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# COMBINED ELECTROLYSIS AND CATALYTIC EXCHANGE (CECE) UPGRADERS – AN ALTERNATIVE TO WATER DISTILLATION (DW) HEAVY WATER UPGRADERS

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## Abstract

All operating CANDU stations are equipped with Water Distillation (DW) systems for heavy water upgrading. An alternative process, Combined Electrolysis and Catalytic Exchange (CECE), is being considered for use in future CANDU stations. The CECE process has several operating advantages over DW systems, including lower emissions and heavy water losses.

Changes in nuclear standards may change seismic requirements and classification of upgrader systems. These changes will likely increase the cost of heavy water upgraders, but the cost increase will be smaller for a CECE upgrader.

Research at Chalk River Labs has identified materials for use in the CECE process that will not chemically or mechanically degrade when exposed to highly tritiated water.

## 1. Introduction

Heavy water upgrading is a unique requirement of CANDU power stations, as both the Primary Heat Transport System (PHTS) and Moderator are filled with heavy water. Upgrading is used to maintain the heavy water at very high purity for optimum station performance. While both the PHTS and Moderator systems are closed loops that have been carefully designed to minimize leakage and light water ingress, there will be some mixing of light water with the heavy water during maintenance and other activities. Two upgrading systems are included to maintain separation between the low-tritium water in the PHTS and the high-tritium water in the Moderator system.

All operating CANDU stations use water distillation (DW) systems for heavy water upgrading. AECL has developed an alternative technology for separating light water and heavy water, known as the Combined Electrolysis and Catalytic Exchange (CECE) process. This process has been fully demonstrated in pilot-scale facilities and the benefits of this process include lower tritium and carbon-14 emissions, lower losses of heavy water and lower requirements for steam, cooling water and chilled water.

AECL is currently considering the replacement of the DW upgrader with a CECE upgrader in the baseline CANDU station design. This change is being considered due to the potential reductions in overall cost and emissions.

There have been concerns raised in the past about the long-term performance of components of the CECE process when exposed to highly tritiated water. Research has been conducted over the last several years to address these issues. There have also been changes in the standards applicable to heavy water upgrader equipment that will impact the costs of both upgrader designs.

This paper discusses the results of this research and how changes in standards may impact the relative costs of the CECE upgrading process compared to water distillation.

# 2. Process descriptions

## 2.1 DW upgrading process

The DW upgrader is designed to take advantage of the small difference in boiling points (relative volatility) between $H_2O$ and $D_2O$, which tends to concentrate the heavier $D_2O$ in the liquid phase and the lighter $H_2O$ in the vapour phase. The relative volatility between $H_2O$ and $D_2O$ is 1.056 at 50°C, which is typical of operating conditions in a DW system.

The $D_2O$ upgrading system in most CANDU stations consists of two DW upgraders, one each for the moderator and PHTS $D_2O$ systems. A schematic diagram of a DW upgrader is shown in Figure 1. The DW upgrader consists of distillation towers, a reboiler, a condenser, evaporators and a vacuum unit. Each distillation tower is filled with a high-performance mass transfer packing. A feed stream of downgraded $D_2O$ is introduced at an intermediate point in the column. Countercurrent flows of water and water vapour come into contact over the packing. The more volatile $H_2O$ migrates to the top of the column, while the heavier $D_2O$ moves to the bottom.

Two product streams are generated in a DW upgrader. The top product, which has a low $D_2O$ concentration, is discarded. The bottom product, of reactor grade purity (>99.8% $D_2O$), is returned to the $D_2O$ management system. In practice, some stations discard the top product with a higher $D_2O$ concentration in order to yield a higher product isotopic.

DW columns operate at below atmospheric pressure (from 13 kPa in the head condenser to 25 kPa in the reboiler) to take advantage of the larger D/H separation factor at lower temperatures. Typical operating temperatures in a DW unit range from 25°C (head cold trap) to 70°C (reboiler). Utility requirements include steam, cooling water, chilled water, and electricity.

## 2.2 CECE upgrading process

The CECE process is based on catalytic hydrogen isotope exchange between water and hydrogen gas which favours heavier hydrogen isotopes (deuterium and tritium) in the water phase and lighter isotopes (protium) in the gas phase. For hydrogen-water exchange, the separation factor is 2.85 at 50°C.

A $D_2O$ upgrading system based on CECE technology also consists of separate HTS and Moderator upgraders. CECE heavy water upgraders combine electrolysis, which splits water into hydrogen and oxygen, with Liquid Phase Catalytic Exchange (LPCE). A schematic diagram of a CECE upgrader is shown in Figure 1.

In the LPCE process, liquid water and hydrogen gas are contacted countercurrently in a column filled with proprietary AECL catalyst. Natural water enters at the top of the column and is enriched in the heavier isotopes (deuterium and tritium) as it passes down the column. A feed stream of downgraded heavy water is introduced at an intermediate point in the column. At the bottom of the column, instead of a reboiler, the water is split into hydrogen (deuterium) and oxygen in the electrolytic cell. The hydrogen is returned to the LPCE column. As the hydrogen passes up the column, the heavier isotopes are stripped by the down-flowing liquid water. At the top of the LPCE column there is no condenser. Hydrogen gas is vented from the top of the LPCE column.

The product stream from a CECE upgrader is a high purity heavy water stream that is returned to the $D_2O$ Management System. Normal operating pressure and temperature of the CECE process are 120-180 kPa and 50-60°C, respectively.

The electrolysis cells (e-cells) at the bottom of the LPCE column split water into hydrogen and oxygen gases. The e-cell also exhibits a kinetic isotope effect that strongly favors the concentration of the heavy isotopes in the liquid phase [1], [2].

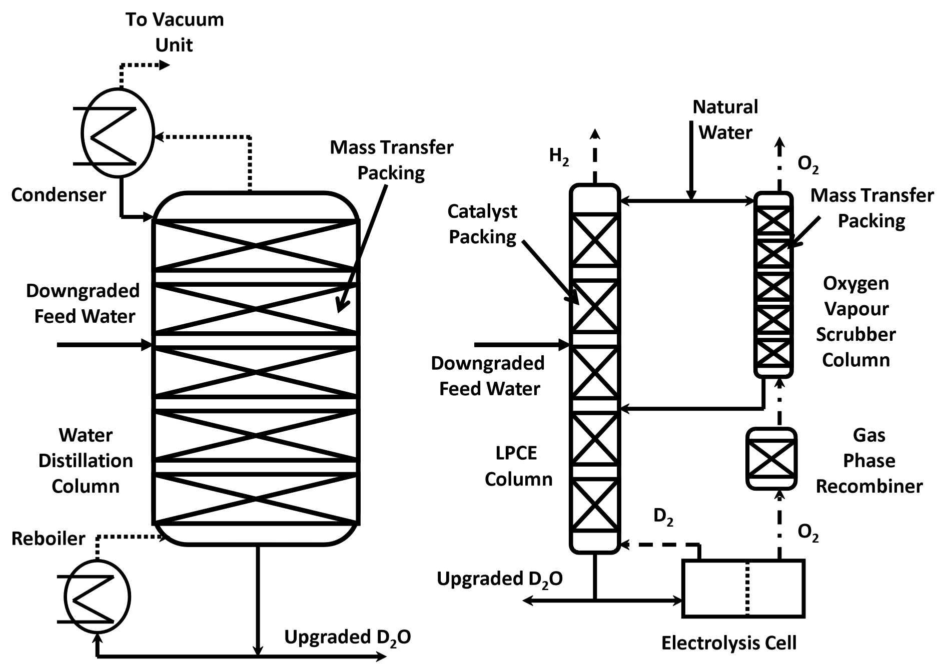


Figure 1 Schematic Diagrams for DW and CECE Upgraders, indicating the relative process sizes

The oxygen stream generated by the electrolysis cell contains trace amounts of hydrogen that must be removed to minimize deuterium and tritium losses. The oxygen stream generated by the electrolysis cell passes through a Gas-Phase Recombiner (GPR) to oxidize any hydrogen isotopes that diffused through the e-cell membrane to the oxygen side. This unit is filled with proprietary AECL catalyst that is similar to that used in the Passive Autocatalytic Recombiners being used for hydrogen mitigation in several CANDU stations. After exit from the GPR, the oxygen stream passes through an Oxygen Vapour Scrubber (OVS), where a counter-current stream of natural water removes the deuterated water vapour from the humid $O_2$ stream and returns the deuterium and tritium to the LPCE column. The oxygen stream can then be safely vented.

## 3. Impacts on capital costs

The DW upgraders that are installed in most CANDU stations were supplied by Sulzer Inc. of Switzerland. In 2004, Sulzer made a business decision to no longer supply a complete heavy water upgrading plant, but would continue to offer the column packing and internals for the upgrader columns as well as a process basic engineering package. Around that time, AECL commissioned an independent study to compare relative costs of the available heavy water upgrader technologies, including DW and CECE. This study was completed in 2005 and concluded that the installed cost of a CECE upgrader would likely be less than the installed cost of a DW upgrader. The results of this study have motivated AECL to consider replacing the DW upgrader with a CECE upgrader in the baseline CANDU station design.

There have also been changes to the standards applied to nuclear power stations that may have an impact on the costs of heavy water upgraders in future CANDU stations. These changes, and their implications, are described below.

### 3.1 Advances in technology

Since the comparative study on upgraders was completed, there have been a number of improvements made that should further reduce the cost of CECE upgraders. One area of improvement is in the design of electrolysis cells. Most commercial electrolysis cells are designed for small-scale production of hydrogen, with the goal of high performance for hydrogen production. AECL has been working with electrolysis cell manufacturers for several years to help them modify their designs to meet the needs of CECE-based heavy water upgrading and detritiation plants. In CECE applications, the cell must have minimal leakage of hydrogen and water to reduce tritium emissions, and must also be constructed of tritium-compatible materials to ensure acceptable long-term performance. Earlier cost estimates for tritium compatible e-cells were much higher than the costs of conventional cells.

The cooperation between AECL and the e-cell manufacturers has resulted in minor modifications of off-the-shelf electrolysis cell designs that have replaced current materials with tritium-compatible materials and increased cell leak-tightness without compromising cell performance. The result is that e-cells suitable for use in the CECE process have been reduced significantly in cost.

There have also been reductions in the cost of catalyst used in LPCE columns. AECL has conducted catalyst development research over many years with a goal of reducing the overall cost of the catalyst needed for a CECE plant. There are two approaches that have been used: developing new formulations to reduce the cost of materials used in catalyst production; and reduce the labour required to produce catalyst. The result of this research is the activity of the catalyst produced has been either maintained or enhanced while the cost of production has fallen. These enhancements have further reduced the capital cost of a CECE upgrader.

### 3.2 Changes to seismic qualification requirements

The heavy water upgrading system is designed and located so that it will not interfere with critical reactor systems during an accident. The system also needs to be designed to meet the requirements of CAN/CSA-N285.0 [3] to minimize the potential for events of severe leakage from tanks or piping containing tritiated heavy water. Thus, critical components/vessels of the upgrading system must be designed to ensure their integrity is maintained during external accident conditions such as earthquakes, tornados, etc., to limit the on-site and off-site consequences during such an event.

All DW upgraders currently in operation have been designed to meet the seismic requirements of the National Building Code of Canada (NBCC). At this time it is uncertain whether the heavy water upgraders in future CANDU stations will have to meet a higher seismic classification level, such as Seismic Category A (maintain pressure boundary integrity or structural integrity during and following the earthquake event) in order to limit releases during seismic events. .

There will be a significant increase in the cost of a DW upgrading system if the heavy water upgrading system is required to meet more stringent seismic qualification levels. The packed towers in the DW upgrading system are typically one metre in diameter and 35 m in height, so the seismic reinforcement structures required are likely to be complex and expensive.

A CECE upgrader, including the upgrader tower structure, has been designed to ensure that the effects of an external hazard such as an earthquake or tornado (with a frequency of $10^{-3}\cdot yr^{-1}$), does not lead to radiation exposures from the site being above site limits. As shown in Figure 1, the LPCE and OVS columns in a CECE upgrader are relatively small compared to the DW column. The LPCE and OVS columns in a CECE upgrader have diameters in the range of 0.15-0.2 m, and the LPCE columns require about 3% of the packed volume of a DW unit. Thus, the seismic reinforcement structures required for the CECE process will likely be much simpler and less expensive.

### 3.3 Changes in CAN/CSA-N285

The most recent revision of the standard CAN/CSA-N285.0 [3] changed the requirements that distinguish between Class 6 and Class 3 components in CANDU nuclear power plants. In previous versions of the standard, a Class 6 system did not contain radioactive substances or contains radioactive substances with a tritium concentration not exceeding 370 GBq tritium per kg $D_2O$ (10 $Ci\cdot kg^{-1}$). In the latest revision of the standard, a Class 6 system may only contain radioactive substances with a tritium concentration not exceeding 74 $GBq\cdot kg^{-1}$ (2 $Ci\cdot kg^{-1}$).

In the designs of DW upgraders, the entire Primary Heat Transport upgrader was classified as Class 6, as the upgrader would only process heavy water with a tritium concentration up to 2 $Ci\cdot kg^{-1}$. For the Moderator upgrader, the heavy water feed may contain tritium concentrations up to 90 $Ci\cdot kg^{-1}$, which is the end-of-life concentration of tritium in the Moderator. Nonetheless, Class 6 was applied to the distillation columns, vacuum unit and any other portion of the plant which normally operates under vacuum or normally contains fluid with a concentration greater than 97.5% $H_2O$ by weight. All other Moderator systems were classified as Class 3. Class 6 to Class 3 code breaks were found on the valves between the DW column and the feed tanks, the bottom product system, the bottom circulation system and the vent system. The services and utilities that supplied both the PHTS and Moderator upgraders were classified as Class 6.

With the change in requirements for Class 6 systems and components, the classification of the PHTS upgrader should not change. However, it seems likely that the distillation columns in the Moderator upgrader will become Class 3. This change in classification would result in a significant increase in the cost of a DW upgrading system.

In a CECE upgrader for the PHTS, the e-cell and associated equipment will contain water with tritium concentrations above 2 $Ci \cdot kg^{-1}$. Assuming a separation factor of two for the E-cells, the highest tritium concentration in the upgrader will be 4 $Ci \cdot kg^{-1}$ at the end of design life. Electrolysis cells are not usually manufactured to meet Class 3 requirements, but these requirements can be met by installing the e-cell within a separately ventilated and monitored enclosure which does not require operator entry.

Under the new version of the standard, both the PHTS and Moderator upgraders using the CECE process would contain some equipment that is Class 3 (mainly the e-cell and bottom LPCE columns) and the majority would remain Class 6. Systems are exempt from Class 3 requirements when the piping used is smaller than ¾-inch, and much of the equipment in the CECE upgrader is small so this exemption would apply. Modular construction techniques were used effectively in the building of the CECE upgrader that was part of the heavy water production demonstration facility in Hamilton, Ontario.

Reactor build projects are now using modular construction techniques as a way to reduce costs and compress project schedules. The smaller equipment used in CECE upgraders would be much simpler to build and install using modular construction than the large columns and equipment used in DW systems. The CECE demonstration projects smaller equipment in the CECE upgrader is much simpler to build and install using

The results of the changes described above would be an increase in the capital cost of the upgrading system, but the fact that the equipment is relatively small means that the cost increase would be smaller for a CECE upgrader than for the DW system.

## 4. Component performance in highly tritiated water

One concern raised about CECE upgraders in the past is the performance and reliability of components when exposed to highly tritiated water. In particular, questions have been raised about the materials used in the catalysts and electrolysis cells and whether they are functionally affected by high tritium levels.

In the CECEUD Demonstration Facility in Chalk River [4], the electrolysis cell was exposed to tritiated water with concentrations up to 220 Ci/kg, while the LPCE catalyst was exposed to tritium concentrations up to 100 Ci/kg. There was no evidence that the high tritium concentrations had any negative impact on the performance of the catalyst. While the electrolysis cell performance was not affected by the high tritium concentrations, the membrane in the electrolysis cell was made of a polysulphone impregnated asbestos membrane separator. Since the use of asbestos is no longer permitted, an alternate material has to be found for the cell membrane.

Over the past several years, AECL has conducted a research program to determine the effect that high radiation levels have on the materials used in CECE process components, and identify materials that will not be adversely affected by the presence of highly tritiated water. The current focus of the research program is to identify suitable materials that can perform well in the highly tritiated environment within the electrolysis cells. A number of well-known sealing materials, such as Viton and EPDM, have been tested for use in tritiated environments and can be used for gaskets and seals.

AECL has been active in evaluating the radiation durability of Nafion[1] and IMET membranes (for HyStat® cells produced by Hydrogenics) with a practical goal to exploit these electrolysis technologies for use in the CECE process. In addition, AECL has been developing new membrane materials that are expected to have high performance within a highly tritiated environment.

### 4.1 Testing of Nafion in PEM cells

There has been a great deal of interest in using Proton Exchange Membrane (PEM) electrolysis cells in the CECE process. PEM Electrolysers offer several advantages compared to conventional alkaline electrolysers. These advantages include compactness, low water inventory and no caustic.

Some materials in PEM cells, such as the membrane and gaskets, are based on polymer materials such as polyperfluorosulfonic acid (PFSA). Materials such as Nafion are widely used as membranes in solid electrolyte in PEM fuel cells and electrolysers because of their high proton conductivity, good chemical stability and mechanical strength. While there are many articles in the literature about preparing PEM membranes to withstand high temperatures or improve performance, there have been few articles that focused on evaluating PEM membranes for radiation resistance [5], [6].

PEM electrolysers are currently being considered for use in tritiated environments, such as the Water Detritiation System (WDS) at the International Thermonuclear Experimental Reactor (ITER). Long term exposure experiments of the PEM membranes in a tritium environment have been completed [7], [8], [9]. To meet ITER requirements, the PEM electrolyser needs to maintain its performance during two years of operation in tritiated water of 243 Ci/kg, the design tritium concentration. This corresponds to an irradiation dose of 530 kGy from tritium. The tests conducted indicated that the Nafion membranes may meet the ITER requirements, but with some loss of performance.

AECL has also completed some baseline characterization of PEM cell membrane materials, mainly Nafion 112. The intent was to develop an understanding of the physical and chemical changes and performance effects for a typical PEM material after doses of gamma radiation as well as beta radiation from tritium. Nafion samples placed in water with hydrogen or oxygen purge gas were irradiated in a $^{60}$Co Gammacell. The doses absorbed by the samples ranged from 140 to 1250 kGy. The physical integrity of the samples was characterized by visual inspection before and after irradiation. When possible, irradiated membrane samples were decontaminated and used to prepare membrane-electrode assemblies (MEA) that were tested in a single fuel cell to determine any change in the proton exchange capacity of the membrane due to irradiation. Water samples from the irradiation vessel were analyzed for total organic carbon (TOC), fluoride, sulfate and sulfur to determine if these impurities originated from the Nafion due to irradiation. Beds of isotope

[1] Nafion is the registered trade name of DuPont.

exchange catalyst were exposed to the purge gases from the irradiation vessel to investigate the potential deactivation characteristics of irradiation products.

Visual observations of the AECL samples showed that gamma irradiation at doses below 400 kGy (equivalent to four years of exposure to tritiated water at 180 $Ci \cdot kg^{-1}$) produced severe damage to the membrane. Increasing the radiation dose increased the damage to the membrane. Since the membrane samples were very fragile, only the samples that received doses less than 400 kGy could be formed into MEAs for fuel cell testing. These irradiated membranes lost 29 to 46% of their proton exchange capacity due to irradiation, which would undoubtedly have a significant effect on the performance of the e-cell. Significant concentrations of TOC, fluoride and sulfate originating from the membrane were detected in the water, confirming the detrimental effects of radiation on the membrane. Exposure of these irradiation products in the hydrogen purge stream to LPCE catalyst produced deactivation of the catalyst. However, the catalyst could be regenerated almost completely by heating it to 120°C with oxygen.

To study the effect of beta radiation, samples of Nafion were placed in tritiated heavy water and stored for over three years. In that time, they were exposed to about 200 kGy of beta radiation. Other Nafion samples in light water were stored similarly in light water that contained no tritium. No visible changes in any of the samples were noted, and analysis of the membranes using scanning electron microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) data did not indicate any major break down of the polymer structure. However, analysis of the water for anions and organic carbon showed similar degradation products as found in previous gamma exposures and by other groups [8].

The samples exposed to tritiated water were decontaminated and made into MEAs for testing in a fuel cell. The loss in proton conducting performance was 20-25% for 200 kGy dose, which was less than the 29-46% loss in proton conductivity observed when the samples were exposed to gamma irradiation.

Thus, AECL's experiments have shown that Nafion will be fundamentally affected by exposure to tritiated water over periods suitable for CANDU upgraders.

## 4.2 Other PEM cell membrane materials

Since AECL's studies have shown that Nafion membranes will not maintain their performance when exposed to tritium and other ionizing radiation, AECL has also initiated programs to develop alternative membranes for a PEM electrolyser that are suitable for long periods of service in water with high tritium concentrations. Several polymers with good radiation resistance have been identified in the literature, such as polysulfone (PSU), poly(ether ether ketone) (PEEK), polystyrene (PS) and polyimide (PI) [10].

As was the case with the studies using Nafion, the studies with other materials include preparation of membranes and membrane electrode assemblies (MEAs), as well as testing the radiation durability of the materials by exposing them to gamma radiation and tritiated water. A number of potential PEM membranes have been prepared and are currently being tested to determine their conductivity and mechanical properties.

In order to provide a high dose to the materials in a short time and to reflect real process conditions involving exposure to high levels of tritium, high specific activity tritiated water (1000 Ci/L) will be used for the exposure tests. Such tritium concentrations are much higher than those found in the water at end-of-life in a CANDU station and the main intention of this was to investigate the use of CECE for concentrating tritium, however, the results are still of practical value for studying upgrading equipment.

### 4.3 Small-scale CECE test facility

The most effective way to determine the stability and performance of e-cell membranes is to construct a complete CECE system and operate it at relevant conditions. Because of the complexity of building facilities to operate with high tritium, AECL has constructed two small-scale closed loop CECE rigs designed for continuous operation. One system was built to perform high tritium tests, while the second system was built to act as a test system to finalize design details and for use as a reference system for operations without tritium. The non-tritiated system, known as mini-CECE-D, has been operating for over one year. Operating experience from this facility has been used to design and construct a similar tritiated system, which is known as mini-CECE-T.

The simplified system flow diagram for mini-CECE-D is given in Figure 2. It was designed as a completely closed system, capable of operating unattended for long periods, but allowing continuous monitoring of the main system performance parameters. Further details of the equipment in the two test facilities are given in Reference [12].

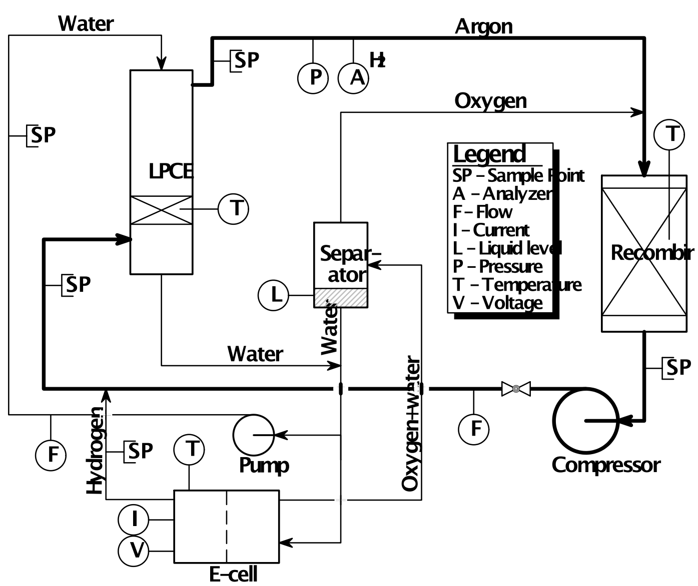


Figure 2 Flow Diagram of mini-CECE-D

The water in the non-tritiated rig is currently at about 50% heavy water to permit the use of a gas chromatograph to the deuterium concentration measurements in the gas phase. The deuterium concentration in the gas phase is typically ~0.4% for the current operating conditions.

The electrolyser is run at constant current and the voltage across the cell is monitored to assess the performance of the cell and membrane(s). Deuterium analyses are used to determine the deuterium distribution through the system to follow the performances of the e-cell, LPCE and recombiner as the system operates.

The rig that will contain tritium, mini-CECE-T, is currently being commissioned. This test rig will have a liquid inventory of 125 mL and a tritium inventory of 125 Ci when filled with heavy water containing 1000 Ci/L of tritium. The rig was designed as a compact unit so that it could be enclosed in a secondary containment (glove box). The performance of the components in the mini-CECE-T will be followed by monitoring the tritium concentrations throughout the system.

The design of mini-CECE-T was based very closely on the experience gained in building and operating mini-CECE-D, along with a good understanding of tritium system safety. The goal was a system able to reliably contain very high tritium concentrations for long periods. In this second CECE system, isotope separation performance will be measured by the separation of tritium from deuterium. A significant advantage of this is that it makes in-line measurement feasible (using ion chambers).

Mini-CECE-T was designed and built by Tyne Engineering Inc. The system, which is currently being commissioned, is larger and more complex than mini-CECE-D, but still small enough to be enclosed in an inert atmosphere (argon) glove box that is kept free of tritium with its own atmosphere clean-up system. The extra features added to the CECE process included a small system to convert tritium gas to tritiated water up to the required concentration (1000 Ci/kg) and equipment to safely transfer tritiated water around the system.

The mini-CECE-T will be put into service in the near future initially with 1000 Ci/kg tritiated water and Nafion 110 cell membrane. When available, the Nafion will be replaced with the most promising materials from the membrane development program and long-term performance of each CECE component will be monitored.

### 4.4 IMET Cell

Another potential candidate for the electrolysis cell is the HyStat® electrolysis cell, marketed by Hydrogenics Corporation. As part of the qualification program, the components of the electrolysis cell that will be exposed to the tritiated electrolyte need to be qualified for the potential irradiation condition that may prevail in the CECE process. The materials that require qualification are the polysulfone cell frames, the EPDM gaskets and the IMET® inorganic membrane.

In the present study IMET® membrane samples were exposed to hydrogen purged 35% KOH at 70ºC and gamma-radiation in two separate tests. The dose that the IMET® membrane samples received was equivalent to about a 5.3 year exposure to 130 Ci•kg$^{-1}$ tritiated water. The results from these tests showed that, within experimental error, the physical properties of the IMET® membranes, which include weight, thickness and linear dimensions, did not change. In addition, chemical analyses of collected samples showed that the Total Organic Carbon (TOC) and sulfur release were both well within acceptable limits.

During the gamma-radiation exposure tests, the vent gas from the reaction vessel passed through a glass column containing the random bed catalyst that could be used in the LPCE column for hydrogen isotope exchange. Some irreversible catalyst deactivation was observed following the radiation exposure tests. The level of catalyst deactivation that was observed would require <1% down time per year, which is within the acceptance criterion.

## 5. Conclusions

The CECE process continues to be a reasonable alternative to the DW process for heavy water upgrading in CANDU stations. A recent independent study concluded that the cost of a CECE upgrader would be less than the cost of a DW upgrader. Replacement of the DW upgrader with a CECE upgrader in the baseline CANDU station design is currently under consideration.

Changes to the standards applied to heavy water upgraders will very likely increase the cost of the system, but the increases in cost for CECE upgraders are expected to be much lower than the cost increase for a DW system. There are expected to be an increased level of seismic requirements for heavy water upgraders in the future, and these changes will have a significant impact on the cost of DW upgraders due to the relatively large equipment. The much smaller CECE upgrader will not be impacted as strongly by these changes. Enhancements in the activity of catalysts have further reduced the size of the equipment required for a CECE upgrader.

The concerns raised in the past about material performance in CECE upgraders are being addressed by a research program currently underway at Chalk River Laboratories. The use of PEM electrolysis cells is currently under study with the goal of reducing the liquid holdup in the system and avoiding the use of caustic. New membrane materials with better radiation resistance are being developed, and these new materials are being tested in a small-scale CECE system that will operate at tritium concentrations that are much higher than the end-of-life conditions within CANDU reactors.

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