CANDU DESIGN OPTIONS WITH DETRITIATION

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Abstract

CANDU® reactors include a number of auxiliary systems to manage the inventory, purification, clean-up and isotopic purity of the heavy water used in the moderator and heat transport system. These systems are designed and installed to treat the moderator and heat transport water in separate parallel systems. One of the reasons for this parallel approach to heavy water management is the tritium inventory in the heavy water. Different levels of tritium accumulate in the moderator and heat transport system during reactor operation, with the moderator water having a much higher tritium concentration. Strict separation of the high-tritium-concentration moderator water from the low-tritium-concentration heat transport system water is an integral component of the CANDU design and operating strategy to limit potential releases of tritium to the containment building atmosphere.

AECL is developing a new cost-effective technology for the detritiation of heavy water based on the Combined Electrolysis and Catalytic Exchange (CECE) process. This detritiation technology has the potential to be integrated into the heavy water management systems of a CANDU reactor. On-line detritiation could be used to limit the concentration of tritium in the moderator and also to detritiate any water collected within the containment building from other sources.

The availability of economic detritiation technology would provide a flexibility to redesign some of the auxiliary heavy water management systems. In particular, there is potential to eliminate some of the duplication in the current management systems and also reduce costs by reclassifying some reactor systems that would have lower maximum tritium concentrations. This paper discusses some of the advantages of detritiation and some of the conceptual design options that detritiation would provide. The goal would be to lower the overall reactor cost with detritiation, but it is premature to assess whether this goal can be achieved.

1. INTRODUCTION

CANDU® reactors include a number of auxiliary systems to manage the inventory, purification, and clean-up of the heavy water used in the moderator and heat transport systems. In the current generation of CANDU reactor designs, the auxiliary systems are constructed in parallel to treat the moderator and heat transport water separately. There are two reasons for this parallel approach to heavy water management. The first reason is the different chemistry control requirements of the heavy water in the two systems. The second reason is different tritium levels in the heavy water of the two systems. Strict separation of the high-tritium-concentration moderator heavy water from the low-tritium-concentration heat transport system heavy water is an integral component of the CANDU design strategy to strictly control potential releases of tritium to the containment building atmosphere.

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A constant target in the design of future CANDU reactors is cost reduction. One potential mechanism for reducing costs is to decrease the number of parallel systems heavy water management systems. This may be possible if a cost-effective detritiation technology is available to provide design options for tritium management.

Tritium is produced in heavy-water reactors as a normal consequence of neutron absorption by the deuterium atoms of the heavy water in the moderator and heat transport system. Tritium also undergoes β decay with a half-life of 12.3 years to balance the rate of tritium production. In a CANDU reactor, the tritium inventory accumulates more rapidly in the moderator than in the heat transport water because the moderator water is continuously exposed to a neutron flux during operation while the heat transport water spends a large fraction of its time outside of the core and absorbs a lower neutron dose. As a consequence, the tritium concentrations slowly increase during normal operation with the tritium concentration always being about 40 times higher in the moderator than in the heat transport system.

CANDU reactors are designed for safe operation with tritium in the moderator and heat transport system up to the end-of-life inventories. The design is based on a defense-in-depth approach supported by management of the heavy water inventories in the reactor based on design principles that include:

- minimization of heavy water leakage from all systems,
- collection of heavy water from known potential leak points (e.g., heat transport pump seals),
- collection of vapour heavy water within the containment building, and
- segregation of the moderator water with its relatively high tritium concentration from the heat transport water with its lower tritium concentration.

The first tree design principles also minimize the potential losses of expensive heavy water from the reactor and contribute to control of the operating costs of the reactor. The design features to minimize heavy water (and tritium) losses from the reactor systems are supported by leak management monitors for tritium in containment air and monitors for heavy water/tritium in process water. Tritium management arises as a natural consequence of good cost-effective management of the heavy water inventory of the reactor.

Segregation of the high-tritium-concentration moderator heavy water from the low-tritium-concentration heat transport heavy water is important because of the potential for leakage of heat transport water is much higher. The heat transport system operates at a much higher temperature and pressure than the moderator and thus has a greater driving force for leakage to containment. In addition, the heat transport system is considerably more complex and has many more locations at which heavy water losses can occur (e.g., the fuelling machine and spent fuel handling system). Maintaining the tritium level in the heat transport system heavy water as low as possible helps to minimize tritium release from these potential leak points.

Strict segregation of high and low tritium level water contributes to reactor construction and operating costs and there is potential for cost savings in eliminating the duplication that segregation requires. The intent of this paper is to outline some of the opportunities for cost reductions that can arise with the availability of detritiation.

2. DETRITIATION

Cost savings through the redesign of heavy water management systems can only be achieved if there is a cost effective process available for tritium removal from the heavy water inventories. The cost savings possible with new heavy water management systems may not be the only consideration in offsetting the cost of detritiation. Reactor owners may also decide to invest in detritiation for the following reasons.

(1) Public safety perceptions. While current reactor stations operate well below regulatory limits, tritium releases contribute to the total station emissions. The release of any radioactive material has a negative public perception burden and there are pressures from the public (and the regulators) to implement ALARA steps to further reduce emissions.

(2) Dose reduction to workers. Tritium in the containment building air contributes to the radiation dose to plant workers and is a factor in the maintenance cost of a reactor. Elimination of tritium at the source (reducing the tritium concentrations in heavy water systems) is one of the health physics strategies that can contribute to reduced worker dose. However, the effectiveness of this strategy is dependent on other workplace safety practices.

The potential contribution of detritiation to tritium management will be tempered by the fact that this can be only one element of an overall strategy to limit potential tritium emissions. It is by no means certain that reduction of the tritium inventories in reactor water will lead to either lower tritium emissions or lower plant worker doses. Both of these objectives also depend on plant management and maintenance standards and practices. Nevertheless, a reduction in the tritium inventories in reactor systems would, in principle, give plant managers the ability to lower emissions and doses and greater flexibility to manage within safety and regulatory emissions limits and dose limits.

3. DETRITIATION TECHNOLOGY

Detritiation of heavy water can be accomplished using several different techniques. The technology chosen will depend on a number of economic and logistical factors. Among these, the quantity of water to be treated and the target level for detritiation loom the largest.

Two different approaches can be adopted for the detritiation of heavy water reactors. The first is establishment of a large central extraction facility with transportation of tritiated heavy water from several nuclear power stations. The second is the establishment of much smaller extraction facilities that are integrated into individual power stations. A significant difference between the approaches is the size and timing of the capital investment that is required.

One advantage of localized, detritiation at individual nuclear stations is the design flexibility that this allows. The tritium extraction facility could be directly integrated into the station heavy-water management systems minimizing the need for storage tanks and heavy water inventories in storage or in transit. Location of the extraction facility within the reactor containment building also can take advantage of the controlled containment atmosphere and tritium monitoring systems to manage potential tritium leakages from the detritiation process.

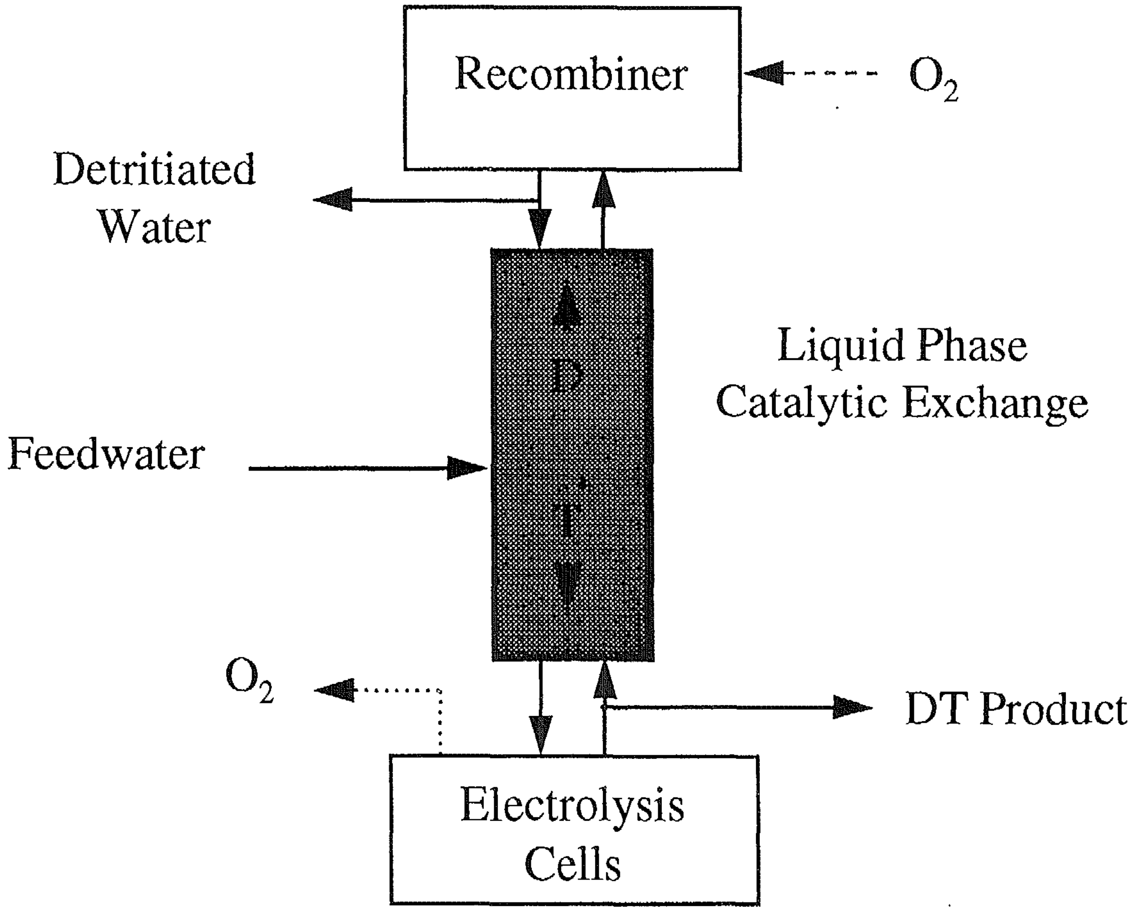

FIGURE 1 Combined Electrolysis and Catalytic Exchange Process (CECE)

4. AECL DETRITIATION TECHNOLOGY

AECL has developed a technology for the separation of the isotopes of hydrogen based on a catalytic exchange process. This technology is known as the Combined Electrolysis and Catalytic Exchange process (CECE)[1]. The CECE process was originally developed for the separation of deuterium from normal hydrogen in light water, but it can also be used to separate trace levels of tritium from deuterium in heavy water.

The CECE process is illustrated schematically in Figure 1. A feedstock of tritiated heavy water is separated into a product stream of heavy water with a reduced tritium concentration and a product stream of deuterium gas enriched in DT. The degree of detritiation of the heavy water and the tritium concentration in the product gas stream can determined by the design of the system. The cost will increase with the degree of detritiation desired and will also be affected by the concentration of tritium in the deuterium gas stream.

The CECE technology provides an alternative to the conventional detritiation systems which include cryogenic distillation. Cryogenic distillation is a capital intensive process that is best suited to the treatment of large quantities of tritiated heavy water. In contrast, the CECE technology can be modularized to the size appropriate to an individual reactor with no capital cost penalty.

The deuterium gas product of a CECE detritiation facility requires further processing. In a large-scale central detritiation facility, the tritium could be further concentrated in this gas by cryogenic distillation. The concentrated tritium would then be stored for sale or disposal (through radioactive decay). For a CECE facility located at a reactor station, the tritium-containing deuterium gas can be stored on titanium beds directly. These beds can then be transported for further tritium concentration at a different facility elsewhere, if desired, or stored to allow tritium decay and the eventual recovery of the deuterium. A large fraction of the operating cost of a CECE facility would be the cost of the titanium beds and the sequestered deuterium. This cost is dependent on the concentration of the tritium in the deuterium gas that can safely be handled and stored. AECL is in the process of developing and proving the CECE detritiation technology.

5. CANDU DESIGN OPTIONS WITH DETRITIATION

With the availability of cost effective detritiation, there are opportunities for more flexibility in the design of the heavy water systems. The flexibility and range of options available will depend on the degree of detritiation that can be achieved. Cost savings can arise in three ways.

(1) Lower system design and construction costs.

One factor in the classification of nuclear systems for engineering design and construction is the maximum radioactivity content of the heavy water (essentially the tritium concentration for most systems). In Canada, systems which will contain less than 10 Ci/kg (370 GBq/kg)of tritium may be designed and constructed to the Canadian Standards Association nuclear code requirements of CSA-N285 Class 6. Systems which may contain more than 10 Ci/kg of tritium must meet the more stringent and more expensive requirements of CSA-N285 Class 3.

(2) Integration of parallel systems.

The availability of detritiation removes a key barrier to the transfer of water between the moderator and heavy water systems. This is particularly true if the detritiation facility is integrated into the plant heavy water management systems.

(3) Improved emissions control.

Reduction of tritium levels in heavy water systems is one element of an overall emissions control strategy. It may allow design changes and cost savings in other areas while achieving improved levels of emissions control.

Clearly the greatest potential for cost reduction would be provided by a detritiation facility with a capacity sufficient to keep the moderator tritium level below 10 Ci/kg and a detritiation efficiency sufficient to produce heavy water with a tritium concentration below 0.1 Ci/kg. Meeting the first target would open up the possibility of designing moderator auxiliary systems to a lower code classification. In practice, a detritiation facility would need the capacity to maintain the moderator at a level somewhat below 10 Ci/kg to provide a margin for plant operation. Achieving this would essentially require that the detritiation facility be sized to remove the annual production of moderator tritium (about 5 Ci/kg per annum in a CANDU 6). Meeting the second target would ensure that any detritiated water which is added to the heat transport system will not increase the tritium concentration in the heat transport water.

The following sections outline in the potential impact of detritiation on several of the heavy water systems in the CANDU reactor where changes could be made and cost savings found. The feasibility of these design changes have not been fully evaluated and hence the options discussed are speculative at present.

5.1 Heavy Water Supply System

The Heavy Water Supply System in the current CANDU reactor designs consists of three subsystems: the D_2O Storage System, the D_2O Cleanup System and the D_2O Upgrader. The D_2O Storage System provides storage tanks and associated equipment for the management of the reactor D_2O inventory. The D_2O Cleanup System provides ion-exchange columns, filters, strainers and associated equipment to remove contamination from heavy water recovered from spills or other sources. The D_2O Upgrader consists of distillation columns and associated equipment remove light water from recovered heavy water and maintain the heat transport and moderator heavy water at the high deuterium isotopic purities required for cost-effective reactor operation.

There are two parallel sets of equipment in all three subsystems (Figure 2 illustrates this with a schematic for the D_2O Storage System). One set of equipment is used to treat water with a high tritium concentration (for the moderator) and the second set is used to treat water with a low tritium concentration (for the heat transport system). The parallel heavy water cleanup and storage systems are normally kept isolated to prevent contamination of the low tritium water with high tritium water.

Detritiation would make possible a major redesign of the D_2O management systems. One option for integrating a detritiation facility into reactor heavy water management is shown

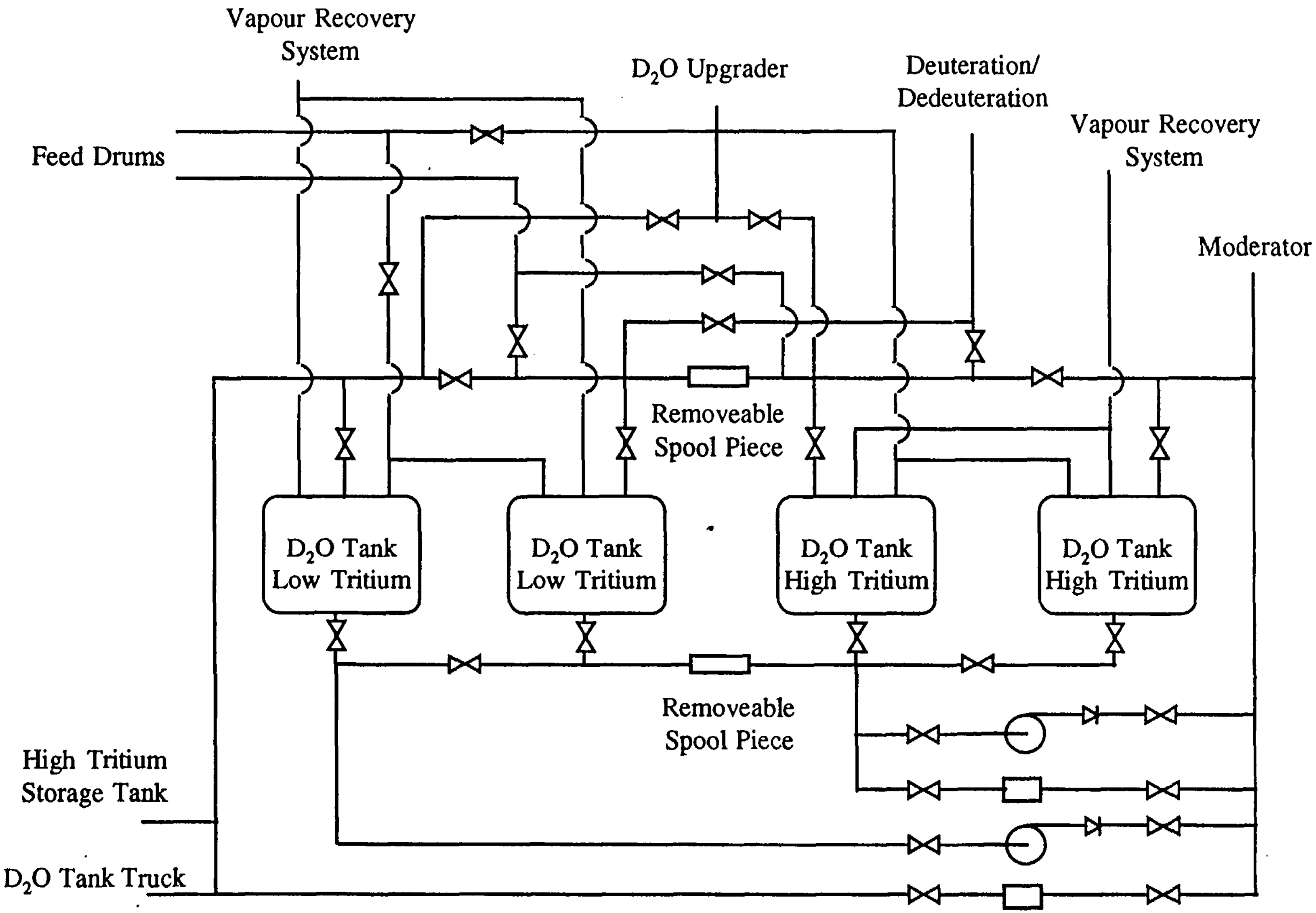

FIGURE 2 Heavy Water Supply System

schematically in Figure 3. Moderator heavy water with a relatively high tritium level would be treated in the detritiation facility and low-tritium water would be cycled back into the moderator and into the heat transport system. Heat transport water with a relatively low tritium level would also be cycled through the moderator after lithium removal.

In addition Figure 4 shows schematically how the other reactor water could be processed. Heavy water from the heat transport system, the leak collection system (and spills) and containment air driers could be processed by a single D_2O Cleanup System to remove lithium and other chemical contaminants. Clean water from this system would be transferred to a single heavy water storage system with three tanks for low-isotopic, high-tritium water, low-isotopic, low-tritium water and high-isotopic high tritium water. Water in the storage system would be processed by the Detritiation Facility and a single D_2O upgrader as required by reactor operations. Water from this the storage system would be used to supply the Deuteration/Dedeuteration System, moderator systems and the heat transport system (with addition of lithium as required to maintain the heat transport chemistry requirements).

This conceptional redesign of the D_2O management system eliminates a considerable amount of equipment. The cost implications of such changes will depend on the full implications of changing the D_2O management philosophy the loads on the remaining management systems and the cost of operating an integrated system. Specific impacts of this conceptual design include the following:

(1) The D_2O Storage System can be constructed to code Class 6 since the tritium concentration in all heavy water would be less than 10 Ci/kg.

(2) The D_2O Upgrader System can be constructed to code Class 6 since the tritium concentration in all heavy water would be less than 10 Ci/kg.

(3) The D_2O Cleanup System would remain code Class 3 to allow for safe handling of events where fission products may be released to the heavy water.

(4) With the elimination of one set of D_2O cleanup equipment, the remaining equipment would need to be redesigned to handle heavy water from all sources and remove lithium.

(5) The single distillation column remaining in the D_2O Upgrader System would need to be redesigned to handle all reactor heavy water.

(6) Elimination of one of the D_2O upgrader columns would save both money and equipment space. The latter impact would particularly help offset the requirements of adding a detritiation facility within the containment building.

5.2 Moderator Purification System

The Moderator Purification System is currently designed to code Class 3 because of the tritium inventory in the moderator water and the accumulation of activation products removed from the moderator water by the ion-exchange resins. Lowering the tritium inventory in the moderator water is unlikely to lead to a change in code classification and cost savings for this system because of the additional radioactivity burden in the ion-exchange resins.

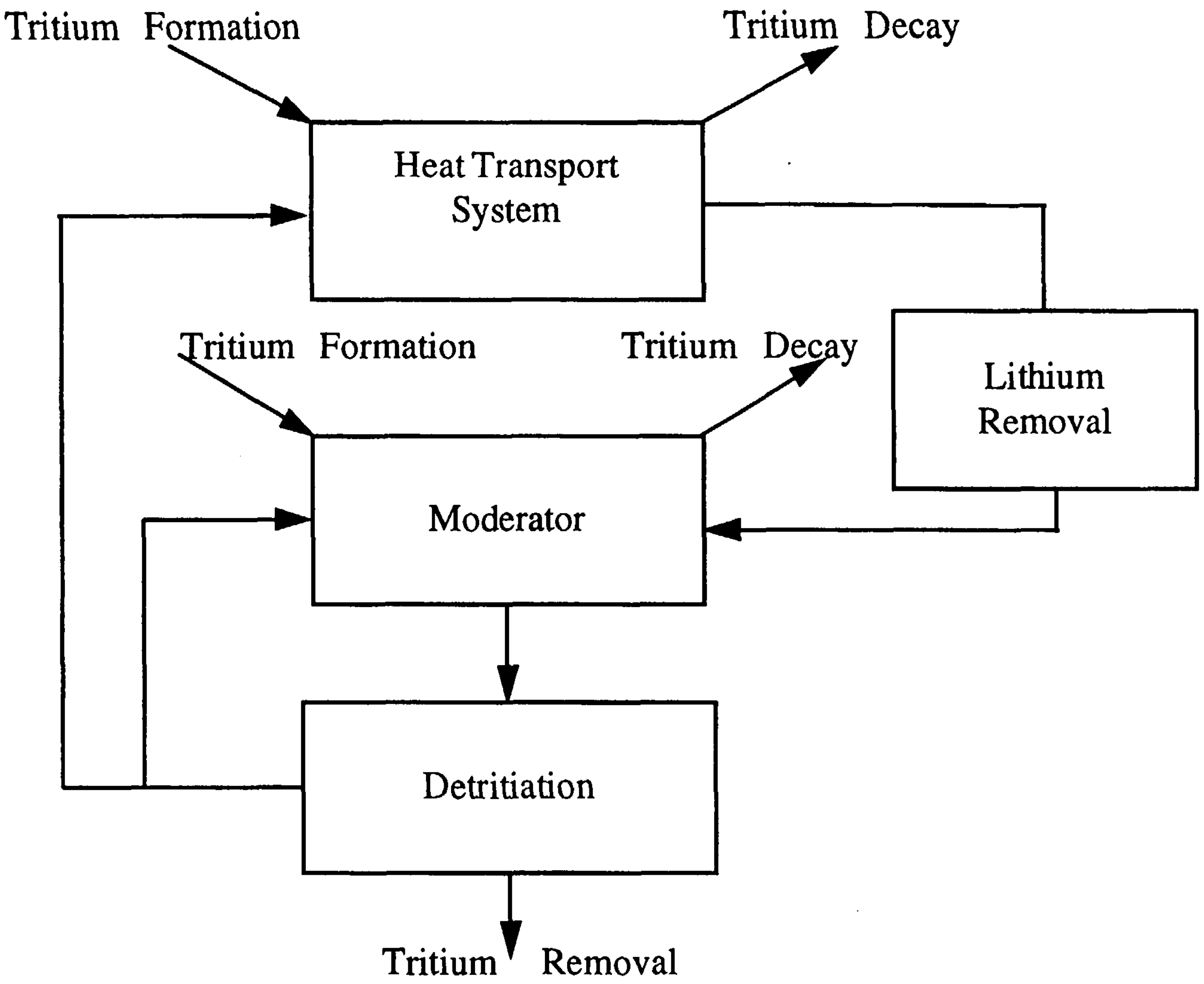
Tritium Formation
Tritium Decay
Heat Transport System
Tritium Formation
Tritium Decay
Lithium Removal
Moderator
Detritiation
Tritium Removal

Figure 3

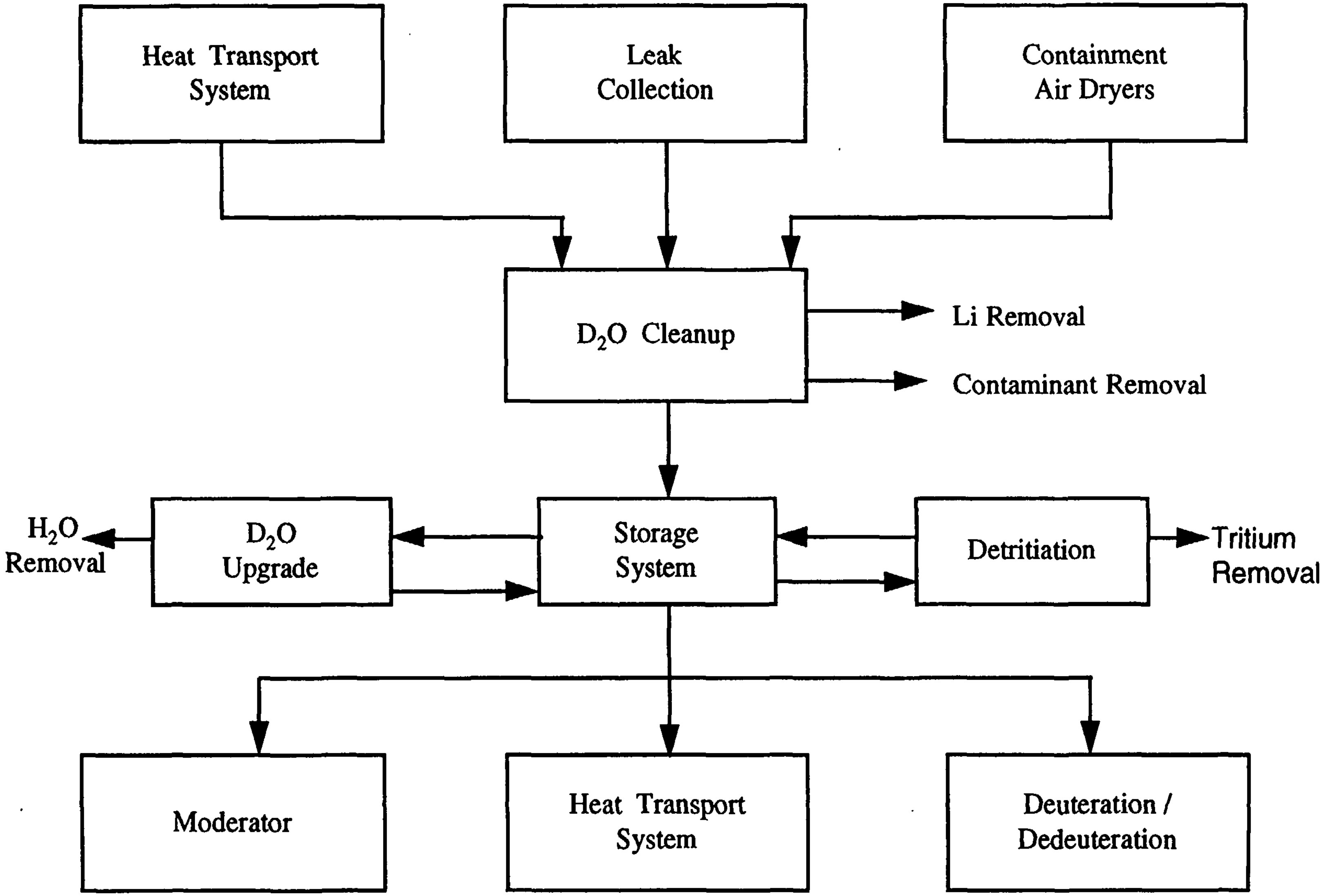

FIGURE 4 Heavy water processed by a single Heavy Water Cleanup System to remove Lithium and other Chemical Containments

5.3 Deuteration/Dedeuteration System

The Deuteration/Dedeuteration System is designed to remove light water from fresh ion-exchange resins prior to their use in the moderator and heat transport water purification systems and then to remove the heavy water from the spent resins. Two parallel duplicate systems are currently provided to handle the moderator and heat transport resins separately and prevent accidental cross-contamination of the water in the two systems. This prevents both tritium addition to the heat transport water and lithium addition to the moderator water.

With the provision of detritiation, it is possible to reduce the Deuteration/Dedeuteration System to a single unit for handling the ion-exchange resins of both the moderator and heat transport purification systems. This becomes possible if the heavy water used for the deuteration step can be taken from the output of the detritiation facility (at pH 7 to ensure the moderator safety systems are not compromised). Heavy water removed from the resins can be transferred to the D_2O Cleanup System and then recycled.

The Deuteration/Dedeuteration System is currently Class 3 because of the tritium level of the heavy water and the inventory of radioactivity on the spent resins being dedeuterated. Since detritiation will not affect the latter activity levels, those elements of the system that will contain the spent resin will need to remain Class 3.

5.4 Moderator Cover Gas System

The Moderator Cover Gas System is a closed gas-recirculating system designed to limit the buildup of deuterium (produced by D_2O radiolysis) in the gas spaces above the moderator. This system is currently designed to code Class 3 based on the tritium concentration in the moderator water and safety analyses of the occupational dose consequences of a system failure. If the moderator tritium concentration can be maintained below 10 Ci/kg it may be possible to redesign this system to code Class 6.

5.5 Heat Transport/Moderator D_2O Collection Systems

The D_2O Collection System consists of two parallel sets of equipment for the collection and transfer of both the moderator and heat transport water from various sources within the reactor building including pump and valve seals. If the D_2O management system is redesigned to manage and detritiate the heavy water collected from all leak points, then half of the current collection tanks and pumps could be eliminated. At present it is possible to directly recirculate leakage water back to the source system. This design change would eliminate direct recirculation of recovered heavy water leaks to either the moderator or heat transport system and would increase the load on the D_2O Cleanup and D_2O Upgrader Systems. Analysis is required to determine whether this would be a cost effective improvement.

5.6 D_2O Vapour Recovery System

CANDU reactors have a D_2O Vapour Recovery System to capture D_2O which escapes to the containment atmosphere from the reactor systems as a result of leakage (during normal operation or maintenance). The recovery system is based on separation of the reactor building into three zones:

(1) The reactor inlet/outlet vaults and steam generator enclosure (accessible only during reactor shutdown),

(2) The accessible area.

(3) The moderator equipment enclosure.

The three zones are designed to provide segregation of the building atmosphere based on tritium content. The segregation is achieved by appropriate air flow barriers and differential pressures to ensure air flow from low-tritium to high-tritium zones. Each zone is provided with ducting, instrumentation and air driers to separately collect D_2O with different tritium contents.

The D_2O vapour recovery system provides two functions. It prevents the escape of leaked D_2O and allows for recycling of a valuable capital asset. It is also a component of the health physics strategy to minimize the dose from airborne tritium to plant workers. For the latter function, the separation of the reactor building into separate zones and the isolation of the moderator enclosure is important because of the high tritium content of water that may leak from moderator systems.

If the moderator tritium level can be maintained below 10 Ci/kg, there may be an opportunity to eliminate the requirement for a separate moderator zone. The reactor containment could be managed with only two zones, only one of which would be normally accessible during reactor operation. This change in ventilation philosophy requires not only low tritium levels in the moderator, but also good maintenance practices on moderator systems and may not be cost effective to implement.

6. CONCLUSION

Detritiation may be considered as one component of the strategy to safely manage the tritium inventories in a heavy water reactor. AECL is working on the development of new technology to remove tritium from heavy water at individual reactors. Detritiation would add to the cost of constructing and operating a reactor. However, there are a number of design changes which on-line detritiation could make possible that could result in substantial cost savings. If the detritiation technology is not too expensive, the advantages gained by redesign could lead to overall savings in the cost of future reactors.

The full benefit of cost savings from detritiation would arise from three major changes in the reactor design philosophy:

(1) Elimination of duplicate parallel equipment for moderator and heat transport water D_2O management system.

(2) Combination of the reactor D_2O vapour and liquid recovery systems.

(3) Reduction in the design requirements (where warranted) to the lower code classification permitted by low tritium levels.

Several conceptual design changes that could be considered with detritiation have been discussed in this paper. The feasibility of these conceptual designs and their cost implications have not been fully evaluated. Until further information becomes available on the costs of improved detritiation technology and a more detailed evaluation of design options is performed, there can be no conclusion regarding the overall cost benefit of detritiation.

REFERENCE

]1] MILLER, J.M., SHMAYDA, W.T., SOOD, S.K., AND SPAGNOLO, D.A., "Technology Developments for Improved Tritium Management", proceedings of the Technical Committee Meeting on Advances in Heavy Water Reactors, IAEA-TECDOC-738, 1994.