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DEVELOPMENT OF FABRY-PEROT INTERFEROMETRIC SENSORS FOR SAFETY-RELATED APPLICATIONS IN NUCLEAR POWER PLANTS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Hanying Liu, MS, BS

The Ohio State University
2001

Dissertation Committee:

Professor Don W. Miller, Adviser, ME/NE
Professor Thomas Blue, ME/NE
Professor Richard Denning, ME/NE/BATTELLE
Professor Mardi C. Hastings, ME/BME

Approved by

Advisor
Nuclear Engineering Program
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Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346
ABSTRACT

Nuclear Power Plant operators and Generation IV plant designers are beginning to consider advanced data transmission and measurement systems to improve system economics and safety, and also to mitigate the stress of obsolescence of instrumentation and control systems. Fiber optic sensors have advantages over traditional sensors such as immunity to electromagnetic interference or radio frequency interference, higher sensitivity and accuracy, smaller size and less weight, higher bandwidth and multiplexing capability. A type of Fabry-Perot fiber optic sensors works on unique interferometric mechanism and data processing technique, and is commercially available from Fiso Technologies, Canada. It employs a Fizeau interferometer and a Charge-Coupled Device (CCD) array to locate the position of the maximum interference fringe intensity. Consequently, the basic measurement mechanism is independent of the absolute light intensity, which is the most likely parameter to be affected by external stressors such as nuclear irradiation and high pressure/temperature.

The Fiso fiber optic temperature sensor was selected for performance evaluation and for potential application in nuclear power plants. The sensing mechanism, static and dynamic models of Fabry-Perot fiber optic temperature sensors
were analyzed and developed. A methodology was developed according to IEEE-323 and ISA-dS67.06 to evaluate Fiso sensors in normal and abnormal design basis accident environments expected in nuclear power plants. Performance evaluation of five Fiso Fabry-Perot temperature sensors in simulated nuclear environments was completed. These environments were gamma only (Co-60) irradiation, mixed neutron/gamma irradiation and design basis accident environment.

Two sensors were tested in gamma irradiation tests with a gamma dose of 15 kGy and 1.33 MGy, respectively. The first sensor exhibited no failure or degradation in performance. The second one demonstrated acceptable performance during and following gamma irradiation.

Three sensors with different gamma irradiation history were irradiated in a mixed neutron/gamma irradiation field, in which the total neutron fluence was $2.6 \times 10^{16}$ neutrons/cm$^2$ and the total gamma dose was 1.09 MGy. All of them demonstrated the same temperature shift of about 34°F but responded linearly to change in temperature. An annealing phenomenon was observed as the environmental temperature increased, which reduced the offset by approximately 63%.

Based on analysis of the sensing mechanism and advantages of Fiso Fabry-Perot fiber optic sensors, and on experimental results from nuclear environment simulation tests and performance evaluation tests, it is concluded that Fiso Fabry-Perot fiber optic sensors have excellent potential for use in safety-related instrumentation channels in nuclear power plants.
Dedicated to my parents

父亲  刘侃如
母亲  廖碧娴
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VITA

1992.........................B.S. Engineering Physics, Tsinghua University, Beijing, China

1995.........................M.S. Nuclear Engineering,
Beijing Institute of Nuclear Engineering, Beijing, China

1992 – 1996..............Assistant Engineer,
Beijing Institute of Nuclear Engineering, Beijing, China

1998.........................Dual M.S. Mechanical and Nuclear Engineering,
The Ohio State University, Columbus, Ohio, USA

1996 – present...........Graduate Research and Teaching Associate,
The Ohio State University, Columbus, Ohio, USA

PUBLICATIONS & TECHNICAL REPORTS


FIELDS OF STUDY

Major Field: Nuclear Engineering

Specialty Areas: Instrumentation and Controls, Fiber Optics
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INTRODUCTION

Instrumentation and control (I&C) systems are very important to the operation, safety and productivity of a nuclear power plant (NPP). Instrumentation and Control systems in current operating plants (Primarily Generation II NPPs) use I&C systems, which were designed in the 1950's. These systems employed analog electronics and a variety of traditional process and radiation sensors for the measurement of safety and control variables such as temperature, pressure and neutron flux. In general, these systems did not change appreciably before 1990.

In the early 90's, plant operators began upgrading many non safety-related control systems from analog to digital in order to improve their performance and to make them more robust. Following the upgrade of the Standard Review Plan in 1997, which substantially improved regulatory guidance related to safety-related digital systems, plants also began to replace their analog safety systems with equivalent digital systems. Since analog instrumentation is becoming obsolescent due to decreasing availability of suppliers and costly maintenance and operation, replacement of analog systems is expected to increase substantially over the next ten years with a predictable regulatory process.
As plant operators began to replace analog systems with digital systems they found that in general, nuclear suppliers were no longer developing custom-designed systems used in nuclear power plants. Therefore, most digital upgrades will use commercially available equipment as the primary basis for future modernization of I&C systems \[32\].

For example, the Electrical Power Research Institute (EPRI) and its member utilities are working together on several projects to support the use of commercially available programmable logic controller (PLC). The goal of this program is to develop pre-qualified platforms for safety-related applications. The first of these applications, two generic platforms, which will be used in comprehensive I&C system upgrades, was approved by the NRC in November of 2000. An important outcome of the EPRI PLC program has been the development of a credible methodology to verify that commercially available software-based digital systems had been designed and constructed with methods equivalent with NRC regulatory guidelines.

In accordance with modernization of I&C systems, plant operators and Generation IV plant designers are beginning to consider advanced data transmission and measurement systems. Anticipating this trend, the NRC in 1998 completed a study of emerging technologies that could be applicable to measurement systems in nuclear power plants (NUREG/CR-5501 \[16\]). This study concluded that advanced fiber optic sensing technology is an emerging technology that should be investigated. The advantages of fiber optic sensors over current traditional sensors they cited include immunity to electromagnetic interference or radio frequency interference (EMI/RFI),
and potential for higher sensitivity and accuracy, smaller size and less weight, higher bandwidth and multiplexing capability. This study also indicated that there had been very little research related to performance evaluation of fiber optic sensors in nuclear plant harsh environments.

To meet the nuclear industry requirement, Fabry-Perot interferometer-based fiber optic temperature sensors were evaluated for potential applications in safety-related systems in nuclear power plants. The Fabry-Perot temperature sensor was selected for two reasons. First its sensing mechanism depends on shift of optical interference patterns instead of absolute light power, which makes it independent to reasonably large changes in light power thus tolerant of external stressors such as radiation, heat and humidity. Second, temperature measurement is very important in the safety and control systems in a nuclear power plant.

The corresponding research requires development of a methodology, which demonstrates that the investigated sensors will be able to perform their required functions in all normal and all expected abnormal environments. These requirements are specified in Regulatory Guide 1.89 (IEEE 323-83). Methods to verify performance requirements are specified in ISA-dS67.06.

The following three objectives were established for this dissertation

1. Provide technical basis for the sensing mechanism of commercially available Fabry-Perot fiber optic sensors to assist potential users in introducing the advanced sensing technology into nuclear power plants.
(2) Evaluate its potential applications in normal and abnormal operation environments encountered in nuclear power plants, which is specified in IEEE323-83. This will be accomplished by verifying the performance of FISO FOT-H sensors in nuclear environment simulation tests including gamma only irradiation, mixed neutron/gamma irradiation, and design basis accident high pressure/temperature environments.

(3) Provide technical analysis associated with further sensor improvement and development, manipulation guidance and on-line surveillance in order to help the NRC in regulatory process and reduce licensing risk.

Literature review for the dissertation was conducted in the following areas:

- Fabry-Perot and other fiber optic sensors, waveguide, sensor design
- Optical signal processing and detection
- Measurement, sensor performance and validation, in-situ surveillance
- Irradiation effects on optical fibers and fiber optic sensors
- Commercial grade dedication of digital I&C systems and components in nuclear power plants
- Safety and safety-related I&C systems in nuclear power plants
- Nuclear regulatory guidelines

The research described in the dissertation includes theoretical and experimental analysis of the sensor sensing mechanisms and dynamic models, performance evaluations of the sensors in the simulated normal and abnormal nuclear environments (through gamma only irradiation, mixed neutron/gamma irradiation and design basis
accident environmental tests), a laser heating method proposed for on-line surveillance of Fabry-Perot fiber optic temperature sensors, theoretical analysis and design of a novel experimental method for the purpose of testing response time of pressure sensors with fast response.

Specifically, the major tasks completed in the dissertation were:

1. Completed a review of research trends and regulatory standards in nuclear industry, and developed a set of experiments to evaluate the performance of Fiso fiber optic temperature sensors.

2. Developed a static response model of Fiso fiber optic temperature sensors.

3. Developed a theoretical dynamic response model and dynamically tested Fiso temperature sensors.

4. Completed gamma only irradiation tests with Fiso temperature sensors.

5. Completed mixed neutron/gamma irradiation tests with Fiso temperature sensors.

6. Completed design basis accident high pressure/temperature tests with Fiso temperature sensors.

7. Completed performance evaluation (static calibration and dynamic test) for each nuclear environment simulation test with the temperature sensors.


9. Analyzed failure modes resulting from external stressors.

9. Developed a theoretical and experimental method to test the response time
of a pressure sensor with fast response.

The dissertation is organized in an order corresponding to the completed tasks. Chapter 1 addresses research trends, requirements and regulatory standards (i.e. IEEE323 and ISA-dS67.06) in nuclear industry, the developed nuclear environment simulation tests and performance evaluation tests, which are consistent with IEEE323 and ISA-dS67.06 respectively. In the meanwhile, Chapter 1 briefly introduces background of optical fibers and fiber optic sensors to give an overall view of the advanced fiber optic sensing technology. More details about waveguide theory, which can be found in fiber optic references \[8,9,11,17,24,27\], are omitted in the dissertation in order to reduce the dissertation length.

Chapter 2 focuses on the Fiso sensor design and component identification. Chapter 3, which may slightly overlap with Chapter 2 when describing component functions, focuses on mathematical description of the sensor sensing mechanism. Because the sensor dynamic model and response time are very important in nuclear power plant operation and also valuable in verifying the effects of nuclear environments on the Fiso sensor dynamic response, Chapter 4 introduces a developed theoretical dynamic model and several empirical dynamic models developed from the experimental results of a plunge test. The experimental method used in Chapter 4 is the same as in the plunge test described in Chapter 5 and is also consistent with ISA-dS67.06 presented in Chapter 1.

Chapters 5 and 6 present the experimental methodology and results of three types of nuclear environment simulation tests and performance evaluation tests with
five Fiso FOT-H fiber optic temperature sensors, respectively. Chapter 7 is dedicated to further research and introduces a method proposed for on-line surveillance of Fabry-Perot fiber optic temperature sensors. Chapter 8 summarizes the contents of the dissertation. A method, which was developed for testing response time of a pressure sensor with fast response, is introduced in Appendix A.
1.1 Instrumentation and Control (I&C) Systems in Nuclear Power Plants

Instrumentation and Control (I&C) systems are very important to nuclear power plant safety, reliability and economics considering their roles in plant operation, control and surveillance. Most of the current operating nuclear power plants (NPP), which are generation II NPPs, were built in the 60's and 70's. Most of the instrumentation and control systems in generation II NPPs are based on analog technology, which is partially becoming obsolescent due to less suppliers, and costly maintenance and operation. Generation III NPPs, which are advanced light water nuclear power plants, are designed to improve the performance of generation II NPPs and have been approved by the Nuclear Regulatory Commission (NRC). However, Generation III nuclear power plants remain much of the technology used in I&C systems the same as generation II NPPs. At present, research is being performed to introduce generation IV nuclear power plants, which are based on a modular design and strive to incorporate more advanced I&C systems and technologies. It implies that emerging advanced I&C systems and technologies are being considered for the next
generation of nuclear power plants. Another motivation to investigate advanced instrumentation and control systems for nuclear industry is driven by upgrading current obsolescent I&C systems and by commercial grade dedication of advanced I&C technologies.

1.1.1 I&C upgrade and commercial grade dedication

Instrumentation and control systems are very important to operation, safety and productivity of a nuclear power plant because I&C systems play a leading role in reactor shutdown, control, reliability and safety margin. If an I&C system is well designed with improved reliability, enhanced productivity, affordable operation and maintenance (O&M) costs, then the overall O&M costs of a nuclear power plant are reduced. If an I&C system is unreliable, lacks necessary functionality or becomes costly to operate and maintain, then overall O&M costs are increased. The O&M costs weigh about 70% of overall annual costs of a nuclear power plant [36]. In this case, it is necessary to consider some improvements or system replacements for current obsolescent I&C systems or for future I&C systems installed in Generation IV NPPs in order to reduce overall O&M costs, and to maintain reliable and cost-effective I&C functionality.

More attention is being focused on modernization of I&C systems in nuclear power plants [34]. Three major concerns are partially or totally confronted by nuclear power plants throughout the world. The first concern is due to aging and obsolescence
associated with I&C systems in nuclear power plants. This problem of aging and obsolete equipment results from power plant operation age and rapid evolution of electrical and electronic technology such as microprocessors, microcontrollers and digital signal processing technology. Aging and obsolescence have different characteristics and are correlated during plant operation. Aging is a phenomenon or process that physical characteristics or functionality of systems, structures or components change with time or usage. These aging systems or components need to be replaced, upgraded or modernized corresponding to utilized regulatory strategies, which are effected by many factors including the item market availability associated with the obsolescence problem. Obsolescence is defined as a state that an item or system can no longer be obtained by normal ways. For example, a manufacturer may remove the requisite item used in an old power plant from the marketed product catalog provided by the manufacturer. Even though the manufacturer may continue to offer a supply of replacement items or a repair service for some time after removing the item from the product catalog, the manufacturing and maintenance costs, and the risk of shortage may increase from a long-term point of view. Absolute obsolescence occurs when a supplier withdraws all forms of support or service previously provided for the needed item. In other words, the consequences of obsolete equipments are mainly associated with the inability to obtain spare parts and supplier support. Therefore, the aging and obsolescence problem is a significant source contributing to increasing costs for plant operation and maintenance.
The second concern results from the increasing need of improved competitiveness driven by deregulation and other market forces, which requires improved plant productivity, reduced O&M costs, and cost-effective modernization of obsolete equipments and systems. The third concern results from the need of improved plant safety and plant modifications in order to meet new safety standards and requirements, which are directly related to licensing of nuclear power plants and, if not met, will force a nuclear power plant to terminate operation. In addition, the two concerns of obsolescence and competitiveness may also result in plant shut down. These concerns drive the decision-making and engineering staffs to make crucial decisions and select appropriate strategy and technology for the purpose of continued plant operation, continued system maintenance, replacement and upgrade.

When consider upgrade and modernization of aging I&C systems, many technical problems need to be solved such as which system to modernize, what technology to use for a particular modernized system, how to introduce new systems and new technology in a plant, how to develop new systems with new technology so as to let them work together with existing systems, how to address new concerns associated with new technology and how to develop requirements needed to support licensing, etc. In general, nuclear suppliers are no longer developing custom-designed systems and making them available to plant operators. Furthermore, resources for research and development (R&D) are decreasing. Therefore, nuclear power utilities are considering the use of commercially available equipments as the main basis for future modernization of I&C systems.\textsuperscript{[32]}.
For example, the Electrical Power Research Institute (EPRI) and its member utilities have been working together on several projects to support the use of commercially available Programmable Logic Controller (PLC) equipments from the early 1990’s. There are three overall goals or phases of these projects. The first one is to produce an approach used to generically pre-qualify PLC platforms which can be cost-effectively used for safety and non-safety applications in nuclear power plants. The phase I research results are shown in EPRI report in 1994 and has obtained a favorable Safety Evaluation Report (SER) from the NRC. The second goal or phase II is to qualify and gain acceptance of a few PLC-based platforms, where two of the selected representative platforms have obtained a favorable SER from the NRC in 2000. The third goal or phase III is to use these pre-qualified platforms for actual applications in nuclear power plants.

Similar concept and strategy are being implemented in research programs in the NRC [33], the EPRI and the International Atomic Energy Agency (IAEA) [34]. The NRC addresses in their research programs emerging technologies and applications, which have the potential to help nuclear power plants in both operating efficiency and safety. NRC regulatory programs require knowledge about emerging technologies and applications in order to make timely decisions on modernization of I&C equipments [33], which means research tasks associated with this area will provide technical information and criteria for regulatory decisions [33]. Using the accumulated technical information, the NRC will be able to make timely regulatory decisions about which systems to modernize, what technology to use, how to incorporate new systems with
new technology, how to address new concerns and regulatory and licensing issues associated with the new systems using new technology.

Technologies and applications being addressed by NRC research programs include predictive maintenance and on-line monitoring systems, advanced measurement instrumentation, smart transmitters, wireless communication and fiber optics, and firewalls. The NRC needs the technical bases associated with advanced measurement technology and also needs technical information to NRC regulatory programs. An example that demonstrates NRC research trends is a study completed in 1998 of emerging technologies, which could be applicable to measurement systems in nuclear power plants (NUREG/CR-5501 [16]). This study concluded that advanced fiber optic sensing technology is an emerging technology that should be investigated. The advantages of fiber optic sensors over current traditional sensors they cited include immunity to electromagnetic interference or radio frequency interference (EMI/RFI), and potential for higher sensitivity and accuracy, smaller size and less weight, higher bandwidth and multiplexing capability. This study also indicated that there had been very little research related to performance evaluation of fiber optic sensors in nuclear plant harsh environments. Based on these requirements and research trends, Fabry-Perot interferometer-based fiber optic temperature sensors were investigated and evaluated in this dissertation for potential applications in safety or safety-related I&C systems in nuclear power plants.
1.1.2 Safety and Safety-related I&C systems

In a nuclear power plant, depending on the importance of an I&C system in effecting public health and safety by mitigating the consequences of design basis events or in effecting the complete plant safety, it is categorized into either safety or safety-related I&C systems. The International Atomic Energy Agency (IAEA) and the Institute of Electrical and Electronics Engineers, Inc, USA (IEEE) both have complete definitions and standard criteria about these systems. This section briefly introduces the concepts of these systems addressed in IAEA standard guide and IEEE standard criteria, and then focuses on the IEEE standard criteria.

In a nuclear power plant, specific I&C systems are designed to automatically detect the onset of unsafe conditions, shut down the plant and initiate engineered systems to respond to fault conditions, which means these I&C systems are very important to plant safety. These systems are characterized as “I&C systems important to safety” in the IAEA guide [30]. In other words, the functions of “I&C systems important to safety” include those necessary to avoid or prevent accident conditions as well as those functions necessary to relieve the consequences of accident conditions. The main functions of “I&C systems important to safety” are control of reactivity, control of heat removal from the core, and limitation of operational discharges and accidental releases, under both normal and accident conditions. Associated functions of “I&C systems important to safety” include protection functions, control functions, monitoring and display functions, and testing functions. Typical classes of “I&C systems important to safety”, which are identified in the new IAEA guide [30], include
protection systems, safety systems, interlock systems, control systems, information systems, limitation systems, and risk reduction systems.

According to established National Practices and IAEA Safety Guide, these “I&C systems important to safety” are classified into two main categories, which are “safety systems” and “safety-related systems” depending on the importance of the system on the plant safety. Figure 1.1 shows classification and specific examples of “I&C systems important to safety”.
Figure 1.1: Examples of I&C systems important to safety (refer to IAEA Safety Guide 50-SG-D8) [30].
Similar to the IAEA guide, IEEE Standard 603-1980 addresses safety systems as those required to protect public health and safety by functioning to mitigate the consequences of design basis events\textsuperscript{[44]}. They can be subdivided into three operational elements of reactor trip system and engineered safety features, auxiliary supporting features, and other auxiliary features. According to their performance characteristics, the safety systems can also be subdivided into three general elements of sense and command features, execute features, and power sources. Table 1.1 lists a typical scope diagram of a safety system. Safety-related systems are characterized in a broader range, which is related to plant safety such as fire protection systems.

The IEEE Std 603-1980 standard criteria is supposed to apply to safety systems and does not necessarily apply to all of the safety-related systems, structures, and equipment required for complete plant safety such as fire protection systems. It is consistent with another interrelated standard IEEE Standard 308-1980 in terms of the defined scope diagram of safety systems. IEEE Standard 308-1980 defines Class 1E power systems as the electrical equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal, or are otherwise essential in preventing significant release of radioactive material to the environment\textsuperscript{[44]}. IEEE 323-1983 provides guidance on qualifying Class 1E electrical equipments and systems in nuclear power plants. IEEE Standard 323, and Standard ISA 67.06, which addresses performance monitoring of nuclear safety-related instruments channels in nuclear power plants, will be discussed in Section 1.2.1.
<table>
<thead>
<tr>
<th>Sense and command features</th>
<th>Execute features</th>
<th>Power sources</th>
</tr>
</thead>
</table>
| Reactor trip system and engineered safety features | -Process sensors  
-Signal conditioning  
-Decision logic  
-Manual switches  
-Process controls  
-Indicators for operator action  
-Limit switches  
-Control circuitry | -RTS trip breakers  
-ESF breakers  
-ESF motors, starters  
-ESF pumps  
-ESF motor operated valves, solenoid valves | NA |

<table>
<thead>
<tr>
<th>Auxiliary supporting features</th>
<th>Execute features</th>
<th>Power sources</th>
</tr>
</thead>
</table>
| -Room temperature sensors  
-Component temperature sensors  
-Pressure switches and regulators  
-Potential transformers  
-Undervoltage relays  
-Diesel start logic  
-Diesel load sequencing logic  
-Limit switches  
-Control circuitry | -HVAC fans, filters  
-Lube pumps  
-Component cooling pumps  
-Breakers, starters, motors  
-Diesel start solenoid  
-Crank motors | -Air compressors and receivers  
-Batteries  
-Diesel generators  
-Inverters  
-Transformers  
-Buswork  
-Distribution panels |

<table>
<thead>
<tr>
<th>Other auxiliary features</th>
<th>Execute features</th>
<th>Power sources</th>
</tr>
</thead>
</table>
| -Built in test equipment and circuitry  
-Bypass and reset circuitry  
-Electric protective relaying  
-Limit switches  
-Diesel overtemperature and lube oil indicators  
-Manual switches | -Safety system isolation devices  
-Breakers to nonessential loads | -Battery chargers  
-Transformers  
-Buswork  
-Distribution panels |

Table 1.1: A typical scope diagram of a safety system⁴⁴.
1.1.3 Temperature Measurement in Nuclear Power Plants

For any instrumentation and control system, the sensor is a fundamental and important component which implements measurement of the real time signal. A typical feedback control system shown in Fig. 1.2 is a good example that specifies the importance of sensors. Sensors measure the plant process parameters (i.e. temperature, pressure, flow rate, etc.) and send the measured data into signal conditioners and other instrumentations to provide displayable or readable data for human machine interface. Based on the data measured by sensors, human or automatic controller make control decisions or send out control signals to the actual plant system, which is controlled to meet prescribed operational requirements. Sensor accuracy and reliability are fundamental and important requirements for the whole control system.

![Diagram of feedback control system](image)

Figure 1.2: The structure of a typical feedback control system.
There are many in-service or redundant sensors installed in a nuclear power plant, which primarily measure temperature, pressure, flow, radiation and liquid level. Temperature measurement is very common among these measurements. Table 1.2 provides a comparison of traditional temperature sensors, which are primarily resistance temperature detectors (RTDs) and thermocouples in nuclear power plants. Although pressure measurement is also very common in nuclear power plants, it is not the focus of this dissertation. Therefore, Fabry-Perot fiber optic pressure sensors are briefly analyzed and recommended for further research.
<table>
<thead>
<tr>
<th>Traditional temperature sensors</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple</td>
<td>Self-powered, simple, rugged, inexpensive, wide variety,</td>
<td>Non-linear, low voltage, reference required, least stable, least sensitive</td>
</tr>
<tr>
<td></td>
<td>wide range</td>
<td></td>
</tr>
<tr>
<td>RTD</td>
<td>Most stable, most accurate, more linear than thermocouple</td>
<td>Expensive, current source required, low absolute resistance, self heating</td>
</tr>
<tr>
<td>Thermistor</td>
<td>High output, fast, two-wire ohms measurement</td>
<td>Non-linear, limited range, fragile, current source required, self heating</td>
</tr>
<tr>
<td>Infrared</td>
<td>No contact required, very fast response time, good stability</td>
<td>High initial cost, more complex support electronics, spot size restricts application, emissivity variations affect readings, accuracy affect by dust, smoke and background radiation</td>
</tr>
<tr>
<td></td>
<td>over time, high repeatability, no oxidation/corrosion to</td>
<td></td>
</tr>
<tr>
<td></td>
<td>affect sensor</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2: Comparisons of traditional temperature sensors.

All I&C equipments are subject to aging and degradation effects during plant operation. Aging management techniques have been developed to predict, detect and deal with aging problems of I&C equipments. Table 1.3 lists a summary of the aging management techniques used for nuclear power plant I&C equipment.
Table 1.3: Aging management techniques used for nuclear power plant I&C equipments.

<table>
<thead>
<tr>
<th>Category of aging management</th>
<th>Aging management techniques</th>
</tr>
</thead>
</table>
| Performance evaluation      | - Calibration (manual calibration, on-line calibration, cross-calibration)  
                                - Response time testing  
                                - In-situ testing and on-line performance measurements  
                                - Self/auto testing |
| Theoretical analysis        | - Vibration analysis and noise analysis  
                                - Trending  
                                - Inspections  
                                - In-service inspections  
                                - Operational feedback  
                                - Accident resistance proof |
| Monitoring and surveillance | - Condition monitoring  
                                - Surveillance, diagnostic testing  
                                - Environmental monitoring |
| Maintenance                 | - Maintenance programmes  
                                - Channel checks  
                                - Replacement |
| Regulation                  | - Record keeping  
                                - Periodic testing  
                                - Spares management  
                                - Quality assurance from suppliers  
                                - Periodic safety reviews |

Substantial research has also been conducted on thermocouples, RTDs, pressure transmitters (including level and flow), sensing lines and thermowells. The
research has focused on environmental conditions that affect sensor performance as sensors age, aging effects on sensor performance, and aging management methods.

In general, temperature and pressure sensors in nuclear power plants are subject to environmental stressors including heat, temperature cycling, humidity, ionizing radiation effects, chemical attack, vibration and mechanical shock. Aging due to exposure to environmental stressors results in degradation in calibration and/or response time of sensors. In other words, aging degradation affects the steady state and dynamic performance of sensors.

According to research and industry experiences, some degradations or potential failure mechanisms were reported on temperature measurements in nuclear power plants. For example, it was reported that twelve resistance thermometers, which are interpreted later as resistance temperature detectors (RTDs), in a nuclear power plant were tested twice in fifteen months. The results showed that the time constants of these sensors either remained unchanged or increased. The average change in time constant was an increase of 22 percent with a maximum increase of 69 percent \[^{37}\]. It was also reported that one of sixteen identical new RTDs in thermowells installed in a nuclear power plant had a time constant three times of the others \[^{37}\].

In nuclear power plants, RTDs have been found with erratic behavior because sensing elements open and close randomly. More specifically, in some instances, the RTD indicates an open circuit for a period of time, and then acts normally \[^{36}\]. In other instances, RTDs with damaged sensing elements drift up for a while and then down and eventually begin to act normal again \[^{36}\]. Although these problems can be
diagnosed and isolated using the Loop Current Step Response (LCSR) test, they may result in extreme adverse consequences on the safety and control of nuclear power plants because all of the temperature sensors installed in the primary coolant are RTDs, which play a very important role in nuclear power plant monitoring and control.

RTD and thermocouple seals are also subject to material aging resulting from environmental stressors and continuous usage so that they dry out, shrink or crack. These could make RTD and thermocouple seals fail allowing moisture to permeate into the sensor, which causes a reduction in insulation resistance. Low insulating resistance can result in temperature measurement errors, which is temperature dependent because a low insulation resistance can change with temperature. Moisture in temperature sensors can also cause noise at the sensor output and greatly increases the vulnerability to electromagnetic interference or radio frequency interference (EMI/RFI). Furthermore, aging or degradation of electrical cable resulting from environmental stressors and continuous usage may also cause crack and moisture permeation, which makes instrumentation and control systems vulnerable to EMI/RFI due to bulky cable transmission, lighting, wireless communication and other electromagnetic fields or components. These EMI/RFI problems may result in common mode failure in measurement, instrumentation and control systems because almost all traditional sensors and instrumentations base on electrical or electronic technology, which is vulnerable to EMI/RFI itself if it is mishandled or incorrectly utilized.
The performance of sensors is mainly related to the sensor calibration accuracy and response time. Therefore, the aging management of temperature and pressure sensors is predominantly implemented through periodic calibration and response time testing. Table 1.4 lists test methods commonly used for performance evaluation and aging management of temperature and pressure sensors used in nuclear power plants.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Performance indicator</th>
<th>Test method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouples</td>
<td>- Calibration accuracy/stability</td>
<td>- Cross-calibration</td>
</tr>
<tr>
<td></td>
<td>- Response time</td>
<td>- Loop current step response (LCSR)</td>
</tr>
<tr>
<td></td>
<td>- Inhomogeneity, parasitic junction, reversed connection</td>
<td>- LCSR test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Insulation resistance test</td>
</tr>
<tr>
<td></td>
<td>- Cables and connectors</td>
<td>- Loop resistance test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Time domain reflectometry test (TDR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- LCSR test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- DC and AC impedance measurements</td>
</tr>
<tr>
<td>RTD</td>
<td>- Calibration accuracy/stability</td>
<td>- Cross-calibration</td>
</tr>
<tr>
<td></td>
<td>- Response time</td>
<td>- LCSR test</td>
</tr>
<tr>
<td></td>
<td>- Electrical parameters</td>
<td>- Insulation resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Loop resistance</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>- Calibration accuracy and stability</td>
<td>- Capacitance</td>
</tr>
<tr>
<td></td>
<td>- Response time</td>
<td>- On-line calibration verification</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Noise analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Power interrupt (PI) test</td>
</tr>
</tbody>
</table>

Table 1.4: Common test methods used for performance evaluation and aging management of temperature and pressure sensors in nuclear power plants.
Although safety-related measurement channels in nuclear power plants use redundant channels or devices, which may be based on different types of operational mechanism and construction to avoid common mode failure, common mode failure due to EMI/RFI is still a common concern for electrical or electronic based systems. For example, both RTDs and thermocouples become more vulnerable to EMI/RFI as they age or degrade due to the usage of electrical wires as sensing elements. Compared with traditional sensors, optical sensors are considered as a new type of sensors based on a different operational mechanism. They use light transmission and modulation technology, which is immune to EMI/RFI. Therefore, they may eliminate or mitigate common mode failures resulting from similar sensing mechanisms or from EMI/RFI, reduce the negative effects of EMI/RFI on sensing or data transmission lines, and reduce relatively bulky cables as nuclear wastes due to nuclear radiation environments in nuclear power plants. Other advantages of fiber optic sensors are described in section 1.3.3.

1.1.4 Radiation Environments in Nuclear Power Plants

There are many kinds of fundamental particles in the physical world. Some of them such as neutron, photon, electron, proton and neutrino are very important in nuclear engineering. In a nuclear reactor, the encountered radiation can be basically classified into two categories associated with two kinds of radiation sources: uncharged particles and charged particles. The uncharged particles include neutron,
gamma (γ-rays), X-rays, etc. The charged particles include beta (β-rays), alpha (α-particles), fission fragments, etc.

In nuclear power plant instrumentation, it is usually not necessary to consider radiation effects of the charged particles such as beta rays and alpha particles because their penetration ranges in matters are very small. However, according to nuclear regulatory and safety guidelines, the gamma rays and neutron radiation should be considered for any new installation of instrument channels or shielding design.

The origination nature and particle energy of gamma rays and neutrons are different. Their interaction mechanisms with matters and radiation effects are also different for different types of radiation. Even for same kind of radiation type, different radiation dose, dose rate, or different irradiated materials may cause different radiation effects and damages on irradiated materials. This section introduces the radiation phenomena and effects of gamma and neutron irradiation.

**Gamma radiation**

All particles in nature behave sometimes like particles and sometimes like waves. Therefore a certain phenomenon can be interpreted either as particle-like behavior or as wave-like behavior. The particle associated with electromagnetic waves is called a photon, which is a particle with zero rest mass and zero charge\(^{[38]}\). It travels in a vacuum at the speed of light. The wavelength of a photon with zero rest mass is

\[
\lambda = \frac{hc}{E} = \frac{1.240}{E}
\]
where \( \lambda \) is in micrometer (\( \mu \text{m} \)), \( E \) is the photon energy in eV, \( h \) is the Planck's constant (4.136*10^{-15} \text{ eV-sec}) and \( c \) is the speed of light in vacuum (3*10^{8} \text{ m/sec}).

Any physical atom consists of a nucleus with nucleons inside, and electrons moving in more or less well-defined orbits outside of the nucleus. Nucleons include neutron and proton. Nucleons also move around in various orbits. Different orbit corresponds to different state and energy level. There is a lowest energy level called the ground state in which an atom or nucleus is normally found. If an atom or nucleus has more energy than its ground state energy, it is said to be in an excited state or in a corresponding energy level.

If an electron is removed from an atom, the atom is ionized. If an electron just moves from a higher energy state to a lower energy state, it is called electronic transition. When ionization or electronic transition occurs for an excited atom, the atom emits a photon with energy equivalent to the energy difference between the initial and final state of the atom.

Similarly, a nucleus in an excited state also intends to return to a lower energy state. Two processes, which are gamma rays emission and internal conversion, compete when the excited nucleus decays to a lower energy level. For the internal conversion, one of the innermost atomic electrons is ejected from the atom, and its remaining hole is filled later by one of the outer atomic electrons. This filling process is accompanied either by emission of an X-ray or by ejection of another outer atomic electron, which is called auger electron emitted in this way.
For gamma ray emission, the excited nucleus emits a high energy photon when it decays to a lower energy level. The energy of the emitted photon is equal to the energy difference between the initial and final nucleus energy state. These photons emitted in this way from nuclei have higher energies than those emitted in electronic transitions. The energy range of these photons is approximately 100 KeV to 10 MeV. High-energy photons produced by nuclei are called gamma rays. In other words, the gamma rays result from the nucleus decay instead of electronic transition.

The excited nucleus can occur as the result of a radioactive decay. A nucleus without a number of protons and neutrons necessary for stability decays by the emission of alpha rays or beta rays or undergo electron capture, all of which may be accompanied by the subsequent emission of gamma rays \[^{38}\]. Many radioisotopes (i.e. Co-60, etc.) undergoing radioactive decay provide gamma irradiation.

Gamma rays interact with matter in three predominant processes: photoelectric effect, pair production and Compton effect. For each kind of interaction, we can define a cross section $\sigma$ to describe the probability of the interaction per unit intensity of gamma rays with one nucleus of the irradiated material in unit time. For example, probabilities of these three processes can be denoted as $\sigma_{pe}$, $\sigma_{pp}$ and $\sigma_c$, respectively, which highly depend on the irradiated material.

For the photoelectric effect, the incident gamma ray interacts with an entire atom, the gamma photon disappears, and one of the atomic electrons is ejected from the atom. The kinetic energy of the ejected photoelectron is equal to the difference between the photon energy and the binding energy of the electron to the atom. The
photoelectric cross section $\sigma_{pe}$ depends on the incident photon energy and the atomic number $Z$ of the irradiated material. It is proportional to $Z^n$, where $n$ is the function of the incident photon energy (i.e. $n$ monotonically increases between 4.05 and 4.6 for the photon energy of 0.1–3 $MeV$).

In the process of pair production, the gamma photon disappears and an electron pair, which is a pair of a positron and a negatron, is created. According to the energy conservation, this effect can only occur if the energy of gamma photon is at least 1.02 $MeV$, which is the total rest mass energy of the two electrons. The pair production cross section $\sigma_{pp}$ is proportional to $Z^2$, where $Z$ is the atomic number of the irradiated material.

The Compton effect is sometimes called Compton scattering, which denotes the elastic scattering of a photon by an electron. The incident photon is scattered and some of its energy is transferred to the kinetic energy of the electron. Because both energy and momentum are conserved in this process, the wavelength of photon after Compton scattering can be obtained in terms of initial wavelength of photon as a function of the scattering angle. The Compton cross section $\sigma_C$ depends on the number of electrons and Compton cross section per electron, which decreases monotonically with increasing photon energy.
Neutron radiation

A neutron is an electrically neutral particle with slightly more mass than a proton. The mass of a neutron is $1.67492 \times 10^{-24}$ g, while the mass of an electron is $9.10956 \times 10^{-28}$ g. When a neutron is not bound into an atomic nucleus, which means it is a free neutron, it is not a stable particle and will decay to a proton. This process accompanied by emission of a negative electron and an antineutrino takes about 12 minutes.

Neutrons are not typically emitted by a radioactive nucleus decay. They are produced by nuclear reaction, in which two nuclei, or a nucleus and a nucleon interact to produce two or more nuclear particles or gamma rays. This process meets the conservation principles in terms of the total number of nucleons, charge, momentum and energy. In a nuclear fission reactor, neutron radiation results from the nuclear reactions that consume fissible materials and provide nuclear power. The fissible materials are usually $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$. These heavy nuclei can absorb one neutron and then break into two light nuclei and emit additional neutrons (i.e. 2 or 3). These emitted neutrons will continue to result in more nuclear reactions. The operation of a nuclear reactor is based on this chain of fission reactions.

The nuclear reaction that a neutron undergoes depends very strongly on its energy. Emitted neutrons cover a wide range of energies. Neutrons can be classified into two groups according to their energy: fast neutrons and thermal neutrons. A fast neutron has a high energy exceeding about 0.1 MeV. The other neutrons with a lower energy are called thermal neutrons. Thermal neutrons have the same average kinetic
energy as gas molecules in the thermal equilibrium environment. Therefore, thermal
neutrons also exhibit a Maxwell distribution depending on temperature.

Because neutrons are electrically neutral and much heavier than charged
electrons, they are not influenced by the atomic electron cloud surrounding nucleus
when they interact with matter. Neutrons directly interact with the nucleus of the
irradiated material in one or more interaction ways: elastic scattering, inelastic
scattering, radiative capture, charged-particle production, neutron-producing reactions
and fission.

The first two can be denoted as \((n, n)\) and \((n, n')\) respectively and neutrons do
not disappear. For inelastic scattering, gamma rays are emitted following the decay of
the excited nucleus, which are stimulated by the incident neutron. These gamma rays
are called inelastic gamma rays. In the radiative capture, which is also absorption
reaction, the incident neutron is absorbed and one or more gamma rays are emitted.
These gamma rays are called capture gamma rays.

In charged-particle producing reaction, the incident neutron may disappear and
some charged-particles such as alpha rays in \((n, \alpha)\) reaction and proton in \((n, p)\)
reaction are emitted. In neutron-producing reaction of the type \((n, 2n)\) and \((n, 3n)\), one
or two more neutrons are emitted due to the incident energetic neutron. In fission
reaction, the nuclei of the fission material split apart and a lot of energy is relieved.
This kind of reaction is the principal source of nuclear energy in a fission reactor.

The probabilities of these reactions are quantitatively described by the
corresponding cross sections, which strongly depend on the irradiated material and the
incident neutron energy. The higher the cross section, the more probable this kind of reaction will occur. For example, boron has a high thermal neutron capture cross section, therefore, boron-doped fibers are not appropriate for applications in neutron irradiation environments.

**Radiation Level**

Radiation levels are quantified in terms of absolute exposure, absorbed dose or dose rate. The basic SI unit of exposure is Roentgen (R), where 1 R is equivalent to the amount of ionizing radiation that produces $3.33 \times 10^{-9}$ C of charges in 1 cm$^3$ of air at standard temperature and pressure. The absorbed dose is usually used to specify the absorbed energy rather than charge in the irradiated material considering that not all types of irradiations result in ionization. The SI unit of dose is Gray (Gy), where 1 Gy = 100 rad. One rad is defined as the energy absorption or deposition of 100 ergs per gram (g) of the irradiated material. The dose rate is the rate of energy deposition in unit of Gy/sec.

For the indirectly ionizing radiation (i.e. gamma rays, fast neutrons and X-rays), Kerma, which is in unit of J/Kg or grays in SI units, is also used to denote the sum of the initial kinetic energies of the primary ionizing particles resulting from radiation (i.e. photoelectrons, Compton electrons or positron-negatron pairs in gamma radiation, etc.) per unit mass of interacting medium.$^9$
Gamma Dosimetry

The purpose of gamma dosimetry in this dissertation is to determine the gamma dose rate on the irradiation site during the mixed field test or the mixed neutron/gamma irradiation test performed in the Ohio State University Research Reactor (OSUURR) beam port #1 facility. The relative gamma and neutron flux intensities are first obtained using the Monte Carlo simulation code (MCNP) \(^3\). MCNP models 3D objects through user defined geometric cells. The model for the beam port environment includes the core, reflector, beam port, holder of irradiated component and the irradiated component itself. MCNP models the production and transportation of neutrons and gamma rays. This simulation process gives the relative gamma and neutron flux intensities.

The neutron flux as a function of energy is determined experimentally based on foil activation method. The absolute gamma flux can be obtained by comparing the neutron spectrum and the relative gamma flux intensities predicted by MCNP. Then the gamma flux is converted to dose by using the Bugle-80 photon kerma factors of silicon and oxygen, which constitute silica fiber glass. This dose is the estimated dose of gamma rays in the mixed radiation field of neutron and gamma rays.

In order to separate the radiation effects of gamma rays from those of neutron on fiber optic sensors, a gamma irradiation test is performed using a \(^{60}\)Co radiation source in the Ohio State University Nuclear Reactor Laboratory Cobalt Irradiator Facility (OSUNRL-CIF). The photon dose rate in the Cobalt Irradiator Facility is obtained following these steps: first converting the air dose rate to exposure rate in air,
then converting it into 1.25 MeV gamma flux, then converting the gamma flux to dose rate in SiO₂ using the Bugle-80 photon kerma factors. Then the radiation time in Cobalt Irradiator Facility can be calculated to approach a predestined dose of gamma radiation, which is selected as the same amount of gamma dose as in the mixed neutron/gamma irradiation test or comparable to a limitation of gamma dose expected within an operation time or expected life time of instrumentations used in a nuclear radiation environment in nuclear power plants.

For example, Table 1.5 shows typical gamma ray dose rates and total doses for particular interventions such as tele-operated maintenance, dismantling, in-core repair or fuel manipulations in a reactor \[^{[13][31]}\]. Under normal operations, the gamma ray dose rates are estimated to be between \(10^5\) Gy/h and 1 Gy/h for possible fiber or fiber optic sensor applications in a nuclear power plant. If considering the plant life time to be 40 years, then the used fibers or fiber optic sensors should withstand these dose rates and a total dose up to 1MGy over 40 years. In accidental conditions, a much higher dose rate up to \(10^4\) Gy/h may be encountered and the total dose limitation depends on the type of accident, its duration and consequence.
### Intervention Gamma ray dose rate | Gamma ray total dose
---|---
Most maintenance work in low radiation environment. Light decontamination operation. | < 0.01 Gy/h | < 10 Gy
Most decontamination work. Interventions on primary loop components. Some hot-cell work. | < 10 Gy/h | < 1 kGy
Reactor vessel intervention. Dismantling work. Hot-cell tasks. | < 1 kGy/h | < 1 MGy
In-core maintenance during reactor stop. Fuel manipulation. | > 1 kGy/h | > 1 MGy

Table 1.5: Typical gamma ray dose rates and total doses encountered during teleoperated interventions in nuclear power plants \(^{[13][31]}\).

**Neutron Dosimetry**

Neutron dosimetry is performed using foil activation analysis to calculate the neutron spectrum and intensity on the irradiation site. The activation foils include many elements such as gold, copper, cobalt, manganese and copper alloy, nickel and aluminum. The activation foils are put in the same site as the tested components. After irradiation of the activation foils, their activity will be subsequently analyzed to compute the neutron flux (in unit of neutron # / (cm\(^2\) *s)) that depends on the neutron energy. This conversion is accomplished in the following processes. First the foil gamma-ray spectrum is measured with a GeLi based detector system. Then the obtained gamma ray spectrum is input into the SAND-II spectrum unfolding code \(^{[12]}\)
to get the neutron spectrum, which is the energy dependent differential neutron flux. The energy dependent differential neutron flux shows the broad energy spectrum characteristic of most light water moderated reactors. The magnitude of the neutron flux varies linearly with reactor power so the neutron flux at full reactor power or other power can also be obtained. Then the differential dose rate distribution over neutron energy can be obtained from the neutron spectrum using the energy dependent kerma factors for silicon and oxygen from the Bugle-80 library \(^\text{[13]}\).

**Radiation Damage and Annealing**

Radiation damage depends on many factors such as irradiation type, energy, irradiation duration and type of irradiated material. The radiation damage caused by a given absorbed dose resulting from one type of radiation may be different from that caused by the same absorbed dose resulting from another type of radiation. One kind of irradiated material may be more vulnerable than others to radiation damages. This dissertation addresses gamma and neutron radiation effects on fiber optic sensors and optical fibers.

On one hand, extensive studies about nuclear radiation effects on optical fibers have been performed in the last two decades. Some common research results have been reported in terms of radiation induced attenuation in optical fibers. However, a satisfactory predictive model has not yet been obtained in terms of the radiation induced attenuation as a function of radiation type, dose, dose rate, optical fiber
structure and optical parameters. On the other hand, very few research data were reported regarding radiation effects on fiber optic sensors.

From macroscopic point of view, the radiation damages on optical fibers may appear as chemical process (i.e. radiolytic process or ionization), change of physical properties (i.e. luminescence and change of refractive index in optical fibers) or change of material properties due to thermal or mechanical stresses. For example, the gamma and neutron radiation will increase temperature in irradiated material due to the deposited energy transferred to heat energy. This will increase thermal stresses and the atomic vibration energy level, which in turns may intensify the radiolytic process.

From microscopic point of view, basically, gamma rays interact with electrons and neutrons interact with nuclei. Therefore, the radiation damage microscopically results from the change or deviation of the atomic or molecular structure, i.e. displacement of nucleus, radiolytic and ionization process, etc.

The radiation damages due to the presence of gamma rays are dominated by the electronic damage, which basically is a radiolytic process. Some radiolytic electrons and holes may be trapped at defect sites and some may recombine with other electrons or holes. And some chemical bonds may be broken due to the energy transfer resulting from the recombination of electron-hole pairs. On the other hand, atoms may also be displaced due to the momentum transfer from these radiolytic electrons. In a summary, the gamma rays interact with the electrons instead of nuclei to excite them and thus secondary electrons and heat may be emitted later. The chemical bonds and
other properties may be changed due to trapping these electrons and the effect of thermal stress, etc.

For example, if considering the gamma radiation damages on optical fibers, the most important effect is the radiation induced attenuation resulting from trapping of radiolytic electrons and holes at defect sites. These sites, which are called color centers, will affect the electromagnetic fields of the transmitted light and absorb light at certain wavelengths. Color centers may already exist during the manufacture process of optical fibers. New color centers will occur at defect sites due to trapping of radiolytic electrons and holes resulting from the nuclear radiation. Color centers may also disappear through thermal or optical process (thermal bleaching or photo bleaching) and thus radiation damage (i.e. radiation induced attenuation) may be partially recovered. These two processes of new color center formation and disappearing of current color centers compete during nuclear irradiation on optical fibers. On the other hand, if considering the atom displacements due to the momentum transfer from the radiolytic electrons, the refractive index is slightly changed and thus the higher order mode of the propagated light may be lost through optical fibers during the data transmission process. However, the effect of atomic displacement resulting from gamma irradiation is not very important.

Neutrons are electrically neutral and have similar mass as nucleons. They will interact directly with nuclei and result in the displacement or excitement of nuclei, which may be accompanied by emissions of gamma rays and x-rays or other nuclear reaction. The neutron irradiation, which may also result in secondary gamma rays or
secondary charged particles due to nuclear reaction or excitement, is likely to have permanent effects on material structures, material or mechanical properties because neutrons interact directly with nuclei. The higher order modes of the transmitted light are likely to escape from the optical fiber because the refractive index variation is greater than that induced by gamma irradiation.

Annealing

Annealing is a kind of phenomenon that radiation induced damages are partially or totally recovered through some approaches after nuclear irradiation. Annealing has been observed in the radiation induced effects on the optical components especially on optical fibers. It can occur in parallel with, or following radiation exposure. Two approaches, which are thermal annealing and photobleaching, have been reported to implement annealing.

Thermal or temperature-aided annealing is observed when raising the temperature of the irradiated components up to a certain value following irradiation. Photobleaching is the recovery of radiation-induced damages by exposing the irradiated components to a light source. For example, photobleaching was observed in pure silica core fibers if they were exposed to the transmitted light again following irradiation [11]. The annealing phenomena observed in irradiation of fibers result from the annealing of the color center. On one hand, the concentration of the color center increases by trapping the radiolytic electrons and holes resulting from the nuclear irradiation. On the other hand, the electrons are more likely to move at a higher
temperature or absorb energy from bleaching light. Therefore, the electrons and holes may disappear through non-radiative recombination. In other words, the color centers may disappear, which is called annealing of color centers, due to thermal and photo bleaching.

1.2 Performance Evaluation of Introduced Devices

Because of the radiation environments and reliability requirements in a nuclear power plant, any instruments considered for potential applications in a safety-related system should be designed, evaluated and tested to meet the nuclear regulatory and safety requirements. This requires development of a methodology, which verifies that the evaluated devices will be able to perform their required functions in all normal and expected abnormal environments. The requirements are specified in Regulatory Guide 1.89 (IEEE 323-1983) [21]. Methods to verify performance requirements are specified in ISA 67.06 [23].

1.2.1 IEEE323 and ISA 67.06

IEEE 323

IEEE 323 is the standard for qualifying class IE equipment for nuclear power generating stations. It addresses principles of qualification, qualification procedures and methods. The qualification process of Class IE equipment includes identification
of the Class IE equipment, equipment performance specifications, performing type
tests, operation experience, analysis, on-going qualification, criteria of failure,
modifications, documentation. Each step includes its own tasks or methods. For
example, equipment performance specifications include nine aspects such as
performance characteristics under defined normal, abnormal, containment test, design
basis event, post design basis event conditions and qualified life. The type test
procedures include general procedure (i.e. test plan, mounting, connections,
monitoring, margin), test sequence, aging, radiation, vibration, operation under normal
and accident conditions, and inspection. Analysis methods include general analysis,
mathematical modeling, extrapolation and determination of qualification. Each step is
generically specified in this standard.

The design basis event environment conditions simulated for a PWR or BWR,
which is specified in IEEE 323, result from a postulated loss of coolant accident
(LOCA). The environment conditions inside the containment are more severe than
those outside of the containment. The environment conditions inside the containment
following the LOCA accident generally consist of exposure to hot gases or vapors (i.e.
steam), and a spray or jet of water, chemical solution or other fluids. Table 1.6 lists
typical in-containment design basis accident test conditions in terms of nuclear
radiation and steam exposure expected for pressurized water reactors. Test conditions
may vary depending on different type of reactors and different locations. Figure 1.3
shows a representative test chamber temperature profile for a combined PWR/BWR
design basis accident test anticipated within the primary containment. Although the
equipment is expected to experience at most only one severe environmental transient as a result of a LOCA event during its installed life, Fig. 1.3 shows two initial steam/chemical transients recommended for accident environment simulation\textsuperscript{[21]}.

<table>
<thead>
<tr>
<th>Type of exposed conditions</th>
<th>Event sequence</th>
<th>Exposed conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure to nuclear radiation</td>
<td>Time</td>
<td>Total dose</td>
</tr>
<tr>
<td>After 1 hour</td>
<td>4 Megarads</td>
<td></td>
</tr>
<tr>
<td>After 12 hours</td>
<td>20 Megarads</td>
<td></td>
</tr>
<tr>
<td>After 1 day</td>
<td>24 Megarads</td>
<td></td>
</tr>
<tr>
<td>After 10 days</td>
<td>40 Megarads</td>
<td></td>
</tr>
<tr>
<td>After 1 month</td>
<td>55 Megarads</td>
<td></td>
</tr>
<tr>
<td>After 6 months</td>
<td>110 Megarads</td>
<td></td>
</tr>
<tr>
<td>After 1 year</td>
<td>150 Megarads</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Steam exposure</th>
<th>Time</th>
<th>Temperature °C(°F)</th>
<th>Gauge Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 10 seconds</td>
<td>48.9 to 148.9 (120 to 300)</td>
<td>0 to 482.6</td>
<td></td>
</tr>
<tr>
<td>10 seconds to 10 hours</td>
<td>148.9 (300)</td>
<td>482.6</td>
<td></td>
</tr>
<tr>
<td>10 hours to 4 days</td>
<td>98.9 (210)</td>
<td>275.8</td>
<td></td>
</tr>
<tr>
<td>4 days to 1 year</td>
<td>75.0 (167)</td>
<td>34.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.6: Typical in-containment design basis accident test conditions\textsuperscript{[21]}.
ISA 67.06

ISA 67.06 specifies the standard of "Performance Monitoring for Nuclear Safety-Related Instrument Channels in Nuclear Power Plants", which is developed by the Instrument Society of America (ISA) Standards Committee. This committee has
determined that the terms "sensor" and "transducer" are interchangeable in the standard specification. The standard was originally approved on October 21, 1980 and the standard revision draft 7 was initiated in September 1999. The objective of this revision draft is to describe methods that could be useful to monitor the performance of protection and process instrumentation systems.

The test methods conceptually introduced in the draft 7 include calibration, channel checks, functional tests and response-time tests. Calibration can be implemented through one or combinations of these techniques including perturbation of the monitored variable, simulation of the monitored variable, online monitoring, cross calibration and diverse parameter comparison. Channel checks are performed to compare two or more instrument channels' indications to verify the performance of the instrument channels or investigate the possibility of common mode failures among channels. Functional tests are performed through injection of test signals to verify if the instrument channels can perform their required design functions. Response time tests, which are intended to test the dynamic response of the instrument channels, can be performed by either direct or indirect test methods or a combination of both. Direct test methods include substitute process perturbation (i.e. ramp input signal, step input signal), power interrupt used for force balance pressure transmitters only, and RTD plunge test only used for laboratory testing. Indirect test methods include noise analysis, loop current step response used for RTDs only and self-heating index method used for RTDs only. The test methods, which were used in the performance evaluation tests of the Fabry-Perot fiber optic temperature sensors investigated in this
dissertation, included calibration, functional tests and response time tests according to the draft 7 of ISA 67.06. Furthermore, on-line monitoring and functional test methods were also used during the following nuclear environment simulation tests designed for the investigated Fabry-Perot fiber optic sensors.

1.2.2 Nuclear environment simulation test

Three types of nuclear environment simulation tests were designed and performed to simulate the nuclear irradiation (gamma and neutron) environment and abnormal accident environment and to evaluate the performance of the selected FISO Fabry-Perot fiber optic temperature sensors. These nuclear environment simulation tests include

- Gamma irradiation test,
- Mixed neutron/gamma irradiation test or mixed field test,
- High temperature/pressure environmental test.

In normal operational environment inside the containment of a nuclear power plant, the dominant radiation results from gamma ray rather than neutron and fission fragments. The gamma irradiation test was designed to determine the effect of gamma irradiation and also to distinguish the effects of neutron radiation from gamma radiation by comparing the experimental results of mixed neutron/gamma irradiation and gamma irradiation test. The gamma irradiation test was performed in the Ohio State University Nuclear Reactor Laboratory Cobalt Irradiator Facility (OSUNRL-
CIF) using the radioisotope Cobalt-60 (half-life 5.3 years for $^{60}\text{Co}$) radiation source, which emits gamma rays with energies of 1.17 and 1.33 $MeV$, respectively. These energy levels are compatible with military specifications and also correspond to the mean energy of gamma rays encountered in nuclear facilities [13]. The energy-spectrum of gamma radiation is much wider for some particular applications such as spent fuel reprocessing.

The goal of the mixed field test was to assess the effects of both neutron and gamma irradiation on the tested temperature sensor. In an actual nuclear power plant environment, some amounts of gamma radiation will be produced out of by-products of neutron irradiation. The radiation environment simulates what is likely to be encountered in an operational environment over a reasonably long service life in a nuclear power plant. The mixed field radiation test was performed in the Ohio State University Research Reactor (OSURR).

The high temperature/pressure environmental test was to evaluate the sensor performance in an abnormal design basis accident specified in IEEE323-83. This environmental test was performed using the pressure vessel facility in the High Bay Laboratory in the Ohio State University.

The nuclear environment simulation tests will be described in Chapter 5 in more details about experimental Setup and Procedures.
1.2.3 Performance evaluation of the selected sensors

Three types of performance evaluation tests were performed according to the requirement described in ISA 67.06 to compare and evaluate the irradiation effects and performance of the tested sensors in nuclear environment simulation tests. The performance evaluation tests include

- Static calibration,
- Dynamic test or plunge test,
- On-line performance monitoring.

This section introduces some concepts about the performance specifications, which are obtained from the static calibration and plunge test programs to verify the performance of the tested Fabry-Perot fiber optic temperature sensors. The experimental setup of the performance evaluation tests is described in Chapter 5.

In a static calibration, all other inputs (desired, interfering, modifying) except the measured parameter - Quantity Under Measurement (QUM)- are kept at constant values. Static calibration is performed to develop the sensor input-output relations from which some performance parameters such as sensitivity, non-linearity, hysteresis and resolution can be determined.

Non-linearity denotes the maximum deviation of the calibration curve from a straight line (i.e. least-squares fit line) [4]. It may be expressed as the greater value between the percentage of the deviation over actual reading and the percentage of the deviation over full-scale reading.
Hysteresis denotes non-uniqueness in the relationship between two variables when one variable increases or decreases. It is usually measured as the percentage difference between the output of increasing load and decreasing load.

Sensitivity is defined as the output change corresponding to a unit change of input variable. For example, the sensitivity of the tested temperature sensor is obtained from the ratio of the change of the sensor temperature over a unit change of the environmental or oven temperature during calibration.

Some dynamic performance parameters such as time constant and rise time, which are very important to specify how fast the tested sensor could respond to a QUTM change, can be obtained from the results of dynamic tests.

Time constant, a characteristic parameter of a typical first order dynamic system, denotes the exponential response of the system output corresponding to a step input. The time constant is equal to the time for a first order system to reach 63.2% of its final output in response to a step input. Rise time is defined as the time interval between 10% and 90% of the final steady state output corresponding to a step input. For an underdamped second order system, the rise time is the time interval between 0% and 100% of the final steady state output due to the existence of overshoots.

1.3 Introduction to Fiber Optic Sensors

Fiber optic sensors employ optical fibers either as a sensing element or as a data transmission line to measure physical or chemical parameters such as
temperature, pressure, strain and chemical concentrations, etc. Since there are many optical parameters such as intensity, phase, wavelength, polarity, refractive index and spectral properties, which may be changed with the Quantity Under Measurement (QUM), there are different categories for current or conceptual fiber optic sensors depending on specific designs and sensing mechanisms.

One common method to classify fiber optic sensors bases on characteristics of light modulation responding to QUM. For example, Hashemian (1998) divided them into four categories: intensity modulated, phase modulated, spectrum modulated, time and frequency modulated [16]. Yeh (1990) divided them into five categories according to the mechanism of light modulation: intensity modulated, phase modulated, frequency modulated, wavelength modulated and polarization modulated [24].

An intensity modulated sensor is the one that measures the modified intensity of the incident light after the light is detected by a detector. The incident light launched from a light source passes through optical fiber and transducer, which changes the intensity of the light with the environmental QUM.

A phase modulated sensor works on the mechanism of comparing the phase of the modulated light with that of a reference light source. The light path length in terms of phase angle is usually measured or sensed in interferometric scheme, which basically includes three kinds of interferometric sensing mechanisms: Fabry-Perot, Mach-Zehnder and Michelson. Compared with intensity modulated sensors, interferometric fiber optic sensors have higher accuracy, sensitivity and usually require more attention on sensor design.
Wavelength modulated sensors, which are also specified as spectrum modulated, vary the spectral properties of the transmitted light corresponding to the QUM change. In other words, the reflected or transmitted light intensity may vary with wavelength or color of the light due to the QUM change (i.e. the measured temperature or pressure) and thus this kind of sensors is also called color probes. For example, a chemical indicator based on wavelength modulation was designed to monitor pH value \(^{24}\).

Frequency modulated sensors modulate frequency of the light signal for the purpose of sensing motion or speed of moving objects. For example, laser Doppler flowmeter \(^{25}\), laser Doppler velocimeters \(^{26}\) based on Doppler effect, in which the frequency of the reflected light or acoustical wave is different from the original frequency when a wave impinges on a moving object.

Another method to classify fiber optic sensors bases on the role of optical fibers in a specific sensor. If the sensing phenomenon takes place in a region outside the optical fiber, then the corresponding fiber optic sensor is classified into extrinsic fiber optic sensors. If the sensing takes place within the fiber itself, then the sensor is an intrinsic fiber optic sensor \(^{17}\). In other words, if the optical fiber is used as a sensing element, then the sensor is intrinsic. If the optical fiber is just used to transmit light to and from a separate sensing device, then the sensor is extrinsic. Yeh also used this definition to divide fiber optic sensors into two types: the pure optical fiber sensor and the remote sensor \(^{24}\).
For fiber optic sensors, the light transmission, modulation and detection based on the use of optical fibers are distinct from traditional sensors, which are usually based on electrical, mechanical, chemical or acoustical mechanism. Background knowledge of fiber optic sensors in terms of optical fibers and the mechanism of light transmission through an optical fiber are introduced in this chapter. Specific knowledge and optical components associated with Fabry-Perot interferometric fiber optic sensors are described in Chapter 2.

1.3.1 Optical fiber

The motivation of implementing better and faster communication stimulates the development of optical fibers and optical communication. In the family of electromagnetic waves, higher and higher frequency range is used to carry more information. For example, the carrier frequency of early radio is in a range of 0.5~2 MHz to carry voice signals requiring a bandwidth of 15 kHz. Television uses a higher carrier frequency up to 100 MHz to carry image signals, which require a bandwidth of about 6 MHz. In 1940s, microwaves in gigahertz domain (1GHz=1x10^9 Hz) was used for radar and then used for terrestrial and satellite communication later [9].

The advent of semiconductor laser opened a totally new window for transmitting information with huge bandwidths. The first achievement of laser action in p-n junction diodes was reported in 1962 by three groups: Hall et al. (1962) at GE, Nathan et al. (1962) at IBM, and Quist et al. (1962) at Lincoln Labs. These GaAs
lasers operated at a temperature of 77K and a wavelength around 850 nm $[27]$, which corresponds to a frequency of about $3.5 \times 10^{14}$ Hz. Imaging if 1 percent of this frequency could be used in a communication system, then a much larger bandwidth of $3.5 \times 10^{12}$ Hz or 3.5 THz could be utilized to carry signals, which is equivalent to about 6x10$^5$ commercial video channels requiring 6 MHz per channel or equivalent to 7x10$^8$ telephone calls requiring 5 KHz per call.

In order to implement better and faster telecommunication and data communication, substantial research has been performed later on optical fibers, which are optical waveguides needed to transmit light carrying useful information. Glass is qualified to be an optical waveguide because it is easy to draw glass into fibers and also because of its optical properties and availability. Attenuation of light in optical fibers is a big issue and the attenuation should be minimized in order to improve the performance and reliability of optical communication. In recent 30 years, manufacturing technique is greatly improved to reduce impurities in glass so that ultra-pure glass fiber can be made with a very low attenuation (i.e. less than 0.2 dB/km near a wavelength of 1500 nm), compared with early glass with an attenuation of about 1000dB/km for near-infrared light. Optical fibers have been widely and successfully used in telecommunications because of its enormous bandwidth, high capacity, low maintenance, small volume and weight when compared with copper wires.

Figure 1.4 shows the structure of an optical fiber. It usually consists of a cylindrical glass core and a glass cladding layer as shown in Fig. 1.4. Outside of the
cladding, it is coated with a jacket, which is usually made of acrylic or some other plastic. The jacketed fibers can be incorporated into cables with one, two or many fibers depending on different cases of applications.

Figure 1.4: The structure of an optical fiber.

**Single mode and multimode fiber**

If considering the continuity of the electro-magnetic field of the transmitted light in an optical fiber, only a few modes that meet light waveguide boundary conditions can be propagated in the fiber. According to the number of transmitted modes, optical fibers consist of single mode fibers and multimode fibers. A single mode fiber only transmits one mode through the fiber but a multimode fiber allows multimode transmission of light. The core diameter of a multimode fiber is much larger than that of a single mode fiber. For example, single mode fibers have small
core radii on the order of 3 μm to 6 μm. Multimode fibers have cores above 25 μm, with typical values of 50 μm and 100 μm. Multimode fibers, which meet telecommunication standards, are usually used in fiber optic sensors [5]. Multimode fibers have several advantages over single mode fibers:

1. A multimode fiber allows the use of a broadband light source because of its larger core dimension.
2. Inexpensive and simple to manufacture.
3. It is easier to couple light in and out of a multimode fiber because of its larger core diameter than a single mode fiber.

Figure 1.5 shows the intensity distribution in an optical fiber supporting thousands of modes.

Figure 1.5: The intensity distribution in an optical fiber supporting thousands of modes.
1.3.2 Totally internally reflected (TIR)

The detailed fundamental waveguide theory of light transmission through an optical fiber is referred to other references \(^\text{[8][9][11][24][27]}\). This section briefly introduces characteristics of light waveguide based on the mechanism of Totally Internally Reflected (TIR). Optical fibers are widely used as light waveguide because the light is totally internally reflected at the interface of the optical fiber core and the cladding. Snell's Law describes light reflection and refraction at any interface between two different materials with different refractive index. When a ray is incident on an interface from material 1 to material 2, with an incident angle of \(\theta_i\) with respect to the interface, the ray is bent according to Snell's Law described as

\[
n_1 \cos \theta_i = n_2 \cos \theta_2,
\]

where the incident angle \(\theta_i\) is defined as the angle between the incident ray and the normal to the reflecting or refracting surface, \(\theta_2\) is the refractive angle with respect to the normal of the interface, \(n_1\) and \(n_2\) are the refractive indices of material 1 and 2 respectively.

If \(n_1 > n_2\), then there exists a critical angle \(\theta_c\) for the incident angle, which results in a zero angle of \(\theta_2\). Therefore, the critical angle is defined as

\[
\theta_c = \cos^{-1} \left( \frac{n_2}{n_1} \right).
\]

If the incident angle to the interface is less than the critical angle, then the light is totally internally reflected (TIR). If a light propagates through a fiber based on TIR,
then it is said to be waveguided. Figure 1.6 shows the corresponding ray diagram in an optical fiber with different incident angles.

![Ray diagram in an optical fiber with different incident angles.](image)

Figure 1.6: Ray diagram in an optical fiber with different incident angles.

In order to receive optical signals at the other end of fibers, light transmission should base on TIR otherwise the light will be eventually and totally lost following long distance light transmission. Two requirements exist in order to guide a light through an optical fiber based on TIR:

1. The refractive index of the fiber core must be higher than that of the cladding
2. The launching angle from air to the fiber core should be less than a maximum acceptance angle, \( \theta_{0,\text{max}} \), where \( \theta_{0,\text{max}} \) depends on the refractive indices of the fiber core, cladding, and air. This angle can be obtained by
applying Snell’s Law at the interface of the air and the fiber core, and the TIR condition at the interface of the fiber core and cladding. For example, if the refractive indexes of the core, cladding and air are 1.5, 1.497 and 1.0 respectively, the critical angle at the interface of the core and cladding is \( \theta_c = \cos^{-1}(n_1 / n_2) \approx 3.624^\circ \). Then the refractive angle \( \theta_2 \) to the normal of the air-core interface is also 3.624°. According to the Snell’s Law, \( \theta_{0,\text{max}} \) to the normal of the air-core interface can be calculated as

\[
\theta_{0,\text{max}} = \sin^{-1}(\sin(\theta_2) \cdot n_{\text{core}} / n_{\text{air}}) \approx 5.441^\circ. \tag{1.3}
\]

Instead of using the above angle directly, we usually define a numerical aperture (NA) of an optical fiber as

\[
\text{NA} = n_0 \sin(\theta_{0,\text{max}}), \tag{1.4}
\]

where \( n_0 \) is the refractive index of the material (usually air) outside the fiber. The smaller the NA, the smaller the acceptance angle.

1.3.3 Advantages and applications

In general, it is practical to implement all-dielectric cable connection for fiber optic sensors, which means an optical cable is made entirely of dielectric (insulating) materials without any metal conductors. In other words, fiber optic sensors are immune to electro-magnetic interference (EMI) and radio frequency interference (RFI) due to light transmission and the used dielectric cables. Therefore, they can be used in strong EMI/RFI environments. If used in nuclear power plants, they may eliminate
common mode failures or mitigate failure consequences due to similar sensing mechanisms of traditional sensors or due to EMI/RFI. Furthermore, they have other potential advantages over traditional sensors, such as higher sensitivity, smaller size, less weight, larger bandwidth and ease of multiplexing. Therefore, they are promising as a new type of sensors for applications of surveillances, measurements and controls in nuclear power plants, submarine and aerospace.

For example, conventional electrical sensors require heavy shielding to prevent electromagnetic interference and corrosion. This shielding usually increases cost and size significantly and also produces bulky nuclear waste due to nuclear activation in a nuclear power plant or nuclear irradiation environment. However, optical fibers are very small and immune to electromagnetic interference and they are not affected by corrosion [17]. There is no cross talk between adjacent optical fiber cables. They can also be used in harsh environment such as high voltage area and high nuclear radiation environment, etc. Therefore, optical fibers have advantages over traditional cables on reducing cost, size and nuclear waste. Furthermore, larger bandwidth of an optical fiber makes it possible to multiplex and transport information from many channels together through an optical fiber. Because of many distinctive advantages, fiber optic sensors have rapidly penetrated traditional sensor markets following reduction of manufacturing cost and quality improvement [17].
Chapter 1 introduced background knowledge of fiber optic sensors. This chapter introduces interferometric fiber optic sensors and then focuses on FISO Fabry-Perot interferometric fiber optic sensors. The design of FISO fiber optic sensors is discussed in this chapter. The next two chapters develop static and dynamic models using theoretical and experimental methods. Chapters 5 and 6 describe experimental methods and results to evaluate the performance of FISO fiber optic temperature sensors in simulated nuclear environments.

2.1 Interferometric fiber optic sensors

Interferometric fiber optic sensors are sensors that rely on interferometric detection or interferometer sensing mechanism. An interferometer is an instrument that employs the interference of light waves for purposes of measurement. Interference means the interaction of two or more beams of coherent or partially coherent light in optics \(^{[43]}\). Interference phenomenon, which was first observed by Young in 1801, is
one of the most important characteristics of the wave nature of light. It can only be observed when superimposing coherent light beams, which should meet the conditions of same polarization, same frequency and constant phase difference among the superimposed light beams. Two orthogonal polarization waves cannot interfere. When two coherent light waves are superimposed, the intensities in the superimposed region vary from point to point. The maximum intensity may exceed the sum of the intensities of the two light waves and the minimum intensity may be zero. The resulted varying intensities can be observed on a screen or detected as interference fringes.

From the light wave (electro-magnetic wave) point of view, interference mechanism can be explained as follows starting with a simple example of superposition of two monochromatic light waves. Assuming two monochromatic waves coming from two point sources $S_1$ and $S_2$ have the same polarization and their electrical fields are superimposed at a point $P$ in the overlapping region or on an observation screen, the superimposed electrical amplitude is described as follows

$$E_1 + E_2 = A_1 \cos \left( \omega_1 t - \frac{2\pi}{\lambda_1} + \phi_1 \right) + A_2 \cos \left( \omega_2 t - \frac{2\pi}{\lambda_2} + \phi_2 \right) \quad (2.1)$$

or

$$E_1 + E_2 = A_1 \cos (\omega_1 t + \alpha_1) + A_2 \cos (\omega_2 t + \alpha_2) \quad (2.2)$$

where $A_1$ and $A_2$ denote the amplitudes of the two light sources, $\omega_1$ and $\omega_2$ are the angular frequencies, $\lambda_1$ and $\lambda_2$ are the wavelengths, $r_1$ and $r_2$ are the distances between the observation point $P$ and two light sources, $\phi_1$ and $\phi_2$ are the initial phases of the
two light waves, $\alpha_1$ and $\alpha_2$ are phases consisted of the initial phase and phase change due to spatial propagation of lights.

The intensity of an optical wave is defined as the square of amplitude averaged over the response time of detectors, which is described as follows

$$I = \left( |E_1 + E_2|^2 \right)$$

$$= \left( A_1^2 \cos(\omega_1 t + \alpha_1) + A_2^2 \cos(\omega_2 t + \alpha_2) + A_1 A_2 \cos((\omega_1 + \omega_2) t + (\alpha_1 + \alpha_2)) \right). \quad (2.3)$$

Because the light frequency is usually in the range of $10^{14} \sim 10^{17}$ Hz, which is much higher than the response time of any physical detector, the detected light intensity is actually the average of many cycles of the light waves. Therefore, the detected light intensity at the case of non-interference is actually given by

$$I = \frac{1}{2} A_1^2 + \frac{1}{2} A_2^2 = I_1 + I_2, \quad (2.4)$$

where $I_1$ and $I_2$ are the intensities of the two light fields. Eq. (2.4) means that the total intensity is the addition of two light fields when no interference occurs.

However, Eq. (2.4) is not applied to the case when the superimposed light beams meet the coherence conditions such as same polarization, same frequency and constant phase difference. If the two light fields oscillate at the same frequency $\omega$, then Eq. (2.3) becomes $^{[43]}$
\[ I = \left( A_1^2 \cos(\alpha x + \alpha_1) + A_2^2 \cos(\alpha x + \alpha_2) + A_1A_2 \cos[2\alpha x + (\alpha_1 + \alpha_2)] + A_1A_2 \cos(\alpha_1 - \alpha_2) \right) \]
\[ = I_1 + I_2 + 2\sqrt{I_1I_2} \cos(\delta), \quad (2.5) \]

where

\[ \delta = \alpha_1 - \alpha_2 = \frac{2\pi(r_1 - r_2)}{\lambda} + (\phi_1 - \phi_2) \quad (2.6) \]

is the phase difference between the two light fields at point P. In order to obtain a stable intensity distribution or observe an interference fringe, it is required to maintain a constant phase difference for any given point inside the overlapping region at any time, which means that the initial phase difference between the two light sources (\(\phi_1 - \phi_2\)) should be kept constant.

If the conditions of coherent waves are met, interference fringes can be observed as an alternation of dark and bright region on an observation screen. A special case of \(\cos \delta = 1\) exists at some points in space for the superimposed light waves, which means the phase difference between the two light waves at these points is an integer multiple of \(2\pi\) or in phase. In this case a maximum intensity is obtained as

\[ I_{\text{max}} = I_1 + I_2 + 2\sqrt{I_1I_2}. \quad (2.7) \]

If the two light waves are 180° out of phase (\(\cos \delta = -1\)), then a minimum intensity is obtained as

\[ I_{\text{min}} = I_1 + I_2 - 2\sqrt{I_1I_2}. \quad (2.8) \]
Constructive interference occurs at those spatial points where the resulted intensity is greater than the sum of the two beam intensities \( I > I_1 + I_2 \). Destructive interference occurs when \( I < I_1 + I_2 \). The visibility of interference fringes is defined as

\[
\nu = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}
\]  

(2.9)

where it is obvious that the visibility value is between 0 and 1. From Eqs. (2.7) and (2.8), the visibility of the interference fringes resulting from two monochromatic light beams is given by

\[
\nu = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} = \frac{2\sqrt{I_1 / I_2}}{1 + I_1 / I_2}
\]  

(2.10)

From Eq. (2.10), the interference fringes of two monochromatic beams have the highest visibility of one when \( I_1 = I_2 \). The closer the intensities of the two light waves, the higher visibility of the interference fringes. But for a real world light source, which always has a finite bandwidth, the interference fringe visibility is always less than one.

Figure 2.1 shows different kinds of interferometric fiber optic sensors and their responding areas of applications. This chapter will briefly introduce three common interferometric fiber optic sensors based on Mach-Zehnder, Michelson and Fabry-Perot Interferometer, and then focus on the FISO Fabry-Perot interferometer based fiber optic temperature sensor.
Figure 2.1: Interferometric fiber optic sensors [16].

Figure 2.2 shows the schematic view of a Mach-Zehnder Interferometric sensor. Mach-Zehnder interferometer uses two fibers to detect temperature. The source of light in sensor sends two signals into two different optical fibers. One fiber is the sensing fiber and the other one serving as the reference fiber is not exposed to the sensing environment. The lights from the two optical fibers are recombined and their phase difference between the two lights is measured in optical detector. This
phase difference is directly related to the fiber length and/or fiber refractive index change, which is subjected to the change of the measured environmental variable.

![Mach-Zehnder Interferometer sensor](image)

**Figure 2.2:** Mach-Zehnder Interferometer sensor\textsuperscript{[16]}.

A Michelson interferometric sensor shown in Fig. 2.3 makes use of reflection caused by placing mirrors at the ends of fibers. The light traveling from the source is split into the sensing and reference fiber coils. And then the light is reflected back through the same coils by reflectors\textsuperscript{[16]}. The phase shift, which is subjected to the change of the measured environmental variable, is measured in the detector.
Figure 2.3: Michelson interferometer sensor [16].

Figure 2.4 shows the schematic view of a Fabry-Perot interferometric sensor. The Fabry-Perot interferometer consists of two mirrors facing each other. The distance between the two mirrors is called the cavity length of the Fabry-Perot Interferometer (FPI). The mechanism of the Fabry-Perot interferometer is described in Chapter 3.

Figure 2.4: Schematic view of a Fabry-Perot Interferometric Sensor.
Although these interferometer concepts were proposed many years ago, their applications in fiber optic sensors are still in progress because a commercially available interferometric fiber optic sensor highly depends on maturity of technologies such as light signal detection and processing technique, actual sensor design and development, etc. Among these interferometric sensors, the Fabry-Perot interferometric sensors use just one optical fiber cable to transmit both the incident light and the reflected light from the FPI. This structure is very helpful in multiplexing sensors and integrating sensors in a large sensing and control system. It also reduces the complexity and possible failure using less optical fiber cable.

2.2 System identification of FISO temperature sensing system

A thorough literature review and product search was completed at the early stage of this research project in order to select a promising commercially available fiber optic temperature sensor \cite{46,15,10}. Fabry-Perot interferometric fiber optic sensors manufactured by FISO technologies in Canada were found to be very promising in the near future due to its characteristic advantages. The selected sensor for commercial grade dedication focused on the FISO fiber optic temperature sensors because of their Fabry-Perot interferometric sensing mechanism, distinct signal processing technology based on patented white light cross correlator and the commercial availability of both
transducers and signal conditioners. Furthermore, FISO sensors, based on their unique
signal processing technique, utilize multimode optical fibers having a much larger
core diameter than single mode fibers. Therefore, they are not necessarily in need of
lasers as light sources but may use inexpensive incoherent light sources (i.e. tungsten
lamps, LED), which reduce manufacturing cost and installation complexity.

A brief description of FISO fiber optic sensors is found on the FISO
Technologies’ website and quoted as follows:

FISO transducers offer great versatility, high accuracy, and large dynamic
range. Our transducers are the most attractive fiber-optic sensors available on the
market today. All of Fiso Technologies’ fiber-optic gauges are designed around a
Fabry-Pérot interferometer (FPI). Basically, a FPI consists of two mirrors facing
each other, the space separating the mirrors being called the cavity length. Light
reflected in the FPI is wavelength-modulated in exact accordance with the cavity
length. Since well-designed FPI gauges convert strain, temperature, load, or pressure
into cavity length variations, the key to the successful use of FPI technology is to find
a practical way of obtaining precise and reliable Fabry-Pérot cavity length
measurements. Fiso’s patented white-light cross-correlator (U.S. patent 5,392,117 and
5,202,939) offers a unique and powerful way to make absolute Fabry-Pérot cavity
length measurements with astonishing accuracy and linearity, thus providing accurate
readings time after time.
To perform measurements, FISO fiber optic transducers must be mated to one of the Fiso's fiber optic signal conditioners. Our signal conditioner are designed to precisely convert the optical signal encoded by the transducer into engineering units such as display in °C or °F, integrated datalogger, RS-232 communication port, analog output in +/- 10 volts or 4-20 mA.

Main features of Fiso's fiber optic sensors:

- Ease of use: no tuning or calibration procedures. Connect the gauge to a FISO signal conditioner, enter the associated 7-digit "Gage Factor" once and you are ready to start measurements.
- Absolute measurements allow the user to disconnect the gauge, shut the system down, etc. while always keeping track of the actual value (i.e. there is no loss of reference).
- Perfect linear response achieved through absolute measurement of the FPI cavity length.
- Insensitivity to light loss due to fiber bending, cable length, or light source fluctuations.
- Versatility of the technique allows the user to perform various types of measurements with the same fiber optic signal conditioner. Fiso offers a wide range of FPI gauges for strain, force & load, temperature, pressure, linear displacement applications.
- Dynamic range of 1:15 000
- Resolution of 0.01% or better
50/125 mm multimode fibers used to make the gauges meet telecommunications standards.

The basic idea of FISO Fabry-Perot interferometer based sensors is to change the Fabry-Perot cavity length with measuring environmental parameters such as environmental temperature, pressure and strain, etc. depending on what physical variable the sensor is designed to measure. For example, the FISO temperature sensor makes use of thermal expansion of pure glass to respond to environmental temperature change and thus to change the FPI cavity length. The FPI cavity length change modulates the transmitted or reflected light through the Fabry-Perot interferometer and the modulated optical signal is processed in a signal conditioner. Different measured parameters such as temperature or pressure change the FPI cavity length due to different sensor head design and structures. The detected intermittent parameter is the FPI cavity length for different types of FISO sensors. Therefore it is possible to use the same optical signal modulation technology using Fabry-Perot interferometer and the same optical signal processing technology for different types of sensors measuring different physical parameters. In other words, the other types of sensors such as pressure or strain sensors share the same signal detection and processing technologies with temperature sensors. In this dissertation, FISO fiber optic temperature sensors are investigated for potential commercial grade dedication to safety-related instrumentation and control systems in nuclear power plants. The sensing mechanism of FISO pressure sensors is briefly introduced in Chapter 7.
From the user's point of view, the FISO temperature sensing system consists of two devices. One device is the temperature transducer, which transforms the environmental temperature into wavelength modulated light intensity using a FPI. The other one is the signal conditioner, which employs an innovative white light cross-correlator and a microprocessor to demodulate and process the light signal from the temperature transducer. One end of the leading optical fiber in the temperature transducer connects to the transducer head during the manufacturing process. During the measurement process, the other end of the leading optical fiber is connected to the signal conditioner using a ST-type connector.

The system level characteristics of the temperature transducer and signal conditioner are described in subsections 2.2.1 and 2.2.2. Further design and component identification of these two devices are described in sections 2.3 and 2.4 respectively.

2.2.1. Temperature transducer

The FISO fiber optic temperature transducer can be designed for applications of temperature measurement in high voltage, RF heating or hazardous environments. For example, FISO fiber optic temperature sensors can be designed to be used in oil-well and natural gas pumping station monitoring, plastic injection molding and extrusion monitoring, liquid level monitoring in hazardous environment, high voltage, medical applications, etc. It can also be designed to operate at different measurement
dynamic ranges by setting different gauge length and the angle of two glass planes of the Fizeau interferometer, which is described later. For example, the FISO FOT-H temperature transducer is designed for high temperature applications. Its measurement temperature range is \(-50 \, ^\circ\text{C} \sim 350 \, ^\circ\text{C}\). Table 2.1 lists available fiber optic temperature transducers and their brief descriptions from FISO technologies. FOT-H temperature transducer is selected for commercial grade dedication research for safety-related applications in nuclear power plants because of its high temperature range. Table 2.2 lists more specifications of the FOT-H transducer provided by the FISO technologies.
<table>
<thead>
<tr>
<th>Transducer type</th>
<th>Brief descriptions</th>
</tr>
</thead>
</table>
| FOT-L           | Dynamic range of -50 ~ 250 °C  
- Accuracy of +/- 1 °C  
- Fully immune to EMI/RFI  
- 1.4 mm outer diameter of sensor head tube  
- Coated with Teflon |
| FOT-H           | Refer to Table 2.2 |
| FOT-M           | Dynamic range of 0 ~ 85 °C  
- Accuracy up to +/- 0.3 °C  
- Fully immune to EMI/RFI  
- 800 μm outer diameter of sensor head tube  
- Designed to fit inside a catheter |
| FOT-C           | Dynamic range of 0 ~ 85 °C  
- Accuracy up to 0.3 °C  
- Response time down to 20 ms  
- Fully immune to EMI/RFI  
- Customized to fit custom specifications |
| FOT-S           | Dynamic range of -50 ~ 250 °C  
- Accuracy of +/- 1 °C  
- Fully immune to EMI/RFI  
- National pipe thread NPT type fitting  
- Stainless steel, ceramic or Teflon  
- May be customized to custom specifications |

Table 2.1: Available FISO temperature transducers and brief descriptions \cite{FISO}.
Parameter Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature range</td>
<td>-50 °C to 350 °C</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 °C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>+/- 1 °C or 1% of reading</td>
</tr>
<tr>
<td>Time Response</td>
<td>2 seconds</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Gage length: 6.5 mm length</td>
</tr>
<tr>
<td></td>
<td>Sensor head protection tube: 1.45 mm O.D., 4 cm length</td>
</tr>
<tr>
<td></td>
<td>Fiber-optic cable: 1.0 mm O.D., 1.5 m length</td>
</tr>
<tr>
<td>Material</td>
<td>Optical fiber: Braided fiberglass/Polyimide cable</td>
</tr>
<tr>
<td></td>
<td>Connector: ST-type connector (i.e. ST-C ceramics)</td>
</tr>
<tr>
<td>Characteristic</td>
<td>Fully immune to EMI/RFI</td>
</tr>
<tr>
<td></td>
<td>Absolute measurement of temperature and the Fabry-Perot cavity length</td>
</tr>
<tr>
<td></td>
<td>Insensitive to light loss due to fiber bending, cable length or light source fluctuations (unique signal processing technique)</td>
</tr>
<tr>
<td></td>
<td>Extension cable length specified by customs</td>
</tr>
<tr>
<td>Application</td>
<td>High temperature microwave applications</td>
</tr>
<tr>
<td>examples</td>
<td>High voltage applications</td>
</tr>
<tr>
<td></td>
<td>RF heating environments</td>
</tr>
<tr>
<td></td>
<td>Hazardous environments</td>
</tr>
<tr>
<td></td>
<td>Petrochemical applications, etc.</td>
</tr>
</tbody>
</table>

Table 2.2: FISO FOT-H temperature sensor specifications.

A FISO FOT-H fiber optic temperature transducer with labeled operating temperature range of fiber optic cable and also with a feedthrough installed between the high temperature and low temperature fiber optic cable is shown in Fig. 2.5. This feedthrough is added for the pressure vessel penetration in the specific application of simulated environmental test. A normal FOT-H sensor does not have a feedthrough and usually has a 2m high temperature fiber optic cable. If longer fiber optic cable is
needed for specific custom application, an extension fiber optic cable with ST-type connector attached at the two ends is used to extend cable length between the FOT-H sensor and the signal conditioner. The length of the extension cable is flexible to meet custom application requirement.

![Diagram of FISO FOT-H transducer with a feedthrough added](image)

Figure 2.5: A FISO FOT-H transducer with a feedthrough added [FISO].
2.2.2 Signal conditioner

Two FTI-10 signal conditioners were used in the experiments performed in this dissertation. The following descriptions of FISO signal conditioners are quoted from FISO technologies:

FISO Technologies' full line of signal conditioners are specifically designed for FISO transducers. Signal conditioning systems are available with various speeds, from 10 to 200KHz sampling rates, and with 1 to 32 channels.

The main advantages of FISO's signal conditioners are:

- Easy of use, no messy tuning or calibration required
- Absolute measurements
- Easy connectivity with other equipment through RS-232, RS-485, +/- 10 Volts or 4-20 mA
- Ultimate long-term reliability
- Fully programmable built-in datalogging capabilities (up to 60,000 samples)
- Interchangeable sensors and simultaneous measurements
- Most signal conditioners are Flash ROM upgradable
- The best price/performance ratio on the market
<table>
<thead>
<tr>
<th>Available signal conditioners</th>
<th>Brief descriptions</th>
</tr>
</thead>
</table>
| **FTI-10** universal entry-level fiber optic signal conditioner | - One channel entry level system  
- Precision (0.025%FS)  
- Resolution (0.01%FS)  
- Portable/battery powered  
- 20 Hz sampling rate  
- Datalogging capabilities (50,000 samples)  
- RS-232 communication port and ±10 volt output  
- 4-20mA analog output optional  
- Liquid crystal display  
- 1/8 DIN enclosure  
- light life expectancy: ~ 40,000 hours of continuous use  
- Operating temperature: -20°C to 40°C |
| **UMI** universal multi-channel fiber optic signal conditioner | - Multi-channel system (4 or 8)  
- Precision (0.025%FS)  
- Resolution (0.01%FS)  
- 20 Hz sampling rate  
- RS-232 and voltage outputs  
- Datalogging capabilities (50 000 samples)  
- Large Vacuum Fluorescent Display (VFD)  
- 1/2 DIN enclosure  
- 150 ms switching rate |
| **DMI** dense multi-channel fiber optic signal conditioner | - Multi-channel system (16 or 32), No display  
- Precision (0.025%FS)  
- Resolution (0.01%FS)  
- 20 Hz sampling rate  
- RS-232 communication port  
- Datalogging capabilities (50 000 samples)  
- Waterproof industrial enclosure |
| **FTI-100i** universal multi-channel signal conditioner | - Multi-channel system  
- Precision (0.05%FS)  
- Resolution (0.01%FS)  
- Large graphics liquid crystal display  
- Up to 1000 Hz sampling rate  
- Datalogging capabilities  
- Optional RS-232 and voltage outputs  
- Available in 4 or 8 channels (sequential dovetail) |

- Continue -
### Table 2.3: lists the current available signal conditioners from FISO technologies.

| BUS system simultaneous fiber optic signal conditioner | - Multi-channel system  
- Precision (0.05%FS)  
- Resolution (0.01%FS)  
- Up to 1000 Hz sampling rate  
- RS-232 and voltage outputs  
- Available in 1 to 8 channels (simultaneous)  
- BUS Systems may be cascaded  
- Full simultaneous readings  
- 19" rack mount |
| VELOCE fast simultaneous fiber optic signal conditioner | - Multi-channel system  
- Precision (0.3%FS)  
- Resolution (0.03%FS)  
- 200 000 Hz sampling rate  
- Voltage outputs  
- Available in 1 to 8 channels (simultaneous)  
- Full simultaneous readings  
- 19" rack mount |
| OSR system optical slip-ring for microwave ovens | - Multi-channel system (8 to 16)  
- Precision (0.025%FS)  
- Resolution (0.01%FS)  
- Windows 95/98 compatible control and data acquisition software  
- RS-232 communication port  
- Works with or without the microwave oven turntable  
- The only solution on the market for temperature measurement inside microwave oven with turntable |
| FTI-OEM OEM universal fiber optic signal conditioner | - Single or Multi-channel system  
- 10 to 50 Hz sampling rate  
- Datalogging capabilities  
- Custom outputs  
- Serial or parallel readings  
- Power (9 to 14 volts) |
In the FISO signal conditioners (i.e. FTI-10), a microcontroller is used to sample and process data, and then convert the processed data into analog voltage output using a digital/analog converter (DAC). Therefore, FISO signal conditioners can provide digital reading on screen, data communication link to computers and also analog voltage output. Furthermore, the signal conditioners can also provide some diagnostic signals such as signal to noise ratio (S/N), light signal, battery capacity, memory usage, etc.

A FISO signal conditioner can be used for any type of FISO fiber optic sensors only if the gauge factor, which is a factor to relate the absolute FPI cavity length to the actual temperature, of a specific sensor is inputted into the microcontroller based signal conditioner. Then the signal conditioner can automatically calculate the actual environmental parameters (i.e. temperature, pressure, strain depending on the connected transducer) from the measured absolute Fabry-Perot cavity length, which will be explained later.

Figure 2.6 shows the diagram of a FISO Fabry-Perot fiber optic temperature sensing system consisting of a transducer and a signal conditioner from the component level. The main components consisting of the transducer and the signal conditioner are also shown in Fig. 2.6 and described in the following two sections.
Figure 2.6: Component diagram of a FISO temperature sensing system.
2.3 Temperature transducer design

The temperature transducer consists of the transducer head, the leading optical fiber, and the connector to the signal conditioner. The most important and complex component is the transducer head, which has different design and sensing mechanism for different types of transducers. A feedthrough shown in Fig. 2.5 may be added to the transducer depending on the penetration requirement of the transducer installation environment. An extension optical fiber may be connected to the transducer connector (i.e. ST-C connector) to extend the cable length.

The transducer or sensor head may vary its structure, material or dimension with different design requirements for different type of temperature sensor. Five FOT-H temperature sensors (numbered #1 ~ #5) are tested in respective nuclear environment simulation test (refer to Table 5.1). Figure 2.7 shows the structure of a FISO FOT-H sensor head in details. Table 2.4 lists the material specifications of those components in the FOT-H sensor head as shown in Fig. 2.7.
Figure 2.7: The structure of a FISO FOT-H sensor head.
<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer Information</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge micro-capillary tube</td>
<td>Capillary quartz</td>
<td>310 μm O.D. (in sensor #3, #4 and #5); 200 μm O.D. (in sensor #1 and #2)</td>
</tr>
<tr>
<td>External micro-capillary tube</td>
<td>TSP530700 Synthetic fused silica</td>
<td>Polymicro Company (-standard polyimide coating, -operation up to 350°C) 530±12 μm I.D. 700±25 μm O.D. 15 mm length</td>
</tr>
<tr>
<td>Incident fiber</td>
<td>Multimode Fiber 50μm/125μm</td>
<td>Ceramoptec (in sensor #3, #4, #5) and Spectran (in sensor #1, #2) 50 μm core O.D. 125 μm cladding O.D.</td>
</tr>
<tr>
<td>Tube for centering</td>
<td>Polymide Code 100-III</td>
<td>MicroLumen Company (-Endure 400°C minimum, -Radiation resistance: 3.0x10^9 rad Gamma dose, -Chemical resistance: excellent, most solvents or solutions) 7 mm length</td>
</tr>
<tr>
<td>Internal cable envelop</td>
<td>Polymide Code 185-III</td>
<td>MicroLumen (Same as above) 2.4 meter length</td>
</tr>
<tr>
<td>External cable envelop</td>
<td>Fiberglass</td>
<td>Omega Engineering</td>
</tr>
<tr>
<td>External gauge envelop</td>
<td>Polymide Code 520-III BLK</td>
<td>MicroLumen (Same as above) 40 mm length</td>
</tr>
<tr>
<td>Tip sealant</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Adhesive</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 2.4: The material source of the FOT-H sensor head.
The leading optical fiber (or incident fiber), which is used in the new FISO sensors (#3, #4 and #5) and also used in current FISO sensors, is obtained from Ceramoptec Company (part # WF50/125/140P). This optical fiber has a pure silica core (50μm core O.D.), a fluorine doped silica clad (125 μm clad O.D.) and a polyimide coating (140μm O.D.). This silica/silica step index optical fiber has a numerical aperture (NA) of 0.22 and an ultra low [OH] concentration. In order to obtain a better visibility of the interference fringe pattern or cross correlation function C(d₀,d) as explained later, the numerical aperture of the multimode optical fiber should be low [6]. A NA of 0.13 and a fiber core diameter from 50μm to 62.5μm are estimated to provide the best visibility of the C(d₀,d) [6]. Because the lowest numerical aperture for commercial multimode fibers is about 0.2, a multimode fiber with a NA of 0.22 and a core O.D. of 50μm is selected for the incident fiber for the FISO sensor. From the research results reported in last decades, the optical fiber, which has pure silica core, low [OH] concentration and no boron doped as specified in Ceramoptec fiber, is the most radiation resistant fiber [13]. Therefore, FISO technologies specify the new sensors as “Radiation hardened”. The leading optical fiber in sensor #1 and #2 has a core diameter of 50±3 μm, a clad diameter of 125±2 μm, a numerical aperture of 0.20±0.015 and attenuation of 2.4~2.5 dB/km at 850nm. It is pure silica core and the cladding may be fluorine doped. The [OH] concentration is not available, but it has little influence on the experiment results and comparisons of the previous and new sensors since the fiber used in new sensors is expected to be optimal on radiation resistance. The diameter of the gauge micro-capillary tube in the new sensors (#3, #4
and #5) is increased up to 310μm from 200μm as in the old sensor #1 and #2, which means that the new sensors are expected to be more robust than the old sensors. The welding technique used in these sensor heads is the same.

The outer diameter of the transducer head is very small (less than 1.4mm). From the sensor head design shown in Fig. 2.7, the gauge micro-capillary tube is isolated peripherally from the external several protection tubes. Basically, the gauge micro-capillary tube and the external micro-capillary tube are separated by an air gap at atmosphere pressure. This air gap isolates the gauge micro-capillary tube and also the FPI cavity from external disturbances such as external pressure, stress or longitudinal thermal expansion of the outer protection tubes. The tip of the sensor head is sealed using the tip sealant. An incident optical fiber, which is located between the sensor head and signal conditioner (or extension cable), is inserted into the gauge micro-capillary tube in the sensor head. At the tip of this incident fiber a very thin ZrO₂ film is deposited and serves as one mirror of the FPI interferometer. Another short contrasting fiber is installed at the bottom end of the gauge micro-capillary tube. The contrasting fiber end is also covered by a thin ZrO₂ film, which serves as another reflecting mirror of the FPI. The tips of these two fibers are aligned and maintained parallel by the precise gauge micro-capillary tube. The distance between the two mirrors is defined as the cavity length of the FPI.

The contrasting fiber is aligned to the incident fiber. These two fibers are welded to the gauge micro-capillary tube at only one end of each fiber, where the distance between the two welding spots is defined as the gauge length. These welding
spots ensure that only the part of the gauge micro-capillary tube and only one end for each fiber, which are located between the two welding spots, contribute to the FPI cavity length change through thermal expansion. The micro-capillary tubes are made of quartz with thermal expansion coefficient of 0.5 microstrain/°C (5x10^{-7}/°C). The incident fiber is also made of quartz with the same thermal expansion coefficient. Quartz is selected for the micro-capillary tube material based on two advantages. First it ensures excellent welding because it is the same material as the incident fiber. Second advantage relates to quartz stiffness because quartz resists elongation. The term “fused quartz” is frequently used synonymously with fused silica. Fused silica is vitreous silica, which is a kind of glass consisting of almost pure silicon dioxide (SiO₂). Fused quartz is the precise terms for glass made by melting natural quartz crystals through oxy-hydrogen melting or electrical melting method. It has been reported that the most radiation hard quartz fibers, which are also used in high energy physics experiments as the active medium in high radiation area calorimetry, are those with quartz clad, with or without aluminum protective coating [42].

On the other hand, the contrasting fiber serving as a reflecting fiber is made of aluminosilicate glass with thermal expansion coefficient of about 3 microstrain/°C (3x10^{-6}/°C). When the measured temperature changes, the gauge micro-capillary tube and the incident fiber expand slightly. But the expansion of the gauge micro-capillary tube is compensated by the expansion of the incident fiber since it is made of the same material and expands in the opposite direction. The aluminosilicate glass fiber expands more than the quartz micro-capillary tube. Therefore the FPI cavity length is changed.
primarily by the thermal expansion of the contrasting fiber, which responds to change in the environmental temperature.

2.4 Component identification in the signal conditioner

A signal conditioner for a sensor is a device used to detect and process the signal transmitted from the transducer and optimize the sensor performance (i.e. linearization). For any fiber optic sensors, it is necessary for signal conditioners to use some optical devices such as a light source, optical fibers, photodetectors, couplers, etc. For a specific fiber optic sensor, its signal conditioner based on different sensing technique may require some other devices to implement the signal conditioning function. For example, the signal conditioners for FISO fiber optic sensors also include other devices such as the Fizeau interferometer, filter and microcontroller. This section describes important characteristic devices used in FISO signal conditioners.

2.4.1 Light source

Optical sources can be classified into two broad categories: coherent and incoherent sources. Coherent sources mainly consist of laser devices, which are high-radiance sources with a high degree of spatial coherence. There are gas laser sources (i.e. HeNe laser), solid state (crystal) lasers (i.e. Nd: YAG laser) and semiconductor
laser diodes. Lasers basically consist of a resonant optical cavity (i.e. Fabry-Perot cavity) filled with a medium having optical gain. The optical light in some frequencies or in several modes will be resonated within the lasing cavity and amplified through the optical gain. But almost all lasers are controlled to resonate in only one fundamental transverse spatial mode and several spatial harmonic modes in temporal frequencies. In other words, lasers output coherent light in a very narrow frequency range.

Incoherent sources may be treated as optical noise generators, in other words, the power outputs of incoherent sources are the variance of the noise waveform generated and thus cover at a very broad band of wavelengths. There is no optical feedback and thus no cavity resonance to contribute to the noise spectrum of incoherent sources, which is a very important difference between incoherent sources and coherent sources.

Incoherent sources, which may be used for fiber optic sensors, are incandescent sources (i.e. tungsten lamps) and semiconductor incoherent source (the Light Emitting Diode LED). LED is simply a p-n junction diode that emits light spontaneously.

Incandescent sources are usually light bulbs, which basically convert all the electrical energy input to them into radiation. The filament of the light bulb radiates as a black body over a very broad band of wavelengths. For black bodies, the Stefan-Boltzmann Law predicts that the total radiated power is in the region of 80 W/cm², which corresponds to an equivalent radiance of around 6 W/(cm² steradian) in a full $4\pi$
steradians, at a typical average filament temperature of 2000K. But only a small percentage of this total radiated energy, which is typically located in the visible and near infra-red wavelength region, contributes to the band of interest for fiber optic sensors. In other words, the useful radiance at 200K will be in the order of 0.1 W/(cm² steradian). As the power in the visible spectrum increases roughly with $T^4$ ($T$ is the absolute temperature of the radiating body), a higher filament temperature of 3000K, which may result in a reliability penalty, will increase the useful radiance to the order of 1 W/(cm² steradian). Tungsten lamps are often used as light sources for certain classes of sensors and also essential to provide pump power for crystal lasers. It was reported in 1984 that tungsten lamps operated at high temperature (i.e. 3000K) and thus unfortunately had low lifetimes (a few hundred hours) but useful optical power may be launched into a fiber to a remote environment [39].

For the current FISO fiber optic temperature sensors, low power tungsten lamps are used as the light sources and the lifetime of used tungsten lamps is expected to be 10 years reported by FISO technologies. Table 2.5 lists comparisons of electro-optic properties of light sources [39]. In Table 2.5, the typical lifetime of incandescent lamps, including tungsten lamps, was reported as 1000 hours in 1984. According to FISO technologies, the lifetime of tungsten lamps used in FISO fiber optic sensors is expected to be 10 years. It is expected that the specified lifetimes might be improved in these years.
<table>
<thead>
<tr>
<th>Light sources</th>
<th>Properties</th>
<th>Comments</th>
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| Incandescent lamps | - Usually black body radiators, light output a strong function of input electrical power, but some lamps (i.e. mercury lamps) have line spectra  
- Power can be high (even watts) but incoherent, spatially and temporally  
- Useful when long-term stability not required unless feedback monitoring incorporated | - Only suitable for use with high numerical aperture (NA) fibers  
- Useful as ultraviolet (UV) short-range  
- Typical lifetime ~1000 hours  
- Noise is shot noise plus current drive effects |
| Solid state lasers Nd YAG | - Center wavelength 1.064 μm  
- Total spectral bandwidth 0–3 nm  
- Output depends on optical input due to optically pumped  
- Typically output is intensity unstable  
- Frequency spectrum varies with crystal temperature and fluctuations in cooling system  
- Power 100 mW continuous wave (CW) upwards | - Pump lamp life typically a few hundred hours  
- Very difficult to obtain single longitudinal mode  
- Spectrum drifts with the fluctuations of the coolant temperature and lamp intensity  
- Noise depends on thermal and electrical variations in pump lamp |
| Gas laser HeNe    | - Center wavelength 0.6238 μm  
- Spectral bandwidth 0.0013 nm  
- Output depends on drive current in electric arc  
- Can be thermally stabilized  
- Deteriorates with age  
- Typical power 1 to 100 mW | - Plasma noise gives noise peak in the MHz region  
- Typical tube life few thousand hours |
- Table 2.5 continue -

| Semiconductor (GaAlAs) laser | - Center wavelength 820-900 nm or around 1.3μm and 1.55μm  
|                            | - Spectral bandwidth 2–4nm  
|                            | - Spectrum depends on source and electrical drive  
|                            | - Output power can be linearly proportional to current over threshold  
|                            | - Power to 50 mW CW  
|                            | - Can be intensity modulated to GHz  | - Complex noise resonance effect especially in the GHz region  
|                            | - Optical spectrum depends on temperature and current  
|                            | - Good lifetime predictions  |

| Semiconductor (GaAlAs) LED | - Center wavelength 800-900 nm or around 1.3μm and 1.55μm  
|                            | - Spectral bandwidth 20-30nm  
|                            | - Light power linearly depends on current over wide range  
|                            | - Light output decreases with aging and temperature increase  
|                            | - Power typically less than 1mW  | - Useful only with multimode fibers due to spatial dependence of light output  
|                            | - Good reliability  
|                            | - Effected by shot noise  |

| Semiconductor (GaAlAs) Superluminescent diode | - Center wavelength 800-900nm  
|                                              | - Spectral bandwidth ~ 5nm  
|                                              | - Light/current curve similar to LED but spatial coherence increased  
|                                              | - Linearity and stability similar to LED  
|                                              | - Power typically 1 to 3 mW  | - Some structures spatially compatible with single-mode fibers  
|                                              | - Relatively new structure  
|                                              | - Lifetime looks good (need test)  
|                                              | - Good as a temporally incoherent, spatially coherent source  
|                                              | - Effected by shot noise  |

Table 2.5: Comparisons of electro-optic properties of light sources.
2.4.2 White light cross-correlator (Fizeau Interferometer)

Figure 2.8 shows the structure of the white-light cross-correlator $^5$. The white-light cross-correlator is actually a Fizeau interferometer, which consists of two flat glass planes with a very small angle controlled by a spacer. The different distances between the two flat planes of the white-light cross-correlator denote a set of cavity lengths. In the signal conditioner FTI-10, the Fizeau interferometer has a group of cavity length from 8 µm to 25 µm along the length of a CCD array, which is 26 mm.

If the cavity length of the Fabry-Perot interferometer is $d$ µm, which is designed to fall between 8 µm and 25 µm, then the wavelength-modulated light from the Fabry-Perot interferometer will be transmitted maximally through the white-light cross-correlator at the position where its cavity length (the distance between the two flat glass planes) is equal to $d$ µm.

![Figure 2.8: Structure of the white-light cross-correlator $^3$.](image)
The white-light cross-correlator performs the cross-correlation function between the intensity spectrum and the simplified intensity transmittance spectrum. It can be described as \[^5\]:

\[
C(d) = \frac{1}{M} \sum_{n=0}^{M-1} X(\lambda_0 + n\Delta\lambda) \frac{1}{1 + F \sin^2 \left( \frac{2\pi d}{\lambda_0 + n\Delta\lambda} \right)}
\] (2.11)

If the cavity length of Fabry-Perot interferometer varies in response to temperature change, the cross-correlation fringe (transmission intensity fringe) out of the cross correlator will shift correspondingly \[^5\]. But the maximum transmission intensity (maximum value of C in equation 2.4) occurs at the pixel of CCD array with which a Fabry-Perot cavity length of d \(\mu\)m is associated. That means the maximum transmission intensity can be detected at the corresponding pixel where the equivalent cavity length of the white-light cross-correlator (Fizeau interferometer) is the same as the cavity length of the Fabry-Perot interferometer (refer to discussions in sections 3.1). The mechanism of detecting the position of the maximum interference intensity instead of absolute intensity itself make the signal conditioner robust and resistant to light loss, which is valuable for applications in harsh environment such as in nuclear irradiation fields where radiation induced light loss is dominant.
2.4.3 Charge-Coupled Device (CCD)

A Charge-Coupled Device (CCD) is an image detector in the family of optoelectronic detectors or photodetectors. The commonly used photodetectors used for light detection include photoconductive detectors, semiconductor photodiodes, photomultipliers and CCD \[^{[43]}\]. Photoconductive detectors are basically doped semiconductors (n-type or p-type). A photoconductive detector is usually connected to a load resistor in series and a bias voltage is applied to them. The "dark" resistance of the detector, which is the resistance without any incident light applied to the detector, is much larger than the selected load resistance \( R \). When a light illuminates the detector chip, those photons with higher energies than ionizing energy, which varies from material to material and has a minimum required energy of \( 0.04\ eV \), excite electrons into the conduction band in n-type semiconductors or generate holes in the valent band of p-type semiconductors. Therefore, the resistance of the detector is reduced through increasing the charge carrier number resulting from the incident light. The voltage across the load resistor \( R \) increases with the decreased resistance of the detector chip. The limitations of photoconductive detectors include severe thermal noise, bulky size and relatively slow response times.

Semiconductor photodiodes, which are based on semiconductor p-n junction technology, overcome most of the limitations of photoconductive detectors. The commonly used semiconductor photodiodes include the simple p-n junction diode, the p-i-n diode and the avalanche photodiode. Descriptions of semiconductor photodiodes are omitted and referred to other references \(^{[43]}\).
semiconductor photodiodes and photomultipliers are single-element detectors suitable for detecting spatially uniform distribution of light intensity.

Spatially varying information such as an image requires an array of small detectors where each small detector called a pixel is used to detect a part of the image. The CCD, which is a commonly used image detector, is basically a shift register formed by an array of closely spaced potential-well capacitors. Each pixel in the CCD is a photodiode. Figure 2.9 schematically shows the structure of a CCD pixel array in the form of potential-well capacitors. A thin layer of silicon dioxide (SiO$_2$) is grown on a silicon substrate. A tiny capacitor is formed after depositing a transparent electrode over the silicon dioxide as a gate. A depletion area or electrical potential-well is created in the silicon substrate directly beneath the gate when a positive electrical potential is applied to the electrode. If the CCD is exposed to light, electron-hole pairs are generated due to the absorption of incident photons, and the electrons generated in the vicinity of the capacitors are stored in the potential well.

![Diagram of a CCD pixel array]

**Figure 2.9:** Structure of a CCD pixel array.
The quantity of electrons stored in the potential well, which is proportional to the incident light intensity at that pixel, is detected at the edge of the CCD area by transferring the charge package through the propagation of potential wells. Figure 2.10 shows the charge transfer states in CCD array.

Figure 2.10: Charge transfer states in CCD array.
The charge collection process can be explained as follows. In phase 1, because gates G_2 and G_5 are turned on while all other gates are turned off, the electrons are collected in wells W_2 and W_5. In phase 2, G_2, G_3, G_5 and G_6 are turned on. Therefore, wells W_2 and W_3 merge into a wider well while W_5 and W_6 also merge into another wider well. In phase 3, G_2 and G_5 are turned off while G_3 and G_6 are still on. Therefore, the electrons previously stored in W_2 are now transferred and stored in W_3 while the electrons previously stored in W_5 are now transferred to W_6. By repeating this charge shift process, all charge packages in the inner pixel will be transferred to the CCD edge pixel and be picked up there by external circuits \[^{[43]}\]. In this way, the detected light intensity at each CCD pixel can be obtained by serially scanning these photodiodes at a fixed scan rate.

The commercial CCD array detector is available from 256x256 to 4096x4096 pixels. The center-to-center distance between adjacent pixels ranges from 10 to 40 μm \[^{[43]}\]. The sensitivity of video CCD cameras is of the order of 10^{-9} W/cm^2. Its sensitivity depends on the exposure or integration time of the CCD and the light intensity. A higher sensitivity can be obtained through integrating and storing data over a relatively long period of time. If adequate light is available, a very short exposure time (i.e. less than 1ns) may be selected to still get a clear picture of high-speed events. The CCD used in FISO fiber optic sensors has 1024x1024 pixels and its width is 26mm. Different CCD scanning rate determines the time of integrating data in the CCD and also the sampling frequency of different FISO signal conditioners. The higher the
CCD scanning rate, the longer the time of integrating data in the CCD and the higher sampling frequency could be achieved.

2.4.4 Optical Coupler

An optical coupler is a device to guide a light from one optical device to another optical device such as from source to fiber, fiber to fiber, and fiber to receiver. Losses can occur when the light is coupled to another optical device. Therefore, each component should be carefully designed and connected. A 2*2 coupler is used in FISO fiber optic sensors to launch white light to one arm of the coupler directed to the incident fiber. And the reflected light from the incident fiber will be guided to another arm of the coupler directed to other signal detection components such as the Fizeau interferometer and CCD in FISO sensors (refer to Fig. 2.6).
3.1 Fabry-Perot Interferometer

FISO fiber optic sensors work on the Fabry-Perot interferometric sensing technique, which is described in this section. A Fabry-Perot interferometer consists of two mirrors where the distance between these two mirrors is defined as the FPI cavity length. The transmitted or reflected light through the FPI is modulated due to the existence of the FPI cavity while the FPI cavity length varies with the environmental temperature. This section introduces the working mechanism of the Fabry-Perot interferometer. Figure 3.1 shows the optical path diagram of a plane wave in the Fabry-Perot interferometer, assuming the plane wave impinges on the surface of one mirror.

As shown in Fig. 3.1, one ray is partially transmitted and partially reflected from the mirror surface. The transmitted light is reflected back and forth on the mirror surfaces of the Fabry-Perot interferometer. There is a phase delay $\phi$ for the two successive reflections out of the first mirror due to an extra optical path of $2\mu \cos \theta$. This phase delay is given by
\[ \phi = \frac{2\pi(2\mu d \cos \theta)}{\lambda_0}, \]  

(3.1)

where \( d \) is the distance between the two mirrors, \( \mu \) is the material permeability in the FPI cavity and \( \lambda_0 \) is the wavelength of the incident light.

Figure 3.1: Optical path diagram of plane wave in the Fabry-Perot Interferometer \(^{[18]}\).

The transmittance, which is defined as the ratio of the transmitted intensity to the incident intensity, is given by
where $R$ and $T$ are the surface intensity reflection and transmission coefficients, and $F$ is defined as the finesse of the cavity, which is $F=4R/(1-R)^2$.

Since $\theta$ is very small, $\cos\theta \approx 1$. Equation (3.2) can be simplified as

$$I_T = \left[ \frac{T}{(1-R)} \right]^2 \frac{1}{1 + F \sin^2(\phi/2)}, \quad (3.2)$$

where $d$ is the cavity length, $\lambda_0$ is the wavelength of the light beam. It shows for a fixed $F$ the transmittance has a maximum value when $d$ is a multiple of $\lambda/2$.

Figure 3.2 shows the transmittance versus cavity length $d$ of the Fabry-Perot interferometer with respect to the Finesse, $F^{[17]}$. Figure 3.3 shows the reflectance of the Fabry-Perot interferometer versus wavelength of the light beam. The dashed curve shown in Fig. 3.3 is the spectrum of a light source of light emitting diode (LED). From these figures, it is observed that the transmitted or reflected light intensity is modulated corresponding to different FPI cavity length and mirror reflectivity.
Figure 3.2: Fabry-Perot intensity transmittance versus cavity length \cite{17}.
3.2 Sensing Mechanism of Fabry-Perot Fiber Optic Sensors

The system function diagram of the FISO fiber optic temperature sensor is shown in Fig. 3.4. In this sensing system, there are several important components:
Fabry-Perot interferometer, white-light cross-correlator and linear CCD array, which were described in Chapter 2. The critical parameter in the sensor head is the Fabry-Perot interferometer cavity length between the two dielectric mirrors. The FPI cavity length is subjected to the environmental temperature change through thermal expansion of the contrasting fiber. If the temperature changes, the FPI cavity length will also change correspondingly. If the FPI cavity length changes, then those transmittance peaks of the transmitted light from the Fabry-Perot interferometer shift to different wavelengths. Similar phenomenon is also applied to the case when the reflected light is modulated by the FPI interferometer and processed by the signal conditioner. The white-light cross-correlator operation is similar to cross-correlation in the time domain. The optical cross-correlator is used to retrieve the information about the spatial position of the maximum transmission fringe. The maximum transmission fringe occurs exactly where the optical path in the cross-correlator is equal to the cavity length. This position can be accurately detected by the linear CCD array. Therefore, the position of the maximum transmission fringe detected by the CCD can be related to the temperature under measurement.
In the FISO temperature sensor, white light from a low power tungsten lamp instead of a LED is launched into the multimode incident fiber and then directed toward the FPI. The light is partially transmitted through and partially reflected at each mirror in the FPI, therefore, part of it bounces back and forth between the two mirrors inside the FPI resulting in a phase shift due to the additional optical path in each cycle. The transmitted (or reflected) light intensities are the product of the transmitted (or reflected) light amplitude and its corresponding complex conjugate. The light field will interfere with itself constructively or destructively due to the phase shift, which

Figure 3.4: Function diagram of FISO fiber optic temperature sensor.
depends on the wavelength and the FPI cavity length. Consequently, the transmitted light intensity is modulated at different wavelengths.

The transmittance $T(d, \lambda)$ and reflectance function $R_{\text{FPI}}(d, \lambda)$ are defined as the ratio of the transmitted or reflected light intensity to the incident light intensity. For normal incidence of light into the FPI, which consists of two mirrors with the same reflectivity, the transmittance function $T(d, \lambda)$ is found to be $^{[5]}$

$$T(d, \lambda) = \frac{1}{1 + F \sin^2 \left(\frac{2 \pi d}{\lambda}\right)}$$ \hspace{1cm} (3.4)

where the finesse $F$ is defined as

$$F = \frac{4R}{(1 - R)^2},$$ \hspace{1cm} (3.5)

$R$ is the reflectivity of the two mirrors of FPI, $n$ is the refractive index of the material between the two mirrors, $d$ is the FPI cavity length, and $\lambda$ is the wavelength of the incident light.

Figure 3.5 shows the transmittance function vs. wavelength in a range of 600nm to 1000nm for a FPI cavity length of 17000nm and a mirror reflectivity of 30%. The maximum transmittances, which means that the light at these wavelengths are fully transmitted, occur when the FPI cavity length is an integer multiple of half of these wavelengths of the incident light. The lights at other wavelengths are partly reflected by the FPI.
Figure 3.5: Transmittance $T(d,\lambda)$ vs. wavelength when $d=17000\text{nm}$.

The signal conditioner in the Fiso sensing system uses a Fizeau interferometer as a light cross-correlator. It consists of two inclined planes covered with dielectric films or it can also be made through depositing a thin film with varied width on a flat glass plate. As a consequence there exists a group of cavities between these two
planes. The optical paths along these cavities are specified as the cavity lengths of the Fizeau interferometer. The modulated light reflected from the FPI in the sensor head is propagated back through the incident fiber, collimated by a cylindrical lens and then cast on one surface of the Fizeau interferometer.

Due to the various cavity lengths of the Fizeau interferometer, the light field interferes with itself and produces interference fringes similar in the form to cross correlation. A linear CCD array faces another inclined plane of the Fizeau interferometer to detect these spatially distributed interference fringes. For any pixel in the CCD array corresponding to a Fizeau cavity length \(d\), the transmitted intensity will be the superposition of the transmitted light at all wavelengths from the FPI (with cavity length \(d_0\)), which is first multiplied by another transmittance term as a function of \(d\) and the considered wavelength. Therefore, the light intensity, which is reflected from the FPI, transmitted through the Fizeau interferometer and then detected at each pixel in the CCD array, is described as

\[
C(d,d_0) = \frac{1}{M} \sum_{n=0}^{M-1} (1-T(d_0, \lambda_n + n\Delta\lambda)) \frac{1}{1 + F_F \sin^2 \left( \frac{2\pi nd}{\lambda_0 + n\Delta\lambda} \right)}.
\]

In other words, the FPI cavity length \(d_0\) can be retrieved by cross correlating the measured transmitted light spectrum \(T(\lambda)\) (or reflected light spectrum \((1-T(\lambda))\)) from the FPI with the theoretical transmittance function from the Fizeau interferometer. Mathematically, it is equivalent to the cross-correlation function and can be described as
\[ C(d, d_o) = \frac{1}{M} \sum_{m=0}^{M-1} \left( 1 - \frac{1}{1 + F_{\text{FPI}} \sin^2 \left( \frac{2 \pi m d_o}{\lambda_o + n \Delta \lambda} \right)} \right) \left( \frac{1}{1 + F_{\text{F}} \sin^2 \left( \frac{2 \pi m d}{\lambda_o + n \Delta \lambda} \right)} \right) \]  \hspace{1cm} (3.7)

where \( F_{\text{FPI}} \) and \( F_{\text{F}} \) denote the finesse of the FPI and Fizeau interferometer respectively, \( T(d_o, \lambda_o + n \Delta \lambda) \) is the transmittance function from the FPI when the FPI cavity length is \( d_o \).

The cross correlation function described in Eq. (3.7) actually denotes the spatial distribution of the interference fringes detected by the CCD array. The maximum value of the cross correlation function \( C(d, d_o) \) is located at the pixel position when the corresponding Fizeau cavity length \( d \) equals the FPI cavity length \( d_o \), which means at this pixel position the Fizeau cavity length \( d \) is correlated to the FPI cavity length \( d_o \). Therefore, the absolute FPI cavity length, which is related to the environmental temperature, can be found from the position of the maximum interference fringe intensity on the CCD.

The reflectivity of the FPI mirrors is important in detecting the spatially distributed cross correlation \( C(d, d_o) \) or the interference fringes. If the mirror reflectivity is too large, the higher order terms in the cross correlation function \( C(d, d_o) \) become significant and thus make it difficult and even impossible to analyze the \( C(d, d_o) \). If the mirror reflectivity is too small, the visibility of the \( C(d, d_o) \) is reduced. The optimal reflectivity of the FPI mirrors is estimated to be 30% \(^6\). And the
reflectivity of 30% should be maintained the same over the whole wavelength range of the white light source.

Figure 3.6 shows this normalized cross-correlation function vs. Fizeau cavity length when the FPI cavity length is 17000nm corresponding to an environmental temperature of 94.8°C for the tested FOT-H sensor. From Fig. 3.6, the maximum cross-correlation value, which specifies the maximum interference fringe intensity, occurs exactly at the Fizeau cavity length of 17000nm.

Figure 3.6: Normalized cross-correlation vs. Fizeau cavity length.
If the environmental temperature changes, the FPI cavity length will change correspondingly due to the thermal expansion of the contrasting fiber. The maximum cross-correlation, or the maximum transmitted intensity of the spatially distributed fringe detected by the CCD array will also shift and its new position is located where the Fizeau cavity length equals the new absolute FPI cavity length. Therefore, the new temperature is calculated from the pixel position corresponding to the maximum intensity of the spatially distributed fringe on the CCD array.

Figure 3.7 shows the cross-correlation vs. Fizeau cavity length when the FPI cavity length is 12000nm corresponding to a temperature of 279.2°C. From Fig. 3.7, it is observed that the maximum interference fringe intensity occurs at a Fizeau cavity length of 12000nm. From Figs. 3.6 and 3.7 or further simulation results, the distances between two adjacent peaks around the maximum peak are equivalent to half of the center wavelength of the incident light and are not dependent on the varied FPI cavity length for a given Fizeau interferometer. The shape of the cross-correlation function around the measured cavity length does not change and just shifts to a new position corresponding to a new FPI cavity length. In other words, the cross correlation signal always has the same frequency if scanning the CCD at a constant frequency. Therefore, a band-pass filter can be designed to retrieve only the useful signal and to suppress the effects of measurement noise or any other light modulation resulting from external disturbances such as the presence of dust, light intensity variation or radiation induced attenuation, etc. [6].

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From the above description, it is observed that the temperature information is modulated into the transmitted or reflected light by the Fabry-Perot interferometer. The modulated light is then transmitted through an optical fiber and demodulated by the Fizeau interferometer in a time that is much less than the thermal dynamic response time of the sensor head. The spatially distributed interference fringe is detected by scanning the CCD array, which means a set of discrete electrical signals
representing the spatially distributed light signals will be generated. The generated electrical signals are compared and filtered to retrieve the pixel position of the maximum interference fringe intensity. For example, if the CCD array has 512 pixels and the CCD scanning rate is 1 kHz, assuming the maximum interference fringe is detected 660.4 μs later after the beginning of the scan, then the maximum interference fringe occurs at the 338th pixel. If the maximum interference fringe intensity shifts to 900.5 μs later, then it corresponds to the 461st pixel. This position is located where the Fizeau cavity length is equivalent to the FPI cavity length, which is related to the environmental temperature.

For the actual FISO FOT-H fiber optic temperature sensor, the reflected light from the FPI is collected and demodulated in the signal conditioner. If the reflected instead of transmitted light from the original FPI is collected, the reflectance from the FPI will be the reversed transmittance as shown in Fig. 3.5, which means the minimum reflectance will appear where the maximum transmittance occurs and vice versa. The normalized cross-correlation will provide the minimum value when d equals d₀. In order to increase signal to noise ratio, the position of a side peak intensity of the interference fringe is still detected by the CCD array, and then the difference between the positions of the minimum interference fringe intensity and the side peak interference intensity is compensated during the calculation of the temperature in a microprocessor. In other words, there is some non-linearity between the absolute FPI cavity length and the actual temperature for the current FISO sensor structure. In order to improve the linearity for this type of sensor, the detected cavity length is further
linearized to obtain the actual environmental temperature, which is performed by the microprocessor that uses a recommended empirical equation for a specific type of Fiso temperature sensor. For example, the temperature was calculated using Eq. (3.8), which was provided by the Fiso Technologies,

\[
T := \frac{-b + b \sqrt{1 + \frac{4a}{b^2L_g}(x - x_0)}}{2a},
\]

where \(T\) is the actual temperature in °C, the empirical coefficients \(a\) and \(b\) are \(-1.65 \times 10^{-9} \, \text{°C}^{-2}\) and \(-3.4 \times 10^{-6} \, \text{°C}^{-1}\) respectively, \(X\) is the measured cavity length in nm, \(X_0\) and \(L_g\) are the offset cavity length and gage length at 0 °C, which can be obtained as following from the gage factor labeled in the form of 4XXXYYY on the gage connector:

\[X_0 = XXX \times 5 + 16000 \, \text{(nm)},\]

\[L_g = YYY \times 2 + 5000 \, \text{(µm)},\]
Feedback control methods are widely used in the control of many physical systems and processes such as nuclear systems, aerospace systems, biomedical systems and chemical processes. In order to design a robust controller for a typical feedback control system, the dynamic model should be identified for the total plant including the measurement sensor, the actuator and the physical or chemical process, which means design of a robust controller that implements precise and stable control requires an accurate mathematic model of the entire plant \(^1\). The dynamic model is also required for sensors used in safety-related measurement channels in nuclear power plants and in other feedback control systems.

Figure 4.1 shows a basic feedback control system. The process outputs are measured using sensors that are suitably selected for the measured process parameters. The controller will output control signals based on the sensor outputs and the model of the entire plant, which consists of the physical process, the sensor and the actuator. The model of the plant depends on the selection of the sensor and the actuator, and the process itself. Measurement noise and disturbance signals are unavoidable in most
process control systems as shown in Fig. 4.1, therefore, the dynamic model of the entire plant including the sensor is required for robust controller design of the controlled process.

![Diagram of a basic feedback control system](image)

Figure 4.1: A basic feedback control system.

Temperature measurement is important and common in many process controls in terms of nuclear power plant operation, automobile and manufacture field. Fiber optic temperature sensors have many potential advantages over traditional temperature sensors, for example, in critical environments such as the strong electro-magnetic interference and/or radio frequency interference (EMI/RFI), in the aerospace field where cable weight and size are critical, and in opto-electrical devices requiring integrated smart sensors.

The Fiso fiber optic temperature sensor as discussed in Chapter 3 works on a FPI sensing mechanism and a Fizeau interferometer demodulation technique, and thus has high accuracy and is resistant to light loss due to external effects such as nuclear radiation, high temperature/pressure and vibration. Chapter 3 also described the static
sensing mechanism of the Fiso Fabry-Perot fiber optic temperature sensor, which will be used to develop a theoretical dynamic model in the following sections of this chapter. Two empirical models, which were developed from the experimental results of a plunge test using the same method as described in Chapter 5, are then compared with the theoretical dynamic model.

4.1 Theoretical Dynamic Model of Fiso Temperature Sensor

Based on previous analysis, we can conclude that the dynamic model of the Fiso temperature sensor depends on the dynamic heat transfer process in the sensor head and the signal processing process in the signal conditioner. Since the sensor head, the external protection tubes and the gauge micro-capillary tube are very small and thin, we assume a thermal lumped model. Since a gap exists between the gauge micro-capillary tube and the external protection tubes, and the micro-capillary tube and the two fibers within the gauge length use the same material as the micro-capillary tube, these elements encircled by the gap were lumped together and called the inner sensing element. Therefore, as shown in Fig. 4.2, the dynamic model of the Fiso temperature sensor is composed of two thermal lumped nodes: the protection tube and the inner sensing element, which are thermally isolated by the gap.
The energy balance equations describing the dynamic heat transfer process are given by Eqs. (4.1) and (4.2),

\[ U_{pt} A_{pt} (T_{env} - T_{pt}) - U_s A_s (T_{pt} - T_s) = C_{pt} M_{pt} \frac{dT_{pt}}{dt}, \]  
\[ (4.1) \]

\[ U_s A_s (T_{pt} - T_s) = C_s M_s \frac{dT_s}{dt}, \]  
\[ (4.2) \]

where subscription pt denotes outside protection tube, subscription s denotes the inner sensing elements including the gauge micro-capillary tube and the two fiber ends within the gauge length, \( U \) is the overall heat transfer coefficient, \( A \) is the total heat transfer area at the boundary, \( C, M \) and \( T \) are the specific heat, mass and temperature of the considered element, and \( T_{env} \) is the environmental temperature.

The Laplace transform of Eq. (4.2) is

\[ T_s(s) = \frac{U_s A_s}{U_s A_s + C_s M_s S} T_{pt}(s). \]  
\[ (4.3) \]
Substituting Eq. (4.3) into the Laplace transform of Eq. (4.1) yields the transfer function between the sensing element and the environmental temperature,

\[
\frac{T_f(s)}{T_{env}(s)} = \frac{1}{C_fM_f s + \left(\frac{C_{pt}M_{pt}}{U_{pt}A_{pt}} s + 1\right)\left(\frac{C_sM_s}{U_sA_s} s + 1\right)}
\]

\[
= \frac{1}{r_{pt}r_s s^2 + \left[r_{pt} + r_s + \frac{C_sM_s}{U_sA_s}\right] s + 1},
\]

where \(r_{pt} = \frac{C_{pt}M_{pt}}{U_{pt}A_{pt}}\), \(r_s = \frac{C_sM_s}{U_sA_s}\).

As discussed above, the change of the FPI cavity length \(L_{FPI}\) is oppositely related to the temperature change of the contrasting fiber and its length change \(L_{cf}\), therefore,

\[
\frac{dL_{FPI}}{dt} = -\frac{dL_{cf}}{dt} = -L_{df} \alpha \frac{dT_f}{dt},
\]

where subscription \(cf\) denotes the contrasting fiber and \(\alpha\) is its thermal expansion coefficient. Combining Eqs. (4.4) and (4.5),

\[
\frac{L_{FPI}(s)}{T_{env}(s)} = \frac{L_{df} \alpha}{r_{pt}r_s s^2 + \left[r_{pt} + r_s + \frac{C_sM_s}{U_sA_s}\right] s + 1}.
\]
Equation (4.6) reflects the dynamic sensing model of the Fiso temperature sensor based on the heat transfer process in the sensor head. The signal processing process can be analyzed as follows.

From the descriptions of Fiso temperature sensor, the FPI cavity length information is transformed into the pixel position of the maximum interference fringe intensity, which is found after scanning the CCD array. The time between the beginning of scanning and the location of maximum interference fringe intensity is used to calculate the actual pixel position and thus to calculate the absolute FPI cavity length. The environmental temperature is then calculated in the microprocessor by linearizing the discrete-time signal of cavity length obtained from scanning the CCD array. This temperature sequence $T[m]$ is obtained by sending a set of impulses to the original CCD sequence $x[n]$ when $m$ is an integer multiple of the CCD sampling period $N$ (or total number of CCD pixels), which is

$$T[m] = \sum_{k=-\infty}^{\infty} x[kN] \delta[m-kN]. \tag{4.7}$$

Using the time expansion theory in the Z-domain and assuming the original sequence $x[n]$ in the Z-domain is $X(z)$, then $T[m]$ corresponds to $X(z^N)$ in the Z-domain. If $X(z)$ has a pole (or zero) at $z=a$, then $X(z^N)$ has a pole (or zero) at $z=a^{1/N}$.

The discrete temperature sequence $T[m]$ is directly displayed on a screen and transformed into an analog temperature signal through a D/A converter. In the signal processing process, a band-pass filter is also used to suppress noise because the spatial
interference fringe shape does not change with environmental temperature as shown in Figs. 3.6 and 3.7. The dynamic model of the D/A converter or the band-pass filter and the $x[n]$ algorithm depends on the sensor circuit type. If these models can be defined in the $Z$-domain, then the model of signal processing in the $s$-domain can also be defined. Because the FPI cavity length $L_{FPI}$ is related to the $x[n]$ sequence retrieved by the CCD array, the theoretical model of the total sensing system can be obtained including the signal processing effect on dynamic model.

Based on the sensing process, it is concluded that the dynamic response of the FISO temperature sensor depends primarily on the heat balance at the transducer head and the signal processing process, which includes scanning the CCD, sampling and linearization. But the time required for signal processing based on optical and electronic process is several orders of magnitude less than the thermal dynamic process. For example, a miniature Fiber Fabry-Perot/Fizeau (FFP/F) probe was reported with bandwidths in excess of 200 KHz [41], which is much faster than a thermal dynamic process. Therefore, the theoretical dynamic model, which is developed as above and based on the thermal dynamic process in the sensor head, is the typical model to represent the dynamics of the entire sensing system including the signal processing process.
4.2 Experimental Dynamic Model of Fiso Temperature Sensor

In order to identify an empirical dynamic model of the sensor, the following experiment was performed. As shown in Fig. 4.3, the setup for the plunge test is designed to observe the dynamic response of the Fiso temperature sensor to a rapid change in temperature. Boiling water and a mixture of ice and water were used to provide the reference temperatures. The Fiso temperature sensor and a reference type-K thermocouple were bundled together and the bundle was first placed into the mixture of ice and water and then rapidly into the boiling water. After reaching temperature equilibrium, it was removed to the mixture of ice and water. During the moving process, the temperature may vary slightly due to the convection and irradiation heat transfer between the sensor head surface and environmental air. However, the sensor head surface is very small, the temperature change when rapidly moving the sensor into another temperature reservoir is also small. The temperature of boiling water is very different from that of the environmental air, therefore it was easy to distinguish the initial state for the step response. Figure 4.4 shows the step response recorded by a HP 35670A Dynamic Signal Analyzer.
Figure 4.3: Setup for temperature plunge test.

Figure 4.4: Recorded step response of the Fiso sensor and the thermocouple.
If the sensor is assumed to be a first order system, then the time constant from the step response is found as follows from Eq. (4.8):

\[ (Y - Y_0) = (Y_{ss} - Y_0)(1 - e^{-\frac{t}{\tau}}), \]  
(4.8)

where \( Y \) is the actual sensor output, \( Y_0 \) is the initial sensor output, \( Y_{ss} \) is the final steady state output following the step change, \( \tau \) is the time constant for the modeled first order system. The time constant, which is obtained from the inverse of the slope of the fit line of \( \ln(1-(Y-Y_0)/(Y_{ss}-Y_0)) \) vs. \( t \), is 0.8048s and the pole is \(-1/0.8048=-1.2426\).

A second empirical model based on a regression analysis was developed as follows. If the system model \( P(s) \) is a rational function, which is the ratio of two polynomials, then this model is finite dimensional. The degree of the denominator polynomial is not less than the degree of numerator polynomial for most causal systems. For the sensor step response shown above, the sensor is a finite dimensional and causal system. Then the step response can be written in the following way using the partial fraction method:

\[ Y_0(s) = P(s) \cdot \frac{1}{s} = \frac{A_0}{s} + \frac{A_1}{s + \alpha_1} + \frac{A_2}{s + \alpha_2} + \cdots + \frac{A_n}{s + \alpha_n}, \]  
(4.9)

or

\[ Y_0(t) = A_0 + A_1 e^{-\alpha_1 t} + A_2 e^{-\alpha_2 t} + \cdots + A_n e^{-\alpha_n t}. \]  
(4.10)

Let \( A_0=Y_{ss} \) (steady state value), and assume \( 0<\alpha_1<\alpha_2<\ldots<\alpha_n \), then this higher order model can be obtained from the measured step response.
The first exponential term with the dominant pole is first used to approximate the experimental data, let

\[ Y_o(t) - Y_{ss} \equiv A_1 e^{-\alpha_1 t}, \]  

(4.11)

for a considered positive step input, \( A_1 < 0 \). The value of \( \ln(-A_1) \) and \( -\alpha_1 \) can be obtained from the intercept and slope of dominant straight line of \( \ln(Y_{ss} - Y_o(t)) \) vs. \( t \).

Once \( A_1 \) and \( \alpha_1 \) are found, then \( A_2 \) and \( \alpha_2 \) can be obtained from the following approximation:

\[ \ln(Y_o(t) - Y_{ss} - A_1 e^{-\alpha_1 t}) \equiv \ln A_2 - \alpha_2 t. \]  

(4.12)

Using the same method, the higher order terms can be found until the right side exponential term can be neglected, which means the corresponding pole is far from the origin and thus can be neglected. The system dynamic model becomes

\[ P(s) = A_0 + \frac{A_1 s}{s + \alpha_1} + \frac{A_2 s}{s + \alpha_2} + \ldots + \frac{A_n s}{s + \alpha_n}. \]  

(4.13)

From the experimental data and described method, the following coefficients were found to be: \( A_1 = -2.2965 \), \( \alpha_1 = 1.3292 \) and \( A_2 = 0.6829 \), \( \alpha_2 = 8.0439 \). Using this regression analysis, the empirical dynamic model of the Fiso sensor was found to be

\[ P(s) = \frac{0.0794s^2 - 1.6965s + 18.1015}{s^2 + 9.3731s + 10.6920}, \]  

(4.14)
which has two poles at -1.3292, -8.0439 and two imaginary zeroes at 10.6832±10.6699i.

Previously we identified the first order model of the Fiso sensor as

\[ P(s) = \frac{2.1160}{s + 1.2426}, \]

which has a pole which differs by six percent from the dominant pole -1.3292 in equation (4.14).

From another point of view, the theoretical model developed in part II is also consistent with the empirical model with similar pole locations. The outside protection tube consists of micro-capillary (quartz) tube and polymide tube. The O.D., I.D. and length of the protection tube in the active sensor head are 1400µm, 530µm, 15mm, respectively. A recommended heat transfer coefficient for the boiling water at 1bar\(^{11}\), 3800 W/m\(^2\)k, is used for \(U_{pt}\) to estimate \(\tau_{pt}\). The quartz density and specific heat were used to estimate \(\tau_{pt}=0.129s\) from \(\tau_{pt}=C_{p}M_{pt}/(U_{pt}A_{pt})\). For the inner sensing element, the dominant heat resistance is located at the air gap between the two micro-capillary tubes. Ignoring convective and radiation heat transfer due to the small size and relative low temperature, the inner heat transfer coefficient \(U_{i}\) is assumed to be \(K/\delta\), where \(K\) and \(\delta\) are the thermal conductivity and thickness of the air gap between the two micro-capillary tubes. The thickness \(\delta\) is about 110 µm. Therefore \(U_{i}\) is calculated to be 232.36 W/m\(^2\)k and \(\tau_{s}=0.547s\) using \(\tau_{s}=C_{p}M_{s}/(U_{s}A_{s})\). The cross term \(C_{p}M_{s}/(U_{pt}A_{pt})\) in

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Eq. (4.4) is calculated to be 0.121s. Then Eq. (4.4) from the theoretical model becomes

\[
\frac{T_i(s)}{T_{env}(s)} = \frac{1}{0.0705s^2 + 0.7966s + 1} = \frac{14.184}{s^2 + 11.299s + 14.184}. \quad (4.16)
\]

The theoretical model is very close to the empirical regression model in Eq. (4.14) in terms of their pole locations. The theoretical model has two poles at -1.4385, -9.8605 and the empirical regression model has two poles at -1.3292, -8.0439, respectively. The theoretical model given by Eq. (4.16) does not include the signal processing process. Therefore, one can assume that the poles due to signal processing have been neglected since they are several orders of magnitude larger than the dominant poles resulting from the heat transfer process. Although there are zeroes at the right half plane for the empirical regression model, these zeroes are not dominant because they are far away from the origin.

Figure 4.5 compares experimental results with step responses simulated by different models using the same static gains as in experimental data. From this figure, the empirical regression model fits very well with the experimental data as it should be since the empirical regression model was developed from the experimental data. The theoretical model, which is based on the actual sensing process, matches the first order model.
In summary, from the theoretical dynamic model of Fiso temperature sensor, the dynamic response was shown to depend primarily on the heat transfer process at the transducer head and not on the signal processing process (i.e. band-pass filter, digital sampling and D/A process, etc) in the signal conditioner. The theoretical model was validated by comparing its simulated response to a step change in environmental temperature with the measured response to a step change in temperature. The
validation process used both a first order model and a higher order model, which was
developed using regression analysis. The higher order model fits the measured data
very well and provides better analysis in identifying the actual sensing system
dynamic response. From Fig. 4.5, the maximum temperature difference between the
first order model and the empirical regression model may be as much as 17°C during
the initial transient. This implies that the first order model loses information at high
frequencies, therefore, it may not be accurate enough for high speed precise real-time
measurement and control.
CHAPTER 5

EXPERIMENTAL METHODOLOGY

5.1 Introduction

This chapter describes the setup and procedures for three types of nuclear environmental simulations and three types of performance evaluations, which were developed to experimentally qualify the FISO Fabry-Perot fiber optic sensors for potential applications in nuclear power plants. Table 5.1 lists the test matrix and experiments implemented on five FISO FOT-H fiber optic temperature sensors. The sensor names and gage factors shown in this table were saved in two signal conditioners to identify a specific sensor and thus calculate the temperature from the measured FPI cavity length, which is performed by the microprocessor. The sensors are numbered one through five as presented in the dissertation for convenience.
<table>
<thead>
<tr>
<th>Sensor list #</th>
<th>Gage factor</th>
<th>Sensor name</th>
<th>Performed experiments</th>
</tr>
</thead>
</table>
| #1           | 4655875     | TEMP1       | **Nuclear environment simulation test:**  
- Gamma irradiation test  
- Environmental test  
**Performance evaluation test:**  
- Static calibration before and after each simulation experiment  
- Dynamic test before and after each simulation experiment  
- On-line monitoring |
| #2           | 4616833     | TEMP3       | **Nuclear environment simulation test:**  
- Mixed neutron/gamma test  
**Performance evaluation test**  
(same as above) |
| #3           | 4566732     | NewT1       | **Nuclear environment simulation test:**  
- Gamma irradiation test  
- Mixed neutron/gamma test  
**Performance evaluation test**  
(same as above) |
| #4           | 4209474     | NewT2       | **Nuclear environment simulation test:**  
- Environmental test  
**Performance evaluation test**  
(same as above) |
| #5           | 4134477     | T3OSU       | **Nuclear environment simulation test:**  
- Mixed neutron/gamma test  
**Performance evaluation test**  
(same as above) |

Table 5.1: List of experiments implemented for FISO FOT-H temperature sensors.
As shown in Table 5.1, each nuclear environmental simulation test was repeated on a different FISO sensor to compare the experimental results. The setup and experimental conditions for the second repeated simulation test may be modified and improved, based on the analysis of the experimental results of the previous simulation test. Each sensor was statically and dynamically calibrated prior to and following each nuclear environment simulation test in order to identify changes in performance resulting from each nuclear environment simulation test. Furthermore, dynamic tests for each tested state were repeated several times for comparisons.

Sensor #1 was subjected to a gamma only irradiation, and then to an environmental test with a high pressure/temperature transient. The sensor #2 was subjected to a mixed neutron/gamma irradiation in the OSU Research Reactor.

When compared with sensors #1 and #2, which have an outer diameter of 200 µm for the gauge micro-capillary tube, sensor #3 through #5 have a larger gauge micro-capillary tube with an outer diameter of 310 µm. The model numbers and specifications of the reference thermocouples and thermocouple thermometers are listed in Table 5.2.
<table>
<thead>
<tr>
<th>Category</th>
<th>Omega model numbers</th>
<th>Quantity</th>
<th>Specifications</th>
</tr>
</thead>
</table>
| Thermocouple        | 5TC-GG-K-30-312     | 5 (#1 ~ #5) | - 5TC type K thermocouple with glass braid insulation, 312 inches length and an AWG gage size of 30  
- Recommended use in nuclear irradiation test due to the glass braid insulation |
|                     | 5TC-TT-K-30-312     | 5 (#1 ~ #5) | - 5TC type K thermocouple with teflon insulation, 312 inches length and an AWG gage size of 30  
- Used in calibration  
- Also used in plunge tests due to its fast response (it may not be very accurate in fluid beds but its absolute reading is not important in plunge tests) |
|                     | KMQSS-010(G)-12     | 1        | - Chromega Alomega type K thermocouple with 304 SS sheath  
- Used in calibration |
| Thermocouple        | MDSS41-TC-A (called "Mono") | 1 | - Programmable for 9 thermocouple calibrations  
- 0.2° accuracy  
- 0.01° resolution  
- 0-10 V analog output |
|                     | CNi3253-C24         | 2 (#1 ~ #2) | - Programmable meter/controller  
- High accuracy of ±0.5°C (0.9°F) or 0.03% FSO  
- Temperature stability ±0.05°C/°C TC @ 25°C  
- 0-10 V analog output |

Table 5.2: The list of the used thermocouples and thermometers.
5.2 Gamma only irradiation test

Gamma only irradiation tests were performed in the Ohio State University Nuclear Reactor Laboratory Cobalt Irradiator Facility (OSUNRL-CIF). Figure 5.1 shows the structure of the OSUNRL-CIF. The radioactive source, which is located at the bottom of a pool of water for radioactive shielding, consists of 14 Co-60 rods, each of which is 18 inch long. These rods are concentrically located around a vertical cylindrical access tube with an inner diameter of six inches. The tube extends above the pool, allowing access to the radiation environment. An aluminum enclosure was fabricated to hold the test components and thermocouples. The enclosure was mounted on a lead support structure, which was used for lowering the test components to the bottom of the cylinder for irradiation. After completing irradiation, the support structure was raised to the top of the access tube.

The height of the water pool or access tube required a cable of 8 meters for the tested and reference temperature sensors so as to protect their signal conditioners from the gamma irradiation environment. An extension optical fiber was used to extend the FOT-H optical fiber length. The sensor head and a portion of the leading cable of the tested FOT-H temperature sensor and reference thermocouples were lowered down to the bottom of the access tube and exposed to the gamma source.
The radiation or exposure time was pre-calculated to reach the designated dose based on the dose rate measured at the irradiation location. For example, assuming that a total dose of 15 kGy needs to be delivered to the tested sensor at a high dose rate, which is 2.5 kGy/hour (tissue-equivalent dose rate) at the location of the test assembly, then the exposure time should be about 6.6 hours.

The test procedures, which are based on guidance given in IEEE Standard 279-1971 and IEEE Standard 323-1983[^3], are described as follows:
(1) Complete the static calibration and dynamic test for the tested sensor prior to the gamma irradiation test.

(2) Assemble the tested and reference sensors, data acquisition system, sensor test holder assembly and connecting cables, etc.

(3) Mount the temperature sensors in the sensor test holder assembly.

(4) Mount reference thermocouples at various positions within the sensor test holder assembly.

(5) Set up the data acquisition system and connect the sensor outputs.

(6) Check the sensor outputs prior to placement of the sensor test holder assembly in the gamma irradiator in order to verify that the sensor outputs are reasonable in the room temperature environment.

(7) Set an appropriate data capture rate or sampling frequency, which is sufficient to record the expected time response without generating excessive amounts of data.

(8) Complete the needed paper work in terms of reactor regulation and test utility safety.

(9) Lower the sensor holder assembly into the gamma irradiator. Record the start time of the experiment and start to record data using data acquisition system. Check the data acquisition process periodically to assure that the experiment is going well and data is being recorded properly.

(10) Retain the sensor and holder assembly as original location until the target dose is attained.
When the desired total dose is reached, remove the holder assembly from the gamma irradiator and return the gamma irradiator to its original unused state.

Complete the static and dynamic performance evaluation test for the tested sensor after the gamma irradiation test to evaluate the gamma irradiation effects on the tested sensor.

Two gamma irradiation tests were performed with FISO FOT-H fiber optic sensors #1 and #3 respectively. For the first gamma irradiation test performed with the FOT-H sensor #1, the tested sensor and three type-K reference thermocouples were mounted on the aluminum enclosure located on the bottom platform of the lead support structure, which was lowered down to the gamma source and has several lead support feet at peripheral locations to assure free and full exposure to the radiation environment.

For the gamma irradiation test on the sensor #1, a total dose of 15 kGy was delivered to the test assembly at a dose rate of 2.275 kGy (SiO$_2$)/hour, which is equivalent to a tissue-equivalent dose rate of 2.5 kGy/hour (1 Gy (tissue)=0.91 Gy (SiO$_2$)). The exposure time was about 6.6 hours. During the exposure, in situ temperatures of the tested and reference sensors were monitored and recorded by a data logger with 5 second sampling interval, which is expected sufficient to capture the temperature time response and also to avoid excess recorded data.
For the gamma irradiation test performed with the FOT-H sensor #3, a short high temperature mullite tube, with an inner diameter of 1cm, was in place of the aluminum enclosure in order to bundle the tested and reference sensors together and also to allow sensor heads to be fully and directly exposed to air. The mullite tube was vertically fixed to the lead support structure. In this way, the sensor heads of the tested and reference sensors can be put closer, and on the other hand, fully exposed to the air in gamma irradiation environment instead of contacting the aluminum enclosure. In other words, it means the sensor temperatures demonstrate the actual sensor performance in gamma irradiation environment and exclude the possible temperature variation due to the gamma irradiation of the aluminum enclosure contacting the sensor head of sensor #1.

For the gamma irradiation test performed with the FOT-H sensor #3, the exposure duration was much longer than sensor #1 gamma irradiation test in order to get a gamma dose comparable to the gamma dose level encountered in the mixed neutron/gamma irradiation test. The gamma irradiation test of sensor #3 was performed for about one month from December 13, 2000 to January 10, 2001. Following removed from the gamma irradiator, the tested sensor #3 was continuously in-situ monitored till January 16, 2001. Four sets of dynamic tests (plunge tests) were performed in January 16, 2001. A static calibration was performed on this sensor and also on another new FOT-H sensor (#5) ten days later.

The dose rate in water, which was measured at the same location as the test assembly in the Cobalt Irradiator, was 5.45 kGy/hour in April 20, 94. From the half
life time of 5.3 years for the Cobalt-60, the tissue-equivalent dose rate deposited on
the test assembly at the same location in December 20, 2000 was estimated to be 1.97
kGy/hour (or 1.79 kGy (SiO₂)/hour). Then the total gamma dose deposited on sensor
#3 in 28 days is calculated to be 1.33 MGy (133 Mrad), which is about 90 times of the
total gamma dose deposited on sensor #1 and also exceeds the gamma dose in the
mixed neutron/gamma irradiation test. The gamma dose of 1.33 MGy also provides
the maximum limit for normal operation of 40 years or some accident cases in a
nuclear power plant as described in Chapter 1.

For the gamma irradiation test performed with the FOT-H sensor #3, a
LabVIEW data acquisition system from National Instruments was used to record the
in-situ experimental data. Figure 5.2 shows the front panel of the data acquisition
system programmed in LabVIEW in the second gamma irradiation test. This front
panel diagram displayed on the computer screen serves as a graphic user interface,
which reports the temperature readings updated at each sampling interval and also
receives inputs such as stop request at any time, or a file path/name or sampling
interval prior to a new data acquisition process.
Figure 5.2: Front panel of the LabVIEW data acquisition system.

Figure 5.3 shows the LabVIEW VI diagram of the data acquisition system, which simulates the actual data acquisition and data recording process. Those parameters inputted from the front panel, such as the sampling interval and file path/name, are automatically sent to the corresponding VI diagram. The analog voltages from the tested and reference sensors were sampled at different channels and changed into digital data through A/D converters and then saved into a file in the computer following the assigned file path. All these functions were implemented by
this VI drive software and the correctly installed hardware of the data acquisition system. Table 5.3 lists some important subVI components shown in Fig. 5.3 [47].

<table>
<thead>
<tr>
<th>VI components</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AI Config.vi</strong></td>
<td>This VI configures the hardware and allocates a buffer for a buffered analog input operation for a specified group of input channels.</td>
</tr>
<tr>
<td><strong>AI Start.vi</strong></td>
<td>This VI starts a buffered analog input operation. It sets the scan rate and trigger conditions and then starts an acquisition.</td>
</tr>
<tr>
<td><strong>AI Read.vi</strong></td>
<td>This VI reads data from a buffered data acquisition.</td>
</tr>
<tr>
<td><strong>AI Clear.vi</strong></td>
<td>This VI clears the analog input task associated with taskID in. It stops the acquisition and releases associated internal resources (i.e. buffers). The AI Config VI or the Analog Input Buffer Config VI should be called before beginning a new acquisition.</td>
</tr>
<tr>
<td><strong>Mean.vi</strong></td>
<td>It computes the mean (average) values in the input sequence.</td>
</tr>
<tr>
<td><strong>Write Characters To File.vi</strong></td>
<td>It writes a character string to a new byte stream file or appends the string to an existing file.</td>
</tr>
</tbody>
</table>

Table 5.3: Explanation of some important subVI components shown in Fig. 5.3.
Figure 5.3: LabVIEW VI diagram of the data acquisition system.
5.3 Mixed neutron/gamma irradiation test

The mixed neutron/gamma irradiation test (or mixed field test) was performed in Beam Port 1 (BP1) of the Ohio State University Research Reactor (OSURR). Figure 5.4 shows the top view of the OSURR and BP1. The OSURR is an open pool, light water moderated research reactor of the type typically operated in a university environment. Its flexible duty cycle provides for the possibility of transient power operation, as well as steady state conditions for up to ten hours of continuous operation.

The OSURR has a variety of experimental facilities (6 inch BP1, 6 inch BP2, 1.3 inch central irradiation facility (CIF), 2 inch rabbit tube, 2.5 inch auxiliary irradiation facility (AIF), graphite thermal column) available to users, depending on the specific needs of a given experiment. For the mixed field tests, the irradiation facility of the Beam Port 1 (BP1) was utilized. This facility provides a horizontal, 6-inch diameter cylindrical volume, perpendicular to the OSURR core on its north face. It provides a radiation environment of sufficient intensity to achieve the desired doses in a reasonable time.
During the mixed neutron/gamma irradiation test, the fiber optic sensors and reference thermocouples were placed at the bottom of BP1 with the sensor heads directly faced the reactor core. In order to ensure repeatable positioning within BP1 facility as well as physical protection during the mounting and insertion steps of the experiment, the sensor heads were relatively fixed in a cylindrical test fixture, which had some holes with appropriate tolerance to properly hold the sensor heads. Appropriate tolerance was selected to ensure that the holes were neither too loose in
order to avoid sensor displacement during the experiment setup, nor too tight in order to avoid excess pressure on sensor heads considering the thermal expansion of the test fixture due to the nuclear radiation heating. The test fixture was, in turn, mechanically joined to one of the beam port shielding plugs, which had feedthroughs for the sensor cables. During the mixed field test, the test fixture and the beam port shielding plugs, which held the tested sensors and a portion of the sensor cables, were placed in the cylindrical volume of BP1. The FISO signal conditioners and thermocouple thermometers were placed outside of BP1 and connected, respectively, to the corresponding lead cables of those temperature transducers in order to on-line monitor the temperatures during the experiment.

Figure 5.5 shows the test fixture mounting the sensor heads of FISO sensor #3 and #5 and the reference thermocouples in the mixed field test. The test fixture used in the mixed field test performed with sensor #3 and #5 was made from aluminum. The test fixture used for the mixed field test performed with FISO sensor #2 was similar to that shown in Fig. 5.5 but it was made from plastic. From the experimental results of the first mixed field test with fiber optic sensor #2, it was observed that there was large temperature difference between the tested fiber optic sensor and the reference sensors. It was also observed that some part of the plastic test fixture had melted. Considering the sensor heads (active measurement range) directly contacted the test fixture, it is supposed that the sensor readings were also influenced by the temperature distribution along the plastic test fixture, which may not be uniform due to the nuclear irradiation effects such as being melted, deformed, and change of thermal properties during the
irradiation process. Therefore, the test fixture, which was used to hold sensor heads in
the second mixed field test with sensors #3 and #5, was made from aluminum, which
provided the sensors a more uniform temperature distribution when exposed to mixed
neutron and gamma radiation. From the experimental results of the second mixed field
test with sensors #3 and #5, the temperature difference between the tested fiber optic
sensors and the reference sensors is more predictable and reasonable than that in the
first mixed field test in which the plastic test fixture was used.

Another difference between the two mixed field tests is that different beam
port shielding plug was used. For the first mixed field test with the fiber optic sensor
#2, the aluminum shielding plug was used and the sensor cables were led through the
inner axial cavity inside the aluminum shielding plug. For the second mixed field test
with fiber optic sensors #3 and #5, the aluminum shielding plug was first tried but
discarded due to a fitting problem. The polymer shielding plug was used and the
sensor cables were led through the axial-oriented groove along the surface of the
polymer shielding plug, which means the sensor cables were more exposed to neutron
and gamma doses when using the polymer shielding plug in the second mixed field
test. But this effect is insignificant because aluminum with the thickness of the
shielding plug is "transparent" to neutron and gamma irradiation. Therefore, the
irradiation time of the second mixed field test was still controlled to be 6 hours, which
is the same as the first mixed field test.
1: Hole for Fiso sensor head (0.15 cm diameter)  
2: Hole for Type-K-10 TC head (0.12 cm diameter)  
Type 6061 aluminum used for all items

Figure 5.5: The test fixture used in the mixed field test on sensor #3 and #5.
After the test fixture and the shielding plug were inserted into the beam port 1, the beam port front window directly facing the reactor was opened so that the tested and reference sensors were directly exposed to a mixed neutron and gamma irradiation field. At the outlet of the beam port 1, some lead and concrete bricks were used to shield neutron or gamma rays escaped out of the beam port 1.

Dosimetry measurements were implemented to establish the neutron flux and gamma dose rate at the irradiation position of the tested sensor. At full operating power, the silicon-equivalent gamma dose rate is 18.1 megarads per hour. The energy dependent differential neutron flux shows the magnitude of the neutron flux varies linearly with reactor power for a broad energy spectrum encountered in light water moderated reactors. Therefore, the total neutron flux in BP1 at full power can be extrapolated to be about 1.2 x 10^{12} nvs from the measured neutron energy distribution at the same location and at reduced reactor power. The irradiation time at full power operation, which was approximately 6 hours, was required to obtain a total neutron fluence of 2.6x10^{16} neutrons/cm^2 and a total gamma dose of 1.09x10^8 rads. For example, for the mixed field test with sensors #3 and #5, the data acquisition system started to record data at zero second. About 5 minutes later, the operator started to increase the reactor power. At 2245 second, the reactor reached its full power of 500 KW. The tested and reference sensors were put in BP1 for 6 hours with the reactor at full power.

The outputs of the tested and reference sensors were recorded during the irradiation period, as well as 20 days following the irradiation to test for possible
annealing of nuclear induced damage. A LabVIEW system similar to the one used in the gamma irradiation test was used for the mixed neutron/gamma irradiation test with some modifications on sampling rate, file path/name and input channels settings (omitted in this part). Figure 5.6 shows the experimental setup showing the data acquisition system and the signal conditioners used in the second mixed field test (from middle to right: two FTI-10, three thermocouple thermometers). Two fiber optic temperature sensors were tested with three type-K thermocouples used for reference.
Figure 5.6: Experimental setup showing data acquisition system and signal conditioners.
The following test procedures for the mixed neutron/gamma irradiation test are based on the guidance in IEEE Standard 279-1971 and IEEE Standard 323-1983:

(1) Complete a static and dynamic calibration of the tested sensor prior to the mixed neutron/gamma irradiation test.

(2) Assemble the tested and reference sensors, data acquisition system, sensor test holder assembly and connecting cables, etc.

(3) Mount the temperature sensors in the sensor test holder assembly (i.e. the test fixture and shielding plug).

(4) Mount reference thermocouples at various positions within the sensor test holder assembly.

(5) Set up the data acquisition system and connect the sensor outputs.

(6) Check the sensor outputs prior to placement in the beam port in order to verify that the sensor outputs are reasonable in the room temperature environment.

(7) Set an appropriate data capture rate or sampling frequency, which is sufficient to record the expected time response without generating excessive amounts of data.

(8) Complete the needed paper work in terms of reactor regulation and test utility safety.

(9) Insert the sensor holder assembly into BP1. Record the start time of the experiment and start to record data using the data acquisition system.
Check the data acquisition process periodically to assure that the experiment is going well and data is being recorded properly.

(10) Increase the reactor power to the full power of 500 KW and continue to monitor the outputs of the tested and reference sensors.

(11) Retain the sensor and holder assembly as original location until the target dose is attained.

(12) When the desired total dose is reached, shut down the reactor. Retain the sensor holder assembly in BP1 overnight and remove it from BP1 on next day.

(13) The tested and reference sensors may become radioactive due to the neutron irradiation. Therefore, store the sensor holder assembly in a shielding tank after remove it from BP1. Continue to monitor the sensor temperatures during this period.

(14) Complete the static and dynamic performance evaluation test after the sensor radioactivity decays to a safe level to allow safe manipulation on the tested sensors.

5.4 Design basis accident simulation test

The purpose of the environmental test or design basis accident simulation test is to evaluate the performance and adequacy of the fiber-optic based sensors in a high temperature and pressure environment similar to the environment expected in the
containment of a nuclear power plant following a loss of coolant accident (LOCA). FOT-H sensors #1 and #4 were subjected to an environmental test respectively, which was designed to qualify the tested sensor in a design basis accident (DBA) environment in accordance with IEEE Standard 323.

For both environmental tests, the tested and reference sensors were exposed to a steam environment in a pressure vessel in the Mechanical Engineering Department in the Ohio State University. A Franklin Software Corporation's Data Sentry data acquisition software was used for automated data acquisition. The software is configured to scan all instrument channels at 10 Hz or faster.

The pressure vessel is a horizontal pressure chamber (60 inch diameter and 128 inch length) with one removable full diameter head. It is rated for 100 Psig at 650 °F and is protected by two 2-inch consolidated model 1980T safety valves. The chamber is insulated inside and outside in order to implement rapid temperature transients. The pressure and temperature transients in the pressure chamber are controlled by injecting superheated steam into the pressure chamber, heating the water at the bottom of the pressure chamber and discharging steam into a condenser to condense, cool and remove steam.

The OSU power plant provides superheated steam (up to 200 Psig) to the pressure chamber via a header with 4 inch diameter. A 262 kW electric superheater in the steam line can be used to increase steam temperature. A shedding vortex flow meter is installed in the header to the pressure chamber. The steam inlet is baffled to prevent direct impingement of high velocity steam jets onto the tested items.
bottom of the pressure chamber, the pressure chamber is fitted with a water column and sight gage near the bottom while it is normally operated with about 9 inch of standing water during soak phases of the test. An 18 kW 480 VAC electric immersion heater, which is operated by Mercury relays controlled by a temperature controller monitoring vessel temperature, is installed at the bottom of the pressure chamber and used to heat water at the bottom of the vessel during the soak periods of DBA test. The condenser connected to the pressure chamber is a direct contact condenser consisting of a shell and four independently operable orifice water spray nozzles with 1 inch diameter.

There were slight differences between the experimental setup and procedures for the environmental tests performed with sensors #1 and #4. For the first environmental test, sensor #1 was tested in a DBA transient and DBA aging test with several other fiber optic pressure sensors and some reference thermocouples for a testing period of 10.75 days. The sensors were placed inside a box constructed of aluminum and designed to protect the sensors and their attached cables from direct impingement by the steam flow. The box was attached to the bottom of the vessel by C-clamps. The remaining cables were inserted inside liquitite tubes designed to protect them from the steam flow. The Fiso temperature sensor, which was first tested in the high gamma radiation field, was then tested in this environment where high pressure, high temperature, flow induced continuous vibration are all confronted by the tested sensor head. The test was run for 10.75 days. The temperature and pressure were monitored by the vessel instrumentation, reference and tested sensors. Data from these
sensors were recorded every 0.05 second during the pressure transient and every 60 seconds for the remainder of the test. A system operational test was done every 20 minutes. Table 5.4 compares the pressure and temperature profiles, which were designed and were actually recorded in the experiment.

<table>
<thead>
<tr>
<th>Designed profile</th>
<th>Actual recorded profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>600</td>
<td>200</td>
</tr>
<tr>
<td>3,600</td>
<td>110</td>
</tr>
<tr>
<td>604,800</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 5.4: Temperature/pressure profile in the environmental test on sensor #1.

For the second environmental test, sensor #4 was tested in a DBA test with three containment hydrogen monitoring sensors and reference thermocouples in a testing period of 16.5 hours. For sensor #4, a stainless steel protection tube was used as an instrument tube to protect the sensor leading cables, which were inserted into the pressure vessel. Figure 5.7 shows the protection tube configuration with sensor #4 and a reference type K grounded junction thermocouple installed. The purpose of the extruded end of the protection tube was to provide mechanical protection of the sensor during the installation and handling process. Two windows were opened on the protection tube around the sensor active sensing area in order to fully expose sensors.
to environmental pressure and temperature change. Heating shrink tube was attached to another end of the protection tube to reduce stress and to avoid damage to the sensor cables leading out of the protection tube. The protection tube was inserted through the pressure vessel penetration. High temperature epoxy was used to seal the small gap between the sensor heads and the steel plug in order to maintain integrity of pressure boundary of the pressure vessel.
Figure 5.7: The protection tube configuration with sensor #4 and reference thermocouple installed.
The design basis accident (DBA) test for sensor #4 was implemented in accordance with pressure and temperature profiles simulated for the Temelin nuclear power plant in the Czech Republic. The simulated DBA test consists of a rapid change of environmental steam pressure and temperature, which at least reaches up to 481.8 kPa absolute (69.9 Psia) and 154.4 °C (309.9 °F) in 12 seconds, and then a more gradual decrease to saturated conditions of at least 121 kPa (17.5 Psia) and 63.0 °C (145.4 °F), which lasts 12 hours. The actual temperature peak is higher than the required minimum value and the readers are referred to the on-line monitoring results presented in Chapter 6. Table 5.5 compares the pressure and temperature profiles, which are required and actually recorded during the DBA test. Functional checking was also performed with the tested and reference sensors after they were installed in the pressure vessel and before the DBA test. The DBA aging test was not performed for sensor #4 due to limitation of facility usage.
<table>
<thead>
<tr>
<th>Elapsed time (s)</th>
<th>Designed profile (minimum requirements)</th>
<th>Actual recorded profile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum temperature (°C)</td>
<td>Minimum absolute pressure (kPa)</td>
</tr>
<tr>
<td>0</td>
<td>68.0</td>
<td>110.0</td>
</tr>
<tr>
<td>1</td>
<td>120.0</td>
<td>187.0</td>
</tr>
<tr>
<td>10</td>
<td>154.4</td>
<td>428.2</td>
</tr>
<tr>
<td>12</td>
<td>154.4</td>
<td>481.8</td>
</tr>
<tr>
<td>25</td>
<td>154.4</td>
<td>481.8</td>
</tr>
<tr>
<td>50</td>
<td>154.2</td>
<td>481.8</td>
</tr>
<tr>
<td>64</td>
<td>154.0</td>
<td>470.1</td>
</tr>
<tr>
<td>100</td>
<td>153.7</td>
<td>440.0</td>
</tr>
<tr>
<td>1050</td>
<td>144.7</td>
<td>412.5</td>
</tr>
<tr>
<td>1920</td>
<td>136.5</td>
<td>387.3</td>
</tr>
<tr>
<td>2400</td>
<td>132.0</td>
<td>376.6</td>
</tr>
<tr>
<td>14000</td>
<td>101.2</td>
<td>132.0</td>
</tr>
</tbody>
</table>

Table 5.5: Pressure and temperature profile requirements for DBA test on sensor #4.

5.5 Performance evaluation test

5.5.1 Static calibration

For static calibration, a calibration bed, which can provide a uniform temperature distribution over the whole calibrated range for the temperature sensors, is required to embed the tested and reference temperature sensors. The optimized high temperature range of the FOT-H sensor is reported by FISO to be 50°C–200°C (for...
most customer application) while its whole measurement range is -50°C ~ 350°C. A water bed is once used as a perfect source to calibrate the sensors in a range of 0°C~100°C and also used to provide standard reference temperature such as 0°C and 100°C. It is recommended that a mixture of water (30%) and ice (70%) is used to provide a reference temperature of 0°C.

For this dissertation research, it is proposed that the sensors are calibrated in a wide temperature range of about 20°C~300°C. A liquid bath, which can be safely heated up to the maximum calibration temperature (i.e. 300°C), is an ideal calibration medium for the sensors. A liquid oil with a higher flash point than the maximum calibration temperature was first considered for the calibration medium but there was concerned that high temperature oil may cause damage on the polyimide tube on the FOT-H sensor head. Although oil has no corrosive effect on optical fibers, the optical fiber may become greasy and change color with time if oil permeates the sensor head sheath and remains inside of the sensor head after the sensor is removed from the oil bed. It is a proper way to use a small tube, which has the same size of the tube inner diameter as the sensor head outer diameter, to separate the sensor head from the oil if using an oil bed to calibrate the sensor. This method will increase the response time of the tested sensors during the calibration. On the other hand, safety manipulation is also a concern because the flash point of some commonly available oil is not far above 300°C, which could cause fire when heating oil to a high temperature close its flash
point. An oven without temperature controller is not qualified for the static calibration because it does not provide a uniform and controllable temperature bath for sensors.

Therefore, an oven with a temperature controller is used for the static calibration. The tested sensors and the reference thermocouples were put in the oven with a controller as close as possible and temperature controlled ovens are proven to be effective to provide a uniform temperature bath for sensors with accepted measurement uncertainty. The oven temperature was increased slowly all the way up to a maximum calibrated temperature and then decreased slowly to the ambient temperature. It took a whole day to do each calibration due to the slowly changing temperature over a wide calibration range. For the static calibrations of sensors #3, #4 and #5, another temperature controlled oven available in the Combustion Lab in the OSU Robinson Laboratory was used.

For the static calibration of the FISO fiber Optic temperature sensor, a Thermolyne F47925 temperature controlled oven and a type-K thermocouple were used to monitor and control the oven temperature. Another type-K thermocouple is located in close proximity to the FISO fiber optic temperature sensor to provide a precise temperature measurement. The setup for static temperature calibration is shown in Fig. 5.8. The procedure calls for a slow increase in temperature over the full calibration range. A Fluke datalogger is used to record the output from the two type-K thermocouples and the FISO temperature sensor.
5.5.2 Dynamic test

The temperature plunge test (benchmark test) is designed to obtain the dynamic performance data for the Fiso temperature sensor \[^{[23]}\]. Figure 5.9 shows the setup of the plunge test. An ice and water mixture and boiling water can provide the standard initial and final state temperature, respectively and thus produce a step input for the sensor system. The Fiso temperature sensor and reference thermocouple were bundled together. The bundle is first placed into the ice and water mixture. It is then removed and rapidly inserted into the boiling water.
During the moving process, the temperature may be influenced due to convection and radiation heat transfer with the air. But because the time is very short and the interface area is also small, the temperature disturbance can be neglected. The results of the experiments support this assumption. After the sensor remains in boiling water (100°C) for a few seconds, the sensor is removed inserted into the ice and water mixture. The fall time can also be obtained from this process.

For the sensor #1 and #2, the output analog voltages of the sensors were recorded using the HP 35670A Dynamic Signal Analyzer. For the sensors #3~#5, an oscilloscope connected with HP BenchLink was used to record data in plunge tests. The readers are referred to the instrument manuals about how to use these instruments.
5.5.3 On-line monitoring

During each nuclear environment simulation test, the in-situ performances, which were recorded by the corresponding data acquisition system, of the tested and reference sensors were also monitored for on-line surveillance. The tested FISO sensors have output options of analog output, RS-232 link and their own buffer recording in signal conditioners. Because there were many channels (up to 5 channels in the mixed field test) needed to be monitored and recorded, the analog outputs from the tested and reference sensors were used for the on-line monitoring in each nuclear environment simulation test.

A LabVIEW code, which is suitable for long term monitoring with a relative large sampling interval, is shown in Figs. 5.2 and 5.3. Another LabVIEW VI code without buffer setting, which is suitable for fast sampling with a small sampling interval (i.e. 20ms), is also programmed for short-term fast sampling in order to monitor any deviation or fluctuation during the nuclear environment simulation test. Figures 5.10 and 5.11 show the front panel and diagram of this fast sampling VI code in LabVIEW. This VI code implements data acquisition with software timed, non-buffered technique. Timing functions control the timing of the loop and in each loop the AI Single Scan is called to read an immediate scan of the channels listed. Each scan is plotted on the chart demonstrated on the front panel after it is read. And this scan data is also saved into the destination file. The lower level intermediate VIs (i.e. AI Config and AI Single Scan) used in this code are referred to LabVIEW manual.
Figure 5.10: The front panel of the fast sampling VI code in LabVIEW.
Read & chart data until an error occurs, or the stop button pressed.

Figure 5.11: The VI diagram of the fast sampling VI code in LabVIEW.
5.6 Summary

Experimental methodology is developed to evaluate the performance of Fiso Fabry-Perot fiber optic temperature sensors in a nuclear irradiation environment and a design basis accident environment. The nuclear environment simulation tests and the sensor performance evaluation tests are designed according to neutron and gamma dose level encountered in a nuclear power plant, the IEEE323 and the ISA 67.06. The sensor performance evaluation tests, which include static calibration, dynamic test, functional checking and on-line monitoring, were performed prior to and following each nuclear environment simulation test for each sensor. Table 5.6 summarizes specifications of nuclear environment simulation tests. The experimental setup and procedures are described in this chapter and the experimental results will be presented in next chapter.
<table>
<thead>
<tr>
<th>Sensor list #</th>
<th>Nuclear Environment Simulation Tests</th>
<th>Specifications</th>
</tr>
</thead>
</table>
| #1           | Gamma irradiation                   | - A total dose of 15 kGy (about 6.6 hours)  
• At a dose rate of 2.5 kGy/hour (tissue)  
• Cobalt irradiator used |
| #1           | Environmental test                  | • Performed DBA transient and aging test (10.75 days)  
• Transient: max(P)=350Kpa, Max(T)=200°C |
| #2           | Mixed neutron/gamma irradiation     | - Total neutron fluence of $2.6 \times 10^{16}$ neutrons/cm² and a total gamma dose of $1.09 \times 10^8$ rads  
• Gamma dose rate is 18.1 Mrad/hour |
| #3           | Gamma irradiation                   | - A total dose of 133 Mrad or 1330 kGy (28 days)  
• At a dose rate of 1.97 kGy/hour  
• Cobalt irradiator used |
| #3           | Mixed neutron/gamma test            | • Same as those specified for sensor #2  
• Performed with sensor #5 together |
| #4           | Environmental test                  | • Performed DBA transient followed by an aging test of about 12 hours  
• Transient: Max(P)=643.7kPa, Max(T)=186.1°C |
| #5           | Mixed neutron/gamma irradiation     | • Same as those specified for sensor #2  
• Performed with sensor #3 together |

Table 5.6: A summary of specifications of nuclear environment simulation tests.
CHAPTER 6

PERFORMANCE ANALYSIS IN NUCLEAR SIMULATION ENVIRONMENT

This chapter provides a performance analysis of Fiso fiber optic temperature sensors based on experimental results for the nuclear environment simulation tests, which were completed in accordance with the procedures described in the previous chapter.

6.1 Experimental Results and Discussions of Gamma Irradiation Test

As shown in Table 5.1, FISO FOT-H sensors #1 and #3 were subjected to gamma only irradiation in a Cobalt-60 irradiator. A total dose of 15 kGy was delivered to sensor #1 at a tissue-equivalent dose rate of 2.5 kGy/hour, which is equivalent to 2.275 kGy (SiO\textsubscript{2}) /hour (1 Gy (tissue)=0.91 Gy (SiO\textsubscript{2})). The exposure time for sensor #1 was about 6.6 hours. A total dose of 133 Mrad (1330 kGy) was delivered to sensor #3 in 28 days at a tissue-equivalent dose rate of 1.97 kGy/hour (1.79 kGy (SiO\textsubscript{2}) /hour).
6.1.1 Gamma irradiation test with sensor #1

6.1.1.1 In-situ on-line performance evaluation

Figure 6.1 shows the on-line sensor outputs and their relative error (*1000) versus cumulative gamma dose during the gamma only irradiation test, where the relative error is enlarged by 1000 times for plotting convenience. As observed in Fig. 6.1, the sensor outputs and the relative error increase slightly with cumulative gamma dose because of gamma heating and different irradiation effects on the two types of sensors. The initial error may result from their small difference in physical location.

![Graph showing on-line sensor outputs and relative error comparisons during gamma irradiation.](image)

Figure 6.1: On-line sensor outputs and relative error (*1000) comparisons during gamma irradiation.
6.1.1.2 Performance comparisons and discussions of sensor #1

Figure 6.2 shows the static calibration curves prior to and following gamma irradiation. The trend line shown in this figure is a least square fit of the data obtained in the processes of increasing and decreasing temperature. Table 6.1 lists comparisons of the performance parameters (i.e. hysteresis, non-linearity and sensitivity) prior to and following the gamma irradiation test.

![Graph showing static calibration curves before and after gamma irradiation.](image)

before: \( y = 1.0019X - 1.7174 \)

after: \( y = 1.0072X - 1.9039 \)

Figure 6.2: The static calibration of sensor #1 prior to and following gamma irradiation.
In Table 6.1, it is noted that hysteresis and non-linearity obtained prior to the irradiation test was larger than those recorded following the irradiation test. Following evaluation of the data in the first calibration and calibrations performed later, it was found that the relative large hysteresis and non-linearity resulted from several experimental data points that were taken before the oven and sensor temperatures stabilized. This problem was avoided in all calibration procedures performed later.

Three groups of plunge tests were implemented for each case prior to and following gamma irradiation. The experimental results of the plunge tests show that the FISO sensor #1 has a time constant comparable to the type-K thermocouple and performs like a first order or overdamped second order system. The time trace signals of all plunge tests are very similar and as the one described in Chapter 4, which provides the experimental data for the theoretical and empirical dynamic models of the
FISO sensor. Therefore, they are omitted in this section. The conservative time constants, which are listed in Table 6.1, were obtained using a simplified first order model.

As shown in Fig. 6.2 and Table 6.1, the off-line performance comparisons support the conclusion that no failure or degradation occurred for the FISO sensor #1 during or following the gamma only irradiation test, therefore, the FISO sensor can be expected to perform very well in the irradiation environment inside containment during normal operation of a nuclear power plant.

6.1.2 Gamma irradiation test with sensor #3

The FOT-H sensor #3 was exposed to gamma irradiation for approximately one month, which deposited a total gamma dose of 133 Mrad on the sensor. Table 6.2 provides a summary of the gamma irradiation test and the corresponding performance evaluations performed with sensor #3.
Table 6.2: Tests performed with sensor #3 prior to and following gamma irradiation.

<table>
<thead>
<tr>
<th>Month/Day/Year</th>
<th>Performed test with sensor #3</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/10/00</td>
<td>Dynamic test</td>
<td>Using LabVIEW to record data</td>
</tr>
<tr>
<td>12/11/00</td>
<td>Calibration</td>
<td>Base condition for the new sensor #3</td>
</tr>
<tr>
<td>12/13/00 ~ 1/10/01</td>
<td>Gamma irradiation test (sensors in gamma irradiator)</td>
<td>On line monitoring (long term and short term data sampling)</td>
</tr>
<tr>
<td>1/10/01 ~ 1/16/01</td>
<td>Sensors in environment</td>
<td>On line monitoring</td>
</tr>
<tr>
<td>1/16/01</td>
<td>Dynamic plunge test</td>
<td>Using LabVIEW to record data</td>
</tr>
<tr>
<td>1/26/01</td>
<td>Post-calibration</td>
<td>Sensor #3, #5 and two FTI-10 signal conditioners tested in this calibration</td>
</tr>
<tr>
<td>1/30/01</td>
<td>Dynamic plunge test</td>
<td>Using oscilloscope and HP BenchLink to record data</td>
</tr>
</tbody>
</table>

Except for several negative readings that were observed during gamma irradiation, the sensor performed satisfactorily during gamma irradiation and in the dynamic test implemented six days following gamma irradiation. A static calibration was performed ten days following the dynamic test. An abnormal phenomenon with low sensitivity was observed at the beginning of the calibration but the sensor performed well after the oven temperature reached 295°F. Sensor #3 responded linearly with environmental temperature during the later increasing and decreasing
temperature. Figures 6.3~6.7 and Tables 6.3~6.5 show the experimental results during and following gamma irradiation of sensor #3.

6.1.2.1 On-line performance

Figure 6.3 shows the in-situ temperature of the tested sensor #3 and the reference type-K thermocouple during the first five days in the gamma only irradiation test when sampling at an interval of five seconds. The temperature difference between the tested FISO sensor #3 and the reference type-K thermocouple was within ±1°F. No abnormal phenomena were observed in this range of gamma irradiation.

![Graph showing temperature readings](image)

**Figure 6.3:** In-situ temperature of sensor #3 and the reference type-K thermocouple during the first five days of gamma only irradiation.
Figure 6.4 shows the in-situ temperature of the tested sensor #3 and the reference type-K thermocouple during the 28 days in the gamma only irradiation test sampling at an interval of five or ten seconds. Sensor #3 recorded a temperature profile very similar to the reference thermocouples. Although the temperature difference between the tested and the reference sensors increased slightly with accumulated gamma dose, the maximum temperature difference was within 1.9°F, which was still within the accuracy specifications for the Fiso and the reference sensors. Therefore, the overall performance of the tested sensor #3 was acceptable. However, several negative readings were observed in the in-situ analog output of the FISO FOT-H temperature sensor #3 after 5.1 and 22.2 days respectively. It is worthy to mention that this kind of abnormal negative reading was also observed in the environmental test for sensor #1, which was first tested in the gamma irradiation test with a low gamma dose. But no abnormal negative readings were observed for sensor #1 during gamma irradiation and no abnormal performance was observed when sensor #3 was exposed to a gamma dose equivalent to sensor #1. It seems that this abnormal negative reading more likely resulted from signal conditioning malfunction rather than effects of direct gamma irradiation.
A LabVIEW code without buffer setting, which could be easily set at a very fast sampling interval such as 10 milliseconds, was also used to monitor sensor short-term performance. Figure 6.5 shows the on-line sensor performances when sampled at 10ms interval on the 20th day of the gamma irradiation test (irradiated for $1.7201 \times 10^6$ s). This short time sampling was performed for 3.5 minutes to avoid extra data when using this fast sampling rate. The mean value of the FISO sensor #3 in this short run
was 72.62 °F and its standard deviation was 0.17 °F. The mean value of the thermocouple GG3 with the CNi32 thermometer was 71.41 °F and its standard deviation was 0.099 °F. The mean value of the thermocouple GG2 with the monogram thermometer was 71.16 °F and its standard deviation was 0.023 °F.

Figure 6.5: The on-line sensor performances on the 20th day of the gamma irradiation test when sampling at 10ms interval.
Table 6.3 compares the sensor on-line performances when sampled at different times. Each of these short term fast samplings took 3~5 minutes at a sampling interval of 10 milliseconds. Considering that there is a small difference in physical locations of these sensors and that the FISO sensor accuracy is ±1.8 °F specified by Fiso Technologies, the comparison of these on-line monitoring data verifies that the FISO sensor performed well with a mean temperature difference of 1.2 °F from the reference thermocouple considering the accuracy of the reference thermocouple is ±1.0 °F.

<table>
<thead>
<tr>
<th>Elapsed Time (s) from the beginning of the gamma test</th>
<th>FISO sensor #3</th>
<th>Thermocouple GG2 +monogram</th>
<th>Thermocouple GG3 +CNi32</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean value (°F)</td>
<td>Standard deviation (°F)</td>
<td>Mean value (°F)</td>
</tr>
<tr>
<td>6.9470 x10^3</td>
<td>72.78</td>
<td>0.148</td>
<td>71.61</td>
</tr>
<tr>
<td>1.2030 x10^6</td>
<td>72.53</td>
<td>0.156</td>
<td>71.19</td>
</tr>
<tr>
<td>1.7197 x10^6</td>
<td>72.62</td>
<td>0.166</td>
<td>71.16</td>
</tr>
<tr>
<td>1.7201 x10^6</td>
<td>72.62</td>
<td>0.166</td>
<td>71.16</td>
</tr>
<tr>
<td>2.4312 x10^6 *in irradiator</td>
<td>72.95</td>
<td>0.148</td>
<td>71.11</td>
</tr>
<tr>
<td>2.9394 x10^5 *out of irradiator</td>
<td>77.82</td>
<td>0.194</td>
<td>77.03</td>
</tr>
</tbody>
</table>

Table 6.3: Comparisons of the sensor on-line performances when sampled at different times with an interval of 10 ms.
6.1.2.2 Performance comparisons and discussions of sensor #3

After the sensors and monitoring systems were located at the ambient environment for six days, three sets of dynamic plunge tests were performed using the fast sampling VI code and the same LabVIEW data acquisition setup. The tested FOT-H sensor #3 and a reference thermocouple were first submerged in a mixture of ice and water, then rapidly inserted into boiling water and then returned to the mixture of ice and water.

For all of these three plunge tests, the temperature readings of sensor #3 were consistent with the boiling water temperature of 100 °C when submerged in the boiling water. The temperature readings of sensor #3, when submerged in the mixture of ice and water, were still consistent with ice point. Table 6.4 compares the time constants of sensor #3 prior to and following gamma irradiation. Based on these experimental results, the analog output and the corresponding temperature from sensor #3 were acceptable for this group of dynamic tests following gamma irradiation.
<table>
<thead>
<tr>
<th>Time constant (s)</th>
<th>Time constant (s)</th>
<th>Time constant (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to gamma irradiation (using LabVIEW)</td>
<td>1.04</td>
<td>1.08</td>
</tr>
<tr>
<td>Following gamma irradiation (using LabVIEW)</td>
<td>1.05</td>
<td>1.09</td>
</tr>
<tr>
<td>Following gamma irradiation and post-calibration (using oscilloscope and HP Benchlink)</td>
<td>1.08</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Table 6.4: Comparison of time constant of sensor #3 prior to and following gamma irradiation.

Based on above results, the FOT-H sensor #3 demonstrated acceptable static and dynamic performance except with several intermittent negative readings observed during the on-line monitoring. These negative readings occurred very rapidly (usually less than 1 second) and then the sensor returned to a normal reading.

It implies that the abnormal negative readings did not result from gamma irradiation effects because the gamma irradiation would result in a relatively long term effect. Furthermore, this kind of negative readings was also observed during the environmental test with sensor #1 (refer to section 6.3.1.1), which was not subjected to gamma irradiation. Therefore, it is concluded that this kind of negative readings was not related to gamma irradiation effects.
Ten days following the first group of dynamic tests, a static calibration was performed with FOT-H sensor #3. Another new FOT-H sensor (sensor #5) and two other reference thermocouples were simultaneously calibrated. At the beginning of the calibration, another abnormal phenomenon was observed for sensor #3, which responded with a low sensitivity to the environmental temperature. The signal conditioners #1 and #2 were connected to the sensor #3 respectively at a fixed oven temperature to do cross calibration and it verified that the sensor #3 did not respond correctly. The internal FPI cavity lengths at several oven temperatures (i.e. 73.6°F, 79.2°F) were also recorded to check if there is any discrepancy between the FPI cavity length and the displayed temperature. The calculated temperature using the correction equation and the gage factor was actually the same as the displayed temperature, which means that the sensor #3 really detected a wrong temperature. The scale used for the two signal conditioners was in the default mode, which was 10 mV/°F. The oven temperature was still controlled to increase in order to complete the static calibration of sensor #5.

However, when the oven temperature increased to 295 °F, it was observed that the sensor #3 reading rapidly returned to a normal and correct reading. At that time, the sensor #3 was being connected to the signal conditioner #1, which was used for the FOT-H sensor #1 in the first gamma irradiation test. Following this transform, the FOT-H sensor #3 responded linearly with the oven temperature when the oven temperature increased to 520 °F and then linearly decreased to ambient temperature. Figure 6.6 shows the static calibration of sensor #3 prior to the gamma irradiation test.
Figure 6.7 shows the whole calibration of the FOT-H sensor #3 connected to the signal conditioner #1 following the gamma irradiation test.

Figure 6.6: Static calibration of sensor #3 prior to the gamma irradiation test.
Increasing temperature: $y = 0.9922x + 0.6385$
$R^2 = 1$ (latter part)

Decreasing temperature: $y = 0.9957x + 0.6722$
$R^2 = 1$

Figure 6.7: Static calibration of sensor #3 following gamma irradiation and dynamic test.
From Fig. 6.7, abnormal readings with low sensitivity were observed in the early stage of increasing temperature in the static calibration following gamma irradiation. Sensor #3 responded linearly for the latter part of increasing temperature in this calibration. Therefore, some performance parameters such as non-linearity and hysteresis were calculated for the latter part of the increasing temperature and decreasing temperature process respectively. The same method was also used for the static calibration prior to the gamma irradiation test. Table 6.5 lists the performance parameters of sensor #3 prior to and following gamma irradiation.

<table>
<thead>
<tr>
<th>Performance parameters of sensor #3</th>
<th>Non-linearity</th>
<th>Sensitivity ($^\circ$F/$^\circ$F)</th>
<th>Hysteresis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to the gamma irradiation test</td>
<td>0.259% (increasing temperature)</td>
<td>0.9964</td>
<td>0.277%</td>
</tr>
<tr>
<td></td>
<td>0.235% (decreasing temperature)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Following gamma irradiation</td>
<td>0.112% (latter part of increasing temperature)</td>
<td>0.9940</td>
<td>0.427%</td>
</tr>
<tr>
<td></td>
<td>0.314% (decreasing temperature)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.5: Comparison of performance parameters of sensor #3 prior to and following gamma irradiation.

From above experimental results of on-line monitoring and performance evaluation tests on sensor #3, this FOT-H sensor #3 demonstrated an overall good
performance prior to and following gamma irradiation, except for several abnormal behaviors such as several negative readings during gamma irradiation and the low readings at the early stage of the calibration (or post-calibration) following gamma irradiation. Based on the experimental results of its on-line monitoring and the dynamic tests prior to the post-calibration, sensor #3 was expected to perform well during the post-calibration following gamma irradiation, which implies the abnormal readings with low sensitivity during post-calibration may result from other unexpected effects rather than gamma irradiation effects. During the post-calibration following gamma irradiation, the signal conditioner #2 was also used to verify the sensor #3 reading (i.e. at 420°F) and it showed that sensor #3 really performed well and normally for the latter part of the post-calibration. Sensor #3 was then exposed to mixed neutron/gamma irradiation with another FOT-H sensor (#5) and three other reference thermocouples. The experimental results of the mixed neutron/gamma test, which are described in the following section, further verified that sensor #3 has recovered from the abnormal readings with low sensitivity.

6.1.3 Discussion of gamma irradiation tests of sensors #1 and #3

Two FOT-H sensors (sensor #1 and #3) were subjected to gamma irradiation. The first sensor exhibited no failure or degradation in performance during and following gamma irradiation, in which a total dose of 15 kGy was delivered at a dose rate of 2.5 kGy/hour. In comparison with the gamma irradiation of sensor #1, the total
dose deposited on sensor #3 was 133 Mrad, which is about 90 times of the total gamma dose deposited on sensor #1 and also exceeds the gamma dose deposited in the mixed neutron/gamma irradiation test. A gamma dose of 133 Mrad equals the maximum dose from the normal operation of 40 years or for severe accident cases in a nuclear power plant as described in Chapter 1.

As described in the last section, two types of abnormal behaviors were observed during or following gamma irradiation of sensor #3. The first one was several negative readings during gamma irradiation and the second was a low reading with low sensitivity at the early stage of the post-calibration of sensor #3. At first, these abnormal behaviors were thought to result from the effects of gamma irradiation. However, after a thorough investigation and comparison of experimental results, it was concluded that these abnormal behaviors were not related to gamma irradiation, which means that the FISO Fabry-Perot fiber optic temperature sensor is resistant to gamma irradiation. The investigation results are discussed in the following paragraphs.

Abnormal phenomenon, which was a sequence of negative readings followed by a return to a normal reading, appeared during gamma irradiation of sensor #3 and appeared in the environmental test with sensor #1. There is no similarity in terms of the environment conditions in the gamma irradiation test and the environmental test. During gamma irradiation, FOT-H sensor #3 was located in air at ambient temperature, pressure and humidity. In the environmental test with sensor #1, there was no gamma irradiation but there was high temperature and pressure environment that would cause negative effects on the tested sensor. Although the FOT-H sensor #1
tested in the environmental test had a history of gamma irradiation prior to that environmental test, no abnormal performance was observed following gamma irradiation of sensor #1. On the other hand, no abnormal behavior was observed during gamma irradiation of sensor #3 after the sensor was exposed to an equivalent gamma dose. Furthermore, these negative readings tended to occur instantly and recover rapidly by the sensor itself, which should not result from any permanent or persistent effects such as gamma irradiation effects on material. Therefore, it was concluded that the abnormal negative readings were not directly related to gamma irradiation.

Further consultation with FISO technologies indicated that if the sensor system encounters a problem, then the analog voltage output demonstrates -10 volt. If the sensor system encounters a low light signal, then the diagnostic system would indicate this problem and display it on the screen rather than display an erratic output. For gamma irradiation of sensor #1, the data recording system was not set to detect a negative -10 volt. The data recording system for gamma irradiation of sensor #3 was set. However, -10 volt was not exactly recorded among those negative readings of sensor #3 due to the discrete data sampling process and rapid occurrence of negative readings. Unfortunately, the diagnostic signals could not be continuously tracked during gamma irradiation because the analog output only records whatever displayed on the sensor front panel and it should be dedicated to on-line monitoring of temperature rather than diagnostic signals. Assuming the sensor system encountered a problem or encountered a low light signal, it could record an abnormal output such as a negative reading. Therefore, the abnormal negative reading is more likely related to
actual sensing or signal processing symptoms such as instant instability of a light source, instant loss of light or malfunction of a data acquisition and processing system. Specifically, based on the sensing mechanism of FISO sensors, the following sources were analyzed and considered as possible causes of the abnormal negative readings:

(1) Instability or non-robust reliability of the tungsten lamp or power supply following long time operation.

It was observed that all these abnormal negative readings were encountered when the FOT-H sensor was connected to FTI-10 signal conditioner #1 instead of FTI-10 #2. Recall that the lifetime of the tungsten lamp as discussed in Chapter 2 is only around 1000 hours although it may be improved to 40000 hours of continuous use as described by FISO technologies. If the tungsten lamp has a transient unsteady emittance or spectrum, the transient may be sensed by the fiber optic sensor, which bases on light modulation and detection.

As mentioned in Chapter 2, the FISO Fabry-Perot temperature sensor is resistant to light intensity losses, which means it is not sensitive to a light intensity change with a similar spectrum distribution. But it may be influenced by a light spectrum change with wavelength. If this case happens, the demodulated signal of the FOT-H sensor may be out of the dynamic range of the CCD array, and thus it may be interpreted in the sensor as loss of light or low signal to noise ratio, which is treated as a problem by the sensor and thus the sensor outputs a negative reading.
(2) Movement of micro-dust may block light transmission and cause a transient loss of light with a bad signal to noise ratio. Since the delicate fiber optic sensors were manufactured in a clean room and because the transient negative readings occurred very rapidly (less than 1s), this assumption is not strongly supported.

(3) As shown in Chapter 2, the gauge micro-capillary tube is separated from the outside micro-capillary tube by an air gap. Excess vibration or aging may cause loose welding spots or gauge micro-capillary tube strain, deflect and deform.

The effects of this strain or deformation on the light transmission through the optical fiber in the sensor head should not be a big concern because the optical fiber is a waveguide based on TIR and the FISO sensor sensing mechanism is resistant to light loss. But this strain or deformation may make the FPI mirrors deviate from their perfect parallel positions, which will effect the light coupling through fibers in the FPI, change the light modulation pattern and thus distort the detected signal. It was observed, however, that no obvious vibration was encountered during gamma irradiation and in the mixed field test performed with sensor #3. The occurrence frequencies of negative readings in these experiments were much less than the environmental test performed with sensor #1, where strong vibrations were encountered due to steam disturbance.
(4) There may be malfunction of the data acquisition and processing in the signal conditioner circuit or embedded hardware/software interface such as synchronization of the trigger signal or data exchange through the bus or in the microprocessor in terms of sampling data, diagnosing, and linearizing the data. But this case is not likely since the hardware should demonstrate a consistent instead of stochastic performance.

For second abnormal phenomenon with low sensitivity as shown in Fig. 6.7, it was observed for about two hours in the early stage of the post-calibration and in a relatively large environmental temperature range of 70 °F ~ 290 °F. However, the transition process leading to a good performance occurred rapidly around 293 °F. The setup parameters of the signal conditioner were kept the same through that transition process, which means the abnormal phenomenon is unexpected if considering that the sensor demonstrated an acceptable dynamic response observed in the dynamic test following gamma irradiation but prior to the post-calibration.

It was recalled that prior to gamma irradiation, there were several trial tests performed with sensor #3 required to fit it into the test fixture in order to test the clearance of the drilled holes on the test fixture, which was to be used in the mixed field test. It was observed that there were scratches along the longitudinal surface of the sensor head protection tube due to the small tolerance of the holes on the test fixture. After the dynamic test following gamma irradiation, sensor #3 was put in its plastic box and the calibration was performed ten days following the dynamic test.
Therefore, a possible external effect if disregarding any signal conditioner problem is that the sensor head may not be dried before putting into its plastic box and there may be steam permeation into the sensor head and into the semi-reflective mirror, which will change the reflectivity and may be recovered instantly. If the protection tube of the sensor head is not scratched or harmed, then this explanation would not be reasonable because the sensor head protection tube should be water-proof. But due to the sensor scratching history and the high dose gamma irradiation, which may change material microstructure, it may make water permeation and low sensitivity response possible.

Anyway, although the two abnormal phenomena were observed temporarily during and following gamma irradiation, sensor #3 performed well from an overall point of view considering it performed well in the latter part of the post-calibration and also performed in a way similar to sensor #5 in the mixed field test performed later. In other words, sensor #3 exhibited no significant performance degradation in a gamma irradiation environment with a total dose of 133 Mrad, which equals to or exceeds the gamma dose expected in an operation environment for fiber optic sensing or transmission devices for 40 years.
6.2 Experimental results and discussions of mixed neutron/gamma irradiation test

6.2.1 Mixed field test with sensor #2

6.2.1.1 On-line performance

Figure 6.8 shows the outputs of the temperature sensing channels over the duration of the mixed field test. Time zero denotes the point at which the steady-state operating power was reached. The reactor was shutdown at about 22,000 seconds. All of the temperature channels recorded the temperature increase associated with nuclear heating of the test components within the holder assembly and heating of the overall environment within BP1 volume. The FISO sensor and the thermocouple in channel 9 were positioned within the holder assembly at a point closest to the reactor core, in contact with the front plate of the holder assembly and thus giving a relative high and rapid temperature increase. The thermocouple in channel 8 was positioned about three inches away from these sensors, near the geometric center of the holder assembly. The thermocouple in channel 7 was located the farthest from the front (core) side of the holder assembly and thus followed the other channels with a slower rate of change and without an initial temperature peak.

The irradiation effects on the holder assembly also influence the on-line temperature sensing. Upon examination of the holder assembly following irradiation, it was found that some of the holder assembly components (Lucite plastic) had undergone harmful changes during irradiation. Both the front- and mid-plane plastic plates had swelled and become brittle and friable, causing shifts in position within the holder assembly and variation in contact with the aluminum walls of the holder
cylinder. Such changes could have affected the conduction of heat out of the assembly volume and the tested sensors. At the end of the test, all of the thermocouple outputs converged to the ambient temperature but the FISO sensor deviated about 34°F from the reference temperature.

Figure 6.8: Temperature channel output in the mixed field test.
6.2.1.2 Performance comparisons and discussions of sensor #2

Figure 6.9 shows the calibration results at three different times following the mixed field test, which were recorded about 66, 80 and 420 days, respectively, following the mixed field test. For the third calibration, three points were calibrated in the total five cycles of increasing and decreasing temperature. The absolute FPI cavity length rather than the actual temperature was recorded at each calibrated point for five cycles in order to observe any drift. The temperature was calculated using the equation provided by the FISO Company.

From Fig. 6.9, a self-recovery phenomenon due to annealing was observed when the oven temperature exceeded 350°F, all three calibration curves converge although a permanent shift remains between the FISO sensor output and the reference temperature. The third calibration curve is linear and no recovery was observed in this process.

Figure 6.9 implies there are two types of temperature shifts that result from the neutron/gamma irradiation effects, one is a short-term shift and the other is a long-term shift. The short-term shift can be recovered by increasing the external temperature. The initial shift of 34 °F can be reduced to a final long-term shift of 12.6 °F by a recovery process, which means about 63% of the initial shift resulting from mixed neutron/gamma irradiation effects can be recovered by increasing the environmental temperature.
Figure 6.9: Static calibration of FISO sensor #2 following the mixed-field test.
6.2.2 Mixed field test with sensors #3 and #5

Two FOT-H sensors (sensors #3 and #5) and three other reference thermocouples were irradiated in a mixed neutron/gamma field for six hours in the OSU research reactor at full power to obtain a total neutron fluence of $2.6 \times 10^{16}$ neutrons/cm$^2$ and a total gamma dose of $1.09 \times 10^8$ rads. It should be mentioned that sensor #3 had been irradiated to a total gamma dose of 133 Mrad in a gamma irradiation test prior to irradiated in a mixed field test, and sensor #5 was a new sensor. The irradiation environment of the mixed field test performed with sensors #3 and #5 is almost the same as the mixed field test performed with sensor #2. The difference was that an aluminum test holder was used instead of a plastic test holder to hold the sensor heads in order to get a more uniform temperature distribution among sensor heads and to eliminate any irradiation effects on deformable plastics. Another difference was that the sensor cables were led along the outer surface of the polymer shielding plug instead of inside the aluminum shielding plug as described in Chapter 5. Table 6.6 lists the date and monitoring tests for reference during and following the mixed field test.
<table>
<thead>
<tr>
<th>Month/Day/Year</th>
<th>Performed test with sensors #3 and #5</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/26/01</td>
<td>Calibration</td>
<td>Sensor #3, #5 and two FTI-10 signal conditioners tested in this calibration</td>
</tr>
<tr>
<td>1/30/01</td>
<td>Dynamic plunge test</td>
<td>Using oscilloscope and HP BenchLink to record data</td>
</tr>
</tbody>
</table>
| 10:39AM ~ 4:39PM 02/01/01 | Mixed field test (sensors in beam port 1, at reactor full power) | - Sensor #3 irradiated in gamma irradiation test  
- Sensor #5: a new sensor  
- On line monitoring (long term and short term data sampling) |
| 5:00PM, 2/1/01 ~ 8:59AM, 2/2/01 | Sensors in beam port 1, reactor shut down | On line monitoring |
| 9:40AM, 2/2/01 ~ 2:19PM, 2/21/01 | Sensors in a shielding tank (outside of BP1) | On line monitoring |
| 3/13/01       | The first calibration following the mixed field test | Sensor #3, #5 and two FTI-10 signal conditioners tested in this calibration |
| 3/15/01       | The second calibration following the mixed field test | Sensor #3, #5 and two FTI-10 signal conditioners tested in this calibration |
| 3/19/01       | Dynamic plunge test                  | Using oscilloscope and HP BenchLink to record data |

Table 6.6: lists the tests performed with sensor #3 and #5 prior to and following the mixed field test.

Radioactive material in the irradiated fiber optic sensors, which we detected one month following the mixed field test, is Sc-46, which has a half-life of 84 days. Sc-46 emits a β ray with an average energy of 0.112 MeV, one γ ray with an average energy of 0.89 MeV and another γ ray with an average energy of 1.12 MeV. All these radiations are emitted with a ratio of 100% per decay. The measured exposure rate is
$0.3 \times 10^{-3}$ rem/hour when the detector is 1 cm from the sensors, which is lower than the limitation of 50 rem/year for hands and 5 rem/year for eyes. Therefore, it was permitted by the OSU Radiation Safety Committee to test the irradiated sensors #3 and #5 for post-evaluation, which was performed about one month following the mixed field test.

### 6.2.2.1 On-line performance

Figure 6.10 shows the in-situ temperature profiles of the tested and reference sensors. From this figure, the thermocouples increased in temperature with accumulated neutron fluence and gamma dose. The two FOT-H sensors displayed trends of temperature profiles similar to one another with a decreasing temperature with accumulated neutron fluence and gamma dose, which means a degradation associated with the nuclear irradiation occurred in both FOT-H sensors. A temperature shift between the FOT-H sensors and the thermocouples was $30^\circ$F and was very close to the shift of $34^\circ$F observed in the mixed field test with sensor #2. The difference between these temperature shifts may result from a slight difference between the total doses deposited in the two mixed field tests. As mentioned in the previous section, sixty three percent of the temperature shift for FOT-H sensor #2, which was irradiated in a mixed neutron/gamma environment similar to that for sensors #3 and #5, was restored in the calibration following the mixed field test. The static calibration
performed with irradiated sensors #3 and #5 also exhibited similar annealing phenomenon, which will be presented later.

Figure 6.10: In-situ temperature profiles of FOT-H sensors #3 and #5 and reference thermocouples.
During the mixed field test, FOT-H sensor #3, which had a high gamma irradiation history, was connected to signal conditioner #1 (the same signal conditioner used in the gamma irradiation test). FOT-H sensor #5 was connected to signal conditioner #2. Figure 6.11 shows the temperature reading from FOT-H sensor #3 with signal conditioner #1 during the mixed field test. Sensor #3 with signal conditioner #1 displayed some negative readings. The displayed temperatures were retrieved from the recorded analog voltage using the default scale of 10mV/°F. Therefore, the negative temperature readings from sensor #3 correspond to those recorded negative voltage outputs.

Figure 6.11: The temperature reading of FOT-H sensor #3 with signal conditioner #1 during the mixed field test.
Figure 6.12 further show the temperature reading from FOT-H sensor #5 with signal conditioner #2 during the mixed field test. Sensor #5, which had no irradiation history, and signal conditioner #2 did not exhibit abnormally except for degradation described previously.

Figure 6.12: The temperature reading of FOT-H sensor #5 with signal conditioner #2 during the mixed field test.
6.2.2.2 Performance comparisons of sensors #3 and #5

Sensor #3:

The static calibration of sensor #3 prior to the mixed field test and following gamma irradiation is shown in Fig. 6.7. Figure 6.13 shows the first static calibration of sensor #3 following the mixed field test. It was observed that the initial temperature shift of 30°F between sensor #3 and the reference thermocouple was very close to the shift of 34°F observed on sensor #2 following the mixed field test. Annealing was also observed in the calibration of sensor #3.

In order to observe annealing clearly, more data were taken for sensors #3 and #5 than for sensor #2 especially around the range of 300~500°F. From Fig. 6.13, the temperature shift between the fiber optic sensor #3 and the reference thermocouple decreases when increasing the oven temperature. A long-term shift of 9.0°F remained in the process of decreasing temperature. It means that 70% of the initial temperature shift of sensor #3 is restored by increasing environmental temperature measured by the sensor. This recovery ratio of 70% in sensor #3 is a little higher than that of 63% in sensor #2, which maybe because sensor #3 was heated to a higher temperature during calibration.
Figure 6.13: The first calibration of sensor #3 following the mixed field test.
The restored shift, which is defined as the temperature difference recorded by sensor #3 between the increasing and decreasing temperature process for a specific reference temperature, is evaluated by the restored percentage RP either relative to the local temperature shift for that local reference temperature or to the initial temperature shift between sensor #3 and the reference temperature. Figure 6.14 shows the restored percentage RP, evaluated by these two methods, versus the reference environmental temperature. From Fig. 6.14, the restored percentage RP relative to local shift is fitted well by a second order polynomial and the RP relative to the initial shift fits by a straight line especially in the high temperature range. The evaluated models of the restored percentage RP are valuable in predicting the nuclear irradiation effects on this type of fiber optic sensors.
Figure 6.14: The evaluated restored percentage RP of sensor #3 following the first calibration.

Another post-calibration was performed with sensor #3 after the first calibration following the mixed field test to verify that if there is further annealing. Figure 6.15 shows the second post-calibration of sensor #3 compared with a new reference thermocouple. From this data, no further annealing occurred in the second
post-calibration. A long-term temperature shift of about 9.3°F was observed in the second calibration, which is consistent with the long-term temperature shift remained in the first calibration.

Figure 6.15: The second post-calibration of sensor #3 following the mixed field test.
From Fig. 6.13, sensor #3 performs linearly with both increasing and decreasing temperature. Due to the annealing phenomenon, the performance parameter of hysteresis is not meaningful and the other parameters such as non-linearity and sensitivity were evaluated for the two processes respectively to provide a reasonable performance evaluation. Table 6.7 compares the performance parameters of sensor #3 in the evaluation prior to the mixed field test and the two calibrations following the mixed field test.

<table>
<thead>
<tr>
<th>Performance parameters</th>
<th>Non-linearity</th>
<th>Sensitivity ($^\circ$F$/^\circ$F)</th>
<th>Hysteresis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to the mixed field test (following the gamma irradiation test)</td>
<td>Latter part of increasing temperature: 0.112%</td>
<td>0.9940</td>
<td>0.427%</td>
</tr>
<tr>
<td></td>
<td>Decreasing temperature: 0.314%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st post-calibration following the mixed field test</td>
<td>Increasing Temperature: 0.466%</td>
<td>Increasing temperature: 1.0497</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Decreasing temperature: 0.244%</td>
<td>Decreasing temperature: 1.0024</td>
<td></td>
</tr>
<tr>
<td>2nd post-calibration following the mixed field test</td>
<td>Increasing Temperature: 0.344%</td>
<td>Increasing temperature: 0.9989</td>
<td>0.513%</td>
</tr>
<tr>
<td></td>
<td>Decreasing temperature: 0.275%</td>
<td>Decreasing temperature: 1.0022</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.7: Comparison of performance parameters of sensor #3 prior to and following the mixed field test.
Table 6.8 compares diagnostic signals prior to and following the mixed field test. The signal to noise ratio (S/N) diagnostic signal is not included in the new FTI-10 signal conditioner (#2). The memory of 0% only denotes that no memory in the FTI-10 itself is used during the data recording process because the analog voltage output or temperature is directly sampled and saved by the computer. Comparison of the diagnostic signals shown in Table 6.8 demonstrates that sensor #3 operated in good condition.

<table>
<thead>
<tr>
<th>Signals</th>
<th>S/N ratio</th>
<th>Light (V)</th>
<th>Gain</th>
<th>Battery</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to 1\textsuperscript{st} calibration</td>
<td>6.48</td>
<td>2.7</td>
<td>12%</td>
<td>70%</td>
<td>0%</td>
</tr>
<tr>
<td>Following 1\textsuperscript{st} calibration</td>
<td>5.94</td>
<td>2.6</td>
<td>14%</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Prior to 2\textsuperscript{nd} calibration</td>
<td>5.97</td>
<td>2.7</td>
<td>14%</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Following 2\textsuperscript{nd} calibration</td>
<td>5.72</td>
<td>2.7</td>
<td>12%</td>
<td>100%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 6.8: Comparison of diagnostic signals of sensor #3 (NewT1) following the mixed field test (connected to FTI-10 signal conditioner #1).

Following the second post-calibration, three groups of dynamic plunge tests were performed with sensor #3 to verify if there were any changes in dynamic performance resulting from mixed neutron/gamma irradiation effects. These plunge tests indicated no abnormal phenomenon. Sensor #3 responded as expected to a step
temperature input. Table 6.9 provides a comparison of time constants of sensor #3 prior to and following the mixed field test. For sensor #3, those time constants obtained prior to the mixed field test are the same as those obtained following gamma irradiation (refer to Table 6.4). Based on data presented in Table 6.9, we concluded that neutron or gamma only or mixed neutron/gamma irradiation affects the dynamic response of sensor #3 within an acceptable error range.

<table>
<thead>
<tr>
<th></th>
<th>Time constant (s) 1\textsuperscript{st} test</th>
<th>Time constant (s) 2\textsuperscript{nd} test</th>
<th>Time constant (s) 3\textsuperscript{rd} test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to the mixed field test and following gamma irradiation (using LabVIEW)</td>
<td>1.05</td>
<td>1.09</td>
<td>1.07</td>
</tr>
<tr>
<td>Prior to the mixed field test and following post-calibration of gamma irradiation (using oscilloscope and HP Benchlink)</td>
<td>1.08</td>
<td>1.11</td>
<td>1.1</td>
</tr>
<tr>
<td>Following the mixed field test (using oscilloscope and HP Benchlink)</td>
<td>1.12</td>
<td>1.04</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 6.9: Comparisons of time constants of sensor #3 prior to and following the mixed field test.
Sensor #5

The performance evaluation tests with sensor #5 are similar to those with sensor #3. Figure 6.16 shows the first static calibration of sensor #5 following the mixed field test. It was observed that the initial temperature shift of 32.3°F between sensor #5 and the reference thermocouple was very close to the shift of 30°F observed for sensor #3 and also to the shift of 34°F observed for sensor #2 following the mixed field test. Annealing phenomenon was also observed in the first post-calibration of sensor #5. In order to fully observe annealing phenomenon, more data were taken for sensors #3 and #5 than for sensor #2 especially around the range of 300–500°F.
Increasing temperature: $y = 1.0513x - 37.916$
$R^2 = 0.9999$

Decreasing temperature: $y = 1.0057x - 10.832$
$R^2 = 1$

Figure 6.16: The first static calibration of sensor #5 following the mixed field test.
From Fig. 6.16, the temperature shift between the fiber optic sensor #5 and the reference thermocouple decreased with increasing the oven temperature. A long-term shift of 8.9°F remained for sensor #5. It means that 72.4% of the initial temperature shift of 32.3°F for sensor #5 was restored by increasing environmental temperature measured by the sensor. From one point of view, the long-term shift of 32.3°F and the restored percentage of 72.4% for sensor #5 are almost the same as the long-term shift of 30°F and the restored percentage of 70% for sensor #3 because these two sensors were irradiated and calibrated using the same process. From another point of view, it means the gamma irradiation or gamma irradiation history does not contribute to the temperature shifting and annealing phenomena because sensor #3 was irradiated in the gamma irradiation test prior to the mixed field test and sensor #5 was not irradiated prior to the mixed field test.

Comparing these results with those of sensor #2 following the mixed field test, the original temperature shifts of sensors #5 and #3 following the mixed field test are about 1.7°F and 4°F lower than that of sensor #2 because sensors #5 and #3 were irradiated to a slightly lower total dose than sensor #2. And the restored percentages of sensors #5 and #3 are a little higher than that of 63% of sensor #2, which is consistent with the fact that sensors #3 and #5 were heated to a higher temperature during the calibration than sensor #2.

Similarly, the restored shift, which is defined as the temperature difference recorded by sensor #5 between the increasing and decreasing temperature process for a specific reference temperature, is evaluated by the restored percentage RP either
relative to the local temperature shift for that local reference temperature or to the initial temperature shift between the sensor #5 and the reference temperature. Figure 6.17 shows the restored percentage RP, evaluated by these two methods, versus the reference environmental temperature for sensor #5. From Fig. 6.17, the restored percentage RP relative to local shift is fitted well by a second order polynomial and the RP relative to the initial shift fits by a straight line especially in the high temperature range.

Figure 6.17: The evaluated restored percentage RP of sensor #5 following the first post-calibration.
Comparing the RP curve of sensor #5 with that of sensor #3, their fitted empirical equations are very close while both sensor #5 and #3 were irradiated in the same neutron environment but with different gamma irradiation history. It implies that this temperature shift phenomenon results from neutron irradiation rather than gamma irradiation. The evaluated models of the restored percentage RP are valuable in predicting the nuclear irradiation effects on this type of fiber optic sensors.

Figure 6.18 shows the second static calibration of sensor #5 following the mixed field test. Sensor #5 exhibited linearity and no annealing phenomenon was observed.
From Fig. 6.16, sensor #5 exhibited linear response to both increasing and decreasing temperature. Due to the annealing phenomenon, the performance parameter of hysteresis is not meaningful and the other parameters (i.e. non-linearity and sensitivity) were evaluated for the two processes respectively to provide a reasonable performance evaluation. The performance parameters in the second calibration were
also evaluated in the same way as the first calibration. Table 6.10 compares the performance parameters of sensor #5 prior to and following the mixed field test. From the experimental data presented in above figures and tables, we concluded that sensor #5 performed in a predictable way similar to sensor #3.

<table>
<thead>
<tr>
<th>Performance parameters of sensor #5</th>
<th>Non-linearity</th>
<th>Sensitivity (°F/°F)</th>
<th>Hysteresis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to the mixed field test</td>
<td>0.29%</td>
<td>1.00</td>
<td>0.276%</td>
</tr>
</tbody>
</table>
| 1st post-calibration following the mixed field test | Increasing temperature: 0.471%  
Decreasing temperature: 0.310% | Increasing temperature: 1.0513  
Decreasing temperature: 1.0057 | N/A |
| 2nd post-calibration following the mixed field test | Increasing temperature: 0.390%  
Decreasing temperature: 0.253% | Increasing temperature: 0.9994  
Decreasing temperature: 1.0034 | 0.503% |

Table 6.10: Comparisons of the performance parameters of sensor #5 prior to and following the mixed field test.

Diagnostic signals of sensor #5 prior to and following each calibration are shown in Table 6.11, which shows that no abnormal diagnostic signals were observed.
<table>
<thead>
<tr>
<th>Signals</th>
<th>Signal (V)</th>
<th>Light (V)</th>
<th>Battery</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to 1st calibration</td>
<td>5.4</td>
<td>2.7</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Following 1st calibration</td>
<td>4.8</td>
<td>2.6</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Following 2nd calibration</td>
<td>5.3</td>
<td>2.8</td>
<td>100%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 6.11: Comparison of the diagnostic signals of sensor #5 (T3OSU) following the mixed field test (connected to FTI-10 signal conditioner #2).

Four days later following the second post-calibration of sensor #5, a group of dynamic plunge tests were performed to evaluate its dynamic performance. Unfortunately, negative readings were observed during the increasing temperature transient following the second plunge test. At first, this negative reading phenomenon was intuitively thought to result from FTI-10 signal conditioner #1. Therefore, FTI-10 signal conditioner #2 was used (refer to group 2 and 4 tests in Table 6.12) to do the dynamic test for several times, and then FTI-10 signal conditioner #1 was used again. Table 6.12 compares the plunge tests performed in order and the experimental observations and results. From this table, negative readings were observed only when signal conditioner #1 was connected to the FISO sensor, which means that negative readings resulted from signal conditioner #1. Based on the sensing mechanism described in Chapter 3 and equation (3.8), a FPI cavity length denoted as $X_0$ for each FISO temperature sensor corresponds to an environmental temperature of 0°C. Any FPI cavity length less than $X_0$ corresponds to a reasonable and measurable temperature
in the sensor dynamic range. However, any FPI cavity length greater than $X_0$ is calculated as a negative temperature and thus the sensor will output a negative analog voltage using its default scale. In this way, negative readings may occur due to interpreting the position or time delay of the maximum interference fringe in the CCD from an opposite direction, which may result from a non-optimized algorithm of signal processing in signal conditioner #1.
<table>
<thead>
<tr>
<th>Group sequence</th>
<th>Plunge tests on sensor #5</th>
<th>Observations and results</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plunge test #1.1</td>
<td>Performed well (unrecorded)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plunge test #1.2~ #1.6</td>
<td>Negative reading was observed</td>
<td>Connected to FTI-10 #1</td>
</tr>
<tr>
<td><strong>Group 2</strong></td>
<td>Test #2.1</td>
<td>No negative reading; Time constant: 0.7 s</td>
<td>Connected to FTI-10 #2</td>
</tr>
<tr>
<td></td>
<td>Test #2.2</td>
<td>No negative reading; Time constant: 0.7s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test #2.3</td>
<td>No negative reading; Time constant: 0.63 s</td>
<td></td>
</tr>
<tr>
<td><strong>Group 3</strong></td>
<td>Test #3.1</td>
<td>Several negative readings were observed; Time constant: 0.74s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test #3.2</td>
<td>One negative reading was observed; Time constant: 0.6s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test #3.3</td>
<td>No negative reading was observed; Time constant: 0.74s</td>
<td>Connected to FTI-10 #1</td>
</tr>
<tr>
<td></td>
<td>Test #3.4</td>
<td>One negative reading was observed; Time constant: 0.7s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test #3.5</td>
<td>Some negative readings were observed; Time constant: 0.7s</td>
<td></td>
</tr>
<tr>
<td><strong>Group 4</strong></td>
<td>Test #4.1</td>
<td>No negative reading; Time constant: 0.76 s</td>
<td>Connected to FTI-10 #2</td>
</tr>
<tr>
<td></td>
<td>Test #4.2</td>
<td>No negative reading; Time constant: 0.75 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test #4.3</td>
<td>No negative reading; Time constant: 0.76 s</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.12: Sequences and observations of plunge tests performed with sensor #5 following the second post-calibration.
6.2.3 Discussions on mixed neutron/gamma irradiation tests

From the experimental data recorded from on-line monitoring of the sensors, the thermocouple temperatures increased with the irradiation time during the full power operation of the reactor, which was expected due to the nuclear heating of the aluminum holder, which was used to hold the tested and reference sensor heads. However, the two FOT-H sensors decreased in temperature with the irradiation time. Since the same temperature trends were recorded for sensor #3 with a gamma irradiation history and sensor #5 without a gamma irradiation history, it implies that this kind of degradation of decreasing temperature versus neutron/gamma irradiation is not related to gamma irradiation or gamma irradiation history.

Possible reasons for this degradation are discussed in the following paragraphs:

a) Neutron irradiation may effect the thermal expansion coefficient (or mechanical properties) of the quartz micro-capillary tube and the quartz incident fiber. But because both of them were made of quartz, the neutron effects on these two items are destructive, therefore, they have minor or no effect on the FPI cavity length as explained in Chapter 2 about the expansion effects of gauge micro-capillary tube on the FPI cavity length.

b) Neutron irradiation effects the thermal expansion coefficient of the aluminosilicate glass (reflecting fiber in the sensor head), then FPI cavity length will be effected and thus change the temperature reading.
c) Neutron irradiation effects local micro-structure of ZrO₂ mirror and thus effects its reflectivity, then the Finesse will also be effected. But intuitively the signal processing technique of FISO sensors using the white light cross-correlator should be tolerant to this effect.

d) The leading optical fiber and the ST connector of the FOT-H were also exposed to neutron and gamma irradiation. If the irradiation induced light loss is not uniformly distributed in the white light wavelength range, then it could possibly affect the position of the maximum interference fringe intensity detected by CCD.

Sensor #3 connected to signal conditioner #1 demonstrated some negative readings during the mixed field test. It was observed, however, that all of those negative readings were observed when the tested sensor was connected to signal conditioner #1. From Table 6.12, negative readings were observed only when FOT-H sensor #5 was connected to signal conditioner #1. This provides further evidence supporting the conclusion that the negative readings result from the malfunction of signal conditioner #1, which was used in the tests performed with sensor #1 and #2, and also in the mixed field test performed with sensor #3.

Although sensor #2 exhibited a temperature shift of 34°F resulting from mixed neutron/gamma irradiation, 63% of the temperature shift was restored by heating the sensor during calibration. As shown in the last section, sensors #3 and #5 had a very similar temperature shift and restored percentage as sensor #2. If these shifts can be
compensated by the on-line sensing or the calibration model of the FISO sensor, then
this type of fiber optic sensor can be useful in nuclear power plant applications that
include a large neutron flux. Actually these shifts can be easily compensated in FISO
fiber optic sensors because this type of sensors works on digital technology based on a
microprocessor.

6.3 Experimental Results and Discussions of Design Basis Accident Test

6.3.1 Design basis accident simulation test with sensor #1

6.3.1.1 On-line performance

The Design Basis Accident (DBA) simulation test or the environmental test
performed with sensor #1 in 1998 was run for approximately 10.75 days. FOT-H
sensor #1 was connected to signal conditioner #1 at that time. Figure 6.19 shows the
outputs of the Fiso sensor and the reference type-K thermocouple during the first
20,000 second of the environmental test. As observed in this figure, the Fiso sensor
followed the temperature transient very well. The observed small deviations may
result from the small difference in physical location of the two sensors, which results
in slightly different thermodynamic conditions at the two locations during the
transient.
Figure 6.19: The sensor outputs during the first 20,000 second of the environmental test.

Figure 6.20 shows the sensor outputs for the entire 10.75 days of the environmental test. From this figure, the two sensors continued to provide matched temperature readings through the entire test period of 10.75 day. However, beginning in the fourth day of the test, the Fiso sensor began exhibiting intermittent behavior, where its analog voltage output rapidly decreased to a negative value and then rapidly returned to the normal readings (in about 0.3s). These aberrations continued on a random basis throughout the remainder of the test. With the exception of the
aberrations in data beginning in the fourth day, the Fiso temperature sensor performed satisfactorily throughout the entire environmental test.

![Graph showing sensor outputs](image)

**Figure 6.20:** The sensor outputs for the entire 10.75 days of the environmental test.

### 6.3.1.2 Performance comparisons and discussions of sensor #1

In the static calibration of Fiso sensor #1 following the environmental test, the Fiso temperature sensor follows the oven temperature (measured by type-K thermocouple) for increasing temperature. But it remained high for decreasing temperature at the latter part of the static calibration. The sensor head of the sensor #1
was opened following the environmental test. Visual evaluation after opening it shows that the gage welding spots, which weld the incident fiber or contrasting fiber to the quartz gauge micro-capillary tube, had loosen. Therefore, the sensor at first behaved erratically and then suffered catastrophic failure, which is not related to the nuclear irradiation effects but more likely related to the vibration and moisture environments encountered in the environmental test. It implies that internal welding methodology is most likely the primary contributor to the observed behavior during this test. Further consultation with the vendor shows that the robustness and reliability of Fiso sensors can be improved by modifying the internal welding methods for the sensor head.

6.3.2 Design basis accident simulation test with sensor #4

6.3.2.1 On-line performance

Figure 6.21 shows the on-line performance of the tested sensor #4 and the reference thermocouple, which were installed in the protection tube, during the whole DBA test. Figure 6.22 shows the on-line performance of the tested sensor during the DBA transient in the first 3100 seconds. From these figures, the tested sensor followed the reference thermocouple very well and no failure was observed during the test.
Figure 6.21: On-line monitoring of the environmental test with sensor #4 in the whole DBA test.
Figure 6.22: On-line monitoring of the environmental test with sensor #4 in the DBA transient of 3100 seconds.
6.3.2.2 Performance comparisons and discussions of sensor #4

Three groups of dynamic plunge test were performed with sensor #4, which was still installed in the protection tube because sensor #4 and the reference thermocouple could not be detached from the protection tube. It has to be mentioned that no time was left to do the plunge test with the protection tube prior to the environmental test. The protection tube and the embedded thermocouple did effect the dynamic response of the tested sensor embedded in the protection tube, therefore, the dynamic test results are not presented due to lack of comparison results. No failure was observed in these dynamic tests with sensor #4.

Following the plunge tests, a static calibration was performed for the assembly of the tested sensor and reference thermocouple with the protection tube. Figure 6.23 shows the calibration of FOT-H sensor #4 following the environmental test. In this calibration, FOT-H sensor #4 was compared with the reference thermocouple installed in the protection tube. Another reference thermocouple was installed very close to the protection tube.
Increasing temperature: \( y = 0.9981x + 0.398 \)  
\( R^2 = 1 \)
Decreasing temperature: \( y = 0.9976x - 3.31 \)  
\( R^2 = 0.9999 \)

Figure 6.23: Calibration of sensor #4 following the environmental test.

Diagnostic signals of sensor #4 were consistent and at normal conditions prior to and following the environmental test. Table 6.13 lists the performance parameters obtained from the calibration following the environmental test. The performance of
this sensor prior to the environmental test is a typical base condition of a new sensor. In the process of increasing temperature during calibration, sensor #4 followed the reference thermocouple temperature very well. When decreasing temperature, there was a maximum temperature difference of 5°F between the tested sensor and the reference thermocouple at a high temperature range, but the temperature difference decreased to about 1°F at a low temperature. Therefore, it resulted in a higher hysteresis. But the overall performance of sensor #4 during calibration was expected if considering external environmental change due to existence of the protection tube used in the calibration. For example, the embedded thermocouple has a metal sheathed sensor head with a larger diameter than the FISO sensor head, and with a white surface rather than a black surface as used in sensor #4, which change the thermocouple response time, heat equilibrium time and heat radiation capacity.

<table>
<thead>
<tr>
<th>Performance parameters (following the environmental test)</th>
<th>Non-linearity</th>
<th>Sensitivity (°F/°F)</th>
<th>Hysteresis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance parameters</td>
<td>Increasing temperature: 0.116%</td>
<td>0.9979</td>
<td>0.789%</td>
</tr>
<tr>
<td></td>
<td>Decreasing temperature: 0.595%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.13: Performance parameters of sensor #4 following the environmental test.
6.3.3 Discussions on design basis accident simulation test

The environments encountered in the design basis accident simulation test are very harsh for fiber optic sensors due to a rapid temperature/pressure transient, vibration, steam soaking process, high temperature and pressure exposure. For example, in the environmental test performed with sensor #1, the temperature increased up to 6 times of the initial value and the pressure increased about 37.4 times in 16 seconds. This rapid change of temperature and pressure results in a high thermal stress and external disturbance on the delicate fiber optic sensor head and optical fiber.

From the environmental test results, sensor #1 worked well and exhibited no failure or degradation in the DBA transient and in the first four days of the DBA aging test. Although some negative readings, which may result from signal conditioner #1, were observed in the last six days of the DBA aging test, sensor #1 still output a reasonable average temperature. Its performance is acceptable in a design basis accident environment since the IEEE 323 specifies that a Class 1E equipment should survive in such an accident environment for four days considering that most of post-accident processing events will be completed in the first four days following a design basis accident.

For the environmental test performed with sensor #4, the temperature/pressure increasing rate is much lower than that in the environmental test performed with sensor #1. The protection tube mimics the instrument channel in actual plant measurement applications and it should be more effective to protect the optical fiber
than the box used in the environmental test performed with sensor #1. Sensor #4 performed well in the performance evaluation tests following the DBA test.
CHAPTER 7

FURTHER STUDY

This chapter is directed to further research on Fabry-Perot fiber optic temperature and pressure sensors in two areas: a new method proposed for on-line surveillance of temperature sensors and a failure mode analysis.

7.1 New Method for On-line Surveillance of Temperature Sensors

Response time is an important parameter in determining dynamic response for measurement and control systems. In-situ response time testing of temperature sensors is important and often necessary especially in critical applications such as in safety-related systems in nuclear power plants, and in safety systems in aerospace, where off-line testing is usually performed [23][68]. Off-line testing can compromise plant efficiency, profits and safety because the process measurement is usually stopped for the off-line testing and the off-line testing environments can not exactly simulate the actual process.

In this section, a method is proposed for on-line surveillance of Fabry-Perot fiber optic temperature sensors. It is proposed to launch a laser light pulse into sensor
head, which has similar construction as the Fiso sensor head. A laser diode or a gas laser will be considered as the heating source. The objective of this method is to transfer a part of laser light power into thermal power deposited in the contrasting fiber as a result of laser heating. The cavity length of the tiny FPI is changed by thermal expansion of the contrasting fiber, named as in Chapter 2, due to the deposition of laser power. The detection of the FPI cavity length will use the same technology as used in Fiso fiber optic sensors. Following the laser power deposition, the temperature or the FPI cavity length profile is recorded and processed using a microprocessor.

For this method of launching laser light into the temperature sensor head and heating the sensor from the inside, the characteristic equation of a dynamic temperature change is developed. It is found to be the same as that of the dynamic process when the sensor is heated from the outside, which is the actual dynamic measurement process. Therefore, if the temperature profile after heating the sensor by a laser pulse from the inside can be recorded, then this temperature profile can be used to predict the response time of the temperature sensor when it is externally heated. This temperature information will then be used in in-situ calibration by comparing it with the measured cavity length.

The proposed method may be applied to any applications of fiber optic temperature sensors, which are designed similar to FISO sensors manufactured by FISO Technologies. For example, the following applications could benefit from this proposed method:
1. In nuclear power plant safety-related measurement and control systems, in-situ response time testing is important and required in order to reduce irradiation exposure and reactor scram frequency due to required off-line response time testing.

2. For temperature measurement and process control in aerospace systems, fiber optic sensors have advantages such as small size and weight, immunization to EMI/RFI, high sensitivity and accuracy. In-situ response time testing can greatly improve safety and measurement accuracy, and predict failures or degradation.

3. Other temperature measurement and process control applications where temperature measurement is important and where it is difficult to implement off-line sensor diagnosis.

4. Continuous in-situ diagnosis and surveillance of fiber optic based temperature sensors.

**Theoretical model**

In this section, a theoretical model is developed for the dynamic response of the sensor when it is heated by laser power from the inside. Due to the construction and small dimensions of the sensor head, it is reasonable to simulate the sensor head using two lumped nodes. Figure 7.1 shows the lumped parameters of the sensor head giving a Fiso Fabry-Perot temperature sensor as an example.
When the sensor is heated due to laser heating, a portion of laser power is transferred into thermal power, which is denoted as $q_{in}(w)$. The dynamic equation is described in Eqs. (7.1) and (7.2),

$$\begin{align*}
q_{in} - U_s A_s (T_s - T_{pt}) &= C_s M_s \frac{dT_s}{dt}, \\
U_s A_s (T_s - T_{pt}) - U_{pt} A_{pt} (T_{pt} - T_{env}) &= C_{pt} M_{pt} \frac{dT_{pt}}{dt},
\end{align*}$$

(7.1)

(7.2)

The equilibrium temperature when those two derivative terms go to zero is calculated as

$$
T_{pt} = T_{env} + \frac{q_{in}}{(U_{pt} A_{pt})},
$$

(7.3)

$$
T_s = T_{env} + \frac{q_{in}}{(1/(U_{pt} A_{pt}) + 1/(U_s A_s))}.
$$

(7.4)

The environmental temperature can be treated as a constant during the laser pulse heating process because the sensor head is very small compared to the environmental bed. The input signal is the deposited heat flux $q_{in}$. Assume the changes
of lumped parameters are denoted as $\delta q_m, \delta T_s, \delta T_{pt}$ relative to their equilibrium values respectively, then Eqs. (7.1) ~ (7.2) become

$$\delta q_m - U_s A_s (\delta T_s - \delta T_{pt}) = C_s M_s \frac{d\delta T_s}{dt},$$  \hspace{1cm} (7.5)

$$U_s A_s (\delta T_s - \delta T_{pt}) - U_{pt} A_{pt} \delta T_{pt} = C_{pt} M_{pt} \frac{d\delta T_{pt}}{dt}. \hspace{1cm} (7.6)$$

Take Laplace transform of Eqs. (7.5) and (7.6), and define $\tau_{pt} = C_{pt} M_{pt} / (U_{pt} A_{pt})$, $\tau_s = C_s M_s / (U_s A_s)$, then the transfer function between $\delta T_s$ and $\delta q_m$ is found to be

$$\frac{\delta T_s(s)}{\delta q_m(s)} = \frac{s + \frac{1}{U_{pt} A_{pt}} + \frac{1}{U_s A_s}}{\tau_{pt} \tau_s s^2 + [\tau_{pt} + \tau_s + \frac{C_s M_s}{U_{pt} A_{pt}}] s + 1}. \hspace{1cm} (7.7)$$

The characteristic equation in Eq. (7.7) is the same as that of the dynamic process of sensor measurement, which is shown in Chapter 4. Therefore, the response time can be obtained through analyzing the temperature increase process through laser inside-self-heating of the Fabry-Perot fiber optic temperature sensor. The detection technique of temperature or the FPI cavity length is similar to that of Fiso fiber optic temperature sensor and referred to Chapter 2~4.

A sample calculation is given as follows to verify that this method is applicable. The sensor design parameters of a Fiso FOT-H temperature sensor, which are included in Chapters 2 and 4, are used in the sample calculation. Assume laser power is 500mW, which is available even in semiconductor lasers, and 10% of laser
power is transferred into thermal power, use $125.1 \text{ W/m}^2\text{K}$ for $U_p$ for relatively low heat transfer coefficient, then using Eq. (7.4) the final temperature increase of the sensing element is predicted to be 20.8°C. This temperature increase is easy to detect in terms of the resolution, dynamic range and laser heating safety of the temperature sensor. Figure 7.2 shows comparison of temperature change for different laser heating duration of a 500mW laser pulse assuming 10% of laser power is absorbed as thermal energy. Figure 7.3 shows three cases in three subfigures respectively. From Figs. 7.2 and 7.3, the temperature starts to increase after the laser is launched and starts to decay when the laser is turned off. Each case follows the same path of temperature increase, which is actually the step response of this sensor system. The decay process corresponds to the turning off of the launched laser pulse.
Figure 7.2: Simulated temperature profiles for different laser heating duration of 500mW laser pulse.
Figure 7.3: Three cases of different laser heating duration.
Figure 7.4 compares different simulated temperature profiles corresponding to different laser power deposited in the sensor head. It shows that laser power will change the final steady state temperature. However, the dynamic characteristic, which is determined by the sensor system, is neither changed by the laser power nor by the laser heating duration.

Figure 7.4: Simulated temperature profiles corresponding to different laser power deposited in the sensor head.
Figure 7.5 compares the laser-heating model developed in this chapter with the experimental and regression models developed in chapter 4. It shows these models have similar response as the leading temperature increasing process, which implies that the dominant poles of these models are very close to the poles of the leading temperature increase.

![Graph comparing models](image)

**Figure 7.5:** Comparison of laser-heating model with the experimental and regression models.
From these results, the proposed method of laser inside-self-heating is applicable to determine the response time of fiber optic temperature sensors. If the inside-self-heating method by launching laser light into sensor head can be implemented practically, then based on previous analysis, it provides a cost effective in-situ measurement of the response time of fiber optic based temperature sensors. It also identifies the characteristic equation and thus the state of the temperature sensor on a continuous basis. Furthermore, knowledge of the state of the sensor on a continuous basis will make diagnosis and surveillance possible to identify degradation and impending failure, which means that this method also provides continuous in-situ diagnosis and surveillance.

The challenge of this proposed method is to find the proper laser source, absorption material and coupling method of launching laser and white light into the optical fiber. Two methods are proposed. One is to use absorption material and another is to implement thin-film coating technique to transfer part of laser energy into thermal energy. The first proposed method is to dope some absorption material, which has high absorption capacity for the selected laser power and wavelength, in the contrasting fiber. These absorption materials should not effect the white light transmission and modulation of the used wavelength range of the Fabry-Perot fiber optic sensors. Because the light source and the light detector can be designed at the same side of the Fabry-Perot interferometer (FPI) as in the studied FOT-H temperature sensors, which means the reflected light from the FPI contributes to the light detection, the transmitted light through the FPI will not effect the FPI mirror performance and
thus not effect the light signal detection of the reflected light from the FPI. Therefore, if the contrasting fiber is doped or consists of some absorption materials for the transmitted laser light, then the absorption of the laser light and the transferred thermal energy deposited in the contrasting fiber will just change the thermal expansion of the contrasting fiber as occurred in the FOT-H temperature sensors. In this way, the FPI cavity length will change with the deposited laser energy or absorbed thermal energy, and the FPI cavity length can still be detected and processed importing the same technique normally used in the FISO fiber optic sensors. A challenge for this method is to select a laser source with proper wavelength, which will not resonate and have high transmittance in a range of the FPI cavity length associated with the measurement or surveillance range.

Another method uses deposition of a thin-film to help absorb laser energy. According to transmission characteristics versus wavelength for an optical thin-film material, it is usually categorized into three regions: region I with fundamental absorption and low transmittance, region II with high transmittance and region III associated with lattice vibration or free carrier absorption. Normally the desired region for thin-film coating material is in region II with high transmittance. The extent and quality of region II depends strongly on the material stoichiometry and purity. Region II is located between the short-wavelength absorption edge of region I and the long-wavelength limit of region III. Region I depends on the electronic structure of the material. Region III transmittance depends on lattice vibrations or free carrier absorption (i.e. in semiconductors).
If an appropriate thin-film material can be selected to include the laser wavelength in its fundamental absorption region, then the light power loss due to absorption can be maximized. A challenge for this method is that the damage of thin-film due to laser power absorption and the scattering contributing to optical loss should be considered for the proper location and material selection of the deposited thin-film and the laser. The optical loss consists of two sources: absorption and scattering. The optical power is either reflected, transmitted or lost due to absorption and scattering.

Light scattering is often of the same order or larger than true absorption. It depends on surface and volume imperfections such as surface roughness, rough internal boundaries and density fluctuations which result from crystallinity, porous microstructures, pin-holes, cracks, splashes, microdust, etc. If light scattering is dominant over light loss for a thin-film, then this technique may be used in combination with doping of absorption material. For example, the contrasting fiber may be doped with high absorption material in the inner volume and an optical thin-film deposited at the surface, which will increase both absorption and scattering of laser light into the inner volume. Further research is out of scope of this dissertation and recommended in the future.
7.2 Fabry-Perot Interferometric Pressure Sensor

Fiso Fabry-Perot fiber optic pressure sensors work on the same signal sensing and processing technology as Fiso fiber optic temperature sensors, which base on measuring the absolute FPI cavity length. Therefore, the Fiso fiber optic pressure sensors are expected to be resistant to nuclear irradiation and harsh environments. In this way, the pressure sensors are worthy of further study considering pressure measurement is also dominant and important in nuclear power plants.

Furthermore, a novel experimental method and its theoretical models, which were first developed to test response time of Optrand fiber optic pressure sensors, are presented in Appendix A. This method can be applied to all pressure sensors for the purpose of response time testing.

The Fiso Fabry-Perot interferometric pressure sensor works on a non-contact deflection measurement of a stainless steel diaphragm instead of a stress measurement used in conventional diaphragm pressure sensors. The Fabry-Perot cavity length is defined as the distance between the inner surface of the stainless steel diaphragm and a quartz window. Light is launched into and collected from the Fabry-Perot cavity through a quartz ball lens. The Fabry-Perot cavity length changes with the deflection of the stainless steel diaphragm, which deflects correspondingly with environmental pressure. The absolute FPI cavity length is measured by the same signal processing technique as used in the Fiso Fabry-Perot fiber optic temperature sensor. Therefore, the same signal conditioner can be used for different type of transducers if different...
gage number and gage factor are inputted into the signal conditioner to identify the actual transducer.

The optical cables in the FISO fiber optic pressure sensor, which have a pure silica core, can be manufactured up to several kilometers long. The resolution and accuracy of the Fiso pressure sensors are 0.01% full scale and 0.1% full scale, respectively. The FISO pressure sensor is mechanically robust due to the all-welded stainless steel construction without any epoxy, sealing rubber or any polymer materials, which is beneficial to applications in nuclear irradiation environments. Considering it is positive to use FISO temperature sensors as advanced sensors in nuclear power plants, the FISO pressure sensors, which use the same signal processing technique as in FISO fiber optic temperature sensors, are expected to be resistant to nuclear irradiation and mechanically robust in harsh environments. It is optimistic and recommended to perform further research on FISO Fabry-Perot fiber optic pressure sensors and their applications in nuclear power plants.

7.3 Failure Mode Analysis

The failure mode analysis is performed for the Fabry-Perot fiber optic temperature sensors based on the sensor design/working mechanism and the proposed working environments for potential applications in a nuclear power plant. Actually, this kind of failure mode analysis can also be applied to other applications of fiber optic sensors.
First the discussion is focused on the failure mode associated with fiber optic design and sensing mechanism. As we know, the better the quality of each component used in the sensor, the better the performance the sensor can achieve. It means, from one aspect, the failure or degradation associated with the sensor design and sensing mechanism could be minimized by improving the quality (i.e. life time, stability, accuracy, etc.) of some critical components such as the light source, CCD, coupling, optical fiber, microprocessor, etc. Besides good quality requirement of each component, the human effects are also critical during the sensor manufacturing process. For example, the quality of welding spots in the sensor head, which define the gauge length, depends on the technician’s experience. A bad welding spot may be easier to get loose after long-term operation in an environment of vibration, thermal or pressure cycling, which will cause catastrophic failure or degradation.

Another example is to eliminate Fresnell reflections, which may cause sensor degradation due to coupler misalignment in long-term operation. Even though no background light directly launched into the CCD array, some background light noise, which may result from the Fresnell reflections occurring at the interface of the connectors, will result in a lower signal to noise ratio. Although the tested FISO Fabry-Perot fiber optic sensors are resistant to radiation induced loss due to their unique sensing and signal processing technique, it is still a good practice to eliminate the Fresnell reflections by putting some refractive index matching gel at the interface where Fresnell reflections may occur. In this way, the sensor system can afford a higher light loss compared to a lower light noise level. Considering it is easier to get
dusty using the refractive index matching gel, it is recommended not to put the matching gel at the detachable surface of the connector.

The occurrence of failure or degradation may also be associated with the installation and operation environments. If this type of Fabry-Perot fiber optic sensors is to be installed in nuclear power plant measurement channels, further channel design and training are needed to ensure proper installation. Optical fibers are delicate and should be handled carefully. Their bending radius should be kept larger than the minimum bending radius specified by the manufacturer. If possible, the channel design should be optimized to exclude optical fibers in the installation environments of high pressure, high humidity, vibration, etc. Optical components especially the connector surface should be kept clean in order to maintain light transmission with good quality. These precautions are helpful to avoid sensor failure or degradation due to optical fiber breakage and mishandling, etc.

From the experimental results, this type of fiber optic sensor is resistant to gamma irradiation. Its performance is predictable in a neutron irradiation environment and thus its performance can be compensated for neutron irradiation effects. For the harsh environment expected in a design basis accident, the sensor is expected to at least survive four days after the accident as shown in the environmental test with sensor #1. If further channel design or improvement is considered to absorb mechanical shock or damage as designed for sensor #4, then the unexpected failure or degradation of the fiber optic sensors can be greatly reduced. Of course, it is expected that the sensor may degrade after long-term operation in temperature cycling
environment due to the material fatigue effects on thermal expansion capacity. The good news is the FISO fiber optic sensors can be easily recalibrated and then the measured temperature or pressure can be obtained using the new gage factor of the degraded sensor, which means that degradation may be compensated by inputting a revised gage factor into the signal conditioner and implementing new measurements. In this way, the Fabry-Perot fiber optic transducer is automatically changed into a new transducer, which may still give a linearized readings.
CHAPTER 8

SUMMARY AND CONCLUSIONS

Fiso Fabry-Perot fiber optic sensors have potential advantages in measurement and control applications for two reasons. First, they have common advantages such as immunity to EMI/RFI, higher sensitivity, smaller size, less weight, larger bandwidth and multiplexing capability compared with traditional sensors. Second, their sensing mechanism is tolerant to the loss of light power, which may result from external disturbances such as nuclear radiation, high temperature/pressure and vibration. The precise position of the maximum interference fringe intensity reflects the actual absolute FPI cavity length, which is directly related to the environmental temperature.

A series of nuclear environment simulation tests and performance evaluation tests was performed on five FISO Fabry-Perot fiber optic FOT-H sensors. The nuclear environment simulation tests simulate the expected harsh environment such as gamma, neutron irradiation fields and design basis accident environment encountered in nuclear power plants.

The experimental results provide good reasons to conclude that this type of fiber optic sensor is resistant to gamma irradiation. Its performance is also predictable.
in a neutron irradiation environment with a predictable temperature offset and annealing phenomenon, and thus its performance can be compensated for neutron irradiation effects. For the harsh environment expected in a design basis accident, the sensor is expected to at least survive four days after the accident as shown in the environmental test on sensor #1.

If further channel design or improvement is considered to absorb mechanical shock or damage as designed for sensor #4, then the unexpected failure or degradation of the fiber optic sensors can be greatly reduced. Of course, it is expected that the sensor may degrade after long-term operation in temperature cycling environment due to the material fatigue effects on thermal expansion capacity. The good news is the FISO fiber optic sensors can be easily recalibrated and then the measured temperature or pressure can be obtained using the new gage factor of the degraded sensor, which means that degradation may be compensated by inputting a revised gage factor into the signal conditioner and implementing new measurements. In this way, the Fabry-Perot fiber optic transducer is automatically changed into a new transducer, which may still give linearized readings. A conclusion can be drawn that this type of fiber optic sensors is promising in the applications in safety-related measurement channels in nuclear power plants.

Therefore, it is recommended to do further research on FISO fiber optic pressure sensors. A new experimental method and its theoretical model are also developed in this dissertation to test the response time of pressure sensors with fast response. A new method is also proposed in this dissertation for the purpose of on-line
surveillance and on-line response time testing of FISO type fiber optic temperature sensors.
BIBLIOGRAPHY


APPENDIX A

A NOVEL METHOD TO DYNAMICALLY TEST PRESSURE SENSORS

This section introduces a new method designed to dynamically test pressure sensors with fast response.

The response time of a pressure sensor is required when it is used in control systems and in some measurement applications. It is often difficult to measure the response time of a pressure sensor since it is difficult to obtain changes in fluid pressure sufficient to characterize the sensor dynamic response.

In this section a relatively simple system is described to measure or validate the response time of pressure sensors with fast dynamic response. The system consists of two chambers isolated by a graphite rupture disk, a device that fully and rapidly opens at a known rupture or break pressure. A pressure transient in the second chamber is initiated by slowly increasing the pressure in the first chamber until reaching the nominal break pressure of the rupture disk.

Performance of the system was validated through comparing a developed theoretical model with measurement of the rise time of the pressure transient by a piezoelectric pressure transducer. The method was verified by comparing the response
to the pressure transient of a tested optical based pressure transducer with the response of the reference piezoelectric pressure transducer. The time constant of the tested Optrand fiber optic pressure sensor was found using the method presented in this section to be 0.488 ms, which is close to the time constant of 0.454 ms measured by another comparison method.

Introduction

Pressure sensors are widely used in measurement and process control in many fields such as aerospace, medicine manufacturing, food processing and power plants. There are many kinds of design mechanisms for pressure sensors. Some pressure sensors are appropriate for static pressure measurement and some for dynamic pressure measurement. In the case of dynamic measurement, the response time of a pressure sensor is a very important parameter, which should be considered when selecting an appropriate pressure sensor for some pressure measurements or for process control. For example, the rise time of the Kistler 609B piezoelectric pressure sensor is about 3 μs, therefore, it is excellent for use in capturing continuous rapid pressure changes.

There are five testing methods that may theoretically be used to analyze the dynamic response of a pressure sensor. They are step response [4], ramp response [4], impulse response, frequency response and noise analysis [4], respectively. The selection of testing method depends on the dynamic performance of the tested sensor, the availability and the performance of a reference sensor, and the pressure input...
signal itself. The theoretical basis for the method for a typical first order or second order system can be found in references [2,4]. It is a challenge to dynamically test pressure sensors. For example, an actual pressure change may be treated as a step input for a pressure sensor with slow response but may not be an ideal step input for a pressure sensor with very rapid response. The ramp response method depends on the ramp input, availability of a reference sensor to characterize the ramp input, and the difference between the tested and the reference sensor. Pressure transients, which are used to test the dynamic response of a pressure sensor, can be generated from, for example, a shock tube that uses a metal diaphragm, a gas tunnel, pump, etc. These methods are relatively complicated and expensive in terms of the availability of specific equipment. For example, the metal diaphragm may not fully open, therefore, the actual pressure transient using a metal diaphragm may be unpredictable.

In this section, we implemented a very simple experimental method that uses a graphite rupture disk, which fully and rapidly opens when exposed to a pressure difference exceeding its rupture pressure. A theoretical model for the pressure transient following the opening of the graphite rupture disk was first developed to predict the rise time of this pressure transient, which was then compared to the response of a reference Kistler piezoelectric pressure sensor in order to verify the developed theoretical model. Then a general model was developed to determine the dimensions of the graphite rupture disk and the two chambers used in the experiment. This experimental method is more predictable based on the verifiable performance of the graphite rupture disk and the fully developed theoretical models presented in this
section. We demonstrated the application of this method by testing the response time of an Optrand fiber optic pressure sensor, which is investigated for potential applications in nuclear power plants, and using a Kistler piezoelectric pressure sensor as a reference.

In general, fiber optic sensors have advantages such as immunity to electromagnetic interference and radio frequency interference (EMI/RFI), higher sensitivity and accuracy, smaller size and less weight, larger bandwidth and multiplexing capacity over traditional sensors. Furthermore, fiber optic sensors may provide different measurement channels, which are based on different sensing mechanism from traditional sensors employed in nuclear power plants, to reduce common mode failures and thus to improve nuclear power plant safety. Optrand fiber optic pressure sensors were investigated and evaluated in a research project, which was performed in The Ohio State University for the purpose of introducing advanced fiber optic sensing technology to nuclear power plants. The experimental method presented in this section was originally designed to evaluate the response time of the tested Optrand sensor and can also be applied to other pressure sensors with similar dynamic performance.

The Optrand fiber optic pressure sensor uses a diaphragm to sense the environmental pressure change. Figure A.1 shows the diagram of the Optrand fiber optic pressure sensor head. An optical fiber is inserted into the sensor head and its tip faces the diaphragm. A light beam from a LED is launched into the optical fiber. The light reflected from the diaphragm is transmitted through the optical fiber and
detected by a photodiode detector. In response to the environmental pressure change, the distance between the diaphragm and the fiber tip changes due to the deformation of the diaphragm. The reflected light intensity is modulated due to the change of the distance between the diaphragm and the fiber tip. Therefore, the pressure change is calculated from the change of the detected modulated light intensity.

![Figure A.1: The diagram of the Optrand fiber optic pressure sensor head.](image)

**Theoretical Model**

Two small chambers with a graphite rupture disk installed between them were designed to test the response time of an Optrand fiber optic pressure sensor. Figure A.2 shows the two chambers. A theoretical model describing the gas dynamic process is developed in this section.
In Fig. A.2, the air pressure in the upstream chamber is controlled to gradually approach the rating pressure of the graphite rupture disk, which specifies a pressure difference between the two chambers when the disk rapidly (i.e. in about 1ms) and fully opens resulting in a fully opened discharge area. Considering the downstream chamber as a control volume, the initial state equation of the air in this chamber is

$$P_{20}V_2 = m_{20}RT,$$  \hspace{1cm} (A.1)

where the initial state parameters $P_{20}$, $V_2$, $m_{20}$, $T$ denote the pressure, volume, mass and temperature, respectively, of the air in the downstream chamber prior to opening of the graphite rupture disk.

When the graphite rupture disk opens, a portion of the air in the upstream chamber is rapidly discharged into the downstream chamber and the pressure in the downstream chamber rapidly increases in order to attain pressure equilibrium with the upstream chamber. This pressure transient is specified as the leading pressure increase
for the downstream chamber. Since the air heat capacity effect is negligible during this very rapid leading pressure transient, which occurs around atmosphere level, an isothermal process is assumed to describe this leading pressure increase process. For the control volume of the downstream chamber, the dynamic process of the leading pressure increase after the rupture disk breaks is described by

\[ \nu_2 \frac{dP_2}{dt} = \frac{dm_2}{dt} = \rho \bar{v} RT, \tag{A.2} \]

where \( P_2 \) and \( m_2 \) are the transient pressure and mass in the downstream chamber respectively, \( A \) is the throat area or the effective discharge area of the graphite rupture disk, and \( \bar{v} \) is the fluid discharge velocity in this pressure transient. Since the volume of the upstream chamber is designed to be larger (i.e. 5 times) than that of the downstream chamber, it is reasonable to assume that Bernoulli equation can be applied to this air discharge process and the initial upstream velocity in the upstream chamber is zero, therefore,

\[ \frac{R_{10}}{\rho} = \frac{1}{2} \bar{v}^2 + \frac{P_2}{\rho}, \tag{A.3} \]

and

\[ \bar{v} = \sqrt{\frac{2}{\rho} \frac{P_{10} - P_2}{\bar{v}}}, \tag{A.4} \]
where $P_{10}$ is the pressure of the upstream chamber, $\rho$ is assumed as the density at the average pressure between these two chambers. From Eq.(A.3) and substituting Eq.(A.4) into Eq.(A.2), we have

$$\frac{V_2}{\sqrt{2\rho RTA}} \frac{dP_2}{dt} = \sqrt{P_{10} - P_2}. \quad (A.5)$$

In order to linearize Eq.(A.5) around the average pressure, let $P_2 = P_{2avg} + \delta P_2$ and $P_{2avg} = \frac{1}{2}(P_{20} + P_{2f})$, where $P_{2f}$ is the final pressure in the downstream chamber. Equation (A.5) becomes

$$\frac{V_2}{\sqrt{2\rho RTA}} \frac{d\delta P_2}{dt} = \sqrt{P_{2avg} (\frac{P_{10} - P_{2avg}}{P_{2avg}} - \frac{\delta P_2}{P_{2avg}})}. \quad (A.6)$$

Let $x = \delta P_2 / P_{2avg}$ and $a = (P_{10} - P_{2avg}) / P_{2avg}$, then

$$\frac{V_2 \sqrt{P_{2avg}}}{\sqrt{2\rho RTA}} \frac{dx}{dt} = \sqrt{a - x}. \quad (A.7)$$

Using a Taylor expansion around zero on the right hand side of Eq.(A.7) and neglecting the second order term $x^2$, then we can rearrange Eq.(A.7) into Eq.(A.8)

$$\frac{2V_2 \sqrt{P_{10} - P_{2avg}}}{\sqrt{2\rho RTA}} \frac{dx}{dt} + x = 2a, \quad (A.8)$$
which describes the dynamic pressure transient after the graphite rupture disk is fully opened. Comparing Eq.(A.8) with the standard form of a first order system as described in Eq.(A.9),

\[ \frac{dx}{dt} + x = 2a, \]  

(A.9)

the rise time \( (t_r=2.2\tau) \) of the leading pressure increase is then obtained as follows

\[ t_r = \frac{4.4V_2\sqrt{P_{10} - P_{2\text{avg}}}}{\sqrt{2pRTA}}. \]  

(A.10)

Assume the volume ratio \( \beta \) and the initial pressure difference \( \Delta P \) between the two chambers, which specify \( V_i=\beta V_2, \Delta P=P_{10}-P_{20} \), are given as the initial chamber design conditions. An isothermal process is assumed to relate \( P_{2\text{avg}} \) to the initial design parameters. The state equations for the control volumes are described by

\[ P_{10}V_1=m_{10}RT, \]  

(A.11)

\[ P_{20}V_2=m_{20}RT, \]  

(A.12)

\[ P_e(V_1+V_2)=(m_{10}+m_{20})RT, \]  

(A.13)

where \( P_e \) is the first reached equilibrium pressure. Substituting Eqs.(A.11), (A.12) and the volume ratio defined by \( \beta \) into Eq.(A.13),

\[ P_e = (\beta P_{10} + P_{20})/(\beta + 1) = P_{20} + \beta/\beta + 1 \Delta P, \]  

(A.14)

Then

\[ P_{2\text{avg}} = \frac{1}{2}(P_{20} + P_e) = P_{20} + \frac{\beta}{2(\beta + 1)} \Delta P. \]  

(A.15)
Substituting Eq.(A.15) into Eq.(A.10), the rise time of the leading pressure transient is given by

\[ t_r = \frac{4.4V_2}{\sqrt{\frac{\beta + 2}{2(\beta + 1)}} \Delta P}}{\sqrt{2\rho RTA}}. \tag{A.16} \]

Two small cylindrical chambers were designed using the following parameters: inner diameter, \( D = 2\text{in} \); the length of the upstream chamber, \( L_1 = 8\text{in} \); volume ratio of the two chambers, \( \beta = 5 \); the initial absolute pressure of the downstream chamber, \( P_{20} = 1\text{atm} \); the rated rupture pressure of the graphite rupture disk or the initial pressure difference between the two chambers, \( \Delta P = 20\text{psi} \). From Eq.(A.16), the calculated time constant of the leading pressure increase was \( \tau = 0.22\text{ms} \) and the corresponding rise time was \( t_r = 0.484\text{ms} \). The experimental setup used in this section was based on these initial conditions and the estimated rise time of 0.484ms.

**Design of the Experimental Method**

When a graphite rupture disk, which is installed between the two chambers, opens at its rating pressure, it provides a rapid pressure transient for the pressure sensors installed in the downstream chamber. Based on the technical data provided for the graphite rupture disk manufactured by Zook Enterprises, the actual disk dimension depends on the desired mass flow rate through it and the initial pressure difference between its upstream and downstream fluid.
In order to estimate the mass flow rate, the discharged air mass was found by using control volume method and applying the state equations to the air in the upstream chamber before and after the breakage of the rupture disk,

\[ P_{10}V_1 = m_1RT_{10}, \quad (A.17) \]

\[ P_eV_1 = m_{1\text{left}}RT_e. \quad (A.18) \]

Assuming \( \Delta m = m_1 - m_{1\text{left}} \), from Eqs.\((A.17)\) and \((A.18)\),

\[ \Delta m = \frac{V_1(P_{10}T_e - P_eT_{10})}{RT_{10}T_e}. \quad (A.19) \]

In order to make the designed experimental method reliable and simple, and to minimize the effects of turbulent flow and uncertainty of the rupture pressure of the graphite rupture disk during the experiment, the chamber dimension and the initial pressure difference between the two chambers is designed or controlled to be small and the chamber pressure is just around atmosphere level. Assuming \( \Delta P = 20 \text{psi} \) and \( \beta = 5 \), the absolute \( P_e \) is calculated to be 31.37psi from Eq.\((A.14)\). The temperature \( T_e \) is calculated from a developed isentropic model

\[ T_e = T_{10}\left(\frac{P_{10}}{P_e}\right)^{\frac{r-1}{r}}, \quad (A.20) \]

where \( T_e \) is the temperature when the pressure equilibrium is reached, \( \gamma \) is a constant of 1.3 for air. Assuming the initial temperature in the upstream chamber is \( T_{10} = 70^\circ \text{F} \), the temperature \( T_e \) is calculated to be 74.95°F, which is close to the initial temperature
and thus supports the use of the isothermal model initially used to describe the
dynamic process of the leading pressure increase.

From the design parameters $D=2\text{in}$, $L_1=8\text{in}$, the volume of the upstream
chamber is calculated to be $V_1=25.12\text{ in}^3$. Then from Eq.(A.19), $\Delta m=2.69\times10^{-4}\text{lb}$. Assume the air can be delivered in a time of $0.484\text{ms}$, which is the estimated rise time of the leading pressure increase, then the calculated mass flow rate is $0.556\ \text{lb/s}$.

In order to get the nominal size of the graphite rupture disk for the designed mass flow rate, the following equation provided by Zook Enterprises was used $^{[49]}$,

$$
a = \frac{W}{KC_1P_0} \sqrt{\frac{t+460}{M}},
$$

where $a$ is the minimum required discharge area of the graphite rupture disk in $\text{in}^2$, $W$ is the given mass flow rate in $\text{lb/sec}$, $K$ is a discharge coefficient to compensate for turbulence and other losses and is 0.62 for air in normal practice, $C_1$ is gas flow constant provided in a given table which is a function of $K$ and $P_{20}/P_{10}$. $t$ is the initial air temperature in $\degree F$, $M$ is the molecular weight which is 28.97 for air. From $P_{10} = 34.7\text{psia}$, $C_1$ is found to be 0.0624 from the provided table. From Eq.(A.21), the calculated discharge area, $a$, is $1.7708\text{in}^2$, which corresponds to a diameter of $1.502\text{in}$. Therefore, the graphite rupture disk used in the experiment was selected from the product catalog with a diameter of $1.5\text{in}$ and a rating pressure of $20\text{psi}$.

To evaluate this method, we used an Optrand fiber optic pressure sensor as the tested sensor and a piezoelectric pressure sensor as the reference sensor in the
experiment. The experimental setup for this test is shown in Fig.A.3. The graphite rupture disk was installed between the two small chambers, which were jointed using an ANSI 150 flange. The dimensions of the rupture disk and the two chambers were shown in above sample calculations. The bottom downstream chamber was about 8in in height and filled with water to approximately 6in. The bottom chamber was filled with water to prevent the graphite fragments from damaging the pressure sensors and also to rapidly transmit the pressure change to the sensors located at the bottom end of the downstream chamber. The air cavity in the downstream chamber was filled with air at atmosphere pressure. A pressure gauge and a solenoid valve were installed at the pipe, which connected the upstream chamber to a high pressure air line providing air stream. The upstream pressure was first increased very slowly to around the rating pressure of the rupture disk. Then it was pressurized to the rated pressure of the graphite rupture disk while supplying a voltage to trigger the solenoid valve, which was used to trigger the HP 35670A dynamic signal analyzer with a limited memory space. In other words, the trigger signal supplied to the solenoid valve was also used to trigger the signal analyzer to record the experimental data from the Optrand sensor and the reference piezoelectric pressure sensor.
Figure A.3: Experimental setup designed for testing the response time of the Optrand pressure sensor.
Experimental Results

Figure A.4 shows the experimental data recorded from the two pressure sensors. From Fig.A.4, it was observed following the leading pressure increase that there existed pressure oscillations, which may result from the pressure wave bouncing back and forth after the breakage of the rupture disk, the oscillation of the free water surface at the bottom chamber and the graphite fragments falling into the water. During the experiments, it was also observed that the graphite rupture disks were fully opened. Repetitive experiments demonstrated consistent experimental phenomena and results especially on the leading pressure increase process.
Figure A.4: The sensor outputs recorded during and after the pressure transient initiated by the breakage of the graphite rupture disk.

Although the sensor outputs reflect the total dynamic process, the most interesting part is found in the leading pressure increase, which is the pressure increase to the first peak after the breakage of the graphite rupture disk. Figure A.5 shows the normalized sensor outputs for the leading pressure increase.
Figure A.5: Normalized sensor outputs during the leading pressure increase process.
The response time of the Kistler 609B piezoelectric pressure sensor is specified by a rise time of 3μs, which is fast enough to follow the calculated rise time of 0.484ms response of the leading pressure increase process as described previously. Therefore, the Kistler sensor output is assumed to measure the actual pressure transient in the downstream chamber without any delay. From the analysis of this leading pressure increase process previously presented and Eq.(A.8), it is reasonable to assume this leading pressure increase process is a first order system responding to a postulated step pressure input, which results from the breakage of the graphite rupture disk. The step response of a first order system is described by

\[ (Y - Y_0) = (Y_{ss} - Y_0)(1 - e^{-\frac{t}{\tau}}), \quad (A.22) \]

where \( Y \) denotes the actual sensor (i.e. Kistler) output, \( Y_0 \) denotes the initial output of the considered sensor, \( Y_{ss} \) denotes the final steady state value of the sensor output for the step response, \( \tau \) is the time constant of the analyzed first order system, which is the process of the leading pressure increase measured by the Kistler sensor. From Eq.(A.22), the time constant is obtained from the inverse of the slope of the fit line of \( \ln(1-(Y-Y_0)/(Y_{ss}-Y_0)) \) vs. \( t \). The time constant of the leading pressure increase is found in this way to be \( \tau_{\text{ex}} = 0.285 \text{ms} \) by least-square fitting the experimental data of the Kistler sensor output shown in Fig.A.5. This time constant obtained from the experimental data of the Kistler sensor output is very close to the calculated theoretical time constant of 0.22ms for the leading pressure increase process as described...
previously. Therefore, it verifies that the theoretical model is valid for the leading pressure transient after the breakage of the graphite rupture disk.

Since the response time of the Optrand fiber optic pressure sensor is expected to be of the same order of magnitude as the rise time of the pressure transient, the pressure transient must be treated as a ramp input instead of a step input. For a ramp response of a first order system, there is a steady state time lag between the ramp input and the system output, which equals the time constant of the first order system \[^4\]. As observed in Fig.A.3, a steady state time lag exists between the output of the Optrand sensor and the output of the Kistler sensor. Therefore, this time lag denotes the time constant of the tested Optrand fiber optic pressure sensor. The time constant of the tested Optrand sensor obtained from this time lag is about 0.488ms, which is in the same order of magnitude as the time constant of the leading pressure increase process. It demonstrates, from another point of view, that the actual pressure transient input resulted from the breakage of the graphite rupture disk should be treated as a ramp input instead of a step input for the tested Optrand pressure sensor, which is consistent with the actual data processing method used in this section.

Another group of repetitive experiments using sinusoidal pressure input and frequency response method was also performed with the tested Optrand fiber optic pressure sensor and those experimental results showed that the rise time of the tested Optrand sensor is 0.998ms, which corresponds to a time constant of 0.454ms. This time constant is consistent with the time constant of 0.488ms obtained by using the method presented in this section.
The method presented in this section can also be applied to applications of testing other pressure sensors with fast dynamic response such as with time constant in the order of millisecond, which is in the same order as the time constant of the leading pressure increase process after the breakage of the graphite rupture disk.