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The effects of climatic factors and still design on solar earth‑water distillation for saturated sand

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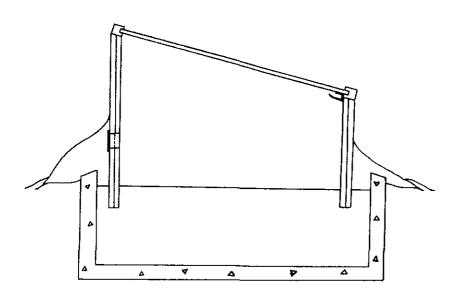*Utah State University*

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INTRODUCTION AND LITERATURE REVIEW

Solar earth-water stills have been used as a means of supplying water for survival in the desert and potentially may be used for providing domestic water. Figure 1 illustrates both a survival still and a hot-box type of solar earth-water still.
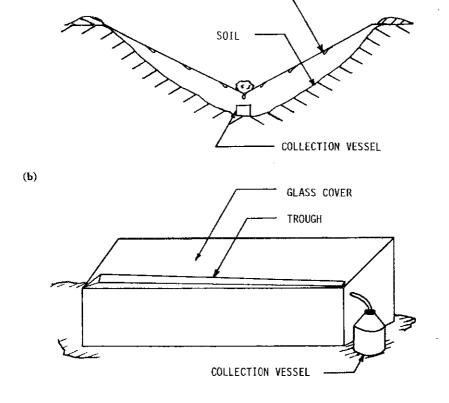
(a)

(b)

Figure 1. Diagram of the (a) survival and (b) hot-box types of solar earth-water stills.

The famous survival still was developed by Jackson and van Bavel (1965) to provide potable drinking water in the desert. The maximum yield obtained was about 1.5 liters per square meter per day.

Kobayashi (1963) studied the hot-box type of solar earth-water still. This consists of an inclined glass lid on a wooden frame set on the ground (Figure 1). Kobayashi found that daytime yields varied with the amount of solar radiation received. The maximum daytime yield was 1.1 liters per square meter. However, the nighttime yield was constant at 0.2 liters per square meter. Kobayashi did not report the number of consecutive days for which these yields were obtained at the same location.

Ahmadzadeh (1978) reported on research he conducted in Iran on the hot-box still. At initial moisture contents of 11 percent, 12 percent and 13 percent, the stills initially yielded 1.45, 1.5 and 1.7 liters per square meter per day, respectively. After 11 days, yield decreased to a constant 0.15 liters per square meter per day. No information was reported for stills operating at or near saturation.

Basically, a solar earth-water still functions because of the greenhouse effect. The heating of the soil surface by solar radiation and the cooling of the glass by the outside air cause the temperature of the moisture at the soil surface to be above that of the glass. Therefore, there exists a temperature gradient with an attendant vapor pressure gradient and the potential for mass transfer. The moisture vaporizes into and circulates within the enclosed air space. It then condenses on the cooler still surfaces. The more nearly perpendicular the glass is to the incoming radiation, the greater will be the amount of radiation entering the still. However, practical experience has shown that the cover slope must not be less than about 16 degrees from the horizontal or water may fall back to the soil surface instead of streaming off the glass for collection.

Because solar earth-water distillation is a method of extracting and purifying soil water, it potentially may be an alternative method of obtaining a potable water supply when conventional means are impossible or uneconomical. For example, it may be used to recycle wastewater for a household or village. It could also be used to purify soil moisture that has been supplemented by polluted water, water contaminated with radioactive fallout (Kobayashi, 1963) or fleshy plant material. Solar earth-water distillation also may be useful in extracting water from the soil near inadequately drained septic tanks.

This report presents the results of research on the hot-box type of solar earth-water still with the soil moisture content maintained at greater than or equal to 9 percent. For soil moisture contents of 9 percent and above, the soil moisture vapor pressure is approximately that of a free water surface.[1]

Solar distillation provides an alternative method of obtaining a potable water supply when conventional means are impossible or uneconomical. Solar earth-water stills do not require the purchase of energy and consequently have a low operating cost. Before solar earth-water distillation can be considered feasible for providing water on a wide scale, research is needed to determine the effects of environmental conditions and still design on yields.

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[1]Thomas (1924) graphed the depression of the vapor pressure with moisture content for sand and other soils.

The objectives of this study were (1) to compare the amount of water produced from stills of two different heights and from stills with light-reflective and light-absorptive interior siding and (2) to develop an empirical expression relating yield to solar radiation, ambient temperature and moisture content for sand maintained at or near saturation.

METHODS AND MATERIALS

The following designs of the hot-box solar earth-water still were constructed at the Agricultural Engineering Lab of the University of Arkansas: a still 20 cm high (as measured from the soil surface to the center of the cover glass) with light-reflective interior siding, a still 40 cm high with light-reflective interior siding and a still 40 cm high with light-absorptive interior siding (i.e., painted flat-black). Each still had a collection area of two-thirds of a square meter (67 cm x 100 cm). The general set-up of the stills is given in Figure 2. The sand enclosed by the stills is referred to as "soil" in this report.
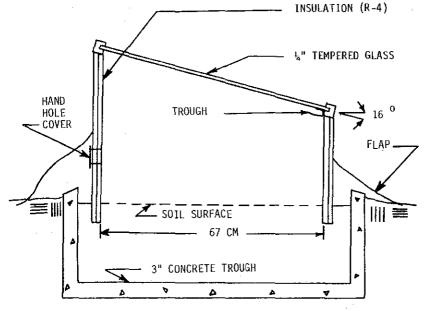
Figure 2. Diagram of a solar earth-water still
used in the study.

Each still was tested with the soil maintained at or near saturation in order to determine the relationship of distillate production to soil moisture content, solar radiation and ambient temperature. The low (20-cm) still, which had reflective siding, was compared to the high (40-cm) still with reflective siding. Also, the high still with absorptive siding was compared to the high still with absorptive siding. A cover slope as close as possible to the normal slope of the incoming solar radiation was used. The slope chosen was 16 degrees, the average of the sun's zenith angle from April

29 to Aug. 13. Coincidently, this is close to the minimum angle at which droplets will flow down the glass rather than drop from it.

Medium sand was chosen as the soil type because it is readily available around the world. The particle-size distribution for the sand used in this study is given in Table 1. The saturated moisture content of the sand, determined gravimetrically, was 24 percent.

Table 1. Particle-size Distribution of the Medium Sand

Separate	Particle Size (mm)	Mass Percentage
Very coarse sand	2.00 - 1.00	4.4
Coarse sand	1.00 - 0.50	9.9
Medium sand	0.50 - 0.25	68.4
Fine sand	0.25 - 0.10	17.0
Very fine sand	0.10 - 0.05	1.2

The low and high stills with reflective siding were compared, and the high stills with reflective and absorptive siding were compared. The low, reflective, the high, reflective and the high, absorptive stills were tested from June 26 to Aug. 4. The low, reflective still was also tested from Aug. 29 to Sept. 21.

Yield of distillate and the moisture content of the soil were measured daily between 8:00 and 8:30 a.m. Soil moisture content was determined gravimetrically on samples taken at depths of 0 to 3 cm. The surface of the soil, which was initially saturated with water, dried to the 9 percent level in about three weeks. The soil was then resaturated, and the process was allowed to repeat itself.

The solar radiation data came from the Solar Poultry House Project, located only 0.4 km from the still sites. The output of a horizontally mounted Eppley pyranometer was integrated over each hour and recorded. The radiation values were adjusted to correct for the geometry of the sun's zenith angle at solar noon and for the still's cover angle to obtain the radiation component that was normal to the still cover.

The ambient temperature was measured 45.7 cm above the ground using a copper-constantan thermocouple and was recorded with a Barber-Coleman 12-point strip chart recorder.

RESULTS AND DISCUSSION

From the data collected, the following values were determined: the component of solar radiation (SR) that entered perpendicular to the still's cover; the maximum, minimum and average daily temperatures ($TMAX$, $TMIN$ and $TAVG$, respectively); and the soil moisture content (MC) at a depth of 1.5 cm. These variables and combinations of these variables, including SR^2, $SR^{3/2}$, $TMAX$ x $TMIN$, $TMAX^2$, $TMIN^2$, SR x $TAVG$, and MC x $TMAX$, were used as independent variables in a regression analysis. A stepwise statistical procedure was used to determine which variables contributed the most to the prediction of yield. This procedure led to the selection of the variables $TMAX$, $TMIN$, MC and SR for the predictive model.

Table 2 shows the range of recorded values for the significant variables and the resulting yields for the three stills. (The actual values are found in Appendix Table 1.) Technical difficulties prevented the stills from functioning properly on the same days. Therefore, the range of values is different for each still. Table 2 also shows daily distillate yield.

Table 2. Environmental Data and Daily Distillate Yield for the Three Solar Earth-Water Stills

Still Design	Environmental Variable				Daily Distillate Yield
	Moisture content	Daily solar radiation[1,2]	Maximum temperature	Minimum temperature	
	%	kJ/m²	°C		g/m²
Low, reflective					
Average	16.9	17,400	30.7	19.1	1,390
Range	9.9-23.0	2,760-26,700	15.1-36.2	3.3-24.6	792-2,020
High, reflective					
Average	12.3	15,100	31.8	20.9	752
Range	9.2-15.0	2,760-25,900	27.9-36.2	19.2-23.1	492-973
High, absorptive					
Average	15.2	16,200	32.0	21.5	884
Range	9.1-24.0	2,760-25,900	24.4-36.2	16.2-25.1	459-1,453

[1]Radiation normal to the cover glass of the still.
[2]The sun's zenith angle at solar noon ranged from 10 to 35 degrees.

Statistical analysis of the yields from the three stills revealed the following at the 0.05 level:

1. The high, reflective and the high, absorptive stills produced similar yields.
2. The low, reflective still produced greater yields than did the high, reflective still.
3. The low, reflective still tested from June 26 to Aug. 4 produced similar yields as the same still tested from Aug. 29 to Sept. 21. This is interesting because the sun is lower in the sky during the latter period, for which 30 degrees would be a more appropriate cover slope.

Regression analysis was performed to develop a predictive equation for yield (Y) of each of the stills. The resulting model is valid when the environmental conditions are within the ranges found in Table 2 and when the sun's zenith angle at solar noon is between 10 and 35 degrees. The model is the following:

$$Y = (Cmc)\ MC + (Csr)\ SR + (Ctx)\ TMAX + (Ctn)\ TMIN + I$$

where Cmc, Csr, Ctx and Ctn are the coefficients of the variables of moisture content (MC), solar radiation (SR), maximum daily temperature (TMAX) and minimum daily temperature (TMIN), respectively, and I is the intercept. Values of the coefficients are listed in Table 3.[2]

[2]Not all variables included in Table 3 are significant at the 0.05 level.

Table 3. Coefficients of the Variables Appearing in the Equation for Predicting Daily Distillate Yield

| Still Design | Equation Parameter[1,2] | | | | | R^2 | Range of SE of Mean of Predicted Yield (g/m²/day) |
	Cmc	Csr	Ctx	Ctn	I		
Low, reflective	-32.3* (10.5)	0.022* (0.006)	28.9 (21.9)	-24.4 (20.6)	1,140* (443)	0.55	40.3 - 152
High, reflective	22.6 (18.6)	0.003 (0.006)	38.1* (13.6)	-40.8 (25.2)	23.7 (775)	0.86	27.0 - 71.6
High, absorptive	-18.1* (7.7)	0.002 (0.005)	71.0* (13.9)	-25.0 (19.9)	-538 (387)	0.70	30.4 - 114

[1]Cmc, Csr, Ctx and Ctn are the coefficients associated with the variables of moisture content, solar radiation and maximum and minimum daily temperatures, respectively; I is the intercept.
[2]Standard error of the estimate is given in parentheses.
*Significant at the 0.05 level.

Predicted yield for the low, reflective still, for example, is calculated from the following equation:

$$Y = -32.3 \, MC + 0.022 \, SR + 28.9 \, TMAX - 24.4 \, TMIN + 1136.$$

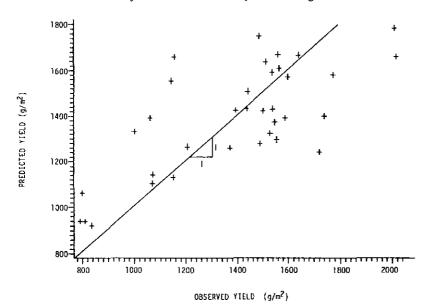Predicted vs. observed yields for this still are plotted in Figure 3.

**Figure 3. Predicted vs. observed yields
from a 20-cm-high, light-reflective solar earth-water still.**

The effects of the environmental variables on yield determine the signs of the coefficients in Table 3. The low, reflective and the high, absorptive stills both showed a slight decrease in yield with an increase in soil moisture. The adverse effect of soil moisture on yield is probably due to the increase in heat capacity and thermal conductivity of the soil that attends an increase in moisture content. (Recall that the equation is for soil moisture contents of greater than 9 percent.) The result is that at 20 percent moisture, more heat is required to cause a certain amount of vaporization than at 9 percent soil moisture. The high, reflective still showed the opposite effect, probably because it was tested under drier conditions than the other stills (Table 2).

Yields generally increased with an increase in solar radiation. This is expected because solar radiation is the main driving energy for evaporation of the soil moisture. Yields also increased with an increase in the maximum daytime temperature because of the greater amount of evaporation.

Yields also increased with a decrease in the minimum nighttime temperature. Any decrease in nighttime temperature would increase the difference in temperature during the night between the air enclosed by the still and the outside air, which would increase the amount of condensation.

Daily efficiency (*EFF*) was calculated from the data on the low, reflective still according to the following equation:

$$EFF \% = 100 Y \Delta H_v / SR$$

where Y is daily distillate yield (g/m^2), ΔH_v is heat of vaporization (2.26 kJ/g for water) and SR is daily solar radiation (kJ/m^2) that enters the still perpendicular to the cover glass. The average efficiency was 25 percent; the range was from 12 percent to 75 percent.

CONCLUSIONS

The following conclusions are based on the data presented in this report:

1. Water production increases with increasing solar radiation, increasing maximum temperature, decreasing minimum temperature and decreasing soil moisture content within the range of values tested. Further work is needed to determine the optimum soil moisture content for the distillation process.
2. The 40-cm-high still with light-reflective interior siding and the 40-cm-high still with light-absorptive interior siding produced similar yields. However, the 20-cm-high still, with light-reflective interior siding, produced greater yields than the 40-cm-high still with the same type of interior siding. Further work is needed to determine the optimum still height.
3. Yield of the 20-cm-high still with reflective siding can be predicted by the following regression equation:

$$Y = -32.3 \, MC + 0.022 \, SR + 28.9 \, TMAX - 24.4 \, TMIN + 1136$$

where Y is daily distillate yield (g/m^2), MC is the soil moisture content (percentage by weight), SR is the daily amount of solar radiation (kJ/m^2) that enters the still perpendicular to the cover glass, and $TMAX$ and $TMIN$ are the daily maximum and minimum ambient temperatures (°C), respectively. This equation is valid for the range of values presented in this report.
4. Solar earth-water distillation is useful when distillate production or soil moisture removal rates of 1 to 2 liters per square meter per day are adequate. For the purpose of producing water for human consumption, this technique would be most appropriate in developing countries. In Arkansas, it may have some applicability as a method of removing excess water from the soil near inadequately drained septic systems. Further research is needed, however, before recommendations can be made.

LITERATURE CITED

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Appendix Table 1. Environmental Data and Daily Distillate Yields of Three Stills on the Basis of a 1-m² Collection Area

				Low, reflective		High, absorptive		High, reflective	
Date (1981)	Daily Radiation[1]	Temperature Max.	Temperature Min.	Daily yield[1]	Moisture content[2]	Daily yield	Moisture content	Daily yield	Moisture content
	kJ/m²	—— °C ——		g/m²	%	g/m²	%	g/m²	%
6/26	4,670	32.2	18.7	1,000	11.4	---	---	---	---
6/27	4,450	31.8	20.1	1,490	11.7	1,070	18.8	---	---
6/28	5,200	34.2	20.2	1,740	10.2	1,110	13.0	845	9.3
6/29	12,000	33.7	21.4	1,440	9.9	1,100	14.8	---	---
7/01	11,100	31.3	20.4	1,080	20.0	747	20.0	765	15.0
7/02	24,400	31.2	19.7	1,540	20.0	1,010	19.0	973	15.0
7/03	13,800	30.4	22.4	1,150	20.0	743	18.0	717	13.0
7/04	5,760	27.9	20.4	792	20.0	516	18.0	492	11.0
7/05	2,750	28.6	19.2	810	19.5	464	18.8	559	9.2
7/06	4,440	29.4	21.1	837	20.6	509	20.0	---	---
7/07	13,500	29.4	22.6	800	21.0	609	24.0	535	10.0
7/08	22,300	33.6	20.0	1,440	20.5	897	21.0	945	15.0
7/09	25,800	35.7	21.1	1,520	17.2	978	17.5	851	13.0
7/10	25,900	36.2	23.1	1,560	15.3	816	17.7	845	12.0
7/11	19,600	35.2	22.5	1,540	13.0	1,030	17.7		
7/12	21,700	34.3	23.0	1,640	10.8	891	15.0		
7/13	19,500	33.1	22.6	1,500	16.5	869	14.5		
7/14	9,640	34.2	24.6	1,720	15.3	962	13.7		
7/15	19,500	35.3	22.2	2,020	11.0	1,450	11.9		
7/16	25,300	35.2	21.9	2,010	11.0	1,340	11.1		
7/17	25,000	34.7	24.7	---	---	430	10.0		
7/18	25,900	35.3	24.9	---	---	1,170	9.2		
7/19	14,200	34.8	24.5	---	---	1,260	9.2		
7/22	25,600	35.4	25.1	---	---	953	10.3		
7/28	16,500	26.6	18.9	---	---	765	19.6		
7/29	7,840	24.4	19.6	---	---	534	11.6		
7/30	6,590	24.7	19.4	---	---	459	10.4		
7/31	23,300	30.6	20.7	---	---	615	12.5		
8/04	20,800	34.9	23.4	1,560	10.7	---	---		
8/07	23,200	28.4	16.2	---	---	747	9.1		
8/29	22,900	31.3	20.9	1,560	22.7				
8/30	22,800	34.4	23.1	1,550	21.4				
8/31	19,500	31.8	22.3	1,370	21.0				

Appendix Table 1. Continued.

Date (1981)	Daily Radiation[1]	Temperature Max.	Temperature Min.	Low, reflective Daily yield[1]	Low, reflective Moisture content[2]	High, absorptive Daily yield	High, absorptive Moisture content	High, reflective Daily yield	High, reflective Moisture content
	kJ/m²	°C	°C	g/m²	%	g/m²	%	g/m²	%
9/02	16,800	28.0	19.3	1,070	23.0				
9/09	23,300	29.5	13.3	1,600	17.7				
9/11	22,000	30.9	20.5	1,150	13.5				
9/14	19,900	34.6	17.5	1,070	23.0				
9/16	18,500	19.4	6.2	1,530	18.6				
9/17	16,400	15.1	3.3	1,210	17.2				
9/18	26,700	19.4	6.6	1,570	14.4				
9/19	22,400	24.1	10.7	1,780	13.7				
9/20	24,200	27.3	15.7	1,590	20.5				
9/21	22,900	31.2	17.8	1,400	20.5				

[1]Solar radiation and daily yield values were obtained from stills having a collection area of 0.67 m². Values obtained from these stills were multiplied by 1.5 to get the solar radiation and daily yield values on the basis of a 1-m² collection area.
[2]Moisture content of the soil is expressed as a percentage by weight.