Fukushima Light Water Detritiation System

Water Distillation Option

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Idaho National Laboratory, Idaho Falls, Idaho

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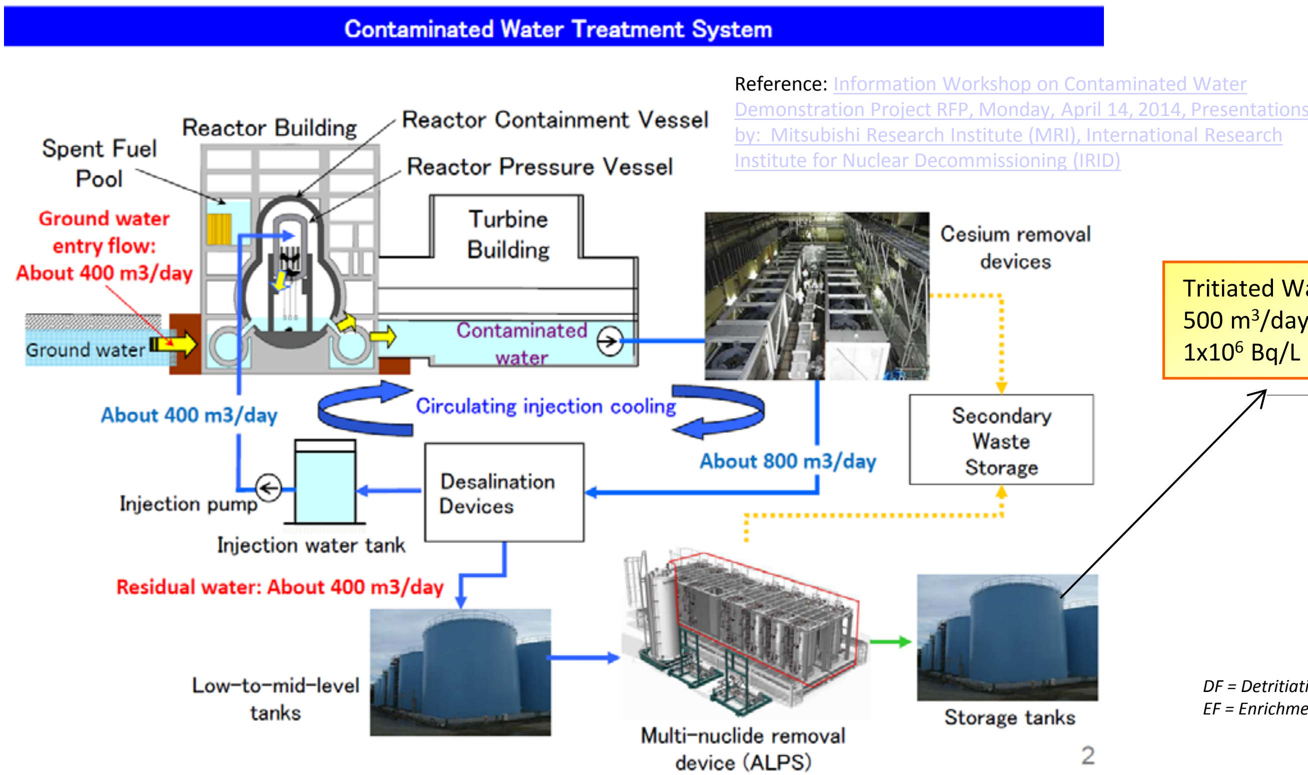
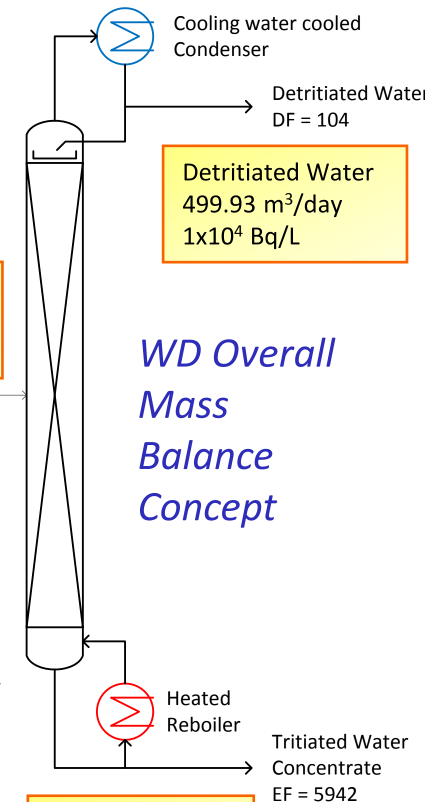
Fukushima Light Water Detritiation Requirement



Tritiated Water
500 m^3/day
1x10^6 Bq/L

DF = Detritiation Factor
EF = Enrichment Factor



WD Overall Mass Balance Concept

Tritiated Water Concentrate
0.07 m^3/day
6.9x10^9 Bq/L

400 m^3/day is accumulation rate. Assume 500 m^3/day capacity is built to also process backlogged water over a number of years.

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Water Distillation (WD) vs Combined Electrolysis & Catalytic Exchange (CECE) – Energy Cost Big Picture

Parameter	Units	WD	CECE	Comment
H/T Separation Factor for Light Water Detritiation	-	1.059 @ 50°C	**5.017 @ 60°C**	CECE separation factor is not the only important consideration.
Boilup or Electrolysis Energy for Reflux	kWh per kg of H_2O	0.66	5 to 6	Energy of electrolysis is much higher than energy of boilup.
COP* for Energy Utilization	Energy multiplier by heat pump or fuel cell	8 to 10 With Heat Pump	1.3 With Fuel Cell	WD recycles energy much more efficiently.
Energy demand for 500 m^3/day throughput	**MW(e)**	**25 to 40**	**155 to 210**	**WD uses much less energy.**

CECE large Separation Factor does not mean low energy consumption!

Even if CECE separation factor was <u>infinity</u>, CECE would require 104 to 125 MW(e) power for 500 m^3/day throughput – about 4 to 5 times more than WD.

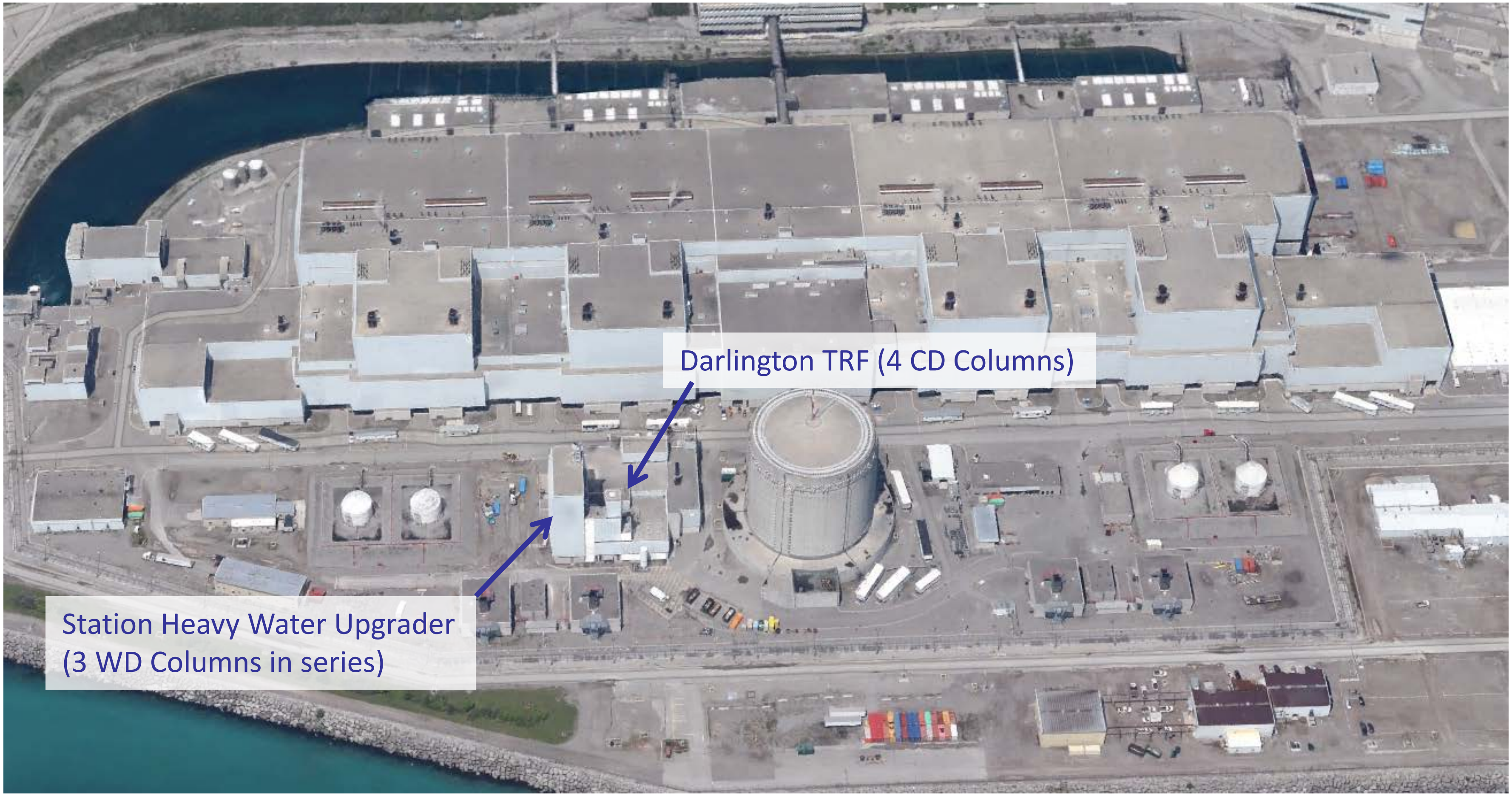
COP = coefficient of performance. For CECE the practicality of energy recovery/recycling is questionable.

WD vs CECE – Hazards Evaluation

Parameter	WD	CECE
Hydrogen Explosion Hazard	No.	Yes
Pure Oxygen Hazard	No.	Yes
Leakage Potential (during normal operation)	Vacuum process – leaks don't result in emission	Above atmospheric process. Greater potential for tritiated hydrogen/water vapor leak
Tritium Inventory	Small. Falling film reboiler has small inventory (less than 0.5 hour residence time). Most of system inventory is in the column packing at much lower tritium concentration.	Large. Electrolyser has large liquid inventory (about 16 hours residence time), much larger than WD reboiler. Electrolyser contains tritium at highest concentration.
Electrolyte handling	No	Yes
Operational complexity and potential for operator error	Simple process	Relatively complex process

Both WD and CECE can be operated safely. ***However, WD has better Inherent Safety.***

WD Industrial Experience: Canada



Source: Google Maps Link

WD Industrial Experience: ^{18}O

- WD is used to produce ^{18}O. There are several producers in the world.
- CIL in Xenia, Ohio has been producing ^{18}O water for the PET community since 1996. The expanded plant produces 250 kg/yr of ^{18}O used for production of ^{18}F in the PET industry, and for other uses in medical research.
- ***Fukushima WD columns could produce ^{18}O in addition to tritium recovery, to offset capital cost and to produce a medically valuable isotope that benefits the medical community.***

Source: Google Maps Link

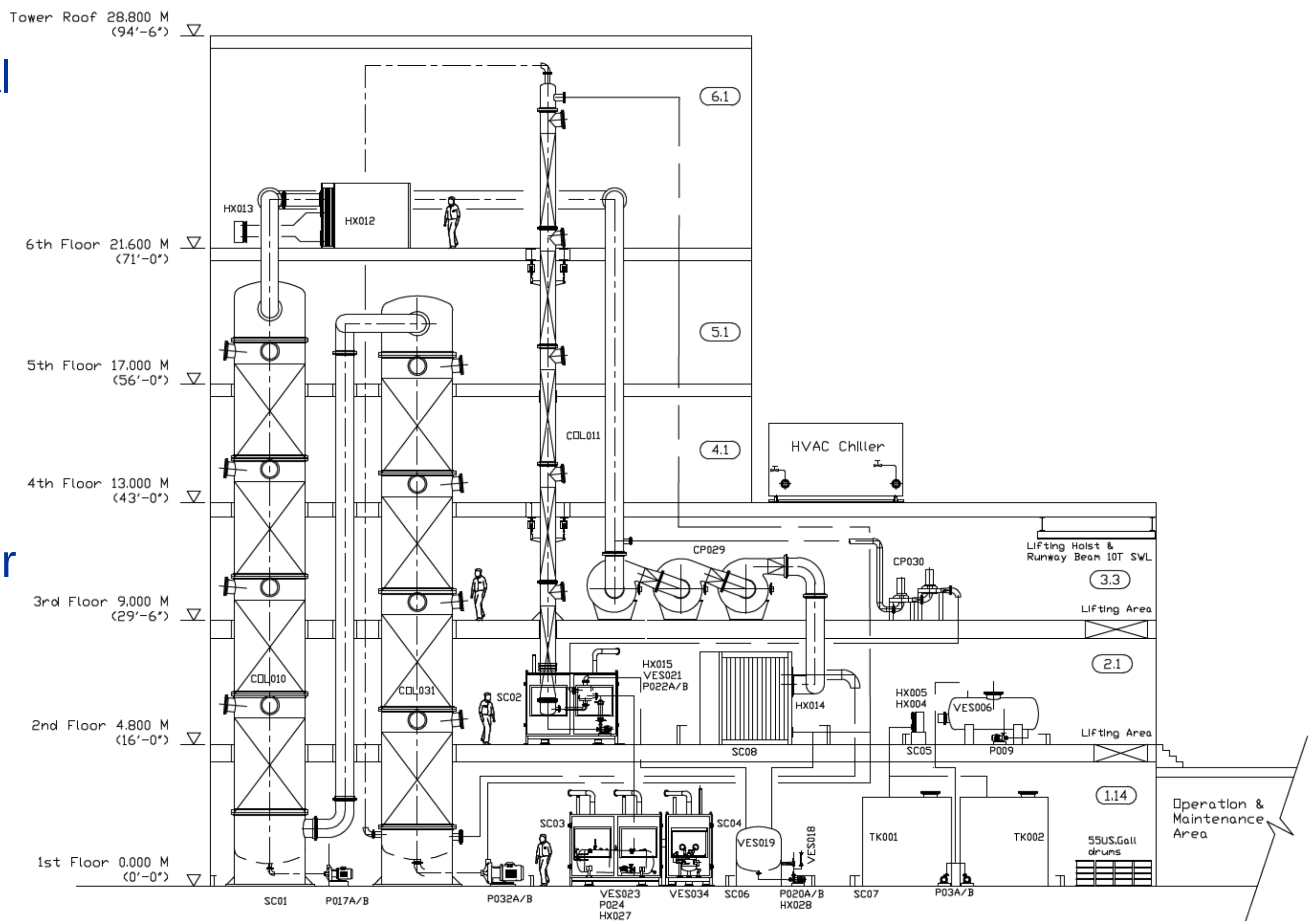
- Cambridge Isotope Laboratories in Xenia, Ohio produces ^{18}O by water distillation using surplus Heavy Water Upgrader columns. Water distillation is the most common technology used for separating Oxygen isotopes.

GEH-C Water Distillation Experience 1

- GEH-C has developed a competitive CY type WD packing.
- Packing surface activation is key to separation performance.
- Surface wetting requires a cupric oxide film.

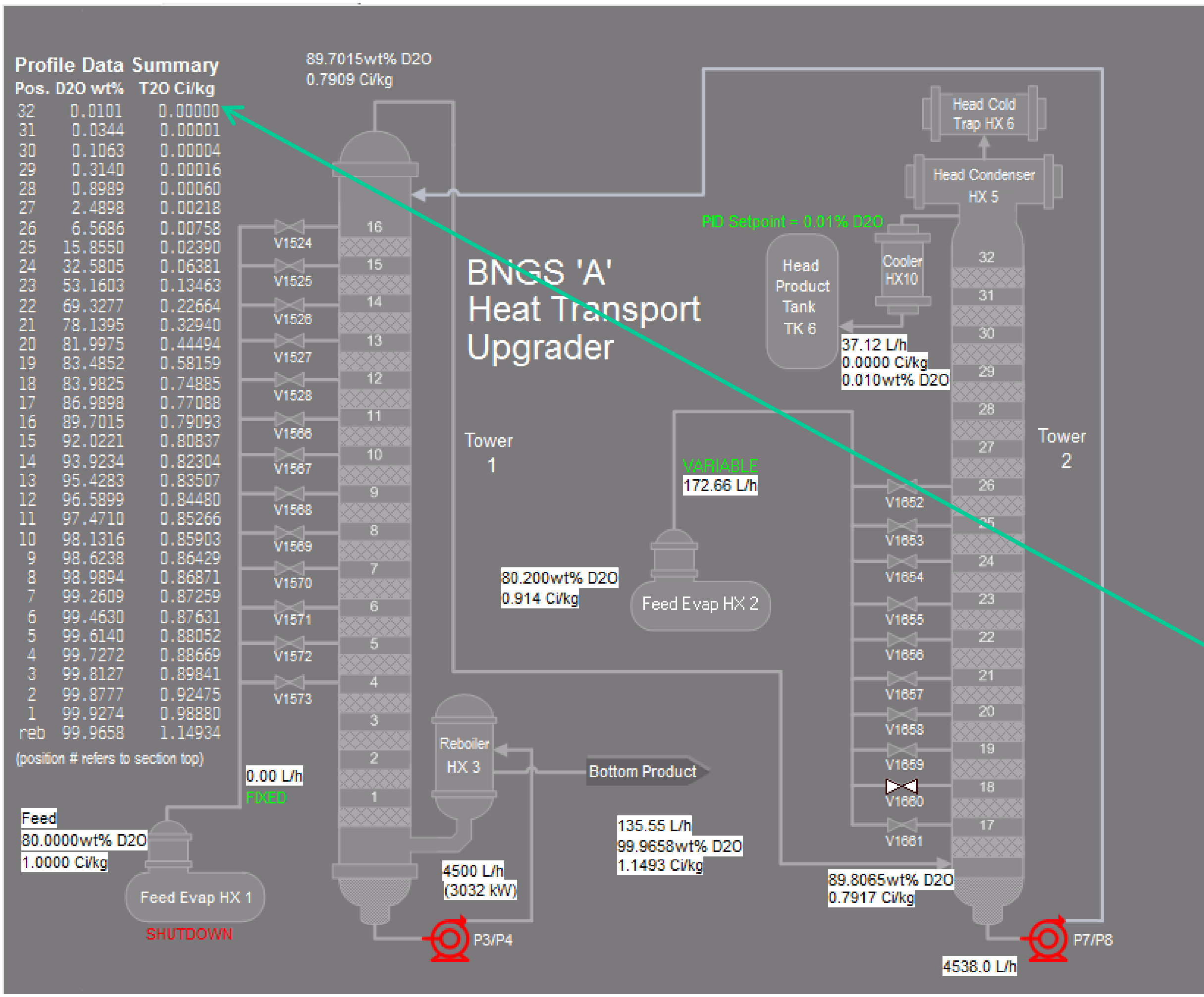
GEH-C Water Distillation Experience 2

- Design of several WD Light Water Detritiation Facilities
- This example shows ***Mechanical Vapor Compression*** for ~90% heat recovery
- 500 kg/h throughput with ~1 MW(e) power



Rolled out view showing elevations

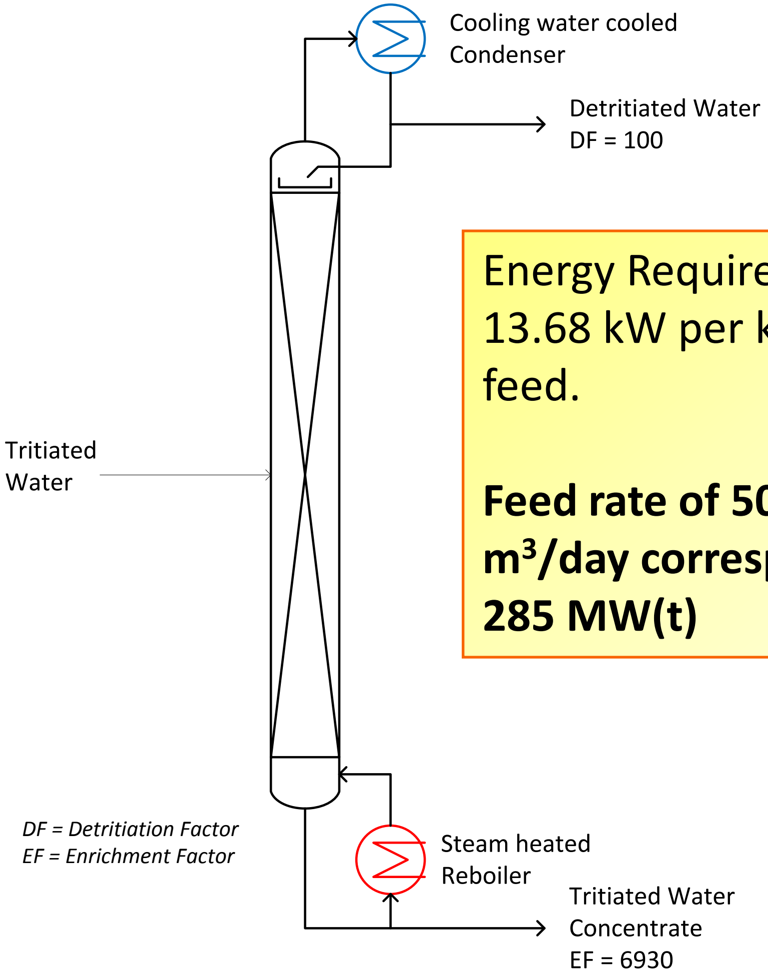
Heavy Water Upgrader Experience



Reference: Ram Davloor, Gretel Steinberg, Anthony Busigin, Salwan Saeed, "Major Rehabilitation of the Bruce A Heat Transport Heavy Water Upgrader and Effect on Overall Upgrader System and Tower Packing Performance", 9th CNS International Conference on CANDU® Maintenance, Toronto, Ontario, Canada, December 4-6, 2011

- Heavy water upgraders in Canada use dynamic simulation to analyze both deuterium and tritium separation in water distillation
- Note that the tritium activity in the head product is very low
- Heavy water upgraders also detritiate water!

WD Energy – Simple Heating & Cooling

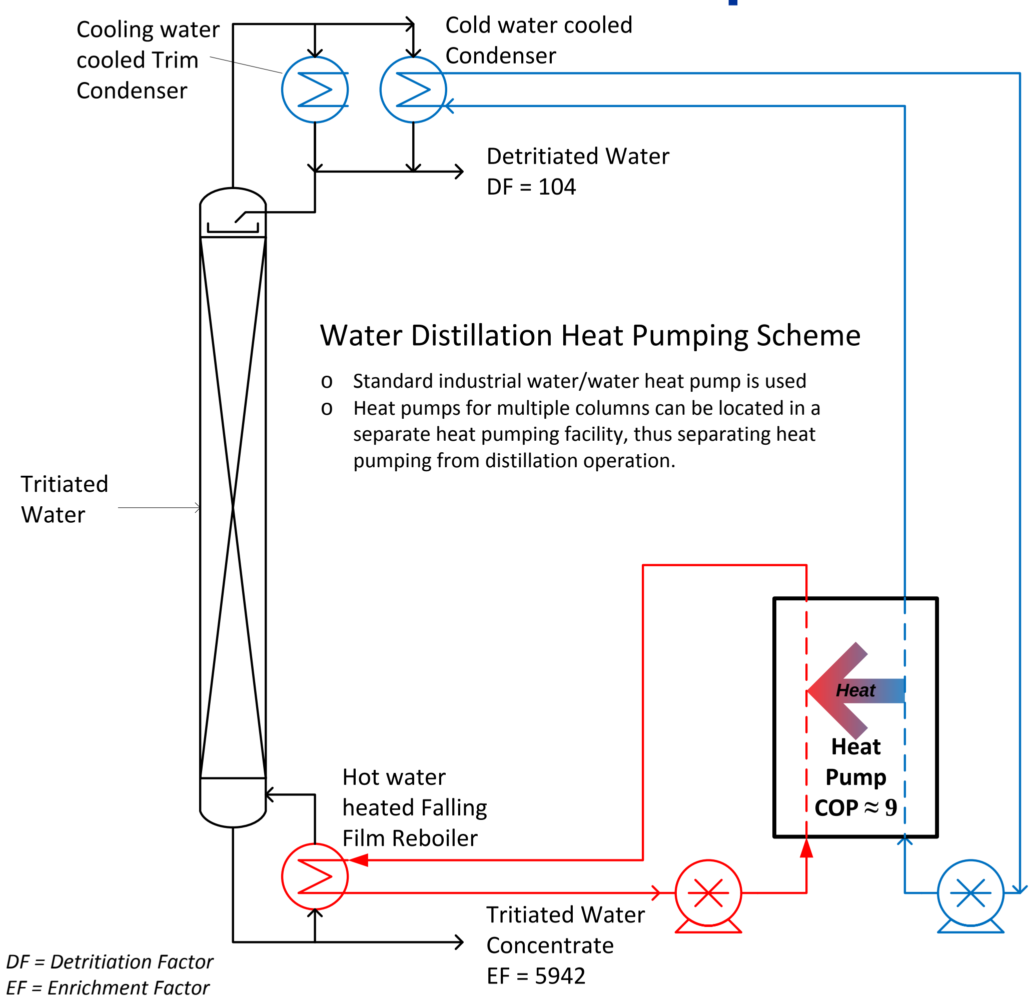


Energy Requirement is 13.68 kW per kg/h of feed.

Feed rate of 500 m^3/day corresponds to 285 MW(t)

- Simple heating and cooling has high energy demand due to high reflux ratio for H_2O/HTO separation – but less energy demand than with H_2O/HDO separation.
- Canadian heavy water upgrader WD columns use inexpensive low pressure turbine exhaust steam.
- Fukushima could supply natural gas reboilers for simple heating – but heat pumping to reduce energy demand can significantly reduce energy cost.

WD Energy – Heat Pump with Hot-Cold Water Circuits – Option 1



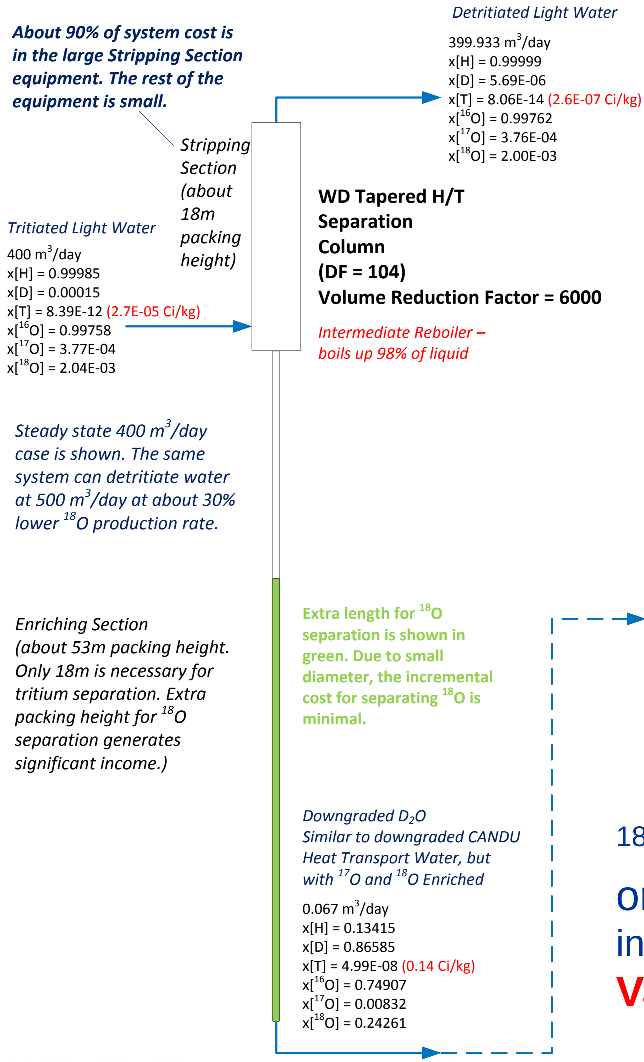
- Industrial Heat Pump, ammonia refrigerant, pumps heat from 38°C to 62°C
- Standard Heat Pump packages available

Energy Requirement is 1.7 kW per kg/h of feed

About 87% of heat energy is recycled within the system

Feed rate of 500 m^3/day corresponds to 35 MW(e)

Fukushima WD Process Block Diagram



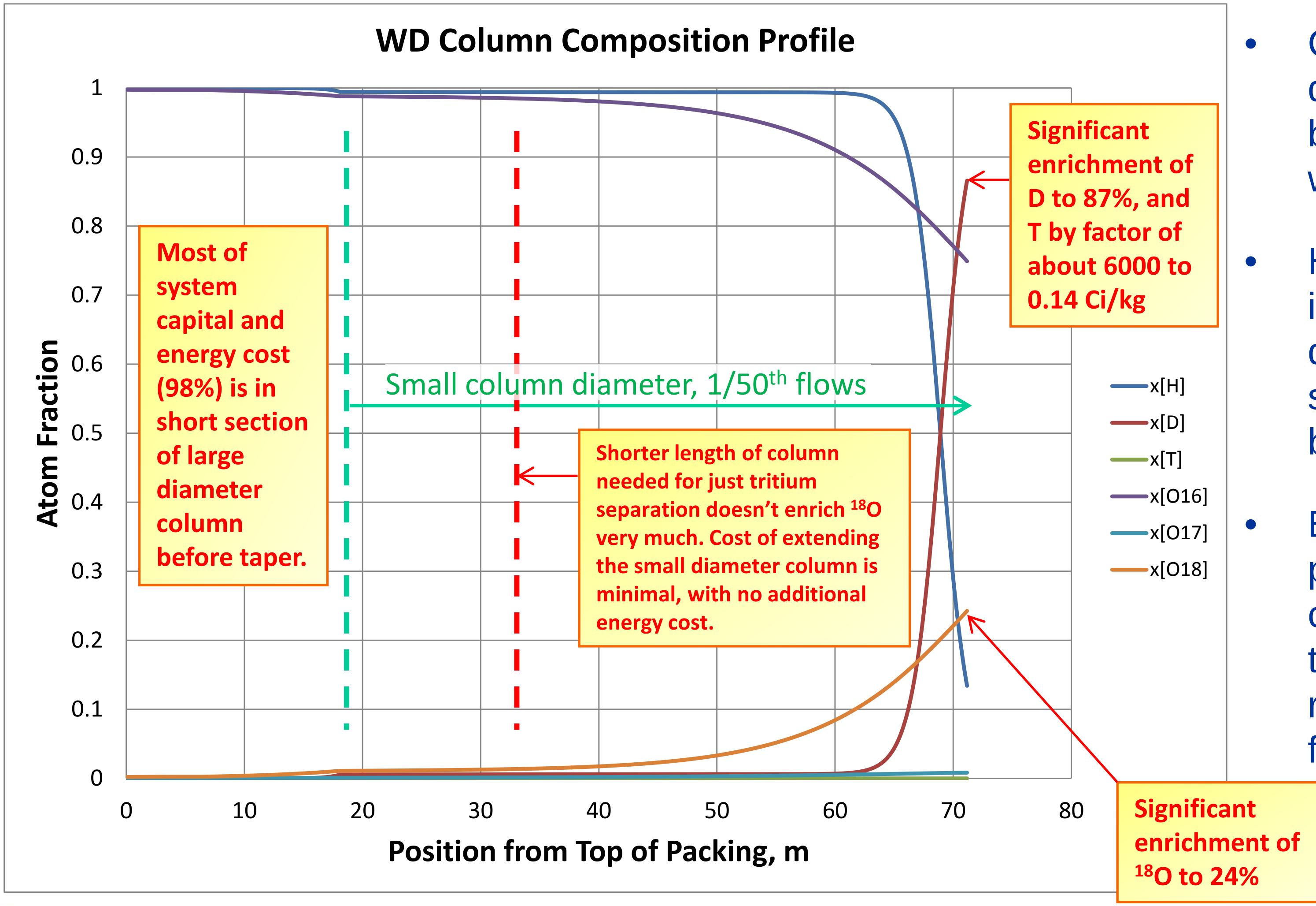
To ^{18}O Recovery and Tritium Disposal

- WD Volume reduction of 6000 produces 85% D_2O, with 0.14 Ci/kg, 67 kg/day
- ^{18}O is easily separated from tritiated water and upgraded to 99%. Nominal value of $H_2{}^{18}O$ is \$100/gram.
- Small volume of tritiated D_2O can be shipped to a Canadian heavy water reactor station for use as D_2O make-up. (Heavy water reactors require 2 to 4 tonne/year of D_2O make-up to compensate for losses.)

^{18}O Production is 16 kg/day at 400 m^3/day throughput or 11 kg/day at 500 m^3/day throughput. (^{18}O production increases at lower detritiation rate due to higher reflux ratio.)

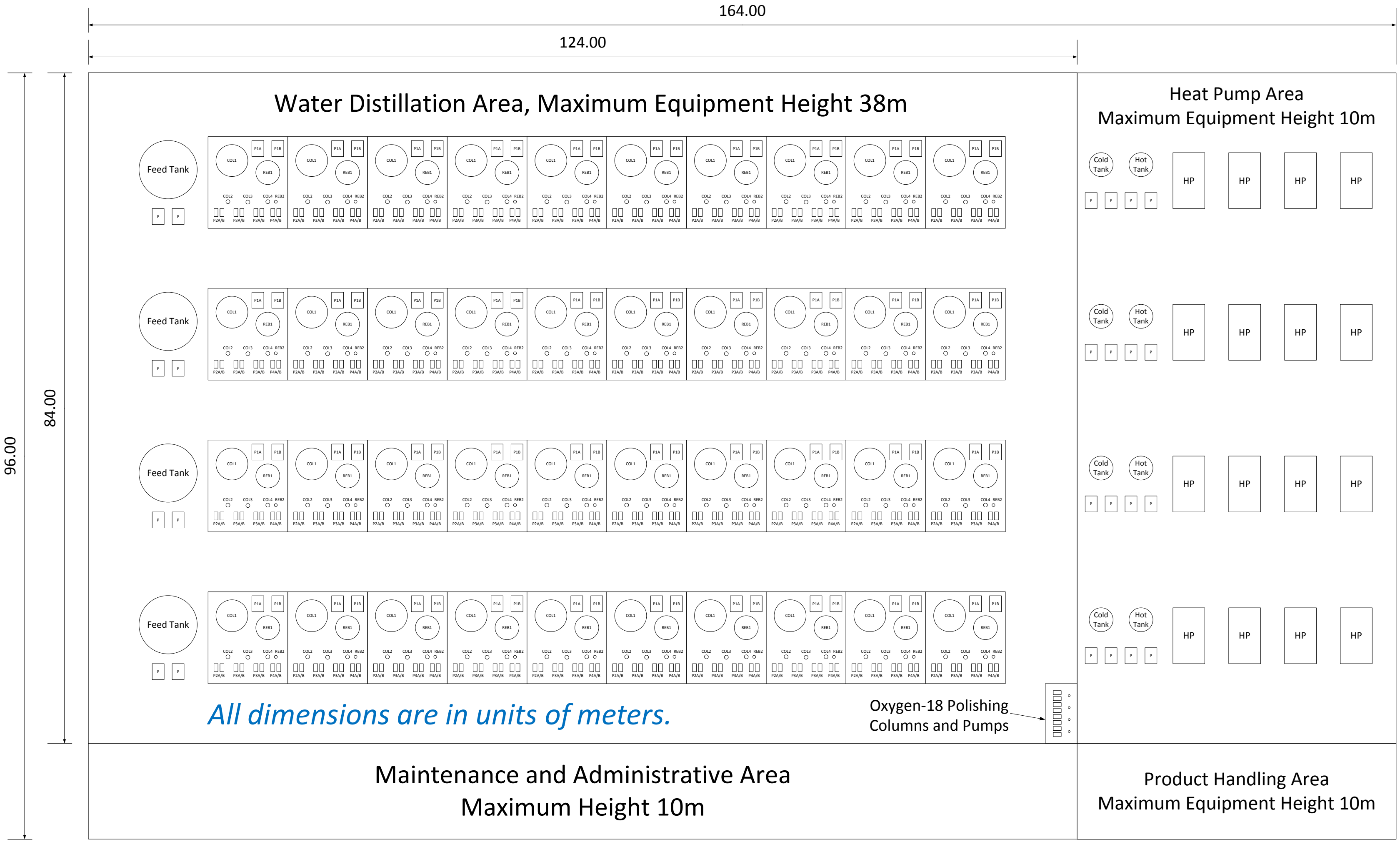
Value of ^{18}O produced is > \$1 million per day!

Fukushima WD Concentration Profile



- Cascade is designed to be mostly light water
- Heavy oxygen isotopes and deuterium rise sharply at the bottom
- Bottom product flow corresponds to a volume reduction factor of 6000

Fukushima WD System Layout 1



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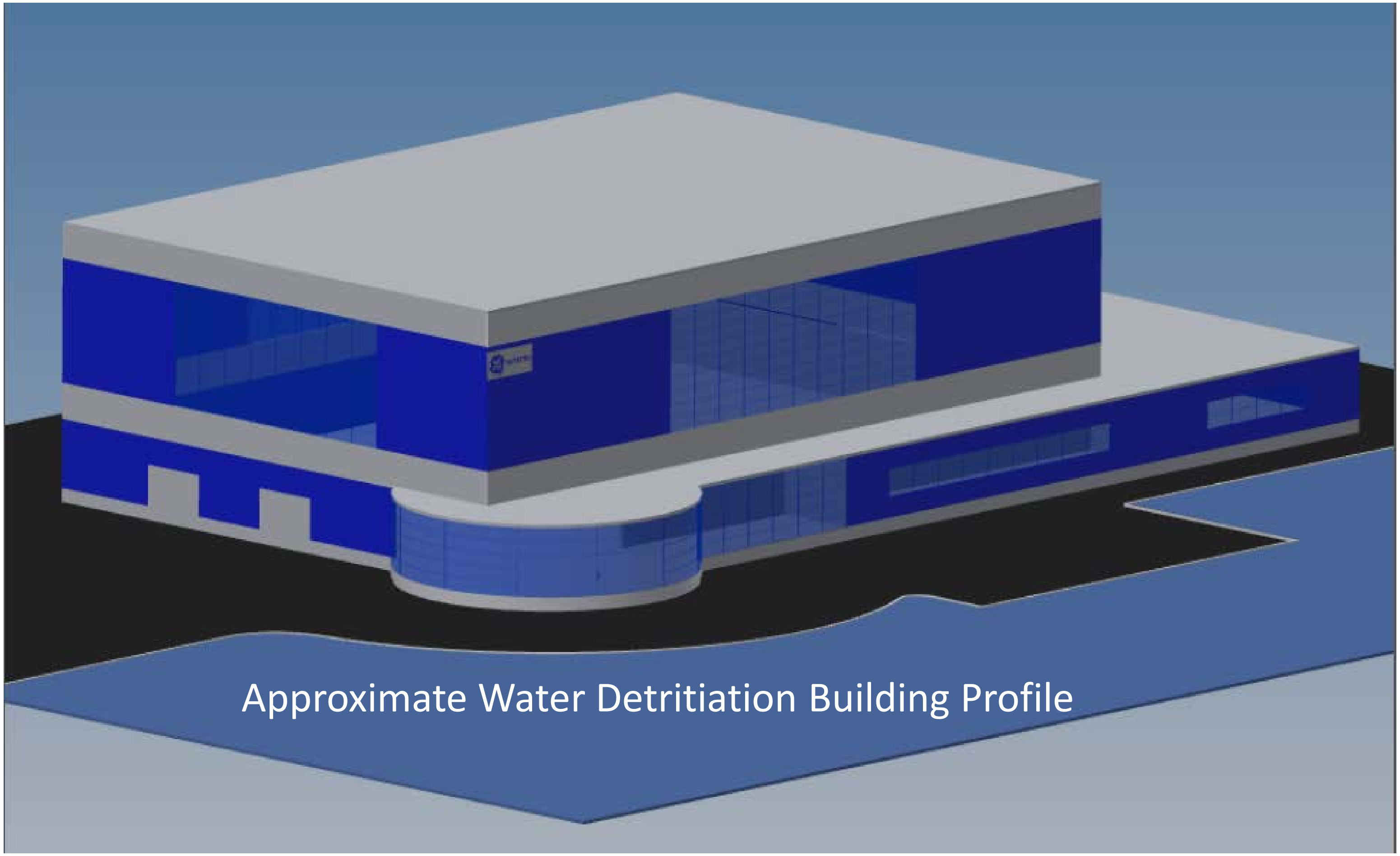
Fukushima WD System Layout 2



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Conclusions

- ✓ WD technology is proven, including scale-up to large diameter
- ✓ WD is a simple, safe and reliable process
- ✓ WD design & simulation codes are proven:
  - steady state
  - dynamic
- ✓ Industrial Heat Pumps are available for recycling heat
- ✓ ^{18}O byproduct will offset or possibly pay for cost of water detritiation
- ✓ ^{18}O production benefits medical diagnostics

We believe WD is the most proven and economic solution for Fukushima water detritiation

Thank you for your attention!

Appendix

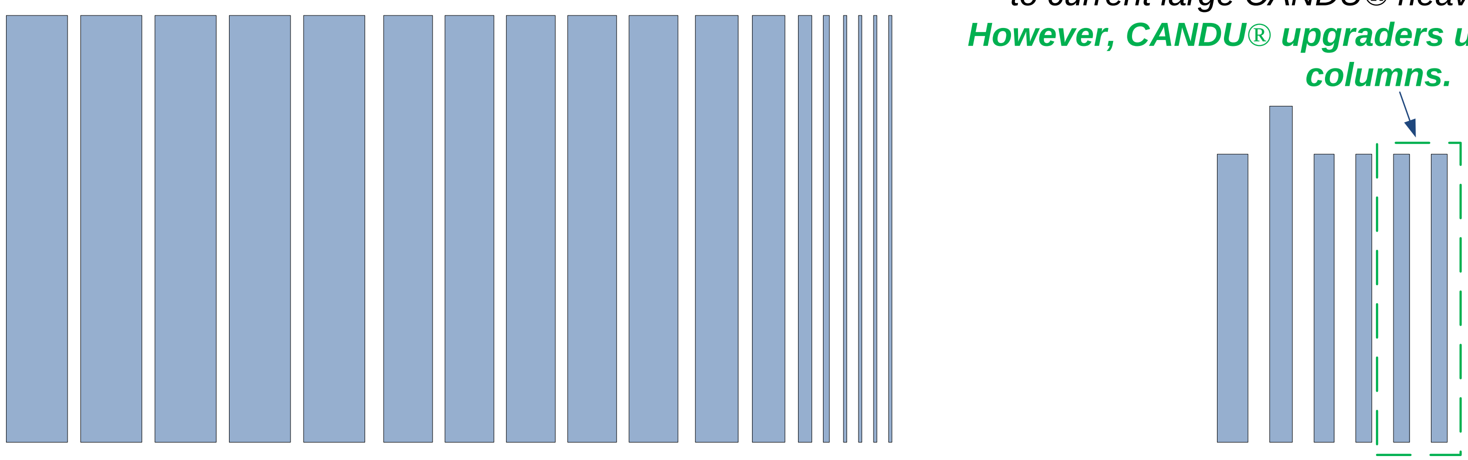
Presentation Outline

1. Fukushima Light Water Detritiation Requirement
2. Water Distillation vs CECE – The Big Picture
3. Water Distillation Industrial Experience
4. Water Distillation ^{18}O Byproduct Opportunity
5. GEH-C & Canadian Water Distillation Experience
6. Water Distillation Process Configuration and Energy Demand:
    a) Mechanical Vapor Compression
    b) Industrial Heat Pump
7. Conclusions

Industrial Scale of Water Distillation

Built 1943-1944

Savannah River individual columns were similar in size to current large CANDU® heavy water upgraders.
However, CANDU® upgraders use only two or three columns.



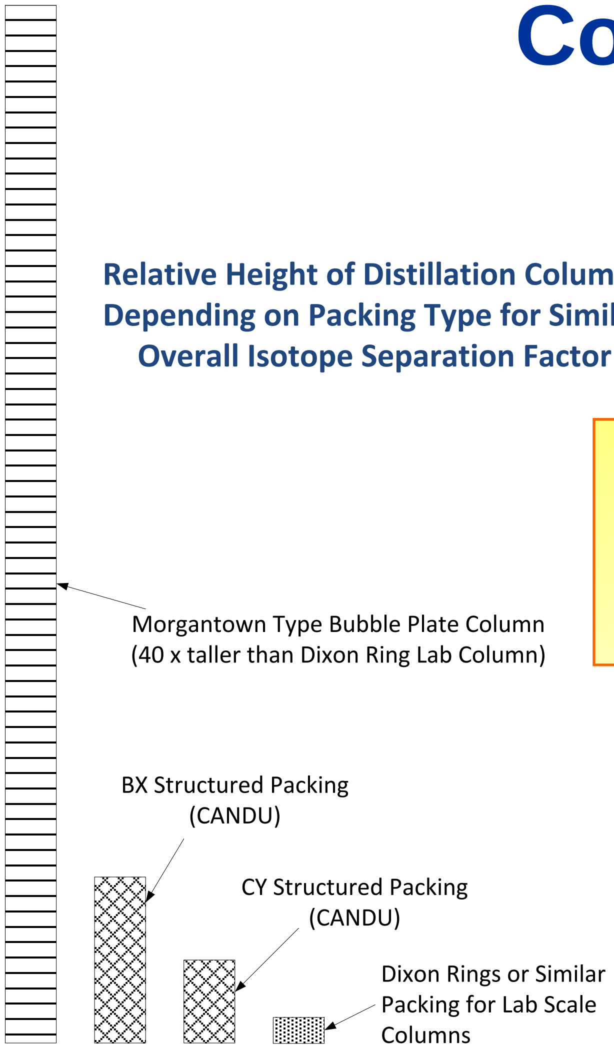
Savannah River WD columns Built Early 1950s.

Used to upgrade heavy water from 20% to 90%.

Morgantown, W. VA., Distillation Plant for Heavy Water　　**Savannah River Water Distillation Plant**

- WD technology is now much more compact than in WW II era.
- Canadian heavy water reactor Heat Transport Upgraders routinely recover tritium and deuterium from mostly light water (typical feed is 70% light water, 30% heavy water, and about 1 Ci/kg tritium in the heavy water component).
- Canadian heavy water reactor Heat Transport Upgraders have been in continuous use since the 1960s, and are the most proven and successful method of large scale light water detritiation, although heavy water upgrading is their primary function.

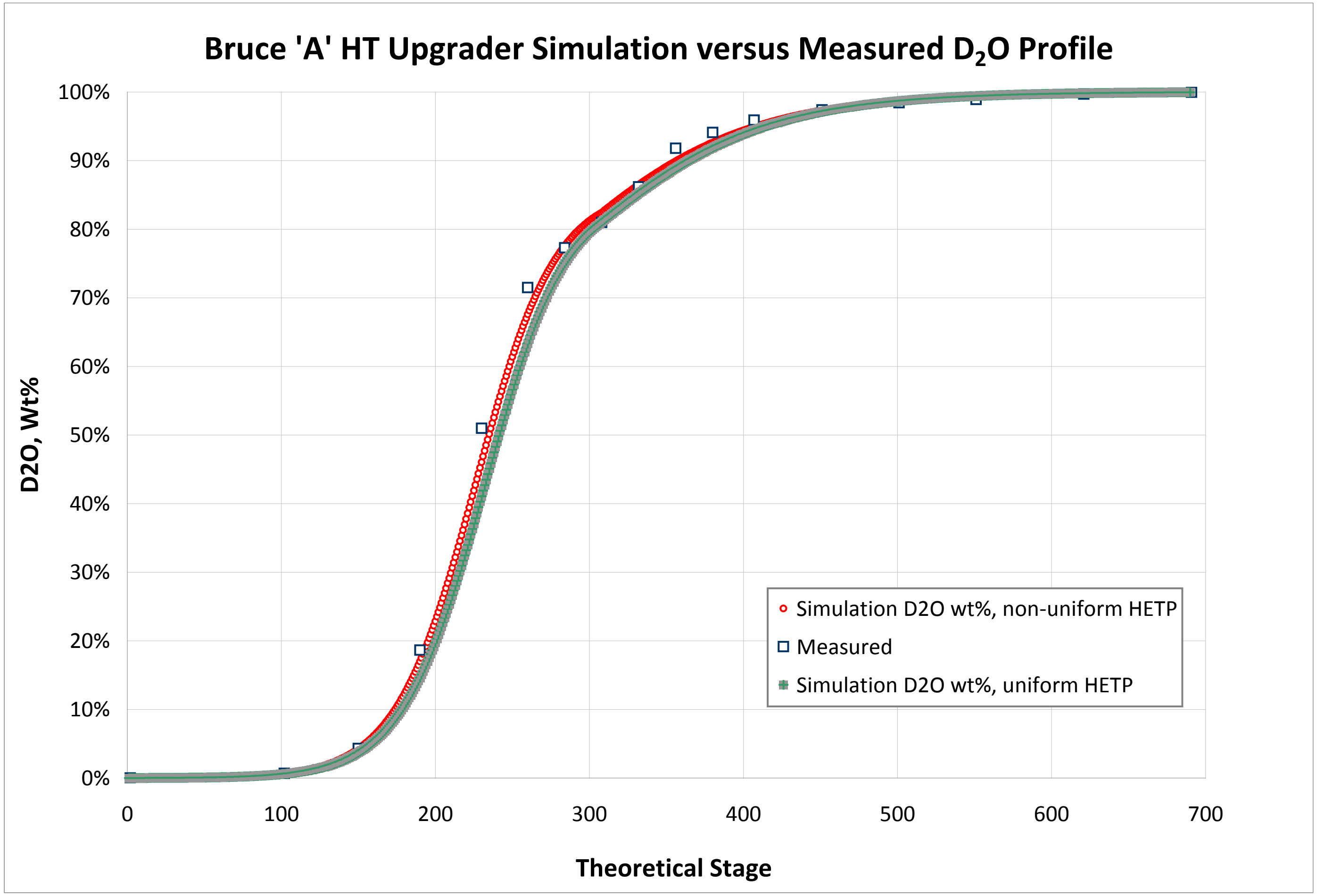
WD High Efficiency Packing – Effect on Column Height



Modern WD Columns are tiny in comparison to historical bubble cap tray columns!

- WW II era used inefficient bubble cap tray columns
- Structured wire gauze packing allows modern WD to be drastically smaller than historical bubble cap tray columns
- Structured packing, like that used in WD columns is used in many other industrial distillation applications at large size.

Heavy Water Upgrader Experience



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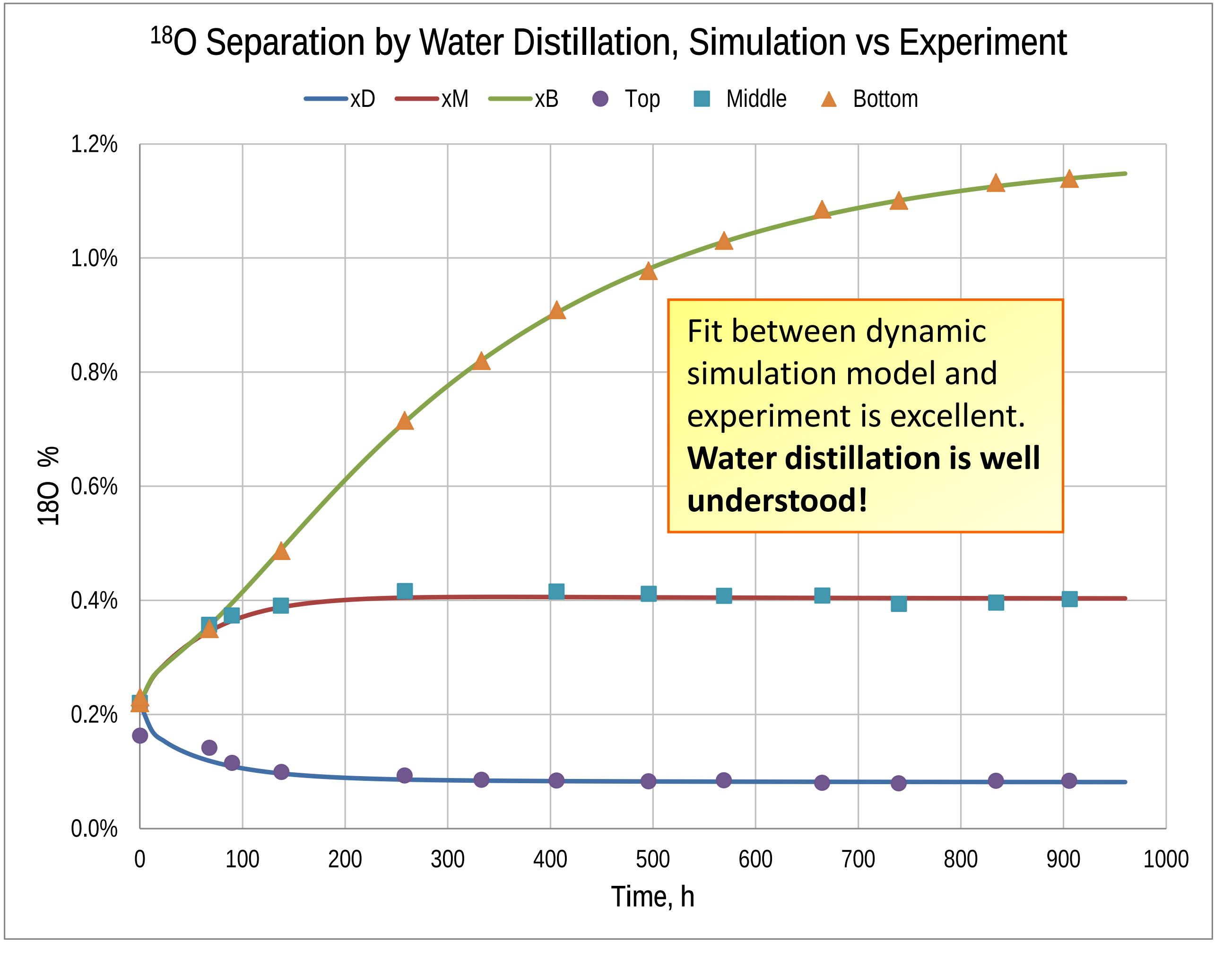
- Dynamic simulation closely matches measured performance
- Dynamic simulation is used to analyze column behavior with varying feed composition, and to simulate column detritiation prior to maintenance shutdown

GEH-C Water Distillation Experience

- GE Healthcare built a water distillation system in the UK to recover tritium from water after thermal oxidation of tritiated organic wastes.
- Inactive commissioning demonstrated WD separation performance by separating oxygen isotopes.



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Heat Pump COP Definition

$$\mathrm{COP} = \text{Coefficient of Performance}$$

$$\mathrm{COP} = \frac{Q}{W}$$

$$Q = \text{Heat supplied to the process}$$

$$W = \text{Work consumed by heat pump}$$

$$\mathrm{COP}_{heating} = \frac{Q_H}{W} = \frac{Q_C + W}{W}$$

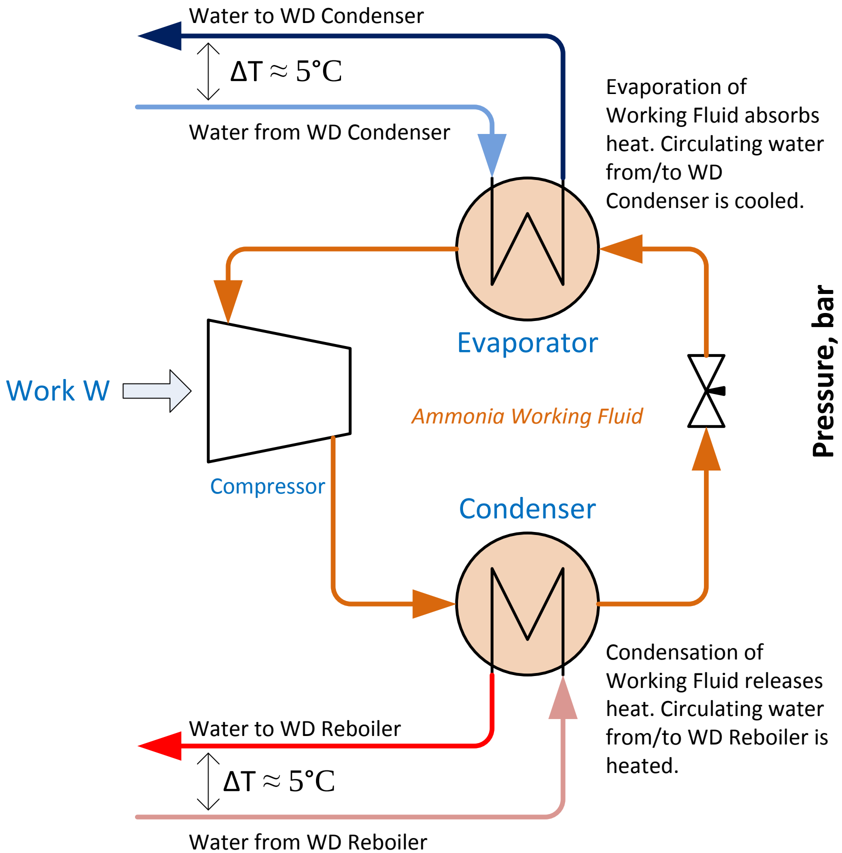
$$\mathrm{COP}_{cooling} = \frac{Q_C}{W}$$

$$Q_C = \text{heat removed from cold reservoir}$$

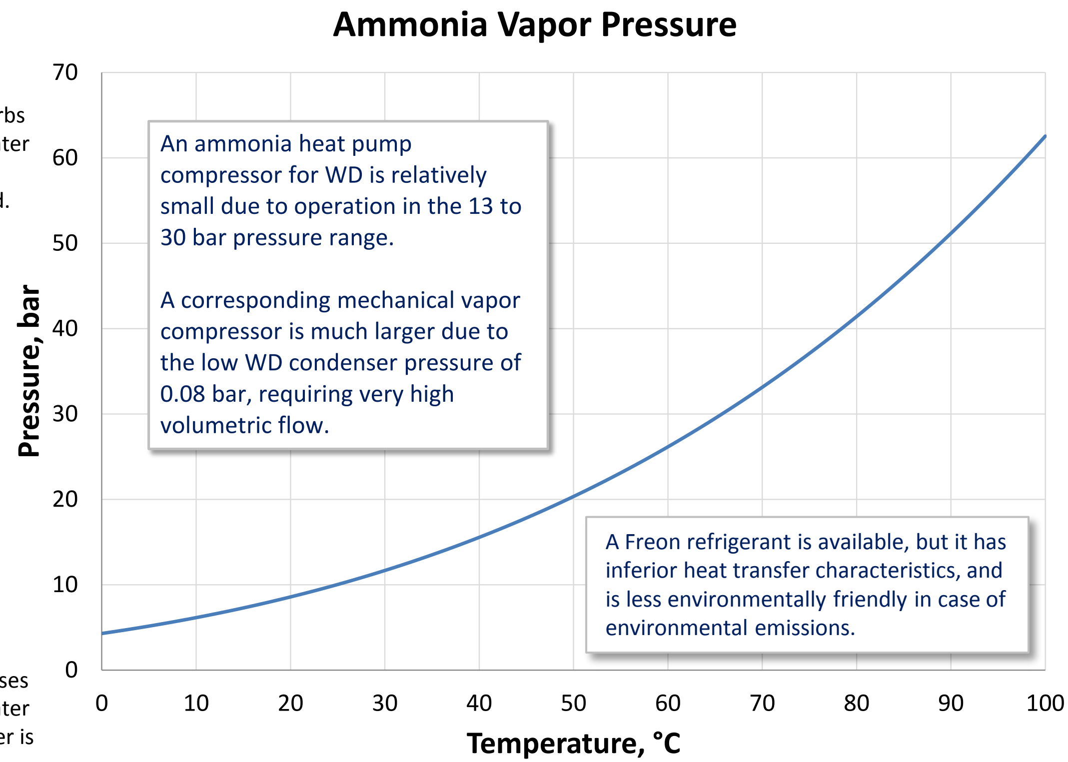
$$Q_H = \text{heat supplied to hot reservoir}$$

WD – Industrial Water/Water Heat Pump

Heat Extracted from Condenser = Q_C



Heat Delivered to Reboiler = $Q_C + W$



The Heat Pump working fluid system is hermetically sealed, like a household refrigerator.

WD Heat Pump Maximum Theoretical Performance

- WD Column Design Characteristics:

  $T_{\text{condenser}} = 315\text{K}\ (42°\text{C}), P = 8\ \text{kPa}$

  $T_{\text{reboiler}} = 320\text{K}\ (47°\text{C}), P = 11.6\ \text{kPa}$ (intermediate reboiler)

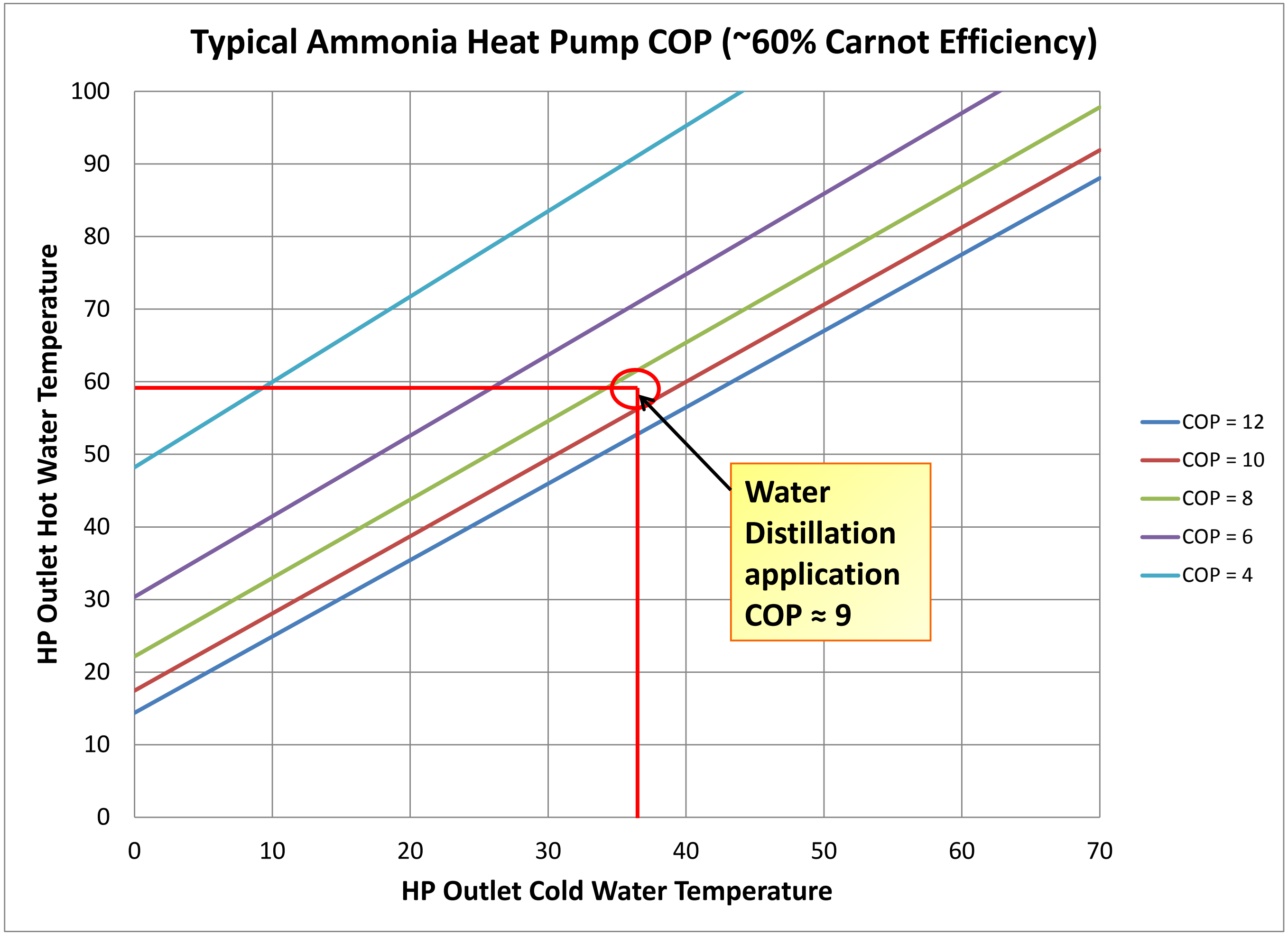
  $\Delta T = 5\text{K across condenser and reboiler heat exchangers}$

$$\text{COP}_{heating,max} = \frac{T_{hot}}{T_{hot} - T_{cold}} \approx \frac{(320+5)}{(320+5)-(315-5)} = 21.67$$

- $\text{COP}_{heating,max}$ is for an ideal Carnot heat pump
- In a practical design, $\text{COP}_{heating}$ of 8 to 10 is readily achievable

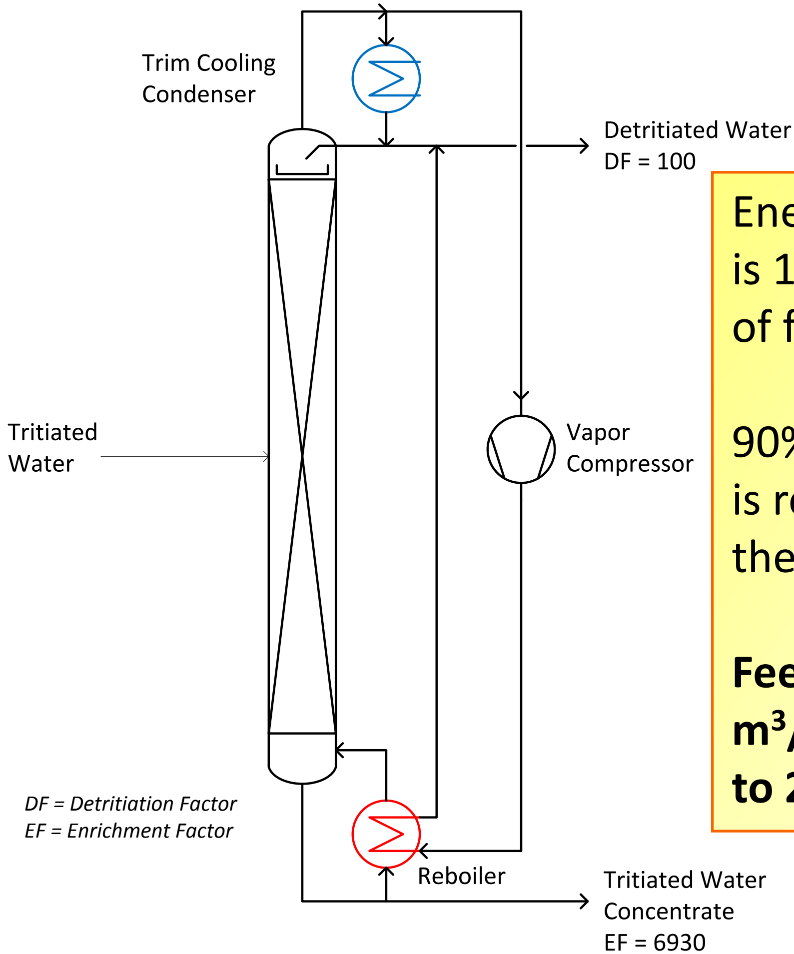
1 kW(e) provides 8 to 10 kW(t) of WD boilup.

WD – Industrial Heat Pump 2



- Typical ammonia heat pump performance
- Heat pumps are available in a wide range of sizes
- Compressor operating life is 20+ years
- Units are hermetically sealed

WD Energy – Direct Mechanical Vapor Compression – Option 2



Energy Requirement is 1.4 kW per kg/h of feed

90% of heat energy is recycled within the system

Feed rate of 500 m^3/day corresponds to 28 MW(e)

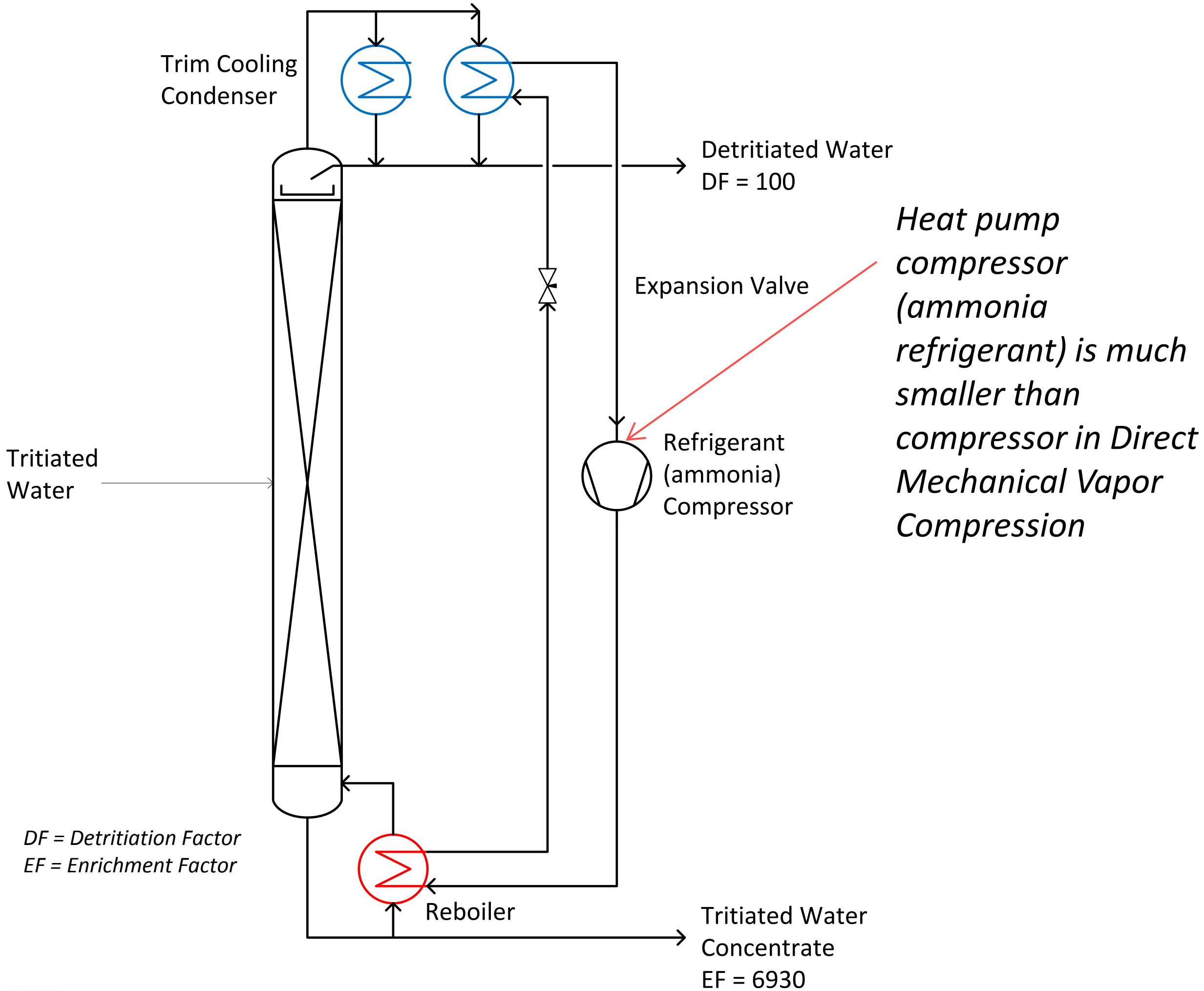
- Mechanical Vapor Compression (MVC) drastically reduces energy cost of distillation.
- Costs associated with steam boiler system are avoided.
- Water vapor MVC is widely used in water desalination, orange juice evaporation, sugar evaporation, etc.
- Capital cost of vapor compressors is often recovered in just one to two years of energy savings

Industrial Scale Mechanical Vapor Compressor

- Steam compressors have been used for over 50 years
- Exceptionally high plant availabilities of 96% – 98% are reported
- MVC specific energy consumption of 7-10 kWh/ton distillate is achieved in sea water desalination application
- WD application at 0.08 bar condenser pressure requires large vapor flow of 7.7 x 10^6 m^3/h for 500 m^3/day detritiation

GE Steam Compressors are available from 5,000 to 250,000 m^3/h. See: www.ge-energy.com/content/multimedia/_files/downloads/Centrifugal_Compressors_SRL.pdf

WD Energy – Auxiliary Heat Pump Circuit – Option 3



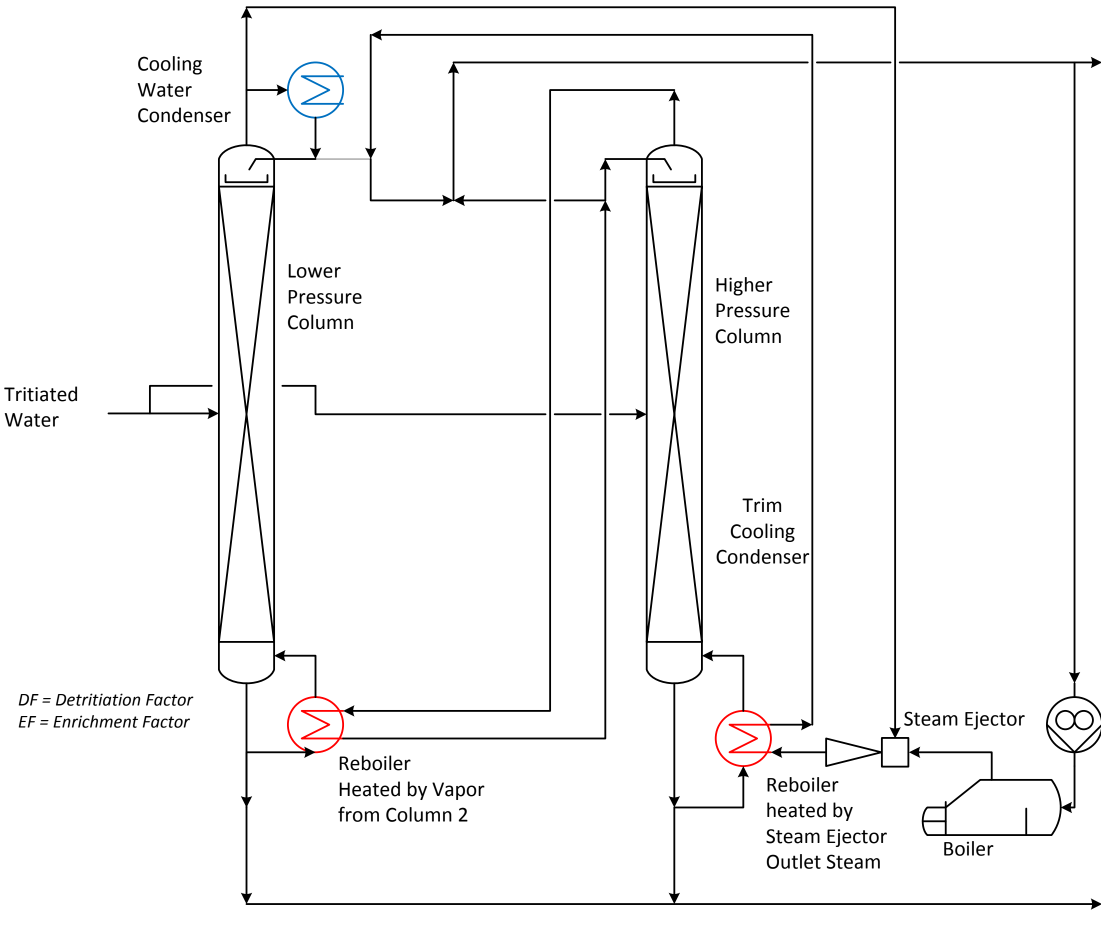
- Auxiliary Heat Pump, ammonia refrigerant, pumps heat from 40°C to 65°C

Energy Requirement is 1.4 kW per kg/h of feed

90% of heat energy is recycled within the system

Feed rate of 500 m^3/day corresponds to 28 MW(e)

WD Energy – Multiple Effect Distillation and Thermocompressor Vapor Compression – Option 4



Energy Requirement is 6 kW per kg/h of feed.

Feed rate of 500 m^3/day corresponds to 124 MW(t)

- Relatively complex process with about 60% energy savings as compared to direct heating and cooling.
- Not as much energy savings as with MVC or Heat Pump alternatives
- There are no mechanical compressors in this alternative, so capital cost is lower.

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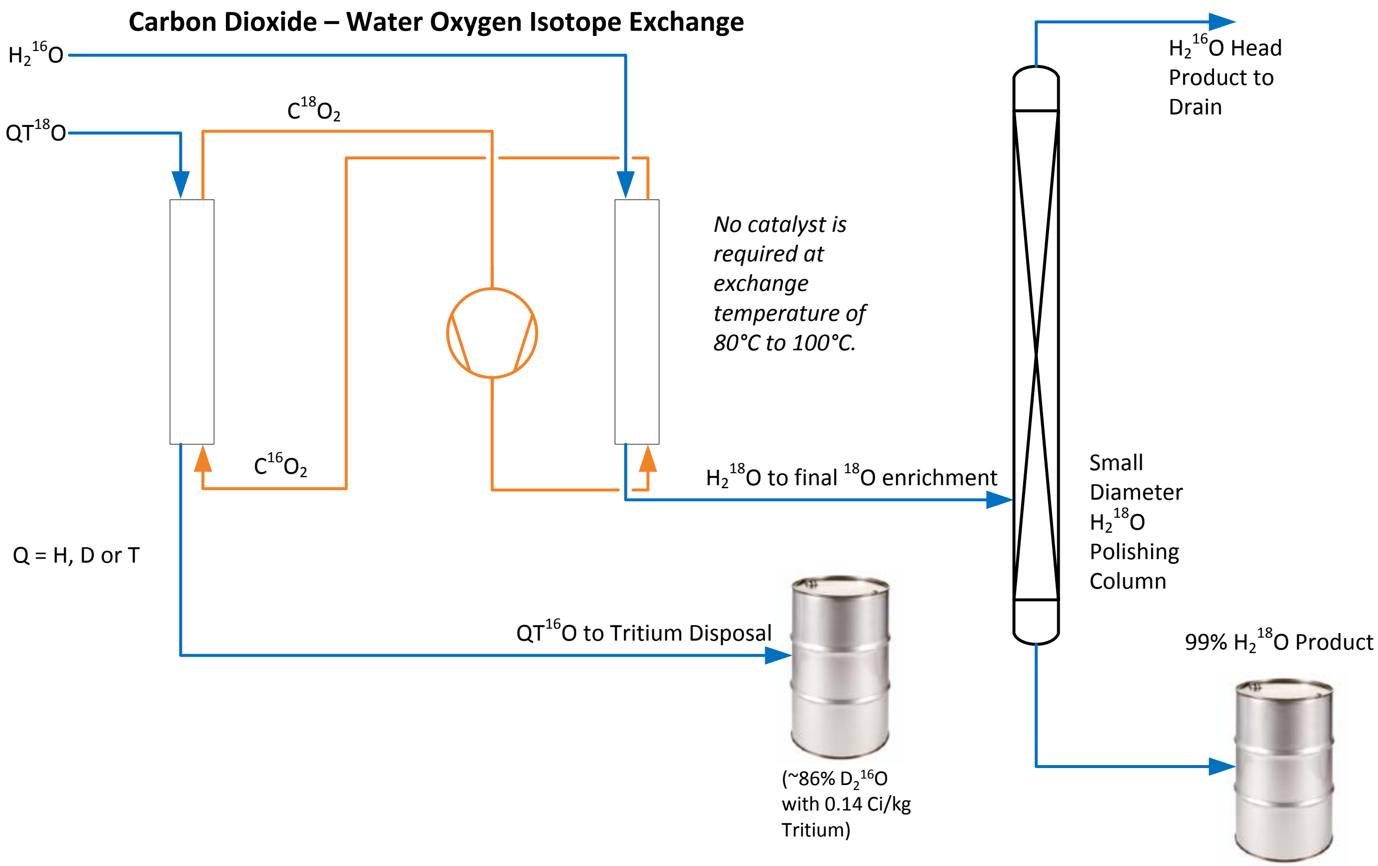
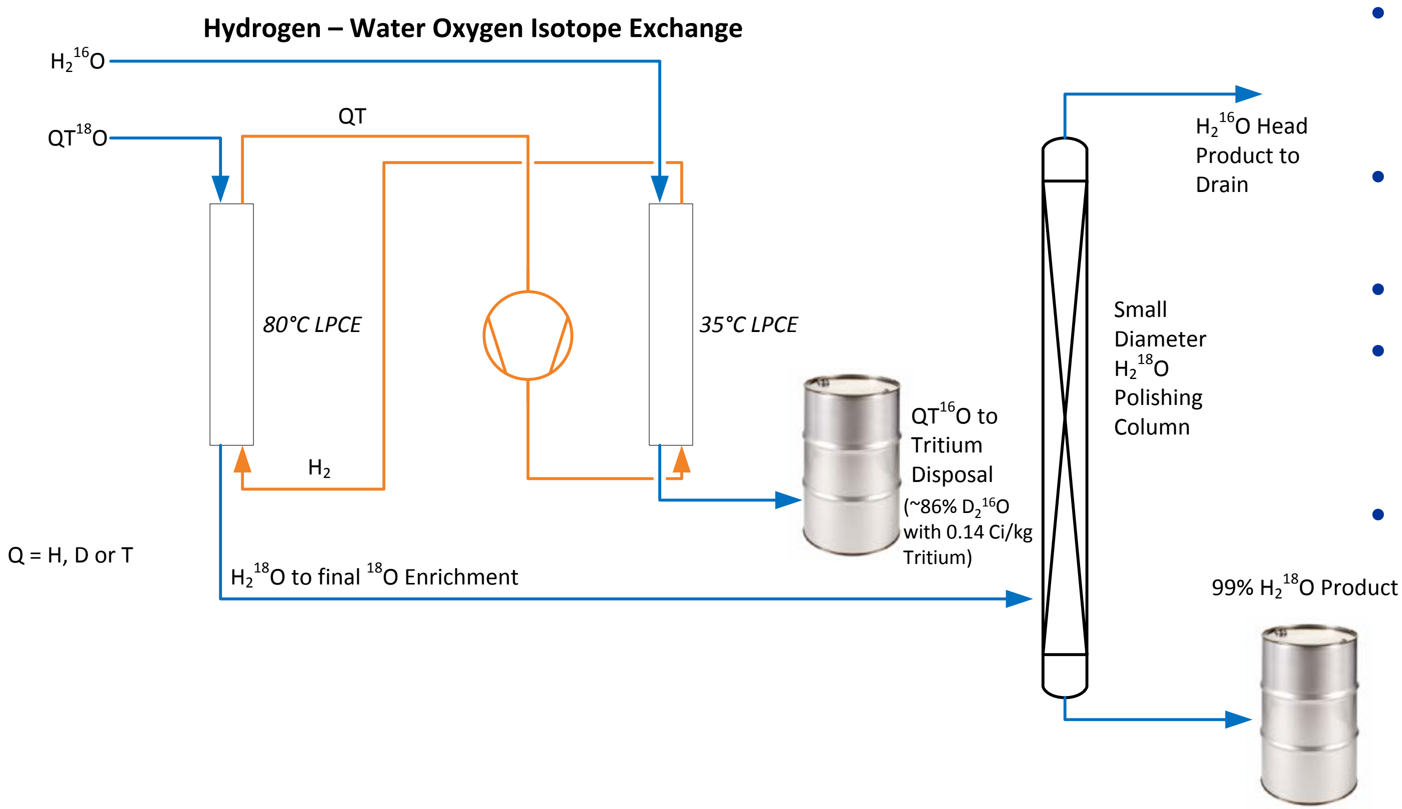
Recovery of ^{18}O from $QT^{18}O$, Option 1



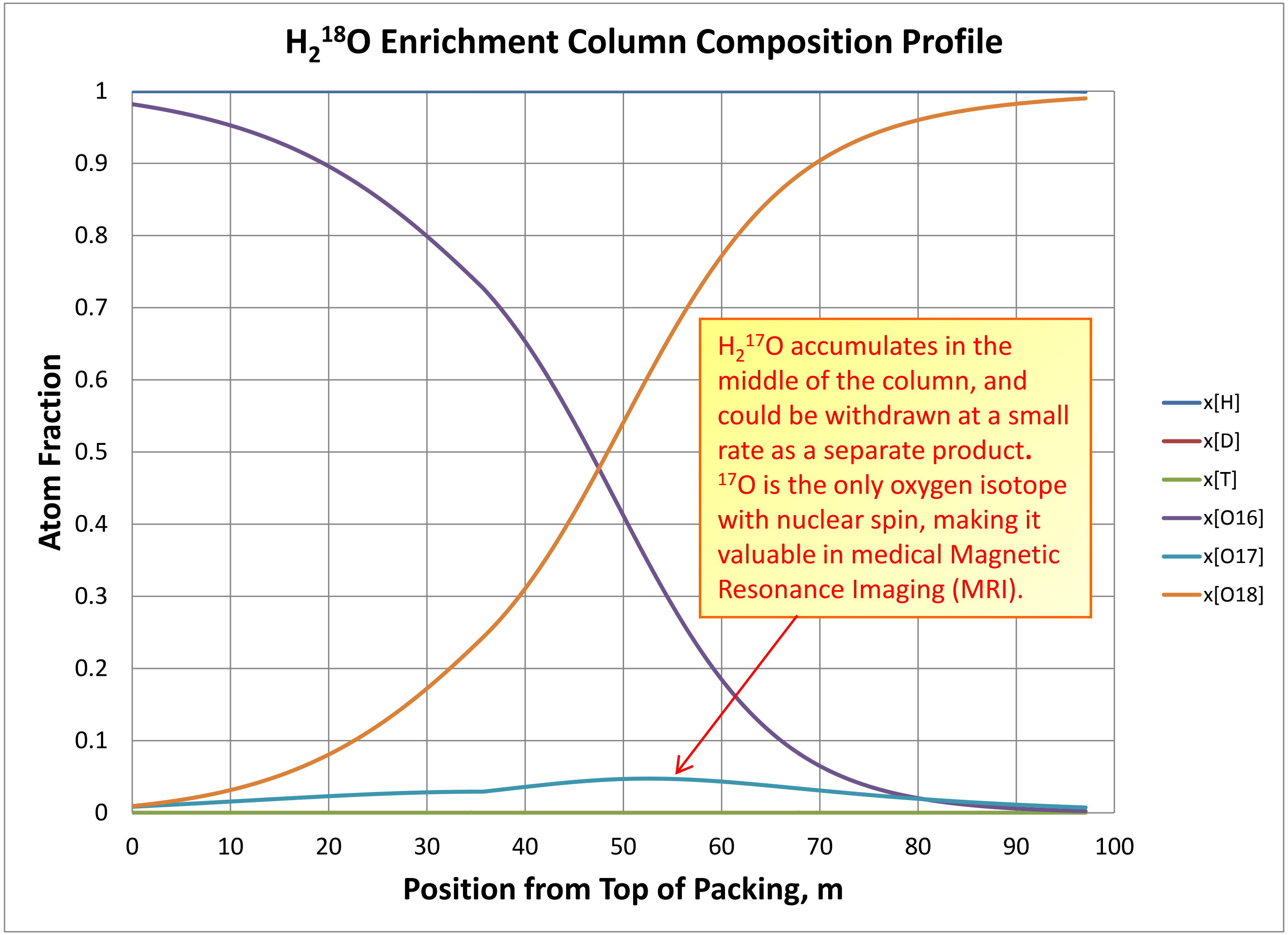
- **No flammability or explosion hazard**
- Exchange rate between water and carbon dioxide is well known
- Exchange is slow at room temperature but fast enough at elevated temperature to not require catalyst
- Equipment is small and inexpensive
- CO_2 molecule does not carry tritium

Recovery of ^{18}O from $QT^{18}O$, Option 2



- **Hydrogen flammability and explosion hazard – but safe closed system**
- No electrolyser is required
- Small LPCE columns
- LPCE Catalyst is more expensive than inert packing
- Q_2 molecule carries tritium between columns

$H_2{}^{18}O$ Product Final Enrichment



- Small diameter column to enrich $H_2{}^{18}O$ to 99% purity
- WD is economic technology for $H_2{}^{18}O$ production irrespective of tritium separation
- $H_2{}^{18}O$ product offsets cost of detritiation.

Water Distillation ^{18}O Byproduct Opportunity

Stable Oxygen Isotope	Natural Abundance
^{16}O	99.758%
^{17}O	0.038%
^{18}O	0.204%

- Almost all the ^{18}O produced in the world is produced by water distillation
- Market value of $H_2{}^{18}O$ is about $100/gram

http://www3.gehealthcare.com/en/products/categories/pet-ct/pet-ct_scanners/discovery_iq

- ^{18}O is the precursor for ^{18}F used in Positron Emission Tomography (PET) medical imaging scanners
- ^{18}F is produced by irradiation of ^{18}O with high energy protons (18 MeV) from a cyclotron. $^{18}O + {}^{1}H \rightarrow {}^{18}F + n$. The target material is $H_2{}^{18}O$.
- ^{18}F is a positron emitter with a half life of 109.77 minutes.