EVOLUTION OF THE ARC-100 REACTOR BUILDING DESIGN

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Abstract

The inaugural ARC-100 small modular reactor is planned to be built at the Point Lepreau site in Maces Bay, New Brunswick. This demonstration unit will be a first-of-a-kind commercial application, with subsequent units also planned for this site. Throughout the CNSC Vendor Design Review (VDR) process, the ARC-100 Reactor Building (RB) design has been modified to achieve cost and schedule savings. ARC's design vendors have studied the most efficient means of reactor building construction, providing significant reductions in construction schedule time. This is achieved through applying construction techniques such as the Vertical Sinking Shaft Machine (VSM) into the erection of the ARC-100 RB and incorporating modular construction when viable. Additionally, design decisions for the reactor building itself have dramatically reduced the amount of safety-related concrete required, while providing better pressure retaining capability. This paper will explore the details of ARC's reactor building and plant design, and how it has evolved to minimize schedule and cost implications.

1. Introduction

The ARC-100 is a Generation IV 100 MWe Sodium-Cooled Fast Reactor (SFR). The ARC-100 is based upon Advanced Reactor Concepts LLC (ARC) and GE-Hitachi Nuclear Energy (GEH) reactor technology that also leverages the proven sodium-cooled fast reactor technology developed by the US Government Department of Energy, which includes the EBR-II reactor that operated successfully for thirty years. This advanced small modular reactor combines the experience from sodium-cooled fast reactors with modern design improvements to meet industry and public expectations for nuclear power generation for a net-zero economy [1].

The ARC-100 reactor is currently in the CNSC Vendor Design Review (VDR) Phase 2 of pre-licencing activities with plans for a first-of-a-kind commercial demonstration unit to be built at the Point Lepreau site following a successful License to Construct application. VDR is a voluntary, pre-licensing process which consists of the submission of deliverables in 19 focus areas, intended to provide early identification and resolution of potential technical issues during the design process. Submissions occur approximately every 3 to 4 months and are followed by a series of ARC presentations to the CNSC on each of the focus areas associated with the submission. Following these presentations, the CNSC can formally transmit Requests for Information (RFI's), in any of the focus areas, for ARC to respond to. The primary purpose of this process is to inform ARC of potential fundamental barriers to licensing of the ARC-100 reactor design. Successful completion of this process does not guarantee the eventual receipt of a License to Prepare Site, License to Construct or License to Operate, but it helps to provide some level of confidence that these licenses may be received [2].

The ARC-100 Reactor Building (aka Concrete Containment Structure) forms an integral part of the Containment system in providing the fundamental safety functions that satisfy the regulatory requirements. Design of the Containment boundary must support As Low As Reasonably Achievable (ALARA), a principle recognized in regulations under the *Nuclear Safety and Control Act*, which seeks to minimize exposure to radiation. Under this principle, it is not sufficient for a licensee of a nuclear facility to merely respect allowable dose limits – instead, efforts must be made to further reduce radiation exposure [3]. The safety functions of the Containment system include the confinement of radioactive material, shielding against radiation to achieve the ALARA principle, control of hazardous substances, including limitation of accidental releases and monitoring of safety-critical parameters to guide operator actions. This paper outlines the evolution of the ARC-100 Reactor Building throughout the VDR process such that the Containment structure meets the regulatory safety goals, while reducing overall construction cost and achieving construction schedule savings.

2. The ARC-100 Reactor Building

2.1 Vendor Design Review Phase 1

During ARC's Vendor Design Review Phase 1, the ARC-100 Containment system design was presented to the Canadian Nuclear Safety Commission (CNSC), as a conceptual design. At this stage, the system was designed as a low leakage Containment system, consisting of a guard vessel and a portion of the reactor support skirt located below ground, as well as a low leakage concrete Containment, partly above ground and partly below ground. The reactor enclosure head had several mechanical and electrical penetrations designed to withstand the internal pressure developed within the primary system. This provided a leak tight environment, designed to limit leakage from the reactor head into the rest of the concrete Containment structure.

Under this configuration, the Containment boundary was comprised of the following elements:

- A Guard Vessel and a portion of the reactor support skirt located below ground.
    - These elements were within a cylindrical reactor cavity. The annulus between the Guard Vessel, the portion of the reactor support skirt located below ground and the cylindrical reactor shield wall formed the collector cylinder portion of the Reactor Vessel Auxiliary Cooling System (RVACS).
    - The reactor closure head and rotatable plug on the Reactor Vessel system formed the top boundary for the Guard Vessel. Also, control rod drive housings were sealed penetrations for the top plate of the Reactor Vessel system.
- A low leakage concrete Containment, which was partly above ground and partly below ground, designed to limit leakage to 1 percent of its contained volume per day under a differential pressure of 2.07 kPa (0.3 psig). This concrete Containment was part of the Reactor Building:
    - The above ground portion of the low leakage concrete Containment was box shaped with a flat concrete roof.
    - A low leakage floor penetration enabling transport of fuel assemblies to and from the above ground and below ground areas.

- The below ground portion was designed primarily for fuel handling, including a hot cell used for fuel surveillance activities.

A section view of this Containment design is shown in Figure 1, where the areas highlighted in red form the Containment boundaries [4].

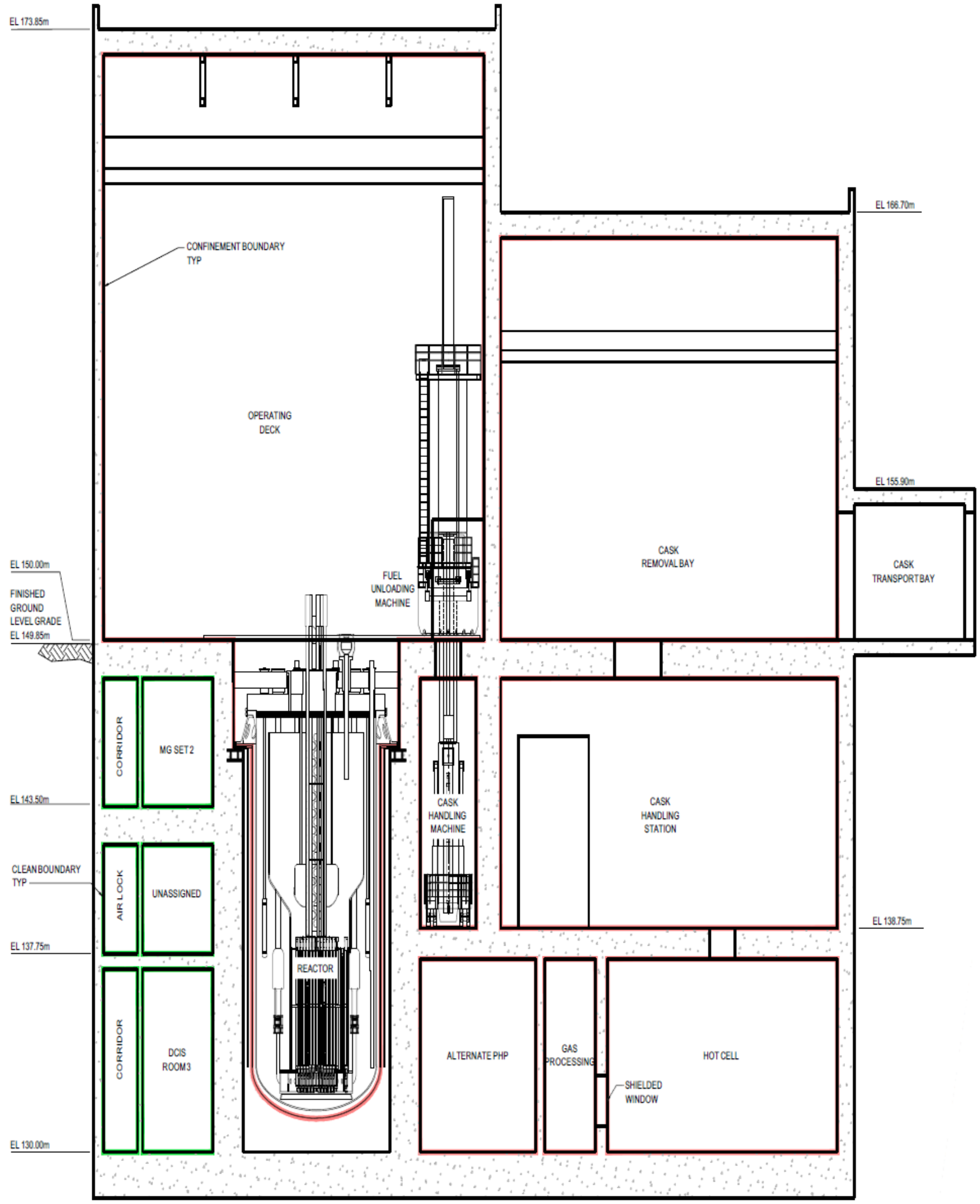

Figure 1: Section View of Containment

2.2 Design change

At the end of VDR Phase 1, it was identified that the Containment design could be improved to minimize the amount of safety related concrete, costly excavation, and plant footprint, all while improving pressure retaining capability of the reactor building.

2.2.1 Below ground structures

OPEX from other SMR designs showed a deep vertical hole for the Reactor Vessel, with a higher base-mat slab for the remaining plant structures. This would allow most of the Reactor Building components, aside from the Reactor Vessel itself, to be located above ground. This provides a significant advantage, from both schedule and cost perspectives, as a large, deep excavation area would be costly and could encounter bedrock and dewatering issues during construction. The new design eliminates significant portions of the below ground concrete Containment intended for fuel handling, including the hot cell used for fuel surveillance activities. Fuel handling still occurs within the Containment structure, but most of the ex-vessel fuel handling equipment required in Containment is housed directly above the reactor, as opposed to beside the reactor.

2.2.2 Low leakage concrete Containment

The next optimization identified was in the structure of the low leakage concrete Containment. The design presented at VDR Phase 1 showed a box-shaped, low leakage concrete Containment (partly above ground and partly below ground) and a below ground cylindrical concrete Containment which housed the reactor and guard vessel. This was optimized by extending the cylindrical Containment, to replace the box-shaped structure. The new design showed a cylindrical, low leakage concrete Containment, which is silo that extends below ground to the base-mat concrete slab and above ground with sufficient height to accommodate fuel handling equipment. Figure 2 shows a comparison of the previous and present concrete Containment structure designs.

The change to a cylindrical, low leakage concrete Containment structure is a proven method to minimize leakage. Construction methods for cylindrical concrete Containment structures are well established for water-cooled nuclear power plants. The CSA N287 series of standards along with international standards, such as those published by the American Concrete Institute and the American Society of Civil Engineers, provide industry practices for the design, construction, inspection and testing of concrete Containment structures. Typical cylindrical Containment Systems for water-cooled reactors can achieve design leakage rates less than 1.0 % of the contained volume per day at Containment design pressures of about 120 kPa. By utilizing proven methods at a much lower design pressure (approx. 2.1 kPa), ARC can achieve a design leakage rate of 0.1% of the contained volume per day. In this way, ARC stays consistent with state-of-the-art design practices, allowing the design to support the ALARA principle.

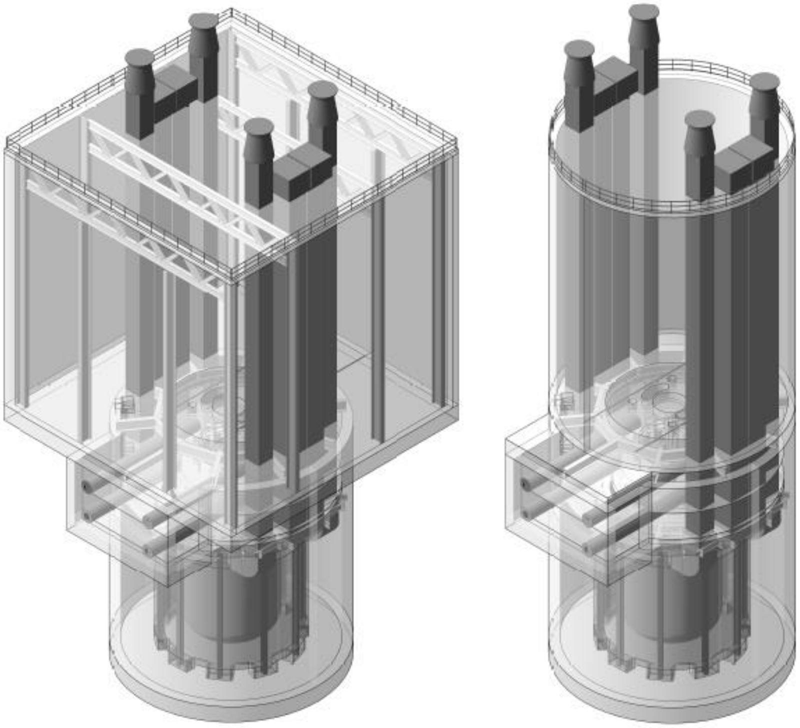

Figure 2: Square versus cylindrical Containment structure

2.2.3 Containment boundary

The final optimization is achieved through a better definition of the Containment boundaries. The Guard Vessel and a portion of the reactor support skirt can be removed from the Containment boundaries. The new Containment boundary is primarily defined as the low leakage, cylindrical, concrete Containment structure.

When the Guard Vessel forms a portion of the Containment boundary, it must be classified as Class 2, under CSA N285.0-12, Clause A.2.1.2, which states, “Components that are part of a system that penetrates the Containment structure and forms part of the Containment boundary, unless otherwise classified as Class 1 or as permitted by Clause A.2.1.3, shall be classified as Class 2.” With the Guard Vessel no longer forming part of the Containment boundary, it can be classified as either Class 3 or Class 6, in accordance with CSA N285.0-12, Clause A.1.5, which states, “Systems and sections of systems not classified as Class 1 or 2 and that contain radioactive substances with a tritium concentration exceeding 74 GBq/kg (2Ci/kg), shall be classified as Class 3.” Systems meeting the requirements of Clause A.1.5, but with tritium concentrations below 74 GBq/kg, can be classified as Class 6 [5]. For ARC, Ar-37, Ar-39 and Ar-41 are the radionuclides of interest, contained in the annulus between the Reactor Vessel and Guard Vessel, to determine the distinction between Class 3 and Class 6 for the Guard Vessel.

The portion of the reactor support skirt that connected the Reactor Vessel to the concrete wall can also be removed from the Containment. Like the Guard Vessel, this allows this support skirt to be changed from Class 2 to either Class 3 or 6, depending on the inventory of radioactive substances produced from neutron activation of the air in the collector cylinder portion of the Reactor Vessel Auxiliary Cooling System (RVACS).

This design change redefines the boundary for the Containment System to the concrete floor, wall and roof of the Containment Structure, along with containment penetrations. Therefore, the Reactor Vessel becomes a system housed within Containment. Figure 3 compares the previous design with the current design, showing the difference in Containment boundaries (not including containment penetrations).

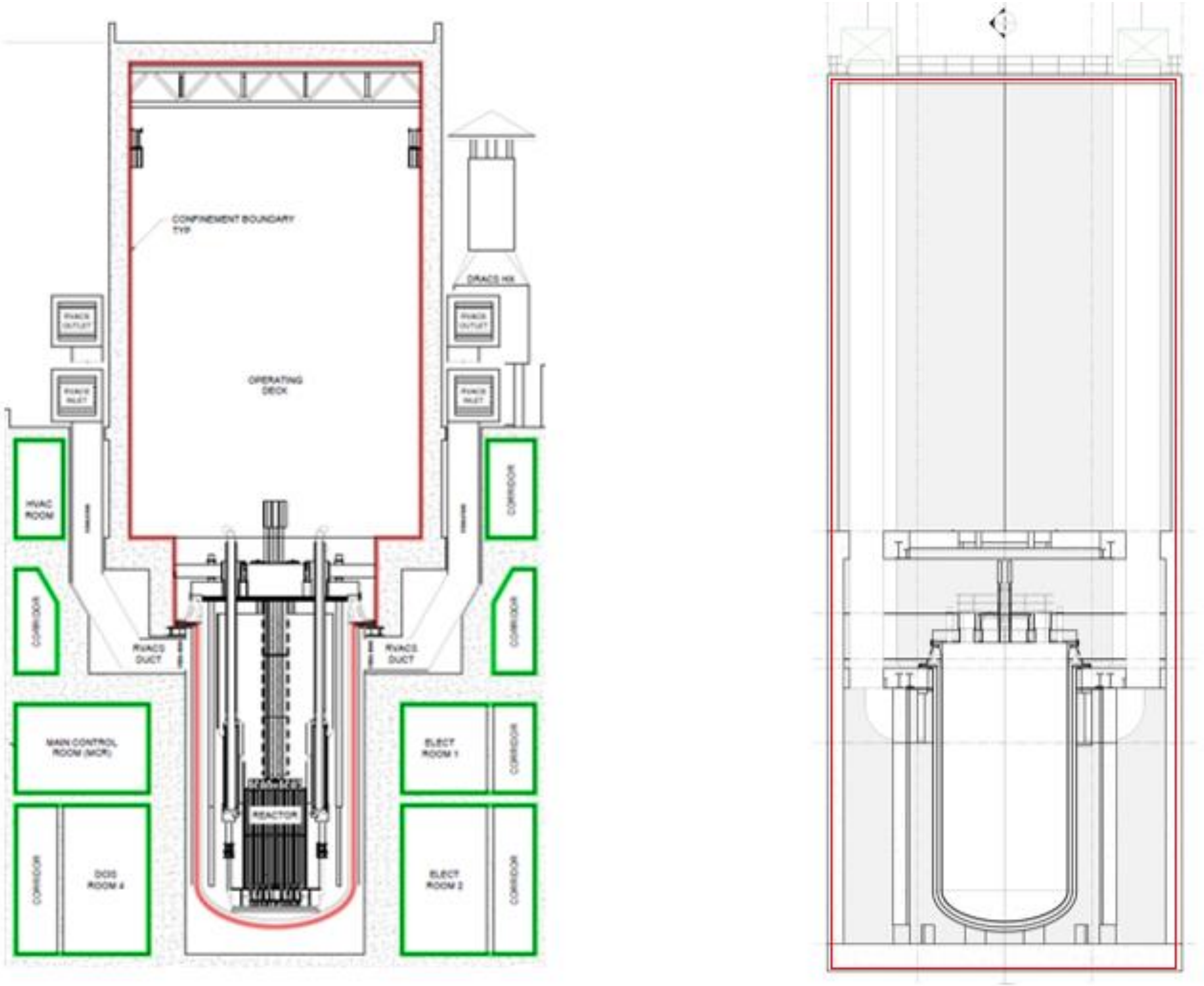

Figure 3: Previous Containment design versus new Containment design

2.3 Vendor Design Review Phase 2

The new design was presented to the CNSC in January 2023. The Reactor Building, which acts as the majority of Containment boundary, houses and structurally supports the Reactor Vessel, Guard Vessel, the Direct Reactor Auxiliary Cooling System (DRACS), the Reactor Vessel Auxiliary Cooling System (RVACS), fuel handling equipment, biological shielding, and associated equipment and structures. ARC's design vendor, United Engineers & Constructors (formerly AECOM) prepared a Design Basis Document for Structural Design of the ARC-100 Building [6], with inputs from the following documents:

- ARC-SPRD-001, Standard Plant Requirements Document
- ARC-100 Generic Civil Design Criteria, 2018 (GCDC)
- ARC Safety Design Guides, (SDGs)
- CSA N287 series for design and construction of Containment structures for nuclear power plants
- CSA N289 series for seismic qualification of nuclear power plants
- National Building Code of Canada 2020 (NBCC)

This Design Basis Document was included in the package three (3) submission to the CNSC as part of VDR Phase 2. The scope of this document is to apply the ARC-100 Design Requirements for the Reactor Building Containment structure by incorporating national, industry and technical standards to produce a set of technical criteria for the design team to use for Reactor Building design. The final objective is to have a Containment structure which meets the safety requirements of the applicable national standards.

Utilizing the inputs of the Design Basis Document, United Engineers & Constructors issued a design report which provided the preliminary structural design of ARC-100 Reactor Building (RB) structure. A three-dimensional (3D) finite element (FE) model was developed with appropriate stiffness and mass. Using the 3D FE model, structural analysis was performed and structural members in the gravity load resisting system and lateral load resisting system were designed. Figure 4 presents the current proposed overall shape of the RB.

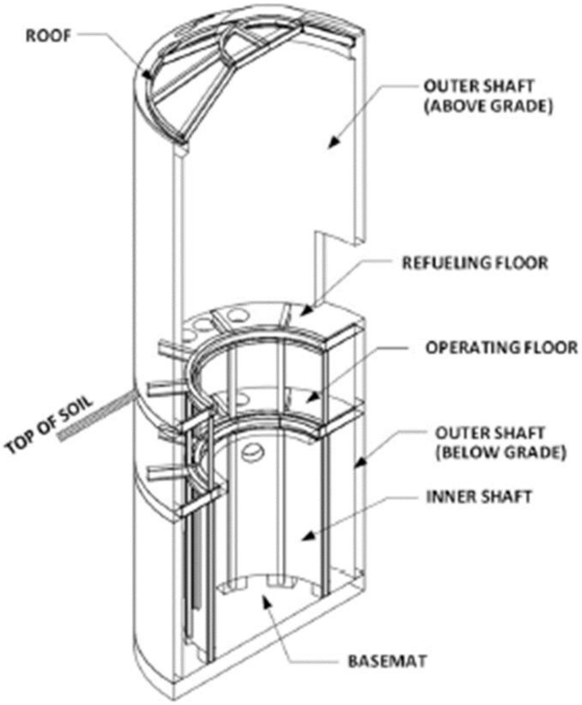

Figure 4: Current Overall Reactor Building Configuration

The RB is embedded in the soil and underlying rock to approximately one half of its height. Above the ground, the RB consists of the cylindrical shear wall, referred to as the outer shaft, and the roof. The refueling floor is a thick reinforced concrete slab at the ground level. It supports fuel handling systems during refueling. The operating floor is a thick reinforced concrete slab located below the refueling floor. The RB is supported at the operating floor level. The outer shaft continues down to the base-mat concrete slab. Between the base-mat slab and the operating floor, there is another concrete shaft, referred to as the inner shaft. The inner shaft surrounds the primary reactor system (reactor vessel and guard vessel) and provides structural support to the operating floor.

3. Use of the Vertical Sinking Shaft Machine (VSM)

ARC's design vendor, United Engineers & Constructors, prepared a report which used the new Reactor Building design to explore efficiencies for construction, both in cost and schedule. They were able to produce estimates far below the initial estimates at the conceptual design stage, in part by utilizing Vertical Shaft construction. Vertical Sinking Shaft Machines (VSM) have been in use since 2006 and have since been used on 75 projects where shafts have been successfully installed. A VSM schematic is depicted in Figure 5. Construction with a VSM proceeds as follows:

1. The site is prepared, and concrete ring foundation (for VSM) is installed.
2. The cutting edge and first pre-cast concrete casing/liner section of the shaft are installed.
3. Soil is excavated and the cutting edge and first pre-cast concrete casing/liner sections are lowered.
4. Installation of the next concrete liner segment and excavation of soil occur simultaneously.
5. The pre-cast liner shaft is lowered.
6. Steps 4 and 5 are repeated until the target excavation depth is reached.

Note: The void/joint between the pre-cast casing/liner sections would be filled with a flowable grout material. The pre-cast casing/liner will act as the outer form for the RB walls which will be slip-formed following the mud-mat and base-mat concrete slab installation.

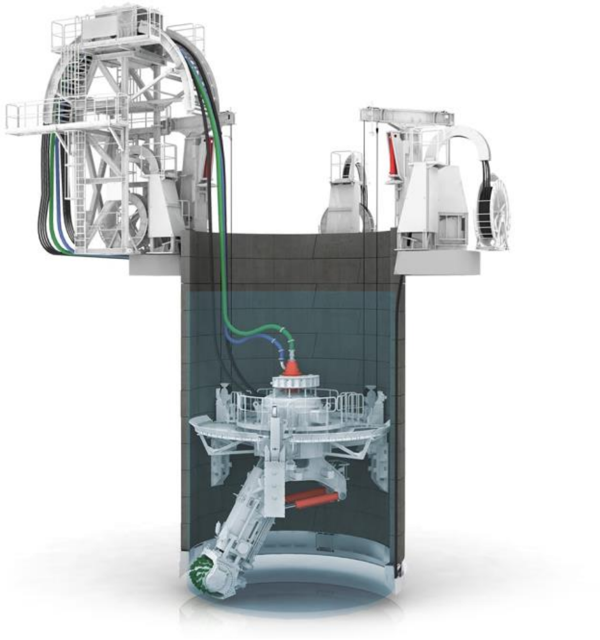

Figure 5: Vertical Sinking Shaft Machine

The use of a VSM provides several benefits. These include minimizing the amount of excavation, minimizing the amount of engineered backfill, performing excavation without lowering groundwater level and reducing construction schedule over conventional methods. The VSM also minimizes human exposure because all installation processes are remotely controlled from the surface, meaning that personnel need not enter the shaft until it has reached the final depth and is fully secured.

Disadvantages of using a VSM are the high capital cost required to purchase the machine, the requirement to hire or train qualified personnel to operate and the need to sell the machine at the completion of the project. However, as ARC intends to deploy a fleet of reactors, the VSM could be reused for many projects, spreading the high capital cost of the machine across these projects [7].

4. Modularization opportunities

United Engineers & Constructors also prepared a modularization study, focused on the ARC Reactor Building. This report was prepared for the initial reactor building design and has not been updated to reflect the new design, but it nonetheless provided some key insights on the possible benefits of modularization. This study developed a plan to integrate modularization, pre-assembly, prefabrication, and offsite fabrication (collectively known as PPMOF), techniques into the construction of the ARC-100 Reactor Building [8].

Currently, the opportunities for modularization of the ARC-100 Reactor Building are limited to the floor slabs that will potentially be composite steel and concrete sections that are assembled and poured prior to being erected/placed in the RB on site. Complete details of this construction sequence have not yet been determined. Modularization of the other plant buildings will be considered during the detailed design phase.

5. Impacts on safety

The evolution of the ARC-100 Reactor Building design has provided several benefits from the perspective of safety. One of the most notable improvements is the use of a cylindrical Containment structure, which provides better leak-tightness and a zoned approach to lower any potential exposure or releases of radioactivity. This conventional design aligns with As Low As Reasonably Achievable (ALARA) principles. In addition to this, the use of a Vertical Sinking Shaft Machine (VSM) provides safety advantages by minimizing human involvement during site excavation.

6. Impacts on schedule & cost

In addition to providing safety benefits, these design changes, along with the use of a VSM, have allowed significant schedule and cost benefits. The most recent schedule estimates are for the ARC-100 Reactor Building structure to be complete 22 months from the start of excavation. This is 11 months faster than the best possible schedule (the fully modularized case) of previous estimates. The use of a VSM gives a schedule benefit of 3 months on its own. These schedule savings alone provide a cost benefit. In addition, the reduction in required safety related concrete reduces the overall cost of the Reactor Building significantly. The change to a cylindrical structure, in combination with the reduction in space required for fuel handling, provides approximately an 80% reduction in the amount of required safety-related concrete, which meet CSA N287 code requirements. Finally, redefinition of the containment boundaries allows for the guard vessel and other components to be reclassified. This reclassification changes the nature of the materials required and/or the amount of qualification testing needed, which in turn provides cost savings.

7. Conclusion

The design of the ARC-100 Reactor Building has evolved through the conceptual design phase as well as Phases 1 and 2 of the CNSC Vendor Design Review. By reducing the magnitude of required below ground structures, costly, time-consuming excavation was significantly reduced. The reconfiguration of the low-leakage concrete containment structure to a cylindrical shape provides better leak tightness and a reduction in the amount of required safety-related concrete. The reclassification of containment boundaries from the guard vessel and other structures to the exterior wall of the cylindrical containment structure, allows for reclassification of these components. Finally, the use of a Vertical Sinking Shaft Machine (VSM) will allow the Reactor Building construction to proceed as quickly and safely as possible. This evolution of the Reactor Building design has had a positive impact on the initial ARC-100 small modular reactor project in construction schedule, cost and safety.

8. References

[1] ARC Clean Technology Canada, “ARC-100 standard plant technical overview”, Rev A, 2022 November 7.

[2] Canadian Nuclear Safety Commission, “Pre-Licensing Vendor Design Review”, 2022 December 16, retrieved from https://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/index.cfm.

[3] Canadian Nuclear Safety Commission, “REGDOC-2.7.1, Radiation Protection”, Version 1.0, 2021 July.

[4] ARC, LLC, “ARC Containment (Confinement) and civil structures important to safety”, Rev. E, 2018 May.

[5] Canadian Standards Association, “N285.0-12: General requirements for pressure retaining systems and components in CANDU nuclear power plants/Material Standards for reactor components for CANDU nuclear power plants”, Update No. 2, November 2014.

[6] ARC Clean Technology Canada, “Design basis document for structural design of ARC-100 reactor building”, Rev. A, 2022 August 25.

[7] AECOM, “Modularization study report”, Rev. E, 2019 November 27.

[8] United Engineers & Constructors, “ARC-100 construction cost estimate and schedule for new reactor building arrangement”, Rev. A, 2022 April 19.