# A Preliminary Study on the Locations of Distributed Fiber Optic Sensors in High-radiation Environments of Nuclear Power Plants

Dongjin Kim[a], Hee Kwon Ku[a], Subin Kim[a], Jongyeol Kim[b], Youngwoong Kim[b], Gukbeen Ryu[b], Wookjin Jeong[b],
Young Ho Kim[c] and Sang Hun Shin[a*]
[a]*FNC Technology Co., Ltd., 13 Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 16954, Korea*
[b]*Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon, 34057, Korea*
[c]*Korea Photonics Technology Institute, 9 Cheomdan Venture-ro 108 beon-gil, Buk-gu, Gwangju, 61007, Korea*
[*]*Corresponding author: ssh9431@fnctech.com*

***Keywords :** Distributed Fiber-Optic Sensors (DFOS), Location selection process, Nuclear power plant, High-radiation environments, Core Damage Frequency (CDF)

## 1. Introduction

As life extension and long term operation (LTO) of in service nuclear power plants (NPPs) expand, maintenance strategies are shifting from time based preventive maintenance to condition based maintenance. In particular, components in the primary system are continuously exposed to harsh environments (high temperature, high pressure, and high radiation). Therefore, the early identification of incipient degradation or leakage indicators, before they progress to significant equipment damage, is critical to reducing the core damage frequency (CDF). This need goes beyond confirming conditions at a few discrete points; it calls for wide-area monitoring based on distributed sensing that provide spatially continuous observations of the monitored components [1].

Despite this need, the current monitoring system of the primary system relies mainly on discontinuous point type instruments such as RTDs and thermocouples, which have structural limitations in capturing spatial gradient-type anomalies occurring in long distance piping or area structures without blind spots. To overcome these limitations and meet the aforementioned wide-area monitoring requirements, distributed fiber-optic sensor (DFOS) technology, which is immune to electromagnetic interference and has excellent environmental resistance, is attracting attention as an alternative. In particular, Distributed Temperature Sensors (DTS) can provide continuous temperature distribution along the piping, and Distributed Acoustic Sensors (DAS) can continuously monitor mechanical anomalies such as micro-vibrations and leakage sounds. In this regard, their potential as an auxiliary wide-area monitoring tool, rather than a direct replacement for existing point type sensors, is being raised [2].

As a preliminary study for the stable integration of a distributed sensor system into the primary system of an operating nuclear power plant, this study proposes a location selection process for distributed DFOS that sequentially verifies technical suitability and field feasibility. This process includes a strategy to minimize burdens such as licensing and design changes by limiting the new equipment to an auxiliary monitoring means that complements blind spots, rather than replacing existing safety class instruments. To review the logical validity of the established process, a preliminary evaluation was conducted for the piping section upstream and downstream of the POSRV. Through this, we aim to provide practical guidelines, such as identifying the required review items at each step and specifying preliminary target outcomes.

## 2. Methods and Results

### 2.1 Derivation of Sensor Application Location Selection Process

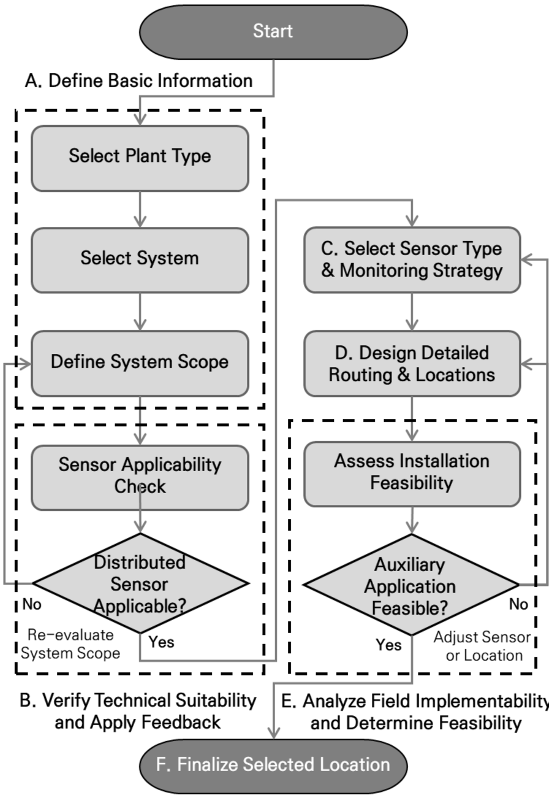

Fig 1. Process for selecting deployment locations of distributed fiber-optic sensors.

Prior to performance qualification, candidate locations must be identified where distributed sensing can meaningfully contribute to safety improvements in operating NPP systems.

As shown in Fig. 1, we established an integrated location selection process featuring a feedback loop. This process sequentially verifies technical suitability and field implementability, returning to upstream steps to redefine the monitoring region when a location is deemed unsuitable.

### *2.2 Detailed Review Items for Each Process Step*

The specific engineering review items performed at each step of the process are as follows.

A. Define Basic Information
  - Identify the target reactor type (PWR, BWR, etc.) and key design characteristics.
  - Select target systems (e.g., the reactor coolant system, RCS) where enhanced monitoring is required.
  - Specify the monitoring scope based on objectives (e.g., continuous segment monitoring, detection of state changes, and long-term trend monitoring).

B. Verify Technical Suitability and Apply Feedback
  - Review the feasibility of deployment considering the physical characteristics of distributed sensors.
  - Determine suitability under the premise of supplementary monitoring rather than full replacement of safety class instrumentation.
  - If distributed sensing is judged unsuitable, return to the system scope definition step and redefine the monitoring region.

C. Select Sensor Type and Monitoring Strategy
  - Match new sensors to complement existing point sensors (e.g., RTD/thermocouple → DTS; vibration sensor → DAS).
  - Establish requirements specific to distributed sensing (e.g., spatial resolution and sampling rate).

D. Design Detailed Routing and Locations
  - Identify candidate installation locations and develop a preliminary routing layout.
  - Develop a plan to segment monitoring sections to ensure data continuity and adequate resolution.

E. Analyze Field Implementability and Determine Feasibility
  - Perform a detailed analysis of physical installation constraints such as insulation configuration and interference with supports.
  - If auxiliary deployment is judged infeasible, return to upstream steps (e.g., adjusting sensor type or reselecting detailed locations) to explore alternatives.

F. Derive Final Demonstration Locations
  - Finalize demonstration locations for which both technical suitability and physical installability are verified.
  - Based on the selected locations, derive detailed sensor requirements and a performance validation roadmap.

### *2.3 Derivation of Preliminary Results*

To verify the logical flow of the proposed integrated process and to illustrate how preliminary design parameters can be derived, a conceptual example was developed for the piping section upstream and downstream of the POSRV using DTS. Table 1 compares the principal review items for the existing RTDs and the proposed DTS within each step of the selection process. The POSRV-related piping section was selected as a representative conceptual case because a micro-leakage event in this area may produce localized thermal disturbances, and such thermal anomalies may be difficult to characterize using only point-type sensors. In this respect, DTS was considered suitable as an auxiliary monitoring tool because it can provide spatially continuous temperature information along the surrounding piping.

Table 1. Comparison of key monitoring parameters at each step for the POSRV piping section (conceptual example)

| Step | Review Item | Existing Point Sensors (RTD) | Proposed DFOS (DTS) |
|---|---|---|---|
| A | Target Measurands | Localized temperature at specific points | Temperature gradients (e.g., ΔT > 3°C*) |
| B | Monitoring Topology | Point based | Continuous linear distributed |
|  | Spatial Coverage Gap | Significant blind spots | Spatially continuous distributed monitoring |
| C | Temperature Resolution | High point accuracy, but unable to measure intervals | Target temperature resolution of ≤ 0.5°C over the monitored section |
|  | Radiation Tolerance | Environmentally Qualified (EQ) | Requires radiation hardened special fibers (e.g., gold-coated, tolerance > 100 kGy) |
| D | Target Location | Specific points on the downstream piping of the POSRV | Entire piping section both upstream and downstream of the POSRV |
|  | Installation Clearance | Direct pipe surface mount or thermowell | Requires sufficient clearance beneath the insulation for fiber routing(<10mm) |
| E | Regulatory Classification | Safety class | Non-safety class |
| F | Expected Output | Time-series data at specific nodes | Spatially continuous thermal profile data over time |

* This value was selected as a conservative illustrative threshold based on prior work showing that micro-leaks could be detected at a temperature change of about 3°C under fiber-optic sensing conditions [3].

This value was selected as an illustrative threshold based on prior work reporting a 3°C detection threshold in fiber-optic leak detection experiments [3].

As shown in Table 1, the proposed DTS exhibits clear differences from the conventional RTD-based monitoring approach, particularly in terms of monitoring topology and spatial coverage. While RTDs provide temperature information only at discrete measurement locations, the DTS enables continuous measurement along the entire piping section, thereby fundamentally eliminating spatial blind spots. In this conceptual example, the DTS was considered for monitoring temperature gradients and localized thermal anomalies associated with small leakage events in regions that may not be sufficiently covered by the existing point-type sensors. Early detection of such anomalies is expected to contribute to reducing initiating event frequencies, thereby potentially lowering CDF.

Based on this comparison, several preliminary design requirements were identified. The monitored region should include both upstream and downstream sections of the POSRV to capture broader thermal behavior across the piping section. A target temperature resolution of ≤ 0.5°C was defined as a preliminary value based on typical DTS performance characteristics. In addition, radiation-tolerant optical fibers suitable for cumulative dose conditions exceeding 100 kGy should be considered, although the exact requirement may vary depending on site-specific radiation conditions. Furthermore, the practical feasibility of fiber routing should be verified by assessing the available clearance beneath the insulation.

From a regulatory perspective, DTS is intended as a non-safety class, auxiliary monitoring tool rather than a replacement for safety class instrumentation. Accordingly, monitoring output can be extended from discrete time-series data to spatially continuous thermal profile data over time along the piping section. These results demonstrate that the proposed process can support the derivation of monitoring requirements, installation constraints, and expected data outputs for site-specific implementation. Because this example remains conceptual, the quantitative values in Table 1 should be regarded as preliminary design targets subject to further validation through site-specific analysis, environmental qualification, and licensing evaluation.

## 3. Conclusions

Before deploying distributed sensing systems in an NPP, it is necessary to establish a preliminary process that screens and selects locations where the sensors can meaningfully contribute to safety improvements, prior to the performance qualification of the sensors themselves. To address this need, this study developed a location selection process that sequentially verifies the technical requirements of NPP systems and on-site installation feasibility, and returns to upstream steps through a feedback loop when constraints are identified.

When the process was preliminarily applied at a conceptual level to the piping section upstream and downstream of the POSRV in the primary system of an operating plant, the usefulness of confining the new sensor system to a supplementary monitoring role was confirmed, particularly in terms of regulatory acceptability. In addition, the process was shown to provide a structured path for deriving locations and defining follow-up actions, such as qualification and validation items and a roadmap for detailed demonstration design.

Nevertheless, the results presented herein are limited to a conceptual demonstration intended to confirm the process operation and logical validity. In future work, we will incorporate actual site data from a reference plant to determine and finalize the optimal demonstration locations.

## Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2022-00144110)

## REFERENCES

[1] R. Khurmi et al., Condition Based Maintenance in Nuclear Power Plants: Limitations & Practicality, 2021 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2021.

[2] J. Wu et al., Distributed Fiber Sensors With High Spatial Resolution in Extreme Radiation Environments in Nuclear Reactor Cores, Journal of Lightwave Technology, vol. 39, no. 14, 2021.

[3] A. D'Aniello et al., Thermal Response to Background Leakages around an Actively Heated Fiber Optic Sensor for Leak Detection in Water Distribution Mains: Modeling the Effect of Heating Power and Time, Tunnelling and Underground Space Technology, vol. 152, art. no. 105904, 2024.