Oak Ridge National Laboratory

Integral Fuel Rod Real-Time Wireless Sensor & Transmitter Irradiation Test and Post Irradiation Examination

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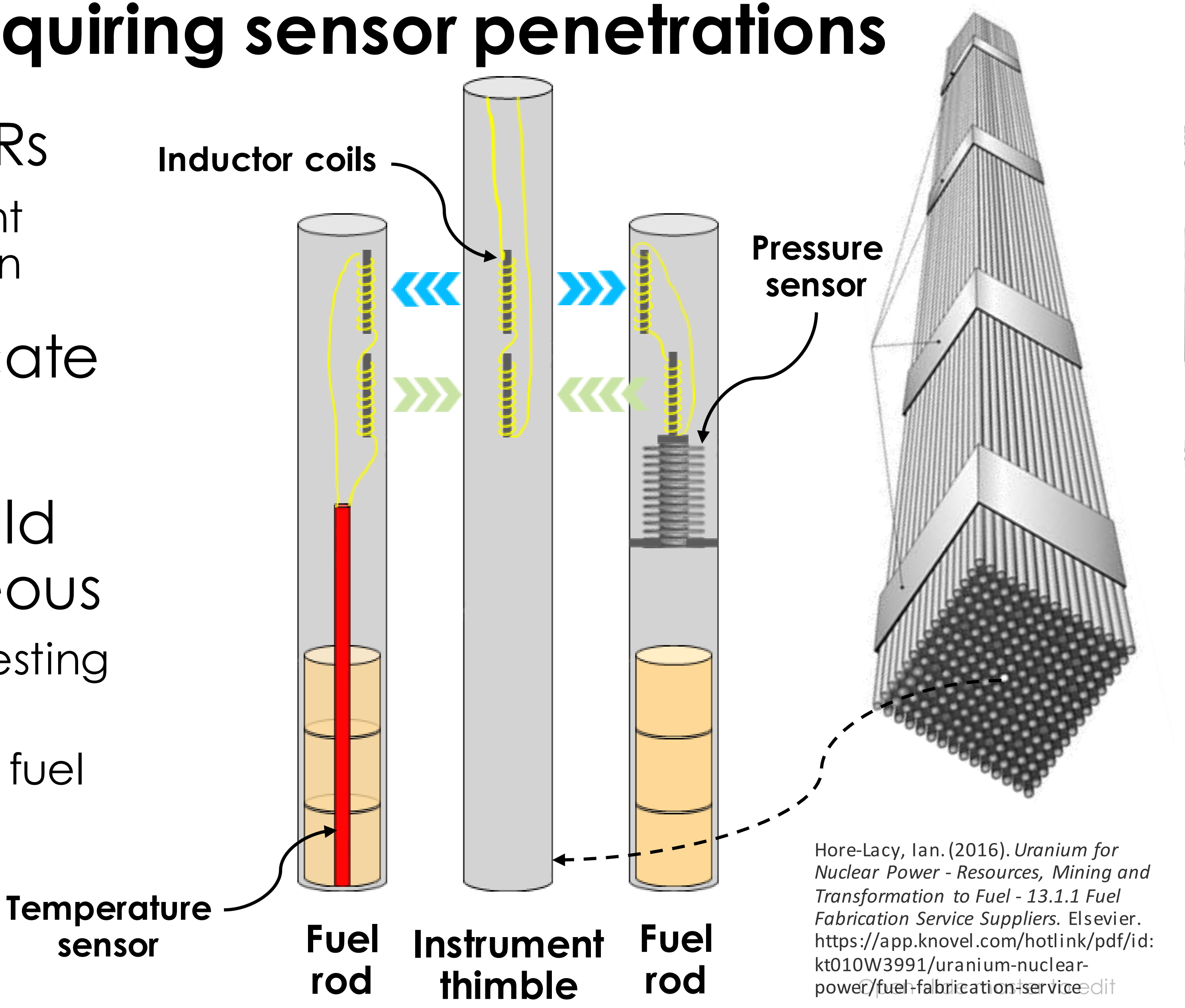
U.S. DEPARTMENT OF ENERGY

Motivation: Online monitoring of fuel rod temperature and pressure without requiring sensor penetrations

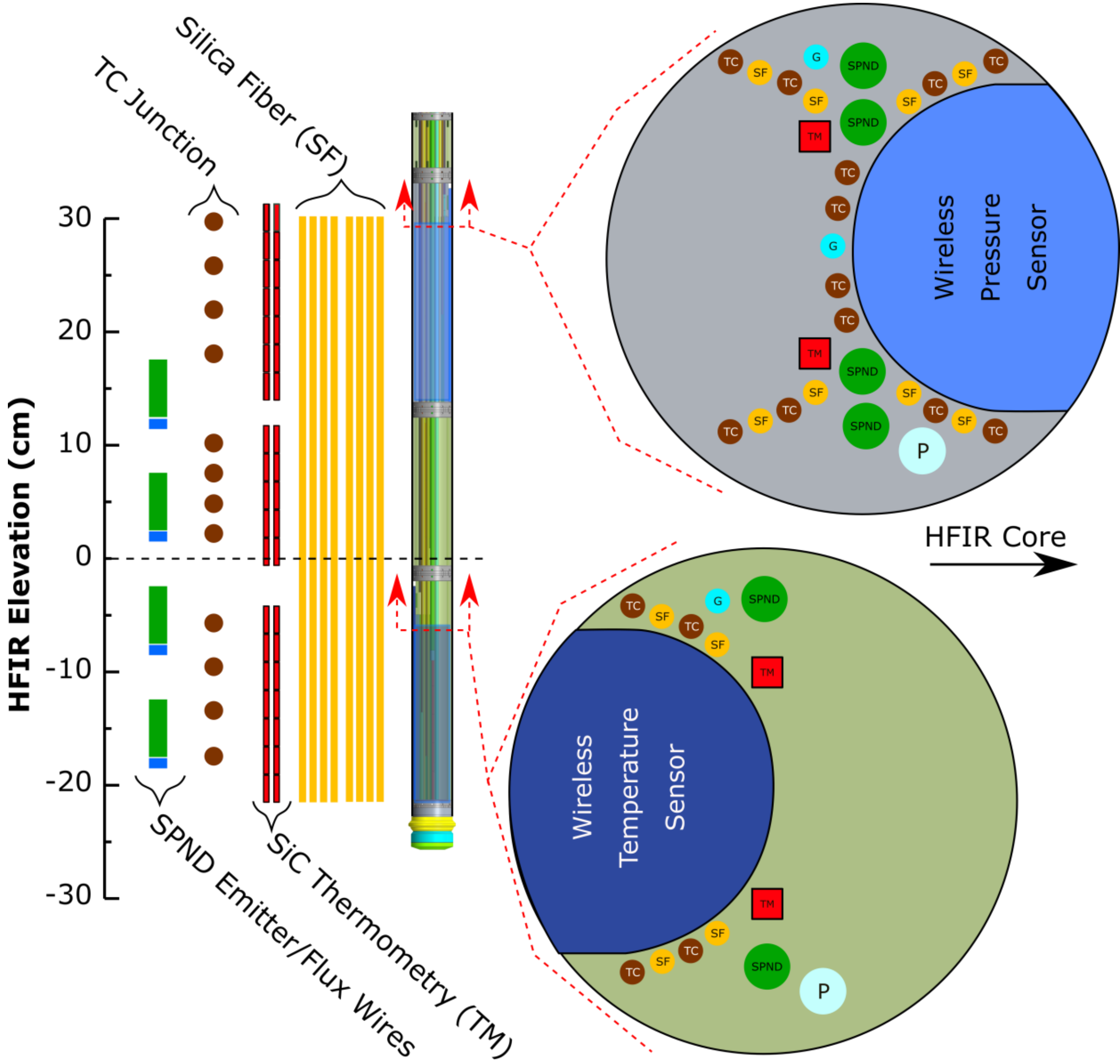
- Goal: In situ data from LTRs
  - Assist in qualification of accident tolerant fuel or burnup extension
- Instrument leads complicate fuel handling
- Wireless transmission would be extremely advantageous
  - Encouraging results from MITR testing
  - Need to demonstrate at high neutron fluence under relevant fuel operating conditions



Hore-Lacy, Ian. (2016). *Uranium for Nuclear Power - Resources, Mining and Transformation to Fuel - 13.1.1 Fuel Fabrication Service Suppliers.* Elsevier. https://app.knovel.com/hotlink/pdf/id:kt010W3991/uranium-nuclear-power/fuel-fabrication-service

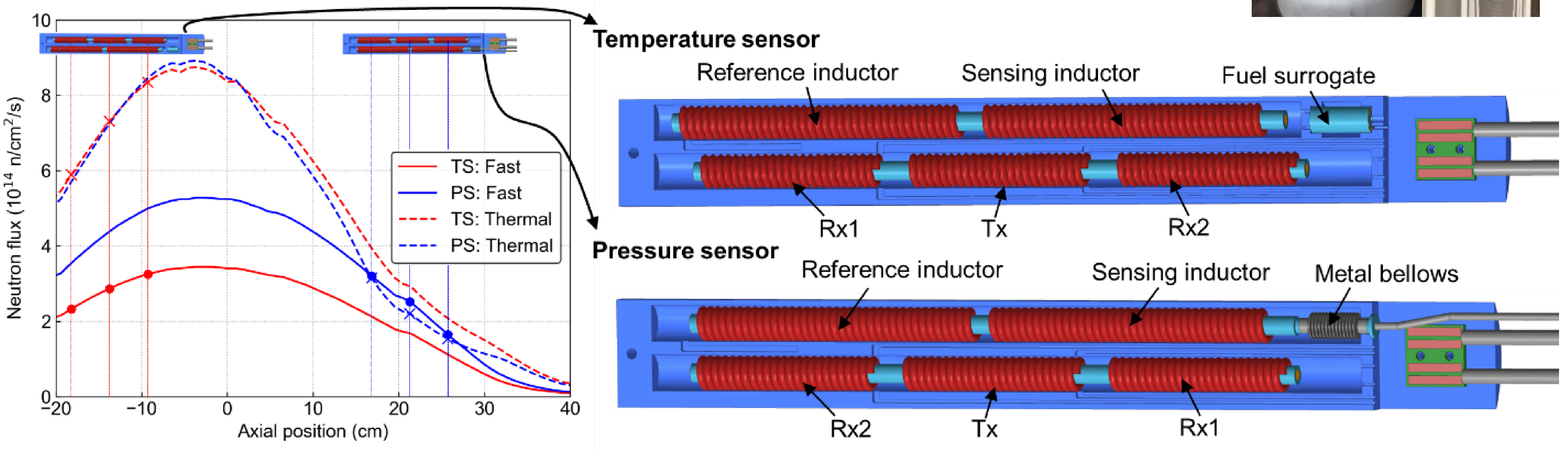
WIRE-21: HFIR's most highly instrumented experiment

- **Primary goal:** Irradiate WEC's wireless temperature & pressure sensors at LWR temperatures
- **Broader goal:** Develop a platform for economical, accelerated testing of advanced sensors
  - Thermocouples (14)
  - Distributed fiber optic temperature sensors (8)
  - Self-powered neutron detectors (4)
  - Passive SiC temperature monitors (38) and flux wires (4)
- Completed 3 HFIR cycles
  - ~3×10^{21} n_{fast}/cm^2
  - ~6×10^{21} $n_{thermal}/cm^2$



WEC's inductively coupled sensor technology

- Wireless transmission to passive circuit with varying resistance (RTD on fuel surrogate) or inductance (core driven by metal bellows)
- Reference inductors account for effects of radiation, inductor temperatures
- Similar fast neutron flux for both sensors (~1.6–3.3×10^{14} n/cm^2/s)
- Thermal neutron flux much larger in temperature sensor vs. pressure sensor



Experiment insertion into HFIR

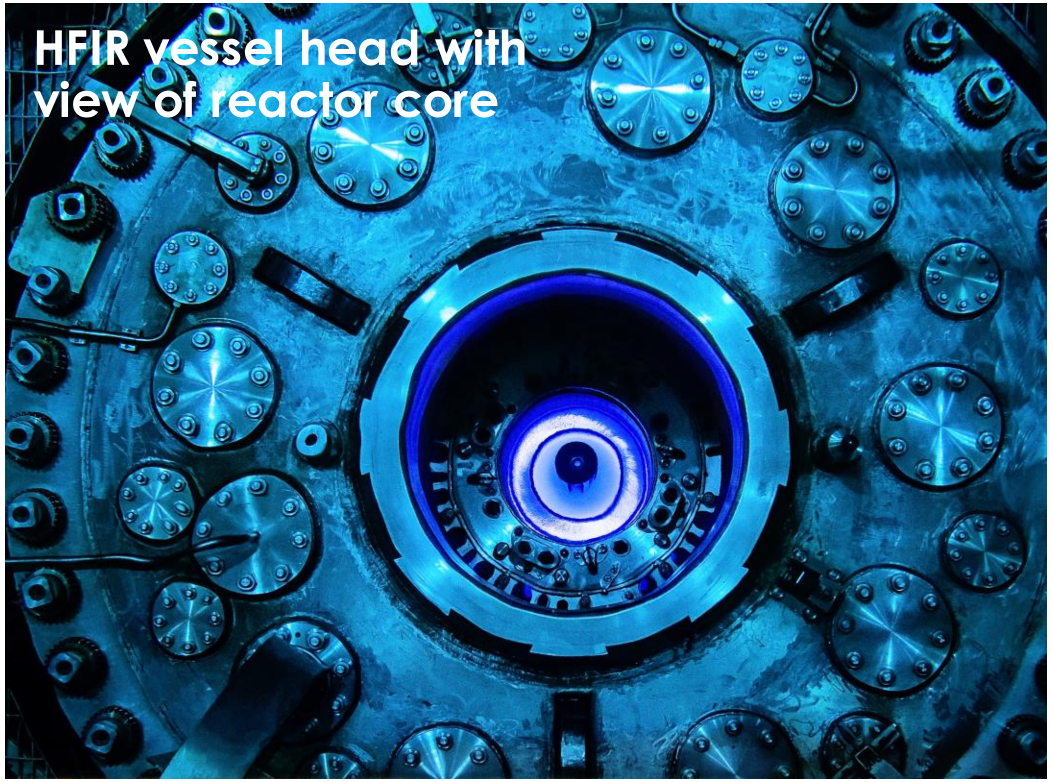
Nuclear Science User Facilities

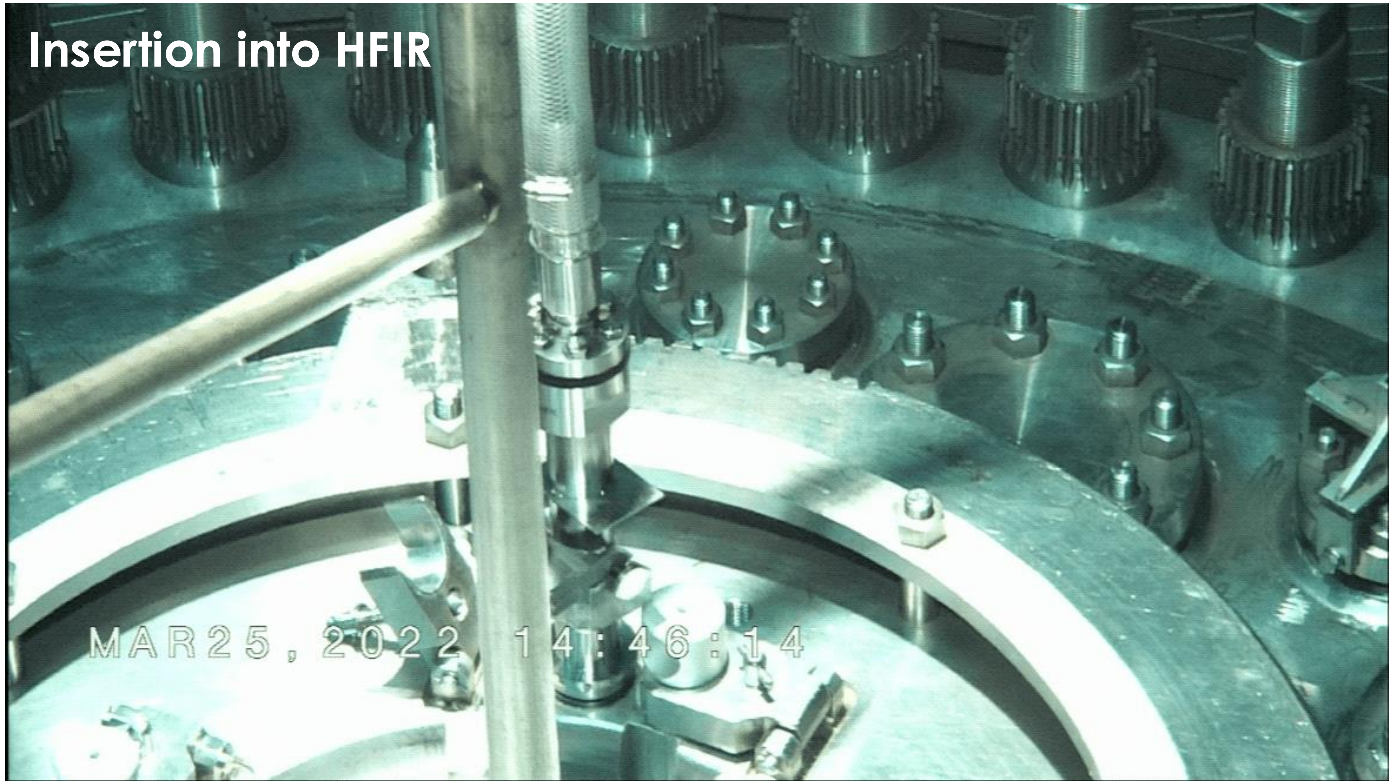
Hoisting


Lowering into pool

Storage prior to insertion


In-pool sensor connections

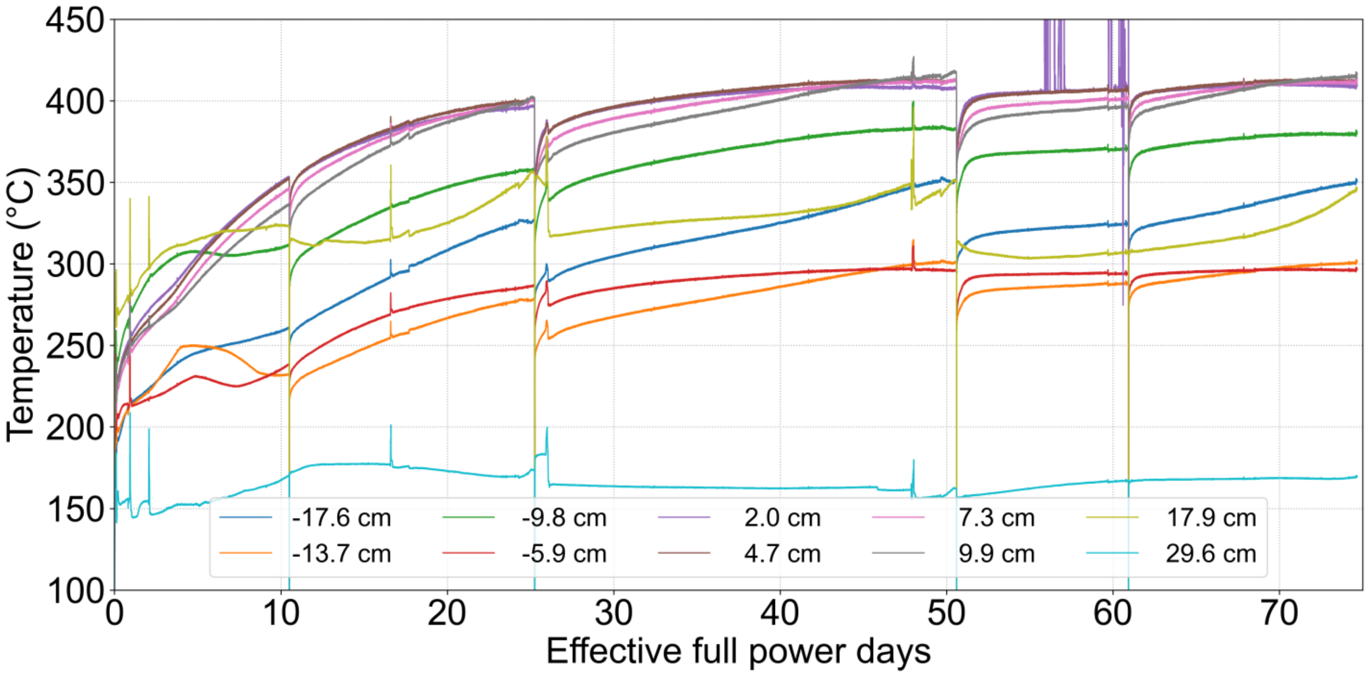

HFIR vessel head with view of reactor core

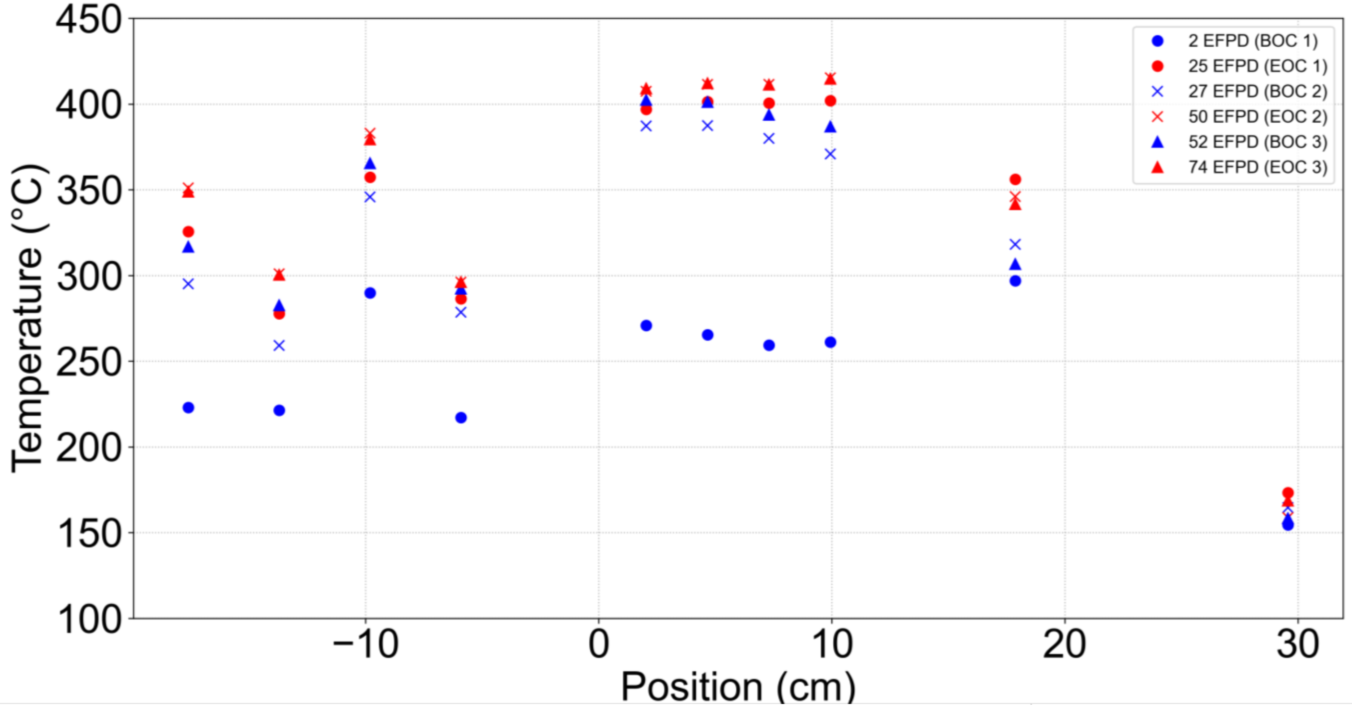


Insertion into HFIR

Operation

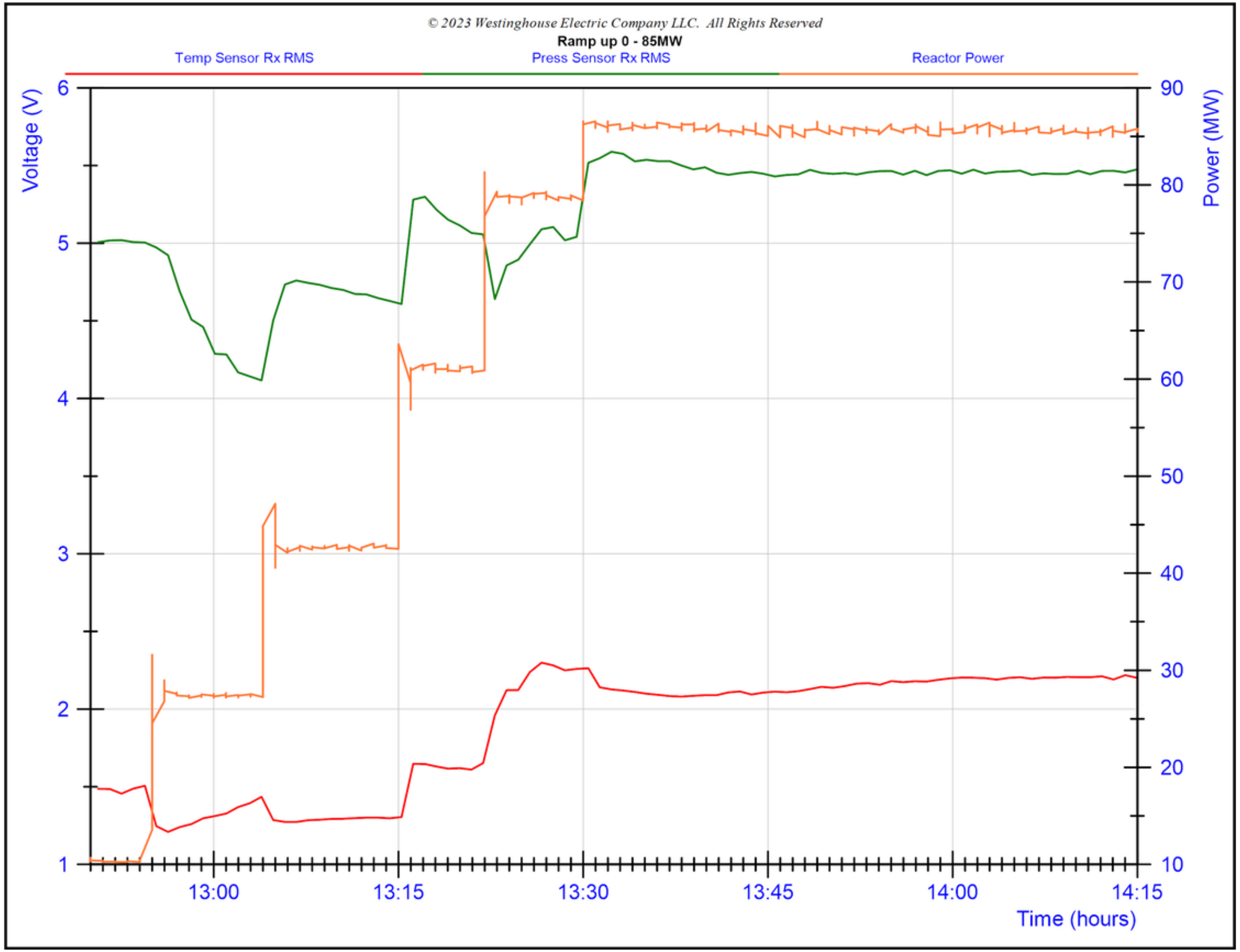
- 3 HFIR cycles completed, 75 effective full power days
- Peak neutron fluence
  - Fast (E>0.1 MeV): 3×10^{21} n/cm^2
  - Thermal (E<1 eV): 6×10^{21} n/cm^2
- Achieved target of ~300–400°C
  - All 10 sheathed TCs survived
  - 2 exposed TCs inside WEC sensors failed
  - Lower temperatures above active fueled region (>25 cm)
  - Initial increases thought to be caused by compaction of graphite holders





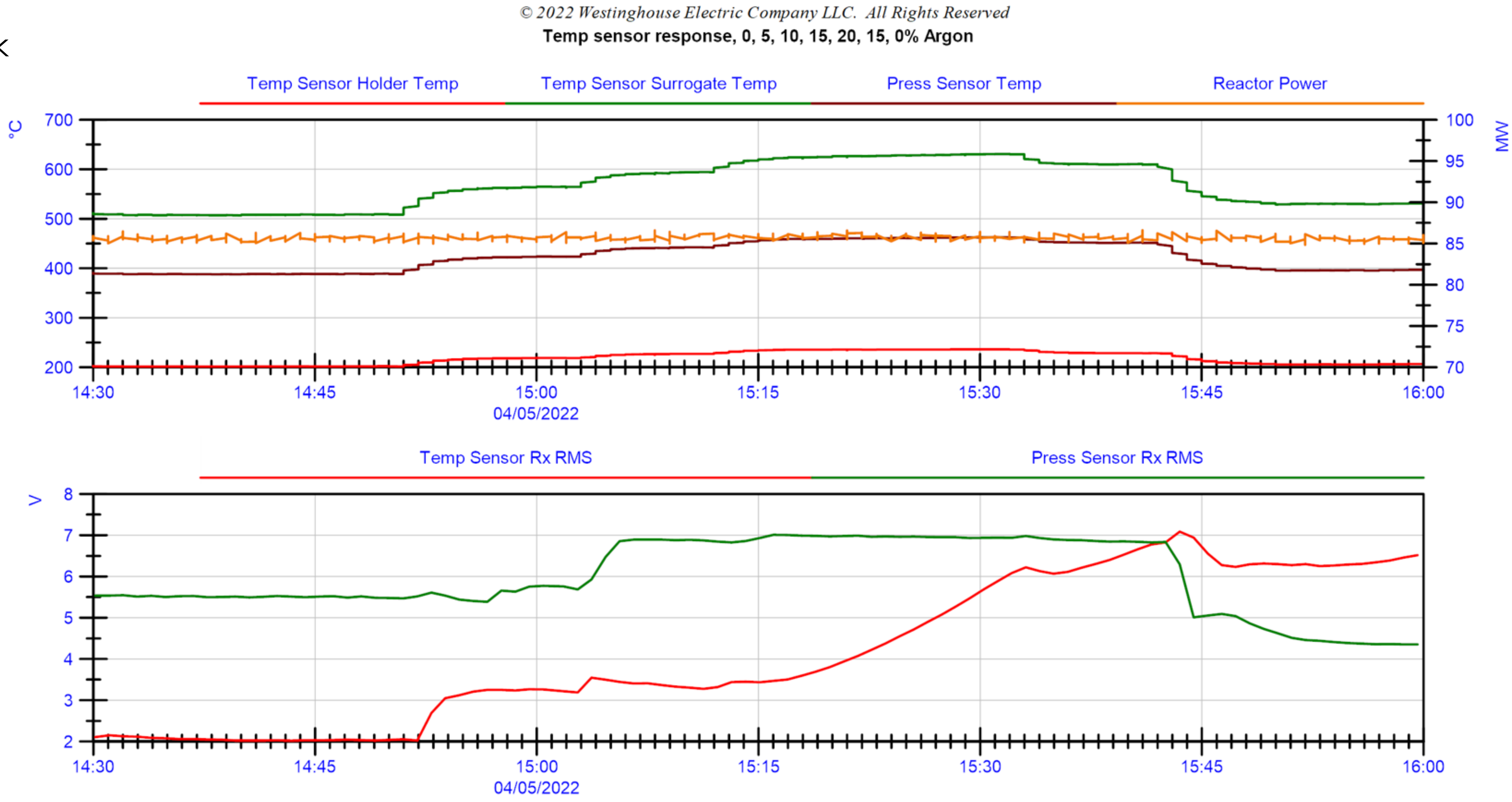
WEC's sensor response during 1st HFIR cycle

- Sensors responded during ascent to full power
- Response not exactly as expected but stabilized at steady state



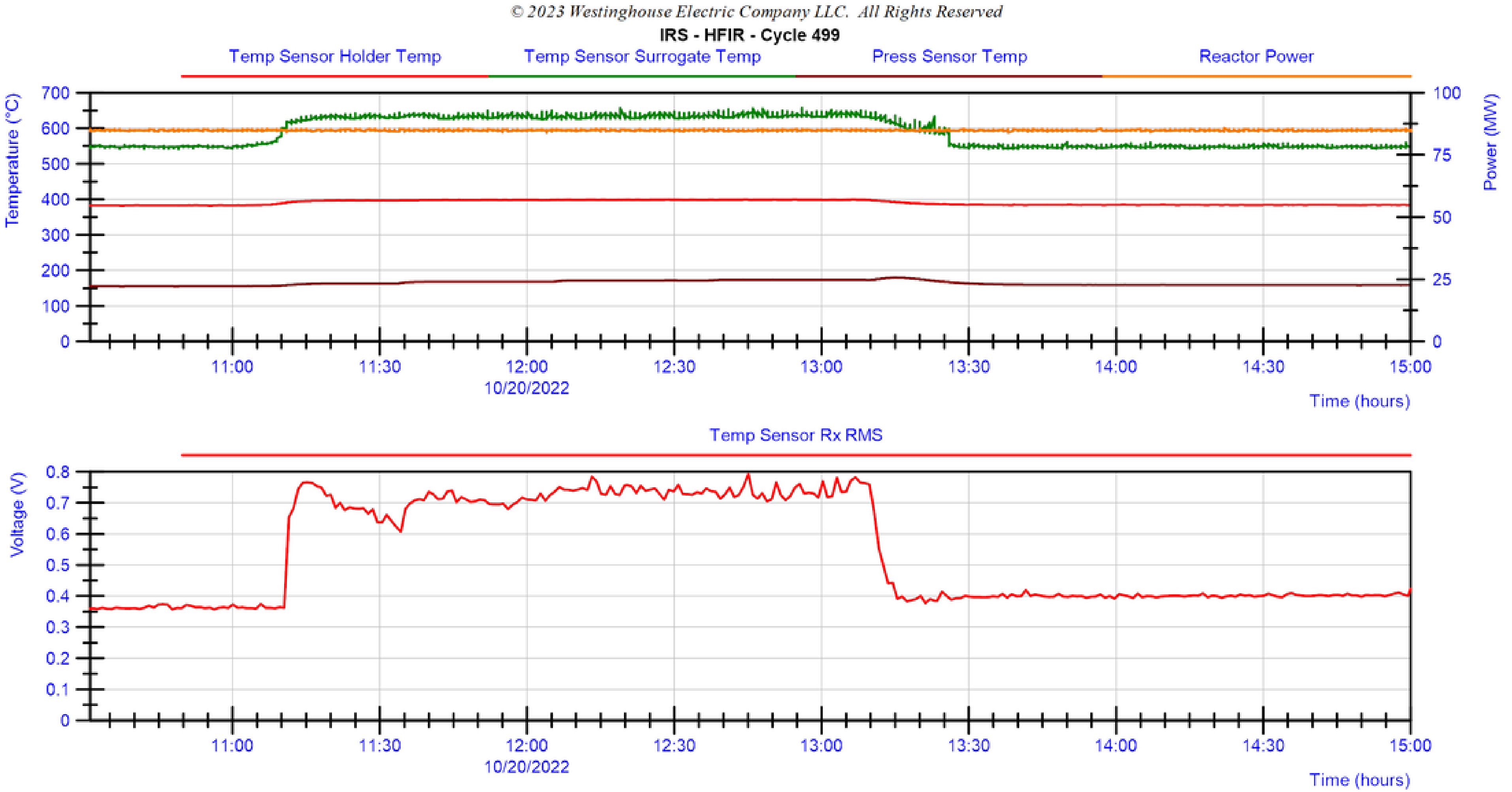
WEC’s response during pressure/temperature transients

- Signal did not track exactly with thermocouple
- Clearly some hysteresis in both sensor signals
  - Temperature: 2 to 6.5 V
  - Pressure: 5.5 to 4.5 V
- Pressure sensor did not respond at all to changes in pressure

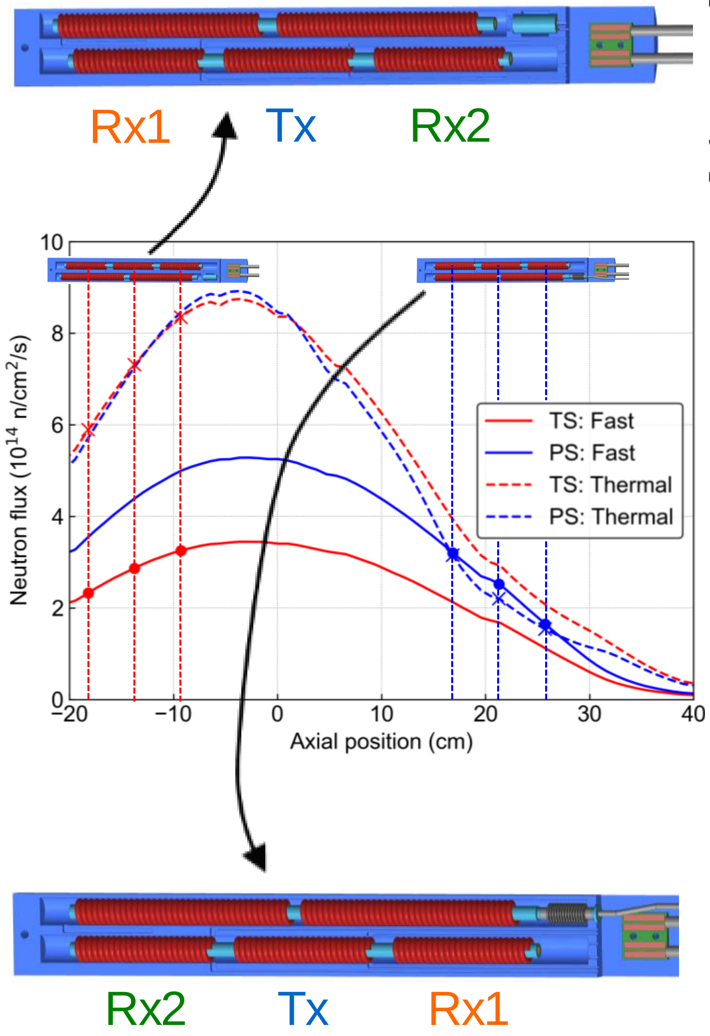


Temperature transient during 2nd HFIR cycle

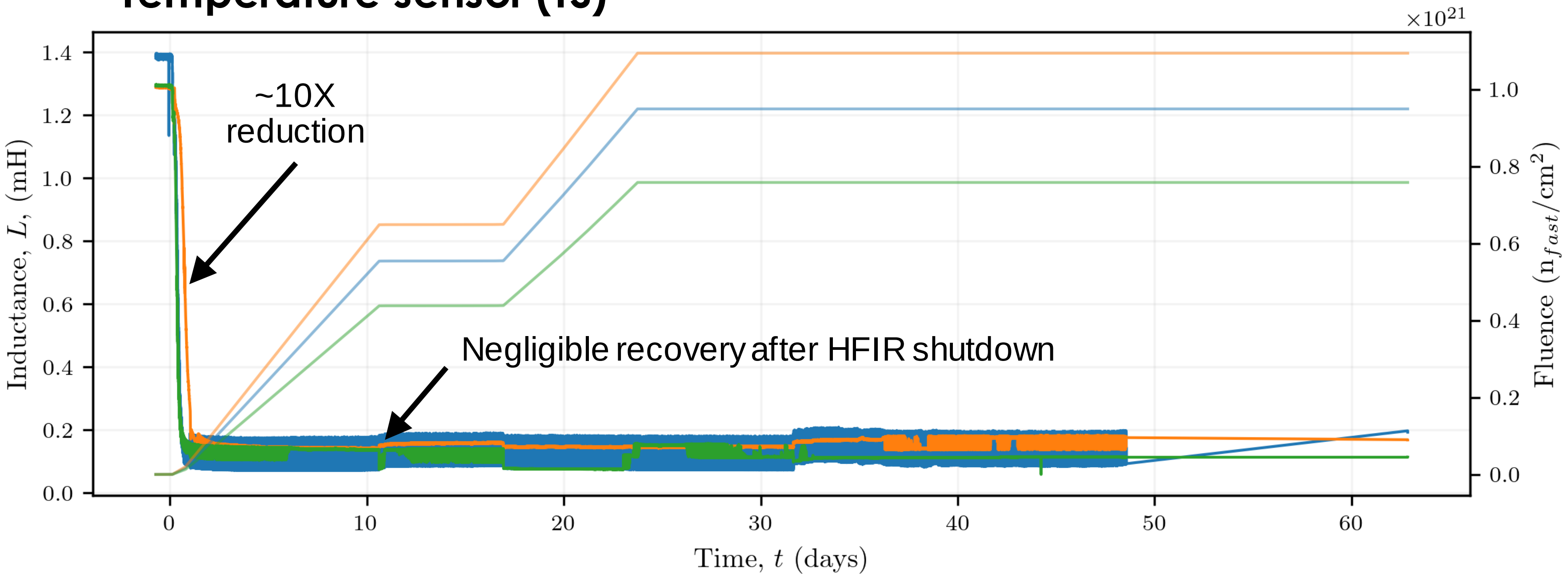
- Signals dropped relatively quickly during the first cycle
  - 6.5 V after 1st cycle transient to 0.35 V
- Sensor still responded as expected to a temperature transient performed in the 2nd cycle



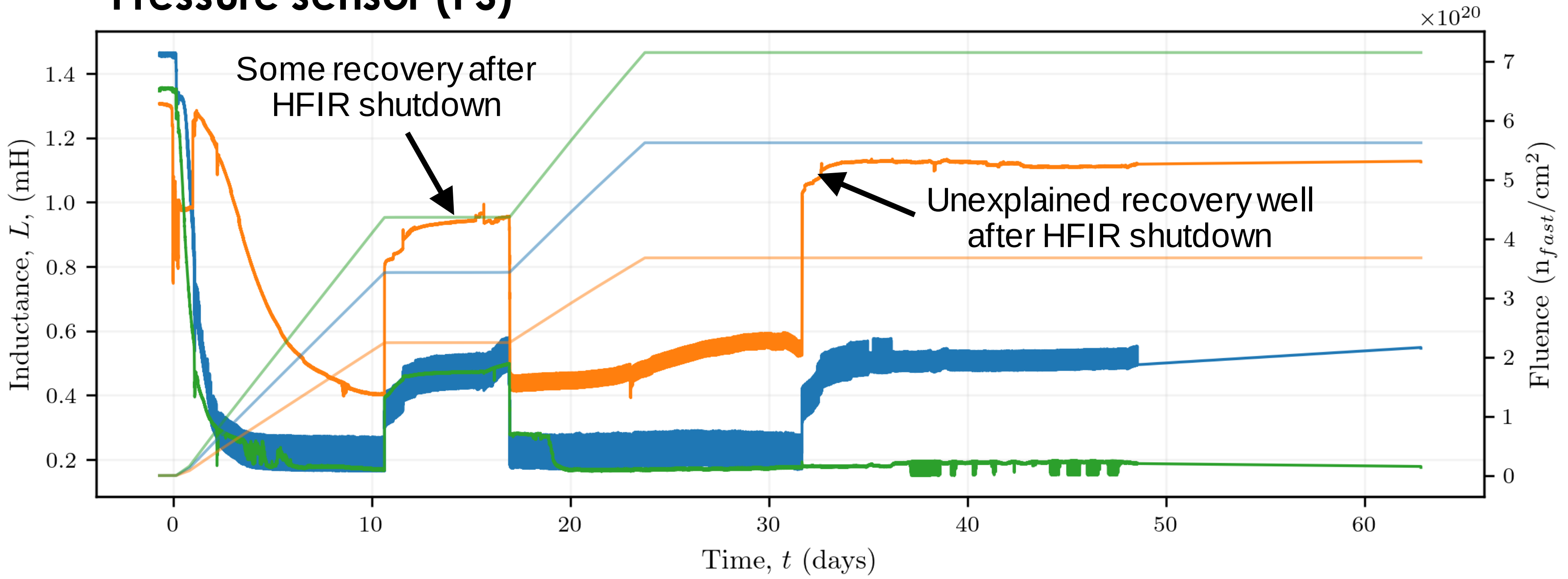
WEC Sensor Inductance Evolutions



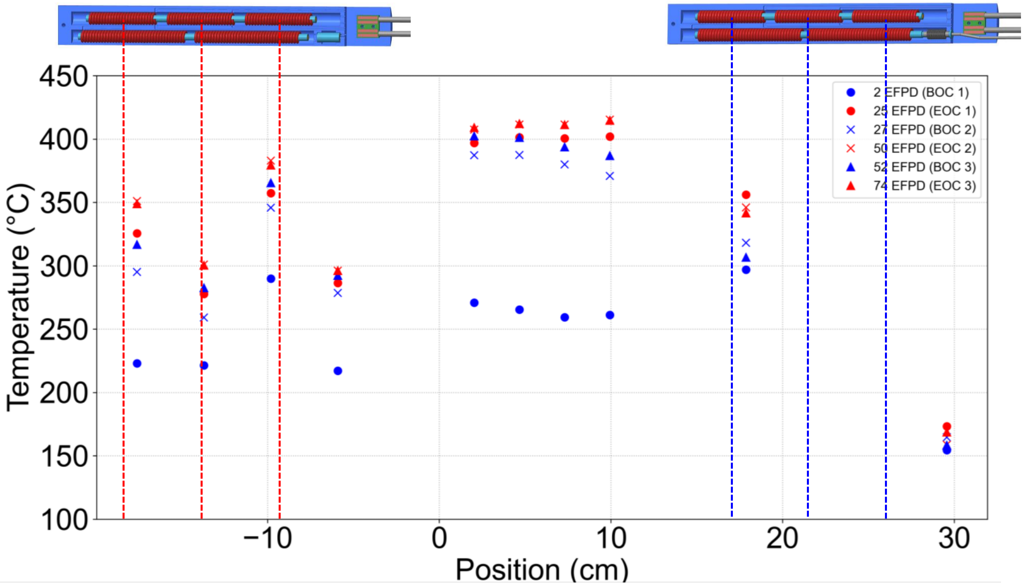
Temperature sensor (TS)



Pressure sensor (PS)

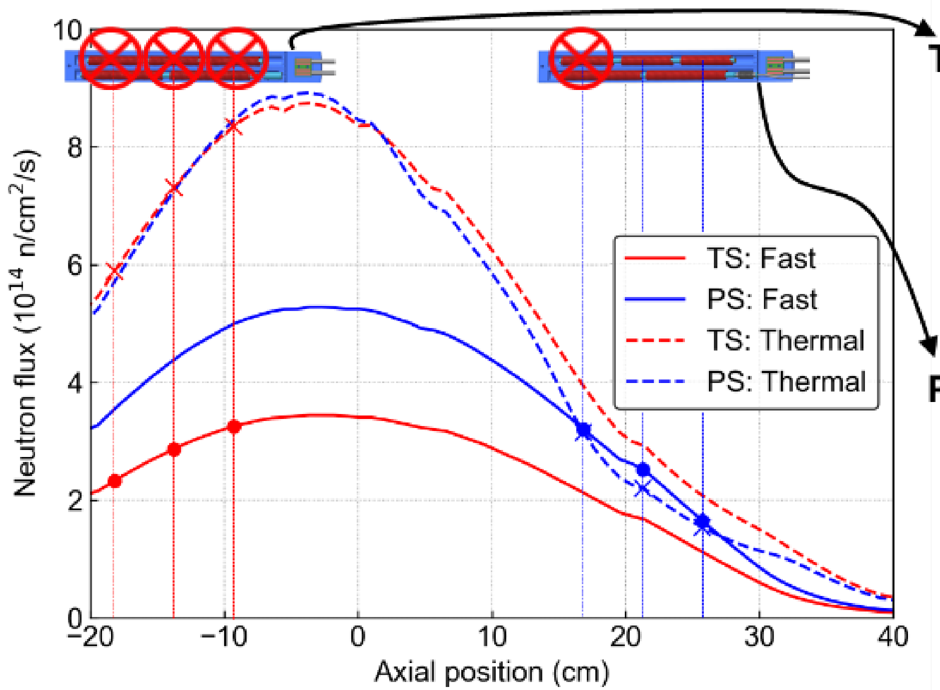


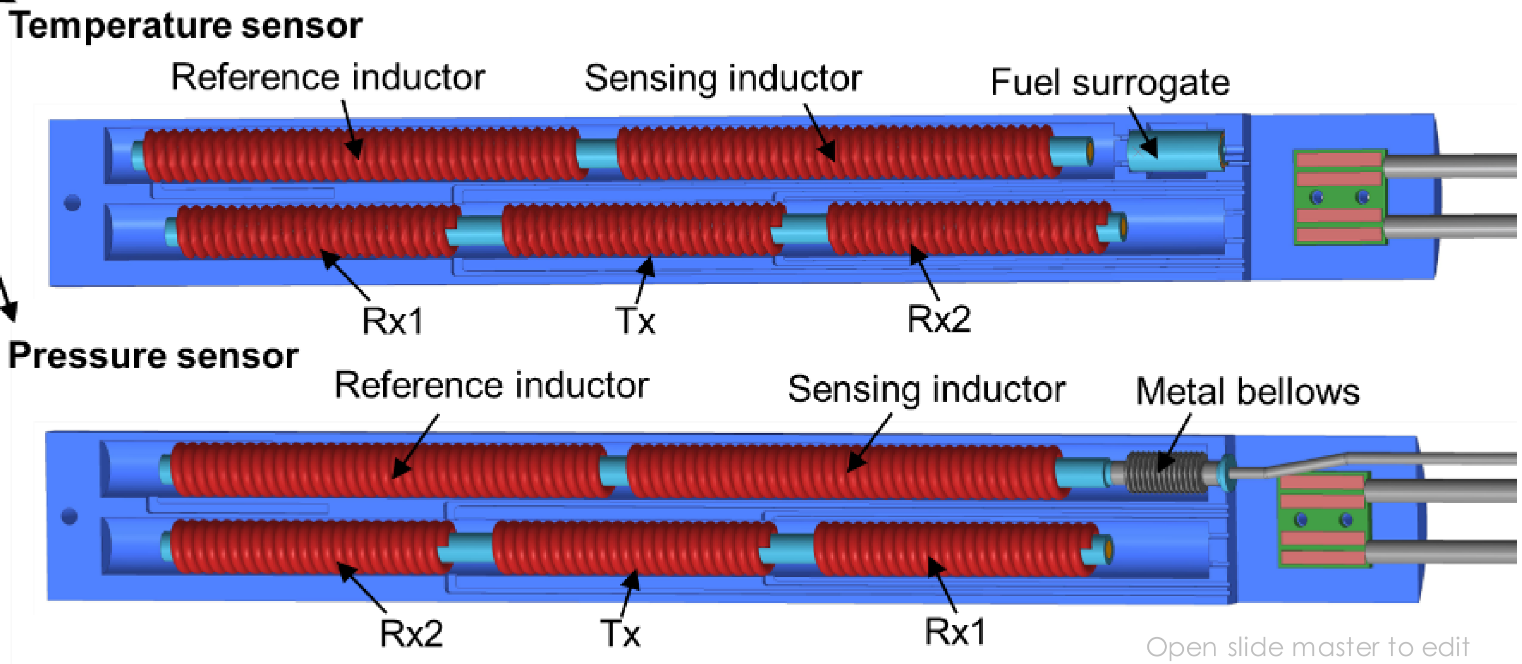
WEC Sensor Inductance Evolutions



~10X reductions in inductance within 2 days, with minimal (~10%) changes in resistance

- Not observed in previous MITR tests at lower flux
- More significant in inductors with higher *thermal* flux
- Similar fast flux in all inductors
- Recovery after reactor scram only observed in 2 inductors tested at lower thermal flux
- All except Rx1 in PS (~25 cm, ~150°C) ran at ~200–300°C during initial drop in inductance
  - Temperature effects should also recover





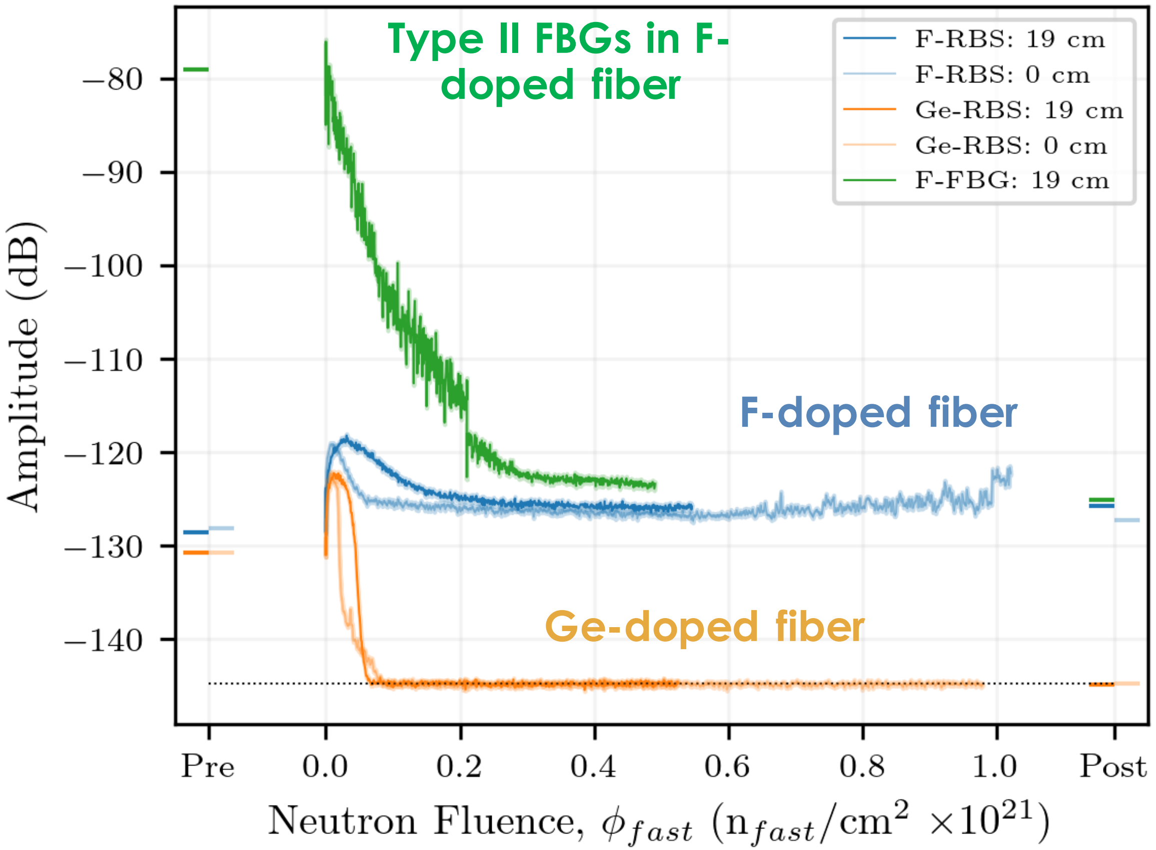
Fiber test matrix

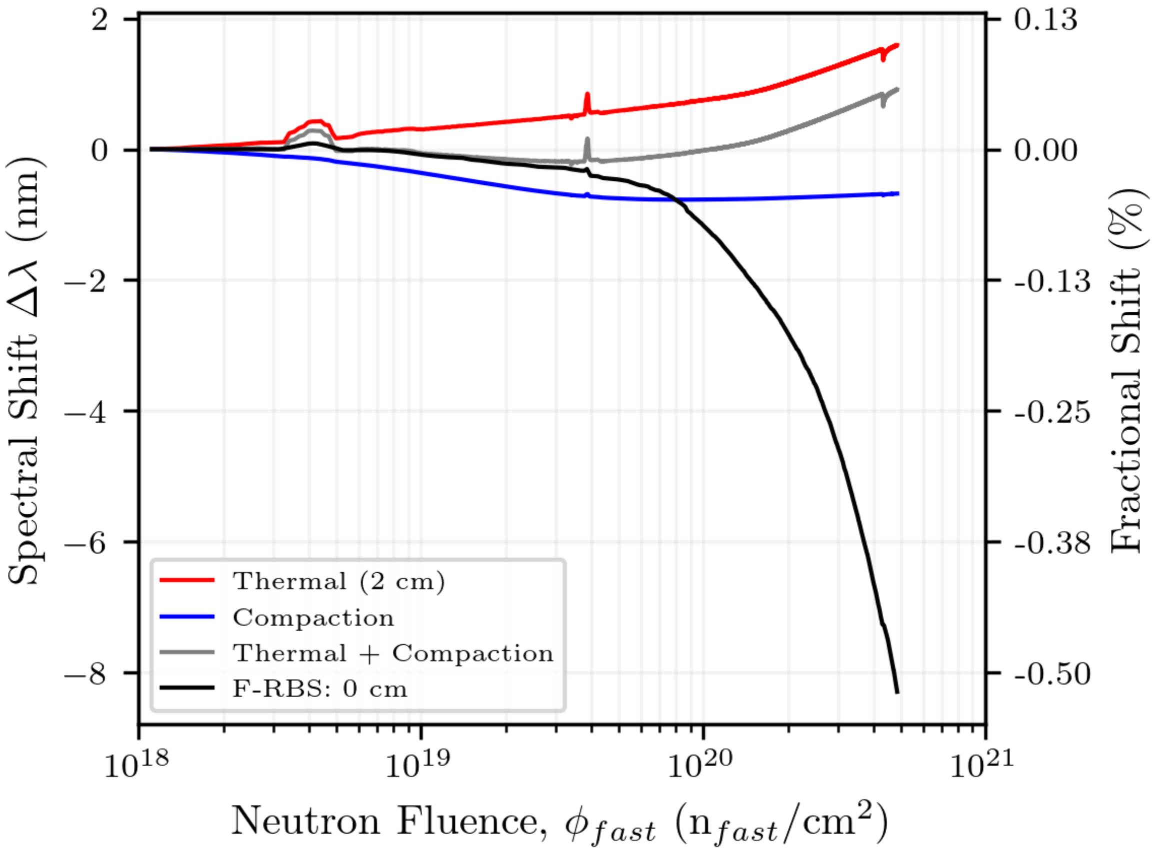
Goal is to understand differences in signal attenuation and drift at high neutron fluence

- Fibers with and without gratings
- Singlemode and hollow core fibers
- Varying fiber dopants (F, Ge)
- Varying grating types (Type I and II)

Fiber	Description	Gratings
1	Pure SiO_2 core, F-doped SiO_2 cladding	N/A
2	Ge-doped SiO_2 core, pure SiO_2 cladding	
3	F-doped SiO_2 core and cladding with Type II gratings	Type II, ~1% reflectivity, ~65 mm spacing
4		
5	Pure SiO_2 core, F-doped SiO_2 cladding with Type II gratings	Type II, ~0.5% reflectivity, ~10 mm spacing
6	Ge-doped SiO_2 core, pure SiO_2 cladding with Type I gratings	Type I, <0.1% reflectivity, ~10 mm spacing
7	Hollow core photonic crystal fiber	N/A
8		

Results: Good and Bad News for F-doped Fibers





Drastic differences in reflected signal amplitudes at high neutron fluence

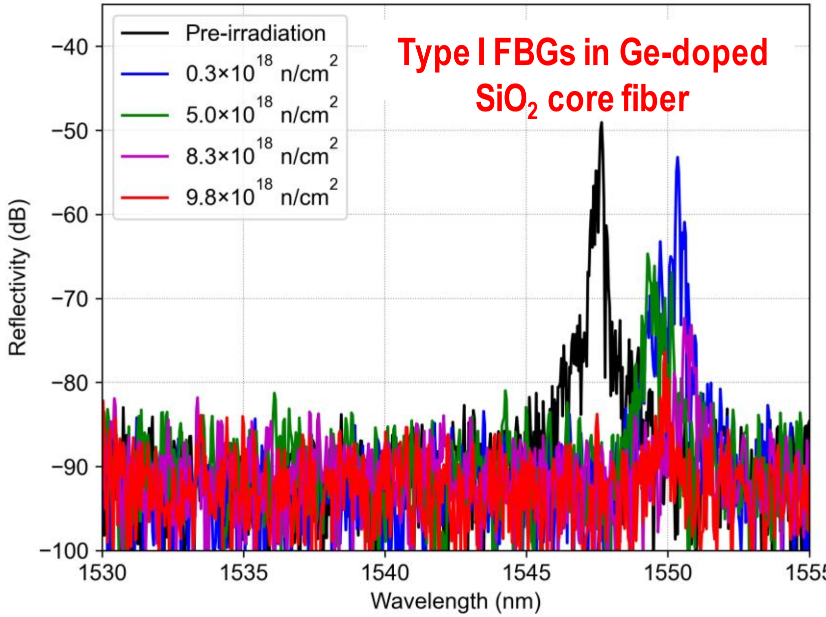
Measured spectral shifts (temperatures) deviate from thermal + compaction models at high neutron fluence (suspected fiber coating effect)

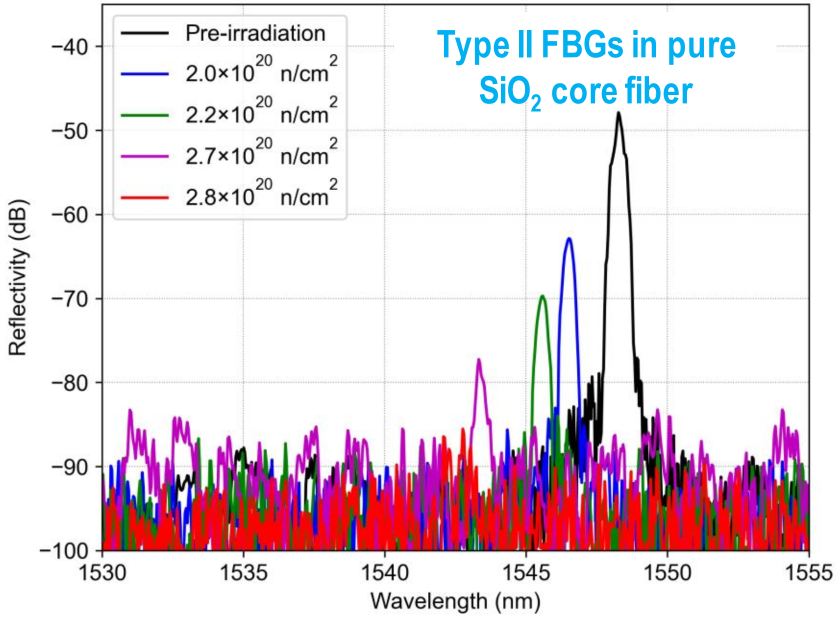
C.M. Petrie and D.C. Sweeney, "Enhanced backscatter and unsaturated blue wavelength shifts in F-doped fused silica optical fibers exposed to extreme neutron radiation damage", *J. Non-Cryst. Solids* **615** (2023) 122441
doi.org/10.1016/j.jnoncrysol.2023.122441

Results: Gratings

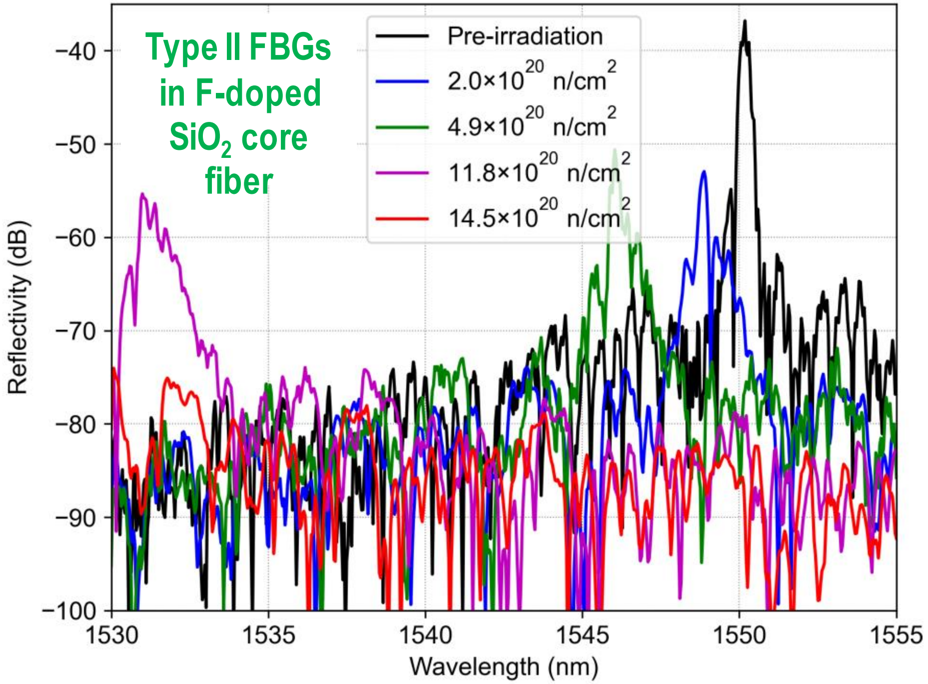
Core dopants and FBG type have strong effect on FBG stability

- Type I FBGs in Ge-doped core fiber erased within 2 days of irradiation (not shown)
- Type II FBGs in pure SiO_2 core fiber attenuated >40 dB during first cycle
- Type II FBGs in F-doped core fiber survived entire experiment but still drifted significantly





D.C. Sweeney et al., "Analysis of WIRE-21 SPND and Optical Fiber Sensor Measurements", ORNL/TM-2023/2024(2023) doi.org/10.2172/1997703



Summary

Novelty

- Most highly instrumented experiment ever conducted in HFIR
- WEC's wireless sensor exposure equivalent to ~1 PWR operating cycle
- Fiber optics tested under highest neutron flux ever reported
- 1st ever testing of SPNDs in HFIR

Results

- WEC sensors performed as expected during installation and startup
  - Change in inductance, due to degradation in permeability of ferromagnetic rod, during the first few hours of testing was greater than expected, reducing coupling sensitivity between transceiver and sensor
  - Not observed in MITR or Halden Reactor (lower neutron flux)
  - Plan to investigate potential degradation mechanisms (transmutation vs. displacement damage)
- Initial fiber optic results show very strong signals but prohibitively large drift
  - Fiber transmission and FBG performance strongly depend on fiber dopants
  - Ongoing ASI efforts to understand effects of fiber coating on observed drift
- SPND and thermocouple data will be useful to compare with passive measurements (SiC temperature monitors, activation wires) under ASI

Questions?

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