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Roadmap for the Completion of the Design and Implementation of a Remote Canister Monitoring System

December 2021

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ABSTRACT

The Office of Environmental Management within the Department of Energy is currently investigating technical issues associated with extended dry storage (50+ years) of aluminum spent nuclear fuel. As part of these efforts, a remote canister-monitoring system (RCMS) has been proposed to collect the real-time data of the environmental conditions in the canisters used for the dry storage of aluminum spent nuclear fuel in the Chemical Processing Plant 603 facility at Idaho National Laboratory. The proposed RCMS would provide the opportunity to evaluate the appropriate technologies for monitoring, to collect canister environment conditions as soon as possible, to verify and validate current laboratory-based study results and analytic modeling approaches, and to potentially identify additional dry storage options for aluminum spent nuclear fuel at the Idaho National Laboratory Site. The document provides a brief update on the progress that has been made toward deploying the RCMS and will present, at a high level, the general system design philosophy behind the project and the key future tasks necessary for the completion of the RCMS system design, fabrication of the RCMS prototype, testing and eventual deployment of the RCMS, and a tentative timeline for these tasks.

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FIGURES

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ACRONYMS

ASNF	aluminum-clad spent nuclear fuel
CPP	Chemical Processing Plant
ConOps	Concept of Operations
DOE-EM	Department of Energy Office of Environmental Management
IFSF	Irradiated Fuel Storage Facility
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering
ISU	Idaho State University
RCMS	Remote Canister-Monitor System
RF	radio frequency
UFM	Used Fuel Management

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1. INTRODUCTION

The purpose of this roadmap document is to formally describe the system design process and associated implementation plan that will be used to deliver a successful Remote Canister Monitoring System (RCMS) for the collection of environmental data inside aluminum-clad spent nuclear fuel (ASNF) dry storage canisters during extended (>50 years) storage.

The development of the RCMS is currently ongoing. Thus, the document provides a brief update on the progress that has been made to date and presents, at a high level, the general system design philosophy. Further, it summarizes the key future tasks necessary for the completion of the RCMS system design, fabrication and testing of the RCMS prototype, and eventual deployment of the RCMS. Furthermore, a tentative timeline for the outstanding tasks is provided.

RCMS design is part of a broad range activities to aid the Department of Energy Office of Environmental Management (DOE-EM) with understanding the technical issues associated with extended dry storage (>50 years) of ASNF. (INL 2017) The RCMS is planned to be installed on ASNF dry storage canisters in the CPP-603 Irradiated Fuel Storage Facility (IFSF) at the Idaho Nuclear Technology and Engineering Center (INTEC). The primary challenge involving extended dry storage of ASNF centers around the behavior of hydrated-oxide, or (oxy)hydroxides corrosion layers—specifically, the radiolytic breakdown of adsorbed and chemically bound water in these corrosion products. This breakdown yields chemical species such as hydrogen gas (H_2). The proposed RCMS roadmap would allow for continuation of evaluating the appropriate technologies for CPP-603 dry storage monitoring via collection of data on canister environment conditions, to verify and validate current laboratory-based study results and analytic modeling approaches, and to potentially identify additional dry storage options for ASNF at the INL Site. (Kitcher 2019) Kitcher 2019 Section 2.2 also contains additional information on the IFSF, fuel and the ASNF Dry Fuel Storage Canisters.

Previous efforts conducted in the 1999-2000 timeframe aimed at gathering such details resulted in a mockup of a system that could be used to gather in-canister environmental data. Figure 1 shows a picture of this design. The design was focused on development of a remote wireless instrumentation package to be deployed on the canister lid with penetrations to allow access to the canister cavity. Key parameters of interest included hydrogen concentration as an indication of the degree of ASNF corrosion or hydrolysis occurring, relative humidity as an indication of the effective dryness of the environment, temperature to help understand its effect on hydrogen generation from radiolysis and the rate of corrosion, and the radiation field, also to help understanding its effect on hydrogen generation from radiolysis and the rate of corrosion. These key parameters were to be measured by commercially available "off-the-shelf" technology where possible. The sensor package would house the necessary detectors and associated electronics and would be deployed on the ASNF canister lid in the CPP-603. Figure 2 shows a picture of the top of the fuel storage area inside CPP-603. The sensor package is intended to be positioned on top of one of the canisters shown. It is unclear why this effort was discontinued.

Figure 1. The initial integrated sensor system prototype was fabricated in 2000 and designed to measure hydrogen, relative humidity, and temperature in a CPP-603 storage canister

Figure 2. The tops of fuel storage canisters inside the CPP-603 fuel storage area rack

2. OVERVIEW OF DESIGN AND IMPLEMENTATION PROCESS

In the RCMS design process it is necessary to ensure that the needs, goals, and objectives of the system being developed are properly defined and that the solution produced meets these needs, goals and objectives with minimal need for rework. Critical steps in this process include soliciting input from stakeholders, understanding the desired behavior of the envisioned system, codifying performance objectives in requirements, and performing a logical decomposition of the necessary functions of the system before proceeding into the design solution definition. Figure 3 shows the iterative nature of a successful novel system design process, as generically outlined by the National Aeronautics and Space Administration (NASA). (NASA, 2016) There are multiple variations to the engineering design process, the NASA process was chosen due to familiarity with this version of the engineering design process. To date, this process has not been explicitly implemented in the RCMS development activities, but the plan is to use this process to formalize the execution of the RCMS development in the future.

In addition to the needs, goals and objectives, the solicitation of stakeholders should also produce clearly defined system constraints and success criteria. These are used to iteratively develop a concept of operations (ConOps, see Figure 3) document that clear defines what the system needs to do and how well these functions must be performed. Ideally, the concept of operations should be free of distinctive system definitions unless the incorporation of existing systems is part of the needs expressed by the stakeholders. The concept of operations should include all scenarios that envelop the “normal” use of the system and any significant “off-normal” scenarios under which the system may be required to perform.

Next, the requirements of the system must be established. These requirements should include functional, performance, interface, operational, safety and other relevant requirements. Each requirement should be unambiguous, precise, quantifiable, feasible, independent, and necessary for the system to meet the specified need. In addition, the set of requirements should be complete and non-redundant. The developed set of requirements is checked for inconsistencies in an iterative process.

After validation that the requirements align with the ConOps, a logical decomposition of the requirements set is executed to inform the system architecture selection and be used to guide the conceptual design of the solution.

Lastly, a conceptual design process will translate the defined set of requirements and the ConOps into a design solution consistent with the system architecture selected through the logical decomposition process. Conceptual design often produces several solution alternatives, from which a preferred solution is identified by considering the relevant trade-offs between alternatives. Once the conceptual design has been completed, reviewed, and approved, a system design description can be issued (not displayed in Figure 3) and used to initiate the preliminary and final design (i.e., the process realization process, see Figure 3).

The objective of the NASA system design process is to ensure that the design solution is developed and implemented in a way that meets the requirements specified in the final design and that the final product meets the needs goals and objectives of the stakeholders and functions according to the envisioned concept of operations. Product implementation includes the procurement, fabrication, assembly, installation, integration, verification and validation of the system, and transition to operations for deployment.

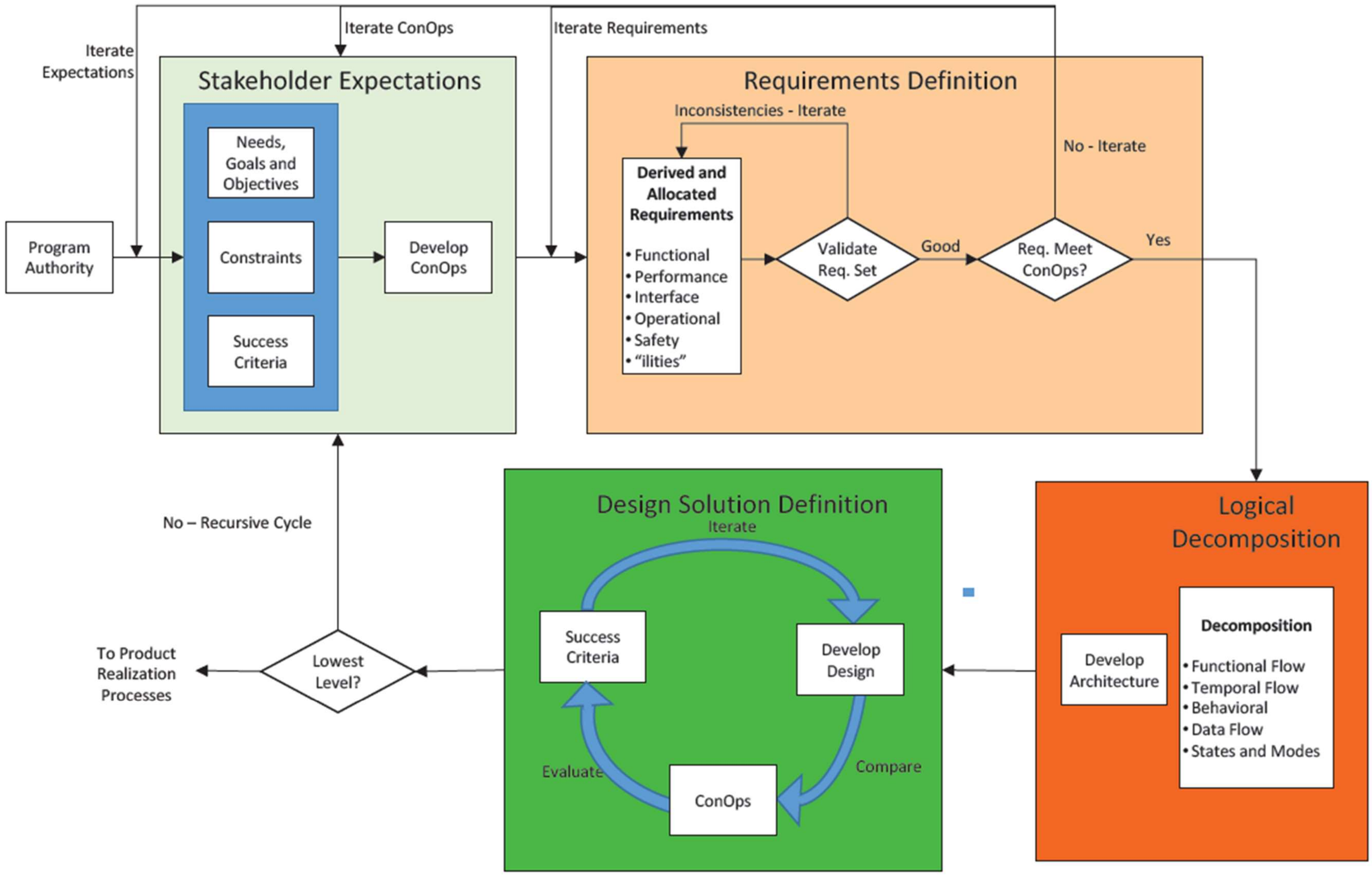

Figure 3. Interrelationships among the system design processes (Reproduced from [Hirshorn, Voss, and Bromley 2016].)

3. COMPLETED RCMS SYSTEM DESIGN EFFORTS

To date, the system design process outlined in Figure 3 has not been implemented, and the RCMS development was limited to selected components of the process. For instance, there has been limited, informal stakeholder identification and engagement. The current list of direct stakeholders for the RCMS are DOE-EM as the relevant program authority, INL as the owners of the design, Westinghouse Electric LLC (Westinghouse) as a key subcontractor and the CPP-603 facility operators as a key indirect stakeholder. DOE-EM is interested in the behavior of ASNF as it ages and the factors influencing its condition in extended storage. Westinghouse and Idaho State University (ISU) performed feasibility studies included later in this section. There have been limited initial discussions with the CPP-603 facility operator, but no formal documentation has been provided to the facility owner, i.e., the Department of Energy (DOE). Other potential stakeholders that will be solicited moving forward are other researchers tasked with addressing issues associated with the extended dry storage of ASNF and other relevant organizations at INL when identified.

3.1 System Requirements

Notable 2019 efforts in the RCMS development process (Kitcher 2019) identified preliminary performance requirements and sizing constraints for the RCMS and how it could be mounted on the top of the canister. The RCMS was envisioned as a discrete, remote, integrated sensor system that could measure hydrogen, relative humidity, temperature, and radiation (dose) with the following desired performance characteristics:

1. One to two years of autonomous operations starting with weekly data transfers to establish routine baseline. After the baseline is established, the sampling rate could potentially be reduced to monthly data transfers.
2. Measure temperature over the range of -20–100°C with a 1°C accuracy. A system capable of gathering spatial information is preferred.
3. Measure relative humidity over the range of 0 – 95 % relative humidity with an accuracy of 5–10%. A system capable of gathering spatial information is preferred.
4. Measure hydrogen gas concentration over the range of 0 – 4% concentration with 1% of the reading accuracy. A system capable of gathering spatial information is preferred.
5. Measure the radiation field within the canister over the range of 0–500R/hr with an accuracy of 1 R/hr.
6. Radiation control to be achieved using shielding.
7. Package does not have to be hermetically sealed. The RCMS is not expected to operate in a radiation contaminated area, so a seal is not needed to preclude contamination.
8. Data transmission range of 100ft without a line of sight. This will be achieved with Wi-Fi or radio frequency (RF) transmission.
9. Package should survive shock of a 2-ft drop on a concrete floor.
10. All processes and data sampling routines should be pre-programmed. There is no requirement for the dynamic changing of processes.
11. The RCMS should be battery powered.
12. The data acquisition system should handle simple Wi-Fi of RF with multiple packages without interference. Data should be collected and stored with a simple data analysis such as graphical

representation and simple statistics (such as the mean, standard deviation, maximum and minimum values).

3.2 Approaches

The developed requirements, in combination with studying the results of the previous efforts in the 1999-2000 timeframe, resulted in the identification of three options for the RCMS architecture hereby referred to as design approaches. The identified approaches considered previous design documents, scoping discussions with the facility operators and prospective vendors, and key challenges that eliminated other proposed approaches. Detailed in FY19 Status Update. (Kitcher 2019).

The first approach includes a technology update on an existing prototype developed in the early 2000's (see Figure 1). The second approach includes the development of a wired system that requires the threading of wired sensors into the canister geometry and acquires spatial data. The third approach consists of a passive system that would acquire spatial information without the complications of wiring the canister. (Kitcher 2019) Figure 4 shows a depiction of the three approaches.

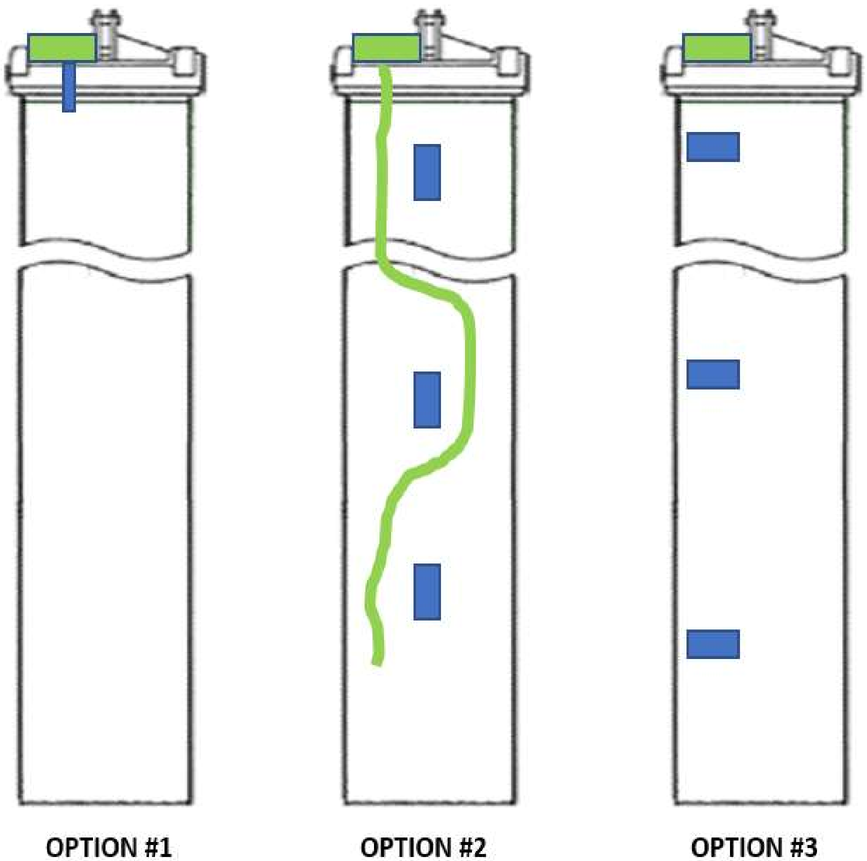

Figure 4. Identified design approaches for the RCMS.

Feasibility studies into the three approaches were performed in FY-20 and FY-21. (Fanning and Kitcher, 2021) The feasibility studies into Approaches 1 and 2 were conducted in collaboration with ISU. The results showed that the lid approach (#1) and the wired approach (#2) were viable as temperature, relative humidity, and hydrogen concentration data were successfully collected and transmitted using a closed Wi-Fi network. The environmental conditions expected in the canister were simulated inside a fabricated control test volume and measured with the components of approach 1 and 2, however, hydrogen testing was not completed due to the failure of all three purchased integrated sensor systems and intermittent spurious hydrogen detection. The durability and commercial reliability of components should be given increased priority in future work.

The feasibility of Approach 3 was investigated by Westinghouse in FY20. Westinghouse performed radiation and temperature sensitivity component testing. Radiation testing of the components to be located inside of the canister (referred to as the "in-canister" components) confirmed that critical sensor and wireless transmission components can operate while receiving an expected 1-year radiological dose originating from the ASNF stored in the canister. The temperature and humidity test of in-canister components confirmed that components can function as required in the specified temperature and humidity environments. The wireless transmission test within the canister showed that both the RF and acoustic methods were viable wireless transmission methods of sensor data within the canister and through metal obstacles.

The study of Approach 3 as well as the complications with Approaches 1 and 2 confirmed that Approach 3 is the preferred method. The hydrogen sensor calibration issues encountered in the studies conducted in collaboration with ISU was communicated to Westinghouse and continued development of the Westinghouse design has been pursued in FY-21 and is currently ongoing. (Fanning and Kitcher 2021) All results to date indicate a promising potential of the technology of Approach 3 and suggest continuations of research and development efforts using this technology in FY-22.

The recently ongoing work has been focused on developing a prototype design that includes mitigating the hydrogen sensing issues that occurred previously in testing Approaches 1 and 2, modal testing of the wireless transmission methods (Approach 3) and mocking up the top third of a dry storage canister by the end of current Westinghouse contract. Specifically, the wireless transmission testing is a continuation of the feasibility analysis of the acoustic and RF methods from the FY-20 Westinghouse feasibility report. Westinghouse successfully mounted wireless transmitters and receivers on the FY-20 mockup (Figure 5) and determined a range of frequencies that are preferable to allow for reliable data transmission within the structure of the mockup. This mockup was utilized to test radio frequency (RF) and acoustical methods of wireless data transfer from within the canister. Both methods were successful, but Westinghouse continued sensitivity testing in the FY-21 contract to better understand the advantages and disadvantages of both methods. By the FY-21 mid-term report, acoustical methods were showing slightly more favorable results, preliminary hydrogen testing have been performed and will continue to be pursued. A down selection of the hydrogen sensors evaluated will be achieved by the end of the FY-21 work.

Figure 5. Canister with RF and acoustic transmitter (right side) and receiver inserted (left side).

The current Westinghouse contract will complete testing other hydrogen sensors, complete the acoustic modal analysis, test the transmission of simulated temperature and humidity data through the canister mockup, and start irradiation testing of selected components. Work was delayed due to contract procurement discussions and was agreed upon to extend into FY22 and complete in December 2021.

3.3 Initial RCMS Architecture

Independent of the chosen approach, the selected system architecture for the RCMS is comprised of three subsystems: the lid system, the in-canister system, and the control room system. The canister lid system (represented by the green box in Figure 4) houses a power delivery system, electronics for transmitting to the control room system, electronics to receive from the in-canister system, and a sensor package for hydrogen sensing. This lid system is located on the top of the canister lid and will use only 1/3 of the area on top of the lid due to lid numeration and locking mechanisms. The in-canister system (represented by the blue boxes in Figure 4, Option 3) is a set of multiple sensors inside the canister at different heights to detect spatial temperature and relative humidity data and send the data to the lid system. The in-canister system will need to be powered and house its own individual transmitting electronics in each location. The control room system will be in the control room located adjacent to the storage area and will receive and store the environmental data transmitted from the canister lid system.

4. ROADMAP TO RCMS COMPLETION

To achieve a deployable, final design there are several decisions still to be made on the systems and their interfaces with the environment they will be in. Some of these design developments include

- final component selection for each of the different systems,
- selection of the most appropriate location for the in-canister systems,
- selection of the in-canister system and canister lid system attachment methods,
- canister system maintenance and eventual disposal,
- which canister will be chosen for the RCMS to be installed,
- shielding configuration to protect the systems from radiation fields.

To abide by the design process outlined in section 2, stakeholder input is required to inform development of these system requirements. In addition to the reports produced so far, this roadmap document will be used to engage with the identified stakeholders to formally document the needs, goals, objectives, constraints, and success criteria for the RCMS and to assist in identifying other stakeholders.

Once the needs, goals, objectives, constraints, and success criteria are defined, a formal documentation of the requirements will be produced. Regular meetings will ensure stakeholders are informed of the design progression through reporting and allow for system requirement input as described by Figure 3 in an iterative process. For example, it is expected that CPP-603 facility requirements will provide guidance on the materials that are allowed inside the fuel storage area. Furthermore, requirements for the interfaces between the RCMS and the existing CPP-603 systems will need to be established (e.g., between the ASNF fuel loading systems, the ASNF itself, and the RCMS lid and in-canister systems. The location of the in-canister system could impact the materials used to enclose and protect the system from irradiation and ensure there is no significant interaction between the RCMS and the fuel inside the canister. The consideration of the in-canister system interacting with the fuel warrants reaching out to the party responsible for the safety of the fuel itself, making them indirect stakeholders. The operation of the RCMS will need to be within the operational envelop of the CPP-603 facility or may necessitate a modification of the relevant safety documentation. It is also pertinent to consider on which canister the RCMS will be installed as this affects the source term for shielding calculations as well as the ability to load onto a clean canister or during canister loading operations. These considerations are all iterations to be included in the ConOps document, see section 2.

Furthermore, the design must be formalized with a clear definition of the important system requirements: systems necessary for the successful gathering of data, the physical location of the systems, system components, and materials used for the shielding, housing, and attaching of the systems in their respective locations. An informal evaluation of the environment in which the RCMS is intended to operate has determined that there will be considerable radiation fields as well as increased temperatures. These are being considered in the current prototyping efforts; Westinghouse has tested several components in their hot cell and plans to continue radiation testing components. Because the exact radiation field strength inside the canister is unknown, it is assumed that the in-canister components will need shielding to protect them from some level of radiation which will vary the type and thickness of shielding located on the housing for the canister lid system and in-canister system components. A formalized environmental analysis would aid the determination of the shielding thicknesses for the RCMS.

The life-cycle processes of the RCMS will be considered in the Logical Decomposition phase. It is possible that maintenance will be required for the RCMS after a period of data gathering. The disposal of the RCMS after enough data is gathered will also need evaluation and input from the CPP-603 facility.

As with any design effort, it is expected that the described process will be iterative with periodic reviews to allow stakeholders to provide feedback. Procurement for the fabrication of the conceptual design should begin when comments from stakeholders are incorporated or mitigated following the presentation of the conceptual design. At this point a prototype of the conceptual design RCMS will then be fabricated and tested. This prototype may not necessarily meet all the requirements necessary for deployment inside CPP-603 but should be as close as possible to the intended design to allow meaningful testing.

The conceptual CPP-603 dry storage canister mockup is intended to provide the necessary platform in which to test the system installation onto a canister, how the shielding may affect the wireless transmission, how robust the system is (drop test), and any other tests determined to be needed for developing the final design. (Design Solutions Definition) Multiple RCMS mockups should be procured for testing purposes. After testing the conceptual design, reporting of the results will allow for the engagement of the stakeholders and integration of the knowledge gained from testing and reporting the results. This may require the repetition of previous design steps to select components and verify their efficacy.

Lastly, the final design will incorporate NQA-1 standards to produce an RCMS robust enough and within the constraints provided by the CPP-603 facility. The final design will then be formally documented, reviewed and reported to the stakeholders.

In parallel to the RCMS design process, readiness of the CPP-603 facility to receive and deploy the RCMS will be evaluated. This evaluation will be initiated at the same time as procurement of the final design fabrication, and will need to consider creating administrative procedures, modifications to the CPP-603 safety documentation for the RCMS, new procedures for the deployment and operation of the RCMS at the facility, and training of the facility operators to deploy and operate the RCMS. This is not an all-inclusive list but is meant to provide a starting point to gain an understanding of the breadth of issues that should be considered. Once readiness is established, the RCMS can then be fabricated as necessary for actual deployment and operation inside CPP-603.

4.1 Product Realization Process

After completion of the design, the RCMS prototype will then be fabricated. Fabrication will be done using the INL procurement process that is based on identifying the appropriate vendors who can fabricate the component as per the design drawings associated system and quality level requirements. Once appropriate vendors are identified and procurement takes place, the final design will be fabricated and sent to the CPP-603 facility. It will undergo various inspections and tests by the facility to verify that the instrumentation is correct and operable, and that the material is of sufficient quality and history and to ensure it is ready for installation on the ASNF canister. The systems will then be installed on the canister lid and inside the canister, then checked for operability and transmission to the control room system. After installation, the ASNF canister will be certified by the CPP-603 facility and the fuel owners to the previously set requirement definitions. The canister will then be loaded with fuel and emplaced in the IFSF to begin data collection.

5. TENTATIVE TIMELINE

This section is a proposed timeline for transitioning from the current pre-conceptual design phase of the RCMS to the final design and deploying the RCMS final design in the CPP-603 facility.

FY-22

- Identify direct and indirect stakeholders
- Generate ConOps document for the RCMS
- Set Requirement Definitions through discussions with stakeholders.
  - Westinghouse to complete contract and provide information necessary to architecture design
  - INL to determine the location of the in-canister sensors
  - INL and CPP-603 facility to collaborate on the facility requirements and NQA-1 standards to incorporate into the design
  - Iterate requirements as necessary
- Formalize the conceptual design and report (Logical Decomposition from Figure 3 would begin here)
  - Incorporate stakeholder feedback
- Determine options for open bid fabrication of conceptual design
- Inquire bids for fabricating the conceptual design (multiples)

FY-23

- Perform testing on the fabricated conceptual design (drop, operability, spatial and wireless data acquisition) at INL (Design Solution Definition)
- Collaborate between INL and the CPP-603 facility on standards and processes necessary to deploy the final design and necessary ASNF canister loading operations
- Finalize the design by incorporation of NQA-1 standards and information gained from the testing of the conceptual design
- Determine cost estimate and bidding options for the final design. (Product Realization Process from Figure 3 would begin here)

FY-24

- Collaborate between INL and the CPP-603 facility for the facility readiness to receive the RCMS and install the RCMS.
- Bid, fabricate, and transport the final design to the CPP-603 facility.

FY-25

- Install RCMS on the ASNF canister
- Perform all operational tests, inspections, certifications prior to ASNF loading operations.
- Load the ASNF canister with fuel and transfer to the IFSF.
- Begin collecting data.

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