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Retractable Sensors for In-Core Service in Material Test Reactors

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Changing the World's Energy Future

Joe Palmer, Randel N Paulsen, Austin D Fleming, Megan Autumn Laing, Troy Unruh, Ge Yang

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Retractable Sensors for In-Core Service in Material Test Reactors

A. J. Palmer[1], R. N. Paulsen[1], G. Yang[2],
A. D. Fleming[1], M. A. Laing[1], and T. C. Unruh[1]
[1]Idaho National Laboratory, United States
[2]North Carolina State University, United States
joe.palmer@inl.gov

***Abstract*—Material test reactors, such as the Advanced Test Reactor at the Idaho National Laboratory, are used to irradiate nuclear fuels and materials to evaluate their performance after long term exposure to an in intense radiation environment. The most critical tests are equipped with instrumentation leads, which allow real-time data collection. However, because of the harsh environment inside high-power material test reactor experiments, very few sensors can survive and maintain their calibrated readings for long durations. Since material test reactors normally run at a constant power and corresponding conditions within reactor experiments typically evolve relatively slowly, we believe that even one or two measurements per day would provide a representative data set. With this in mind, Idaho National Laboratory has begun to develop a mechanism capable of periodically inserting a very-small-diameter sensor (typically a thermocouple or optical fiber) into the measurement location, leaving the sensor for roughly 1- 3 minutes to allow it to reach equilibrium and transmit the signal, and then remove it from the high-neutron flux and high-temperature region. Small-diameter capillary tubes, up to 8 m long, would guide the sensors to the appropriate locations. These capillary tubes serve as very deep, thin-walled thermowells. The distance a thermocouple or optical fiber would need to traverse 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 and high-temperature environment during even the longest irradiation experiment. To date, Idaho National Laboratory has developed two styles of drive mechanisms. Both drive mechanisms have been fabricated and tested in a laboratory setting and can handle a hard mineral-insulated cable (such as thermocouples) or optical fibers encased in a small-diameter tube. The sensor sizes tested to date are 1–1.6 mm diameter.**

***Keywords*—In-Pile Instrumentation, Material and Test Reactors, Irradiation Testing, Sensor Uncertainty, Sensor Reliability.**

I. Introduction

The very harsh environment of a high-power materials test reactor can produce unpredictable sensor drift, and the potential for such drift leads to uncertainties in the measurements from such sensors. A clear example of this was observed during the recently completed AGR-5/6/7 test conducted at Idaho National Laboratory (INL) in the Advanced Test Reactor (ATR). Fig. 1 shows thermocouple readings from the capsule located at the core mid-plane. Two of the thermocouples nearest the fuel stacks exhibited an unexplained temperature rise after about 150 days of irradiation (circled in red). The temperature rise was not predicted by the thermal model, and researchers were left to wonder whether these readings were spurious or accurately reflected actual capsule conditions [1].

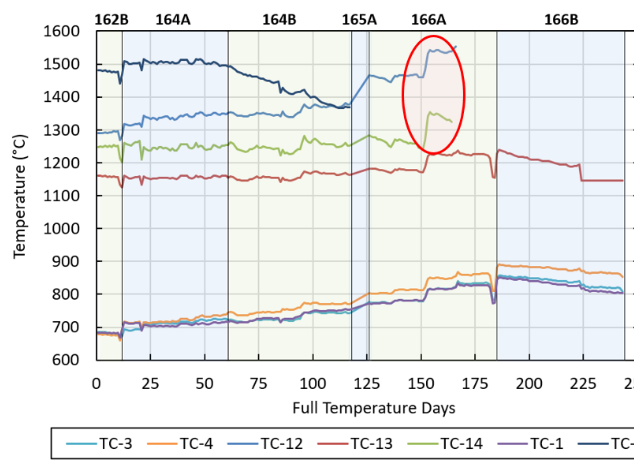

Fig. 1. Indications of unexpected temperature rise during AGR-5/6/7 fuel experiment.

Another sensor technology that exhibits similar problems on a much shorter timescale is sensors based on optical fibers (OFs). Such sensors are promising for in-core applications because of their versatility and high data transmission rates. However, OF-based sensors are subject to macroscopic changes due to fast neutron and gamma irradiation. Two of these changes are radiation-induced attenuation (RIA), which degrades the fiber signal transmission capacity, reduces the sensing range of distributed sensors, and changes the refractive index; and radiation-induced compaction, (RIC) which changes the refractive index and causes significant sensor drift.

Two of the most likely applications for OFs are temperature and pressure measurement. Both RIA and RIC affect sensor reliability and drift in temperature and pressure applications. Another potential application, perhaps the "holy-grail" application for OFs, would be imaging specimens during irradiation, as shown in Fig. 2. This application would be most affected by RIA effects.

Peak fast neutron fluence for OF applications has traditionally been on the order of 1.0 E19 n/cm^2 (the specific limit depends on sensor type). Annual fast fluence in ATR at the core mid-plane is roughly 4.0 E21 n/cm^2, so clearly there is a large mismatch between demand and capability for OFs.

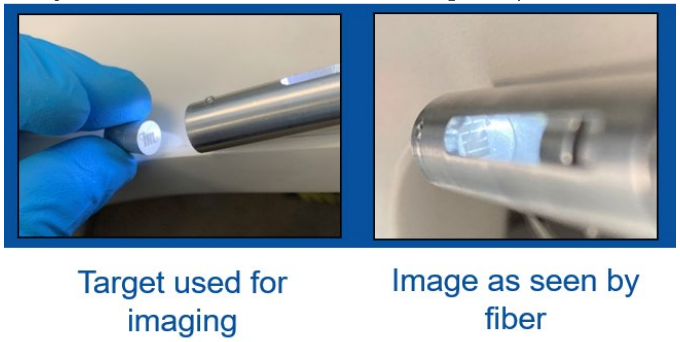

Fig. 2. One application for optical fibers—imaging during irradiation.

II. A Potential Solution

Our work is based on the observation that material test reactors normally run at constant power and the corresponding conditions within reactor experiments typically evolve relatively slowly. Therefore, even one or two reliable measurements per day would provide a nearly complete and representative data set. The idea is to incorporate a mechanism capable of pushing a very-small-diameter sensor (typically a thermocouple, self-powered neutron detector (SPND), or optical fiber) into the measurement location, leaving the sensor for 2 or 3 minutes to allow it to reach equilibrium and transmit the signal, and then pulling it up and away from the high-neutron flux and high-temperature region to a retracted position where it would spend the great majority of its time.

Small-diameter capillary tubes would guide the sensors to the appropriate locations. The distance a thermocouple or other hard-sheathed sensor would need to move is on the order of 40–80 cm. These capillary tubes would essentially serve as very thin and deep thermowells.

By adopting this infrequent cycling strategy, the thermocouple or optical fiber would spend only a few hours in the high-neutron flux and high-temperature environment over even the longest irradiation experiment.

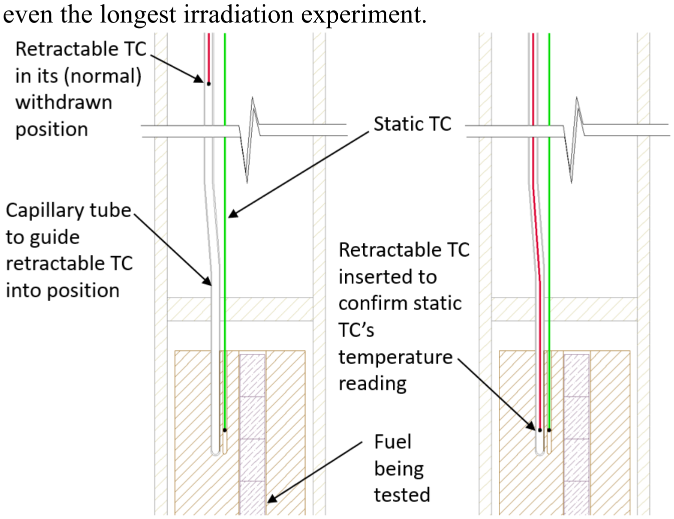

Fig. 3. Retractable TC to confirm temperature measurements.

Given this basic concept, design decisions must be made as to where to place the drive mechanism and how large would it be.

The drive could be placed inside the test itself or as a separate apparatus outside of the reactor boundary. One challenge of note is that ATR has no flanges (or ports) accessible during reactor operations. Therefore the drive system has to be completely automated for any application in ATR (many other test reactors do not have this limitation).

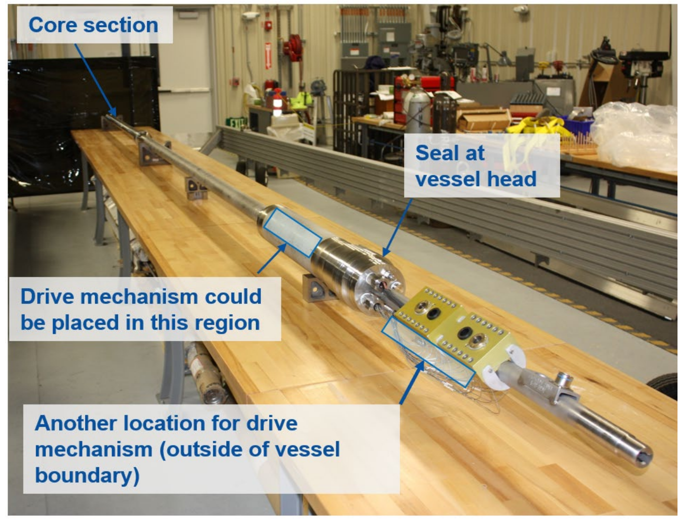

Fig. 4. Example of ATR fuels test with possible locations for sensor drive system identified.

Fig. 4 shows two options for locating the drive mechanism in an ATR fuel test. One location would be inside the test rig itself. The other would have it attached to the instrumentation stalk, which is outside the reactor vessel boundary. In either case, the drive mechanism would need to be quite small, on the order of 50 mm diameter by 1,000 mm long (preferrably shorter).

III. Similar Applications in Industry

Driving a sensor cable deep into a conduit is not a unique application. A similar engineering challenge has been solved with the Traversing Incore Probe (TIP) system used in boiling-water reactors to move a series of radiation sensors into various locations within a reactor core [2]. A schematic of this system is shown in Fig. 5 as well as a photo of the drive system. The drive system is larger than an office desk, and thus of a completely different scale compared to what is needed for the retractable sensor discussed above.

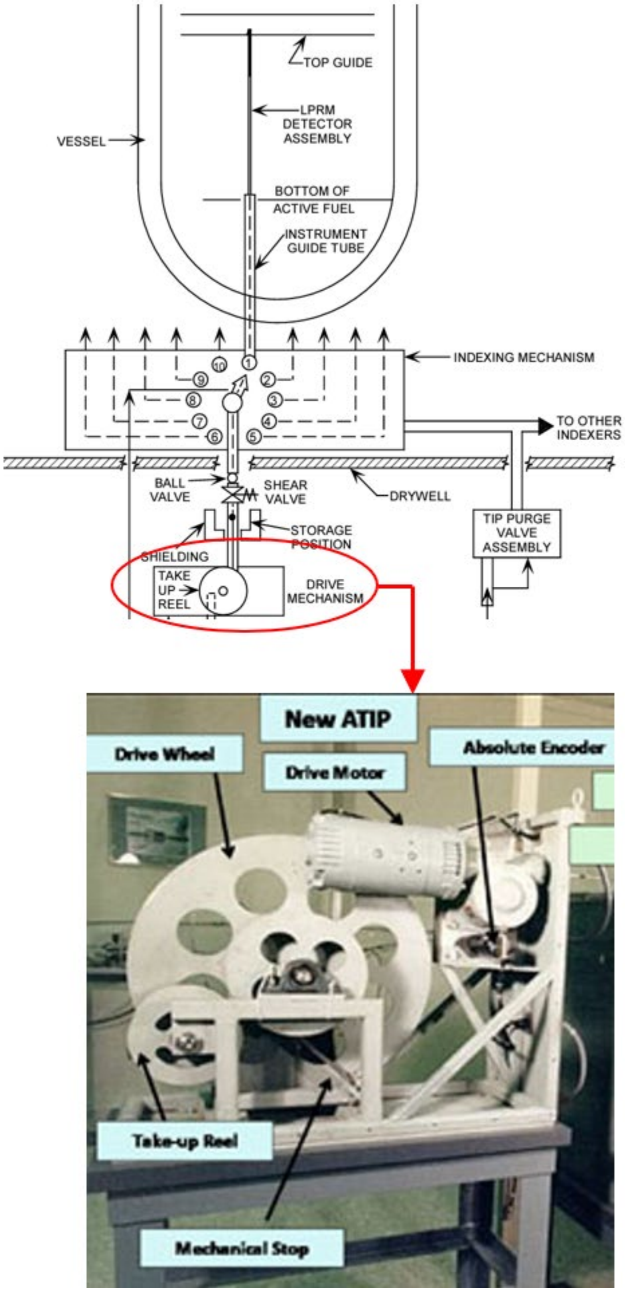

Fig. 5. Traversing in-core probe system for boiling-water reactors.

Fig. 6 shows equipment used to insert large fiber-optic cables into long lengths of preinstalled underground conduit. Again, the scale of these systems precludes their use in reactor experiments, but the general concept is applicable.

Fig. 6. Examples of friction drive systems used to insert cables into underground conduits.

IV. Drive Systems Tested to Date

Two approaches were identified for a retractable sensor drive, each with advantages:

- Counter-rotating wheels driving the cable by friction
- Lead screw and carriage.

Fig. 7 is an illustration of the wire feed mechanism for a small Metal Inert Gas (MIG) welder. This wire feed system pushes long lengths of weld wire into a guide tube (which is essentially what is needed for a retractable sensor concept). A mechanism similar to that shown in Fig. 7 was designed and fabricated—see Fig. 8. Because this mechanism uses a friction drive, with the potential for slip, limit switches were used on each end of the range of travel to stop the drive and provide a positive indication of the location of the tip of the sensor. This mechanism exhibited good reliability during bench-top testing.

This friction drive system has the advantage of theoretically being able to move the sensor through any insertion distance (just as the large utility cable can be inserted hundreds of meters into a conduit as shown in Fig. 6).

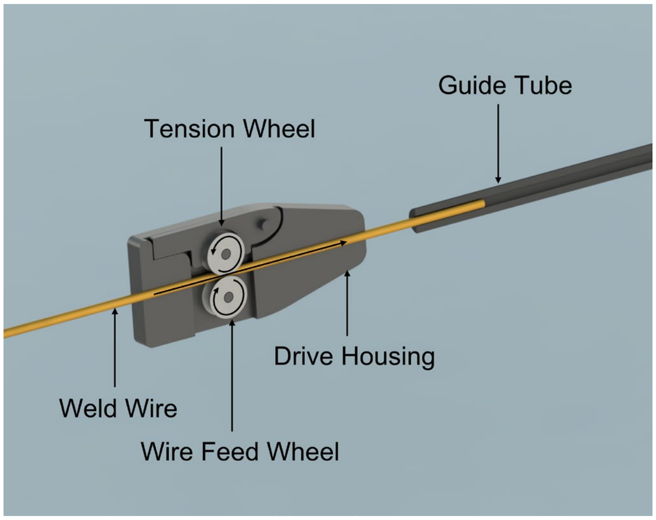

Fig. 7. MIG welder drive system.

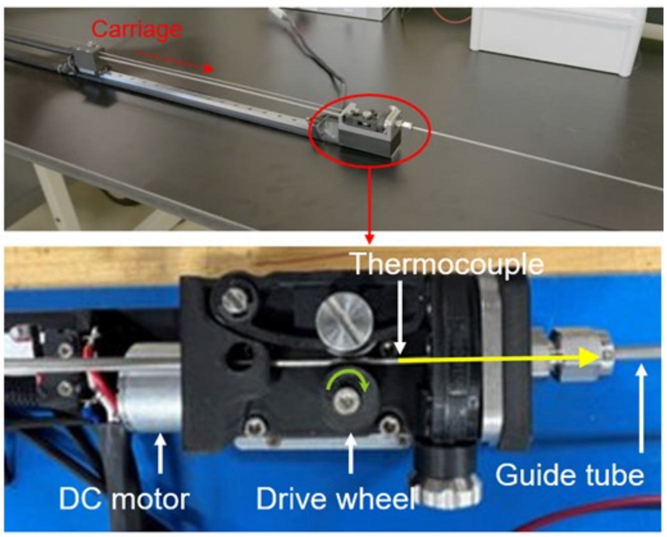

Fig. 8. Drive using a friction wheel based on MIG welder.

The second drive system type was based on a leadscrew and carriage arrangement. This type of drive has a couple of advantages over the friction wheel drive described above. First, it is a positive drive system in that the sensor cables can be coupled to the carriage. Second, more than one sensor can be inserted with a single drive mechanism. One disadvantage, is that the cable has a free span between the carriage and the opening to the guide tube, and thus the cable can buckle if long insertion lengths are attempted (as illustrated in Fig. 9).

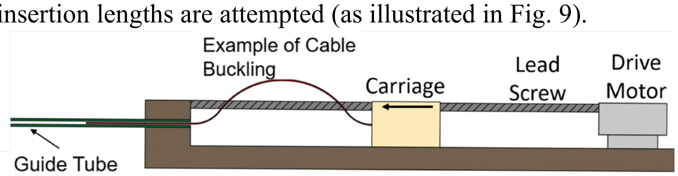

Fig. 9. Carriage and lead screw system with an example of buckling.

This problem is avoided with the friction drive system because the drive wheel is only a few millimeters from the opening of the guide tube. The problem has largely been overcome in the carriage and lead screw design as well, by placing a support tube over the cable, as shown in Fig. 10. This prevents buckling in all but the longest of insertion lengths.

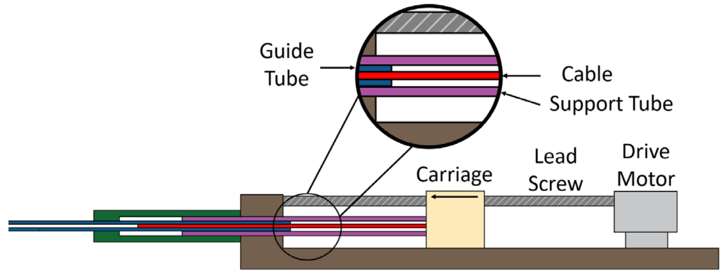

Fig. 10. Schematic of carriage and lead screw design with support tube over the cable to prevent buckling.

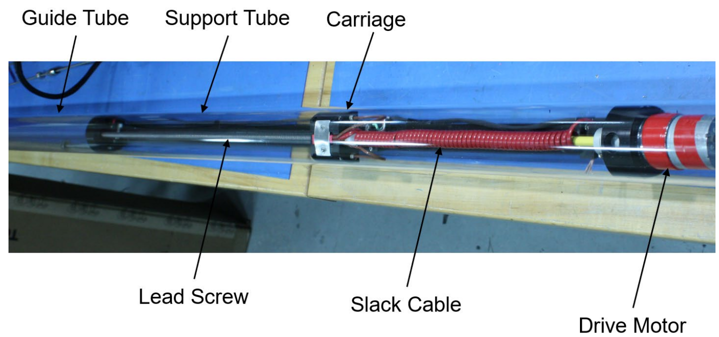

Fig. 11. Bench-top carriage and lead screw system developed and tested at INL (in a non-rad environment).

The cable diameters tested with both systems varied between 1.0 and 1.6 mm. Because space is so restricted within reactor experiments, these are standard sensor sizes. However, because the concept requires a guide tube to direct the sensor to the location of interest, additional space must be allocated for the guide tubes. The size of the guide tubes is on the order of 3 mm. As a result, it is clear that this concept is not feasible for sensors much larger than the 1.6 mm size tested.

V. Deployment Strategy

The retractable sensor prototypes constructed to date were funded as part of the U.S. Dept of Energy's Advanced Sensor and Instrumentation (ASI) initiative. The ASI program funds developmental sensor activities and is responsible for shepherding such developments from bench-top testing and low-dose irradiations through to prototypical operation in a high-power test reactor operating at an elevated temperature. INL has two reactors suitable for early-stage testing: the Transient Reactor Test Facility (TREAT) and Neutron Radiography (NRAD) reactors. Both are capable of reaching fast neutron fluences on the order of 1E17 n/cm^2 using their typical limited operating schedules. As development proceeds, sensors can be tested in the Ohio State University Research Reactor (OSURR) and North Carolina State PULSTAR reactor, both of which have furnaces in dry positions and are capable of reaching 800^{o}C or more. The final test reactor available to the ASI program (prior to deployment in ATR or the High Flux Isotope Reactor (HFIR)) is the Massachusetts Institute of Technology reactor (MITR), which is capable of producing neutron fluxes comparable to commercial power reactors and has sufficient nuclear heating to produce temperatures of 800^{o}C or higher without the use of a furnace.

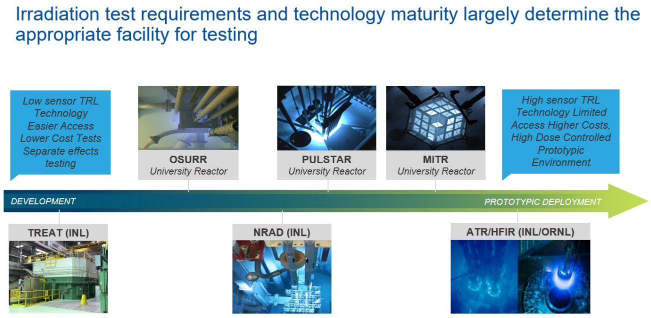

Fig. 12. Reactors available for testing as sensor technology matures.

VI. SUMMARY

The conditions within most irradiation experiments evolve relatively slowly. Therefore, a continuous data stream with measurement acquisition times on the order of seconds or minutes is typically unnecessary. Even one or two reliable measurements per day would provide sufficient data for most materials or fuels irradiation experiments. Under these assumptions, it appears that sensor reliability and accuracy can be improved by only periodically inserting some sensors into the harsh in-core environment. However, because of space restrictions, the engineering challenges to accomplish this objective are formidable. To date, INL has developed two styles of drive mechanisms to insert and retract small-diameter sensors. The first is based on counter-rotating friction wheels that drive the sensors in a manner similar to a small MIG welder. This has the advantage of being able to accommodate a very long insertion length. The second is based on a lead-screw drive mechanism and has the advantages of positive attachment and being able to move more than one sensor at a time. Both drive mechanisms have been fabricated and tested in a laboratory setting and can handle hard-mineral-insulated cable (such as thermocouples) or OFs encased in a small-diameter tube. The sensor sizes tested to date are 1–1.6 mm diameter. Work in this area is ongoing with an eye toward demonstration in university research reactors prior to full deployment in a high-power MTR, such as ATR or HFIR.

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