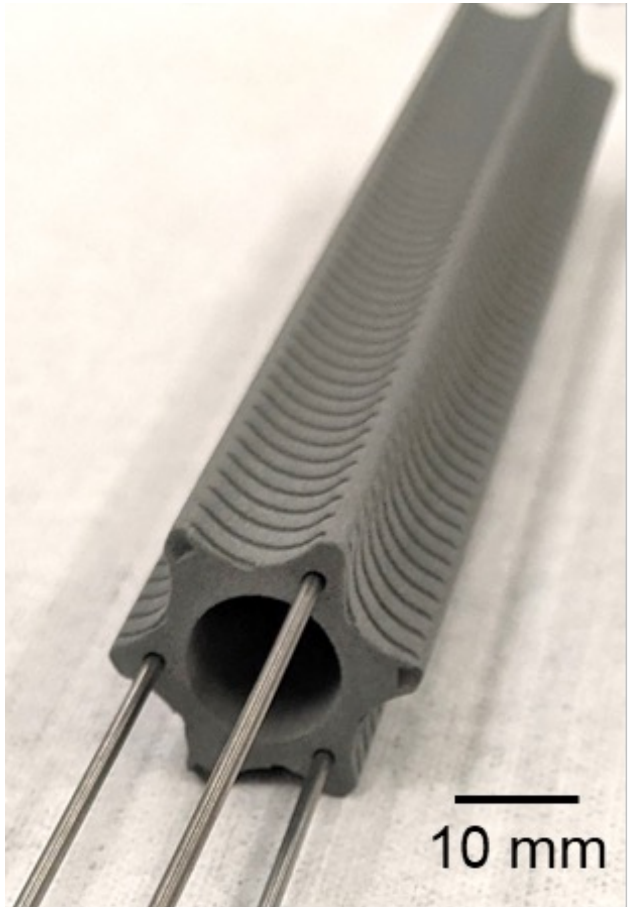
Corrosion of Davis-Besse reactor vessel head [1]



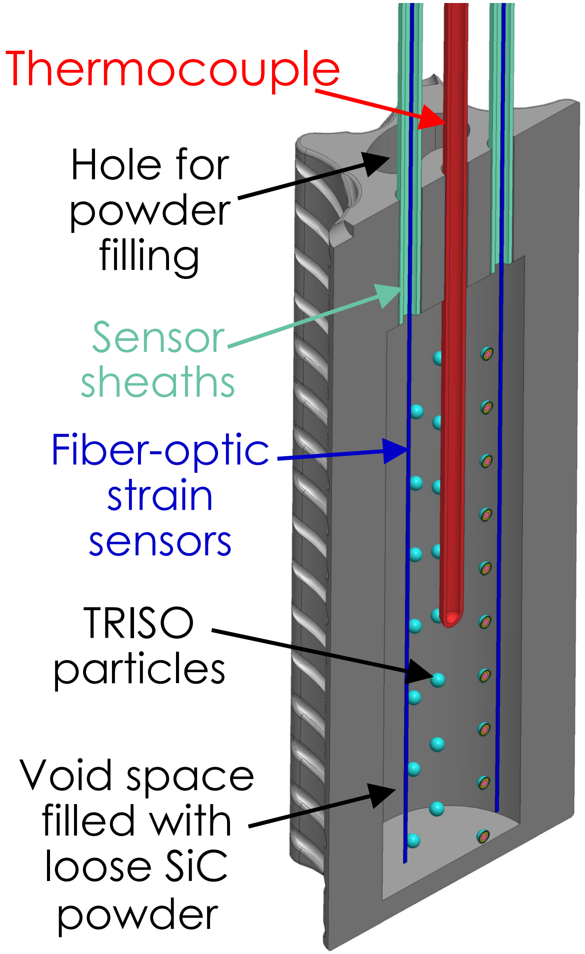
Reduce operation and maintenance costs through improved local health monitoring

[1] "2002 Davis-Besse Reactor Pressure Vessel Heard Degradation Knowledge Management Digest," NUREG/KM-0005, February 2014, U.S. Nuclear Regulatory Commission.

TCR fuel fabrication process offer opportunity to embed sensors directly in fuel during fabrication



Option 1: Press sensor into tight-fitting channels in binder jet printed SiC part



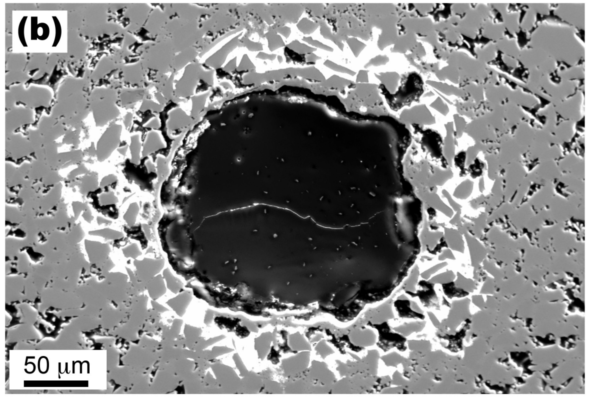
Option 2: Print part with void region to be filled with sensor, other materials (e.g., fuel), and loose SiC powder

Both: Densify entire assembly using CVI, embedding sensors in dense SiC part

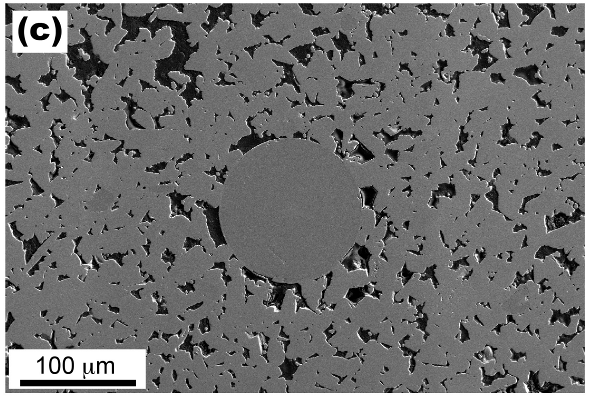
[1] C.M. Petrie et al., "Embedded sensors in additively manufactured silicon carbide," *Journal of Nuclear Materials* **552** (2021) 153012.

Embedding fiber-optic sensors

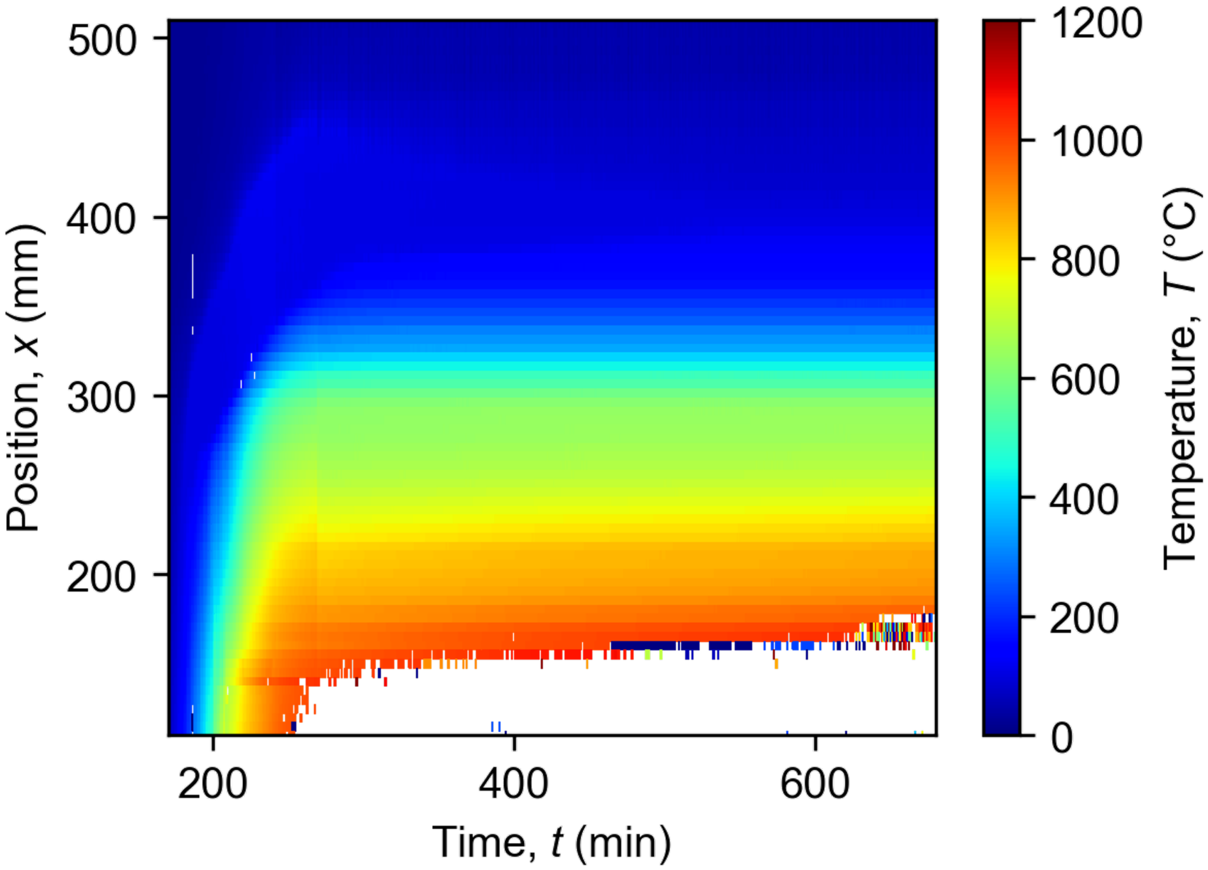
- Fiber optics can monitor spatially distributed temperatures during CVI and can be embedded in SiC
- However, sensor leads are fragile and often break
- More development needed (coatings do not survive ~1,000°C)



Cu coated fiber



Bare fiber

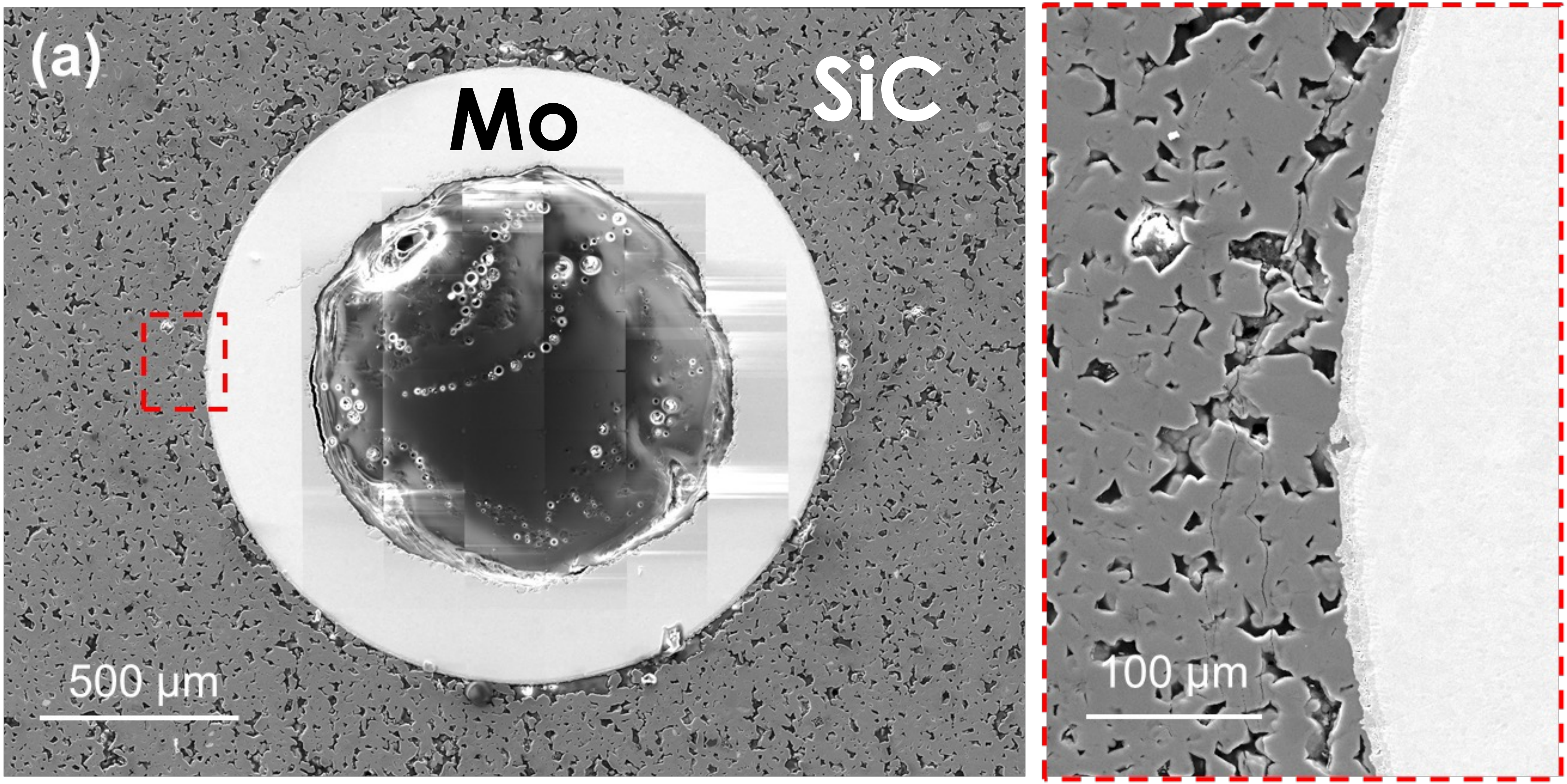


Distributed fiber optic temperature measurements during CVI

Oak Ridge National Laboratory

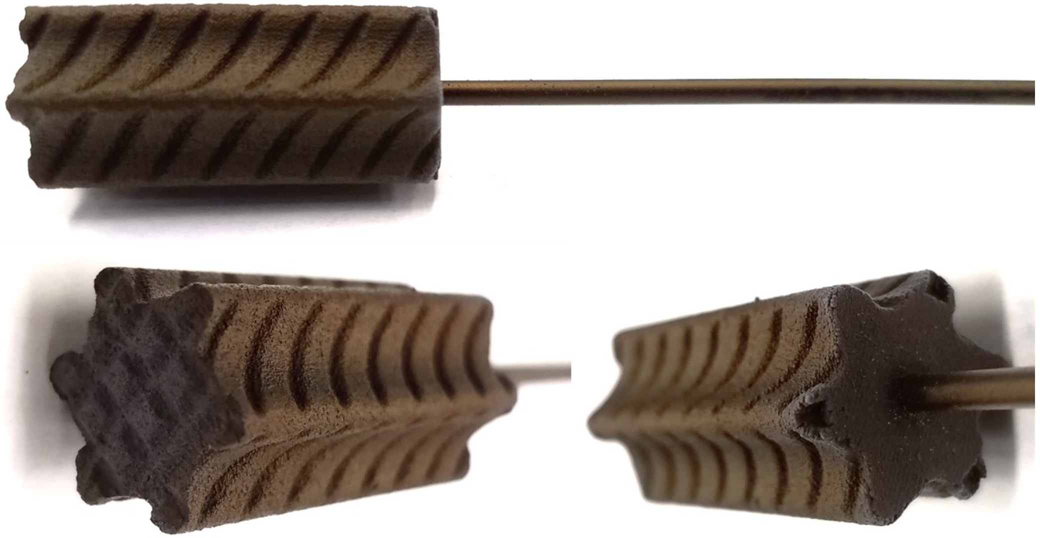
[1] C.M. Petrie et al., "Embedded sensors in additively manufactured silicon carbide," *Journal of Nuclear Materials* **552** (2021) 153012.

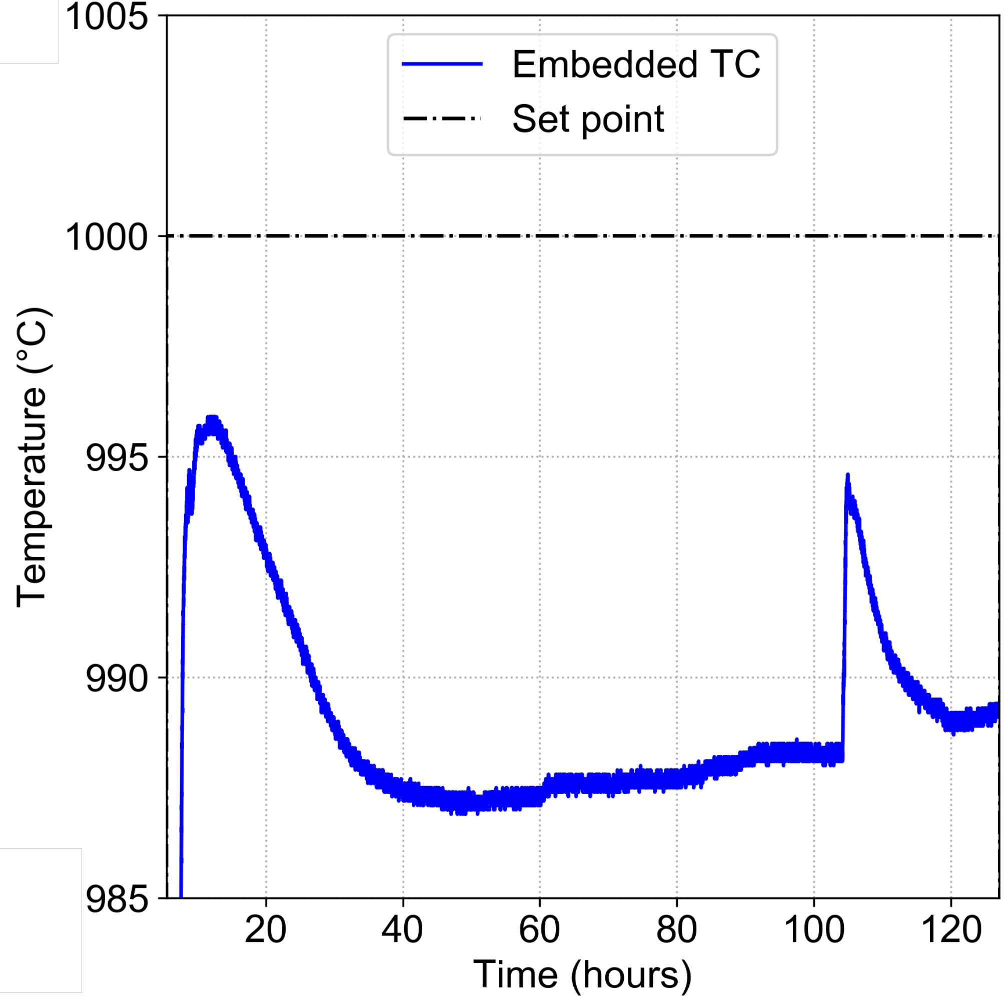
Characterization of embedded thermocouple



In situ measurements using embedded thermocouple during CVI

- CVI process allows embedding sensors at strategic locations within AM fuels
  - Direct monitoring of limiting fuel temperatures
  - Self-shielding neutron flux monitoring
  - Potential for spatially distributed fiber optic measurements of temperature and strain
  - **Technology patented and licensed by USNC**





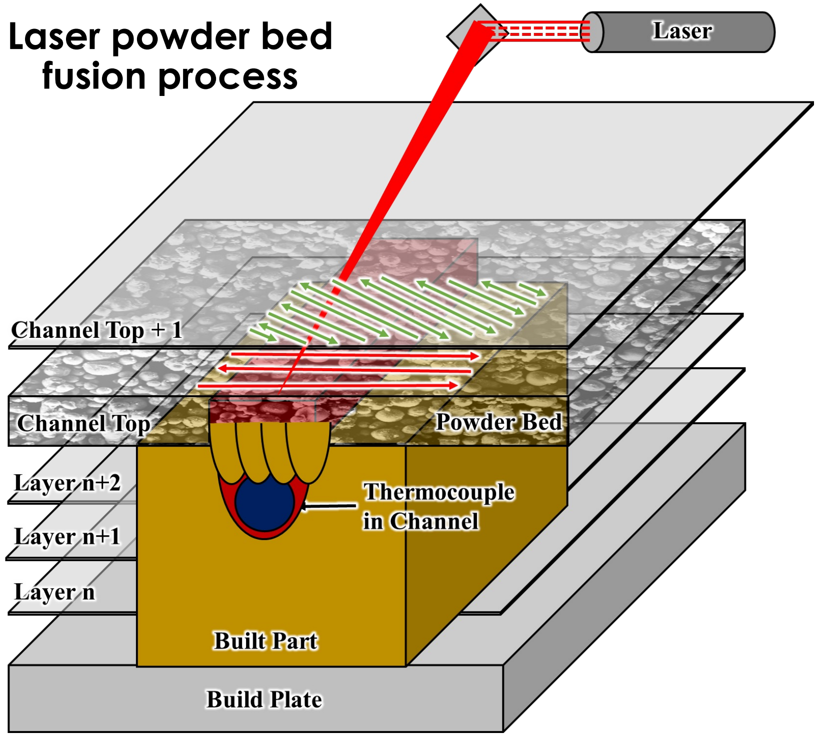
Thermocouple identified a slightly lower process temperature and a loss of CVI process gases prior to terminating the run

[1] C.M. Petrie et al., “Embedded sensors in additively manufactured silicon carbide,” *Journal of Nuclear Materials* **552** (2021) 153012.

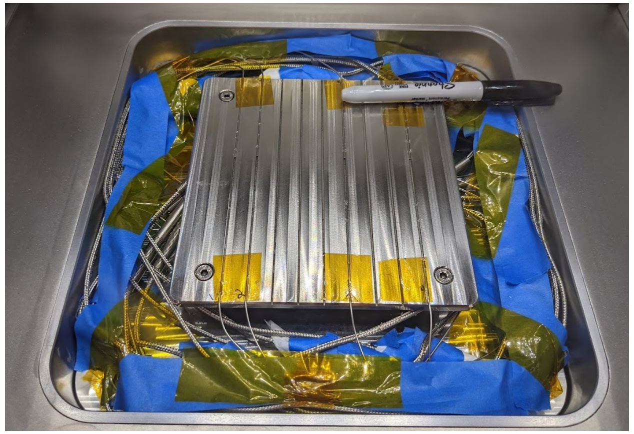
Extension to metal systems to attract wider industry interest

- Laser powder bed fusion can fabricate complex geometries with high precision for a wide range of material systems
  - Possible to embed sensors at strategic locations within complex metal components
  - Must melt through powder layer up to sensor sheath without damaging the sensor
  - Starting with 316 stainless steel, a common material for nuclear applications

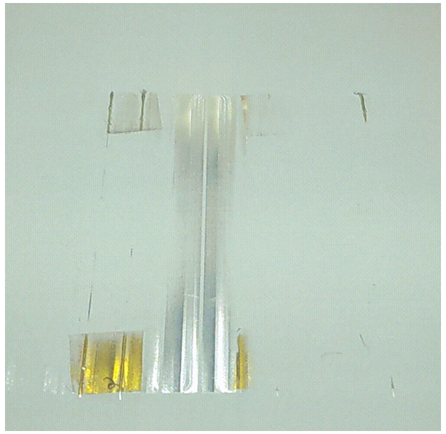
Laser powder bed fusion process



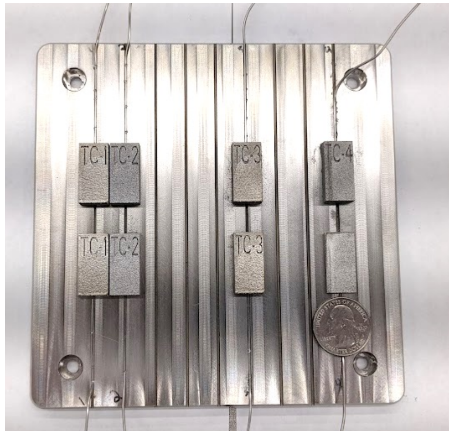
Spot-weld thermocouples in printed/machined channels



Print over top to embed sensors



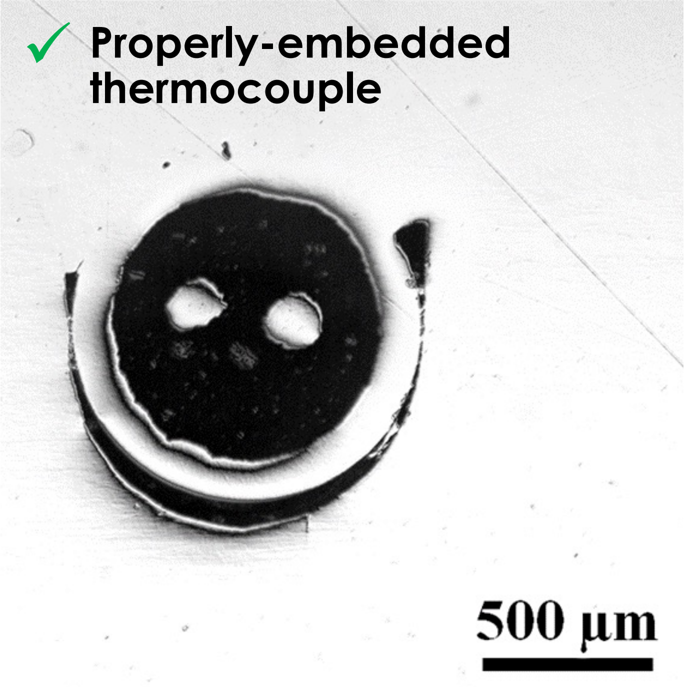
Remove from powder bed

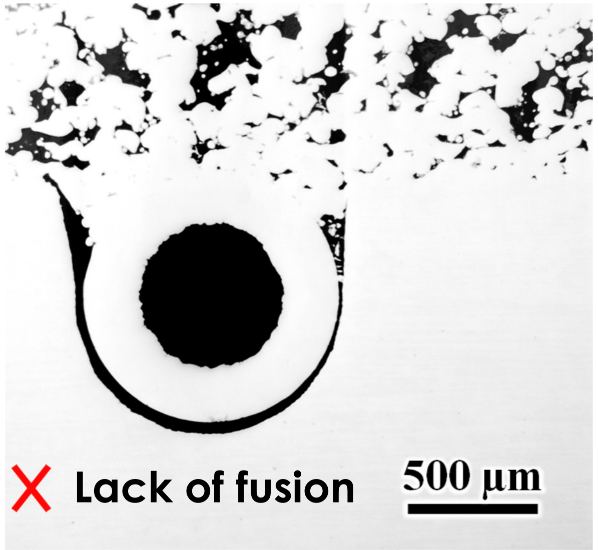


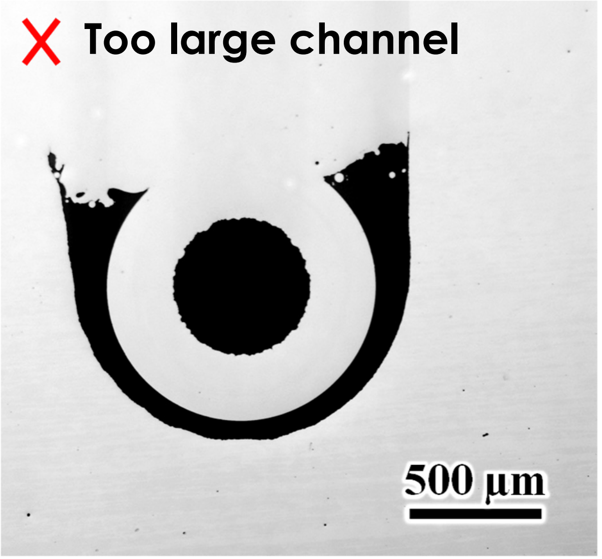
Remove part from build plate

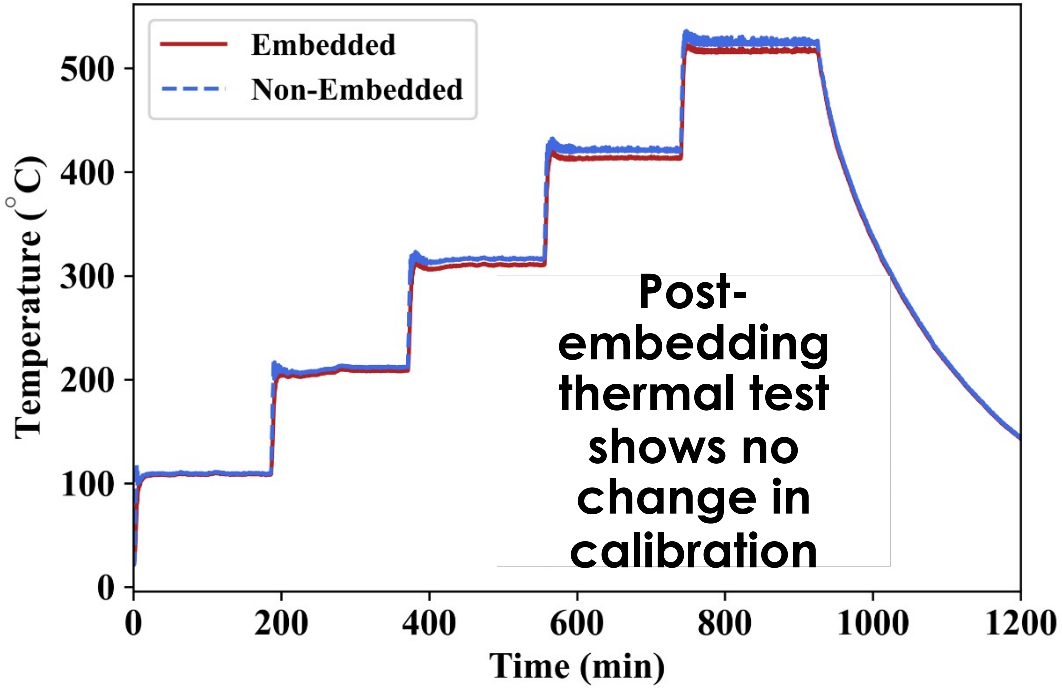
Performance of embedded thermocouples

- Optimized channel dimensions and printing parameters to control melt pool
- Quality verified using optical microscopy, X-ray computed tomography (XCT), and thermal testing



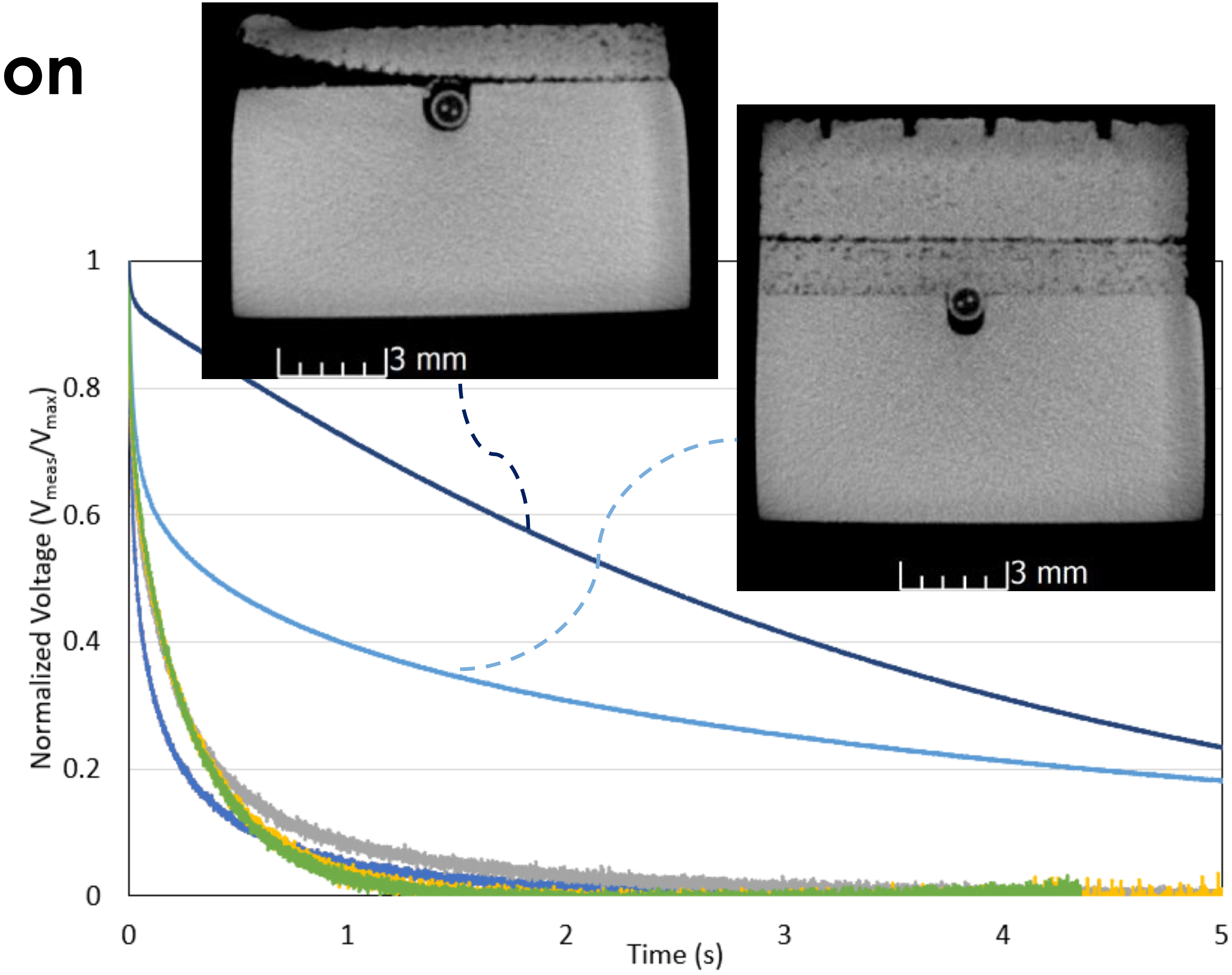






AMS SBIR collaboration

- Analysis and Measurement Services Corporation (AMS) is non-destructively assessing how well sensors are embedded
  - Loop current step response (LCSR) technique
  - Transient heating of the thermocouple junction to measure response time



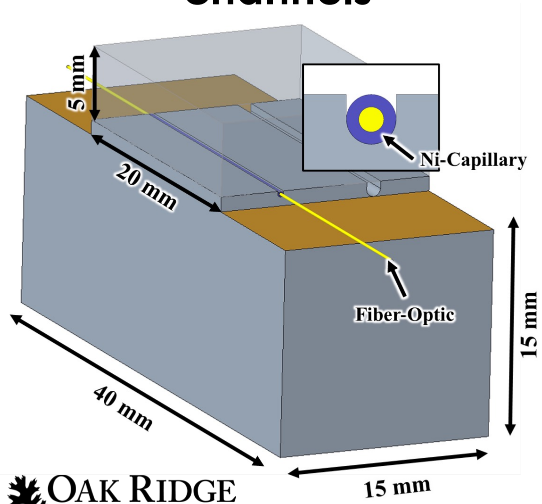
Images courtesy of AMS

LCSR response time consistent for most embedded sensors except for two with printing defects or improperly sized channels

Embedded optical fibers for distributed temperature and strain monitoring

- Fiber-optic sensors can provide sub-cm spatially resolved temperature and strain along the entire fiber
- Requires even finer control of melt pool to bond fiber without damage, which requires metal fiber coatings

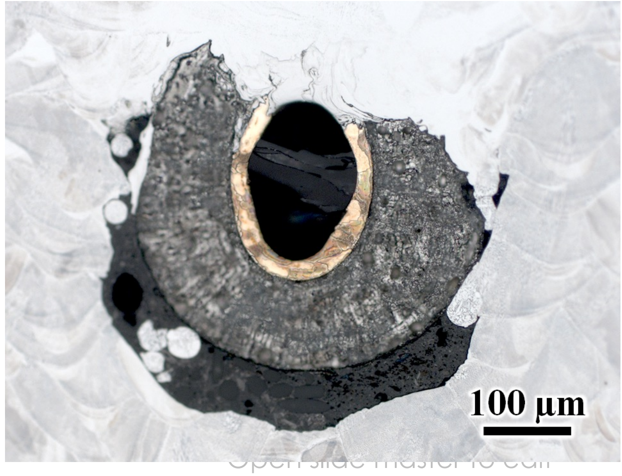
Place fiber in printed channels



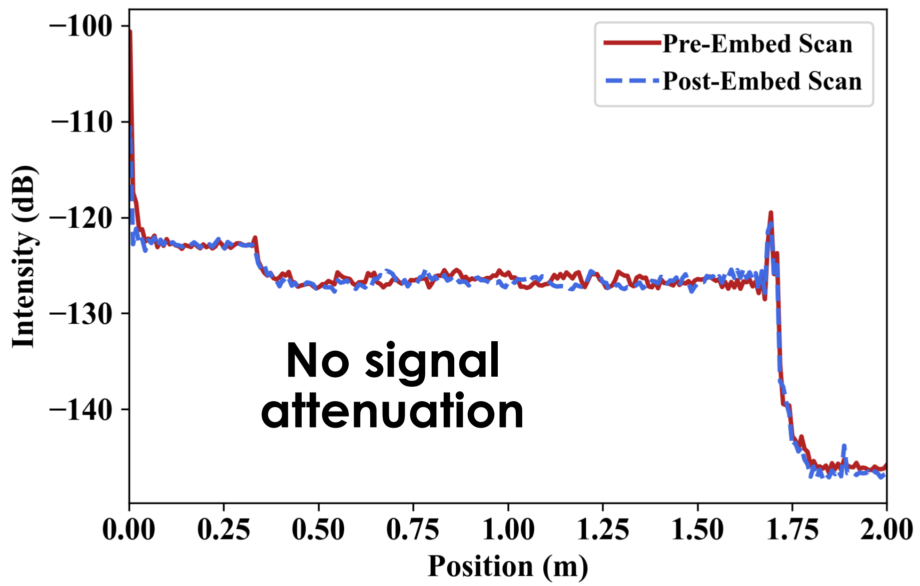
Spot weld in channel

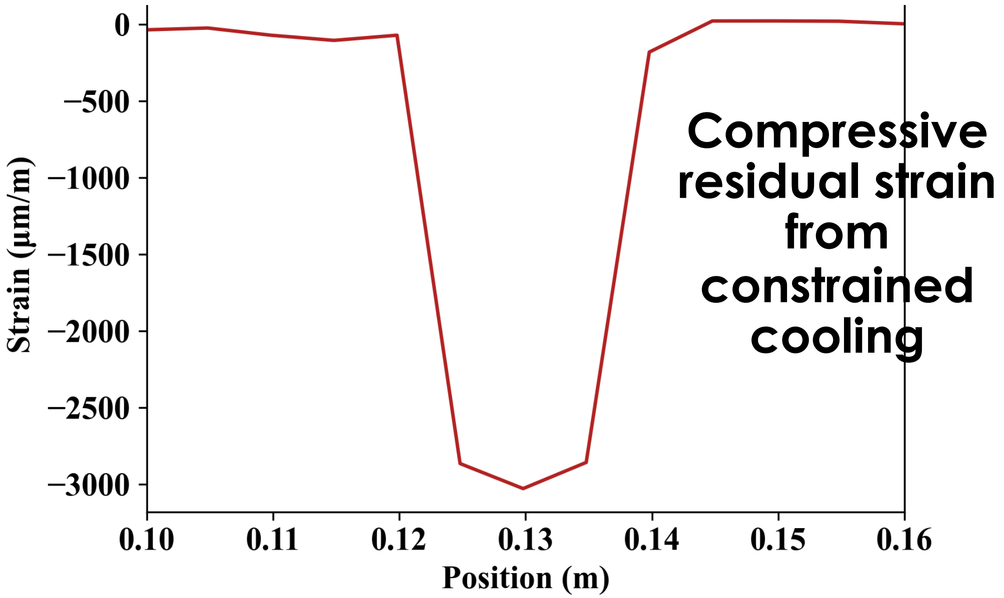
Print over fibers

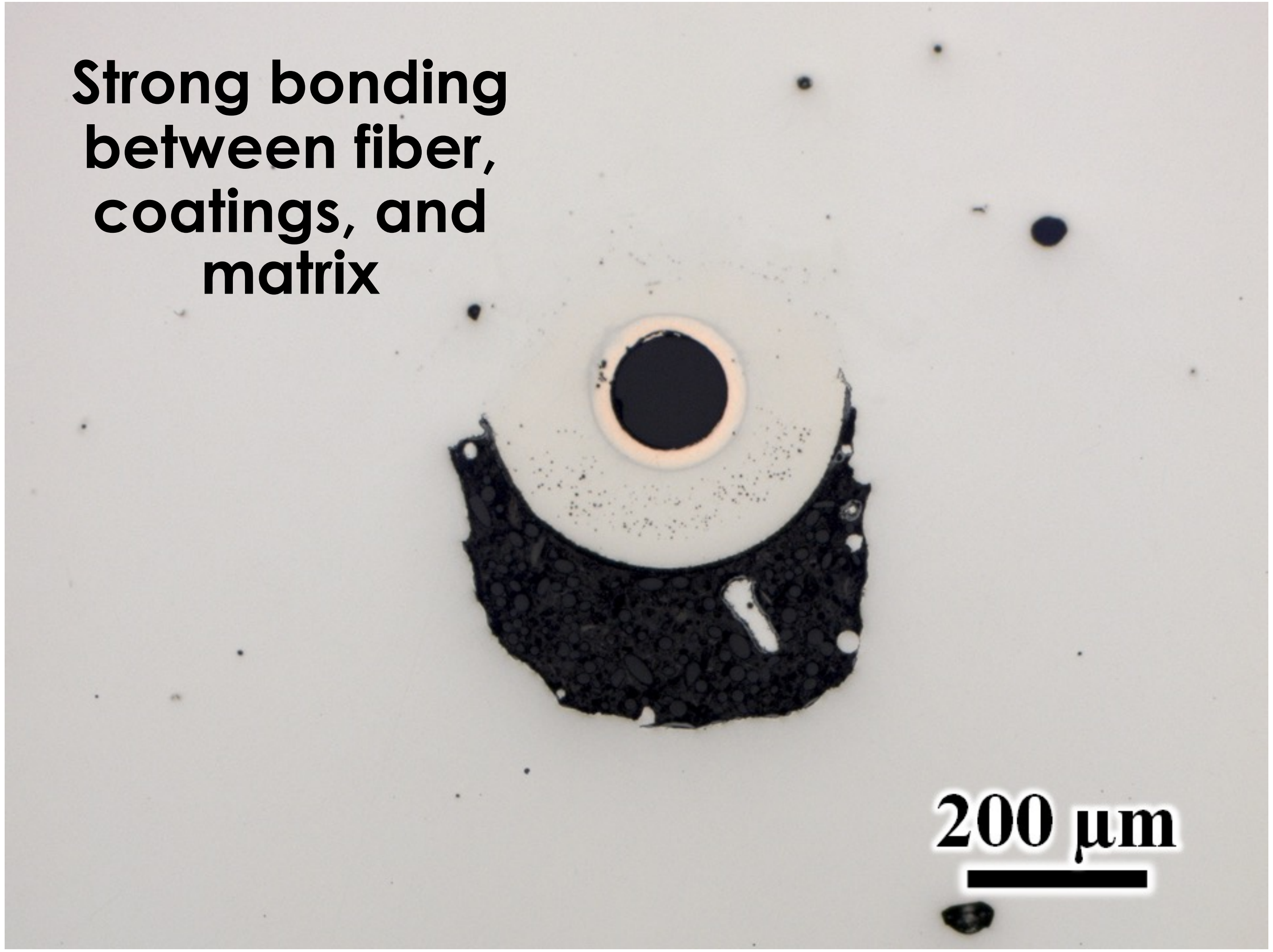
Characterize performance and melt pool penetration



Characterization of embedded optical fibers

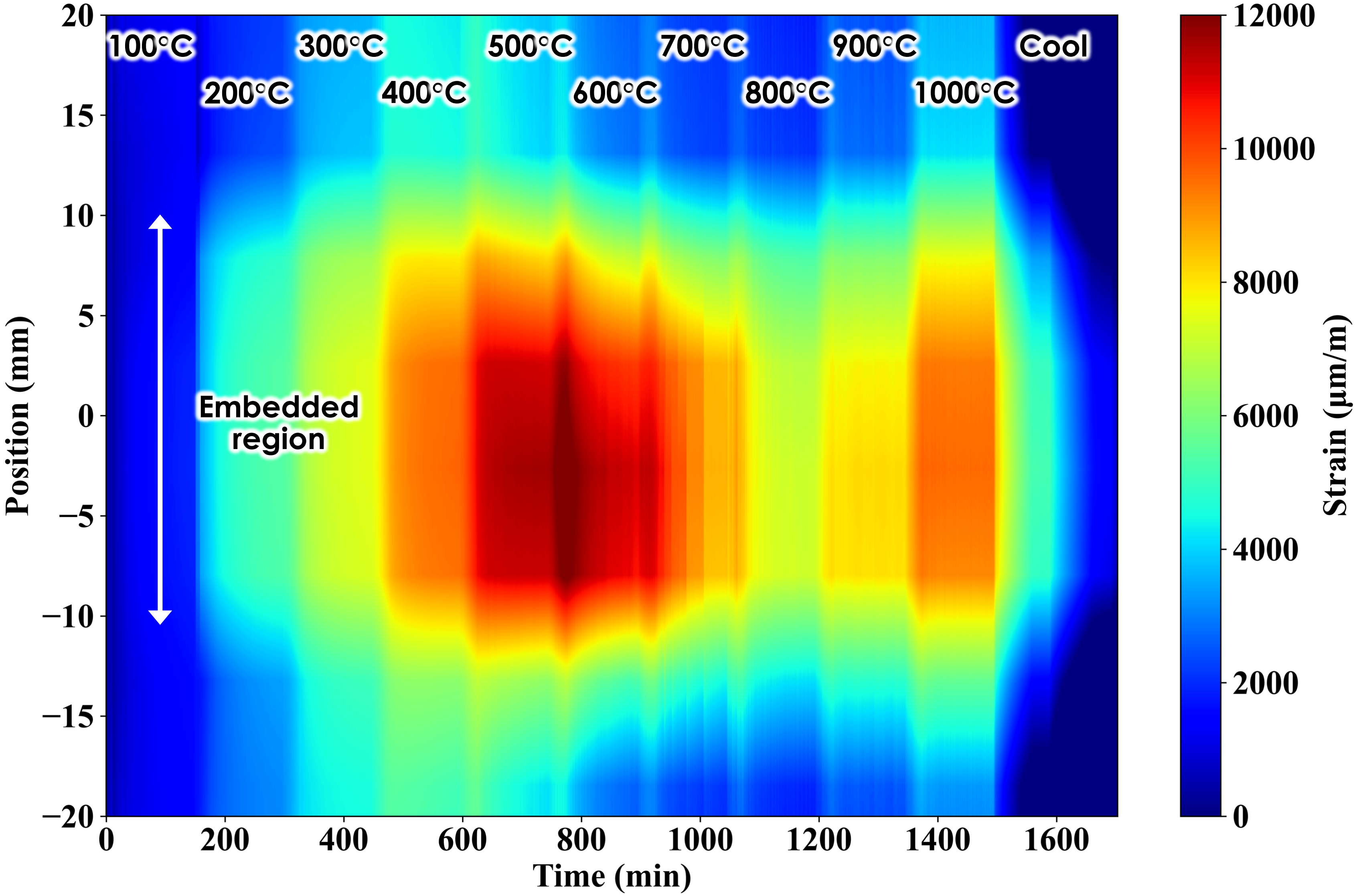






Thermal testing

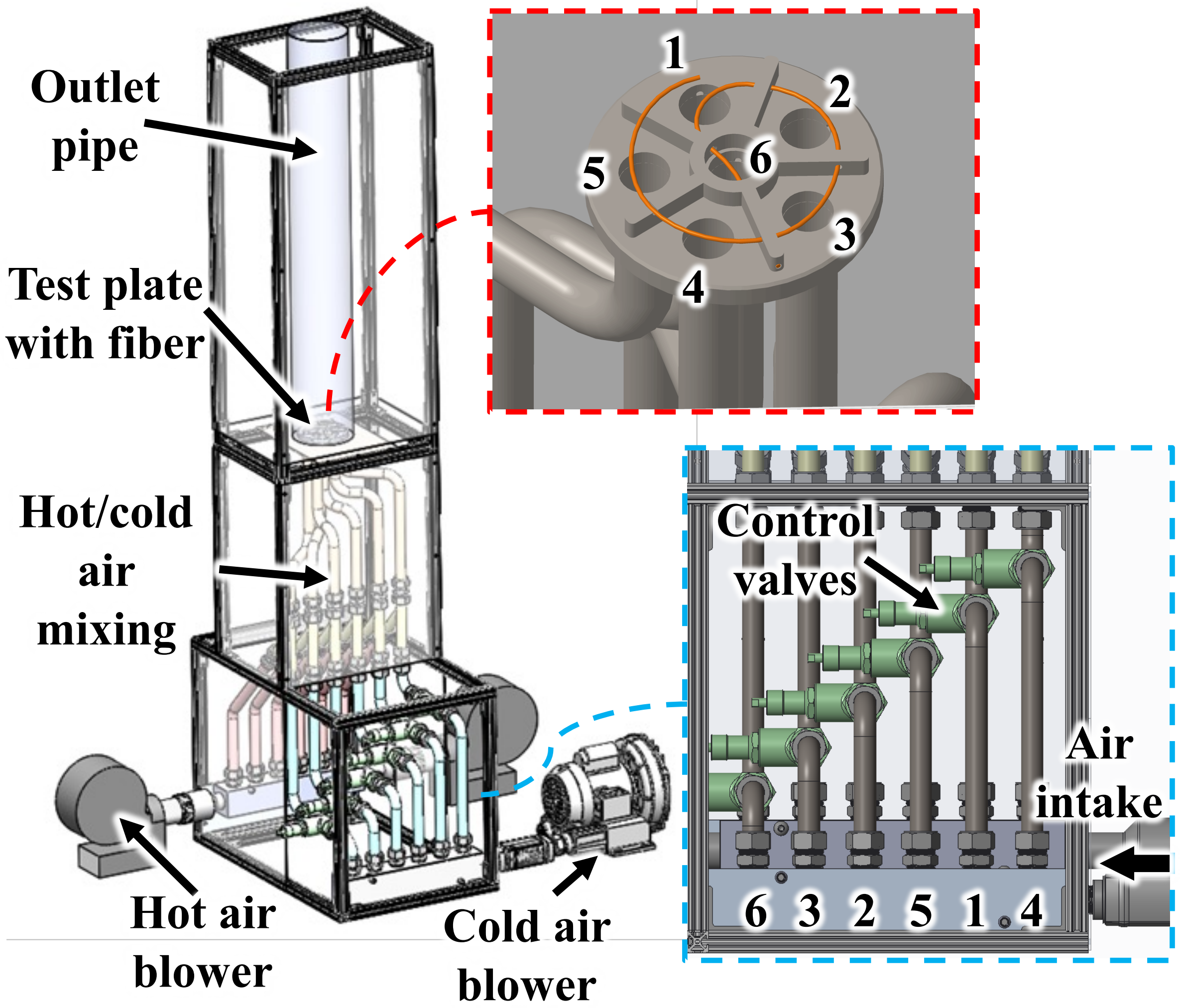
- Fiber retains some strain coupling up to 1,000°C!
  - Enabled by adaptive reference signal processing techniques [1–3]
- Strain up to 12,000 μm/m
  - After compensating for temperature-induced changes in refractive index
  - Some relaxation at 500–800°C but strain increases at 900–1000°C
- Fiber survived highest thermal strain ever reported using 100% metal
  - LBPF SS316 matrix, Cu+Ni fiber coating



[1] D.C. Sweeney and C.M. Petrie, “Extending the Range of Distributed Fiber Optic Strain Measurements Using a Local Adaptive Reference Approach,” *Optics Letters* **47** (2022) 269-272.
[2] D.C. Sweeney, D. Sweeney, and C.M. Petrie, “Graphical Optimization of Spectral Shift Reconstructions for Optical Backscatter Reflectometry,” *Sensors* **21** (2021) 6154.
[3] D.C. Sweeney, A.M. Schrell, and C.M. Petrie, “An Adaptive Reference Scheme to Extend the Functional Range of Optical Backscatter Reflectometry in Extreme Environments,” *IEEE Sensors* **21** (2021) 498-509.

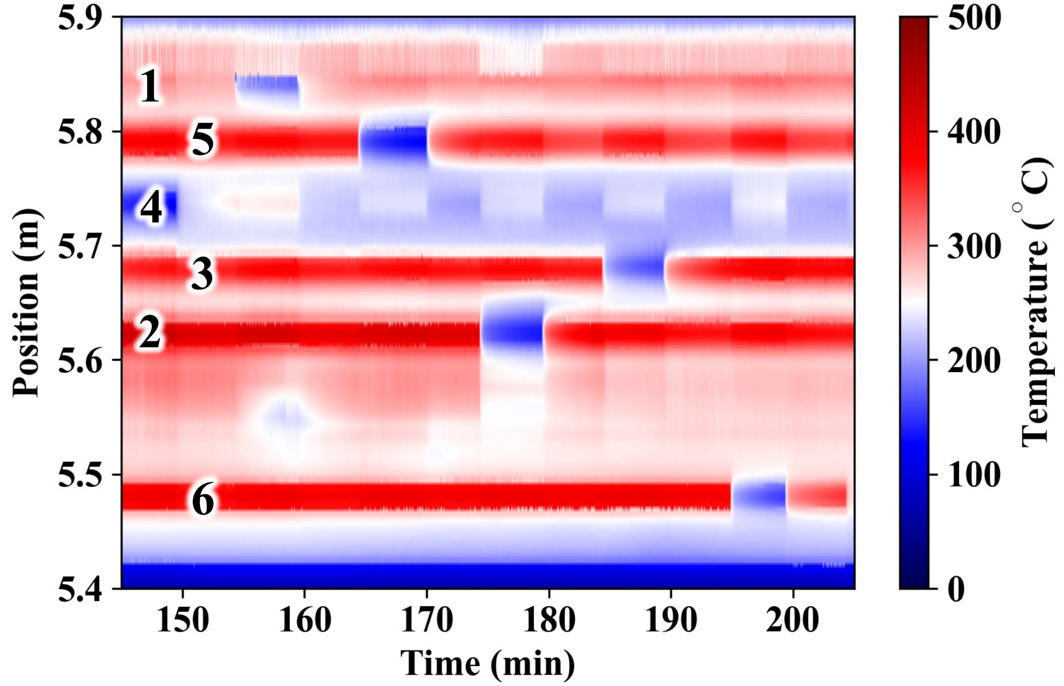
Local core outlet temperature monitoring

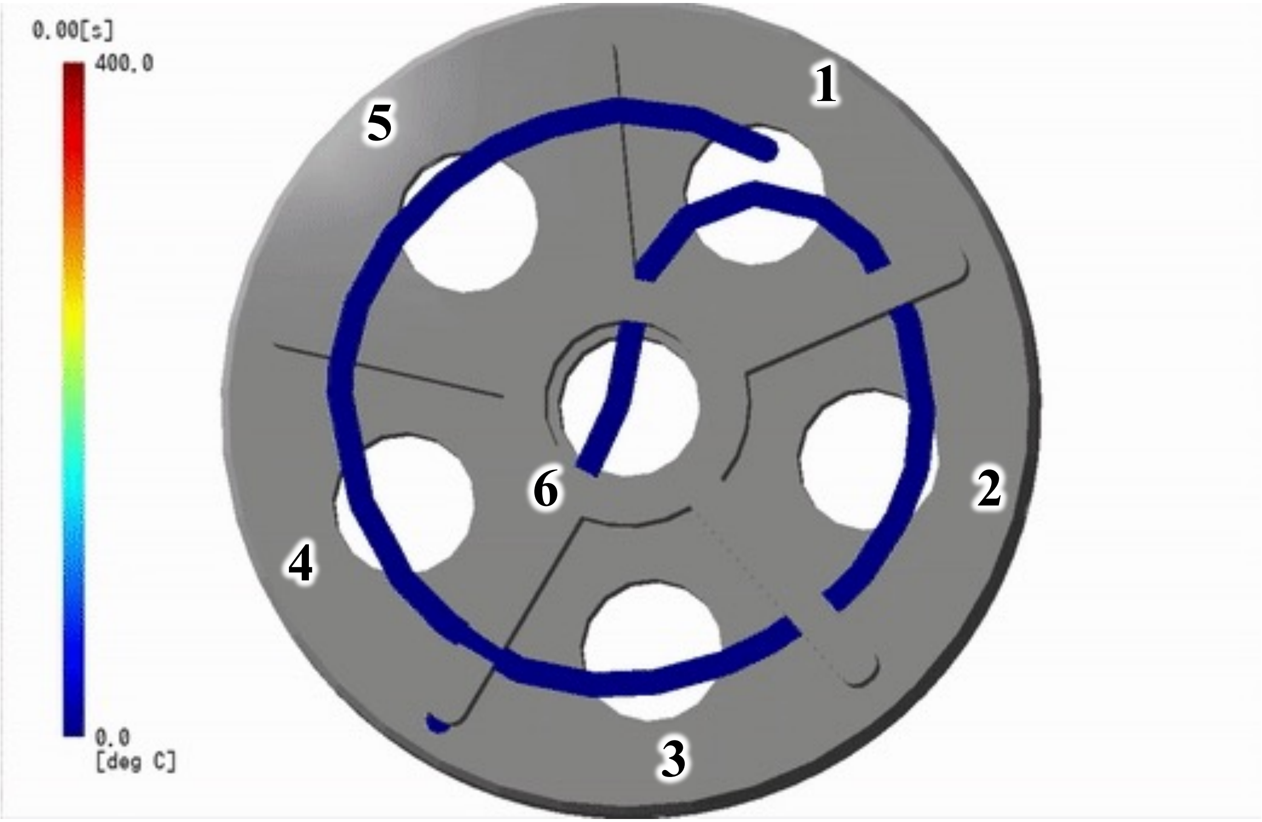
- Accurate measurements of core outlet temperature are critical to determining the total thermal power
- Gas-cooled reactors like TCR are known to have large variations in coolant outlet temperature (up to 300°C) and flow velocity (~50 to 100 m/s)
- Mixed coolant temperature also can't detect local temperature gradients or potential flow blockages that could compromise the integrity of fuel or structural materials
- It is not feasible for thermocouples to measure all coolant channel temperatures
  - Too many vessel penetrations, even for a microreactor
- **Distributed fiber optic sensors could provide ability to measure all coolant outlet temperatures with a single fiber**

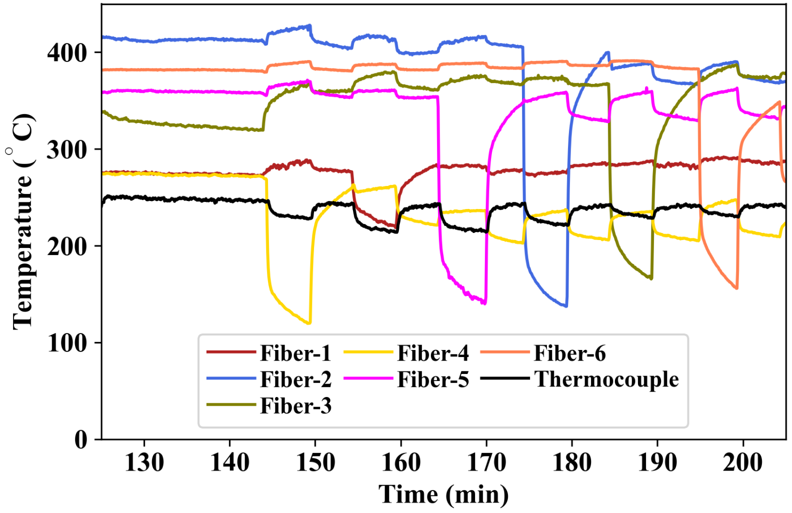


Experimental setup to mix multiple air streams using hot and cold air blowers and control valves

Demonstration results

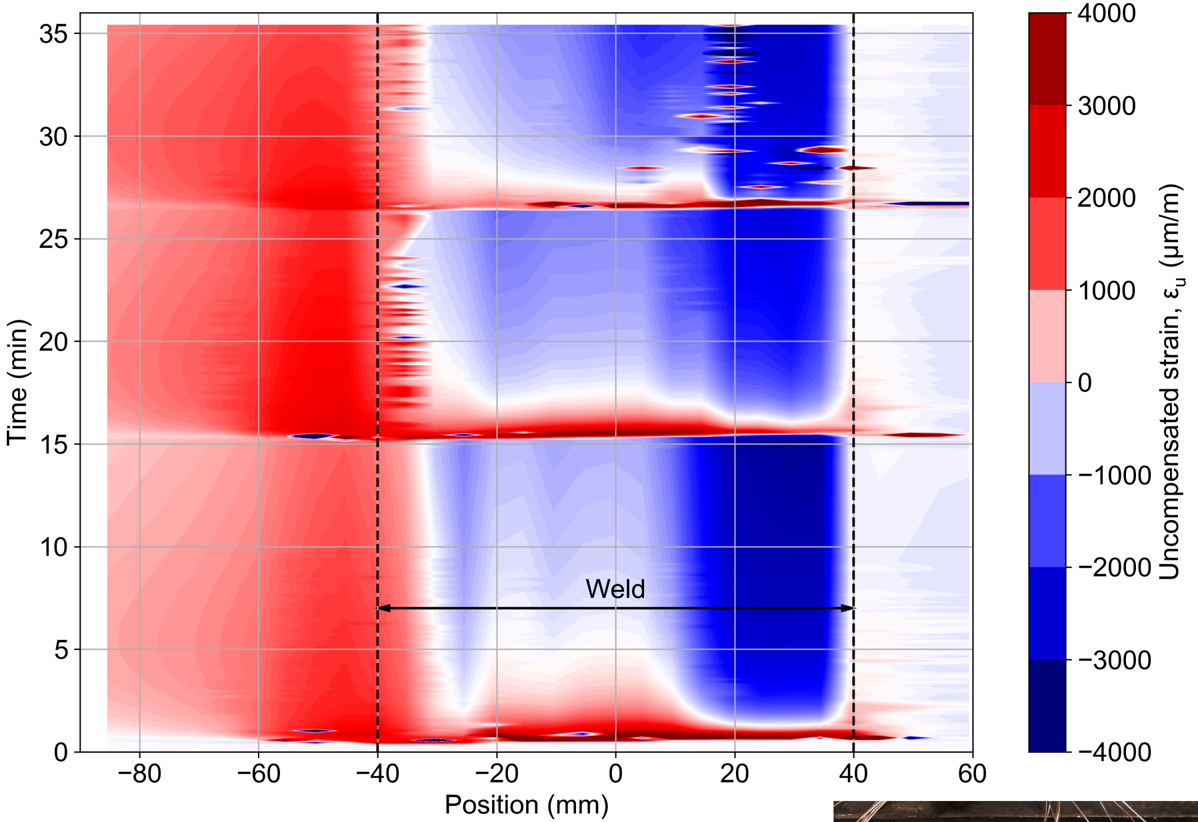




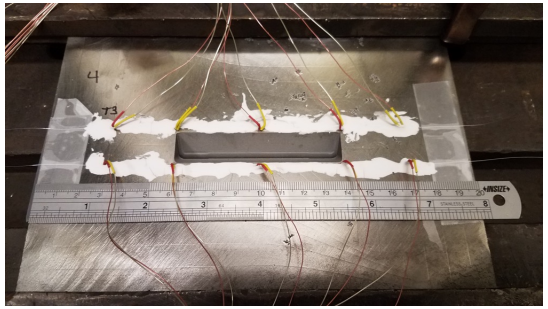


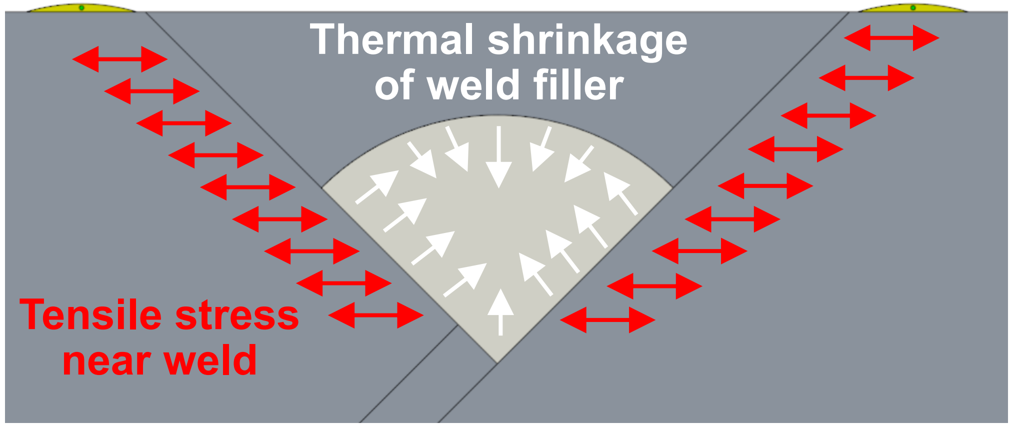
Fiber-optic sensors provide higher sensitivity and location-specific temperature variations compared to the thermocouple measuring the mixed outlet temperature.

Future opportunities: Monitoring/controlling residual strain

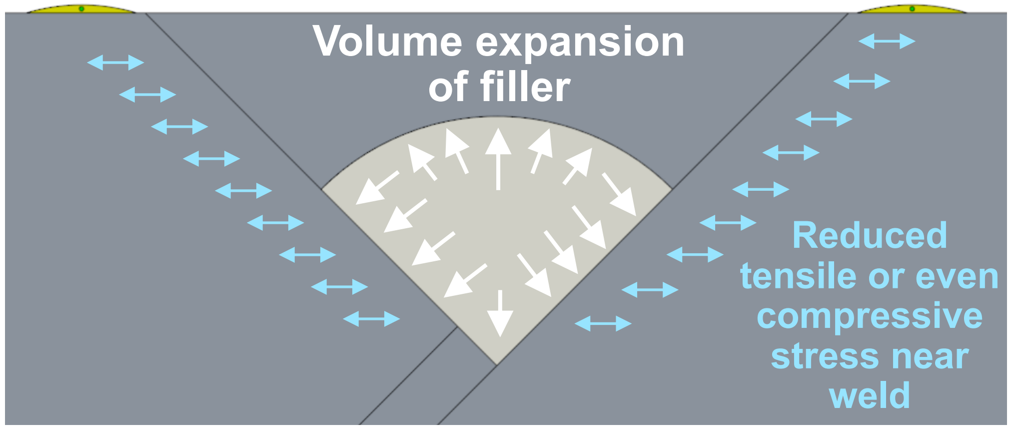


In situ strain monitoring during welding with low transformation temperature filler to induce compressive strain in heat affected zone





Typical material solidification



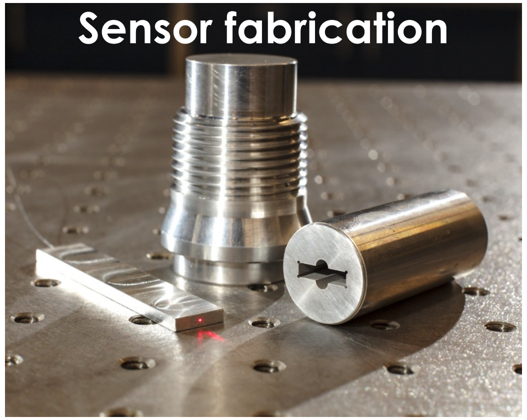
Using low transformation temperature filler that undergoes phase change during cooling

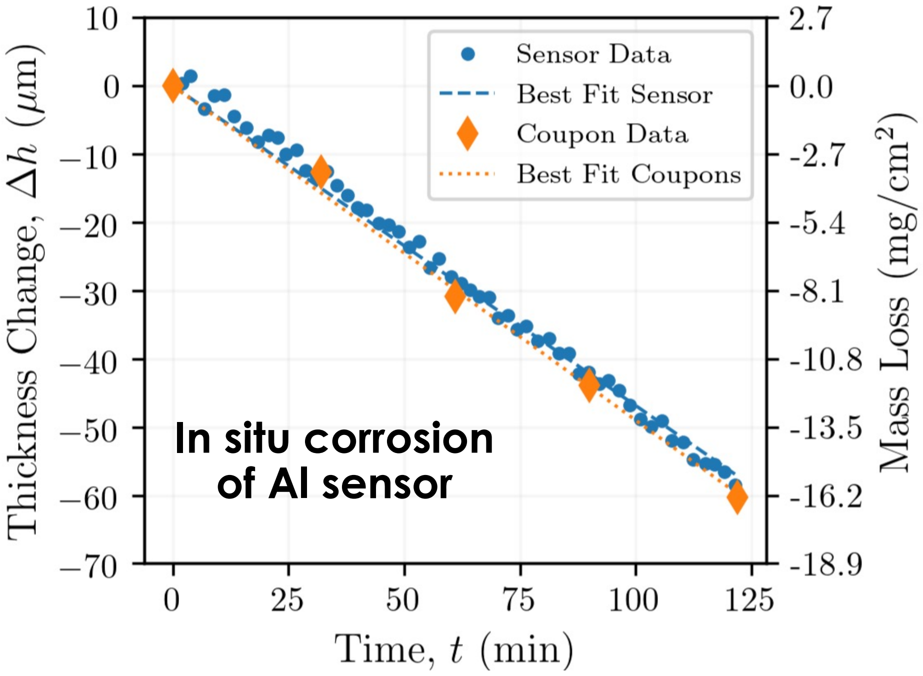
C.M. Petrie and N. Sridharan, "In situ measurement of phase transformations and residual stress evolution during welding using spatially-distributed fiber optic strain sensors," *Measurement Science and Technology* **31** (2020) 125602.

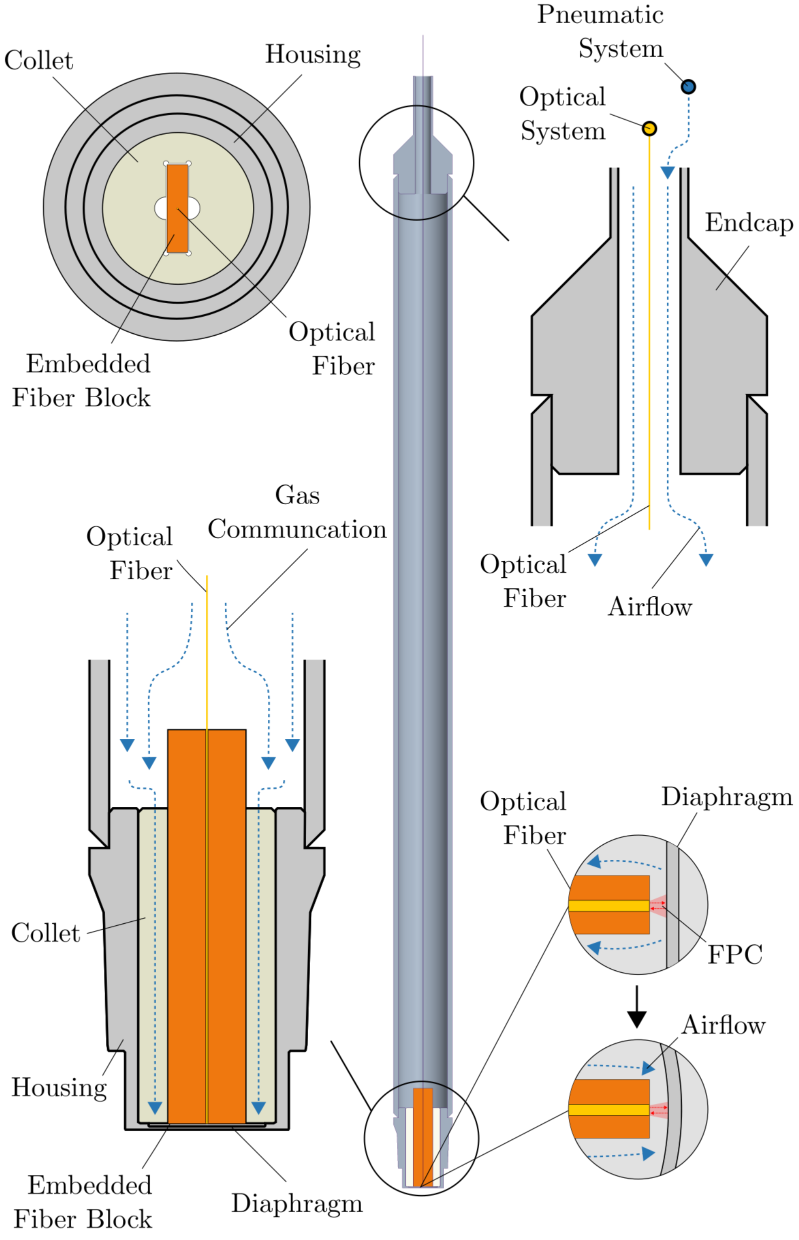
Future opportunities: Multi-modal embedded sensors for component qualification

- Metal AM-embedded optical fiber monitors diaphragm displacement
- Static external pressure
- Temperature (with inline Bragg grating)
- Flow-induced vibration, acoustic emission, or loose parts monitoring (dynamic displacement)
- Corrosion (VTR funded)
  - Sensor housing internally pressurized with gas
  - Stiffness related to diaphragm thickness, which changes as outer surface corrodes
  - Fiber doesn't have to contact fluid

Sensitivity of a microphone





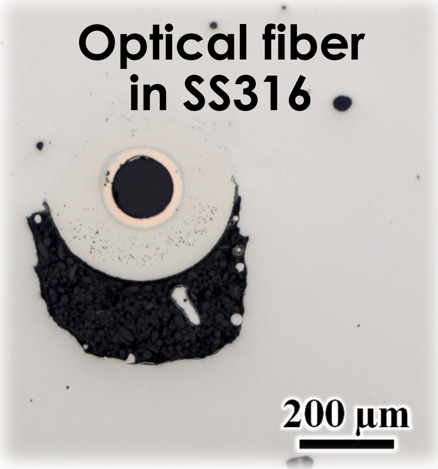


Sensor schematic [1,2]

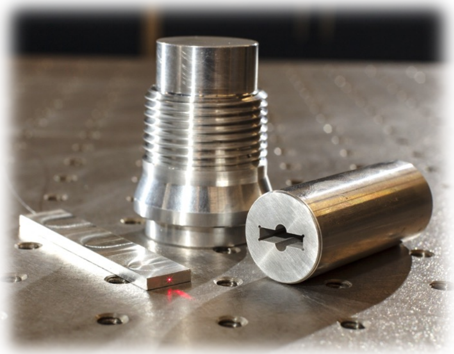
[1] D.C. Sweeney, A.M. Schrell, and C.M. Petrie, "Pressure-Driven Fiber-Optic Sensor for Online Corrosion Monitoring," *IEEE Trans. Instrum. Meas.* ***70*** (2021) 9510310.
[2] C.M. Petrie, D.C. Sweeney, and Y. Liu, US Non-Provisional Patent No. US 2021/0033479 A1, Application No. 16/865,475, published February 4, 2021.

Summary and conclusions

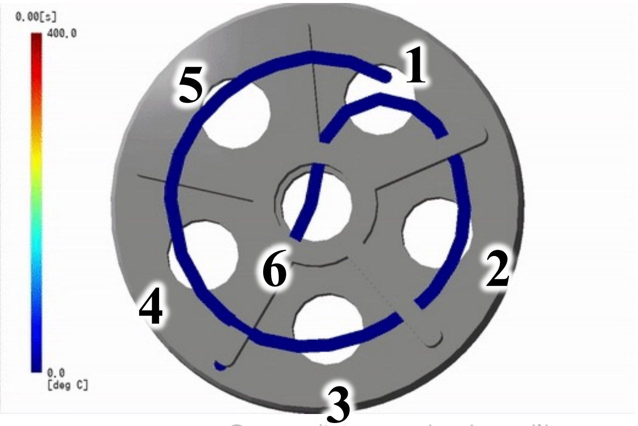
- ORNL has demonstrated the ability to embed in relevant AM nuclear materials at locations that are otherwise impossible or impractical to reach
  - SiC, SS316
  - Thermocouples, spatially distributed fiber optic temperature and strain sensors
  - Relevant temperatures (up to 1000°C)
- Industry is interested
  - USNC has license SiC sensor embedding
  - AMS has active SBIR work to evaluate quality of metal-embedded sensors
- Now we are thinking about how to extend this technology to a wider range of applications
  - Monitoring/controlling residual strain during AM
  - Multi-modal sensor integration for component qualification (pressure, temperature, corrosion, flow-induced vibration, acoustic emissions, loose parts monitoring)



TCs in SiC



Multi-modal AM-embedded sensor



Local core outlet temperature monitoring

Questions?

Chris Petrie, petriecm@ornl.gov

Oak Ridge National Laboratory