
Future Trends in Heavy Water Production

By M.R. Galley

Tendances futures de la production d'eau lourde

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Presented at the Fourth Pacific
Basin Conference,
Vancouver, 1983 September 11-15

Présenté lors de la quatrième
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à Vancouver, du 11 au 15 septembre
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RÉSUMÉ

La production mondiale d'eau lourde, qui couvre près de cinquante ans, a connu de fréquentes pénuries; mais cette situation n'est plus la même, du moins au Canada. On dispose maintenant de bonnes réserves d'eau lourde et d'une capacité de production installée suffisante pour répondre à la demande, au Canada comme à l'étranger, au cours des dix prochaines années sinon plus. Plus de 90% des stocks d'eau lourde ont été produits par le procédé GS. Cependant, il se peut que l'on choisisse une autre méthode lorsque le moment sera venu de relancer la production d'eau lourde. D'autres pays tels que l'Inde et l'Argentine ont déjà choisi le procédé de l'échange ammoniac-hydrogène comme technologie de rechange pour répondre aux besoins d'une partie de leur propres programmes de production. Malgré les surplus actuels d'eau lourde, la recherche et le développement de nouvelles technologies sont très actives, en particulier au Canada et au Japon, car on sait qu'il subsiste d'excellentes occasions pour la production future à l'aide de procédés moins onéreux et plus acceptables, du point de vue écologique, que le procédé GS déjà éprouvé ou que l'option ammoniac-hydrogène. Le présent compte rendu fait état des perspectives que nous laissent entrevoir certains de ces nouveaux procédés; il les compare aux méthodes actuelles établies et évalue leur impact éventuel sur la situation future en matière d'approvisionnement.

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ABSTRACT

World heavy water production has spanned nearly fifty years and, for much of that period, the commodity was often in short supply, but that situation has changed, at least in Canada. There are now adequate reserves of heavy water and sufficient installed production capacity to service Canadian domestic and export demands for the next ten years or beyond. More than 90% of the world's inventory of heavy water has been produced by the GS process but this may not be the method that is chosen when the time comes to expand heavy water production again. Other countries, such as India and Argentina, have already chosen ammonia-hydrogen exchange as an alternative technology for part of their domestic production programs. Despite the present surplus of heavy water, research and development of new technologies is very active, particularly in Canada and Japan, because it is recognized that there are still attractive opportunities for future production by processes that are both less expensive and environmentally more acceptable, than either the demonstrated GS process or ammonia-hydrogen alternative. This paper describes the prospects for some of these new processes, contrasts them with the present established methods and assesses the probable impact on the future supply situation.

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1.0 INTRODUCTION

The commercial production of heavy water has covered a period of nearly fifty years and has involved the use of several quite different processes which include both physical and chemical separation methods. Heavy water is a key component for the operation of natural uranium reactors of the CANDU type, being equivalent in importance to uranium enrichment in light water reactors (LWRs). However, unlike uranium enrichment, the technology of heavy water production has been developed fairly openly and there are innumerable references to hydrogen isotope separation techniques in the published literature. Many researchers have been attracted to the separation of hydrogen isotopes because they are the easiest to separate, the separation factors are relatively large and many different methods are possible. Those methods that are practical are also more typical of standard industrial separation processes than the special techniques needed to separate the uranium isotopes. The fact that R&D programs on the separation of hydrogen isotopes are relatively inexpensive and more straightforward than for uranium isotopes has allowed many nations to participate in R&D and, in several instances, to proceed to commercial production.

Using information that has been gained through Canada's involvement in heavy water production, this paper attempts to assess the current status of heavy water production technologies and to predict what the future trends will be. It is appropriate to conduct a review of this type at the present time because, for the first time in the history of heavy water production, there is an overall world surplus of production capacity and there is now time to consider whether present methods are adequate and whether there are prospects for new and less expensive methods of production.

2.0 HISTORY OF HEAVY WATER PRODUCTION

The first heavy water production plant, based on the electrolysis of water, was built at Rjukan, Norway in 1934 and, in a modified form, it is still in operation. During World War II, three water distillation plants were built in the U.S.A. and a combined electrolysis/hydrogen-water exchange plant was built at Trail, B.C., Canada. The distillation plants were only in service for about two years, but the Trail plant operated until 1956. Renewed interest in the production of heavy water in the U.S.A. led to the construction of the Dana and Savannah River plants utilizing the water-hydrogen sulphide exchange (GS) process. Dana operated from 1952 to 1958 then leaving Savannah River as the principal Western World supply of heavy water. The capaci-

ty of Savannah River was progressively reduced by closing sections of the plant until production finally ceased at the end of 1981.

From the 1950's onwards, several smaller plants or pilot plants using various processes were built and operated for short periods in the Federal Republic of Germany, France, Switzerland and India. A hydrogen distillation plant was built in the Soviet Union and a GS process plant was built in the Peoples Republic of China but few details are known of their capacity.

Large scale production of heavy water started in Canada in 1970 and, within a few years, the plants at Bruce, Port Hawkesbury and Glace Bay accounted for more than 90% of the Western World's installed production capacity.⁽¹⁾ These Canadian plants use the GS process that was first employed at Dana and Savannah River.

3.0 STATUS OF HEAVY WATER PRODUCTION IN CANADA

The economic recession at the beginning of this decade has reduced the demand for heavy water production in Canada to the extent that all plants are now operating well below their maximum demonstrated capacity. There are also two plants, Bruce HWP-D and La Prade, each with a nominal capacity of 800 Mg D₂O/a that have been mothballed in a partially completed state. There is no immediate prospect of these plants being completed and put into operation.

3.1 Bruce HWP-A and B, Ontario Hydro

Because of very low electrical load growth forecasts and the subsequent deferral of heavy water demands for Ontario Hydro's committed nuclear program, Ontario Hydro is faced with less demand for production from BHWP-A and B. This reduction in demand and an inventory reduction program has led to reduced outputs from BHWP-A and B.

Since 1982 October, the four enriching units that comprise BHWP-A and B have been derated to 80% of their demonstrated capability and it is expected that this will continue until the mid-1980's when there is a possibility of two of the four units being mothballed temporarily or permanently shut down. The remaining two operating units will be capable of meeting current scheduled demands for the Pickering-B, Bruce-B and Darlington Generating Stations.

3.2 Port Hawkesbury HWP & Glace Bay HWP, AECL

At the time of writing, 1983 January, these plants are in full operation but at slightly reduced flows and temperatures in order to conserve energy. AECL has proposed to the Canadian Government that these plants be shut down because an adequate inventory of heavy water has now been established. It is not clear at

this time if or when these plants will be mothballed or decommissioned.

AECL has now accumulated an adequate reserve of heavy water that is sufficient to service the CANDU stations now in operation outside the Province of Ontario and to provide the initial heavy water charges for at least two new 600 MWe CANDUs.

4.0 WORLD-WIDE HEAVY WATER PRODUCTION

Outside Canada, heavy water is currently produced in Norway, India and probably in the Peoples Republic of

TABLE 1
OPERATING HEAVY WATER PRODUCTION PLANTS

	Start-Up (Year)	Nominal Capacity (Mg D ₂ O/a)	Process
Canada			
Port Hawkesbury ⁽¹⁾ (AECL)	1970	400	GS + DW ⁽⁵⁾
Bruce HWP-A (Ontario Hydro)	1973	800	GS + DW
Glace Bay ⁽²⁾ (AECL)	1976	400	GS + DW
Bruce HWP-B (Ontario Hydro)	1979	800	GS + DW
India			
Nangal (DAE)	1962	14	Electrolysis + Hydrogen distillation
Baroda (Gujarat Fertilizers)	1981 ⁽³⁾	67	Monothermal ammonia- hydrogen + ammonia distillation
Tuticorin (Southern Petro- Chemical Industries)	1981	71	Monothermal ammonia- hydrogen + ammonia distillation
Talcher (Fertilizer Corporation of India)	1982 ⁽⁴⁾	63	Bithermal ammonia- hydrogen + ammonia- water + DW
Kota (DAE)	1982 ⁽⁴⁾	100	GS + DW
Norway			
Rjukan (Norsk Hydro)	1934	12	Electrolysis + steam- hydrogen exchange + DW

NOTES:

(1) Owned and operated by Canadian General Electric Co. until 1975.

(2) Rebuilt from original plant.

(3) First started in 1977 but set back by fire.

(4) Unconfirmed.

(5) Hydrogen sulphide — water exchange (GS) with final enrichment by water distillation (DW).

China and the Soviet Union. In the past, plants have also operated in France, the Federal Republic of Germany, Switzerland and the United States but none of these are still functioning. New plants are under construction in India and Argentina and planned in Romania.

Tables 1 and 2 show the type of processes used in these various plants and their approximate capacity. Despite the emergence of hydrogen-based processes, the thirty year old GS system is being used for new

plants in India and is being proposed for use in Romania and Argentina. The continuing interest in the GS process suggests that its production costs are still competitive and also that it is the only demonstrated process for situations where the desired output is in excess of the extractable deuterium in available hydrogen or synthesis gas streams. The production plants established or proposed in countries other than Canada and the United States will now be briefly reviewed.

TABLE 2
PROCESSES USED FOR THE PRODUCTION OF HEAVY WATER

Process	Plant	Status
Water Distillation (DW) (see note below)	Morgantown, W. Va. Childersburg, Ala. Dana, Ind. (U.S.A.)	Operated from 1943 to 1945
Electrolysis	Rjukan & Glomfjord (Norway)	In operation
	Nangal, India	In operation
	Trail, B.C., Canada	Operated from 1944 to 1956
	Domat Ems, Switzerland	Operated from 1960 to 1967
Hydrogen-Sulphide- Water Exchange (GS)	Peoples Republic of China	Unknown
	Dana, Ind., (USA)	Operated from 1952 to 1958
	Savannah River, S.C. (USA)	Operated from 1952 to 1981
	Port Hawkesbury, N.S. (Canada)	In operation
	Glace Bay, N.S. (Canada)	In operation
	Bruce A&B, Ont., (Canada)	In operation
Hydrogen Distillation	Kota, India	Commissioning
	Domat Ems, Switzerland	Operated from 1960 to 1967
	Hoechst, F.R.G.	Operated from 1958 to 1960
	Toulouse, France	Operated from 1958 to 1960
	Nangal, India	In operation
Methanolic Ammonia- Hydrogen Exchange	Soviet Union	Unknown
	Mazingarbe, France	Operated from 1968 to 1972
	Baroda, India	In operation
Bithermal Ammonia- Hydrogen Exchange	Tuticorin, India	In operation
	Talcher, India	Commissioning
Steam-Hydrogen Exchange	Trail, B.C., Canada	Operated from 1944 to 1956
	Rjukan, Norway	In operation

NOTE: Water Distillation (DW) has been widely used as a final enrichment step for the GS and other processes.

4.1 Norway

The Rjukan and Glomfjord plants of Norsk Hydro in Norway manufacture heavy water as a byproduct of the electrolysis of water where the hydrogen is used for the manufacture of ammonia and fertilizers. Originally built as a conventional electrolytic cascade, the plants now incorporate steam-hydrogen exchange steps to recover some deuterium which would otherwise be lost in the electrolytic hydrogen product.⁽²⁾ This modification avoids the economic penalty of burning some hydrogen and recycling the water produced to a preceding stage. Final enrichment to reactor grade was also by electrolysis but has since been changed to water distillation. The future of heavy water production from these plants is now uncertain and there are reports that Norsk Hydro are considering closure.

4.2 India

India is believed to have three operating heavy water plants, two plants being commissioned and a proposal for two new heavy water plants. The first plant at Nangal⁽³⁾ started operating in 1962 and the process is based on the electrolysis of water followed by the distillation of liquid hydrogen. This latter process had been piloted by Linde at Hoechst in the Federal Republic of Germany using a flowsheet devised by Clusuis and Starke.⁽²⁾⁽⁴⁾ The performance of this plant is reported⁽³⁾ to be excellent and it continues to produce about 14 Mg D₂O/a.

When India decided to construct CANDU power stations, a need arose for much larger heavy water plants and construction began in 1972 on a second heavy water plant at Kota near the Rajasthan Atomic Power Station. The Kota plant is rated at 100 Mg D₂O/a and utilizes the GS process but because India did not have access to technology or equipment from North America after 1974, there have been considerable delays in completing this plant.

India was also involved in a program of construction of several large ammonia plants to fulfill its huge fertilizer requirements and the consequent availability of synthesis gas ($N_2 + 3H_2$) prompted a decision to incorporate heavy water production with three of these plants. The 67 Mg D₂O/a plant at Baroda and the 71 Mg D₂O/a at Tuticorin utilize the monothermal ammonia-hydrogen exchange process demonstrated at Mazingarbe, France (see Section 4.3). The 63 Mg D₂O/a plant at Talcher will use the bithermal ammonia-hydrogen exchange process developed by Uhde in the Federal Republic of Germany.

In addition to the delays experienced for the large GS plant at Kota, the two operating ammonia-hydrogen plants at Baroda and Tuticorin suffered acute operating problems. The plant at Baroda suffered a set-back during commissioning as a result of an explosion and fire in 1977 December and it and the Tuticorin plant have been constrained by dependence on their associated ammonia plants. It has been suggested⁽³⁾ that future plants would be more reliable if they obtained their feed

from a water-hydrogen or water-ammonia exchange step and if their dependence on outside energy supplies is minimized.

Recent reports from India^(3a) state that the Baroda and Tuticorin plants are in operation while Talcher and Kota are in advanced stages of commissioning. Proposals have been made for the construction of a coal-fired 185 Mg D₂O/a GS process plant at Manuguru and a 110 Mg D₂O/a ammonia-hydrogen plant at Thal Vaishet which would be associated with a fertilizer plant. Further plants will be needed by the year 2000 in order to satisfy India's target of 10,000 MW installed nuclear capacity.

4.3 France

Although France is no longer a producer of heavy water, it was responsible for the full-scale demonstration of the monothermal ammonia-hydrogen exchange process which was subsequently adopted by India and Argentina. When France was considering a program of heavy water reactors in the 1960's, a heavy water production plant was constructed at Mazingarbe. This plant utilizing technology developed by Sulzer, the CEA and other organizations in France, was coupled to a 330 Mg/a ammonia plant and was designed to produce 26 Mg D₂O/a. Production commenced in 1968 and the plant operated satisfactorily⁽⁵⁾ until 1972 when there was an explosion in the ammonia synthesis plant and all operations ceased. The experience gained from this process was used by the consortium Groupement l'Eau Lourde Procédé Ammoniac (GELPRA) for the design of the Baroda and Tuticorin plants in India and by Sulzer for the plant at Arroyito in Argentina.

France also had a small hydrogen distillation plant of 2 Mg D₂O/a capacity which was designed by L'Air Liquide and operated in Toulouse from 1958 to 1960.

4.4 Federal Republic of Germany

Heavy water production within the Federal Republic of Germany has been limited to the small hydrogen distillation plant at Hoechst⁽⁶⁾ which was capable of producing 6 Mg D₂O/a and operated from 1958 to 1960. However, there has been considerable involvement by research organizations (Karlsruhe) and companies (Linde and Uhde^(7,5)) in the development and construction of new processes. Linde has been prominent in the design of hydrogen distillation systems and Uhde designed the bithermal ammonia-hydrogen exchange plant at Talcher in India.

4.5 Switzerland

Sulzer Brothers Limited of Winterthur have played a leading role in the development, design and construction of heavy water production and nuclear reactor D₂O upgrading plants throughout the world. Within Switzerland itself, a small production plant (2 Mg D₂O/a) based on electrolysis, hydrogen distillation and water distillation operated from 1960 to 1967 at Domat Ems. Sulzer's experience in the development of packings for vacuum distillation systems has been extensively ap-

plied to heavy water upgrading systems at nuclear reactor sites and in association with a variety of primary enrichment systems. Sulzer also developed the venturi contactor used in their monothermal ammonia-hydrogen exchange process and, with Atomic Energy of Canada Limited^{(7,2)(7,3)}, conducted development work on the amine-hydrogen exchange process. Sulzer are currently involved in the construction of the Arroyito plant in Argentina.

4.6 Argentina

Argentina will soon become a substantial producer of heavy water when the 250 Mg D₂O/a plant at Arroyito is completed in 1985. This plant has been designed by Sulzer Brothers Limited and uses their monothermal ammonia-hydrogen exchange process. The continuous supply of deuterium from river water is effected by means of a water-ammonia transfer stage⁽¹⁴⁾. The plant is located adjacent to a hydraulic generating station and a natural gas field and will receive its energy from these sources.

The Arroyito heavy water plant has sufficient supply capability to produce the 2,500 Mg D₂O required between now and the year 2000 for the Atucha 2 nuclear generating station plus three other PHWR stations.

Argentina is also constructing a small GS process pilot plant with a 3 Mg/a supply capability. There are plans for the installation of an 80 Mg D₂O/a modular GS plant close to the ammonia-hydrogen plant at Arroyito but no schedule has been published.

4.7 Romania

Romania has built and operated a small GS process pilot plant and is believed to be planning the construction of a much larger GS process plant to support their CANDU nuclear power station program.

4.8 Soviet Union

The Soviet Union is known to be capable of producing substantial quantities of heavy water, as demonstrated by their past sales to India and Canada, but their current production methods have not been disclosed. A small scale plant based on electrolysis and hydrogen distillation was described by Becker⁽⁶⁾⁽¹⁶⁾ but other processes may now be in use.

4.9 The Peoples Republic of China

The Peoples Republic of China is believed to operate a GS process plant capable of producing approximately 20 Mg D₂O/a but no details have been published.

5.0 PRODUCTION PROCESSES IN USE OR PROPOSED

There have been several exhaustive reviews of the many possible ways of separating deuterium from hydrogen-containing sources and it is not intended to comment upon all of these in this paper. When Atomic Energy of Canada Limited became involved⁽¹⁵⁾ in the

development of heavy water production processes in the early 1950's, all known options were considered⁽⁸⁾ but few of these appeared to be economically attractive. The search for improved processes was described by Miller⁽⁹⁾ in 1975 and more recently by Rae^(7,1) in 1978. This section will summarily review those processes that have been used or have been seriously considered for use in full-scale production plants (see Table 3).

5.1 Water Distillation

Water distillation was only used briefly as a primary production method in the U.S.A. during World War II when cost was not a first consideration. The capital cost and energy requirements are excessive because of the low separation factor (about 1.05 at 50°C) but the process does become attractive when the feed material is already enriched to a concentration of 10% D₂O or higher. In this latter situation, water distillation is widely used as the final enrichment step for a variety of primary extraction processes and for upgrading the inventory of heavy water reactors. The process is both simple and reliable and benefits from great advances made in the design of high efficiency packing materials for vacuum distillation. In recent years, the availability of huge amounts of low grade waste heat from nuclear power complexes prompted a re-examination of water distillation as a primary process^(7,8) but even with low cost heat, the process is too capital intensive to be economic in comparison to the GS process, thus confirming several other earlier studies.

5.2 Hydrogen Distillation

This process is attractive because the separation factor is relatively high (1.5 at 23K) but this is offset by the cost of purifying and liquefying hydrogen. The method has been used for small plants in France, the Federal Republic of Germany, Switzerland and the Soviet Union where the feedstock was either electrolytic hydrogen or synthesis gas. The only operating facility at present is the Nangal plant in India where hydrogen distillation is used as the principal enrichment step. For large scale production, the process would require a source of pure, cold hydrogen and such streams may eventually be available if hydrogen becomes a widely used fuel. Hydrogen distillation is not likely to be competitive with processes such as ammonia-hydrogen exchange when the feedstock is synthesis gas due to the cost and complication of temporarily removing the nitrogen. Any future application of hydrogen distillation would only be an economic proposition if the full cost of hydrogen production and liquefaction was charged to some other process.

5.3 Electrolysis of Water

The electrolysis of water has two major advantages for heavy water production processes: the separation factor attainable in an electrolytic cell is the highest known for any process (except laser isotope separation) and the product hydrogen is very pure and hence suitable as direct feed to catalytic exchange processes (CECE) or

hydrogen distillation. Heavy water cannot be economically produced by electrolysis as a primary method unless the energy costs are charged to the end-user of the hydrogen. This is the case in Norway and India where the hydrogen is used for ammonia production, but in most situations it is usually less expensive to make hydrogen as synthesis gas by the steam-reforming of hydrocarbons. Electrolysis is also used as a method of upgrading the isotopic content of heavy water, particularly where the feed material already contains more than 50% D₂O. As will be discussed later, electrolysis could be widely used as a production method in the future if the "hydrogen economy" becomes a reality.

5.4 Water-Hydrogen Sulphide Exchange - the GS Process

This process has been described in detail many times⁽¹⁾ and has now probably reached its ultimate state of development in Canada. The only improvements that could be made are probably associated with contactor efficiency, leading to small benefits in heat economy.

Numerous flowsheet variations have been used or suggested which could yield improved recovery but at the expense of increased complexity of control. The GS process is still attractive because the many years of operating experience in Canada and the U.S.A. guarantee that, with access to this extensive know-how, a plant will perform as designed and at a known cost. The principal disadvantages of the GS process are that it is not economical in small unit sizes, there are environmental limitations and it is unsuitable for operation in a tropical climate unless expensive refrigeration is provided. In the latter case, this leads to high energy consumption or higher capital costs for a heat recovery system.

5.5 Monothermal Ammonia-Hydrogen Exchange

The Mazingarbe plant in France first used this process where deuterium is extracted from synthesis gas by contact with liquid ammonia in the presence of a catalyst (see Fig. 1). Further enrichment was by ammonia-hydrogen exchange at low temperatures with reflux

TABLE 3
NEW PROCESSES FOR HEAVY WATER PRODUCTION

Process	Status
Water-fed, monothermal ammonia-hydrogen exchange	250 Mg D ₂ O/a plant under construction at Arroyito, Argentina.
Monothermal hydrogen-water exchange (CECE process) based on electrolysis.	Pilot plant proposed for addition to electrolytic facility at Varennes, Que., Canada.
Bithermal hydrogen-water exchange.	R&D in progress to develop a catalyst for high pressure hot tower service.
Methane-hydrogen exchange plus hydrogen distillation	Inactive, energy costs are unattractive.
Monothermal or Bithermal amine-hydrogen exchange.	Inactive, but available as an alternative to ammonia-hydrogen exchange.
Monothermal hydrogen-water exchange (SRHWE Process) based on steam reforming of hydrocarbons.	R&D in progress.
Laser Isotope Separation Processes	Fundamental R&D in progress.

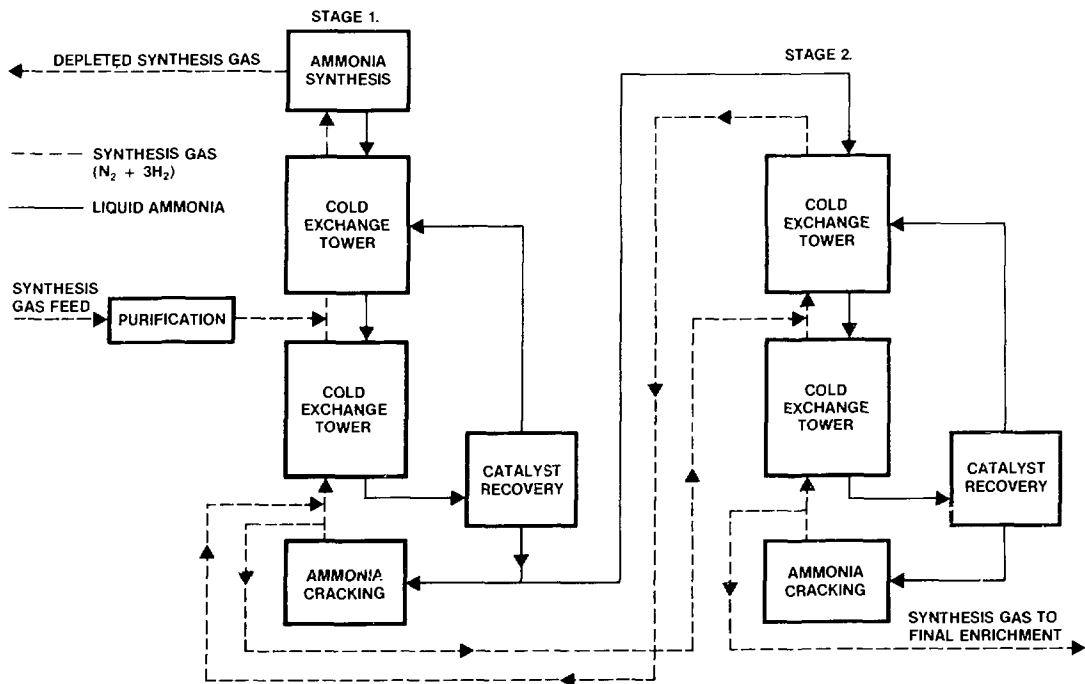


FIGURE 1 MONOTHERMAL AMMONIA-HYDROGEN EXCHANGE PROCESS AS USED AT BARODA AND TUTICORIN, INDIA

being provided by cracking ammonia to nitrogen and hydrogen. The process can extract up to 80% of the deuterium in the synthesis gas feed but the plant output is directly proportional to the size of the associated ammonia production plant. Mazingarbe was reported to have run very well during its lifetime but the performance of the similar Baroda and Tuticorin plants in India has been disappointing.⁽³⁾ However, this has not been primarily due to the ammonia-hydrogen exchange process but rather to the reliability of the ammonia plant and energy supplies.

Operation of the ammonia-hydrogen exchange process without links to a complex chemical plant should be demonstrated at Arroyito in Argentina where feed is introduced by equilibrating depleted ammonia vapour with water at natural concentration (see Fig. 2). This "front-end" step should permit the construction of monothermal ammonia-hydrogen exchange plants of any desired size.

5.6 Bithermal Ammonia-Hydrogen Exchange

The Talcher plant in India, designed by Uhde, uses the same chemical exchange reaction but the flowsheet is quite different (see Fig. 3). Reflux is provided by the use of a hot tower in addition to the cold tower, as in the GS process, thus obviating the need for cracking ammonia. The exchange tower internals are conventional sieve trays in contrast to the venturi contactors used by

Sulzer in the monothermal process. So far, no operating experience has been reported from Talcher and it is not known how performance will compare with the monothermal plants. The bithermal process could also be adapted to incorporate a water-feed step.

5.7 Bithermal Amine-Hydrogen Exchange

When Atomic Energy of Canada Limited (AECL) completed their survey⁽⁸⁾ of potential new processes for the production of heavy water in about 1968, they concluded that amine-hydrogen exchange was the most promising new method. The principal advantage over ammonia-hydrogen exchange was seen to be better separation factors, faster exchange rates^(7,4) and lower pressure operation. Pilot plant trials by AECL^(7,2) showed that the efficiency of conventional contactors was very low, but better than for the ammonia-hydrogen process, thus necessitating long contact times and relatively high pressure drops in the cold towers. A cooperative development program with Sulzer Bros. was started in 1974 and this resulted in successful pilot plant trials of the venturi contactor in the amine system. Sulzer prepared a detailed design for incorporating an amine-hydrogen exchange plant with an ammonia plant to be built in Western Canada. This proposal for a prototype plant coincided with an improvement in the performance of the GS process plants in Canada, and downward revisions in the rate of growth of nuclear

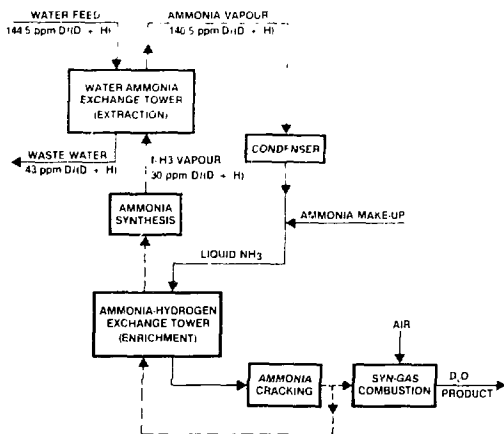


FIGURE 2 WATER-FED MONOTHERMAL AMMONIA-HYDROGEN EXCHANGE PROCESS FOR ARROYITO HWP, ARGENTINA

power so that the need for an alternative process began to disappear. At that time (1976), the amine process showed promise of producing heavy water at lower cost than the GS process, and probably lower than the ammonia process. Development work ceased shortly thereafter and there have not been any opportunities to revive the project since that time.

5.8 Hydrogen-Water Exchange

This exchange process has always been considered to be potentially attractive for two main reasons: rapid exchange of deuterium between water and hydrogen would facilitate the design of front-ends for various hydrogen based heavy water processes (see Fig. 4) and the separation factors are high enough to make a bithermal system an attractive alternative to the GS process. Many attempts were made to find a catalyst for the mixed phase reaction that would not become "blocked" by liquid water. The breakthrough came in 1970 when W.H. Stevens^(7,6) of AECL invented a "wet-proofed" platinum catalyst. During the following twelve years, the performance of this catalyst has been steadily improved and many potential applications have been discovered both for hydrogen-isotope separation and other purposes.

5.8.1 Combined Electrolysis and Catalytic Exchange (CECE Process) (Monothermal Hydrogen-Water Exchange)

One of the first suggested applications for the wet-proofed catalyst was in the CECE Process^(7,7) where a catalyst column can be used to pre-enrich the feed to a bipolar electrolytic cell by transferring deuterium from the hydrogen off-gas to the incoming water feed (see Fig. 5). This operation is analogous to the steam-

hydrogen exchange steps used at Trail and Rjukan. A three stage cascade of such units could produce reactor grade heavy water with relatively few transfer units in each stage. If the cost of hydrogen production could be charged to the end-user, the differential cost of heavy water production would be much lower than other known processes because the energy costs would be negligible. Alternatively, electrolytic hydrogen production could be made to be an economic proposition if the cost of production could be partially offset by revenue from the sale of byproduct heavy water. In either of these situations, it is now believed that the CECE process would have lower production costs than a conventional electrolytic cascade with hydrogen burners.

5.8.2 Bithermal Hydrogen-Water Exchange

The CECE process would be limited to relatively small unit sizes (6 MW of electrolysis power produces about 1 Mg D₂O/a) unless the demand for electrolytic hydrogen increases dramatically but a bithermal process could be built to any unit size.

The flowsheet would resemble the GS process (see Fig. 6) but fewer theoretical plates (or transfer units) would be needed because of the more favourable separation factors. Another advantage would be a less corrosive system with minimal environmental risk. This process will require the development of a version of the wet proof catalyst that will operate at higher temperatures (up to 150°C) and high pressures (up to 5000 kPa). However, the exchange rate is adversely affected by pressure and optimum energy utilization may dictate lower hot tower temperatures.

5.9 Laser Isotope Separation

The newest technology to impact on hydrogen isotope separation has been laser isotope separation (LIS) where particular isotopes of a substance can be selectively excited and then reacted to form an enriched product. Chalk River Nuclear Laboratories (CRNL) of AECL have already demonstrated that trace quantities of heavy water can be produced by LIS action on fluorine⁽¹¹⁾. Although the cost of providing laser energy is very high, it may to some extent be compensated by the very large single step separation factors, with values as high as 7000, that are attainable. At Ontario Hydro Research Division⁽¹⁰⁾, in addition to fundamental R&D, work is ongoing on evaluating the economics and conceptual designs for a LIS heavy water production facility.

A key design factor for a viable commercial process is the replenishment of the deuterium content of the starting material by an exchange step with water or hydrogen. Work is underway on this re-deuteration problem and the associated energy requirements.

Research and development work will continue on LIS heavy water production and will be diversified to cover the wide range of isotope separations which are amenable to this technique.

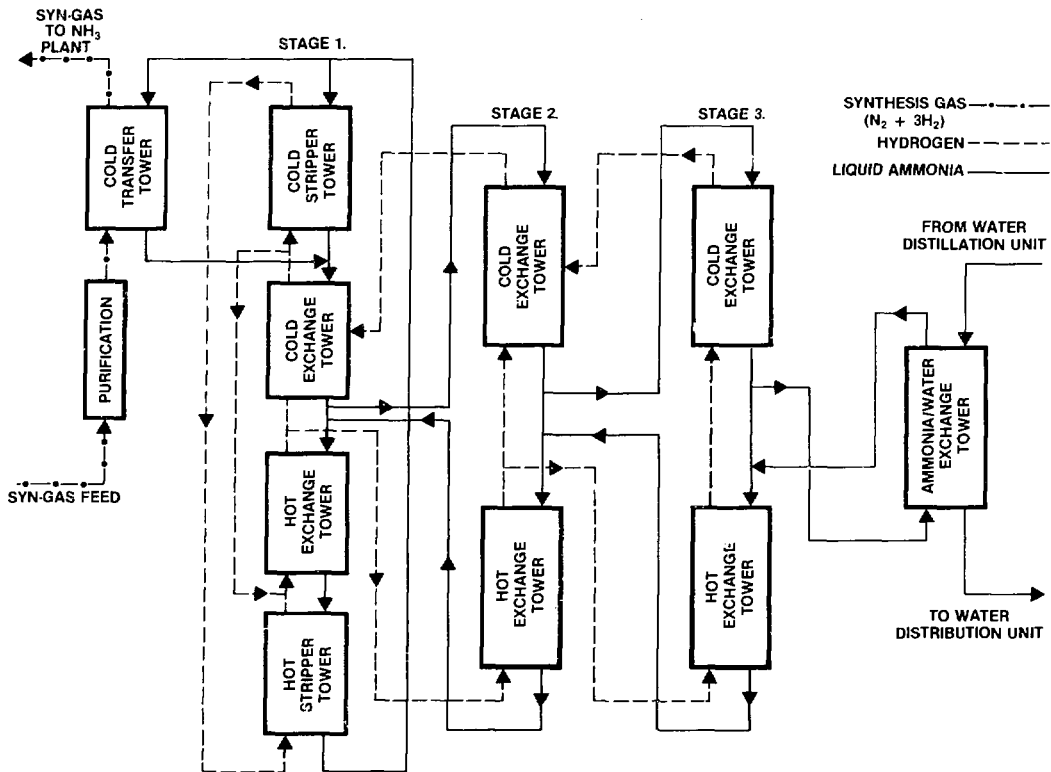


FIGURE 3 BITHERMAL AMMONIA-HYDROGEN EXCHANGE PROCESS AS USED AT TALCHER, INDIA

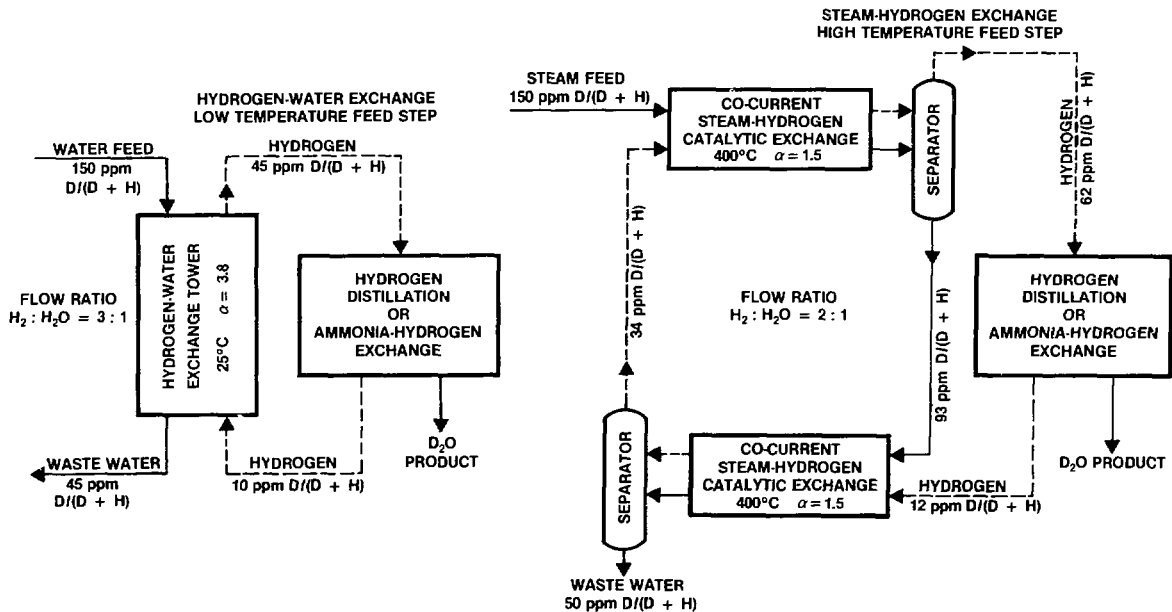


FIGURE 4 PROCESSES FOR TRANSFER OF DEUTERIUM FROM WATER OR STEAM TO HYDROGEN

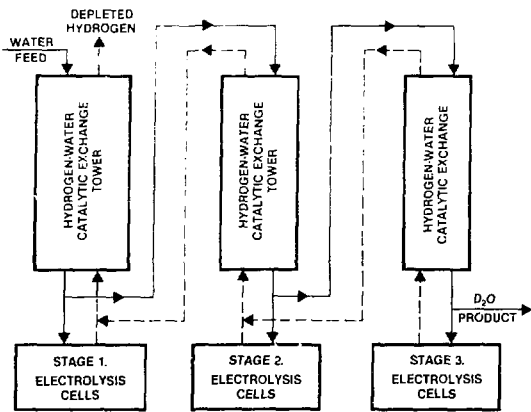


FIGURE 5 COMBINED ELECTROLYSIS AND CATALYTIC EXCHANGE (CECE) PROCESS

6.0 THE NEED FOR NEW HEAVY WATER PROCESSES

6.1 The Market

The current excess supply capability with respect to heavy water production has been well publicized within Canada, but this is not a world-wide phenomenon. In India there is currently a shortage of heavy water that is delaying the start-up of CANDU reactors but hopefully the existing heavy water production plants will eventually fulfill this need. India has also announced plans for further heavy water plant construction to prevent a recurrence of this situation. Other countries who are building CANDU reactors, such as Romania and Argentina, have heavy water plant construction programs. In the

case of Argentina, heavy water will also be required for Atucha-2 which is a KWU PHWR. In Japan, heavy water will be required for the 600 MWe ATR station but there are as yet no announced plans for domestic heavy water production. The known world demand for heavy water is summarized in Table 4.

It is not unreasonable to expect that the world economic recession will come to an end and there will be a revival in demand for nuclear power generation. When this happens, the market share for CANDU is likely to increase because of the unsurpassed performance record that has been established over the last ten years. With an increase in demand for CANDU stations, there will be a concomitant demand for heavy water. Confidence in an eventual resurgence of interest in the construction of new CANDU systems provides a strong incentive to maintain and improve heavy water production facilities. It should be remembered that the lead time for supplying heavy water to a newly committed CANDU is about four years, which is considerably less than the time needed to build, commission and operate a heavy water plant to produce the initial heavy water charge.

6.2 The Supply Potential

Canada is quite capable of supplying all known heavy water demands throughout the world but it is acknowledged that some potential customers will prefer to establish their own domestic sources of supply. With the plants already in operation, or nearing completion, India will have the potential to produce about 400 Mg D_2O/a which will be sufficient for supplying the initial charges for more than one 200 MWe CANDU reactor per year. The extent of the Romanian heavy water plant construction program is not known, but in Argentina the 250 Mg D_2O/a plant at Arroyito will be able to support the needs of one new 600 MWe PHWR every two to three years.

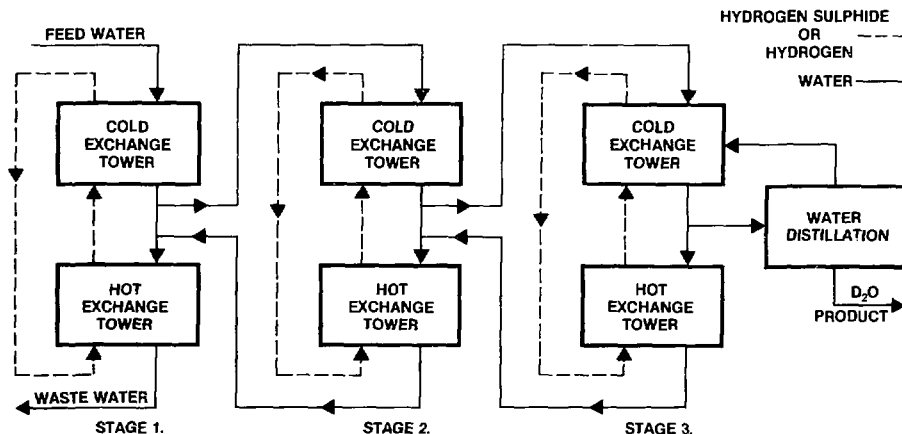


FIGURE 6 BITHERMAL EXCHANGE PROCESS: WATER/HYDROGEN SULPHIDE (GS) OR WATER/HYDROGEN

The plants currently in operation in Canada have a demonstrated capability to produce 1850 Mg D₂O/a and completion of the mothballed plants at Bruce-D and La Prade would bring this total to about 3300 Mg D₂O/a. This latter output could allow the construction of about five 600 MWe CANDUs per year, with a generous contingency and allowance for small make-up requirements of about 0.5% of station inventory per year. With no more CANDUs committed beyond the Darlington GS, it is obvious that Canada has excess heavy water pro-

duction capacity for the next few years. Nevertheless, with expectations of a resurgence in demand in Canada, there is still a case for maintaining and optimizing GS production capability to minimize the cost of heavy water and make CANDU stations an even more attractive proposition. The existence of partially completed GS plants in Canada gives assurance that additional production capacity can be brought on line at lower cost than by the construction of entirely new facilities.

TABLE 4
FUTURE DEMAND FOR HEAVY WATER
(Based on requirements for PHWRs under construction or committed)

Generating Station	Gross Output (MWe)	D ₂ O Inventory (Megagrams)	Year Required
Canada			
Pickering - 6	540	459	1984
Pickering - 7	540	459	1985
Pickering - 8	540	459	1985
Bruce - 5	808	775	1985
Bruce - 6	808	775	1984
Bruce - 7	808	775	1986
Bruce - 8	808	775	1987
Darlington - 1	936	765	1989
Darlington - 2	936	765	1988
Darlington - 3	936	765	1991
Darlington - 4	936	765	1992
Argentina			
Atucha - 2	745	570	1986
Romania			
Cernavoda - 1	679	490	1988
Cernavoda - 2	679	490	1989
Italy			
Cirene	40	70	1985
India			
Madras - 1	235	240	1983
Madras - 2	235	240	1984
Narora - 1	235	240	1986
Narora - 2	235	240	1987
Kakrapar - 1	235	240	1990
Kakrapar - 2	235	240	1991

6.3 Production Costs

The investment in heavy water in a CANDU reactor represents about 30% of the cost of the nuclear steam supply system (NSSS) or nearly 20% of the total station cost. A reduction in the unit mass cost of heavy water will, therefore, have a significant impact on the initial capital cost of a new CANDU station. When the time comes to construct new heavy water production facilities, there will be a step jump in unit mass costs, if the GS process is retained, because construction costs have soared during the past ten years whereas some of the existing plants will have been substantially amortized. For new plant construction there is, therefore, a strong incentive to devise new heavy water production processes that will yield lower product costs through either lower construction costs, lower energy costs or a combination of both.

An additional incentive to reduce heavy water production costs comes from potential competition with enriched PWR or BWR systems. The advances in laser isotope separation, which may hold promise for less expensive heavy water, have also been successfully applied to the separation of uranium isotopes. It is probable that the cost of uranium enrichment will fall and this may provide further inducement to reduce heavy water production costs through the development of new processes.

6.4 Environmental Considerations

Although highly successful in meeting 90% of the world's demand for heavy water, the GS process is not without difficulties in respect of finding suitable locations for plant sites. The GS process needs clean fresh water and a low cost energy supply. In some highly industrialized countries clean water is difficult to provide and, unless there is already a nuclear industry, the energy (as steam) will have to come from burning coal or oil. Nuclear steam is the most attractive energy source, as has been amply demonstrated by the Bruce HWP of Ontario Hydro⁽¹⁾ but this has to be planned well in advance of heavy water plant construction. In most industrialized countries, the technical requirements for locating GS plants usually mean the choice of a site in an already heavily industrialized and populated region. The GS process requires a large inventory of toxic hydrogen sulphide and, despite an excellent safety record, there is a perceived risk to the surrounding population from an accidental release of this gas. For this reason, licensing authorities in Canada require that GS plants be constructed where there is restricted and controlled public access or that the plants be provided with means to safely disperse any accidental releases of hydrogen sulphide gas. It is expected that other countries will impose similar restrictions and this will make a suitable site selection quite difficult. Another aspect that must be considered is the environmental impact because traces of hydrogen sulphide in the ef-

fluent could be injurious to aquatic life and traces in the atmosphere are readily apparent by their odour. These trace releases can be successfully controlled but will inevitably raise objections from environmentalist groups during the plant site selection, construction and commissioning phases. There is, therefore, an advantage to be gained from developing new heavy water production processes that, as well as being economically attractive, do not pose such a perceived risk to public safety or the environment.

6.5 Production Plant Size

When Canada embarked on its program for building heavy water plants during the 1966 to 1973 period it was firmly believed that large unit size plants, up to the limit of current technology, would yield minimum unit mass costs. This was probably true in an expanding economy when the plant's output was thought to be fully committed for many years ahead. In the latter half of the 1970's, it was realized that over-construction was taking place and it became quite costly to halt the work underway at La Prade and Bruce-D. In the case of La Prade, which was a unique design, in retrospect it might have been prudent to have built a series of smaller units whose construction dates could have been staggered. In this way, the final capacity of the plant could have been more closely tailored to the market that it had to serve. Consequently, there is now likely to be a reluctance to build further plants with production capacities as large as 400 to 800 Mg D₂O/a unless the advantages of the economy of scale are an over-riding factor.

In the course of marketing CANDU stations abroad, AECL has learned that some potential customers would like to be able to supply their own heavy water make-up requirements rather than continue to be dependent upon the original supplier. This infers that there is a need for small heavy water production plants with capacities in the range of 5 to 25 Mg D₂O/a to supply make-up for installed nuclear capacities ranging from 1200 MWe to 6000 MWe or to stockpile heavy water for use in future units. The GS process cannot easily be scaled down to this size range without a dramatic increase in cost of the product. No country can supply a small independent heavy water plant of this size using a fully demonstrated process. Parasitic plants of the ammonia-hydrogen type are available but their long term reliability is unproven. There is, therefore, a growing need to develop an independent small plant that can produce heavy water at the same or less cost as the present GS units

7.0 RESEARCH AND DEVELOPMENT PROGRAMS

Current trends in Canada and elsewhere in the development of new processes strongly favour schemes based

on hydrogen-water exchange, for short to medium term application, and LIS for the long term. Expenditure of R&D effort on hydrogen-water exchange can be justified on the basis that the process can have applications other than the primary production of heavy water; the most obvious of which is the separation of tritium from both hydrogen (protium) and deuterium. Tritium separation techniques will be required in the future to support a fusion program as well as the more immediate need of recovering tritium from irradiated heavy water. This concentration of attention on hydrogen-water exchange does not mean that all other processes have been abandoned, but special circumstances will be needed to revive some earlier proposals.

Since the thorough reviews in the 1960's, no promising new chemical exchange mechanisms have been suggested except perhaps methane-hydrogen exchange.⁽¹²⁾ This process is based on the exchange of deuterium between hydrogen and methane in the gas phase at high temperatures and pressures in the presence of a catalyst. Depleted hydrogen would be replenished in deuterium content by several co-current equilibrations with methane of natural deuterium concentration. Overall counter-current contact would be achieved by low temperature separation of the two gases between each catalyst bed and the re-enriched hydrogen would then serve as feed to a hydrogen distillation system. The flowsheet is analogous to the steam-hydrogen process shown in Figure 4, where methane is substituted for steam. The process requires vast amounts of refrigeration for separating methane and hydrogen plus supplementary heat for the high temperature catalysis. It is possible that this process could be economically attractive if built in conjunction with an unloading terminal for liquefied natural gas (LNG) where the feedstock is already cold and could provide some of the refrigeration load. However, even LNG is not cold enough and supplementary refrigeration would be needed.

In Canada, work on the synthesis gas fed amine-hydrogen exchange process is unlikely to be re-started because the advantages over the similar ammonia-hydrogen exchange process are not considered large enough to warrant the construction of a prototype plant. A re-evaluation of a water-fed version of the bithermal amine-hydrogen process may be warranted on the basis of the potentially low energy consumption characteristics. Both the ammonia-hydrogen and amine-hydrogen processes suffer the disadvantages attendant with operation in conjunction with an ammonia production plant. The conservation of deuterium requires integration of some of the ammonia plant's condensate streams with the heavy water production unit and the latter unit will never achieve a greater reliability than the parent ammonia plant. This disadvantage has already been manifest in India but should be avoidable in Argentina through the use of a water feed step. However, the energy requirements of this step will not be in-

considerable because water and ammonia are not easy to completely separate into dry ammonia and pure water. It will be interesting to see how the economics of the Arroyito plant eventually compare with the GS process.

Research on laser isotope separation (LIS) processes is active in Canada within both Ontario Hydro⁽¹⁰⁾ and AECL⁽¹¹⁾, including studies of how deuterium could be transferred to the reactive species from an inexpensive feed material. LIS is regarded as a long range R&D topic but one that is worth pursuing because, like hydrogen-water exchange, there is a possibility of specialized applications being found.

Heavy water R&D within Ontario Hydro is carried out at the Ontario Hydro Research laboratories in Toronto and the program is now focused on LIS systems. Earlier work on water distillation systems that use nuclear waste heat has been completed.

The AECL R&D program at the Chalk River Nuclear Laboratories (CRNL) covers four main areas of heavy water production technology: support for the GS process plants of AECL and Ontario Hydro; development of the wet-proof hydrogen-water exchange catalyst and associated processes; fundamental research into LIS systems; evaluation of new processes and re-evaluation of established processes in the light of changing economics and new discoveries. At CRNL there are also close links between these programs and the work being carried on applications of the wet-proof catalyst to H-D-T separations and the cryogenic distillation of hydrogen. The GS process R&D program is now limited to the provision of specialized support for the operating plants in the areas of materials behaviour, process control, mechanical performance and process chemistry. However, many of the techniques developed during the intense period of GS process R&D from 1969 to about 1980 have proved extremely useful for application to the hydrogen-water exchange system. These techniques include process simulation, novel flowsheet development, isotopic analysis methods, process chemistry control methods and mass transfer studies.

Heavy water R&D programs in other countries are not known in detail except through the appearance of published papers. Through this source and technical exchanges it is evident that a major program on hydrogen-water exchange, using catalysts similar to those developed in Canada, is underway in Japan. Hydrogen-water catalyst development is also underway in India in connection with the provision of a water feed step for their ammonia-hydrogen exchange plants. Romania has built and operated a small GS process plant, complete with a water distillation (DW) unit, and intends to use the knowledge gained for the design and construction of a full scale production plant. A small GS process pilot plant is also under construction in Argentina⁽¹⁴⁾ to provide an alternative in the selection of technology for future heavy water plants.

8.0 FUTURE DEVELOPMENTS

CANDU generating stations have established an enviable record for reliability and, generically, PHWRs have demonstrated cumulative load factors that are superior to any other type of nuclear station. When the demand for electricity increases again, PHWRs will be assured of an increasing share of the market. The CANDU system will be adaptable⁽¹⁷⁾ to any future changes in nuclear fuel cycle philosophy, including operation with low-enriched fuel or as a partial breeder with thorium⁽¹⁸⁾. CANDU stations will remain competitive and the demand for heavy water is expected to increase again. The foregoing sections of this report have suggested that two established processes, GS and ammonia-hydrogen exchange, will predominate in the short term (up to 5 years), processes based on hydrogen-water exchange will appear in the medium term (5 to 15 years) and LIS processes may prove attractive in the long term.

8.1 Future Prospects for the GS Process

The operating GS plants in Canada are performing very well and no major modifications are anticipated in the future. During routine maintenance shutdowns the opportunity may be taken to modify or replace sieve trays in the older plants in order to reduce the consumption of steam per unit mass of product but only if there is an economic justification in terms of production cost. If the La Prade Heavy Water Plant is completed and put into operation, some process and mechanical design changes may be made as a result of experience gained from the other plants since the La Prade design was formulated in 1974. In the event that further GS process plants beyond La Prade and Bruce Heavy Water Plant-D are committed in Canada, it is almost certain that these will be located so that they can be supplied by nuclear steam systems. However, the desirability of building heavy water plants of small unit sizes may preclude the construction of further GS process plants until there is a major increase in electricity demand.

Outside Canada, there will still be active development of the GS process in India, Romania and Argentina, as described earlier. It is possible that other countries may choose to adopt the GS process because of the apparent availability of design information.

8.2 Future Prospects for the Ammonia-Hydrogen Exchange Process

The monothermal and bithermal ammonia-hydrogen exchange processes have only accumulated a few years of operating experience: four years at Mazingarbe and about the same period in India, although actual operation of the bithermal process has not been confirmed. These processes are probably at the same stage of development that the GS plants in Canada had reached by the early 1970's, but with only four years prior operation

at Mazingarbe compared to twenty years at Savannah River. Little is known about the actual performance of the plants in India except that they have suffered from unreliable operation of the parent ammonia plants, an experience that also affected Mazingarbe. India has indicated that a water feed step would be preferred for future plants of this type so that they can run independently. The plant in Argentina will have a water feed step but it is not known if this choice was made as a consequence of the Indian experience or whether it was occasioned by the need to extract more deuterium than there was available in synthesis gas streams. There is no doubt that a water-ammonia or water-hydrogen front end exchange step will eliminate some of the unreliability but it will also significantly increase the cost of heavy water production and add to the complexity of operation. Low temperature (25°C) hydrogen-water exchange is possible using the wet-proof catalyst (Fig.4) but can only supply hydrogen enriched to about 45 ppm deuterium which imposes an additional load on the ammonia-hydrogen exchange step. High temperature steam-hydrogen exchange would ameliorate this problem at the expense of a large additional energy requirement. AECL's earlier design studies on the amine-hydrogen exchange process suggested that the incorporation of water feed will raise production costs to values close to those of the GS process. Further ammonia-hydrogen exchange plants may be built, especially in India, but this process may eventually be superseded by variants of the hydrogen-water exchange process.

8.3 Future Prospects for Hydrogen-Water Exchange Processes

Hydrogen-water exchange, using the wet-proof platinum catalyst developed by AECL, has not yet been demonstrated in a prototype plant. However, pilot plant tests at CRNL have shown that the catalyst will retain its efficiency for at least two years and that it can be readily regenerated if it is accidentally poisoned by impurities in the water or hydrogen streams. Great advances have been made in the development of less expensive support structures and the specific activities of current versions of the catalyst are an order of magnitude greater than a few years ago. It is expected that there will be an opportunity to demonstrate the catalyst in a prototype CECE configuration in Quebec. In conjunction with studies of future uses for hydrogen, an advanced electrolytic plant has been constructed jointly by Noranda-Electrolyzer and Hydro Quebec. This plant is primarily intended to test the operation of new high-performance electrolytic cells that have been developed by Noranda-Electrolyzer. This plant is now in operation and there are proposals to add catalyst columns and convert to the CECE process in the near future.

There is not likely to be widespread use of the CECE process in Canada because it is less expensive to produce hydrogen or synthesis gas from the steam-reforming of natural gas. However, the use of electrolysis and, hence, the CECE process, could become

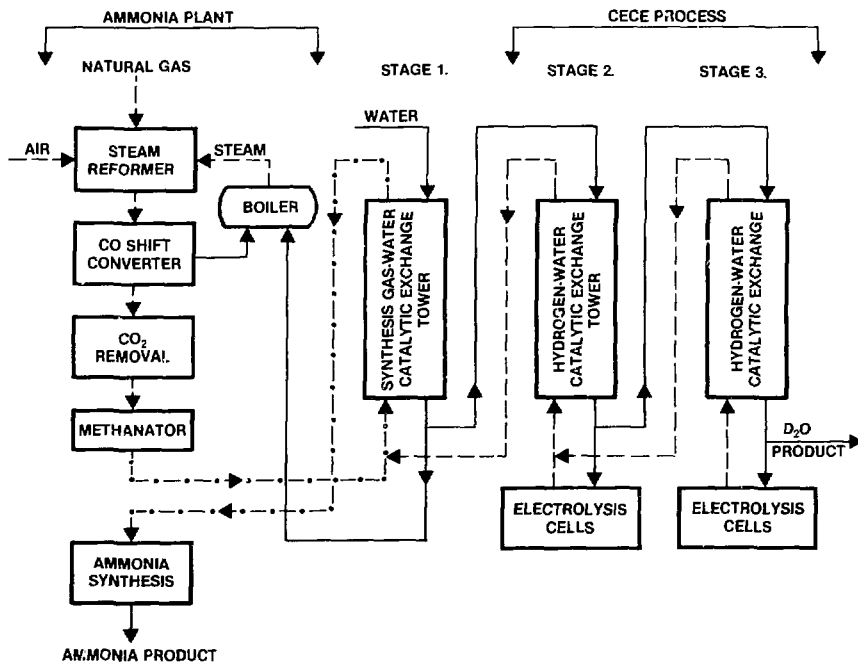


FIGURE 7 STEAM REFORMING HYDROGEN-WATER EXCHANGE (SRHWE) PROCESS

attractive in regions such as northern Quebec where electricity is more readily available than natural gas and where there is a need for hydrogen in some metallurgical processes. The CECE process will be most useful for supplying relatively small quantities of heavy water for make-up purposes because a large plant would require a formidable electricity supply: the production of 60 Mg D_2O/a would need 375 MW of electrolysis power.

The flowsheet for the CECE process, Fig. 5, is a simple example of a monothermal hydrogen-water exchange system where the phase conversion of water to hydrogen by electrolysis is analogous to the thermal cracking of ammonia in the monothermal ammonia-hydrogen exchange process. Monothermal processes are attractive because they result in systems with a minimum number of transfer units and, hence, minimum exchange tower volume, but the energy demand must also be low.

In bithermal systems, such as the GS process, the hot towers serve the same purpose as a phase converter by transferring deuterium from the liquid phase to the gas phase, but they do so incompletely, although with generally acceptable heat requirements. This incomplete transformation results in a need for larger cold towers to effect a given degree of deuterium enrichment and thus increases the overall cost of the process. Complete phase conversion by electrolysis is very energy intensive and is only economic for hydrogen production in special circumstances, thus

limiting the potential for application of the CECE process, but there is an alternative.

Industrial hydrogen, or synthesis gas, is normally produced by steam-reforming of a hydrocarbon feedstock, followed by shift conversion. In this process, approximately 50% of the feed is steam which is converted to hydrogen along with the hydrogen contained in the hydrocarbon feed. A steam-reforming/shift conversion system is therefore partially analogous to phase conversion by electrolysis: the principal difference being that the deuterium content of the product hydrogen depends equally upon the deuterium contents of the incoming steam and hydrocarbon feed. Such a system could, therefore, replace the electrolytic cells of at least the first stage of the CECE process where the catalyst column would be used to transfer deuterium from the product hydrogen to the water needed by the reforming system (see Fig. 7). This would cause deuterium to accumulate in the steam and condensate systems of the reformer, to a level that would ultimately be limited by the rate of leakage of water or steam. A steam-reformer/shift conversion system is not a perfect phase conversion system because of the dilution by the hydrocarbon feed containing deuterium at natural concentration. However, this is not a severe disadvantage and only causes a modest increase in the number of transfer units required in the catalyst column. AECL have called this scheme the Steam Reforming Hydrogen Water Exchange (SRHWE) process, but the idea is not

new. The concept of such a process was disclosed in the preamble to a patent⁽¹³⁾ by Hartmann, assigned to Sulzer Bros. and filed in 1971. In that document, the process concept was described but stated to be impracticable because no suitable catalyst was available. This was true in 1971 but the situation has now changed through the development of the wet-proofed catalyst and AECL believe that the SRHWE process could be a viable alternative method for the production of heavy water. The SRHWE process does have some disadvantages: the steam reformer/snift conversion system must be reasonably leak tight to permit a significant enrichment of deuterium and the process is parasitic to synthesis gas production. However, both these disadvantages also apply to the ammonia-hydrogen exchange process. The principal attraction of the SRHWE process is the modest energy requirement and AECL will continue development in parallel with the CECE process because both are seen as promising methods for small scale, less than 100 Mg D₂O/a, production of heavy water at competitive costs.

In order to use the hydrogen-water exchange system for large scale heavy water production (more than 100 Mg D₂O/a per unit), an independent process is required and bithermal exchange, analogous to the GS process, is the obvious route. The performance of the wet-proofed catalyst developed by AECL is promising for application in the cold towers of a bithermal process but further R&D will need to be undertaken to develop a version of the catalyst that will perform at high pressure in the hot exchange tower. If this development is successful, bithermal hydrogen-water exchange will have several advantages over the GS process: the fluids are not toxic or corrosive; fewer transfer units are required; the energy requirements should be lower; if hydrogen escapes it will disperse more rapidly than hydrogen sulphide and there should be minimal safety or environ-

mental restrictions on plant location. Bithermal hydrogen-water exchange is seen as the eventual successor to the GS process for large scale heavy water production in the 1990's.

Although bithermal hydrogen-water exchange has several potential advantages, it may not be significantly less expensive than the GS process if problems are encountered in the development of a catalyst for the hot tower. A compromise must be made between obtaining the lowest possible separation factor and obtaining a reasonable rate of exchange. Choosing a high hot tower temperature results in a favourable separation factor but requires a high pressure to suppress the water vapour component of the hot hydrogen gas. This high pressure will probably result in a significant reduction in the exchange rate.

Lowering the hot tower temperature to reduce this effect will also narrow the difference between cold and hot tower separation factors and increase the quantities of water and hydrogen that must be processed for a given heavy water production rate. One possible solution to this dilemma is illustrated in Figure 8 where the hot tower is replaced by a tower exchanging deuterium between water and ammonia vapour at a separation factor close to unity. This step is achieved by circulating synthesis gas, instead of pure hydrogen, through the cold tower and then converting it to ammonia vapour in a conventional synthesis loop. After passage through the water-ammonia vapour exchange tower, the ammonia vapour is cracked back to synthesis gas again. These processes of alternately synthesizing and cracking ammonia and the water-ammonia vapour exchange step are also to be used at the Arroyito plant in Argentina, albeit for a different flowsheet, and the technology already exists. It remains to be established if this scheme could be an economic alternative to a conventional hot tower in the bithermal hydrogen-water exchange process.

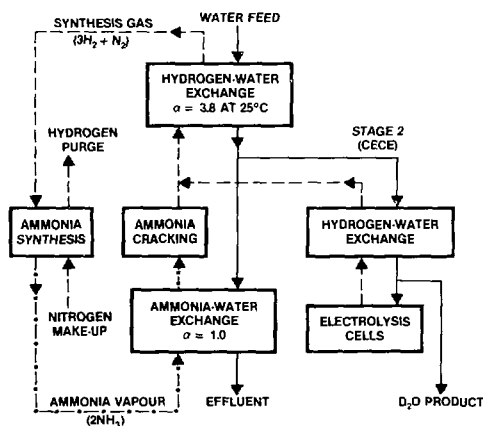


FIGURE 8 COMBINED HYDROGEN-WATER AND AMMONIA-WATER EXCHANGE

8.4 Future Prospects for Laser-Isotope Separation Processes

It is difficult to predict how successful the development of LIS processes will be for hydrogen isotope separation, but it is probable that several favourably reactive species will be found. Fluoroform has been demonstrated to be a candidate system but it is not known how this compound could be economically "re-charged" with deuterium. Also, little work has been done so far in estimating the power requirements and efficiency of an industrialized version of this process. However, the fact that LIS systems have been shown to have extremely high separation factors will ensure that R&D will continue.

9.0 CONCLUSIONS

A prediction of future trends in heavy water production is subjective, inevitably based on incomplete informa-

tion and will depend firstly on the future state of the world economy and secondly on the need for nuclear power within that economy. At the time of writing, (1983 January) there are signs of a drop in world crude oil prices and an excess of supply. If this trend continues, it will reduce the immediate incentive to develop alternative energy sources such as the so-called "hydrogen economy" based on (nuclear) electricity. In the short term, this could delay the need to develop large scale electrolytic hydrogen facilities, which could support the CECE process, and prolong the viability of the GS process by rendering its energy cost component less significant.

In the absence of reliable forecasts, the conclusions that follow are predicated on a steady recovery of the world economy and no dramatic changes in the cost or availability of crude oil and natural gas. If the lessons of the last ten years are heeded this will lead to a gradual recovery of the demand for nuclear electricity and an increasing share of that market for CANDU stations. The demand for heavy water should increase again in the 1990's and will surpass current production capability during that decade.

In Canada, the GS process will remain the principal means of heavy water production until the end of this century unless there is a major breakthrough in the cost effectiveness of new processes. When additional production capacity is needed again in Canada, the cost of completing mothballed GS process plants will have to be weighed against the cost and risk of introducing new processes, if they are available. It is expected that there will be a pilot scale demonstration of the CECE process in Quebec but construction of prototype variants of the CECE process, such as SRHWE, will depend upon AECL's assessment of the market potential for such processes at home or abroad.

It is likely that further GS process plants will be built in India, Romania and possibly in Argentina because GS is seen to be a reliable and demonstrated process and considerable published information is available. However, it should be remembered that the reliability now obtained in Canada has been achieved at considerable cost in R&D⁽¹⁾ to advance the technology beyond the published experience of the Dana and Savannah River Plants. This new technology is vital to the achievement of reliable and economic heavy water production by the GS process.

Future prospects for the ammonia-hydrogen exchange processes are difficult to predict because they depend on the future success of the plants in India and Argentina but, it is reasonable to expect that there will be a movement towards independent water-fed processes.

Heavy water R&D has already become focused on hydrogen-water exchange processes in Canada, Japan and probably elsewhere and it is expected to continue at about the present level of investment for the next few years. LIS system research will also continue because this technique is applicable to almost any isotope separation problem.

The installed production capacity in Canada will ensure an adequate supply of heavy water for any CANDU stations committed during the next ten years and, if the present level of R&D is maintained, there will be assurance that heavy water will continue to be available at the lowest possible production cost.

10.0 ACKNOWLEDGEMENT

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