# High Temperature Operable, Harsh Environment Tolerant Flow Sensors for Nuclear Reactor Applications

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## *Motivation and Background*

A commonly noted sensor need for Generation-IV nuclear power systems is flow sensing in the coolant or liquid fuel loops in order to monitor fluid velocity and characterize mixing/cooling. The ability to deploy a distribution of flow measurement sensors within the reactor pressure vessel will improve the ability to continuously measure the margin available to reaching design basis limits. This information could be used to allow the reactor to operate at higher temperatures, which would improve the thermal efficiency and allow more electricity to be generated from the same nuclear fuel investment. Such a sensor must be able to tolerate high-temperature, pressure, and radiation (neutron and gamma) environments while being minimally disruptive of the flow.

Flow monitoring is particularly important in small modular reactor (SMR) designs where coolant flow is driven by natural convective flow. In contrast to existing light-water reactors, this is a concern because there are no coolant pumps providing indication and control of flow. A number of other power systems and industrial processes would benefit from high-temperature flow monitoring, including metal production and refining, concentrating solar power systems, and molten salt reactors.

To support SMR development and operations as well as other industries, Sporian Microsystems is developing a flow sensor for use in SMR pressure vessels under a Phase IIB award from the Department of Energy Small Business Innovation Research program.

## *Technical Approach*

Sporian Microsystems specializes in miniaturized, low-power sensor systems for remote environmental monitoring applications, and has previously developed a range of compact sensing technologies for government research and private industry customers. Sporian's sensor technology is based on the combination of advanced ceramics, packaging for harsh environments, and advanced integrated electronics.

Sporian's flow sensor operates on the principle of thermal anemometry. Compared to other types of flowmeters, this approach allows measurement in non-tubular vessels such as the annular downcomer of an SMR. Thermal flow sensors also provide a large range of measurable flow rates that, combined with Sporian's high-temperature-operable probe design, makes the sensor useful in a wide range of harsh systems and processes. While this is not a novel concept, Sporian's patented sensor technology (US #10,436,661) is set apart by its ability to operate at high temperatures (500°C, pushing to 800°C) and pressures (2000 psi and possibly higher) thanks to high-temperature materials and packaging techniques.

More than just a transducer or sensing element, the flow sensing system includes electronics with "smart" signal conditioning approaches, implementing features such as digital communications, internal compensation (temperature), internal calibration (output data in engineering units), and sensor self-identification in a highly integrated (<1 in3) "bump-on-cable" format. Typically, the electronics are physically separated from the probe by a length of rigid (mineral-insulated) or flexible cable as shown in Figure 1, but electronics can also be integrated into the probe head.

***Figure 1. Sporian flow sensor with drive electronics.***

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## *Results*

During Phase II of this effort, Sporian followed an iterative design-build-test cycle to improve reliability and performance, especially with respect to issues of hermeticity, material compatibility, and flow-sensing performance.

- SMR environmental suitability: Prototypes have demonstrated hermeticity and stable output during 100-hour soaks in borated water at 300°C and pressures up to 2300 psi.
- Vibration: Prototypes have passed 20G vibration testing per MIL-STD-810G.
- Thermal shock: Prototypes have passed thermal shock testing between 20°C and 350°C per MIL-STD-810G.
- Thermal cycling: Prototypes have passed thermal cycling testing per MIL-STD-810G with 350 cycles between 20°C and 350°C.
- Accelerated aging: Prototypes have completed functional testing following 650 hours at 550°C, corresponding to approximately 30 years at 300°C. Some drift was observed, but it appears to be predictable.

Flow sensing performance has been characterized in a low-temperature (<100°C) water flow test loop, and performance under different conditions has been estimated based on dimensionless thermal-fluid analysis. Figure 2 shows an example dataset from Sporian's flow sensor compared to a commercial turbine flowmeter. Interestingly, the change from laminar to turbulent flow is detected in the neighborhood of 0.5 m/s. Preliminary performance specifications are summarized in Table 1. The measurement range is limited by the capabilities of the test loop, and it is possible that higher or lower flow velocities will be measurable given improved calibration.

***Table 1. Pre-commercial product specifications.***

| | |
|---|---|
| Measurement Range | 0.05–1.10 m/s |
| Accuracy | ± 1% FS |
| Resolution | ± 0.01 m/s |
| Output | 0–5 VDC, 4–20 mA, Ethernet |
| Probe Diameter | 0.625 in. (customizable) |
| Probe Length | 5 in. (customizable) |

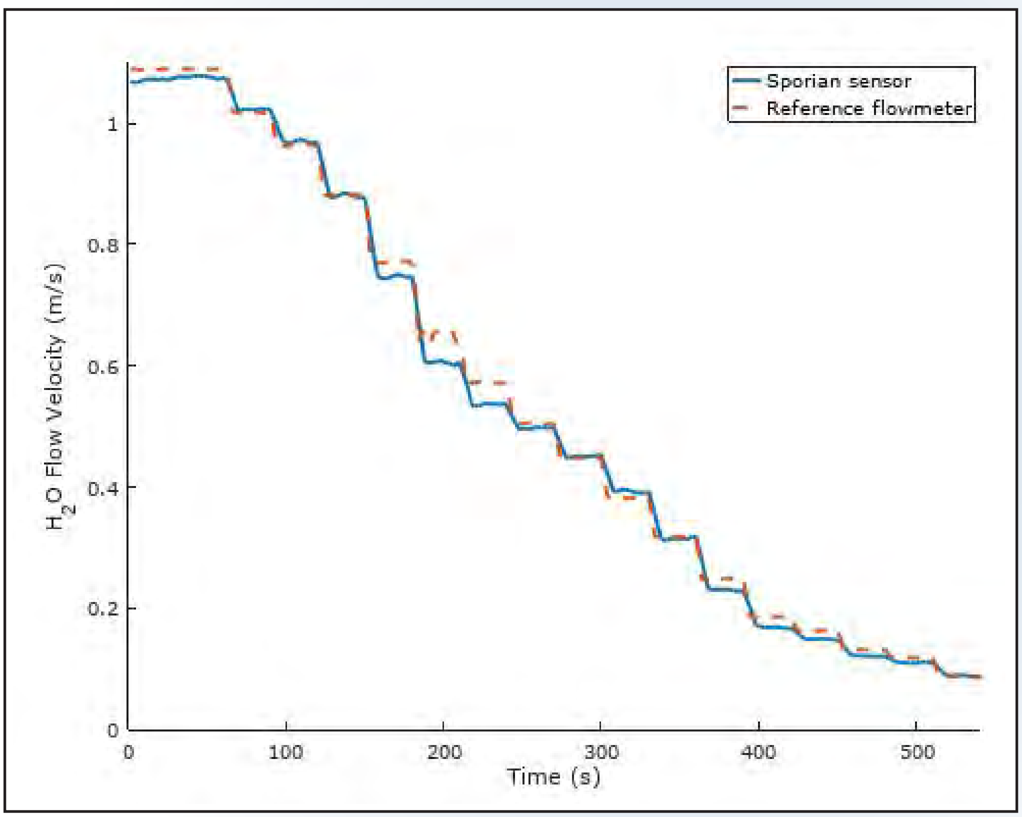


***Figure 2. Sporian thermal sensor vs commercial turbine flowmeter, with a transition to turbulence above 0.5 m/s.***

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Prototype flow sensors have undergone preliminary testing in pressurized water reactor system test loops at Analysis and Measurement Services Corporation, Oregon State University, and Southwest Research Institute.

While prototypes passed these tests, the design and processes are not yet validated across a statistically significant sample size. An important part of Sporian's future work is extensive validation testing in preparation for commercial sales.

## *Additional Applications*

Sporian is adapting this flow sensor technology for use in molten salt systems under a separate Small Business Innovation Research award (Phase II pending). Phase I development consisted of packaging redesign for operation in highly corrosive chloride and fluoride salts at temperatures up to 800°C.

Phase I culminated in a prototype flow sensor being tested in a pumped LiF-BeF2 loop at the University of Wisconsin-Madison. Post-experiment analysis was limited due to beryllium contamination, but there were no signs of damage to the sensor element or packaging.

## *Status and Availability*

This technology is currently in the transition phase from development to commercialization thanks to a Phase IIB award through the Department of Energy. This transition is being accomplished through:

- System risk assessment, including Design Failure Mode and Effects Analysis
- Implementation of quality standards in line with 10 CFR 50, Appendix B, supported by consulting services of United Controls International
- Extensive validation testing at Sporian as well as in third-party system test facilities, including the Critical Heat Flux Test facility at Texas A&M University.

As a small business with finite resources, Sporian's testing capabilities are limited. We are always interested in discussing the possibility of providing sensor systems on an evaluation basis.

This phase of development is scheduled to be completed in the fall of 2021, and commercial sales are expected to begin around the same time.

## *Acknowledgement*

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## *Disclaimer*