Research plan for the development of optical fiber pressure sensors for nuclear applications

Austin Fleming, Joshua Daw, James Smith, Patrick Calderoni

June 2018

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance
Research plan for the development of optical fiber pressure sensors for nuclear applications

Austin Fleming, Joshua Daw, James Smith, Patrick Calderoni

June 2018

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy

Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517
Research plan for the development of optical fiber pressure sensors for nuclear applications

Austin Fleming, Josh Daw, James Smith, Pattrick Calderoni

June 2018
DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.
Research plan for the development of optical fiber pressure sensors for nuclear applications

Austin Fleming, Josh Daw, James Smith, Patrnick Calderoni

June 2018

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of ______
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517
Research plan for the development of optical fiber pressure sensors for nuclear applications

June 2018

Approved by:

Name
Title [optional]

Name
Title [optional]

Name
Title [optional]

Name
Title [optional]
SUMMARY

Fiber optic pressure sensors are desirable for nuclear applications because they are low mass/small size, immune to electromagnetic interference, high sensitivity, and have multiplexing and multimodal measurement capabilities. Much research and development has been conducted on developing fiber optic based sensors and they are now considered a class of standard instrumentation in many industries. Specifically, for pressure sensing, a wide range of fiber based sensors have been developed for various pressure ranges and environments. This vast body of research will be leveraged for the development of pressure sensors for nuclear applications.

Four pressure measurement scenarios were considered which would benefit from a fiber optic based pressure sensor. These scenarios include pressure measurement in the fuel rod plenum, coolant pressure during LOCA testing, advanced coolant (helium, sodium, molten salt) pressure for flow loop operation, and high pressures resulting for direct fuel-coolant interaction. Each scenario has unique pressure, temperature, and material requirements for the sensor.

From a survey of commercially available sensors and a literature review; it has been determined that an extrinsic Fabry-Perot interferometer approach is the most appropriate for the various measurement requirements. The experience and knowledge base for Fabry-Perot interferometers can be leveraged since they are the most common fiber optic based pressure sensors available commercially and found in literature. These pressure sensors rely on the interference of light in a gas filled cavity, which minimizes the impact of radiation induced attenuation and compaction on the measurement, compared to intrinsic sensing techniques. The measurement range of these sensors is based on the stiffness of the diaphragm that deflects under pressure. This allows for a suite of fiber based sensors to be developed by interchanging this diaphragm for the requirements of each application.

Key material and design considerations have been identified for the development of a Fabry-Perot interferometry pressure measurement for nuclear applications. These include high temperature bonding between the glass fiber optic and metal housing, identifying diaphragm materials & geometry, and minimizing cross sensitivity to temperature or implementing compensation techniques found in literature. Overcoming these challenges will develop a pathway for a fiber optic based pressure sensor for nuclear applications, and additionally can be leveraged for other sensing application based on Fabry-Perot interferometers, such as temperature, strain (creep & deformation), vibration, and index of refraction.
CONTENTS

SUMMARY ........................................................................................................................................... iii

CONTENTS ........................................................................................................................................... iv

ACRONYMS .......................................................................................................................................... v

1. Introduction ................................................................................................................................... 1

2. Overview of Fiber Optic Pressure Measurement Scenarios ............................................................. 1
   2.1 Plenum Pressure .................................................................................................................. 1
   2.2 Loss of Coolant Accident .................................................................................................... 2
   2.3 Advanced Coolant Pressure ................................................................................................. 2
   2.4 Fuel-Coolant Interaction ...................................................................................................... 2
   2.5 Potential impact of fiber-based pressure sensors .................................................................. 2

3. Fiber Optic Pressure Sensor Background ....................................................................................... 3
   3.1 Microbend ........................................................................................................................... 3
   3.2 Fabry-Perot ......................................................................................................................... 4
   3.3 Gratings .............................................................................................................................. 5
   3.4 Other Techniques ................................................................................................................ 5

4. Development Plan for an In-pile Fiber-Optic Pressure Sensor ........................................................ 5
   4.1 Outline of Development Plan ............................................................................................... 5

5. References ..................................................................................................................................... 7

FIGURES

Figure 1 Diagram of a diaphragm based extrinsic Fabry-Perot pressure sensor ........................................ 4

TABLES

Table 1 Summary of desired pressure measurement scenarios and their respective conditions ............ 3
ACRONYMS

LOCA  Loss of Coolant Accident
LVDT  Linear Variable Differential Transformer
PWR  Pressurized Water Reactors
Research plan for the development of optical fiber pressure sensors for nuclear applications

1. Introduction

Fiber optic sensors are now common in a variety of industries because of their inherent advantages of light weight, immunity to electromagnetic interference, high sensitivity, small size, and multiplexing capabilities. In addition to telecommunication, optical fibers have made significant contributions to the medical and petroleum industries by leveraging the advantages listed above. A variety of optical interactions are exploited as sensing mechanisms in optical fibers. These interactions can be within (intrinsic) or external (extrinsic) to the fiber, and can also be a point measurement or over a distributed length of the fiber. This measurement flexibility is fundamental to the utility of fiber optic sensors.

Specifically for the nuclear industry, the small size and multiplexing capabilities are of high interest for test reactor experiments where space for sensors is limited and there are many parameters of interest. Deploying optical fibers in nuclear environments has its own unique set of challenges. Particularly the radiation effects on the optical fiber which include radiation induced attenuation and fiber compaction. These challenges should be considered in the design and deployment of any fiber optic sensors in nuclear environments. Even with these challenges, fiber optics have been successfully deployed at the Nevada Test Site and more recently in targeted applications in nuclear reactors by European researchers.

Fiber optic sensors have the capability to measure a wide variety of parameters, and are promising for many different in-pile applications. This report will detail the development plan for the use of in-pile optical fiber based pressure measurements. The report will begin by describing some targeted pressure measurement scenarios that are interest to the nuclear community. These scenarios will drive the requirements and challenges of deploying a fiber optic based pressure sensor. A background of fiber optic based pressure sensors covering the various types and operating mechanisms will be covered. This will include a section describing the fiber optic pressure sensors commercially available. The plan for developing and deploying fiber optic sensors in test reactors will then be described in detail.

2. Overview of Fiber Optic Pressure Measurement Scenarios

Pressure measurements are routinely made in many industrial applications, but often in the nuclear industry there are unique requirements that are not found in other applications. There is a wide variety of desired pressure measurements for nuclear fuel testing in test reactors. Some common pressure measurement scenarios include fuel rod plenum pressure, coolant pressure during design basis accident scenarios such as Loss of Coolant Accident (LOCA), water and other advanced coolant pressure through flow loops (helium, sodium and molten salts), and pressure spikes during fuel-coolant interactions. The motivation, challenges, and requirements for a pressure measurement in each scenario will be briefly discussed in this section. These will provide the guidelines for determining appropriate pressure measurement techniques for these scenarios.

2.1 Plenum Pressure

Fresh fuel rods are pressured with 2 MPa of helium which provides an inert environment and a high thermal conductivity to transfer heat to the fuel cladding and ultimately coolant. Fission gases precipitate into bubbles resulting in fuel swelling. These gases will propagate to grain boundaries and eventually migrate to the plenum of the fuel rod, a process that can be drastically accelerated by the formation of cracks or other mechanical instability of the fuel matrix. This fuel swelling and release of fission gas causes increased pressure inside the fuel rod. The fission gas stored in the fuel compared to that which is released to the plenum is dependent on fuel burnup and the temperature history (temperature and ramp rates). Understanding and predicting the fission gas release is important for fuel performance and safety considerations. The limited space in the plenum region of a fuel rod limits the feasible technologies that can be deployed. The two most common approaches for measuring plenum pressure are a Linear Variable...
Differential Transformer (LVDT) or acoustic based. The LVDT based plenum pressure measurement has largely been developed by the Norwegian Institute for Energy Technology’s Halden Reactor Project\(^8-9\). These pressure sensors are composed of miniaturized bellows connected to the ferrite core of an LVDT. The bellows are pressurized to provide resistance to displacement. The acoustic based sensors utilize a small cavity above the plenum with a tube between the cavity and the plenum to allow for gas exchange. At the top of the cavity is piezoelectric transducer which generates an acoustic wave in the cavity. The acoustic waves propagate through this cavity, are reflected, and then detected by the transducer. The velocity of the acoustic waves is dependent on gas composition and the echo attenuation is dependent on the pressure in the cavity\(^6,10\).

### 2.2 Loss of Coolant Accident

As one of the design basis accident conditions, the performance of nuclear fuel during a LOCA is important. In LOCA testing it is important to measure the environment conditions (temperature & pressure) to provide an accurate understanding of the fuels behavior during this time. This includes measurements from the nominal PWR conditions, to the dry-out period, and finally the rewetting. In these tests the timing of temperature & pressure events is important and high-speed pressure measurements are necessary to provide a complete picture of the experiment.

### 2.3 Advanced Coolant Pressure

Helium, sodium and molten salt coolants operate at significantly lower pressures than Pressurized Water Reactors (PWR), so pressure is not as influential in determining the thermal hydraulics performance as it is for water cooled systems. However, pressure measurements in advanced coolants are necessary to control flow loops operation. While these pressures are lower and a fast time response is less important, the pressure sensors compatible with these materials are limited, and generally their footprints are not easily incorporated into experiments. These coolants also have the added difficulty of higher operating temperatures than PWR reactors. The ability to deploy a discreet and accurate pressure sensor that is compatible at these high temperature and advanced coolants would significantly improve the capability to monitor the flow loops of these advanced coolants.

### 2.4 Fuel-Coolant Interaction

Fuel-coolant interactions occur when hot fuel interacts directly with the coolant following a breach in the fuel cladding. When this fragmented or melted fuel rapidly transfers its energy to the liquid coolant causing the coolant to vaporize quickly, which can create shock waves in the fuel-coolant mixture and extreme pressures\(^11\). This series of events can occur very rapidly after the fuel is fragmented and mixed with coolant, on the order of milliseconds to seconds\(^11\). A high-speed and high-pressure sensor is necessary to resolve the spikes in pressure that occur during this process. This requirement is in addition to being able to withstand PWR conditions and the fuel-coolant interaction event.

### 2.5 Potential impact of fiber-based pressure sensors

As a class of sensors, fiber optics have a unique set of characteristics that make them highly desirable and versatile compared to traditional sensors. The widely recognized advantages include:
- Immunity to electromagnetic interference & ground loops
- Multiplexing and multi-modal capability (distributed sensors, multiple point sensors, multiple measurement variables)
- Small footprint/lightweight
- Long distance signal transmission
- High sensitivity
These advantages are emphasized for in-pile applications where available instrumentation space and geometries are limiting. The benefit of multiplexed sensors to experiment vehicle design is difficult to overstate. Minimizing the number of feedthroughs for pressure boundaries, significantly reducing the assembly time, and providing measurements that are otherwise not possible are a few of these benefits. Table 1 provides a summary of the desired pressure measurements for in-pile applications.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pressure Range</th>
<th>Operating Temperature</th>
<th>Time Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plenum</td>
<td>2 MPa to 10 MPa</td>
<td>300 °C</td>
<td></td>
</tr>
<tr>
<td>LOCA Scenario</td>
<td>Atm to 15.5 MPa</td>
<td>300 °C</td>
<td>&lt;1 ms</td>
</tr>
<tr>
<td>Helium/Sodium/Molten Salt</td>
<td>ATM to 2 MPa</td>
<td>500 °C - 900 °C</td>
<td></td>
</tr>
<tr>
<td>Coolant Interaction</td>
<td>Atm to 50 MPa</td>
<td>300 °C</td>
<td>&lt;1 ms</td>
</tr>
</tbody>
</table>

### 3. Fiber Optic Pressure Sensor Background

A clear understanding of the fiber optic pressure sensors in literature and those commercially available is requisite to formulate a clear path forward for the development process. This section provides a brief literature review of the extensive research that has been conducted in this area, and describes some of the commercially available fiber optic pressure sensors. These sensors are discussed with an eye toward an in-pile deployment of each type of sensor.

#### 3.1 Microbend

Microbends in optical fiber are very small bends of the optical fiber which promote coupling between modes in the fiber optic. This includes coupling to light transmission modes, which essentially acts as a source of attenuation. Microbends are generally caused by lateral contact to the fiber, and optical fibers are normally protected to help minimize their influence. However, utilizing this loss mechanism provided some of the earliest fiber optic pressure sensors. Microbend sensors generally use the external pressure to apply force to an object with surface characteristics that cause the fiber have a series microbends. Often these surface characteristics are two corrugated plates. These sensors are light intensity sensors since the microbends cause an attenuation of the light propagating in the fiber. They have been widely used since the 1980’s and have been used in many applications.

These sensors have been shown to be robust, but they do have some limitations based on their operations. The main limitation being the sensor relies on a measurement of the magnitude of transmitted light for the determination of pressure. Therefore, any other factor that influences the light intensity at the distal end of the fiber will influence the measurement. Power fluctuations from the light source, insertion loss from components, and attenuation in the fiber all impact the light intensity. In some applications these parameters can be well characterized and assumed to be constant with reasonable results. In the case of in-pile instrumentation, often several fiber connections are required for practical assembly of experiment vehicles, which can make the calibration for insertion loss difficult due to repeatability concerns between connections. Additionally, changing environmental factors can impact both the insertion loss of these connections and the attenuation in the fiber itself. Prominently for in-pile applications, as this technique is intensity based, the fiber darkening from radiation would directly influence this measurement and would result in sensor drift.
3.2 Fabry-Perot

Fabry-Perot sensors are commonly found which are based on a Fabry-Perot interferometer that consists of two reflecting surfaces with a gas gap between them. The reflecting surfaces cause interference of the light reflecting between the surfaces which is dependent on the length of the optical path between the mirrors. This is determined by the distance between the surfaces and the index of refraction of the space between them. The details of operation are well documented in literature. Extrinsc Fabry-Perot pressure sensors have been widely used in many applications. The most common type is the diaphragm-based sensor where the distal end of a fiber optic is in a sealed cavity with a flexible diaphragm opposite of it in the cavity, see Figure 1. The end of the fiber and the reflective diaphragm compose the two reflecting surfaces of the Fabry-Perot interferometer. Pressure changes result in a deformation of the diaphragm which changes the distance between the reflecting surfaces. The light reflected back down the fiber is determined by the interference and is wavelength dependent. The reflected light is at a maximum when the round-trip optical path length is equal to the wavelength of light. Specifically this is given by \( \lambda = 2nL \) where \( L \) is the length of the cavity, \( n \) is the index of refraction of the medium in the cavity, and \( \lambda \) is the wavelength of light where the maximum reflection will occur. This causes an interference pattern to occur in the wavelength spectrum of the light reflect back into the fiber. This pattern is measured and used to interpret pressure through a calibration.

![Figure 1 Diagram of a diaphragm based extrinsic Fabry-Perot pressure sensor](image)

Diaphragm-based extrinsic Fabry-Perot sensors have been widely from applications in the medical industry to measuring blast pressures. These types of sensors are also commercially available for a range of applications.

This class of sensors gets its versatility from the design considerations of the diaphragm. The range of these sensors is based on the stiffness of the diaphragm which allows it to be “tuned” for different pressure ranges and responses based on the application. The measurement is also based on the interference of light in a cavity which makes it more resilient to changes in the attenuation (insertion loss, fiber attenuation, etc.). Additionally, the optical path length of this cavity is not influenced by radiation induced compaction of optical fibers.

Non-diaphragm based extrinsic Fabry-Perot pressure sensors have also been developed. These operate by external pressure forces causing strain in a housing in which the optical fiber is mounted with a mirror opposing it. These types of sensors have been deployed in the fossil fuel industry. These type sensors have also been mounted to a structure in which the structural deformation is measured rather than the deformation due to pressure changes. Most notably this has been developed to measure creep for in-pile applications.

Intrinsic Fabry-Perot sensors are similarly composed of two reflecting surfaces, but the cavity between the surfaces is optical fiber instead of gas filled or a vacuum. Similar to extrinsic Fabry-Perot sensors, these have been deployed in a range of applications. These intrinsic sensors can be attached to a structure to measure strain and relate that to pressure. They are also commonly used for the temperature compensation of extrinsic Fabry-Perot sensors. They achieve this temperature compensation through the thermal expansion of the fiber and/or the change of index of refraction of the fiber material.
3.3 Gratings

Fiber gratings, in general, are periodic changes of the refractive index inscribed into an optical fiber core. These structures cause spectral variations in the transmitted and reflected light. These gratings reflect a light of a certain wavelength which corresponds to the period of the grating. Several types of fiber gratings have been studied extensively in literature 35-37. The reflected wavelength of light is dependent on the period of the grating, therefore, any changes in the fiber which change the period of the grating can be monitored by the wavelength of the reflected light. Two common measurements made with fiber gratings are strain and temperature measurements. These strain measurements can be adapted to measure pressure when they are attached to a structure that will deform with changes in pressure 35. Other work has been conducted where the pressure interacts directly with the fiber with no surrounding structure, with varying degrees of sensitivity and accuracy 36-38.

3.4 Other Techniques

Fiber optic pressure sensors have been developed based on a variety of other techniques. For completeness a few of these will be briefly described in this section. One of these techniques is known as a ringdown pressure sensor. In these sensors a fiber optic loop is made between two fiber couplers and a short laser pulse is injected by one leg of the first coupler, and the light is monitored by a leg of the second coupler. The round trip time for the light pulse is on the order of 100’s ns, and the ringdown time is on the order of micro seconds. The force induced by pressure on the fiber optic causes changes in the attenuation which result in a change in ringing downtime. Therefore the ringdown time can be calibrated to measure external pressure 39-41.

Distributed fiber optic sensors can measure parameters over large distances with relatively good resolution. These measurements are commonly made for temperature and strain, and are based on Brillouin, Rayleigh, or Raman scattering of light in standard optical fiber. There are commercially available systems capable of performing these measurements and have been used routinely. To a lesser extent distributed pressure measurements have been made. Tong et al. developed a technique based on light polarization and the pressure-induced birefringence 42. Choi et al. used a distributed sensor to detect pressure on a buried optical fiber for perimeter security purposes for the detection of intruders 43.

4. Development Plan for an In-pile Fiber-Optic Pressure Sensor

The high potential impact of in-pile fiber optic pressure sensors provide motivation for their development. This section outlines the plan for developing fiber optic pressure sensors for the in-pile applications that were described in Section 2. This plan will describe the approach and pathway to developing these sensors by leveraging technology that is commercially available and found in literature. Key capability and technology gaps will be identified that are essential to the development of these sensors.

4.1 Outline of Development Plan

All the fiber optic pressure sensors discussed in Section 3 have specialized applications where they’re appropriate for deployment. For in-pile applications there are unique requirements for operating temperature, pressure, and strict geometry limitations. The potential variable attenuation from insertion loss at multiple connectors and fiber attenuation from radiation darkening and other environmental changes makes any light intensity-based sensor undesirable. Radiation induced fiber compaction is an added complication for any intrinsic sensor, which can be a significant source of drift. For these reasons, an extrinsic Fabry-Perot interferometric pressure sensor has been determined to be the most feasible for performing in-pile pressure measurements for the targeted applications.

Extrinsic Fabry-Perot interferometric pressure sensors are commercially available and found extensively in literature evidencing a high technology readiness level. From a survey of commercially available pressure sensors, there are none that currently meet all of the requirements for the targeted in-
pile applications. However, there are sensors that meet the individual requirements independently. For example a commercial vendor has been identified with Extrinsic Fabry-Perot sensors that can operate up to 1000 °C which is suitable for all targeted applications, but the maximum pressure does not meet the targeted need. Similarly, other manufacturers have high pressure sensors, but with low maximum operating temperatures. Lastly, extrinsic Fabry-Perot interferometric pressure sensors have been used to measure blast pressures indicating it’s capability to perform high speed pressure measurements. This indicates there are no technological barriers to achieving the temperature, pressure, and time response considerations required for the targeted deployments. However, there are significant challenges to overcome for the development of these sensors. Some of the identified challenges include:

- **Material Selection:**
  - High temperature bonding between the glass fiber optic and a metal housing
  - Identify housing and diaphragm materials that are compatible with thermal expansion coefficients of glass, minimal interaction with gamma and neutron radiation, and compatible with advanced coolants.

- **Design Considerations:**
  - Diaphragm geometry to ensure measurable deformation over the range of desired pressures, ensure adequate response time, and immune to vibration.
  - Minimize thermal expansion of cavity through design or utilize one of the temperature compensation techniques found in literature 27, 44-50.

It is recognized that it is unlikely a pressure sensor will be developed that is adequate for all of the targeted deployment scenarios. Due to the versatility of extrinsic Fabry-Perot sensors, a base sensor design will be developed with some modularity to account for the different deployments. Examples of this type of modularity include changing the pressure range by adapting the diaphragm material or geometry, and/or the cavity can be pressurized at different levels. Implementing solutions to these key technology challenges, unique to in-pile deployments, will be key to developing a suite of in-pile fiber optic pressure sensors. Many of these challenges are common to all extrinsic Fabry-Perot sensors, therefore, developments and solutions from other projects can be crosscutting. Especially since extrinsic Fabry-Perot sensors have been used for temperature, pressure, strain (creep & deformation), vibration, and index of refraction measurements.
5. References