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Architecture and Components for the Remote Canister-Monitoring System

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ABSTRACT

This report documents the selected system architecture and components surveyed for the development of a remote canister-monitoring system (RCMS) for determining and monitoring environmental conditions within dry fuel storage canisters containing aluminum-clad spent nuclear fuel at Idaho National Laboratory's CPP-603 facility. These efforts are in support of the Department of Energy Office of Environmental Management investigations into the technical issues associated with extended dry storage (50+ years) of aluminum-clad spent nuclear fuel. It is important to resolve questions regarding storage because the Advanced Test Reactor (which is the majority of the ASNF inventory) is expected to continue producing approximately 100 elements of spent fuel per year for at least another twenty years. The parameters to be monitored by the RCMS include temperature, relative humidity, hydrogen gas concentration, and radiation environment (dose). Components for use in the RCMS are selected based on the expected environmental conditions within the canister and the CPP-603 fuel storage area and the desired performance of the RCMS. Several of these components have been purchased and are currently undergoing component testing to confirm their suitability and resilience for use in delivering the RCMS. Additional components may be identified through the course of design and may be selected in the future. Furthermore, changing performance, interfacing, and compatibility requirements and the results of component testing may necessitate revisiting component selection.

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ACRONYMS

ASNF	aluminum-clad spent nuclear fuel
CPP	Chemical Processing Plant
DOE-EM	Department of Energy Office of Environmental Management
INL	Idaho National Laboratory
RCMS	Remote Canister-Monitor System
RF	radio frequency

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Architecture and Components for the Remote Canister-Monitoring System

1. INTRODUCTION

This report provides an update on efforts to develop a remote canister-monitoring system (RCMS) for measuring environmental conditions in storage canisters holding aluminum-clad spent nuclear fuel (ASNF) at Idaho National Laboratory's (INL) CPP-603 facility. The purpose of this report is to formally document the technical considerations behind the choice of system architecture and components selected thus far.

The Department of Energy Office of Environmental Management is currently investigating technical issues associated with extended dry storage (50+ years) of ASNF (INL 2017). As part of these efforts, the RCMS was proposed as a means to collect real-time data of the environmental conditions in the canisters used for the dry storage of ASNF. This data could be used to further validate and verify the developed understanding that extended dry storage of ASNF is safe and viable (Eidelpes et. al, 2021) and to further improve the understanding on ASNF behavior during extended dry storage. The idea is to demonstrate the RCMS capabilities in a demonstration project at INL. The capability to establish and monitor the performance of ASNF in situ provides the opportunity to evaluate the appropriate technologies for monitoring, collect canister environment conditions as soon as possible, verify and validate current laboratory-based study results and analytic modeling approaches, and potentially identify additional or alternative dry storage options for ASNF at the INL site. To this end, the selected parameters to be monitored by the RCMS include temperature, relative humidity, hydrogen gas concentration, and radiation (dose).

Indeed, there has been a long-standing interest in measuring these parameters to better understand hydrogen generation from radiolysis from ASNF. Previous efforts from the 1999–2000 timeframe to measure these same parameters considered two system architectures. The first was to collect discrete gas samples from the fuel storage canisters to be returned to a laboratory for analysis. Due to complications with the sample scheme, this option was abandoned. The second was to develop an instrumentation package that could be installed on the canister lid to transmit the data by radio frequency (RF) to a data acquisition system. These efforts resulted in a mockup prototype of an integrated sensor system. The sensors and electronics were placed in a shielded compartment with a penetration in the lid to allow gas circulation and direct radiation monitoring. The prototype was capable of sensing temperature, relative humidity, hydrogen gas, and the radiation field using a miniature Geiger-Muller tube. Figure 1 shows the first prototype made in the 1999–2000 timeframe.

Through informal discussions with the Department of Energy Office of Environmental Management and operators of the CPP-603 facility where the ASNF is stored, a set of preliminary desired performance characteristics were compiled (Kitcher 2019). Table 1 shows a list of desired performance from the sensors in the RCMS. In addition to these sensors, additional components needed for the RCMS are a battery to power the RCMS, a data transmission capability via Wi-Fi or RF, and a radiation shield. The battery should be able to power the RCMS for a minimum of 1 year of autonomous operations, starting with weekly data transfers to establish a routine baseline. Current engineering judgement suggests that data collected over this time period will be sufficient to allow credible conclusions to be made. Continued data collection beyond this 1-year timeframe will be considered as need arises. After the baseline is established, the sampling rate could potentially be reduced to monthly data transfers. The radiation shield should reduce the dose rate and total dose to the sensors and electronics to allow operation for a minimum of 1 year without a degradation in performance. The data transmission capability should have a range of 600 ft without line-of-sight. This should allow transmission to an antenna within the fuel storage area. The data can then be transmitted via a wired connection out of the fuel storage area to the data acquisition/processing system. This list of desired performance characteristics is by no means complete and will be updated as additional desired performance characteristics are identified or design tradeoffs are encountered.

Figure 1. Early 2000s integrated sensor system prototype for monitoring environmental conditions in ASNF storage canisters.

Table 1. Desired performance of sensors for RCMS.

Parameter	Desired Measurable Range	Desired Measurement Accuracy	Comments
Dose (mrem/hr.)	0–2000	± 20 mrem/hr.	Collection of data at multiple points in canister is desirable
Temperature (°C)	-25–125	± 2°C	Collection of data at multiple points in canister is desirable
Relative humidity (%)	5–95	± 2%	Collection of data at multiple points in canister is desirable
Pressure (psia)	13–30	± 2 psia	Necessary for calibration of relative humidity and hydrogen concentration data
Hydrogen concentration (vol. %)	0–4	± 0.1%	Need to establish the minimum detectable limit to produce an alarm signal. Hydrogen concentrations below this will not detected.

The RCMS design discussions held to date resulted in the identification of three system architecture options for the RCMS. The first approach was to perform a technology update on the prototype developed in Fiscal Year 2000. This first approach would allow collection of point estimate data by measuring the conditions inside the headspace of the canister. This is achieved either by inserting the integrated sensor into the canister headspace or by actively pumping a sample of the headspace gas to the sensor for analysis. The second approach is to develop a wired sensor system that requires threading wired sensors into the canister fuel bucket geometry. This second approach would allow the acquisition of intra-canister, vertical axis, spatial information for the parameters of interest. The third approach is a passive system that would also acquire intra-canister, vertical axis, spatial information for the parameters of interest, without the need for a wired system. This would be achieved by inserting discrete sensor packages that communicate wirelessly with the control unit situated in the shielded compartment on top of the canister lid. Some parameters of interest such as pressure would be measured within the lid package. The passive system, if successful, could have benefits in terms of maintenance and operation within the storage facilities. Figure 2 shows a drawing of the three approaches (Option #1-#3 are Approaches 1-3). The green box is the electronics in the shielded compartment on top of the canister lid. The blue boxes indicate where sensors would be placed, and spatial information collected. Additional information on the identified approaches can be found in (Kitcher 2019).

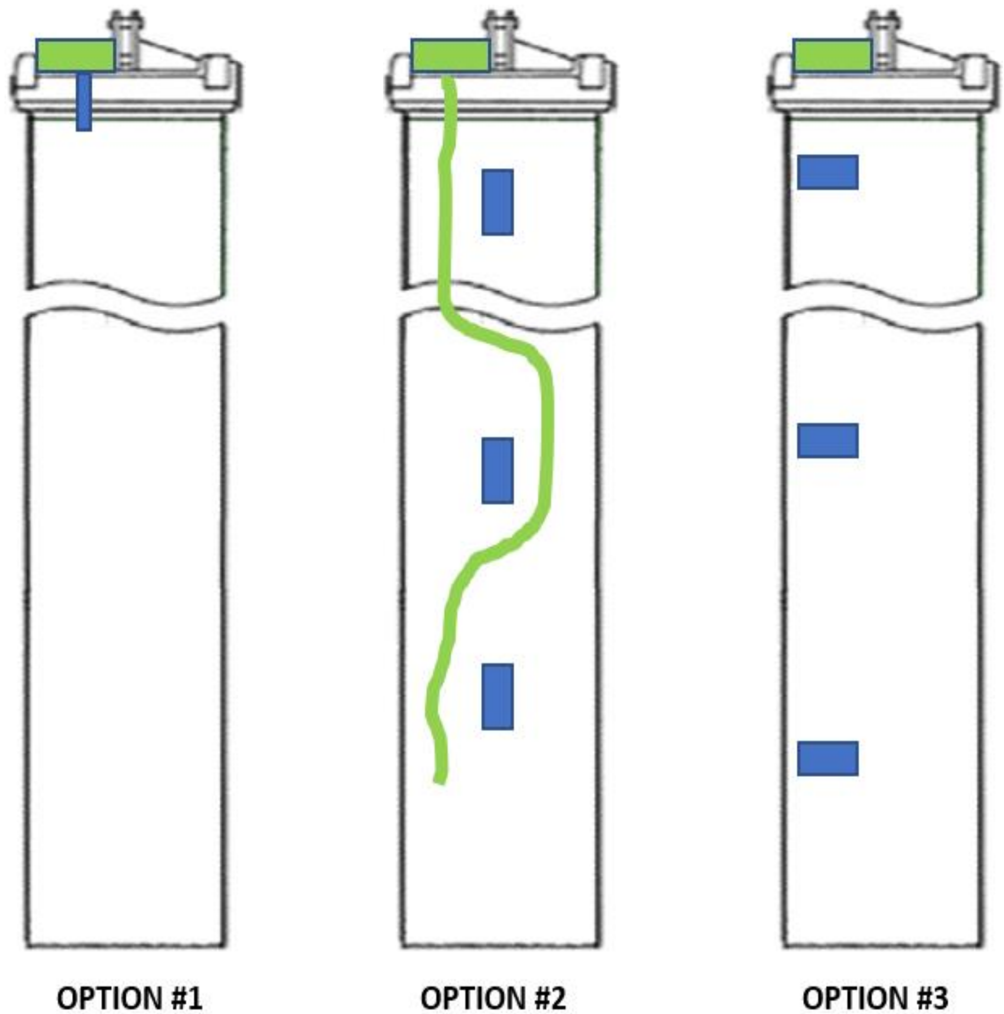

Figure 2. Identified design approaches for the RCMS (Option #1-#3 are Approaches 1-3).

2. FEASIBILITY STUDIES INTO RCMS ARCHITECTURE OPTIONS

Based on these options for RCMS system architecture, feasibility studies were performed to verify that the proposed approaches could be realized. The feasibility study into Approaches 1 and 2 were performed in collaboration with Idaho State University using components procured following a component selection process (Kitcher 2020). In general, several options were identified that meet the required performance characteristics for each component. Several commercially available integrated sensor units were found featuring integrated temperature, relative humidity, and hydrogen. These units also had a data transmission capability via Wi-Fi and some limited data storage and processing capabilities. Given that this represents a significant portion of the design effort, such a unit was selected as the core of the integrated system. Of the integrated sensor units, the offering from the N5 digital multi-gas sensor module was selected as it offers low power requirements and hydrogen concentration, temperature, and humidity sensing on a single chip. Figure 3 shows the N5 module. The integrated N5 sensor was evaluated for its capability to reliably measure temperature, relative humidity, and hydrogen concentration. In general, the performance of the N5 unit for temperature measurement for the integrated N5 unit was satisfactory. The N5 unit responded to relative humidity quickly, often within 30 seconds, but had difficulty with saturated conditions. Initial results from hydrogen testing were accurate within 10% of the reference value of the hydrogen concentrations introduced, but the N5 sensors were not able to reproduce this measurement after sustained testing. This was due to a combination of drift in the sensor response, spurious readings with no hydrogen present in the control volume, and mechanical failure of one of the N5 units tested. While it does not meet the requirement of measuring hydrogen concentration, the N5 sensor did detect hydrogen and prove feasible as a hydrogen detector for the RCMS. Thus, the results provided proof of concept for the approach but the N5 unit itself is not feasible as a component for the RCMS moving forward.

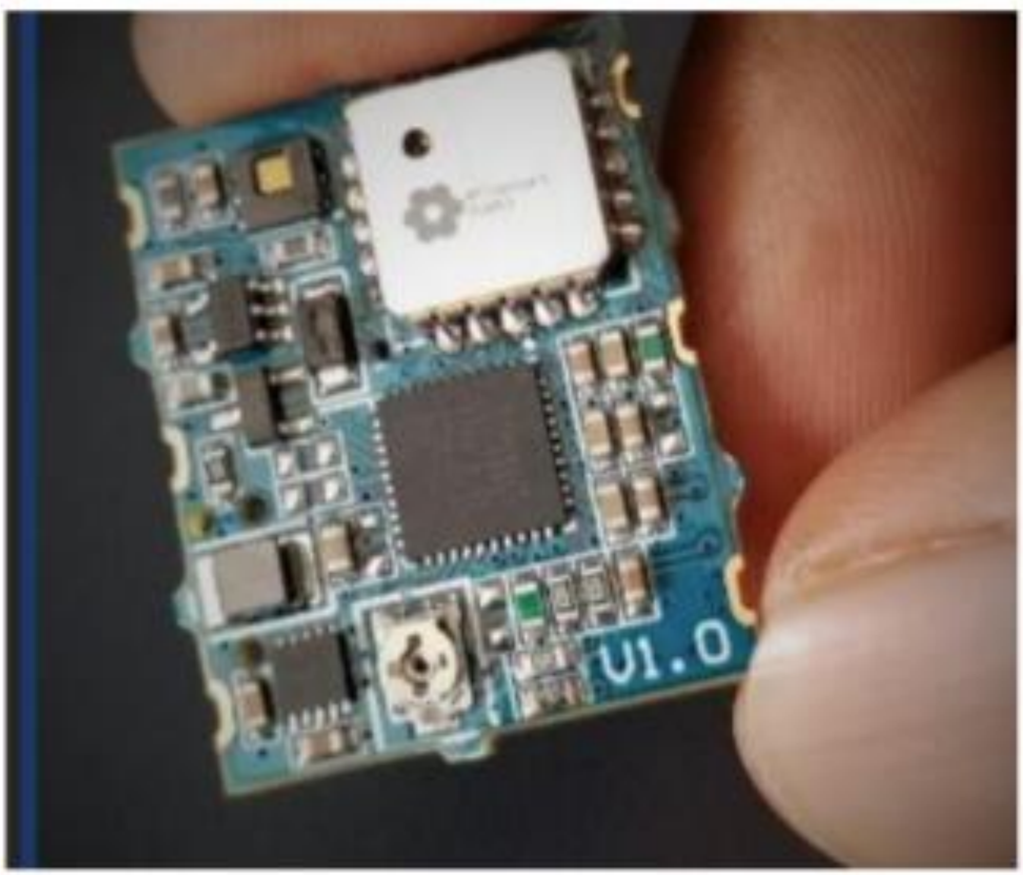

Figure 3. An image of the N5 digital gas module (taken from the N5 module product sheet).

The feasibility study into Approach 3 was performed through a subcontract to Westinghouse Electric Company LLC (Westinghouse). Westinghouse conducted the component selection, procurement, and testing. The lid system, for measuring hydrogen, pressure, and radiation, were modeled to fit within an enclosure to be deployed on top of the canister lid, as shown in Figure 4. This physical constraint facilitated the down-selection process of the sensors and electronics configuration options. Radiation tests of in-canister components confirmed that critical sensor (temperature and relative humidity sensors and associated circuits) and wireless transmission components (transmitters, receivers, and associated circuits) can operate while receiving a 1-year dose representative of that expected in a CPP-603 dry storage canister. Testing the in-canister sensors confirmed that these components can function as required in the temperature and humidity environment specified. Testing the wireless transmission of data from within the canister to the compartment on top of the canister lid showed that both the RF and acoustic methods were viable wireless transmission methods of sensor data within the canister and through metal obstacles. Radiation tests of several sets of AA batteries were under two different simulated loads showed that this battery source could also survive the expected 1-year dose. Thus, Approach 3 is the currently preferred RCMS architecture.

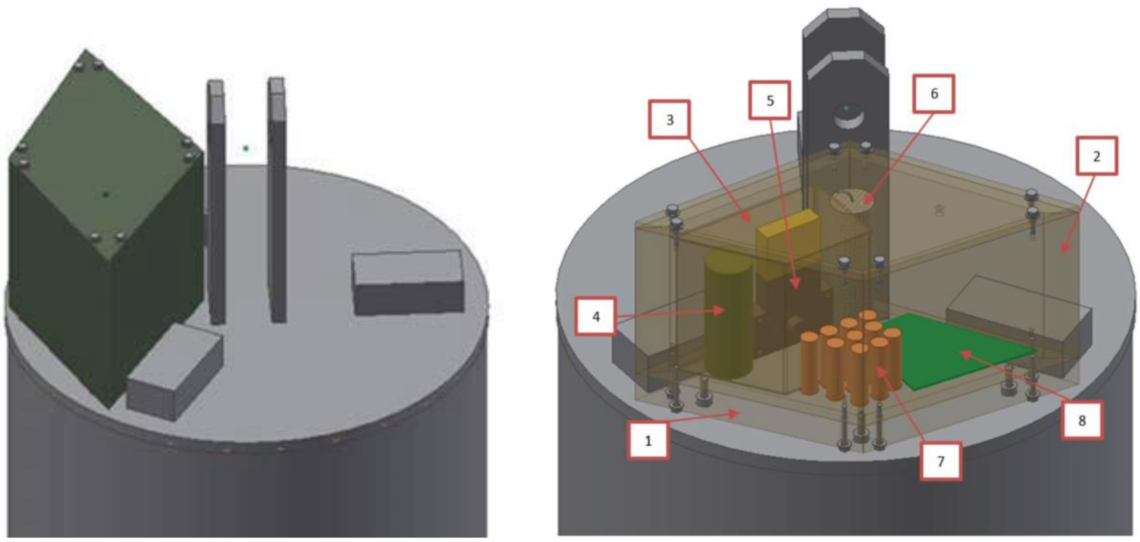

Figure 4. CAD model showing selected components within the shielded package geometry, 1) tungsten shield/base, 2) outer enclosure, 3) inner enclosure, 4) pressure sensor, 5) hydrogen sensor, 6) radiation sensor, 7) battery bank, and 8) printed circuit board.

3. ARCHITECTURE AND FUNCTIONALITY REQUIRED FOR APPROACH 3

The promising potential demonstrated by the feasibility study results support the continued effort into the development of an RCMS prototype in Fiscal Year 2022. As Approach 3 is the preferred approach, it will be pursued in collaboration with Westinghouse. The RCMS architecture for the implementation of Approach 3 can be best conceptualized as three interconnected subsystems: (i) the control room subsystem, (ii) the canister lid subsystem, and (iii) the in-canister subsystem.

i. The control room subsystem will be in the control room located adjacent to the storage area and will be the system that will receive and store the environmental data that is transmitted from the canister lid system.

ii. The canister lid system (represented by the green box in Figure 2 and modeled in Figure 4) is located on the top of the canister lid and houses a power delivery system, electronics for transmitting to the control room subsystem, electronics to receive from the in-canister system, and a sensor package for hydrogen concentration, radiation field, and pressure sensing.

iii. The in-canister system (represented by the blue boxes in Figure 2, Option 3) is a set of sensors inside the canister at different heights to detect spatial temperature and relative humidity data and send the data to the lid system via an RF or acoustic signal. At present, no decision regarding number or position (axially or radially) within the canister geometry has been made. The in-canister system will need to be powered and house its own individual transmitting electronics in each location. Figure 5 shows a clearer depiction of the selected RCMS system architecture.

A precise definition of the functionalities of these three subsystems is needed in order to allow appropriate selection of the components to be used in their implementation. Table 2 shows the RCMS subsystem functionalities that have been identified to date (based on the feasibility study) and lists components considered for meeting this functionality where available.

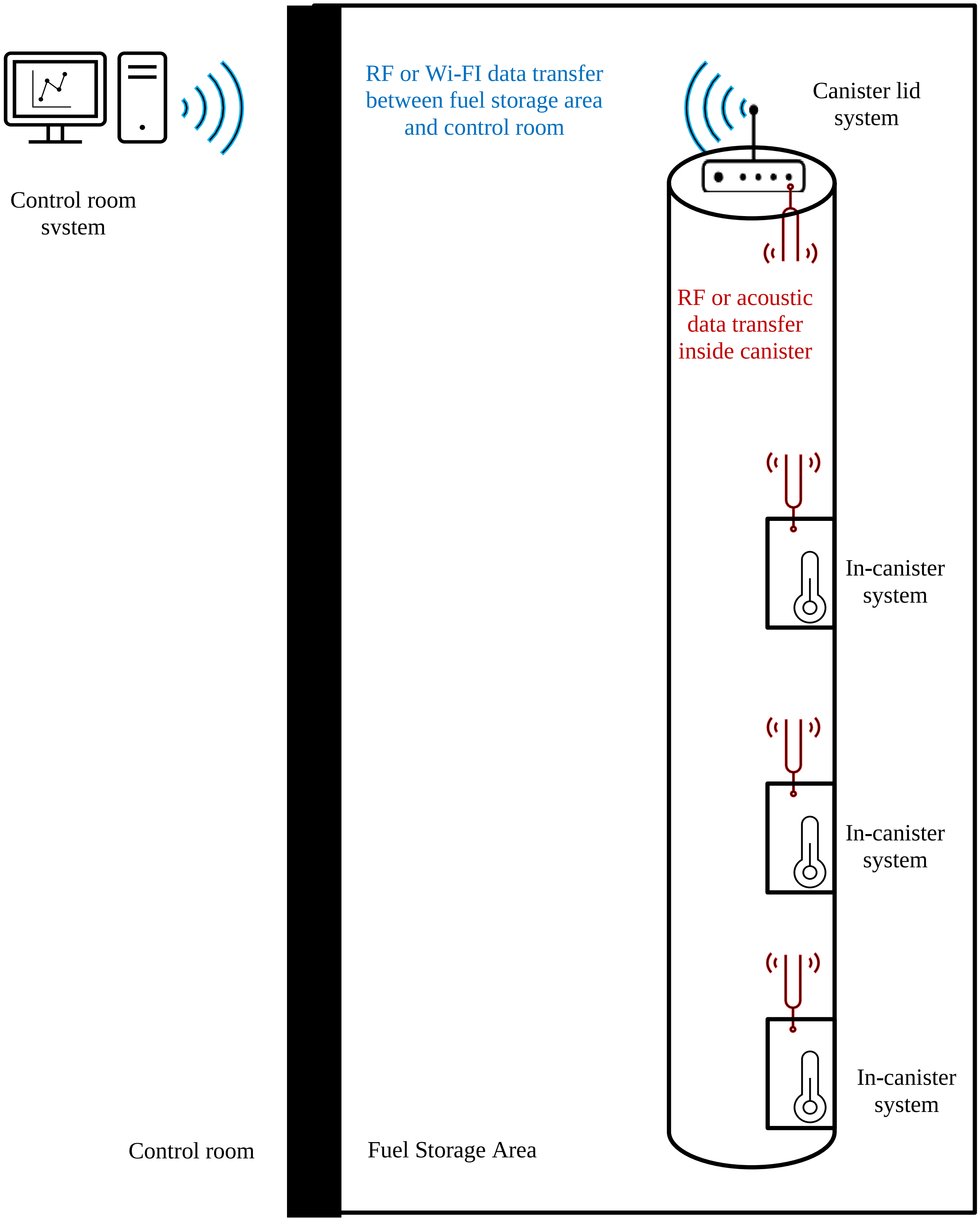

Figure 5. Selected RCMS architecture showing the control room, canister lid, and in-canister subsystems.

Table 2. Subsystem functionality of the RCMS and components considered.

RCMS Subsystem	Functionality	Components Considered
Control Room Subsystem	Receive data transfer from canister lid system	Computer with RF/Wi-Fi receiving capability and access to INL server
	Process data received from canister lid system	
	Display data received from canister lid system	
	Log data received	
Canister Lid Subsystem	Shield canister lid from radiation dose	Lightweight gamma shield material (e.g., tungsten)
	Measure hydrogen concentration	H2Sense Model 5100, Monnit Alta Integrated Package, NevadaNano MPS Flammable Gas Sensor, SGX Sensortech Catalytic Combustible Gas Sensor
	Measure radiation field	Radiation sensor
	Receive temperature data from multiple in-canister systems	RF or acoustic receiver
	Transmit data to control room subsystem	RF or Wi-Fi transmitter
	Power for canister lid system components	AA batteries
	Control sampling frequency	TBD
	Attach to canister lid	TBD
In-Canister Subsystem	Measure temperature data	Custom resonant frequency-based temperature sensor
	Transmit temperature data to canister lid system	RF or acoustic transmitter
	Power for in-canister lid system	TBD
	Shield in-canister components from radiation field	TBD
	Attach in-canister system to fuel basket or canister	TBD

4. COMPONENT SELECTION

Additional design principles for the RCMS that have not yet been stated as requirements include low cost, small size of the lid and in-canister systems due to space limitations both on the canister lid and within the canister geometry , minimizing weight of package, low power consumption, and acceptability for deployment in the CPP-603 facility. In general, several options were identified that meet the required performance characteristics for each component. Additional components may be identified through the course of the design and may be selected in the future. Furthermore, changing performance, interfacing, and compatibility requirements and the results of component testing may necessitate revisiting component selection.

4.1 Pressure Sensors

Pressure measurements are needed to appropriately calibrate the hydrogen concentration and humidity readings. There are a multitude of industrial pressure sensors available on the market; however, there are very few qualified to be radiation resistant. Radiation resistant pressure sensors are expensive, therefore traditional industrial pressure sensors were investigated to keep costs as low as possible. A commercially available industrial pressure sensor is shown in Figure 6. The selected sensor, MKS Instruments PN 722B13TGA2FA, is desirable because it is industrial grade, low power, and sized appropriately for the canister lid. The output of the sensor is 0–10 volts of direct current, which can easily be converted to a digital signal and transmitted wirelessly. The pressure sensor must be shielded from ionizing radiation to ensure reliable long-term performance. The associated pressure sensor electronics that capture and digitize the sensor signal also must be shielded.

Figure 6. The MKS Instruments PN 722B13TGA2FA pressure sensor is an example of commercially available pressure sensors.

4.2 Hydrogen Sensor

The selection process for choosing a hydrogen gas concentration sensor consisted of a literature survey of commercially available and custom hydrogen sensors that meet the performance requirements and design constraints of the RCMS. The exploration included technologies developed for, and deployed, in nuclear power as well as other industries. The survey included both hydrogen sensors with integrated wireless capabilities and those that were standalone with standard wired voltage or current outputs. Both options offer advantages and disadvantages. Integrated modules are expected to be more susceptible to radiation damage but could simplify integration of the electronics. Standalone units are expected to be less susceptible but add complexity with respect to the wireless transmission of data from the multiple different sensors. Table 3 shows a list of sensors surveyed and their key features.

Table 3. Hydrogen sensors surveyed.

Sensor	Key features
H2Sense Model 5100	Expected to have good radiation resistance
Monnit Alta Integrated Package PN MNS2-9-W2-GS-C1, Sensor PN 3SPCO1000F (electrochemical sensor)	Extremely low power requirements Projected 10+ years in non-rad environment Integrated temperature measurement and Wi-Fi capability
NevadaNano MPS Flammable Gas Sensor	Measure temperature, pressure, humidity, and a number of flammable gasses, including hydrogen Reported long lifetime and no need for calibration
SGX Sensortech VQ548MP-DA MEM's Catalytic Combustible Gas Sensor	Expected to have good radiation resistance Extremely low power requirements

4.3 Radiation Sensor

Many radiation detection systems were evaluated. The primary detection device is a Geiger-Muller tube powered by a battery-operated radiation meter. The Mirion GMP-12SD and RDS-31 devices, respectively form a commercially available integrated system that is controlled by an external computer, with the computer and the radiation meter communicating via an RF signal. A Geiger-Muller tube was selected for the radiation measurement since only the magnitude of ionizing radiation is required. The content of the radiation (i.e., gamma, x-ray, alpha, and beta) is not required. Additionally, neutrons cannot be monitored with this device. The battery for this example system specifically operates for four months without having to be recharged or replaced, and the system runs on two AA batteries. This estimate was calculated assuming daily usage of eight hours per day. Given these power requirements, periodic measurements over a two-year period will be achievable with this or a similar device.

5. CONCLUSION

The RCMS being developed if successful will provide the capability to determine and monitor environmental conditions inside storage containers where ASNF are currently stored. The environmental parameters of interest include temperature, relative humidity, hydrogen gas concentration, and radiation dose. Through literature study of previous efforts and feasibility studies, a RCMS system architected has been selected. The architecture of the selected system consists of three subsystems: the control room subsystem (i.e., Wi-Fi receiver and DAQ), the canister lid subsystem (battery, Wi-Fi transmitter, RF or acoustic signal receiver, hydrogen sensor, pressure sensor, radiation sensor) and the in-canister subsystem (battery, RH sensor, temp sensor, including RF or acoustic transmitter. Using the established performance requirements, and feasibility study results, several commercially available components for performing the key functionalities of the RCMS have been identified.

FY-22 activities include the development of functions and operation requirements to allow for deploying the RCMS in CPP-603. The engineering and design work will be conducted in collaboration with Westinghouse. The plan is procuring a RCMS prototype and to test it extensively. The component selection described in this report will become the starting point for purchasing and incorporating the required components into this prototype. Additional components may be identified through the course of design and may be selected in the future. Furthermore, changing performance, interfacing, and compatibility requirements and the results of component testing may necessitate revisiting component selection.

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