INL/CON-23-72797-Revision-0

Retractable Sensors for In-Core Service in Material Test Reactors

June 2023

Changing the World's Energy Future

Joe Palmer, Austin D Fleming, Randel N Paulsen, Troy Unruh

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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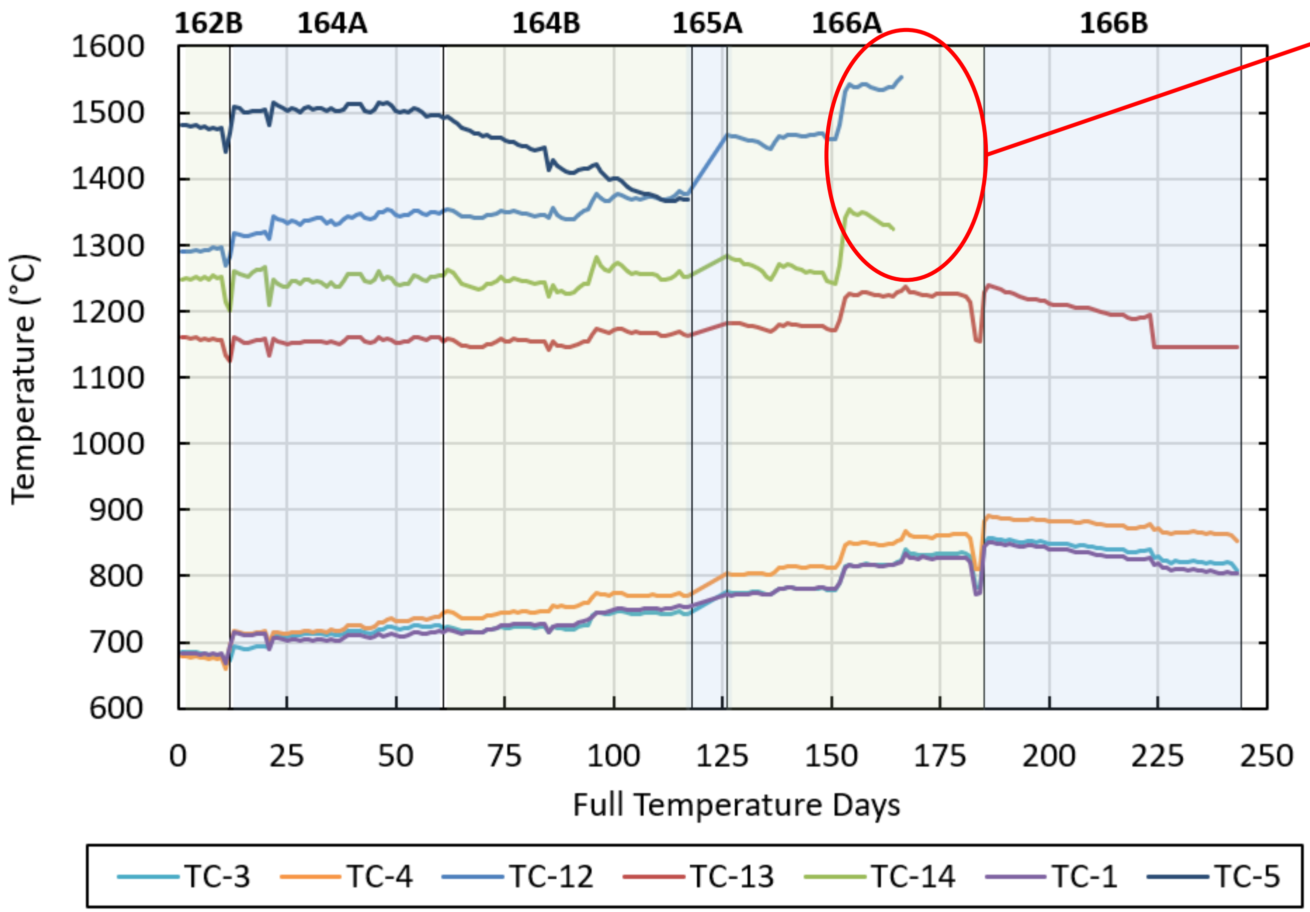
Joe Palmer
Reactor Experiment Designer
Collaborators:
Dr. Austin Fleming (INL)
Dr. Ge Yang (NCSU)
Randel Paulsen (INL)
Megan Laing (INL)
Troy Unruh (INL)

Retractable Sensors for In-Core Applications

The Problem

- Material Test Reactors (MTRs) such as the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) are used to irradiate nuclear fuels and materials to evaluate their performance after high levels of exposure to a reactor in-core environment.
- The most critical tests are equipped with instrumentation leads, which allow real-time data collection.
- However, because of the very harsh environment inside high-power MTR experiments, there are very few sensors that can survive and maintain their calibrated readings for the required duration in order to obtain the high neutron doses needed for new fuels and materials qualification.
- In this case, sponsoring programs accept low reliability of instruments, frequently collecting useful data for only part of the experiment duration.

Example of Mysterious Thermocouple Trends that may or may not be Valid



These abrupt temperature rises were not predicted by the thermal model.

Are they real or some type of thermocouple drift?

If real, then fuel temperatures were ~150ºC higher than the model predicts.

Optical Fibers are a Promising Technology for In-Core Applications

- For in-core applications, optical fibers are a promising solution, however, they are not very radiation tolerant
- Peak fast neutron fluence has traditionally been 1E19 n/cm^2 for optical fiber applications
- Annual core mid-plane fast fluence in ATR is roughly 4E21 n/cm^2, so clearly there is a large mismatch between demand and capability

A Holy-Grail Application for Optical Fibers would be Imaging of Specimens during Irradiation

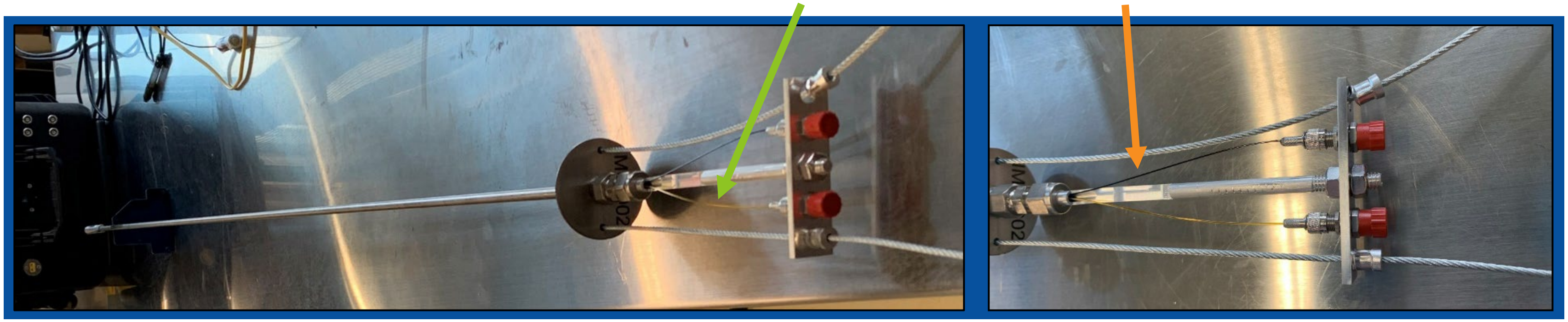
INL Logo Target used for Imaging

Target used for Imaging

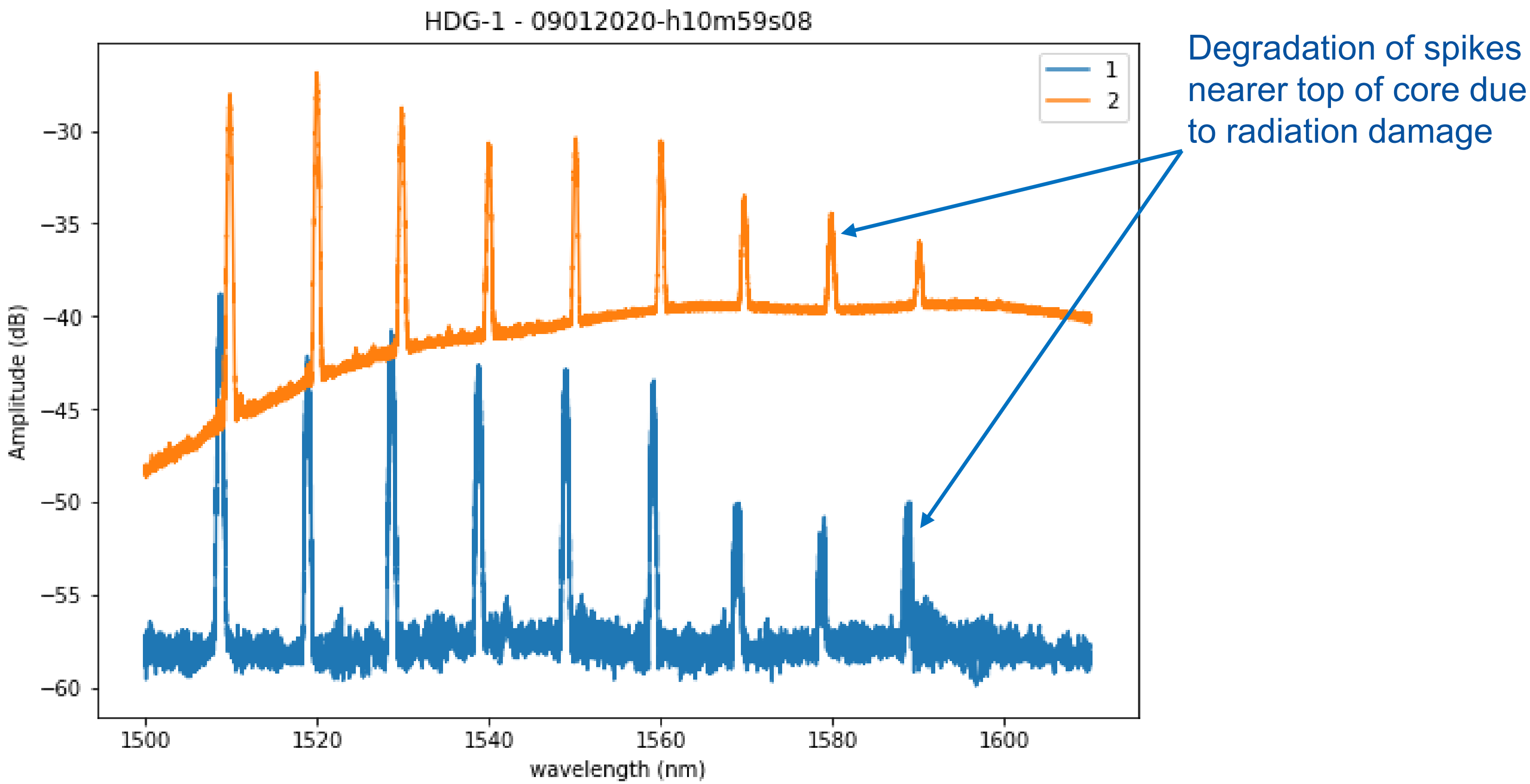
Illumination Fiber

Image Bundle

In-Pile Lens Assembly



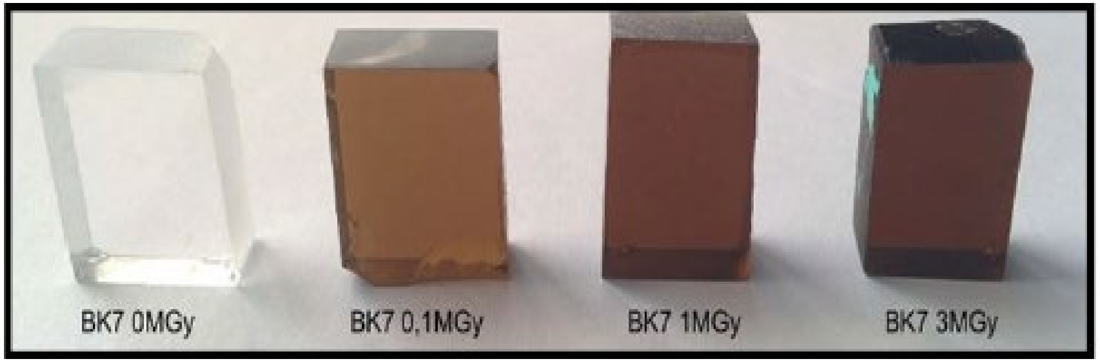
Example of Optical Fiber Signal Degradation due to Fast Neutron Fluence



Example response from fiber optic sensors during irradiation in HDG-1

Macroscopic Changes in Optical Fiber Under Radiation

- Radiation-induced Attenuation (RIA)
  - Occurs due to the creation of color centers
  - Degrades the fiber signal transmission capacity
  - Degrades the sensing range of distributed sensors
  - Changes the refractive index of the optical fiber
- Radiation-induced Compaction (RIC)
  - Causes changes in refractive index
  - Of primary importance when using optical fibers that are robust to RIA
  - Causes significant sensor drift

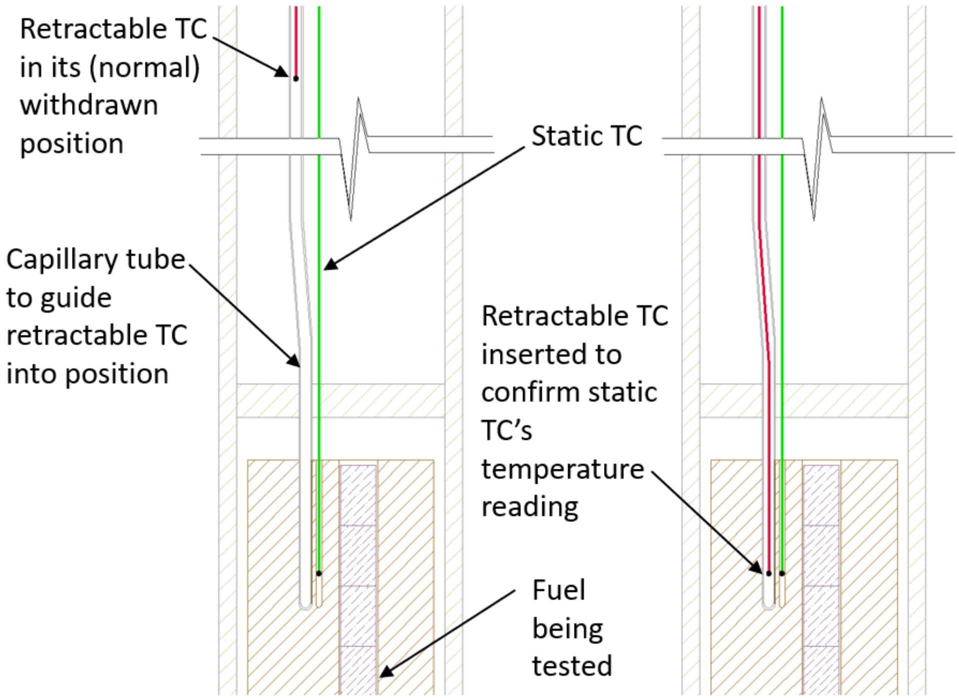


A Solution to Degradation of Sensors Operated in High-Radiation Environments

- The work described herein is based on the observation that MTRs normally run at constant power and the corresponding conditions within reactor experiments typically evolve relatively slowly.
- Therefore, even one or two measurements per day would provide a complete and representative data set.
- The idea is to incorporate a mechanism capable of pushing a very small-diameter sensor (typically a thermocouple, SPND, or optical fiber) into the location to be measured, leave the sensor for roughly 60 seconds to allow it to reach equilibrium and transmit the signal, then pull it up and away from the high neutron flux and high-temperature region.

Supplemental Sensors are Guided to Measurement Spots using Capillary Tubes

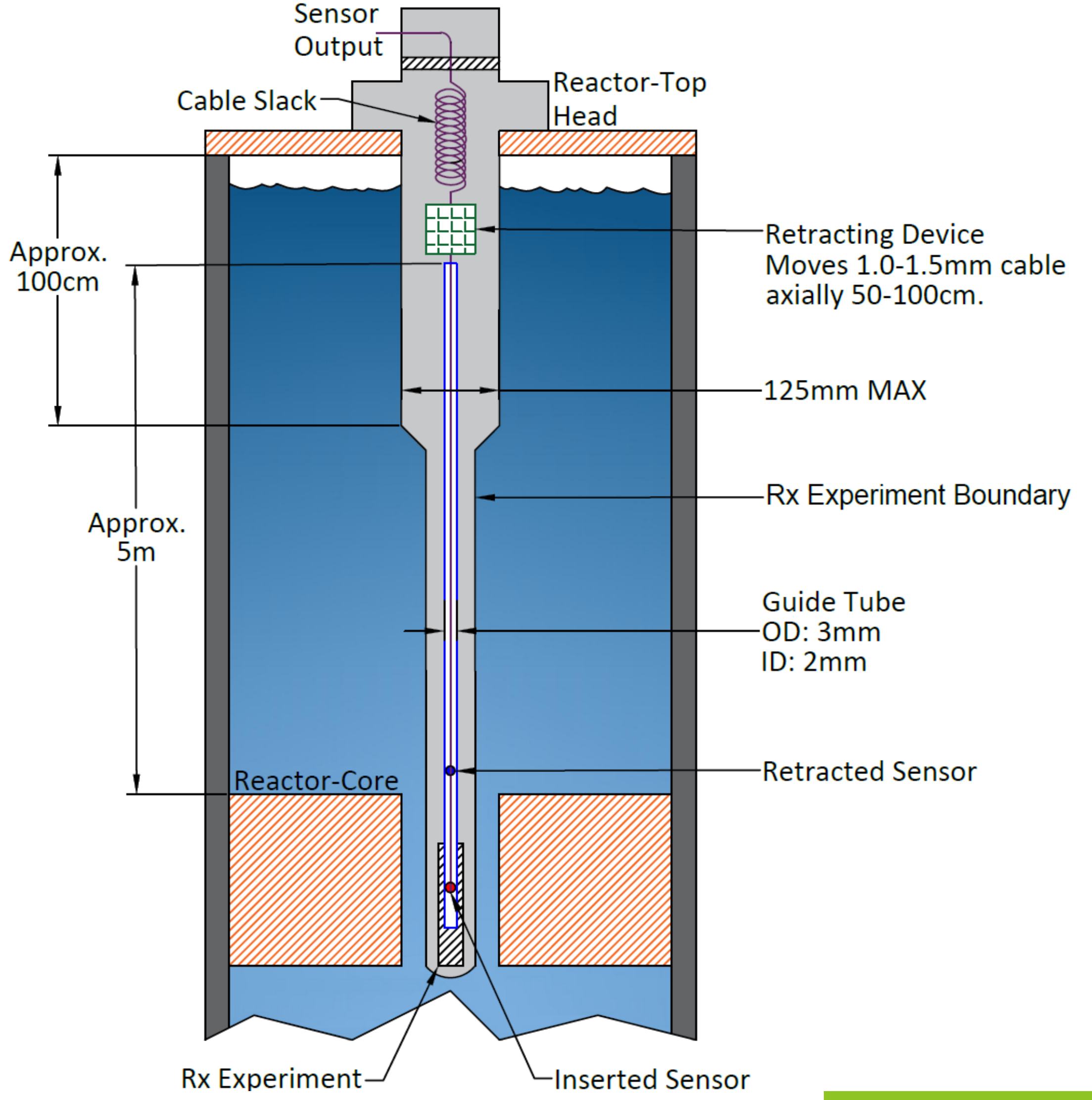
- Small-diameter capillary tubes would guide the sensors to the appropriate locations. The distance a thermocouple or optical fiber would need to move is on the order of 40–80 cm.
- By adopting this infrequent cycling strategy, the thermocouple or optical fiber would spend only a few hours in the high-neutron flux/high-temperature environment over the duration of even the longest irradiation experiment.



Where could the Drive Mechanism be Placed? And How Big would it be?

- ATR has no flanges accessible during reactor operations (many other test reactors do not have this limitation).
- Would the drive be placed inside the test itself or as a separate apparatus outside of the reactor boundary?

How would this be Implemented Physically?

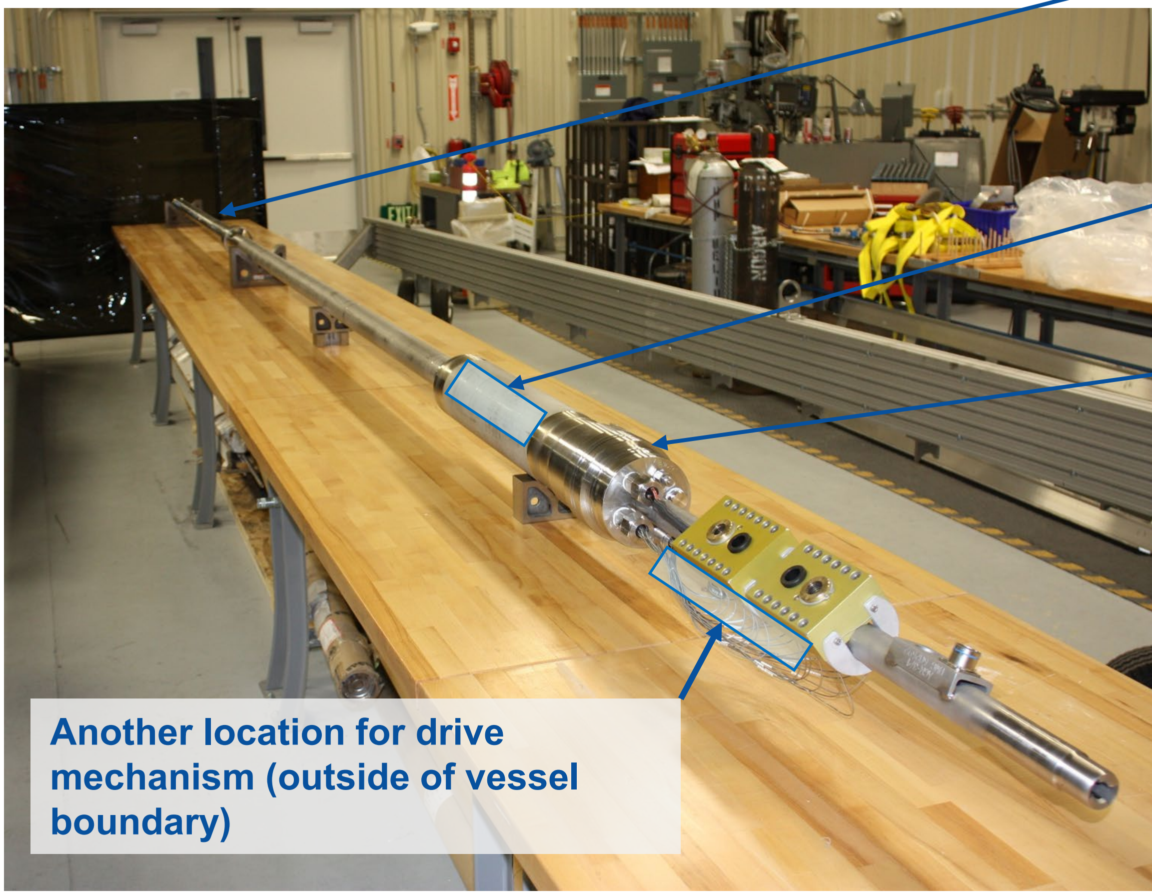


How would this be Implemented Physically?

Core section

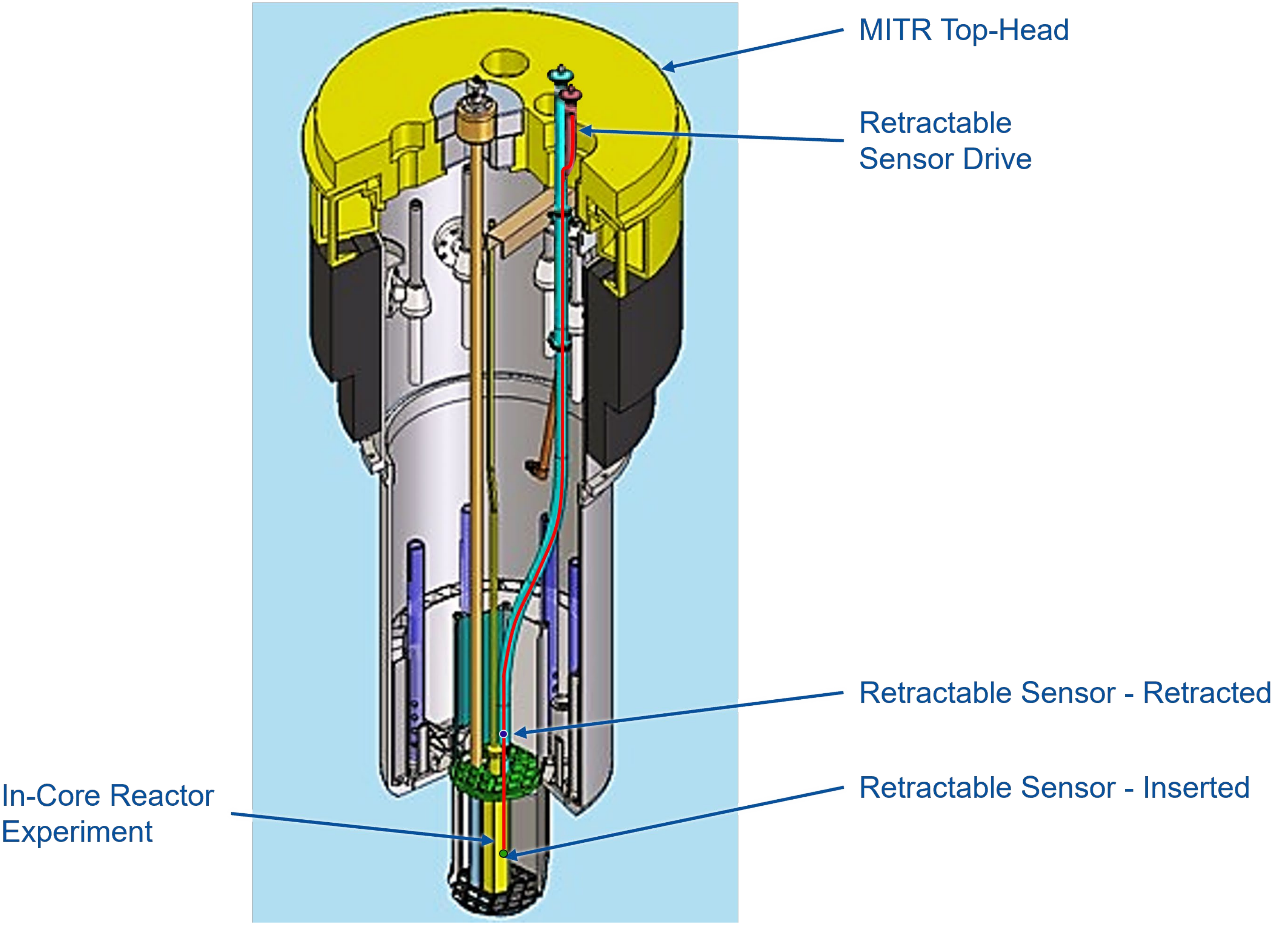
Drive mechanism could be placed in this region

Seal at vessel head

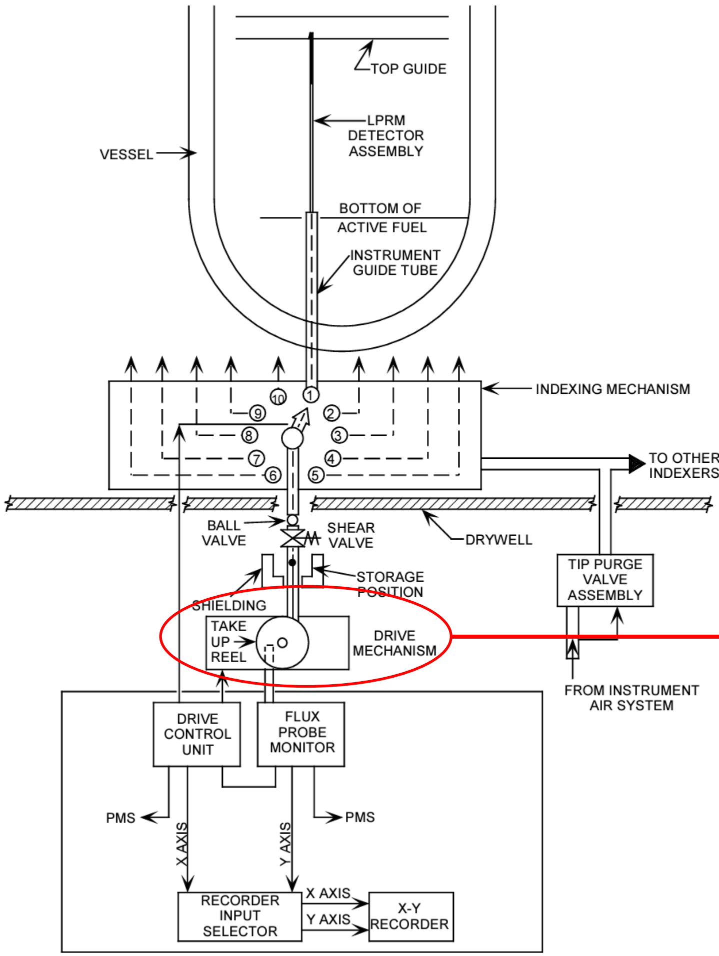


Example of an ATR instrumented TRi-structural ISOtropic (TRISO)-fuels test

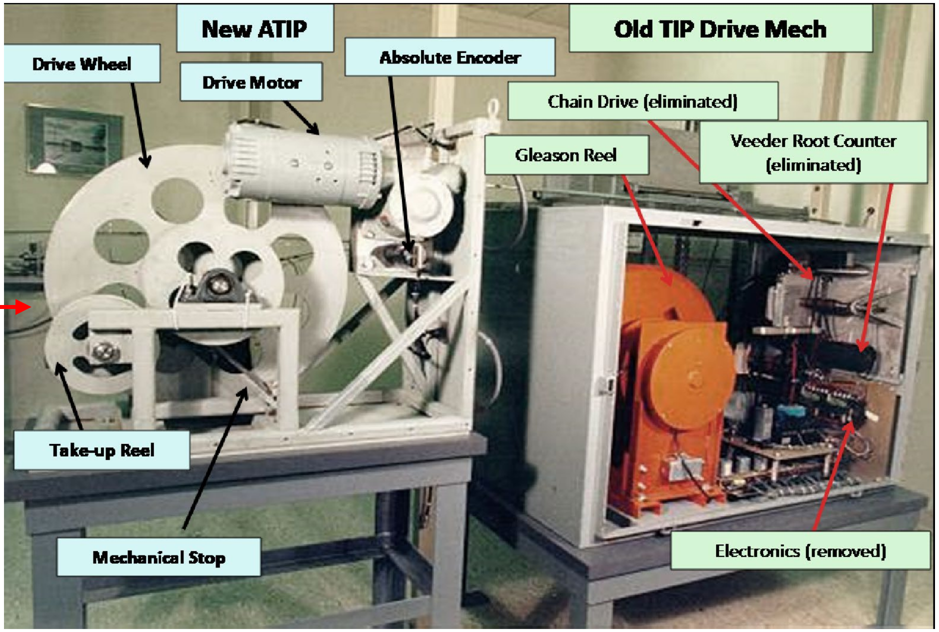
MITR Retractable Sensor Installed above Rx Top-Head



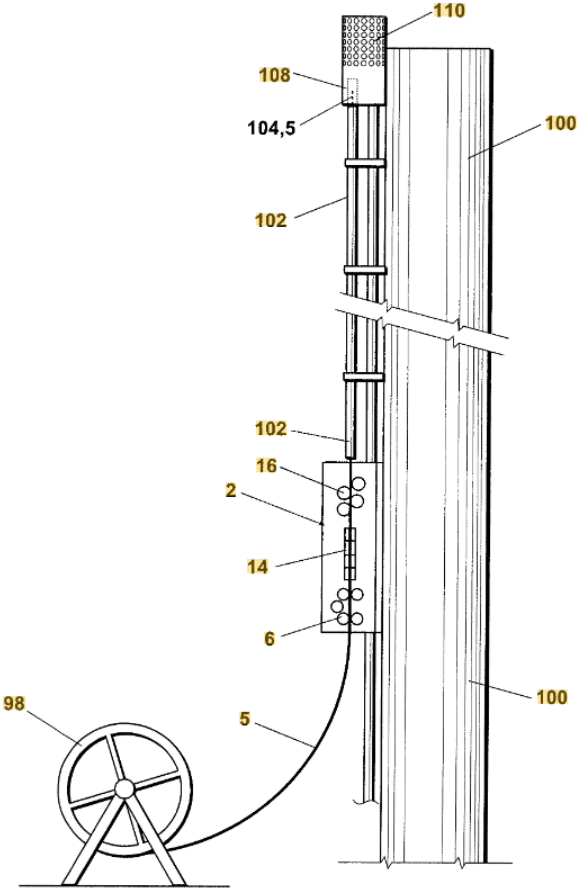
Prior Work—Traversing In-core Probe (TIP) used in BWR reactors



Scale of the TIP system is very large—Drive system is the size of an office desk



Related Industrial Patents



US Patent US8485010B1

Drive Rollers for Wire Feeding Mechanism

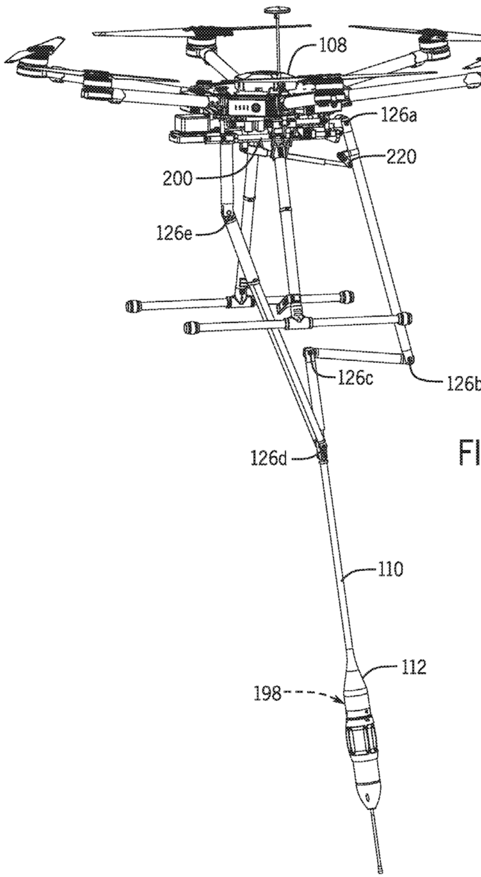


FIG. 7A

US Patent US10627386

Unmanned Aerial Retractable Boom Vehicle

Utilities (Fiber Optics) are Installed with a Drive System—but very Large

These are Better Scaled for our Purposes

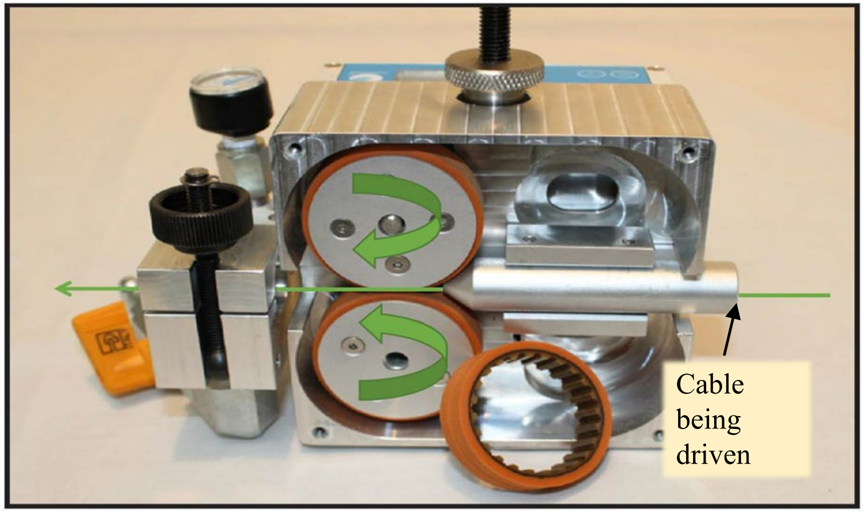
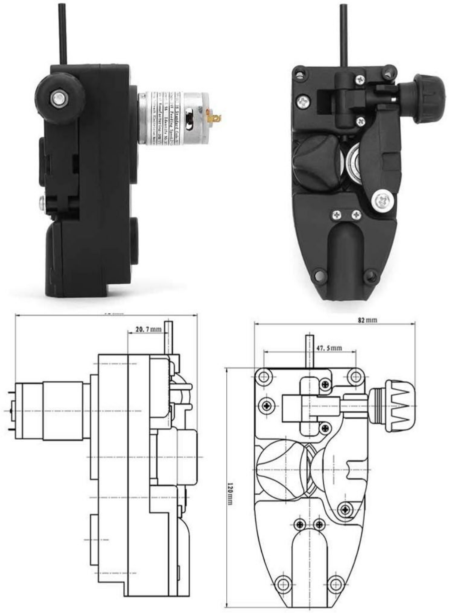


Figure 1. Fiber driving mechanism, Model 150, by Condux International, Inc.



Drive system of small MIG welder

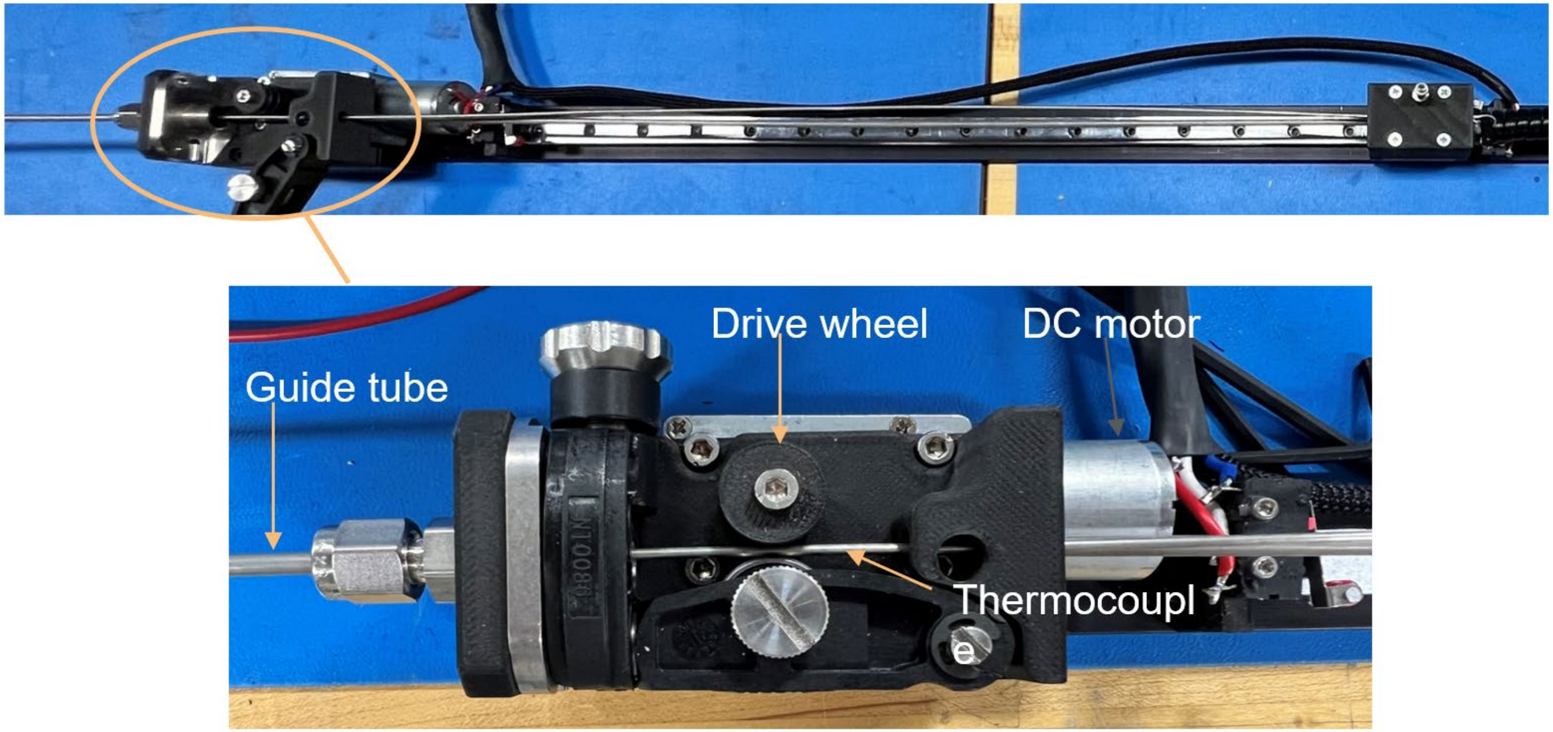
Wire Feeder - Video

Two Approaches have been Identified for a Miniature Retractable Sensor Drive

- Counter rotating wheels
  - In principle, any length of insertion depth is feasible

- Lead screw and carriage
  - Cable firmly attached to carriage
  - More than one sensor may be inserted by a single drive
  - Need to address potential for buckling of sensor cable

For Effective Incorporation into a Reactor, Miniaturization is Key

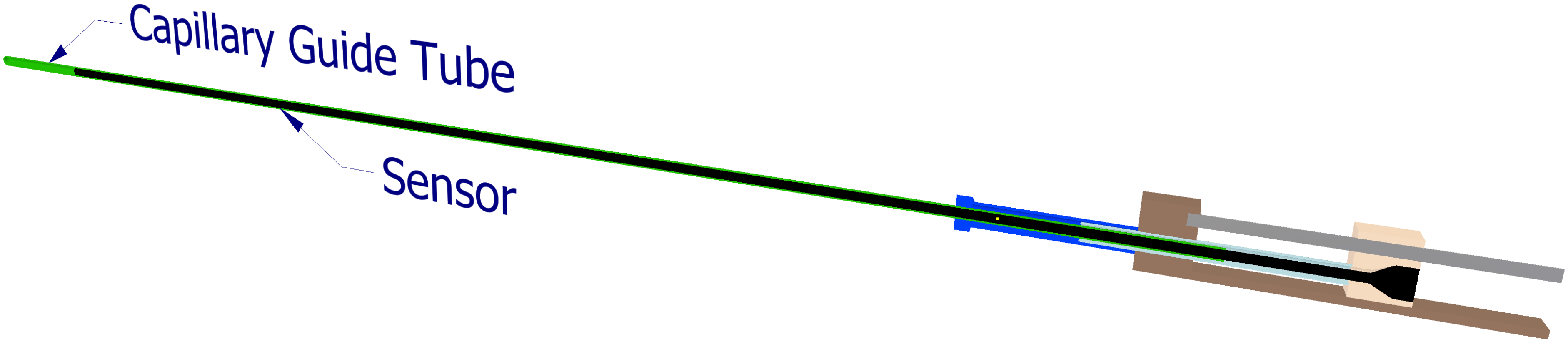


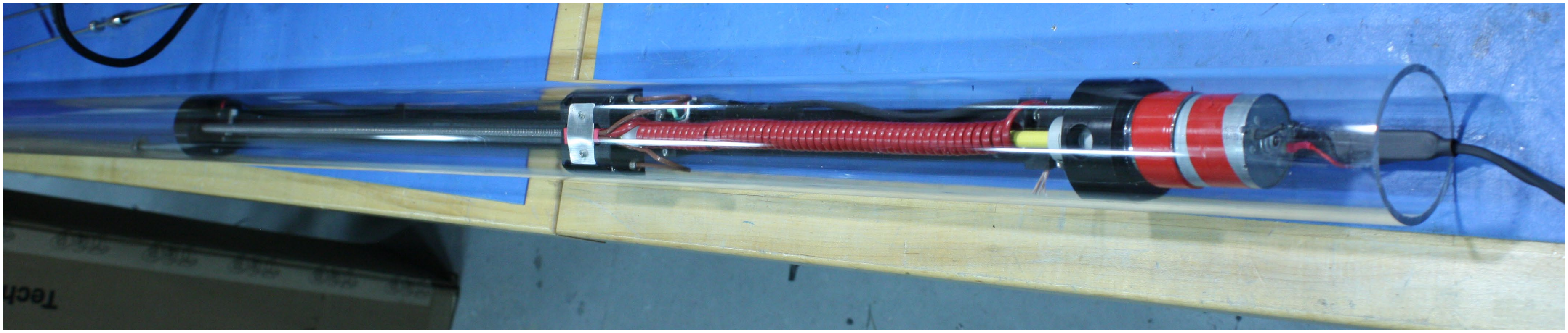
Drive for Retractable Sensor Mechanism – Counter Rotating Drive Wheels

Gen II Roller-Wheel Retractable Sensor in Operation

Could still be a bit smaller (squashed vertically)

Lead Screw Based Retractable Sensor





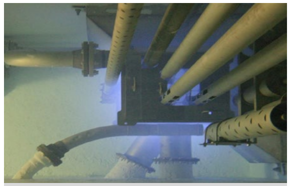
Lead Screw Based Retractable Sensor - Video

Retractable Sensor Operational Diagram - Video

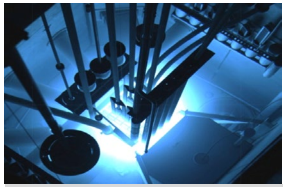
Development and Testing of Retractable Sensor System

Irradiation test requirements and technology maturity largely determine the appropriate facility for testing

Low sensor TRL Technology Easier Access Lower Cost Tests Separate effects testing



OSURR
University Reactor



PULSTAR
University Reactor

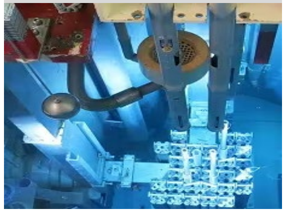
MITR
University Reactor

High sensor TRL Technology Limited Access Higher Costs, High Dose Controlled Prototypic Environment

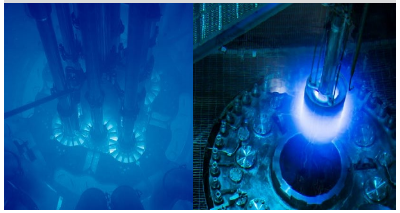
DEVELOPMENT → *PROTOTYPIC DEPLOYMENT*

TREAT (INL)

NRAD (INL)



ATR/HFIR (INL/ORNL)



Phased Approach to Qualification of Sensors under Irradiation Environments

Laboratory-based Testing
Benchtop, Furnace, Autoclave testing (non-nuclear).

Concurrent/Initial Nuclear Testing
Low cost, rapid deployment, generally uncontrolled environment instrumentation may be included in experiment funded by other programs.

Qualification Nuclear Testing
Highly controlled environment, reference measurements for measurand in addition to cross sensitivity parameters. National Institute of Standards and Technology (NIST) traceable references where appropriate.

Specialized devices are required to provide a *known* environment to benchmark sensors, define sensor uncertainty, and ultimately qualify for deployment.

- Measurement Parameters: Temperature, Neutrons (Flux/fluence/spectrum), Pressure, Displacement

Device for qualifying temperature and neutron sensors

- High dose, transient, gamma-only irradiation devices for each measurement parameter
- Requirements for temperature and neutron sensors are very similar

	Temperature/ Neutron	Pressure	Displacement
High Dose	X	X	X
Transient	X		X
Gamma Only	X	X	

Idaho National Laboratory