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Rev. 0

Evaluation of Evaporation Technologies for Treating Contaminated Groundwater (U)

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Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

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SAVANNAH RIVER SITE

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Aiken, SC 29808

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Introduction

Evaporation has occasionally been considered as a potentially viable technology for treating SRS groundwater contaminated with radionuclides and metals (e.g. Bibler, 1990; Fulbright et al., 1996). The high cost of operating the F- and H-area seepage basin chemical treatment units, compared to conventional wastewater treatment costs, has prompted renewed interest in evaporation strategies for groundwater remediation. The direct operating cost for the F- and H-area seepage basins Water Treatment Units (WTUs) including materials and labor is approximately $0.047 per gallon treated (Table 1), or $47 per 1000 gallons. Typical wastewater/sewage treatment costs are on the order of a few dollars per 1000 gallons.

Evaporation could be used to achieve two different endpoints. First, non-volatile solute contaminants (metals and most radionuclides) could be greatly concentrated (e.g. 100:1), and the low volume concentrate combined with other liquid radioactive wastes in the separations area for subsequent treatment and disposal. The condensate stream, comprising 99% of the feed stream, would be clean except for volatile radionuclides. These would include tritium, I-129, and Tc-99, essentially at groundwater concentrations. Thus, the bulk of the extracted groundwater could likely be irrigated rather than re-injected into the ground. Avoiding the need for up-gradient reinjection would facilitate efficient capture of the down-gradient plume. Secondly, the concentrated waste stream could be reduced to dry solids and disposed of as solid radioactive waste. Evaporation technologies could play a role in either or both processes. This study considers the technical and economic feasibility of several passive and active evaporation technologies for treatment of groundwater contaminated with radionuclides and metals.

Table 1 Representative operational costs for the F- and H-area Water Treatment Units (WTUs); data courtesy of Stephani Fuller, July 19, 2002.

Cost	*Units*	*Item*
0.0460	$/gal	low of range
0.0770	$/gal	high of range
0.0615	$/gal	average total cost
1.1394		Essential Site Services (ESS) factor
1.1497		General and Administrative (G&A) factor
1.310		overhead factor (ESS x G&A)
0.047	$/gal	direct *operating* cost, *including labor*

Technical analysis of evaporation technologies

Evaporation is an energy intensive process, due to the large heat of vaporization of water (Table 2). For example, the total energy required to warm and then vaporize groundwater initially at 20°C is approximately 2.7 kW-hr/gal or 9300 BTU/gal at atmospheric pressure. The heat of vaporization comprises 87% of the total energy. Were the energy supplied by natural gas purchased at current rates, the fuel cost alone for direct evaporative heating would be about $0.056 per gallon. This amount exceeds current costs for the F- and H-area WTUs (Table 1). So, energy costs must be significantly reduced in order for evaporation to be a viable alternative to the WTUs, and other applications in general.

Energy costs can be greatly reduced by utilizing a "free" source energy such as solar heating, sensible heat in low-humidity wind, or waste heat from another process. Alternatively, energy can be used more efficiently through the use of "multiple-effects", and heat pump technologies such as Mechanical Vapor Recompression (MVR). Both approaches offer substantially lower total (capital + operating) costs, and make evaporation a potentially viable alternative to the F- and H-area WTUs.

In the sections that follow, several passive and active technologies for concentrating contaminated groundwater through evaporation are analyzed in more detail for technical merit. In the context of this report, "passive" means the energy source used to vaporize water comes from a natural source, such as solar insolation or wind. "Active" refers to an engineered source of energy, such as fossil fuel or nuclear power. Finally, techniques for drying a concentrated liquid waste stream to produce a solid waste are considered.

Table 2 Energy and cost required to vaporize water from an initial temperature of 20°C (68°F) at atmospheric pressure.

Parameter	*Symbol*	*SI units*		*English units*	
Groundwater temperature	T_{GW}	20	C	68	F
Boiling temperature at 1 atm	T_{boil}	100	C	212	F
Specific heat	c_p	4.216	kJ/kg-K	1.007	BTU/lbm-R
Heat of vaporization	h_{fg}	2257	kJ/kg	970.4	BTU/lbm
Enthalpy required to boil GW	Δh	2594	kJ	1115	BTU
Ratio	$h_{fg}/\Delta h$	87%		87%	
Density @ 20C	ρ_f	998	kg/m^3	62.3	lbm/ft^3
Enthalpy per unit volume	$\rho_f \Delta h$	2.59E+06	kJ/m^3	6.95E+04	BTU/ft^3
		2.72	kW-hr/gal	9290	BTU/gal
Energy cost				0.6	$/therm
		0.0205	$/kW-hr	0.000006	$/BTU
Evaporation cost		0.056	$/gal	0.056	$/gal

Passive evaporation technologies for liquid concentration

Solar radiation or "insolation" is a natural source of energy that can supply part or all of the energy required to evaporate water. An inherent limitation of solar heating concepts is the relatively low power density of solar insolation. Figure 1 shows a map of annual average solar insolation in kW-hr/m^2-day for the continental United States and Mexico. At the Savannah River Site, solar insolation averages about 4.5 kW-hr/m^2-day (Table 3). To put this number in perspective, suppose all solar radiation goes towards vaporizing water initially at 100°C. This is an unrealistic scenario that provides a convenient upper bound on the evaporation rate that could be achieved with solar heating. As shown in Table 4, a large area is required for solar evaporation, at least 5.6 acres per gpm to be evaporated. Solar evaporation can be technically feasible if sufficient land is available.

Another natural source of energy is the sensible heat that can be extracted from low (<100%) humidity air through evaporative cooling. The climate of South Carolina is somewhat humid (Table 5), which is obviously not conducive to evaporation. Nevertheless, wind can naturally deliver large volumes of air to an evaporation facility and make evaporative cooling a potentially viable technology from a technical standpoint. For example, if air at average SRS conditions (64°F, 68% humidity) is delivered by an average wind (6.1 mph) through a 20 ft high by 100 ft wide cross-sectional area and brought to 100% humidity through evaporative cooling, then 14 gpm would be evaporated (Table 6).

Passive evaporation technologies typically use both solar heating and evaporative cooling in varying proportions. For example, an evaporation pond will be warmed by solar radiation, and extract sensible heat from unsaturated air blowing over the pond surface. In the sections below, solar evaporation, solar distillation, spray evaporation, and combined solar and spray evaporation are further analyzed from a technical feasibility standpoint.

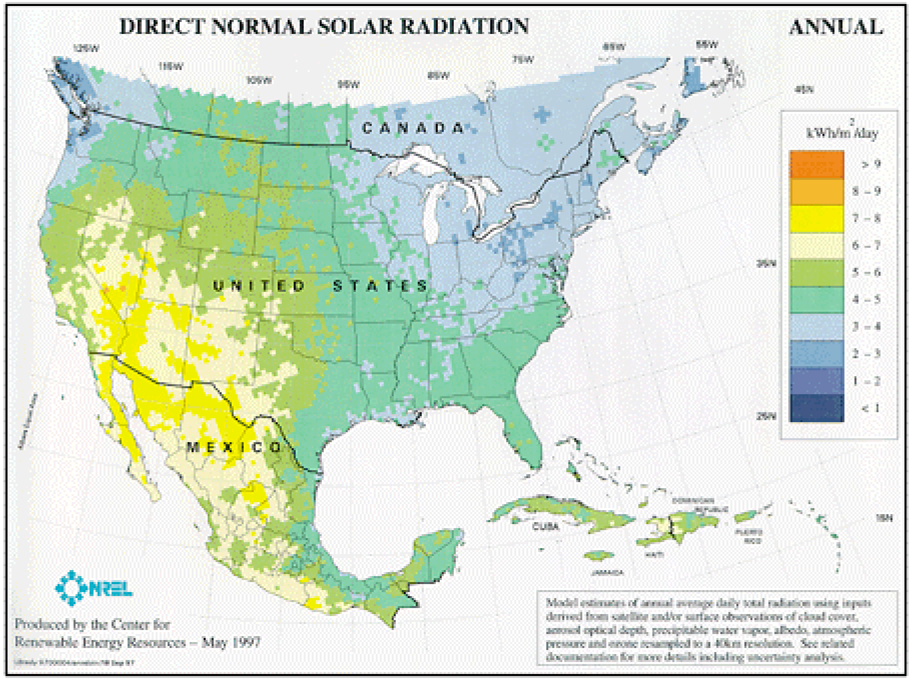

Figure 1 Solar insolation map for the continental United States and Mexico.

Table 3 Estimates of average solar insolation at or near the Savannah River Site.

units	*Krieth & Kreider (1978)* [1]	*Focus Solar* [2]	*SRS 1995* [3]	*SRS 1996* [4]
ly/d	400		372	388
$kW\text{-}hr/m^2\text{-}d$	4.6	4.6	4.3	4.5
$BTU/hr\text{-}ft^2$	61	61	57	59
$BTU/d\text{-}ft^2$	1471	1459	1368	1427
W/m^2	193	192	180	188

[1] Figure 2.24 and Table A2.4 (Charleston)

[2] www.focus-solar.com/insolation_levels_us.htm

[3] WSRC-TR-96-0309

[4] WSRC-TR-97-0214

Table 4 Theoretical upper bound estimate of the solar evaporation rate at the Savannah River Site.

	Metric		*English*	
Energy flux	4.5	kW-hr/m^2-d	59	BTU/hr-ft^2
Heat of vaporization	2257	kJ/kg	970	BTU/lbm
Water density	958	kg/m^3	60	lbm/ft^3
Evaporation rates	8.67E-08	m/s	1.02E-03	ft/hr
	2.74	m^3/m^2-yr	67	gal/ft^2-yr
	5.56	gpm/acre	5.56	gpm/acre
	108	in/yr	108	in/yr
	0.18	gal/ft^2-d	0.18	gal/ft^2-d
	1.98	gal/m^2-d	1.98	gal/m^2-d

Table 5 Climate of the Savannah River Site and surroundings.

Annual/ average climate data	SC State Climatology Office	Aiken 4 NE station	SRS Weather Center
Temperature (F)	64	64.0	64.7
Precipitation (in/yr)	48	49.66	51.1
Humidity			68%
Wind speed (mph)	8		6.1
Pan evaporation (in/yr)	57		

Table 6 Adiabatic saturation calculation for average SRS conditions and a 20 ft by 100 ft cross-sectional area.

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations								
Constants								*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)					
molecular wt. air	M_a	28.9645	lbm/lbmole					from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)					
Incoming air stream								
pressure	p	14.7	psia					
temperature	t	64	F	17.8	C	523.67	R	SRS conditions
relative humidity	φ	0.68	unitless					
sat. pressure	p_{ws}	0.2991	psia					eqn (4)
water vap. pres.	p_w	0.2034	psia					eqn (22)
humidity ratio	W, γ	0.008725	unitless	61.07	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.012916	unitless					eqn (21)
deg. of saturation	μ	0.6755	unitless					eqn (10)
specific volume	ν	13.38	ft^3/lbm_a					eqn (26)
		13.27	ft^3/lbm					using (1+γ) factor and eqn (26)
		13.20	ft^3/lbm					using ideal gas law
specific enthalpy	h	24.87	BTU/lbm_a					eqn (30)
Outgoing for adiabatic saturation/evaporation								
pressure	p	14.7	psia					
temperature	t	57.46	F	14.1	C	517.13	R	
relative humidity	φ	1.00	unitless					
sat. pressure	p_{ws}	0.2370	psia					eqn (4)
water vap. pres.	p_w	0.2370	psia					eqn (22)
humidity ratio	W, γ	0.010193	lbm_w/lbm_a	71.35	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.010193	unitless					eqn (21)
deg. of saturation	μ	1.0000	unitless					eqn (10)
specific volume	ν	13.25	ft^3/lbm_a					eqn (26)
		13.11	ft^3/lbm					using (1+γ) factor and eqn (26)
		13.03	ft^3/lbm					using ideal gas law
specific enthalpy	h	24.87	BTU/lbm_a					eqn (30)
Differences								
temperature	Δt	-6.5	F					
relative humidity	Δφ	0.32	unitless					
enthalpy	Δh	0.00	BTU/lbm_a					
humidity ratio	ΔW, Δγ	0.001468	lbm_w/lbm_a	10.28	grains/lbm_a			
Evaporation system parameters								
Wind speed	v	6.1	mi/hr	8.95	ft/s			
Height	h	20.0	ft					
Width	w	100.0	ft					
Xsec area	A	2000	ft^2					
Incoming wet air vol. flow	Q	17893	ft^3/s	1.1E+06	ft^3/min (cfm)			
Dry air mass flow	m_a	1337	lbm_a/s					
Evaporation rate	m_e	1.96	lbm_w/s	117.77	lbm_w/min			
Liq. water density	ρ	62.3	lbm/ft^3					@ 70F
Evaporation rate	Q_e	0.032	ft^3/s	14.1	gal/min	848	gal/hr	

Solar evaporation: Evaporation from an open body of water exposed to atmospheric conditions is termed "solar evaporation" in this report. Evaporation rates from Class A land pans (unpainted galvanized metal, 4 ft diameter, 10 in deep) have been measured by the U.S. Weather Bureau at 450 field locations across the United States (Fetter, 1988). Pan evaporation at the SRS is approximately 57 in/yr compared to average rainfall of 48-51 in/yr (Table 5). The evaporation rate from a large body of water (e.g. reservoir) is typically 70-80% smaller than the pan evaporation rate on an annual average basis. Thus net evaporation rate from a large open pond at the SRS is estimated to be negligible (Table 7). This assessment agrees with experience with H-area seepage basin #3, which became plugged in the 1960's. Over a subsequent 3 year period, the water level in the basin was unchanged. Therefore, simple pond evaporation is not technically viable at the SRS.

Furthermore, an examination of the solar radiative properties listed in Table 8 suggests that only marginal improvement could be achieved by altering pond construction materials. Solar heating can be improved by increasing the absorptance of incoming short-wave solar radiation, and decreasing heat losses through emittance of thermal (long-wave length) energy. Materials with high short-wave absorptance and low long-wave emittance are termed "selective" solar heating materials. Note that wet sand already has a high short-wave absorptance (α) compared to a perfect black-body ($\alpha = 1$). The long-wave emittance (ε) of wet sand is high, offering opportunity for improvement. However, no practical construction materials with low ε were identified in this study. Galvanized sheet iron has relatively selective solar radiative properties, which should also be representative of a Class A land pan. In this respect, evaporation rates from a shallow pond lined with a selective solar material might be similar to pan evaporation rates. Even in this hypothetical and optimistic scenario, the net evaporation rate is marginal (Table 7, Upper limit). Thus solar evaporation is not technically viable at the SRS (Figure 2).

For future reference, it is noted that an efficiency for solar evaporation can be defined as the actual evaporation rate, e.g. Table 7, divided by the theoretical upper bound computed in Table 4. The efficiency of natural evaporation from an SRS pond is estimated to be roughly 40% (Figure 2, Table 9).

Table 7 Upper limit, optimistic and pessimistic estimates of net pond evaporation at the Savannah River Site.

Net natural evaporation						
	Upper limit		*Optimistic*		*Pessimistic*	
Pan evaporation	57	in/yr	57	in/yr	57	in/yr
Pan coefficient	1		0.8		0.7	
Evaporation	57	in/yr	45.6	in/yr	39.9	in/yr
Rainfall	48	in/yr	48	in/yr	51	in/yr
Net	9	in/yr	-2.4	in/yr	-11.1	in/yr
	0.46	gpm/acre	-0.12	gpm/acre	-0.57	gpm/acre

Table 8 Selected solar radiative properties.

Radiative properties

	Water	*Wet sand*	*Bare moist ground*	*Rough concrete*	*Galvanized sheet iron, oxidized*
Short-wave absorptance	0.94	0.91	0.90	0.60	0.80
Long-wave emittance	0.955	0.95	0.95	0.97	0.28

notes:
class A pan bottom probably has solar absorptance of 0.80 (black-body = 1.0)
earthen pond would have absorptance of about 0.90

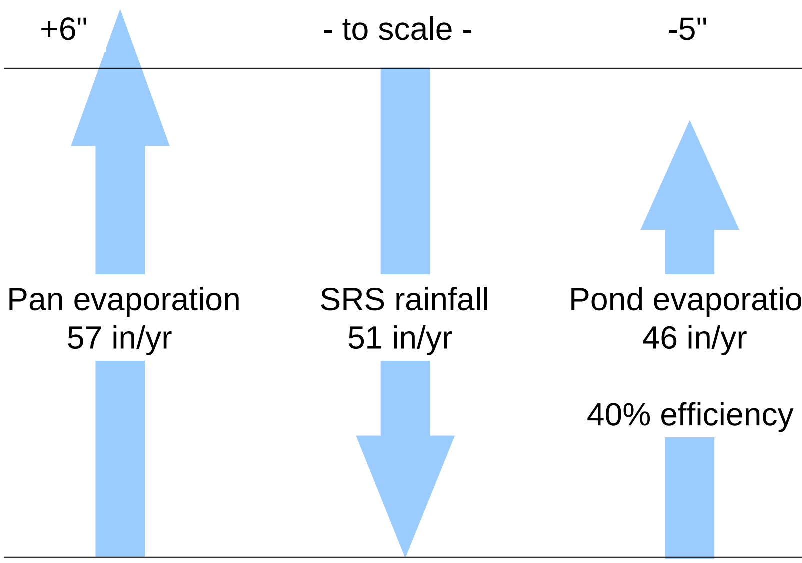

Figure 2 Graphical comparison of pan and pond evaporation to rainfall.

Table 9 Efficiency of solar evaporation.

Efficiency of natural evaporation

	Pan evaporation (Solar surrogate?)	Optimistic lake evaporation	Nominal lake evaporation
Insolation	4.5 kW-hr/m^2-d	4.5 kW-hr/m^2-d	4.5 kW-hr/m^2-d
Production	57 in/yr	45.6 in/yr	39.9 in/yr
	0.097 gal/ft^2-d	0.078 gal/ft^2-d	0.068 gal/ft^2-d
Upper bound	0.18 gal/ft^2-d	0.18 gal/ft^2-d	0.18 gal/ft^2-d
Efficiency	53%	42%	37%

Solar distillation: While significant evaporation occurs naturally from an open pond, rainfall essentially negates any net gain in water loss. Significant net gains in water evaporated can be achieved through solar distillation (Figure 3). The transparent cover eliminates any rainfall influx to the system, thus achieving a net gain even though the direct evaporation rate is smaller than an open evaporation system. Because the system is closed to the atmosphere, evaporation occurs solely through solar heating of the liquid pool. Water vapor subsequently condenses on the cooler underside of the transparent cover, and the clean distillate runs off to perimeter collection trays.

Solar stills are available commercially for home or personal use (e.g. Figure 3), but such models are too small and expensive to warrant further consideration. Large basin-type stills offer practical capacities and lower costs through economy of scale. Kreith and Kreider (1978, Figure 8.19) have collected production data for several large basin-type stills, and found that the average performance is well represented by the equation

$$P = 1.1 \times 10^{-3} \left(\frac{I_S}{100} \right)^{1.4} \tag{1}$$

where I_S is the solar insolation in BTU/ft^2-day and P is the production of distillate in gal/ft^2-day. They note that the corresponding efficiency of large basin-type stills is about 25% at an insolation, which agrees with a Technical Brief published by The Schumacher Centre for Technology & Development (http://www.itdg.org/). McCluney (1984) at the Florida Solar Energy Center reports production rates corresponding to efficiencies ranging from 25 to 40%. The production rates under SRS conditions corresponding to these efficiency estimates are summarized in Table 10.

Solar distillation is technically viable, but at a typical evaporation rate of 1.37 gpm/acre, clearly requires a large area to implement. The economic feasibility of solar distillation is considered later in the report.

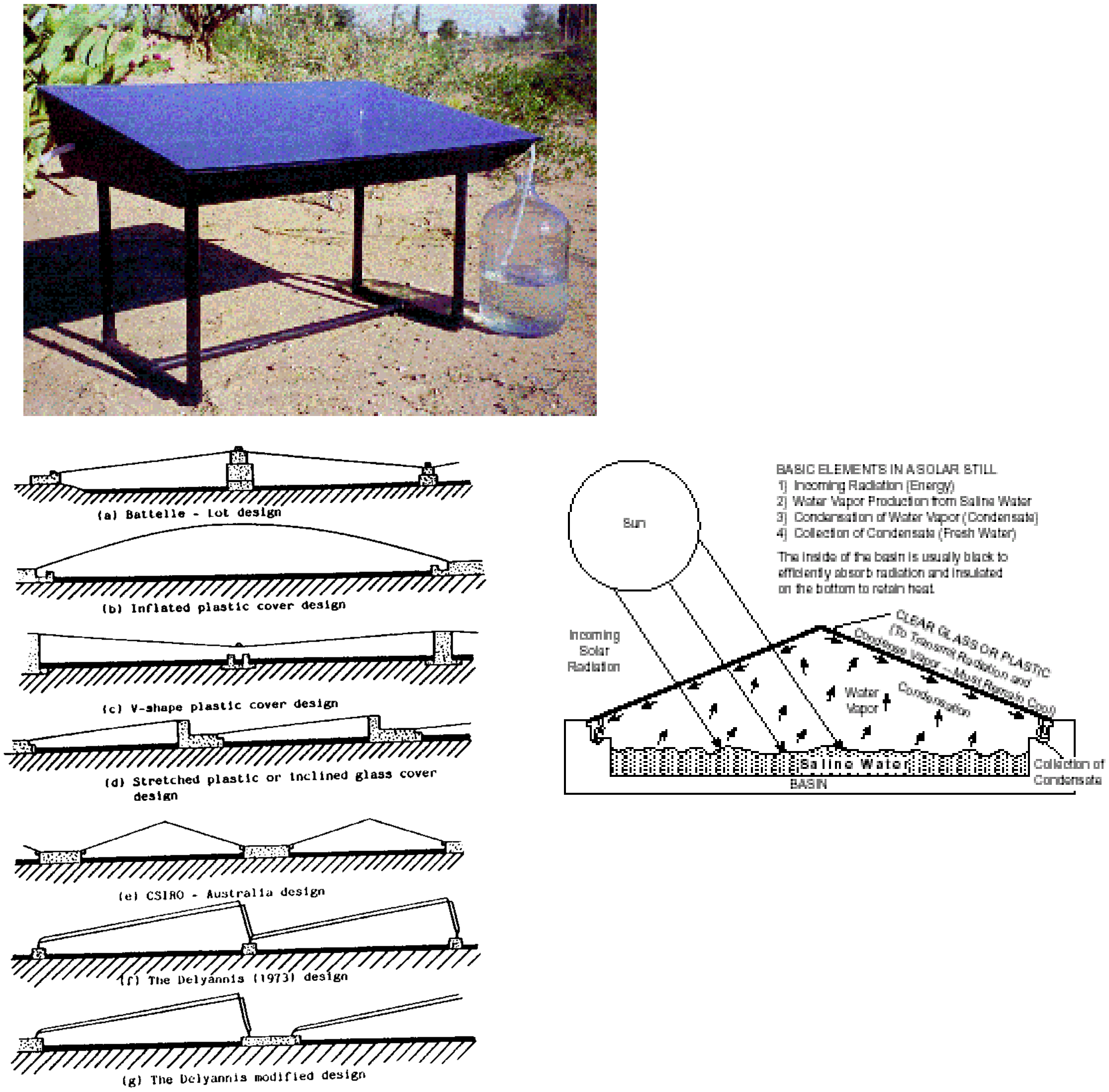

Figure 3 Examples of small and large-scale solar distillation designs.

Table 10 Production and efficiency of solar distillation under SRS conditions.

Estimated distillation rates under SC conditions - large basin stills

	Kreith & Kreider (1978)	*FSEC-EN-3 (1984)*	*Schumacher Centre for Technology & Development*
Insolation	4.5 kW-hr/m^2-d	4.5 kW-hr/m^2-d	
	1427 BTU/d-ft^2		
Production	0.045 gal/ft^2-d	0.059 gal/ft^2-d	0.046 gal/ft2-d
	0.49 gal/m^2-d	0.64 gal/m^2-d	0.49 gal/m^2-d
	26.6 in/yr	34.8 in/yr	26.9 in/yr
	1.37 gpm/acre	1.80 gpm/acre	1.39 gpm/acre
Upper bound	0.18 gal/ft^2-d	0.18 gal/ft2-d	0.18 gal/ft2-d
Efficiency	25%	32%	25%

<u>Spray evaporation</u>: In contrast to solar evaporation and distillation, spray evaporation relies on the sensible heat that can be extracted from low (<100%) humidity air to drive evaporation. Incoming dry air is brought into contact with a fine droplet spray, and simultaneously cooled and humidified through evaporative cooling. The evaporation rate is controlled by a number of factors. Important factors are the flowrate, temperature, and humidity of the incoming air stream, and the distribution, residence time, and size of spray droplets. As hot, dry, windy conditions are most favorable to spray evaporation, field applications are primarily in arid or semi-arid portions of the United States. Quantitative performance or design data for the Southeast US was essentially unavailable from the those vendors supplying industrial sprayers for wastewater evaporation identified in an internet search.

Snow Machines, Inc. (SMI) manufactures sprayers designed for industrial wastewater evaporation using modified snow-making technology. A sales representative reported that a client in NE South Dakota evaporated 300 acre-ft of water from a 300 acre holding pond over a 7 month (summer?) period using 20 SMI sprayers. The climate at the site is uncertain, but the analysis shown in Table 11 produces net evaporation (rainfall - solar evaporation) estimates of 3.6 and 5 in/yr. So, not all of the 300 acre-ft water loss can be attributed to the use of sprayers. The net effect of spray evaporation is estimated to be 12 to 16 gpm per machine (Table 12). Relative to the supply flowrate of approximately 77.5 gpm, the efficiency ranged from 16 to 21%.

The annual average temperature and humidity for NE South Dakota are estimated to be 46°F and 26% (Table 11), compared to 64°F and 68% at the SRS (Table 5). To estimate the performance of spray evaporation at the SRS based on field experience in South Dakota, the adiabatic saturation /swamp cooler calculation in Table 6 is repeated in Table 13 for South Dakota temperature and humidity. The estimated evaporation rate for South Dakota temperature and humidity conditions is 25.5 gpm, compared to 14.1 gpm under SRS conditions. That is, adiabatic saturation rate for the SRS is 55% of the rate for South Dakota. This suggests that SMI sprayer performance at the SRS might be on the order of 7 gpm per sprayer and 9% efficiency.

The evaporation rate that could be achieved through spraying would exhibit daily and seasonal fluctuations, due to daily and seasonal temperature and humidity variations. The lowest evaporation rates at the SRS would probably occur in January, when the average temperature is about 46°F. Monthly average humidity is about the same as the annual average of 68%. An adiabatic saturation calculation for January conditions is shown in Table 14. The estimated evaporation rate of 10.5 gpm is 74% of the annual average result of 14.1 gpm in Table 6.

In addition to evaporation rate, spray drift is another important technical consideration. Because most of the contaminated feed water falls to the ground, spray evaporation would presumably have to be combined with a lined catch basin of sufficient size to avoid significant spray drift problems. Snow Machines, Inc. reports that clients typically shut down spray evaporators if the wind speed exceeds approximately 10 mph. Apart from that statement, technical data on spray drift was not available from vendors through either published information or personal contacts with sales representatives. Field experiments at the SRS using rental units are suggested as the best approach for quantifying spray drift under SRS conditions.

Figure 4 Spray evaporation using snow-making technology modified for wastewater treatment (photos reproduced from Snow Machines Inc. website).

Table 11 Estimated climate at location of Snow Machines Inc. client in NE South Dakota.

Sioux Falls, SD data											
	Avg high	Avg low	Avg dew point	Avg temp.	Avg rel. humidity	Precipitation					
Jan	25	5	6			0.6					
Feb	30	10	13			0.8					
Mar	42	22	23			1.6					
Apr	58	35	33			2.5					
May	71	47	45			3.3					
Jun	80	57	55			4.0					
Jul	86	62	60			2.9					
Aug	84	60	59			3.3					
Sep	74	49	49			2.8					
Oct	62	37	36			1.6					
Nov	43	23	24			1.0					
Dec	30	11	13			0.7					
Avg	57.1	34.8	34.7	**46.0**	**26%**	**25.1**					
	source data			my calcs							
South Dakota											
				Avg temp.		Precipitation					
				44.8		**18.32**					
East Central District											
						Precipitation	Pan Evap.	Lake Evap.		Net Evap.	
						23	**38**	26.6		3.6	
USGS											
				Area (acre)	Evap (acre-ft)		Pan Evap. (in/yr)	Lake Evap. (in/yr)	Pan Coeff.		
Missouri River drainage							48	36	0.75		
Estimate for Snow Machines client in NE South Dakota											
						Precipitation		Lake Evap.		Net Evap.	
						23		**28 ?**		**5 ?**	in/yr
										0.26	gpm/acre
										0.14	Mgal/acre-yr
										3.12	gal/ft^2-yr
										0.28	gal/m^2-yr
										0.13	m^3/m^2-yr

Table 12 Analysis of Snow Machines Inc. application in NE South Dakota.

Snow Machines client in NE South Dakota						
					(summer use?)	
Total losses						
loss	300	acre-ft				
time	7	months				
rate	319	gal/min	514	acre-ft/yr		
area	300	acre				
flux	20.6	in/yr				
machines	20					
Net lake evaporation						
flux	0 ?	in/yr	3.6 ?	in/yr	5 ?	in/yr
Snow machine net effect (marginal increase)						
flux	20.6	in/yr	17.0	in/yr	15.6	in/yr
rate	319	gal/min	263	gal/min	241	gal/min
rate/machine	15.9	gal/min	13.2	gal/min	12.1	gal/min
supply flow	77.5	gal/min	77.5	gal/min	77.5	gal/min
efficiency	21%		17%		16%	

Table 13 Adiabatic saturation calculation for South Dakota conditions, a 6.1 mph wind, and a 20 ft by 100 ft cross-sectional area.

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations								
Constants								*source*
univ. gas const.	*R*	1545.33	ft-lbf/(lbmole-R)					
molecular wt. air	M_a	28.9645	lbm/lbmole					from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)					
Incoming air stream								
pressure	p	14.7	psia					
temperature	t	46	F	7.8	C	505.67	R	South Dakota
relative humidity	ϕ	0.26	unitless					
sat. pressure	p_{ws}	0.1552	psia					eqn (4)
water vap. pres.	p_w	0.0408	psia					eqn (22)
humidity ratio	W, γ	0.001731	unitless	12.12	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.006635	unitless					eqn (21)
deg. of saturation	μ	0.2609	unitless					eqn (10)
specific volume	ν	12.78	ft^3/lbm_a					eqn (26)
		12.76	ft^3/lbm					using (1+γ) factor and eqn (26)
		12.75	ft^3/lbm					using ideal gas law
specific enthalpy	h	12.91	BTU/lbm_a					eqn (30)
Outgoing for adiabatic saturation/evaporation								
pressure	p	14.7	psia					
temperature	t	34.70	F	1.5	C	494.37	R	
relative humidity	ϕ	1.00	unitless					
sat. pressure	p_{ws}	0.1000	psia					eqn (4)
water vap. pres.	p_w	0.1000	psia					eqn (22)
humidity ratio	W, γ	0.004259	lbm_w/lbm_a	29.82	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.004259	unitless					eqn (21)
deg. of saturation	μ	1.0000	unitless					eqn (10)
specific volume	ν	12.55	ft^3/lbm_a					eqn (26)
		12.49	ft^3/lbm					using (1+γ) factor and eqn (26)
		12.46	ft^3/lbm					using ideal gas law
specific enthalpy	h	12.91	BTU/lbm_a					eqn (30)
Differences								
temperature	Δt	-11.3	F					
relative humidity	$\Delta\phi$	0.74	unitless					
enthalpy	Δh	0.00	BTU/lbm_a					
humidity ratio	ΔW, $\Delta\gamma$	0.002528	lbm_w/lbm_a	17.70	grains/lbm_a			
Evaporation system parameters								
Wind speed	v	6.1	mi/hr	8.95	ft/s			
Height	h	20.0	ft					
Width	w	100.0	ft					
Xsec area	A	2000	ft^2					
Incoming wet air vol. flow	Q	17893	ft^3/s	1.1E+06	ft^3/min (cfm)			
Dry air mass flow	m_a	1400	lbm_a/s					
Evaporation rate	m_e	3.54	lbm_w/s	212.35	lbm_w/min			
Liq. water density	ρ	62.3	lbm/ft^3					@ 70F
Evaporation rate	Q_e	0.057	ft^3/s	25.5	gal/min	1530	gal/hr	

Table 14 Adiabatic saturation calculation for average SRS conditions in January and a 20 ft by 100 ft cross-sectional area.

Adiabatic saturation / swamp cooler calculation using ASHRAE (1985) equations								
Constants								*source*
univ. gas const.	R	1545.33	ft-lbf/(lbmole-R)					
molecular wt. air	M_a	28.9645	lbm/lbmole					from eqn (24)
air gas constant	R_a	53.35	ft-lbf/(lbm-R)					
Incoming air stream								
pressure	p	14.7	psia					
temperature	t	46	F	7.8	C	505.67	R	SRS conditions in January
relative humidity	ϕ	0.68	unitless					
sat. pressure	p_{ws}	0.1552	psia					eqn (4)
water vap. pres.	p_w	0.1055	psia					eqn (22)
humidity ratio	W, γ	0.004497	unitless	31.48	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.006635	unitless					eqn (21)
deg. of saturation	μ	0.6777	unitless					eqn (10)
specific volume	ν	12.84	ft^3/lbm_a					eqn (26)
		12.78	ft^3/lbm					using (1+γ) factor and eqn (26)
		12.75	ft^3/lbm					using ideal gas law
specific enthalpy	h	15.90	BTU/lbm_a					eqn (30)
Outgoing for adiabatic saturation/evaporation								
pressure	p	14.7	psia					
temperature	t	41.34	F	5.2	C	501.01	R	
relative humidity	ϕ	1.00	unitless					
sat. pressure	p_{ws}	0.1298	psia					eqn (4)
water vap. pres.	p_w	0.1298	psia					eqn (22)
humidity ratio	W, γ	0.005541	lbm_w/lbm_a	38.79	grains/lbm_a			eqn (20)
sat. humidity ratio	W_s	0.005541	unitless					eqn (21)
deg. of saturation	μ	1.0000	unitless					eqn (10)
specific volume	ν	12.74	ft^3/lbm_a					eqn (26)
		12.67	ft^3/lbm					using (1+γ) factor and eqn (26)
		12.63	ft^3/lbm					using ideal gas law
specific enthalpy	h	15.90	BTU/lbm_a					eqn (30)
Differences								
temperature	Δt	-4.7	F					
relative humidity	$\Delta\phi$	0.32	unitless					
enthalpy	Δh	0.00	BTU/lbm_a					
humidity ratio	ΔW, $\Delta\gamma$	0.001044	lbm_w/lbm_a	7.31	grains/lbm_a			
Evaporation system parameters								
Wind speed	v	6.1	mi/hr	8.95	ft/s			
Height	h	20.0	ft					
Width	w	100.0	ft					
Xsec area	A	2000	ft^2					
Incoming wet air vol. flow	Q	17893	ft^3/s	1.1E+06	ft^3/min (cfm)			
Dry air mass flow	m_a	1394	lbm_a/s					
Evaporation rate	m_e	1.46	lbm_w/s	87.35	lbm_w/min			
Liq. water density	ρ	62.3	lbm/ft^3					@ 70F
Evaporation rate	Q_e	0.023	ft^3/s	10.5	gal/min	629	gal/hr	

Combined solar and spray evaporation: At a conceptual level, passive evaporation can be optimized through the following enhancements to the technologies considered above:

1. utilize both forms of passive energy, solar insolation and "dry" air sensible heat

2. maximize solar heating

3. maximize contact with wind-driven ambient air

4. eliminate rainfall influx

A conceptual design with the above attributes is depicted in Figure 5. Item 1. is achieved by utilizing both solar and spray evaporation during normal operation. Solar heating is maximized by using a black-body liner floating on the water surface. Solar insolation goes primarily toward heating a thin film of water on the upper surface of the liner, resulting from collection of un-evaporated spray droplets. Contact with ambient air is maximized through the use of commercial sprayers with a large throw (e.g. Figure 4). Rainfall is eliminated from the system by inflating the surface liner with air during rain events (Figure 5). Air inflation would be accomplished through a small blower discharging beneath the cover. The technology of air inflated structures is well established and used in a variety of applications (e.g. stadiums, agricultural crop drying, temporary buildings).

In principle, such a system might evaporate 50 gpm on an annual average basis, using a 10 acre lined catch basin and 3 SMI sprayers (Table 15). However, this performance estimate is highly uncertain. The spray evaporation rate is uncertain because rigorous technical performance data from vendors is not available for SRS conditions. The pond evaporation rate using the shallow liner is assumed to be the same as pan evaporation for this climate, but the actual rate is unknown. Also, spray evaporation over the pond would reduce pond evaporation, so the individual spray and pond evaporation rates are not directly additive in practice. Spray evaporation would cool and humidify the ambient air, and un-evaporated droplets falling to the pond would cool the surface water. So, while the concept looks rather promising, technical feasibility must be graded low given the approach is only at a conceptual stage.

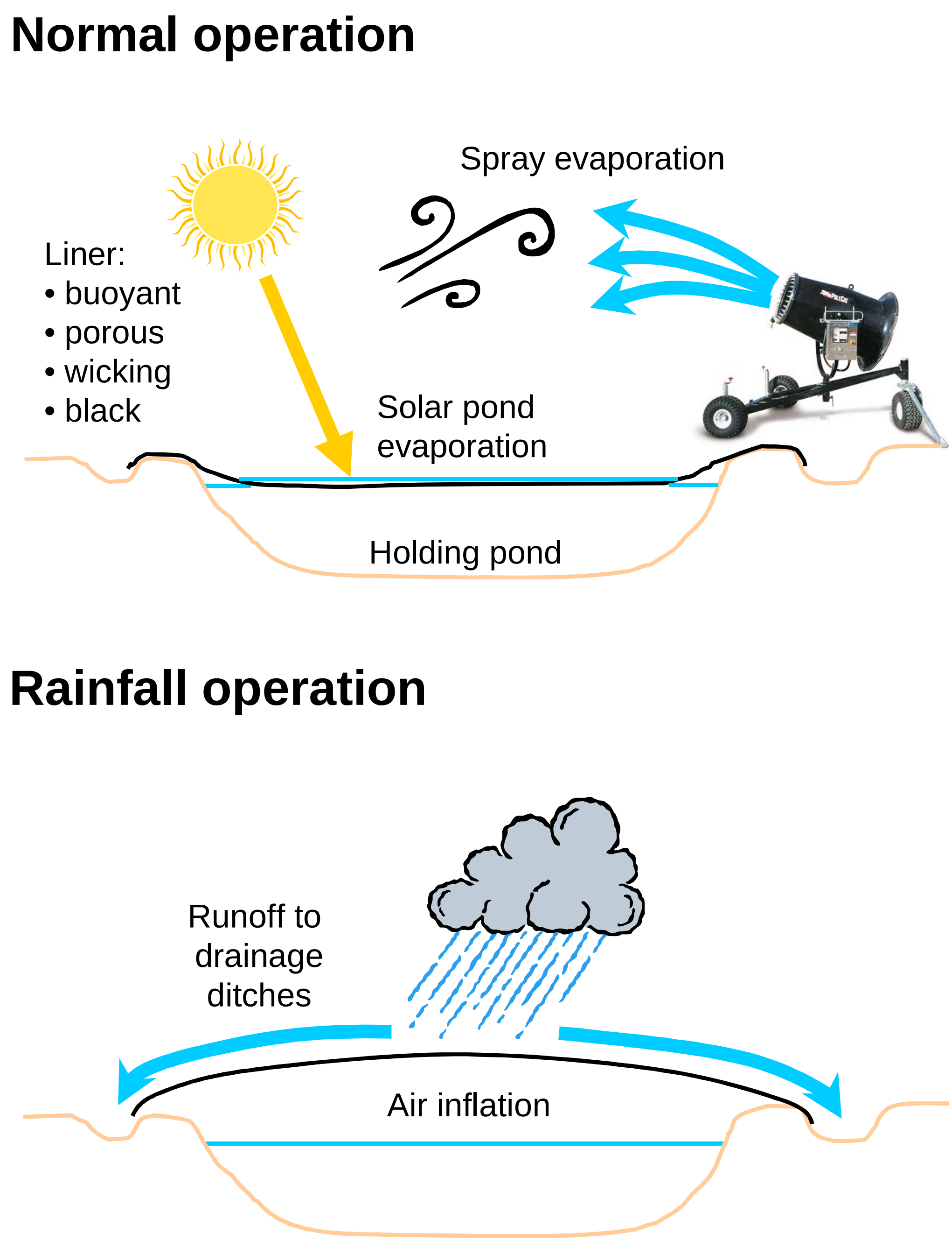

Figure 5 Conceptual design of an optimal passive evaporation system.

Table 15 Estimated performance of an optimal conceptual design for passive evaporation of contaminated groundwater.

Design specs.			
Flowrate needed	50	gpm	
Conceptual design			
Spray evaporation	7.25	gpm/machine	
	3	machines	
	21.75	gpm	
+Solar evaporation	28.25	gpm	
	57	in/yr	pan evaporation rate
	2.94	gpm/acre	
	9.6	acres	

Active evaporation technologies for liquid concentration

In the context of this report, "active" refers to an engineered source of energy such as fossil fuel or nuclear power. As discussed earlier, evaporation by simple direct heating is expensive for a purchased energy source (Table 1). Energy efficiency can be significantly increased through the use of multiple-effects, and heat pump technologies such as Mechanical Vapor Recompression.

Multiple effects refers to multiple boiling-condensation cycles operated in combination, where vapor from the first effect becomes the heat source for the second effort, and so forth. Each subsequent effect is operated at a higher vacuum than the previous effect. Many evaporators are steam driven. A single-effect steam-driven evaporator is said to have a theoretical "economy" of 1, in that 1 lbm of steam supplied can theoretically evaporate 1 lbm of feed water. The actual economy is lower due to preheating requirements, heat losses, and other factors. A two-effect evaporator has an economy of roughly 2. In other words, only 1/2 lbm of steam is needed to evaporate 1 lbm of feed water. In general, an n-effect evaporator has a nominal/theoretical economy of n. Capital equipment costs increase with each added effect, and counter-balance energy savings. The lowest total cost (capital + operating) is usually achieved with a small number of multiple-effects.

Mechanical Vapor Recompression (MVR) also offers significant energy savings compared to single-effect direct heating evaporation. With MVR added to a single-effect evaporator operating under vacuum, vapor from the separator is mechanically compressed to the pressure corresponding to the saturation temperature required on the steam side of the heat exchanger. Essentially, the energy required to produce the vapor is recovered by recompression and used to vaporize additional feed water. Typically, little or no steam input is required to an MVR system after start-up. Most of the energy cost comes from the electricity required to drive the compressor motor.

Scale buildup on heat exchanger surfaces can be a serious problem with evaporation technology in general, and leads to lower energy efficiency and capacity. Scaling is not expected to be a significant issue for F- and H-area groundwater treatment. For a concentration factor on the order of 100:1, precipitation of dissolved solids should be minimal.

Compared to passive/solar evaporation, active evaporation technologies are well developed and readily available from commercial vendors. Technical feasibility is not an issue.

Technologies for reduction to dry solids

Evaporation can also be used to reduce a concentrated solute to a dry solid. Such an operation is typically referred to as a "drying" or "crystallization". Again, active technologies are well developed and commercially available, so technical feasibility is not an issue. One technology of interest is spray drying involving flash evaporation (Figure 6). Feed wastewater is sprayed into a high-temperature combustion chamber as atomized droplets. Water is instantly vaporized, and metals and non-volatile radionuclides collect in the bottom of the combustion chamber or exhaust filter as a dry ash residue. Any combustible solutes are incinerated. Assuming groundwater is first concentrated by say 100:1 in a prior process, the flowrate going to the flash evaporator would be very small. Energy and capital equipment costs are then relatively low. Air permitting may be an issue with this technology.

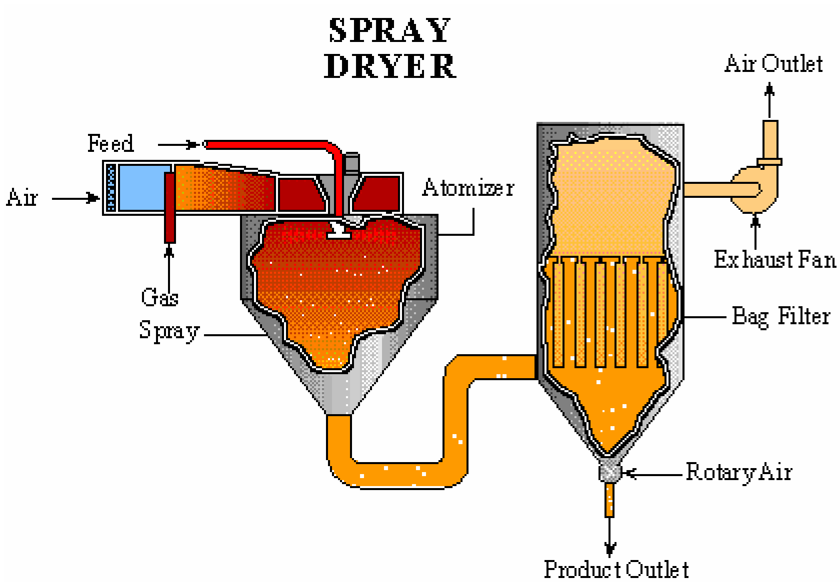

Figure 6 Example spray dryer (reproduced from www.ionics.com).

Economic analysis

Active evaporation technologies are well developed and robust, and some passive evaporation designs also appear to be technically feasible. For these technologies, cost is a primary consideration in assessing alternatives to the F- and H-area WTUs. Because the Water Treatment Units have already been built, capital cost for continued operation of the current systems is essentially zero, and only operating costs are relevant to a cost comparison. For any alternative, both capital and operating costs must be considered. This immediately puts evaporation technologies at a financial disadvantage, as capital costs are significant for these alternatives.

In any analysis involving future income or expenses, the "time value of money" should be recognized. Amounts occurring in the future are inherently less valuable, and should therefore be discounted according an appropriate discount or interest rate. US Office of Management and Budget Circular No. A-94 provides guidance on selecting a discount rate. In this study, the life span of capital equipment is assumed to be 20 years, and the discount rate is set to the interpolated real (inflation adjusted) Treasury rate for a 20 year term, averaged over the past 20 years. As shown in Table 16, this rate is 4.4%.

With any alternative, the total cost will be comprised of an initial capital cost and ongoing operating costs over the life of the facility. The time value of money concept can be used to convert a uniform monetary amount (A) occurring each interest period into an equivalent present value (P), for direct comparison to present capital costs. Conversely, a present value (P) can be translated into an equivalent series of uniform amounts paid each interest period (A). The formulas for these "uniform series present worth" and "capital recovery" conversions are given in Table 17. For an annual interest rate of 4.4% and 20 years, the capital recovery factor is 0.0762. In the analyses that follow, capital costs are converted into annualized capital costs using a capital recovery factor. Annualized capital costs plus annual operating costs constitute the annual total cost of an alternative. For convenience, this amount is divided by the annual volume of groundwater treated, yielding total cost per gallon treated (i.e. $/gal).

To convert historical amounts into 2001 constant dollars for example, the Consumer Price Index generated by the US Bureau of Labor Statistics (Table 18) is used as follows

$$2001\$ = \frac{2001\,CPI}{y\,CPI} \times y\$ \tag{2}$$

where *y* is the historical year. Equation (2) is an adjustment for inflation. Occasionally costs in the literature are cited in a foreign currency. In this study, such amounts are converted to US $ using current exchange rates.

Table 16 Forecast real US Treasury interest rates over the past 20 years.

Forecast Date	10 yr	30 yr	20 yr interpolated
1983	5.3	5.6	5.5
1984	6.1	6.4	6.3
1985	7.1	7.4	7.3
1986	5.9	6.7	6.3
1987	3.8	4.4	4.1
1988	5.1	5.6	5.4
1989	5.8	6.1	6.0
1990	4.2	4.6	4.4
1991	3.9	4.2	4.1
1992	3.6	3.8	3.7
1993	4.3	4.5	4.4
1994	2.7	2.8	2.8
1995	4.8	4.9	4.9
1996	2.8	3.0	2.9
1997	3.5	3.6	3.6
1998	3.6	3.8	3.7
1999	2.7	2.9	2.8
2000	4.0	4.2	4.1
2001	3.2	3.2	3.2
2002	3.1	3.9	3.5
20 yr average			**4.4**

Table 17 Time value of money financial formulas.

Factor	*Formula*
Capital recovery	$A/P = \dfrac{i(1+i)^n}{(1+i)^n - 1}$
Uniform series present worth	$P/A = \dfrac{(1+i)^n - 1}{i(1+i)^n}$

Table 18 Consumer Price Indices for 1970 through 2001.

year	*CPI*
1970	38.8
1971	40.5
1972	41.8
1973	44.4
1974	49.3
1975	53.8
1976	56.9
1977	60.6
1978	65.2
1979	72.6
1980	82.4
1981	90.9
1982	96.5
1983	99.6
1984	103.9
1985	107.6
1986	109.6
1987	113.6
1988	118.3
1989	124.0
1990	130.7
1991	136.2
1992	140.3
1993	144.5
1994	148.2
1995	152.4
1996	156.9
1997	160.5
1998	163.0
1999	166.6
2000	172.2
2001	177.1

Passive technologies

Solar evaporation, solar distillation, spray evaporation, and optimal solar and spray evaporation were analyzed above for technical viability. Solar evaporation, and spray evaporation without a collection pond, were determined to be technically unfeasible. Solar distillation is clearly feasible from a technical standpoint. The conceptual design for an optimal combined solar and spray evaporation system shown in Figure 5 is unproven, but appears very promising from a cost perspective. These latter two technologies warrant further financial analysis.

Cost data from the 1970's and 1980's for solar distillation is available from the sources listed in Table 10. The cost of solar distillation is almost entirely comprised of capital costs. As shown in Table 19, the solar distillation is estimated to cost approximate $0.03 per gallon evaporated. Labor costs for operating the still are not included, but should be minimal. Solar distillation appears to be competitive with current operating costs of the F- and H-area WTUs (0.047 $/gal, Table 2) in a best-estimate sense.

For the combined solar and spray evaporation system shown in Figure 5, cost analysis is more difficult because the design is only at the conceptual stage. Nevertheless, a scoping analysis of costs can be developed using vendor and commercial pricing as shown in Table 20. Design costs and labor for system operation are not considered. The result, $0.005/gal, is rather encouraging, but highly uncertain and incomplete.

Table 19 Cost analysis for large basin-type solar distillation under SC conditions.

Estimated distillation rates under SC conditions - large basin stills

	Kreith & Kreider (1978)	*FSEC-EN-3 (1984)*	*Schumacher Centre for Technology & Development*
Insolation	4.5 kW-hr/m^2-d	4.5 kW-hr/m^2-d	
	1427 BTU/d-ft^2		
Production	0.045 gal/ft^2-d	0.059 gal/ft^2-d	0.046 gal/ft2-d
	0.49 gal/m^2-d	0.64 gal/m^2-d	0.49 gal/m^2-d
	26.6 in/yr	34.8 in/yr	26.9 in/yr
	1.37 gpm/acre	1.80 gpm/acre	1.39 gpm/acre
Upper bound	0.18 gal/ft^2-d	0.18 gal/ft2-d	0.18 gal/ft2-d
Efficiency	25%	32%	25%
Capital costs	2.25 ~1975 US$/$ft^2$	50 ~1984 US$/$m^2$	60 UK$/$m^2$
Currency factor	1	1	1.46
Inflation factor	3.29	1.70	1 ?
2001 US$	7.4 US$/$ft^2$	7.9 US$/$ft^2$	8.1 US$/$ft^2$
	80 US$/$m^2$	85 US$/$m^2$	88 US$/$m^2$
Unit cost	0.23 US M$/gpm	0.19 US M$/gpm	0.25 US M$/gpm
Life span	20+ years	20? years	25 years
Interest rate	0.044	0.044	0.044
Capital recovery factor, A/P	0.0762	0.0762	0.0667
Annualized capital cost	17883 US $/gpm-yr	14640 US $/gpm-yr	17011 US $/gpm-yr
	0.034 US $/gal	0.028 US $/gal	0.032 US $/gal

Table 20 Partial cost analysis for an optimal solar and spray evaporation system.

Design specs.			
Flowrate needed	50	gpm	
Conceptual design			
Spray evaporation	7.25	gpm/machine	
	3	machines	
	21.75	gpm	
+Solar evaporation	28.25	gpm	
	57	in/yr	pan evaporation rate
	2.94	gpm/acre	
	9.6	acres	
Capital cost	659,324	$	
Operating cost	48,000	$/yr	
Lifespan	10	yr	
Interest	0.044		
Capital recovery factor	0.1258		
Annualized capital cost	82,915	$/yr	
Annual cost	130,915	$/yr	
	0.005	US $/gal	
	4.98	US $/1000-gal	
	2,618	$/gpm-yr	
Capital cost detail …			
Holding pond			
earthen pond	3,300	$/acre	
under-layment	5,200	$/acre	
liner	11,300	$/acre	
air roof material	8,300	$/acre	
liner installation	35,000	$/acre	
supporting infastructure	?	$/acre	
"total" cost	63,100	$/acre	
Evaporative sprayer			
Capital cost	18,000	$/machine	
Operating cost	16,000	$/yr	

Active technologies

Fulbright and others (1996) analyzed a number of technologies, including evaporation, for treating or managing tritiated groundwater at the SRS. A summary of their cost analysis of a direct evaporation system is provided in Table 21. The cost is not competitive with current F- and H-area WTU operating costs, presumably due to high energy requirements of direct, single-effect, evaporation.

Several vendors were approached in this study for accurate capital and operating cost information for their respective products assuming a 25 gpm capacity. Two vendors, Vacom and Severn Trent Services, responded with information sufficiently detailed for a comprehensive cost estimate. As shown in Table 22, total cost excluding labor is lower than current WTU costs (Table 2) for both vendors. Operator attention would be minimal, 2-4 hours per 24/7 week, according to Vacom. Corresponding labor requirements in the SRS environment are uncertain, but speculated to be 28 hrs/wk. With the addition of labor costs, evaporation is still competitive (e.g. Vacom system).

Table 21 Cost analysis of direct evaporation by Fulbright and others (1996).

Fulbright and others (1996) - direct heating		
0.066	$/gal	total cost in 1995 dollars
152.4		1995 CPI
177.1		2001 CPI
1.16		ratio
0.0767	$/gal	total cost in 2001 dollars, *including labor*
1.63		ratio to F/H cost

Table 22 Cost analyses of Vacom and Severn Trent Services evaporation systems.

Vacom			**Severn Trent Services**		
25	gal/min	capacity	25	gal/min	capacity
13,140,000	gal/yr	"	13,140,000	gal/yr	"
900,000		evaporator cost	560,000		evaporator cost
100,000		dryer cost			dryer cost
1,000,000	$	capital cost	560,000	$	capital cost
76,211	$/yr	annualized capital cost	42,678	$/yr	annualized capital cost
0.0058	$/gal	"	0.0032	$/gal	"
0.0136	$/gal	electric cost		$/gal	electric cost
0.0040	$/gal	steam cost		$/gal	steam cost
0.0176	$/gal	operating cost	0.0200	$/gal	operating cost
0.0234	$/gal	total cost, *excluding labor*	0.0232	$/gal	total cost, *excluding labor*
0.50		ratio to F/H	0.50		ratio to F/H
28	hrs/wk	labor guess	28	hrs/wk	labor guess
1456	hrs/yr	annual labor	1456	hrs/yr	annual labor
70	$/hr	labor rate	70	$/hr	labor rate
101920	$/yr	labor cost	101920	$/yr	labor cost
0.0078	$/gal		0.0078	$/gal	
0.0312	$/gal	total cost, *including labor*	0.0310	$/gal	total cost, *including labor*
0.66		ratio to F/H	0.66		ratio to F/H

Summary and conclusions

Table 23 summarizes the results of the above technical and economic analyses of evaporation for treatment of contaminated groundwater.

With respect to technical feasibility, active evaporation technologies are highly reliable and robust. There appear to be no major technical barriers to using engineered evaporators for treatment of F- and H-area groundwater. Simple, single-effect, evaporation using direct heating is not cost competitive with continued operation of the current Water Treatment Units. However, more efficient systems (e.g. Vacom product) are estimated to be somewhat more cost efficient than the WTUs. More rigorous financial analysis is needed to confirm the cost savings projected in Table 23.

Certain passive technologies appear to be technically viable in a best-estimate sense, but after considering uncertainties and a lack of field installations in the southeast US, adequate performance cannot be guaranteed with high confidence. Also, the land requirements are large. The most reliable passive technology is solar distillation, which has been field tested at large scale at several locations. Available data indicates solar distillation costs would be similar to an efficient fossil fuel driven evaporator, and less than current WTU operating costs. An optimal design combining solar pond and spray evaporation could potentially offer the least expensive alternative. However, the idea proposed herein is only in the conceptual stage and thus unproven.

The best alternative to chemical treatment of F- and H-area groundwater appears to be a two-stage system involving fossil fuel powered evaporators. The first stage would employ an efficient (e.g. multiple-effects and/or MVR) evaporator to greatly concentrate solutes (e.g. 100:1) in the feed water. The concentrate would then be fed to a flash evaporator to produce a dry ash residue of metals and non-volatile radionuclides. The low volume dry ash could then be disposed of as solid waste. Significant reductions in solid waste disposal volumes could be achieved.

Table 23 Summary of technical and economic feasibility of evaporation technologies.

Cost		**Reliability**	**Technology**		
($/gal)	*($/kgal)*	*(1 - 3) index*	*Class*	*Category*	*Specific*
0.047	47	3	Active	Chemical	F- and H- WTUs (costs for continued operation only)
0.077	77	3		Evaporation	Direct heating - Fulbright and others (1996)
0.031	31	3			Vacom
0.031	31	3			Severn Trent Services
0.030	30	2	Passive		Solar distillation - large scale
0.005+	5	1			Optimal solar and spray evaporation concept

References

Bibler, J. P., 1990, F/H area ground water remediation technology, Savannah River Technology Center interoffice memorandum IWT-LWP-90-0021, March 13.

Kreith, F., and J. F. Kreider, 1978, Principles of solar engineering, Hemisphere Publishing, Washington and McGraw-Hill, New York.

Fetter, C. W., 1988, Applied hydrogeology, 2nd edition, Macmillan, New York.

Fulbright, H. H., A. L. Schwirian-Spann, K. M. Jerome, B. B. Looney and V. Van Brunt, 1996, Status and practicality of detritiation and tritium reduction strategies for environmental remediation, WSRC-RP-96-0075, Rev. 0.

McCluney, W. R., 1984, Solar distillation of water, Florida Solar Energy Center, Energy Note FSEC-EN-3-80.