Review and Evaluation of Water Detritiation Technologies for Watts Bar Primary Cooling Water

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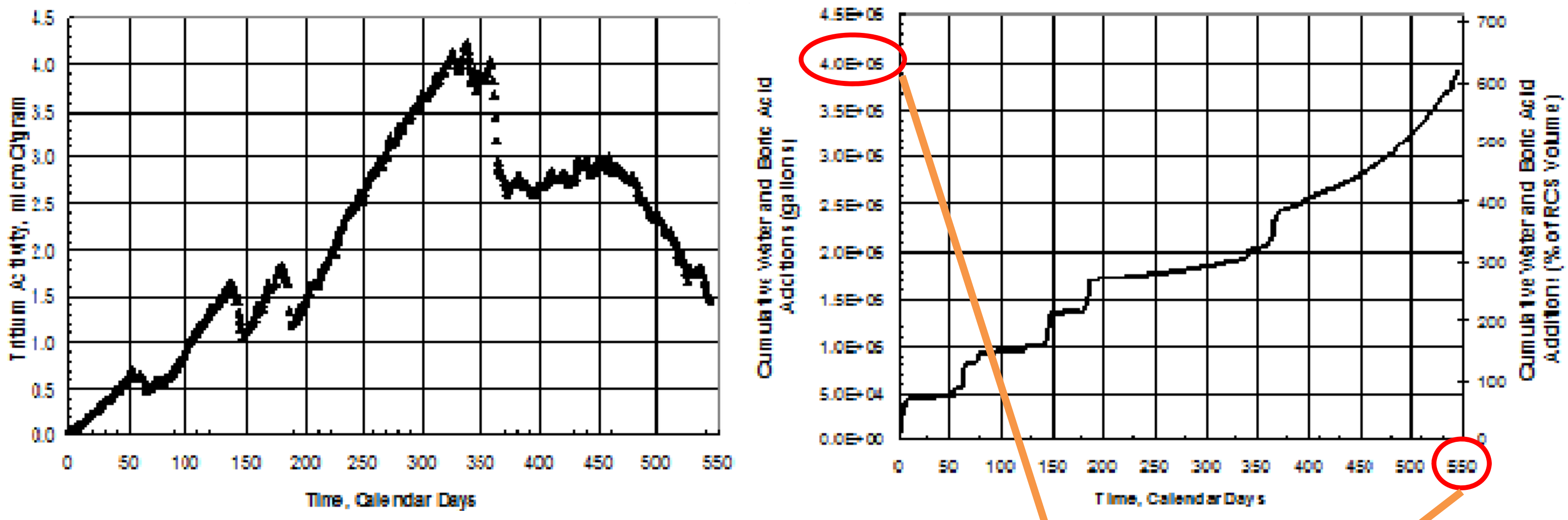
Background

- Tritium in the primary cooling water of the Watts Bar Nuclear Reactor
    - not captured nor treated but released to the river
    - Tritiated water concentration is well below the EPA's drinking water standard of 20 pCi/g met after mixed with the river
- Increased number of TPBARs may increase the amount of tritium in the cooling water
    - reactor contains 368 TPBARs, but 1504 will be used during the "equilibrium" phase
    - higher tritium levels may necessitate other pathways for tritiated water disposition

Report Purpose

- Identify and evaluate disposal pathways for disposition of tritium-containing primary cooling water from Watts Bar
    - include the current approach of direct disposal into the Tennessee River
    - consider alternatives to reduce tritium prior to discharge
    - concentrated tritium stream will be grouted and disposed of in a commercial near-surface burial site
    - costs are rough order of magnitude estimates only

Conditions Considered



Tritium activity and water discharge volume for Cycle 9, Watts Bar Unit 1

Overall Assumptions		
Total Volume	390,000	gallons
Processing Duration	550	days
Operating Efficiency	80%	--
Average ^{3}H Conc.	14	uCi/g
Target Decontamination Factor	140	--
Target Concentration Factor	100	--

0.6 gpm water flow rate

Previous Work

- This work is based previous tritium mitigation alternatives analyses:
  - Hanford Site Wastewaters (1997, 2004, 2009)
  - Savannah River Site (1998)
  - CANDU Reactors (1984, 1990)
  - Fukushima Daiichi Nuclear Plant (2013, 2014)
  - Recent literature
- Use of previous cost estimates from literature:
  - adjusted to 2015 dollars
  - system sizing based on six-tenths-factor rule
  - processes for isotope enrichment are “in most instances . . . indifferent to the feed concentration.” (Miller 1998)
  - 10 year lifetime, linear depreciation

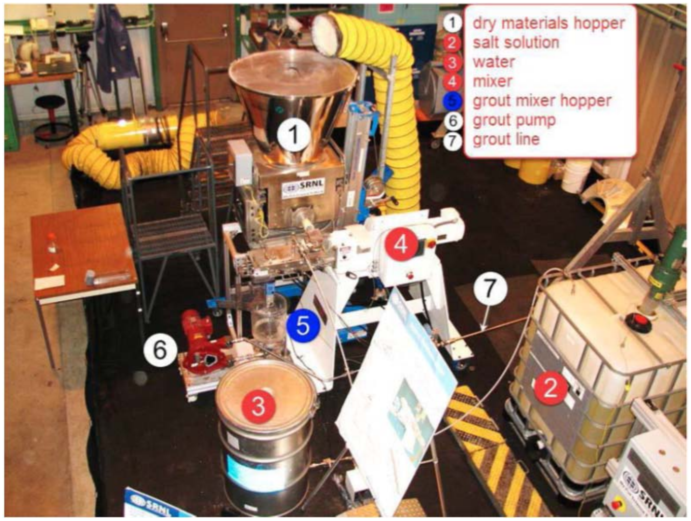
Approach

- When Literature Cost Not Available
  - Operating costs based on electricity and natural gas costs
  - Facility footprint for nuclear facility estimate \$3500/ft^2
  - Use available current cost data from DOE Energy Efficiency and Renewable Energy (EERE)
    - Electrolysis, Hydrogen Liquefaction, Fuel Cells
- Estimate of Technology Readiness (TRL) from DOE EM

TRL Level	Scale of Testing	Fidelity	Environment
9	Full	Identical	Operational (Full Range)
8	Full	Identical	Operational (Limited Range)
7	Full	Similar	Relevant
6	Engineering/Pilot	Similar	Relevant
5	Lab/Bench	Similar	Relevant
3-4	Lab	Pieces	Simulated
1-2	None	Paper	Simulated

Tritium Disposal Alternatives— No Tritium Separation

- Direct Disposal into the River (**$0.7/gallon**)
  - Only analysis and sampling required
- Grout Disposal of Tritiated Water (**$12/gallon**)
  - Use phosphate/sulfate waste grout (high water)
  - 2018 disposal costs for Waste Control Specialists (WCS)
  - Equipment cost based on grouting study and SRS Engineering Scale Continuous Processing Facility (ESCPF)



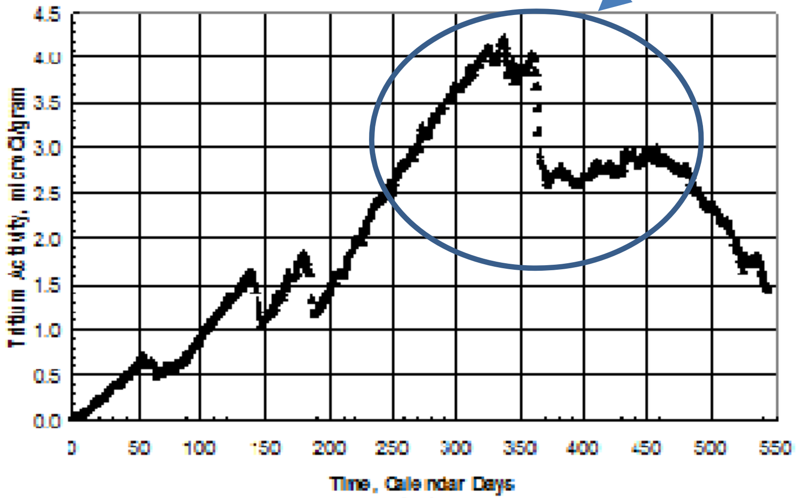
ESCPF

Characteristic	Cost	Units
Type of Grout	Phosphate/Sulfate Waste	
Ratio cement to water	7.5	lb/gallon water
Density of Cement	11.7	lb/gallon grout
Composition of Solids	41 wt% Portland cement 40 wt% Fly Ash 11 wt% Attapulgite clay 8 wt% Indian Red Pottery Clay	
WCS Class A LLW Base Disposal Cost	$876	$/cubic yard
WCS Class A LLW Drum Surcharge	$417	$/cubic yard
Water Shipping Cost	$2.50	$/gallon
*** WCS costs area based on Year 5 (2018)**		

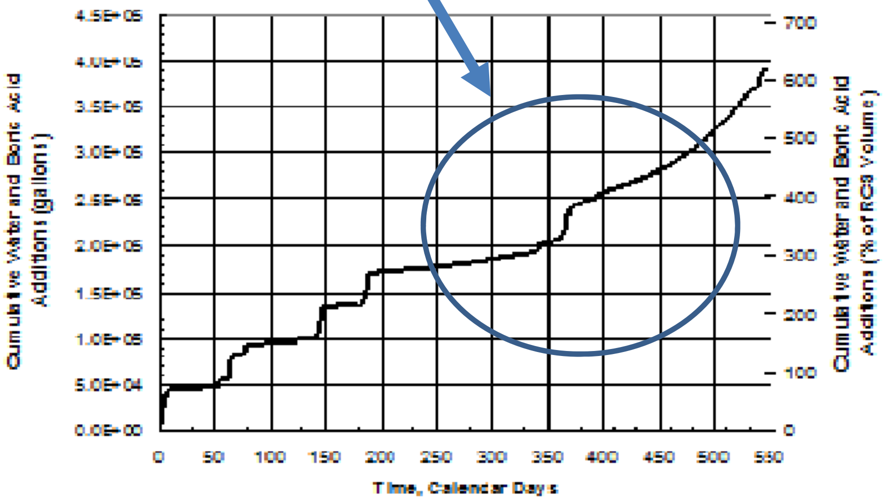
Combined Direct Disposal and Grout Disposal

- Assume 1/3 of water is grouted and 2/3 disposed of into river
- Reduced cost: **$5.5/gallon**

High Concentration Tritium for Grout Disposal



(a)



(b)

Tritium: Hydrogen Separation Factors for Developed Tritium Removal Technologies

	Low Temperature		High Temperature	
Dual Temperatures Processes	**T (°C)**	**T/H**	**T (°C)**	**T/H**
Water Bithermal	60	5.289	150	2.918
Girdler Sulfide	32	3.599	130	2.563
Ammonia Bithermal	-30	16.1	40	8.6
Single Temperature Processes	**T (°C)**	**T/H**		
Catalytic Exchange	60	5.289		
Water Distillation	50	1.059		
Electrolysis	50-80	15		
Cryogenic Distillation	-250	1.8		
Graphene Oxide Membrane	100	1.6		
Adsorption Processes	RT	1.4		

Operating and Capital Costs Estimated for these Technologies

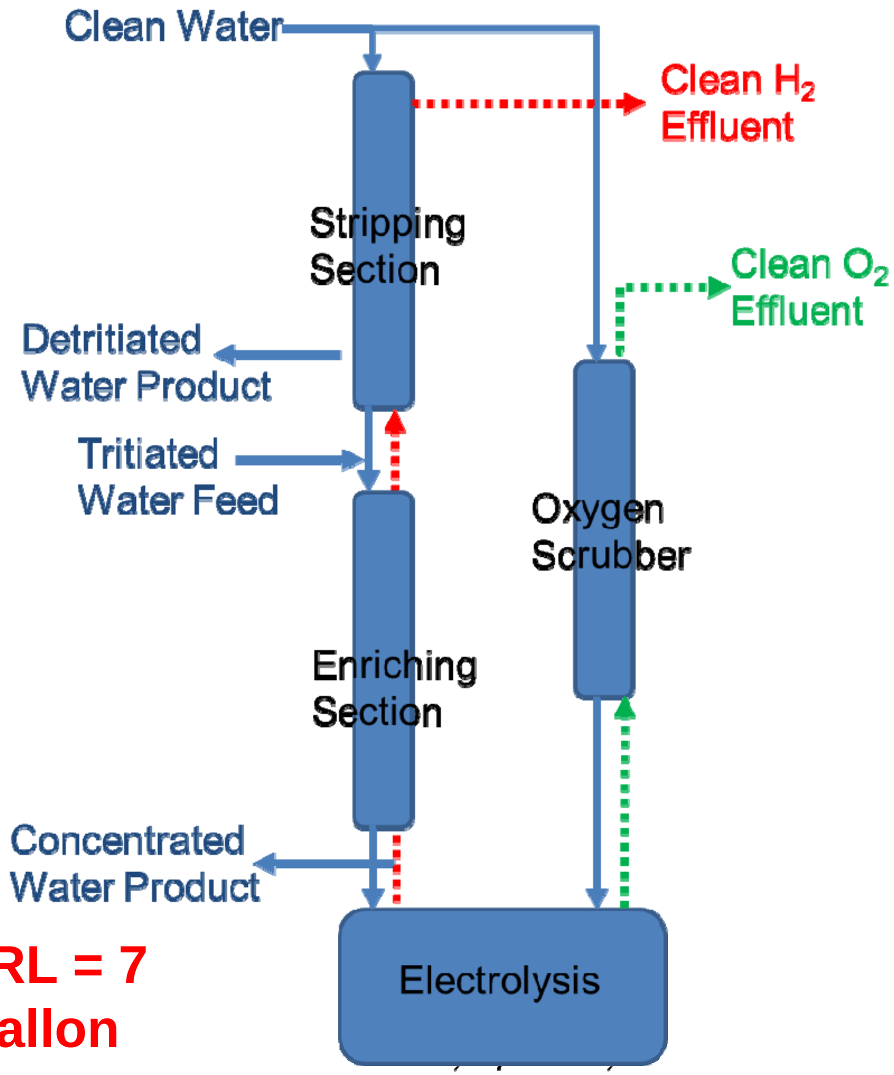
Water Distillation

- Lowest separation factor
  - High reflux → high heat usage + large diameter columns
  - > 200 theoretical plates→ tall columns
- Use of heat pump and improved packing address column size and heat requirements
- Well developed technology
- Working with water → Very safe

Capital + Operating = $19/gallon
TRL = 7

Water/Gas Catalytic Exchange: Vapor Phase, Liquid Phase, or Combined Electrolysis

- VPCE, LPCE and CECE all based on the equation
  - HT(g) + H_2O (l) ←→ HTO (l) + H_2 (g)
- VPCE and LPCE processes well developed
  - DF = 25-35
- CECE plants have achieved higher DFs
  - DF = 30,000 - 50,000
  - Commercial at ~1 kg/hr scales
  - 30X scale-up required



CECE: TRL = 6   VPCE/LPCE: TRL = 7

CECE: Capital + Operating = $7/gallon

Facilities Use Water/Gas Catalytic Exchange

Facility	Technologies	Input Capacity, gpm	Input ^{3}H, µCi/g
Darlington, TRF	VPCE	1.6	30,000
Grenoble	VPCE	0.1	3000
AECL Test	LPCE	0.03	23,000
Chalk River, TEP	LPCE	0.09	35,000
Wolsung	LPCE	0.44	10,000-60,000
Mound	CECE	0.09	Unknown
Mol	CECE	0.007	2×10^{-3}
KFK	CECE	0.004	100
FUGEN	CECE	0.004	4000

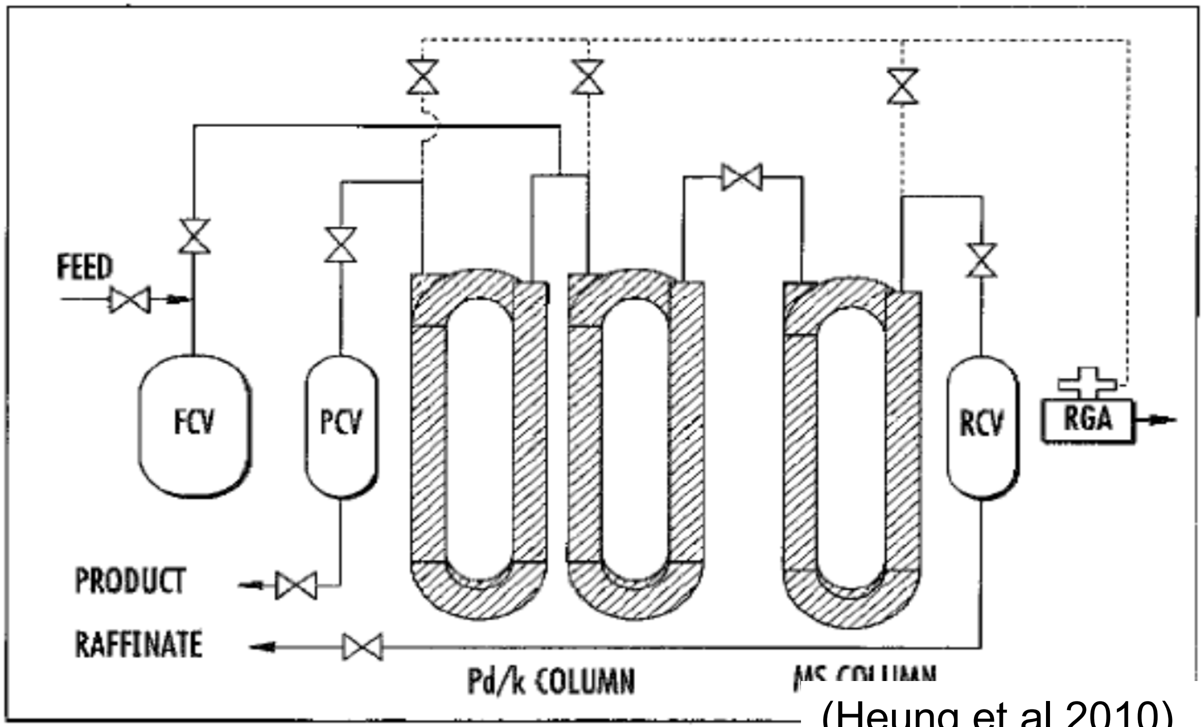
Watts Bar Application:

Flow Required = 0.6 gpm

Input ^{3}H, µCi/g = 14

Thermal Cycle Adsorption Process (TCAP) + Electrolysis

- Semi-continuous temperature swing chromatographic process
- Tritium concentrates at far end of Pd/k column & protium concentrates at far end of MS column
- Used for tritium purification



(Heung et al 2010)

TCAP-E Cost Estimate

- Estimate includes cost of electrolysis, electricity and heat for cooling and heating, Pd metal cost, facility cost, and tritium disposal

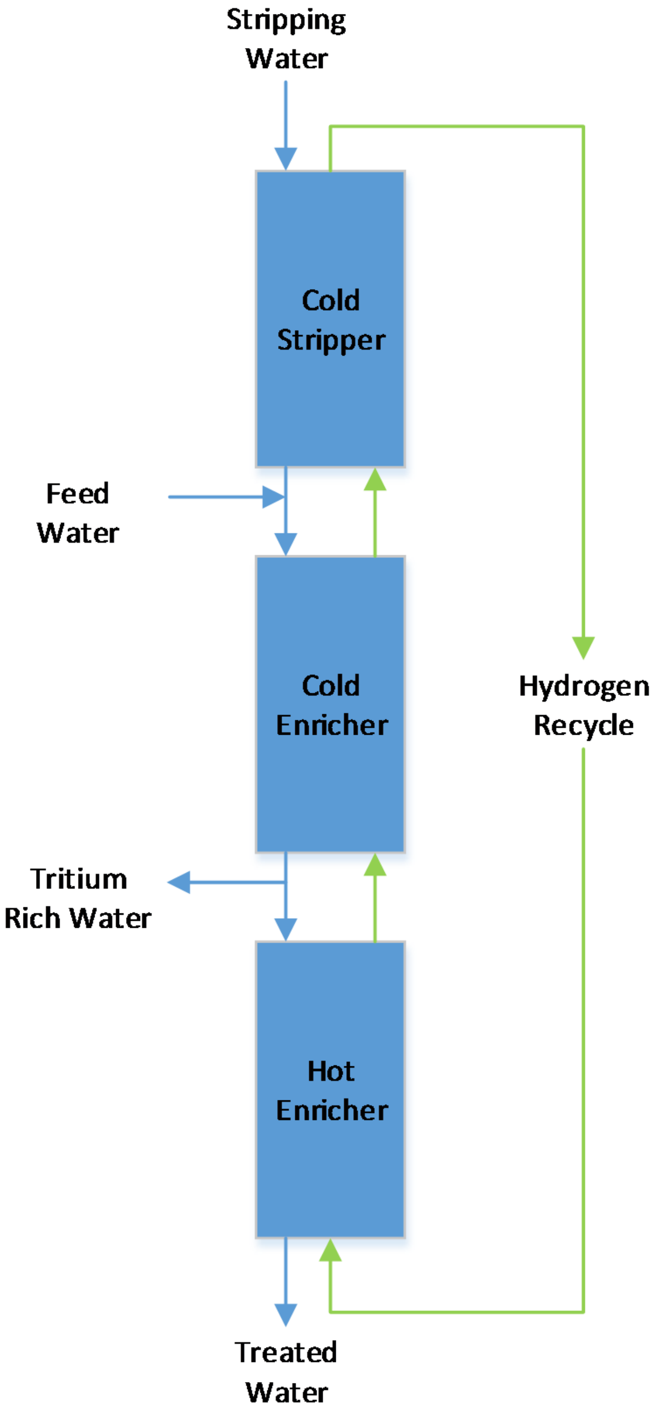
	Pd/k Column	MS Column	Units
Throughput Rate	12.8	40.4	L H_2 / kg bed / cycle
Mass fraction Pd	27%	0%	--
Temperature Differential Pd/k Bed	200	90	°C
Cycle time	16		min/cycle
Absorbent Fractional Heat Load	50%		--
COP for Cryocooling	0.5		--
Footprint of Mini-TCAP (4 sl/cycle)	18		ft^2

Capital + Operating = $17/gallon

TRL = 6

Bithermal Processes

- Hydrogen-Water (H_2)
  - 50 to 170ºC, 5 MPa
  - **$7/gallon + TRL 6**
- Girdler Sulfide (H_2S)
  - H_2S toxic, corrosive, flammable
  - 32 to 130ºC, 2 MPa
  - **$11/gallon + TRL 7**
- Ammonia-Hydrogen (NH_3)
  - -30 to 40ºC, 15 MPa
  - **$165/gallon + TRU 7**



Other Processes Evaluated

- Multiple Electrolysis Cycle Process
  - Feed electrolyzed 9 times for DF = 10,000, CF = 100
  - Use fuel cells to recover some electricity
  - $Cell\ concentration = \frac{1}{\sqrt{\propto}} * H2\ Product\ Concentration$
  - **$22/gallon + TRL 5**
- Cryogenic Distillation
  - Issues with safety, purification, liquefaction
  - **$9/gallon + TRL 6**
- Graphene Oxide Membrane
  - Direct tritiated water clean-up
  - Low energy, but extremely high capital cost
  - **$227/gallon + TRL 3**

Separation Techniques Not Costed

- Low TRL / Research Level Techniques
  - Selective Laser Excitation (fluoro- and chloro-alkanes)
  - Freeze concentration ($\Delta T_{melt} = 4.49^{o}C$)
  - Pressure swing adsorption (synthetic zeolites)
  - Palladium membrane reactor (alternative electrolysis)
  - Chromatographic adsorption (isotopically swamping of tritium loaded molecular sieve bed)
  - Thermal diffusion (T gradient)
  - Formic acid electrolysis (8X faster kinetics than water)
  - Functionalized Zn and Cu MOF adsorption (increased cryogenic temperature)

Summary of Results

Proposed Technology	Technology Readiness Level	Estimated Cost					
		($/gallon)	< $1	$ 1-10	$ 1-20	$20-100	> $100
Direct River Disposal	8	$0.7	🟩				
Grout High Tritium Water	7	$5.5	🟩	🟩			
Girdler Sulfide Process	7	$11	🟩	🟩	🟩		
Grout Entire Volume	7	$12	🟩	🟩	🟩		
Water Distillation	7	$19	🟩	🟩	🟩		
Ammonia-Hydrogen Bithermal Process	7	> $165	🟩	🟩	🟩	🟩	🟩
Combined Electrolysis Catalytic Exchange	6	$6.6	🟩	🟩			
Bithermal Hydrogen-Water Process	6	$7.3	🟩	🟩			
Cryogenic Distillation Process	6	$8.9	🟩	🟩			
Thermal Cycle Adsorption Process	6	$17	🟩	🟩	🟩		
Multiple Electrolysis Cycle Process	5	$22	🟩	🟩	🟩	🟩	
Graphene Oxide Membrane Process	3	> $227	🟩	🟩	🟩	🟩	🟩

Conclusions and Recommendations

- As expected, direct disposal of tritiated water into the river is least expensive
- Grouting 1/3 tritiated water with higher concentration significant reduces the overall cost of disposal
- Separating the tritium with CECE or bithermal H_2-H_2O may be less expensive than grouting entire volume
- Estimates are only rough order of magnitude. Additional design and costing analysis is needed.