Optimization of Darlington Tritium Removal Facility Performance: Effects of Key Process Variables

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Introduction

Ontario Hydro has constructed a Tritium Removal Facility (DTRF) at its Darlington Nuclear Generating Station to extract tritium from the heavy water moderator water of its CANDU heavy water nuclear reactors. Detritiation of moderator water will reduce occupational exposure to tritium and will reduce environmental emissions. The front end of the process system consists of an eight-stage Vapour Phase Catalytic Exchange (VPCE) section which extracts tritium from heavy water into a deuterium gas stream. The tritium is then concentrated to 99.9 percent purity by cryogenic distillation and stored in immobilized form in containers. The DTRF process flowsheet is shown in Figure 1.

For the DTRF, as with any complex process system, the development of an optimum operating strategy requires an understanding of the process and the process parameters which may be set to achieve desired plant performance. For example, one could choose to maximize system throughput at the expense of a lower detritiation factor, or one could choose to minimize operating costs and accept a lower tritium production rate. This paper discusses the major process variables in the DTRF and how they affect system performance. The results presented here are based on computer simulations carried out using Ontario Hydro's FLOSHEET process simulation program [1].

DTRF Performance Objectives

For DTRF operation, the following major performance objectives can be identified:

1. minimize operating costs;
2. maximize the rate at which heavy water is detritiated;
3. maximize the detritiation factor for processed heavy water;
4. maximize the overall tritium production rate; and
5. maximize tritium product purity.

Other objectives may also be defined, but these are probably the most important ones.

Not all of the above objectives are complementary. In general, if plant performance is optimized with respect to only one objective, other objectives are compromised. Therefore, choosing an *overall best* strategy involves tradeoffs.

In this paper, the relative weights which could be assigned to different performance objectives are not discussed, since they depend on factors such as requirements for tritium product purity, feed concentration, and detritiation factor, which will be better defined later.

As with any existing plant, operating strategies must take into account physical and operational constraints to plant operation. For example, it is not helpful to derive an optimum feedrate for the DTRF which is in excess of the processing capabilities of the installed equipment, unless design modifications are an acceptable option. Of course, design modifications involve additional expense and system unavailability, which must be properly accounted for.

Major Process Variables

The major process variables which affect DTRF performance are:

1. feedrate of heavy water;
2. deuterium gas flowrate between the VPCE and the cyogenic distillation cascade;
3. reflux ratio in the Low Tritium Column (LTC); and
4. tritium product drawoff rate from the cryogenic distillation cascade.

The following four sections discuss the effects of adjusting these key process variables.

D_2O Feedrate to the VPCE

It is desirable for the DTRF to be able to process tritiated heavy water at as high a rate as possible. The benefits of a high throughput are high tritium production rate, reduced average tritium levels in reactor moderator systems, and accompanying reduced occupational exposure to tritium. The main drawbacks are a higher overall operating cost (although cost per curie of

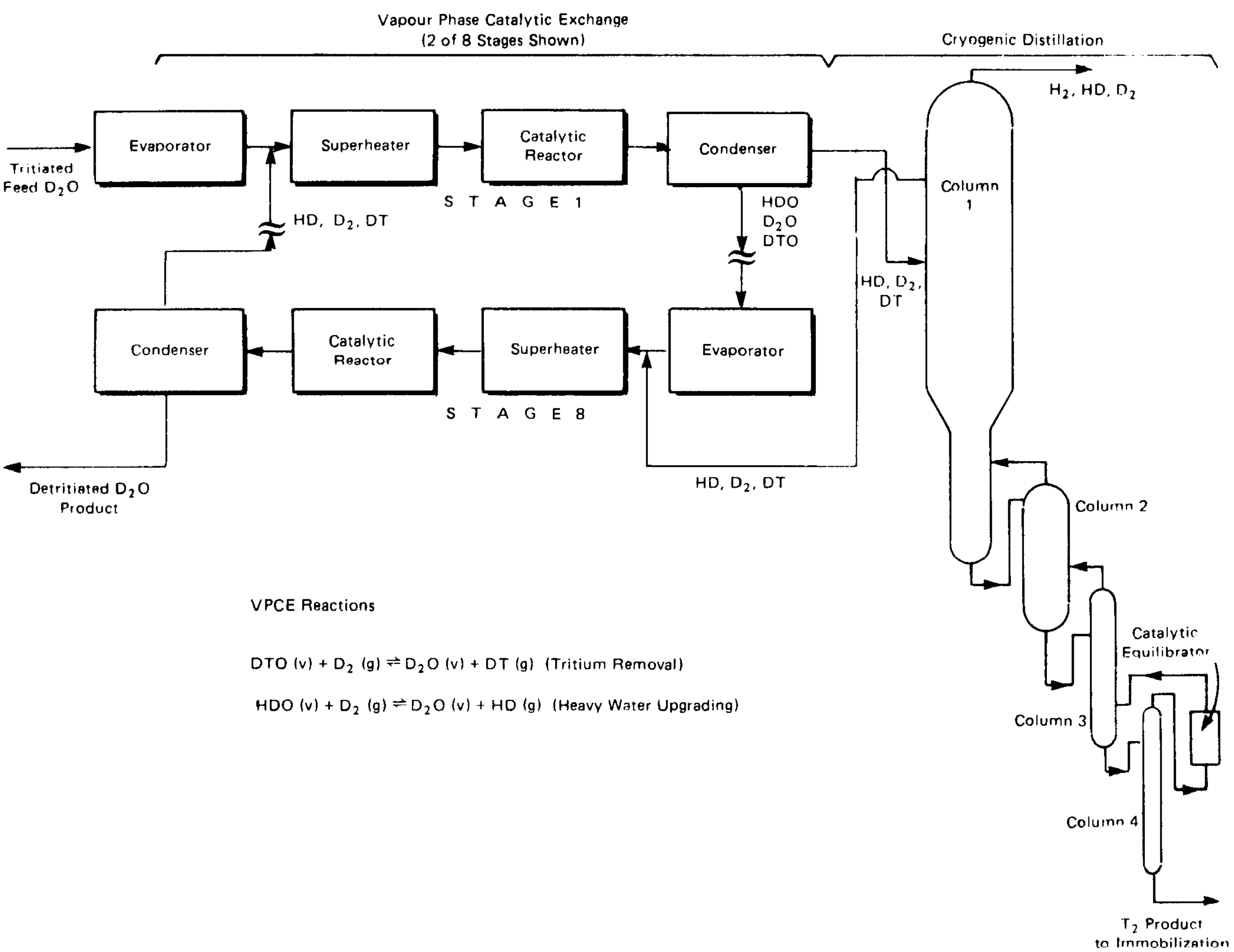

Figure 1: Darlington Tritium Removal Facility process flow diagram.

tritium extracted may be lower) and possibly a lower detritiation factor.

One way to increase the throughput of heavy water through the DTRF is simply to increase the heavy water feedrate to the front end VPCE process while keeping all other variables constant. An increase in the feedrate can be accomplished by taking advantage of system design margins. Calculations show that, provided that the VPCE has sufficient reboiler and superheater capacity, the heavy water throughput can be increased by about 10 percent over the design values without the detritiation factor dropping below 30. The actual system may be even more capable if the designer (Sulzer Canada, Inc.) has assumed conservative values for key design parameters such as height of an equivalent theoretical plate (HETP) in the cryogenic distillation columns, reboiler, and superheater capacity in the VPCE, etc.

For the system as designed, Figure 2 presents simulation results which illustrate the relationship between liquid feedrate, detritiation factor and overall tritium removal rate.

Calculations suggest that the main heavy water processing limitation in the DTRF system is the VPCE front end. A possible design change to increase the D_2O throughput would be to add an electrolysis unit

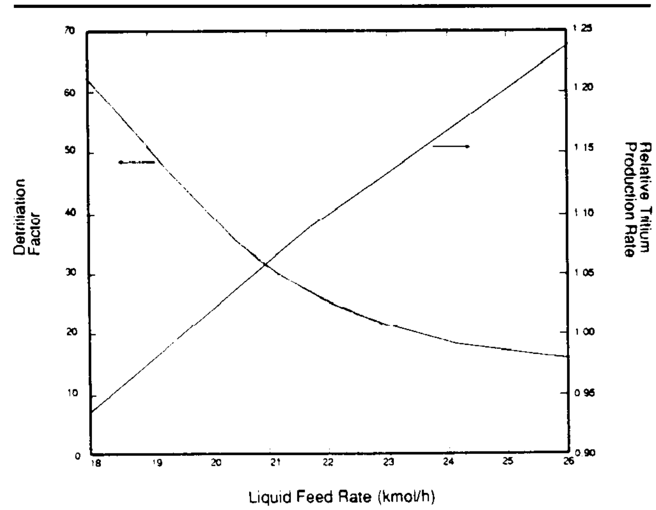

Figure 2: Relationship between liquid feedrate, detritiation factor and overall tritium removal rate.

to work in parallel with the VPCE. In this configuration, if the total deuterium gas feedrate to the cryogenic distillation cascade is kept the same as before, the tritium extraction rate will be increased due to a higher concentration of tritium in the gas. This is because the mole fraction of tritium in deuterium gas leaving the VPCE is approximately one half of the tritium mole fraction in the liquid feed. In the case of an electrolysis unit, the mole fraction of tritium in the outlet gas stream is the same as the mole fraction in the input liquid stream. Therefore, if the VPCE were to be completely replaced by an electrolysis front end, the tritium extraction rate would be doubled. If an electrolysis unit is used in parallel with the existing VPCE, the improvement in tritium extraction would be proportional to the fraction of the gas coming from the electrolysis unit.

D_2 Gas Flowrate through the VPCE

The rate of flow of D_2 gas between the VPCE and the cryogenic distillation cascade affects the isotope separation characteristics of both the VPCE and the cryogenic distillation cascade. Figure 3 shows the detritiation factor for heavy water as a function of D_2 gas flow, with all other factors being held constant (34 Ci / kg feed case). If the gas flow is decreased, then the heavy water detritiation factor decreases, although the molar tritium concentration in the deuterium gas feed to the cryogenic distillation cascade increases. Also, if the deuterium gas feed rate to the cryogenic distillation cascade decreases, the reboiler duty in the LTC can be decreased proportionately (the reflux ratio is assumed to be held constant). This results in a saving of energy, since the cryogenic refrigeration load is decreased. In the DTRF design, a decrease in the gas flowrate of 10 percent should be possible while still maintaining a detritiation factor of 30.

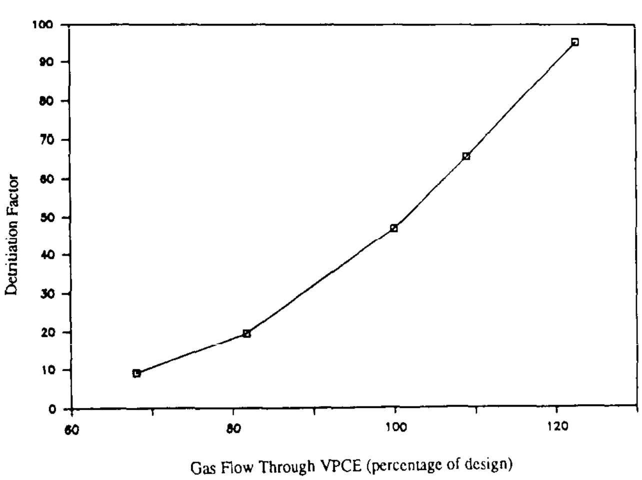

Figure 3: Relationship between detritiation factor and deuterium gas flow through the VPCE. The reflux ratio in the first column of the cryogenic distillation (the Low Tritium Column) is assumed to be held constant.

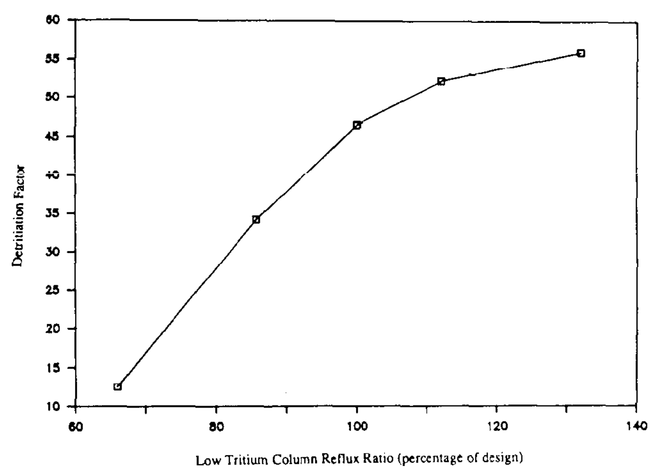

Figure 4: The effect of varying the reflux ratio in the first column (Low Tritium Column) in the cryogenic distillation cascade.

LTC Reflux Ratio

If the reflux ratio in the LTC is varied, while all other factors are kept constant, the heavy water detritiation factor will be affected. Figure 4 illustrates the relationship between detritiation factor and LTC reflux ratio for the 34 Ci / kg feed case. A lower reflux ratio results in energy savings due to decreased cryogenic refrigeration load. However, the tritium concentration in the gas returning to the VPCE from the cryogenic distillation cascade will increase and result in a lower detritiation factor.

Tritium Product Drawoff Rate

In the final column of the cryogenic distillation cascade there is no direct measure of tritium product purity, and tritium drawoffs are based on mass balance calculations of how much tritium has accumulated in the system. Tritium product drawoff rate is related to tritium product purity. If drawoffs are too frequent (by even 1 percent), then a high tritium product purity, such as 99.9 percent purity, will not be met. For each 1 percent excess drawoff rate, the tritium product purity decreases by about 1 percent. Considerable care will be required to operate the system for very high purity product specifications.

Downgraded Heavy Water Feed

Normally the DTRF will process only reactor-grade heavy water (>99.8% D_2O). If downgraded heavy water is introduced into the system, the detritiation efficiency will decrease because the HTO-triated species is not effectively removed by the cryogenic distillation system, and also because the presence of the HDO decreases the tritium extraction efficiency of the VPCE. The effect of small amounts of light water in the heavy water feed to the DTRF is illustrated in Figure 5. Even small amounts of light water (<1%) can significantly decrease the processed heavy water detritiation factor.

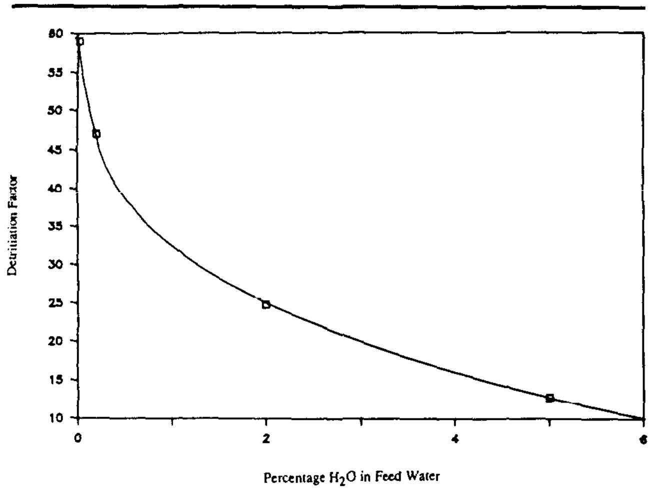

Figure 5: Detritiation factor when processing downgraded heavy water. Even small amounts of light water cause a significant drop in the detritiation factor.

Conclusions

1. The deuterium gas flowrate between the VPCE and the cryogenic distillation cascade affects the detritiation factor for processed heavy water and the refrigeration requirements of the Low Tritium Column (assuming a constant reflux ratio). Decreased gas flow results in energy savings but reduces the heavy water detritiation factor. An optimum value is, therefore, a tradeoff between operating cost and detritiation factor. Figure 3 shows the relationship between detritiation factor and deuterium gas flowrate.
2. The reflux ratio in the Low Tritium Column affects the detritiation factor for processed heavy water and the cryogenic refrigeration load. Reducing the reflux ratio would result in energy savings but would also reduce the detritiation factor, as illustrated in Figure 4. This figure shows that, at the design feedrate (assuming 34 Ci / kg heavy water feed), not much is to be gained by increasing the reflux ratio above the design value, since the detritiation factor increases only marginally.
3. Tritium product drawoff rate from the cryogenic distillation cascade affects product purity. In order to be assured of a tritium product purity of at least 99.9 percent, considerable care will need to be exercised in timing the tritium drawoffs from the final high tritium column.
4. The capability of the DTRF process equipment should be determined as accurately as possible during commissioning, in order that optimum operating strategies may be determined. Some of the calculations reported here will need to be updated to include actual performance data.
5. It may be desirable to operate the DTRF at detritiation factors which are a function of feed concentration. The best operating conditions depend on both the required detritiation factor and a consideration of operating costs.
6. To achieve high detritiation factors for processed heavy water, the heavy water feed to the DTRF should have very low protium levels.

Acknowledgement

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Reference

1. Sepa TR. Busigin A. *FLOSHEET: Computer Simulation of Hydrogen Isotope Separation Processes*. 35th Chemical Engineering Conference, Canadian Society for Chemical Engineering, Calgary, October 6–9, 1985.