ACR-1000® ENVIRONMENTAL PERFORMANCE DESIGN IMPROVEMENTS

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Abstract

The ACR-1000®design is the next evolution of the proven CANDU® reactor design. One of the key objectives for this project was to improve station environmental performance based on the As Low As Reasonably Achievable (ALARA) principle, and station operating experience, feedback from owners of CANDU stations, and industry best available techniques. Design improvements, based on these concepts to improve the environmental performance of the ACR-1000 reactor and protect workers, the public, and the environment, are presented in this paper.

1. Introduction

Atomic Energy of Canada Limited (AECL) has established a successful, internationally recognized line of CANDU[1] pressurised heavy water reactors (PHWR) that use a heavy water moderator, in particular, the medium-sized CANDU 6 reactor. AECL has consistently adopted an evolutionary approach to the enhancement of CANDU nuclear power plant designs over the last 30 years. The current CANDU 6 reactor design has been developed further in the market-ready Advanced CANDU Reactor (ACR) reactor design.

The ACR-1000[2] design has evolved from AECL's in-depth knowledge of CANDU structures, systems, components, and materials, as well as from the experience and feedback received from owners and operators of CANDU plants. The ACR-1000 design features significant environmental performance improvements based on the As Low As Reasonably Achieveable (ALARA)[3] principle while retaining the proven benefits of the CANDU family of nuclear power plants.

1.1 Scope

This paper summarizes the design aspects of the ACR-1000 reactor that contribute to improving the environmental performance of the nuclear power plant (NPP) by ensuring that radionuclide production and release mechanisms are minimized. This paper also describes the ALARA principle and how it was applied to the design of those systems and processes of the ACR-1000 reactor that impact environmental performance and which protect workers, the public, and the environment.

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[1] CANDU® (CANadian Deuterium Uranium®) is a registered trademark of Atomic Energy of Canada Limited (AECL), 2009.

[2] ACR-1000® (Advanced CANDU Reactor®) is a registered trademark of Atomic Energy of Canada Limited (AECL), 2009.

[3] ALARA: As Low As Reasonably Achievable, social and economic factors taken into account.

2. Source terms

For NPPs, environmental performance is determined by measuring the airborne and waterborne radionuclides described below. These radionuclides are closely monitored and controlled by operating CANDU NPPs [1], and in the ACR-1000 NPP, by several systems that have a direct impact on the environment.

2.1 Airborne source terms

1. Tritium (^{3}H)

   Tritium is produced primarily by neutron activation of deuterium in the reaction $^{2}H(n,\gamma)^{3}H$ in heavy water contained in the reactor core of a CANDU NPP. Tritium is also produced from the lithium added to the coolant for chemistry control through the $^{6}Li(n,\alpha)^{3}H$ reaction.

2. Carbon-14 (^{14}C)

   Carbon-14 is produced in the moderator and moderator cover gas of a CANDU reactor via a $^{17}O(n,\alpha)^{14}C$ reaction due to the high thermal neutron fluxes in the reactor core. Carbon-14 is also produced in small quantities in the annulus gas system in the $^{14}N(n,p)^{14}C$ and $^{17}O(n, \alpha)^{14}C$ reactions from traces of nitrogen and oxygen present in the carbon dioxide annulus gas system cover gas. A small amount of ^{14}C is also produced by the ^{17}O present in the uranium dioxide fuel.

3. Radioiodines (e.g., ^{131}I)

   Radioiodines are fission products that may be present in the coolant of the heat transport system of a CANDU reactor. They are generated by fission in the uranium fuel and are retained within the individual fuel element of the fuel bundles unless there is a fuel element sheath failure that may release in radioiodine releases to the heat transport system coolant. If there are no fuel element sheath defects, then there are essentially no radioiodines in the heat transport system coolant. Any defective bundles would be detected and removed on-power and therefore there are normally very low radioiodine inventories present in the heat transport system coolant.

4. Noble Gases

   Argon-41 is generated from the ^{40}Ar impurities in the helium of the moderator cover gas and in the carbon dioxide of the annulus gas system of a CANDU reactor. It is also generated in the heat transport system by the activation of argon impurities in air that enters the system.

   Fission product noble gases, including radioisotopes of xenon and krypton, which are generated as fission products in the uranium fuel and are contained by the fuel sheath, may also be present in the heat transport system. The release of fission product noble gases to the heat transport system coolant is governed by the same process as for radioiodines.

5. Particulates

   In a CANDU reactor, particulate originates as corrosion and activation products from the heat transport system as well as from fission products, the calandria shell, calandria tubes, and the operation of reactivity devices.

To monitor and control airborne radionuclides, process systems in the ACR-1000 reactor vent air to the ventilation system which is used to collect exhaust air from all areas of the plant. The exhaust air from eight major streams in the reactor building (fuel off-gassing hood, spent fuel magazine, pressure and inventory control degasser condenser and coolant storage tank, heat transport system leakage collection tank, and fuelling machine water system) is then passed through the gaseous waste management system. The gaseous waste management system incorporates a filter train and the off-gas management system to purify the air. The filtration system includes high-efficiency particulate air filters and charcoal filters to remove particulate and radioiodines, respectively. The off-gas management system increases the residence time of the air by delaying its passage to the stack to allow for the decay of noble gases.

To monitor and control airborne heavy water, the heavy water systems located in the maintenance building and reactor building are atmospherically separated and vented to a vapour recovery system such that the heavy water can be captured and recycled.

Figure 1 illustrates the ventilation and vapour recovery pathways for the ACR-1000 reactor.

2.2 Waterborne source terms

1. Tritium (^{3}H)

   See Section 2.1 for a description of ^{3}H source terms.

2. Carbon-14 (^{14}C)

   See Section 2.1 for a description of ^{14}C source terms.

3. Gross beta-gamma

   In a CANDU reactor, gross beta-gamma consists of fission and activation products that are not classified in any of the other categories. Mass transport and solution-dissolution mechanisms result in the activation of corrosion products in the reactor core and their deposition in various parts of the circuit, or suspension in the coolant.

Light water, which is used in the ACR-1000 reactor process systems, is collected in the drainage systems and processed in the radioactive liquid waste management system. The radioactive liquid waste management system has improved segregation of liquid streams at source and throughout processing and storage. The system is designed to collect water from all systems in the NPP and purify it to remove contaminants. All purified water is monitored to ensure that purification requirements are consistently being achieved.

Figure 2 illustrates the drainage pathways.

3. ALARA design principle

The ALARA principle ensures that a system within the NPP is designed with emphasis on radiation protection for workers, the public, and the environment, and the minimization of radionuclide production and release mechanisms.

The design of the CANDU family of NPPs, and specifically the ACR-1000 reactor, conforms to the ALARA principle by ensuring that the design option was selected to minimize the environmental impact, while taking into account a wide range of factors including technological maturity, availability and reliability, operational safety, radiation protection, and social and economic factors.

To apply the ALARA principle to ACR-1000 systems that have a direct impact on the environment, a best available technique (BAT) assessment was conducted. The basic principles for determining a BAT involve identifying options, assessing environmental effects and considering economics. The principles of precaution and prevention are also relevant factors in BAT determinations.

The BAT methodology includes analysis of technically and economically feasible alternatives, a cost-benefit analysis of potentially adverse environmental effects of each feasible alternative, and a scoring system to evaluate each alternative. Reasons for selection of the proposed option including justification for rejection of other alternatives must be documented.

The BAT assessment demonstrated that process and technology alternatives had been considered and assessed in the systems' design, and that the best approach overall was selected for minimizing the impact of the ACR-1000 reactor on the environment.

4. ACR-1000 design improvements

Significant environmental performance improvements are inherent in the ACR-1000 design:

- Light water is used as coolant and for the entire fuel handling process instead of heavy water.
- Low enriched uranium is used in the fuel instead of natural uranium lowering the thermal neutron flux in the core.
- The lattice pitch in the reactor core is reduced contributing to a more compact reactor design and less heavy water in the reactor core.

These design changes minimize the use of heavy water in the ACR-1000 reactor and decrease the thermal neutron flux in the reactor core, which leads to a decrease in the production of ^{3}H and ^{14}C.

Additional environmental performance design improvements, which have been applied to the ACR-1000 reactor design, are summarised below. The improvements are categorised based on their importance to source term reduction for the most significant radionuclides; ^{3}H and ^{14}C. Environmental performance design improvements, which impact on the other airborne and waterborne source terms, are discussed separately.

4.1 Tritium

1. Lithium depleted to 0.1% ^{6}Li is used for chemistry control in the heat transport system reducing the formation of ^{3}H from the $^{6}Li(n,\alpha)^{3}H$ reaction in the reactor core.
2. The design of the reactor building ensures control over moderator heavy water through the relocation of all heavy water related systems (moderator purification system, moderator cover gas system, moderator poison system, liquid injection shutdown system, and deuteration/dedeuteration system) inside dried areas of the

reactor building, with increased reactor building moderator dryer capacity using rotary desiccant wheel dryers. Also, to prevent downgrading of heavy water and minimize the heavy water upgrading requirement from the reactor building, the ACR-1000 design has incorporated dryers at the inlet to the reactor building ventilation system to minimize the migration of light water into dried areas.

Furthermore, the reactor building vapour recovery system has been designed as a two-loop system, which ensures atmospheric separation between the reactor building moderator room and reactor building moderator auxiliary room (See Figure 1). This ensures that air from the two rooms does not mix, since the moderator room is expected to contain higher levels of tritium activity and this source can be processed separately.

A BAT assessment was conducted for the reactor building vapour recovery system to determine the best process to reduce airborne ^{3}H in the reactor building. Therefore, a purge dryer has been installed to collect heavy water in the air discharged from the reactor building. The purge dryer further reduces the dew point of the air to minimize the amount of heavy water released.

3. The design of the maintenance building ensures control over heavy water releases in heavy water management areas of the maintenance building by moving all the heavy water management systems into an atmospherically separated area of the maintenance building. This area is connected to the maintenance building vapour recover system to ensure that heavy water is collected.

   Also, to prevent downgrading of heavy water and minimize the heavy water upgrading requirement from the maintenance building, the ACR-1000 design has incorporated a double-door airlock at the entrance to the heavy water management area to minimize the migration of light water into dried areas. This improvement ensures that the heavy water collected by the maintenance building vapour recovery system is economical to upgrade, thereby avoiding the possibility of the collected downgraded heavy water being sent to the radioactive liquid waste management system.

4. A BAT assessment was conducted for available processes for treating moderator spent resin produced in the moderator purification system. The moderator spent resin will therefore be dewatered instead of dedeuterated to decrease the overall water requirement and reduce the amount of heavy water that must be upgraded as a result of this process.

   Furthermore, the moderator spent resin slurry function used to transport moderator spent resin to the radioactive solid spent resin handling system storage tanks will be recirculating and will use permanent connections to the moderator purification system to avoid spillage, thereby eliminating the need for frequent slurry water additions. This ensures that the amount of heavy water that must be upgraded as a result of this process is minimized.

4.2 Carbon-14

1. Sub-micron filters have been installed downstream of the moderator ion exchange columns in the moderator purification system to capture resin fines. This will

prevent resin fines from reaching the reactor core where the fines form carbonate and bicarbonate ions from ^{12}C. Consequently, saturation of the ion exchange columns with ^{12}C, which competes for ion exchange sites with ^{14}C, will be avoided.

2. The moderator cover gas is constantly circulated through the vertical reactivity mechanism thimbles, which pass through the reactor core, to prevent stagnation and build up of gases including ^{14}C.
3. The annulus gas system design is improved to include an improved compressor, which minimizes air ingress to the circuit and reduces the requirement to purge the annulus gas system frequently.
4. A BAT assessment was conducted for available processes to improve the segregation of moderator spent resin, which contains ^{14}C, from non-moderator spent resin, which does not contain significant quantities of ^{14}C. As a result, the moderator spent resin handling functions were designed to segregate the moderator spent resin from the non-moderator spent resin at source and throughout the slurrying and storage process.

4.3 Other Airborne

Other airborne radionuclides that are monitored in the ACR-1000 NPP include radioiodine, noble gases (argon, krypton, xenon), and particulates.

1. The use of stainless steel components in the heat transport system decreases corrosion product production, activation, and activity.
2. As described in Section 4.2, the annulus gas system is improved to minimize the ingress of air and, since air contains ^{40}Ar impurities, this improvement also minimizes ^{41}Ar production.
3. Since the entire fuel handling process will be performed under water, radioiodines and noble gases will not off-gas during handling of depleted fuel and a snout blow-down system will collect water from the fuelling machine snout such that it is not released into the reactor vault.
4. Nitrogen cover gas is used for the fuelling machine to prevent air ingress to the coolant during refuelling operations, thereby lowering the production of ^{41}Ar.
5. An absorber material for the mechanical zone control system has been selected that minimizes the production of cobalt, antimony, and other airborne particulate.
6. A BAT assessment of available technologies for the off-gas management system was conducted to ensure that ^{41}Ar, and xenon and krypton were delayed sufficiently for decay. As part of the BAT process, a sub-system of the off-gas management system, the annulus gas system purge delay tanks, were added to the design to address ^{41}Ar. During the BAT process, it was determined that a significant portion of the ^{41}Ar produced in the station originates from the annulus gas system. Since the charcoal adsorber bed in the off-gas management system does not delay ^{41}Ar sufficiently for decay, the annulus gas system purge delay tanks use a separate delay mechanism.

4.4 Other Waterborne

1. The use of stainless steel components in the heat transport system decreases corrosion product production, activation, and activity.
2. A BAT assessment of available technologies for the radioactive liquid waste management system was conducted. Therefore, a parallel-stream treatment circuit has been incorporated in the radioactive liquid waste management system design to ensure that all water used in the NPP is treated to remove suspended solids, organics and oils, radiological and non-radiological contaminants, and to adjust chemistry.

5. ACR-1000 radiation protection

The environmental performance improvements that have been described in this paper also have a direct impact on radiation protection for personnel within the ACR-1000 NPP, and for the public and the environment. During the ACR-1000 design phase, application of the ALARA principle ensured that the design improvement considered was also examined from a radiation protection perspective.

Due to the significant environmental performance improvements inherent in the ACR-1000 design and the environmental performance improvements described in this paper, radiation protection improvements are also inherent in the ACR-1000 design. A component of the BAT assessment methodology and selection process discussed in this paper, for systems that have a direct impact on the environment, was to examine the impact of the design option on radiation protection.

6. Conclusions

The ALARA principle has been systematically applied to the design of the ACR-1000 reactor with emphasis on radiation protection for workers, the public, and the environment, and the minimization of radionuclide production and release mechanisms.

The ACR-1000 NPP is capable of achieving excellent environmental performance based on the environmental performance improvements discussed in this paper. A BAT assessment of systems that have a direct impact on environmental protection ensured that the best available techniques have been used in the design of these systems and that industry design and operating experience have been taken into consideration.

7. References

[1] CNSC, “Radioactive Releases Data from Canadian Nuclear Generating Stations 1994-2003”, INFO-0210, Rev. 12, January 2005.

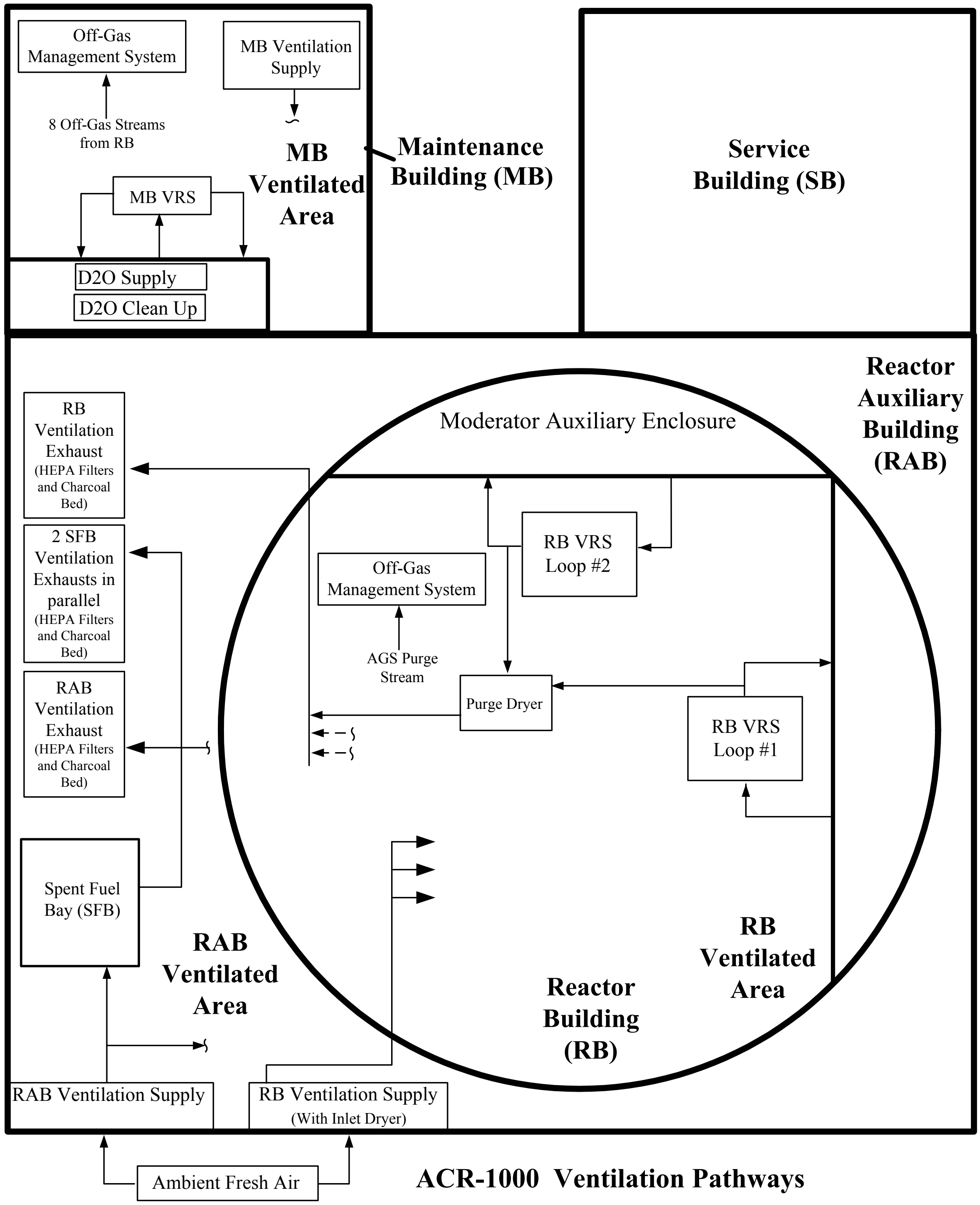

Figure 1 ACR-1000 Ventilation Pathways

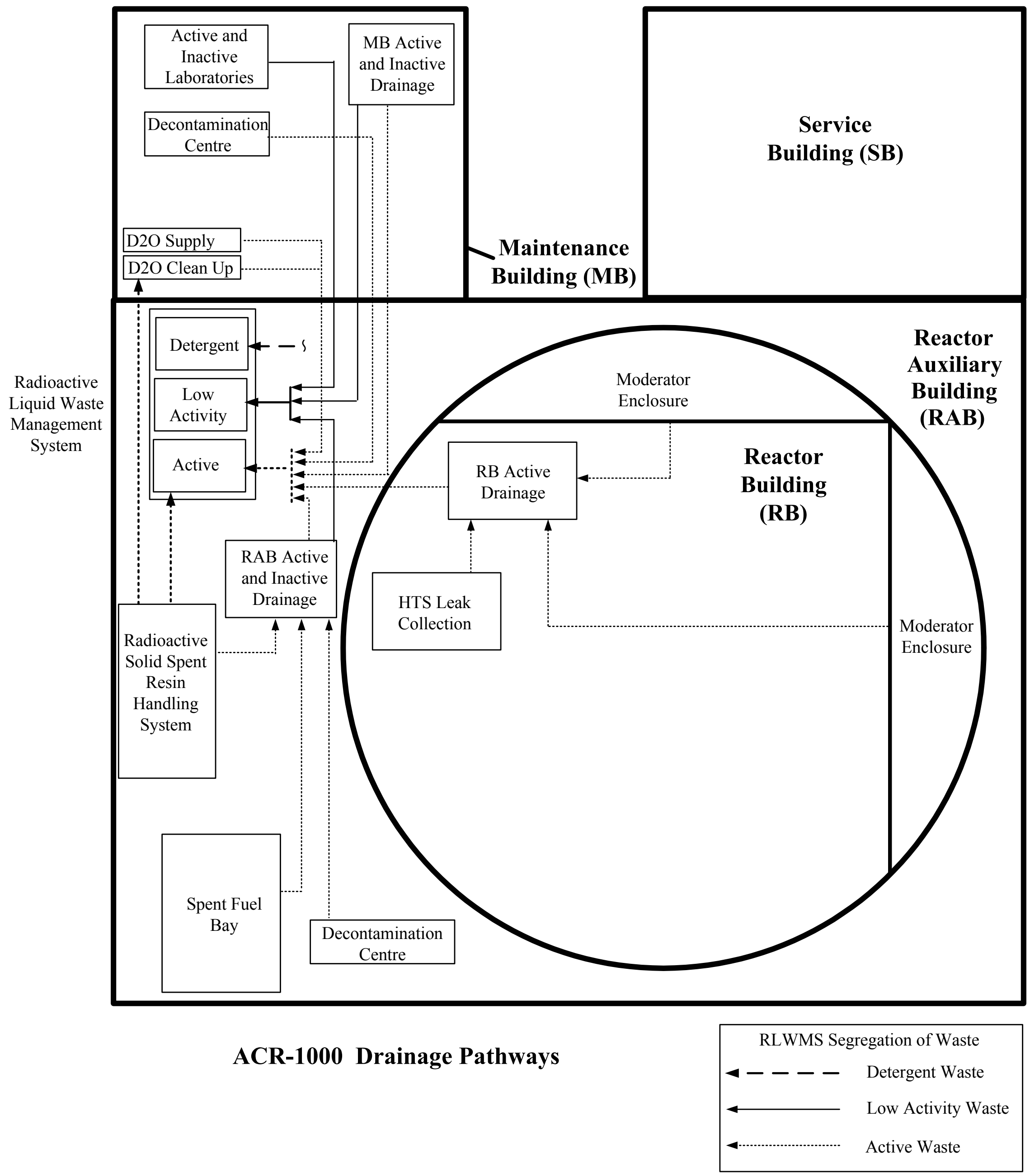

Figure 2 ACR-1000 Drainage Pathways