Deliverable B

Berke Dai

Caleb Gilbert

Visisht Kaushik

Quin Ramos

Ian Kahuro

January 24, 2025

Abstract

This report outlines the development of a pipe sampling device for Canadian Nuclear Laboratories (CNL) to obtain radioactive samples from CANDU reactor fuel pipes. The project addresses key design constraints, including general functionality, dimensions, portability, and safety, to meet CNL's operational requirements. The proposed solution aims to improve upon existing sampling methods by enhancing durability, modularity, and operator safety while maintaining a cost-effective approach within a $100 budget. Key considerations include ensuring the device's ability to collect samples within the specified weight range, achieving a reach of 15 feet within a 4-inch diameter pipe, and incorporating real-time feedback mechanisms to communicate device status and sample retrieval progress. This report evaluates current sampling solutions, identifies limitations such as portability challenges and safety risks, and proposes improvements to enhance efficiency and reliability. The conclusions and recommendations section highlights future steps, focusing on prototype development and testing to refine the design and address client concerns.

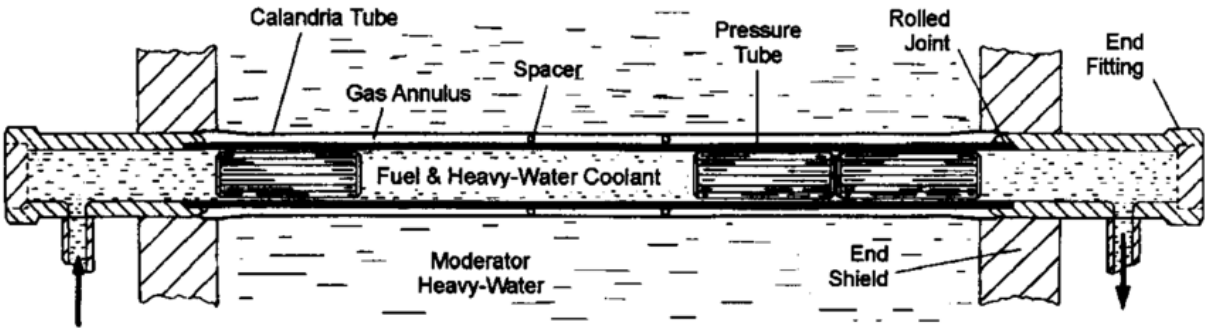

Figure 1: Cross-sectional diagram of a CANDU reactor fuel channel, illustrating key components such as the calandria tube, pressure tube, fuel and heavy-water coolant, and moderator heavy-water. The diagram highlights the structural elements and spatial constraints within which the sampling device must operate.

Table of Contents

1 Introduction ……..……4

2 Design Constraints and Needs ……..…….……4

2.1 General Function ……..……5

2.2 Dimensional ……..……5

2.3 Portability ……5

2.4 Safety ……..6

2.5 Operator Feedback ……..7

3 Existing Solutions and Concerns ……...8

4 Conclusions and Recommendations ……10

5 Future Work ……....10

6 References ……11

1 Introduction

Fuel pipes are essential components across various industries, including oil and gas, electricity, water treatment, and nuclear power. In the nuclear sector—particularly within CANDU reactors—these pipes require regular inspections to ensure both operational safety and compliance with regulatory standards. A crucial part of this inspection process involves extracting metal samples from different sections of the pipe to assess hydrogen embrittlement, which is a key factor in evaluating the pipes' structural integrity and long-term performance.

Canadian Nuclear Laboratories (CNL), a leading research and technology organization in the nuclear industry, faces several challenges with their current sampling methods. The existing techniques often rely on manual processes that introduce safety risks, such as potential radiation exposure, and lack the precision needed for accurate sample collection. Additionally, these methods are not cost-effective for repeated use. As a result, CNL is seeking an innovative solution that can efficiently extract samples from a 4-inch diameter, 15-foot-long fuel pipe while prioritizing operator safety, device durability, and overall operational efficiency.

This project focuses on designing and developing a new pipe sampling device that meets CNL's specific needs. The solution must address key constraints such as affordability, portability, and fail-safe operation. It should be modular, lightweight, and easy to handle, making it suitable for deployment in confined spaces while minimizing exposure to hazardous materials. Furthermore, the device should provide real-time feedback to the operator, ensuring successful sample retrieval and system status monitoring to prevent potential operational errors.

The following report provides a detailed analysis of the design constraints, existing solutions, and areas for improvement. It outlines a clear problem statement that reflects CNL's requirements and offers recommendations for future development to deliver a safe, reliable, and efficient sampling solution.

2 Design Constraints and Needs

The sampling device must fulfill the client's operational and safety needs by addressing five key design factors: **Functionality, Dimensions, Portability, Safety, and Operator Feedback.** It should efficiently collect samples while being easy to use and preserving sample integrity. The device must fit within the specified pipe size and function effectively across its full length.

Portability is crucial, requiring a lightweight, modular design for easy transport and assembly. Safety remains a top priority, with fail-safe features, operator protection, and real-time monitoring to mitigate risks. Additionally, the device should provide clear system status updates via visual, audible, and remote notifications to enhance efficiency and prevent errors.

By meeting these constraints, the device will ensure a reliable, safe, and practical sampling solution that aligns with the client's requirements and regulatory standards.

2.1 General Function

The proposed sampling device must effectively collect metal samples from CANDU reactor fuel pipes, with each sample weighing between 30 to 80 milligrams. To ensure operator safety and sample integrity, the device should securely contain the samples, preventing any direct contact during both collection and removal processes. The design should facilitate easy retrieval of the samples in a controlled environment, minimizing contamination risks.

While adhering to a target budget of approximately $100, it is acknowledged that certain design requirements may necessitate exceeding this limit to ensure durability and functionality. The device must be robust enough to withstand the demanding conditions typical of nuclear facility operations, including exposure to radiation, temperature variations, and potential mechanical stresses. Additionally, it should be designed for repeated use, maintaining performance and safety standards over multiple sampling operations.

2.2 Dimensional Constraints

The sampling device is designed for use within the fuel channels of a CANDU-6 reactor. Each fuel channel contains 12 fuel bundles and consists of a zirconium-niobium alloy pressure tube, which is positioned inside a zirconium alloy calandria tube. The pressure tube has an inner diameter of approximately 103 mm (4 inches) and a length of about 5.944 meters (19.5 feet). (CanTeach)

With these dimensions in mind, the device must be capable of navigating the 4-inch inner diameter and operating effectively along the entire 19.5-foot length of the pressure tube. This requires a thoughtful approach to the device's size, flexibility, and maneuverability to ensure it can access and collect samples from the required locations without damaging the pressure tube or fuel bundles.

In short, the design must carefully balance functionality, safety, durability, and size constraints to create a cost-effective and reliable sampling solution that meets the specific application requirements.

2.3 Portability

Portability is a key factor in ensuring the pipe sampling device is practical for field use. The system should be lightweight and modular to allow for easy transport and deployment. Several important aspects should be considered, including:

- **Modular Design:**
    - The device should be built in detachable sections that can be quickly assembled and disassembled. This modular approach makes transportation more manageable and allows the system to adapt to different operational environments. Additionally, reusability of components should be prioritized to minimize environmental impact and ensure longevity.
- **Weight Optimization:**
    - The materials chosen for the device should strike a balance between strength and lightweight properties, allowing a single person to carry it without excessive strain or risk of injury. Lightweight alloys or composite materials should be considered to enhance portability without compromising durability.
- **Ease of Handling:**
    - The design should include ergonomic handles and grips to make carrying and maneuvering the device more comfortable. Clear visual indicators showing the best way to hold and transport the device can further assist operators, ensuring safe and efficient handling.

By focusing on these key factors, the design will ensure that the sampling device is not only portable but also user-friendly, meeting the practical needs of operators working in the field.

2.4 Safety Considerations

Ensuring the safety of both operators and the environment is a top priority in the design and operation of the pipe sampling device, especially given its use in a radioactive environment. To minimize risks and maintain operational integrity, several critical safety features and protocols must be incorporated:

Fail-Safe Mechanism

If the device malfunctions, it's essential that it can be safely removed from the pipe without causing damage or compromising containment. Since the device will be operating within pipes that contain radioactive materials, any breach during extraction could result in hazardous leaks or spills. To prevent such incidents, the design should include a fail-safe mechanism that allows for secure detachment and smooth withdrawal, ensuring both the device and the pipe system remain intact. This approach follows the principle that in the

event of failure, the system should default to a safe condition, reducing potential risks. (IAEA Publications)

Sample Containment and Operator Protection

To safeguard operators, the device must be designed to prevent any direct contact with the collected sample at all stages of the process. An automatic containment system should securely store the sample within a sealed vessel, eliminating exposure to radioactive materials. The containment vessel should allow for easy and safe transfer to laboratory settings without requiring direct handling. In addition, operators must follow established safety protocols, such as wearing appropriate personal protective equipment (PPE) and utilizing remote handling techniques to further minimize exposure risks. (ehs.berkeley.edu)

Operational Feedback System

Since operators cannot visually monitor the device's internal operation during sampling, an integrated feedback system is crucial. This system should provide real-time updates on the device's status, including:

- **Operational Status:** Ensuring the device is functioning properly.
- **Sampling Progress:** Notifications to indicate when sampling starts and when it is successfully completed.
- **Error Detection:** Alerts to warn operators of malfunctions or deviations from expected performance.

By incorporating these safety measures, the design will adhere to the highest safety standards, protecting both personnel and the environment from potential hazards associated with radioactive material sampling.

2.5 System Status and Operator Feedback

Clear and effective communication between the sampling device and the operator is essential for ensuring safe and efficient operation, especially in environments that involve hazardous materials. A well-designed feedback system improves operational awareness, minimizes the risk of errors, and enables timely responses to system conditions. Key aspects to consider include:

Visual Status Indicators

- **LED Indicators:** The device should include LED lights that provide real-time updates on its operational status. Different colors and blinking patterns can indicate various states, such as power on/off, active sampling, or standby mode, making it easy for operators to quickly understand the current status at a glance.

- **Display Panels:** Small display screens can be integrated to provide detailed information, including system diagnostics, sampling progress, and error messages. This allows operators to assess the device's condition more accurately and take the necessary actions as needed.

Audible Alerts

- **Sound Notifications:** Audible signals should be implemented to notify operators of important events, such as when sampling starts, when it's completed, or if an issue arises. Using distinct tones or sound patterns for different alerts will help ensure clarity and prompt response.

Remote Monitoring Capabilities

- **Wireless Connectivity:** The device should be equipped with wireless communication features, such as Wi-Fi or Bluetooth, to enable remote monitoring and control. This is especially useful in high-risk areas, allowing operators to manage operations from a safe distance.

- **Integration with Monitoring Systems:** Connecting the device to centralized monitoring platforms, such as Supervisory Control and Data Acquisition (SCADA) systems, can provide a comprehensive view of operations and allow for data logging and real-time analysis. This integration enhances decision-making and improves overall oversight.

User Notifications

- **Maintenance Alerts:** The system should be programmed to notify operators about scheduled maintenance, calibration requirements, or potential system malfunctions. These proactive alerts help maintain the device's performance and ensure compliance with safety protocols.

- **Battery Status Warnings:** Low battery notifications should be included to prevent unexpected power loss during critical operations, ensuring continuous functionality when needed.

By incorporating these feedback mechanisms, the sampling device will provide operators with crucial real-time information, improving safety, efficiency, and overall operational effectiveness.

3 Existing Sampling Methods: Challenges and Limitations

Current sampling methods in the nuclear industry—such as mechanical, automated, and vacuum-based techniques—each come with their own set of challenges and limitations.

- **Mechanical Sampling:** These devices often require manual or semi-automated insertion, which can result in precision issues, sample contamination, and increased radiation exposure for operators.
- **Automated Systems:** While they offer greater accuracy and consistency, they tend to be expensive, complex to maintain, and may struggle to adapt to the specific constraints of CANDU fuel pipes.
- **Vacuum-Based Techniques:** These methods minimize contamination risks through non-contact sample collection but are limited by pressure requirements, potential sample integrity issues, and high energy consumption.

Common challenges across these methods include:

- **Portability Issues:** Many existing devices are bulky and difficult to transport, with limited modularity, making deployment in confined spaces challenging.
- **Safety Concerns:** The absence of fail-safe features and design flaws can increase operator exposure to hazardous materials.
- **High Costs:** Specialized materials and proprietary technologies often push costs beyond budget limits.
- **Sampling Inefficiency:** Inconsistent sample quality and difficulty in achieving precise sample collection further hinder operational effectiveness.

Proposed Improvements

To overcome these limitations, future solutions should focus on:

- **Enhanced Modularity:** Incorporating collapsible and interchangeable parts to improve portability and reduce environmental impact.
- **Improved Safety Features:** Implementing real-time feedback systems and automatic sealing mechanisms to enhance operator protection and process security.
- **Cost Efficiency:** Exploring alternative durable materials and simplifying mechanical and electronic components to reduce overall costs.
- **User-Friendly Design:** Ensuring the device is easy to operate with comprehensive training modules for efficient deployment.

By addressing these challenges, the proposed sampling device can provide a more practical, safe, and cost-effective solution that meets the client's operational needs.

4 Conclusions and Recommendations

Developing a pipe sampling device for Canadian Nuclear Laboratories (CNL) requires addressing key limitations found in current sampling methods, which often struggle with portability, safety, cost-efficiency, and sampling accuracy.

To tackle these challenges, the following recommendations are proposed:

- **Modular Design:** Introduce a collapsible, interchangeable component system to improve portability and allow for easier deployment in confined spaces.
- **Enhanced Safety:** Integrate real-time feedback systems to monitor operational status and incorporate automatic sealing mechanisms to securely contain samples upon extraction.
- **Cost Efficiency:** Utilize durable yet cost-effective materials and simplify both mechanical and electronic components to reduce expenses without sacrificing performance.
- **User-Friendly Operation:** Develop intuitive controls and provide thorough training materials to ensure operators can use the device effectively and safely.

By implementing these recommendations, the new sampling device will meet CNL's specific needs while setting a higher benchmark for safety, efficiency, and cost-effectiveness in high-risk environments.

5 Future Work

Moving forward with the development of the pipe sampling device requires a thorough approach that aligns with the client’s requirements and operational needs. The design will incorporate essential features to ensure both functionality and safety within nuclear facilities. Key focus areas include:

- **Prototype Development and Testing:** Build and evaluate a prototype under simulated operating conditions to identify design flaws and opportunities for improvement.
- **Material Selection:** Explore durable, radiation-resistant materials that balance performance with cost-effectiveness to ensure long-term reliability in nuclear environments.
- **Feedback System Integration:** Implement real-time monitoring features to provide operators with instant status updates, improving safety and efficiency.
- **Regulatory Compliance:** Ensure the device meets all industry standards and nuclear regulations to facilitate approval and seamless integration into operations.

By addressing these key areas, the project aims to deliver a reliable, easy-to-use, and fully compliant sampling device that meets the rigorous demands of nuclear energy applications.

6 References

1. Canadian Nuclear Safety Commission, “CANDU Reactor Systems Overview,” available at https://www.nuclearsafety.gc.ca, accessed January 2025.

2. CANTEACH, “CANDU 6 Technical Summary,” 2006, available at https://canteach.candu.org/Content%20Library/20044603.pdf, accessed January 2025.

3. International Atomic Energy Agency, “Sampling Procedures for Nuclear Materials,” IAEA Technical Reports, 2008, pp. 1-120. Available at https://www-pub.iaea.org/MTCD/Publications/PDF/te_626_web.pdf.

4. Berkeley Environmental, Health & Safety, “Radiation Safety Manual,” University of California, Berkeley, 2022, available at https://ehs.berkeley.edu/radiation-safety-manual, accessed January 2025.

5. U.S. Nuclear Regulatory Commission, “Regulatory Guide on Radiation Safety,” ML091671561, 2009, available at https://www.nrc.gov/docs/ML0916/ML091671561.pdf, accessed January 2025.

6. Department of Homeland Security, “Portable Radiation Air Samplers,” Technical Note 0910-508, 2010, available at https://www.dhs.gov/sites/default/files/publications/PortRadAirSamplers-TN_0910-508.pdf, accessed January 2025.