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Solar Evaporation Correlations at the Salar de Atacama

Jerome A. Lukes and George C. Lukes

Lukes Process Development Corporation, Ogden, Utah, USA

ABSTRACT

Laboratory vapor pressure determinations on brine over a broad range of compositions were correlated to predict the vapor pressure activity of Salar de Atacama brines from the beginning to the end of the solar evaporation process. The activity range was 0.73 to 0.33. The predicted brine activities together with the weather data were used to develop two equations for predicting brine evaporation. One of these evaporation equations uses radiation and the average of the maximum and minimum ambient temperatures as weather variables. The other equation uses water pan evaporation as the weather variable.

The two evaporation equations indicate that at the salar brine activity acts as an efficiency factor on radiation or water pan evaporation. The water pan equation may provide a useful tool for predicting brine evaporation rates at other locations when Class A water pan evaporation data are available along with brine vapor activity.

The effect of pan size on evaporation was also studied and the results of that study are described in this paper.

INTRODUCTION

The Salar de Atacama is a large dry lake (salar) located in northern Chile near the Argentine border. The salar, at an elevation of 2300 m, is 200 km due east of Antofagasta, Chile, and is bisected by the Tropic of Capricorn. The weather at the salar is ideal for solar evaporation: warm and dry with high solar radiation and very low rainfall.

The salar is a massive salt deposit containing a large reserve of brine. The main part of the deposit is located in what is called the nucleus: an area about 35 by 35 km. The brine, which fills the pores of the salt body, is saturated with sodium chloride and contains large amounts of magnesium, potassium, lithium, sulfate, and boron. The brine level is about 50 cm below the surface of the salt.

In 1986 Minsal Ltda., a company owned by AMAX de Chile, Inc., Corporacion de Fomento de la Produccion, and Molybdenos y Metales S.A., undertook an extensive development program to study all phases of the commercial recovery of products from the Salar de Atacama. As part of that program the rate of evaporation from brines at various concentrations was studied.

PAN AND POND OPERATIONS

The magnesium brines at the salar which are available to Minsal for processing can be classified into two types: high sulfate brines and low sulfate brines. The high sulfate brines are located in the northern portion of the salar, while the low sulfate brines are located in the southwest portion of the salar.

Table 1 lists some typical brine compositions found in the nucleus of the salar. After studying these brine compositions it was decided to run the pan tests for pond chemistry and evaporation rates on the brines from the sites called Nury and Sara. Nury, located 7 km north of Sara, has a high sulfate brine, while Sara was at the location of a medium sulfate brine.

Each site contained 8 evaporation pans. At the Nury site there were two 9 m diameter pans and six 3 m diameter pans. At Sara there were two 9 m diameter pans, three 5 m diameter pans, and three 3 m diameter pans. At the Nury site the pans were operated from February of 1986 until November of 1988. The Sara site was operated from February of 1986 until April of 1988. Each pan was buried and had a side wall of 60 cm. The pans were operated at nearly constant levels: 9 m diameter at 45 cm, 5 m diameter at 50 cm, and 3 m diameter at 55 cm. Each pan was fitted with maximum–minimum thermometers, both of the floating and the submerged type, and hook gauges to measure brine elevation.

Flow from pan to pan was in series with the largest pans first. For the initial 14 months of operation the last three pans at each site were operated

TABLE 1

Brine compositions at the Salar de Atacama

Site	Mg	Ca	Na	K	Li	Cl	SO_4	H_3BO_3
Sara	1.14	0.03	7.23	2.12	0.16	16.14	1.57	0.31
Nury	0.89	0.02	8.10	1.52	0.12	15.55	2.09	0.35
Omega	0.91	0.03	8.05	1.79	0.14	16.04	1.93	0.32
Other	2.04	0.09	4.40	3.67	0.42	18.46	0.44	0.39

with two pans in series and one pan in parallel. Subsequently all pans were operated in series flow.

The Nury site also had a weather station which contained an evaporation pan, maximum–minimum thermometers, wet bulb and dry bulb thermometers, a wind run integrator, a radiation meter, a sun-hour meter, and a rain gauge. Weather data were recorded daily.

At both pan sites daily readings of brine level and of maximum–minimum brine surface and bottom temperatures from each pan were recorded. Brine transfers were made sequentially to fill the pans: once a week in the winter, three times a week in the summer, and twice a week in the spring and fall. The frequency of transfers was made to minimize variations in brine compositions in a given pan.

Each transfer into and out of a pan was carefully measured using a metering tank fitted with a sight glass. Samples of each transfer were taken for chemical analysis. One third of each pan area was harvested every six weeks in the winter and every four weeks in the summer. The harvest was weighed and sampled and the pan volume reduction due to harvesting was recorded.

Two other locations in addition to Sara and Nury were selected for scale-up tests. One location, called Elmer (3 km southeast of Nury), had a 9 m diameter pan and a 3 m diameter pan. The other location, Omega, located 500 m to the east of Elmer, had a 100 m square pond (10,000 m^2) and a 50 m square pond (2,500 m^2). The large ponds at Omega and the 9 m pan at Elmer were operated for a period of one year, while the 3 m pan at Elmer began operations at the same time as Omega and continues to this day. The pans at Elmer and the ponds at Omega were fed the same brine and all were operated at the same brine concentration: a concentration representing the mid point with respect to pond area of the evaporation process.

The pan operations were supported by laboratory studies conducted by the University of Antofagasta and the University del Norte and supervised by Minsal Ltda. personnel and their consultants. With respect to evaporation rate, the most important of these support studies was the determination of brine vapor pressure over a broad range of brine compositions and brine types.

All of the data taken at the pan sites and the weather station, along with the results of chemical analysis and vapor pressure studies, were entered into a database for later processing into the appropriate correlations.

BRINE ACTIVITY

The primary reason that brines of different compositions evaporate at different rates is because of differences in vapor pressure (Bonython, 1966). Therefore, to be able to predict the evaporation rate of any brine that may be evaporated at the Salar de Atacama, it was necessary to determine the vapor pressure of these brines. The vapor pressure of brines from the pans and laboratory evaporation tests was measured at several pressures varying from 10 to 35 mm Hg absolute and the activity of each brine was calculated. Activity is defined as the vapor pressure of the brine at a given temperature divided by the vapor pressure of water at the same temperature.

As a result of a regression analysis Equation (1) was obtained for the prediction of brine activity.

$$A = 0.741 - 0.057(SM) + 0.0235(SM)^2 + 0.041\,K - 0.0065\,K^2 - 0.0175\,MgL - 0.0028\,MgL^2 \quad (1)$$

where A = activity of salar brines at various stages of concentration; SM = ratio of sulfate to magnesium plus lithium as magnesium; K = weight percent potassium in the brine; MgL = weight percent magnesium plus lithium as magnesium in the brine; $R^2 = 0.99$ (an indicator of the reliability of the regression). Number of observations = 24.

The R squared value is very high and the constant 0.741 is very close to the 0.75 activity of a pure sodium chloride brine which was determined by Leopold (1926). Figure 1 is a plot of Mg^{2+} plus Li^+ as Mg^{2+} versus the measured and calculated values of activity. During the course of the salar studies it was found to be convenient to plot compositions and results using percent Mg^{2+} plus percent Li^+ calculated as the equivalent amount of Mg^{2+}. The range of concentrations in weight percent used for Equation (1) were quite broad: Mg^{2+}, 0.88–8.28; Li^+, 0.11–4.51; K^+, 0.1–3.5; SO_4^{2-}, 0.1–6.5. All of the brines were saturated with sodium chloride.

THREE METER DIAMETER PAN CORRELATIONS

The large amount of evaporation and weather data was reduced to weekly averages. Initially, it

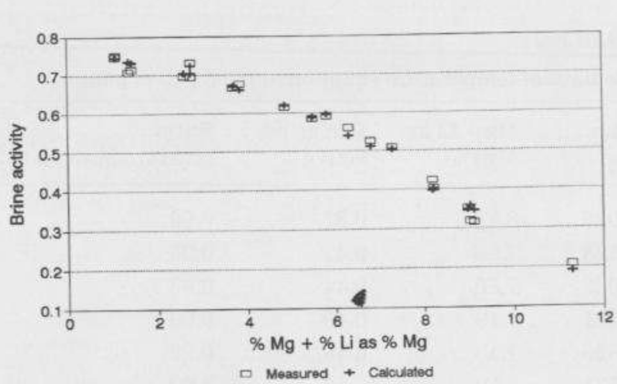

Fig. 1. Salar de Atacama: measured and calculated brine activities.

was thought that an energy balance on each pan would be used to determine mass and heat transfer coefficients for use in the evaporation equation. However, it became apparent that two other approaches could be used to obtain equations to predict evaporation: a correlation wherein weather inputs such as radiation, ambient temperatures, wind run, and absolute humidity could be used to predict evaporation empirically; and a correlation wherein only water pan evaporation would be the weather input to the empirical equation. Water pan evaporation represents the effect of all the weather conditions on the evaporation of water. Both of these approaches would include brine activity.

Data from the 3 m diameter pans at Nury, Sara, and Elmer were used to obtain the evaporation correlations. In addition, these correlations for Nury, Sara, and Elmer were compared with the evaporation data from the 9 m pan at Elmer and the large ponds at Omega. The final comparison was between the 3 and 9 m pans at Elmer and the 100 and 50 m ponds at Omega.

The weather at the salar is very consistent from year to year. This consistency is demonstrated in Fig. 2, which graphically shows monthly averages of temperature, radiation, and water pan evaporation. The weather data used in the correlations were on the basis of weekly averages.

The following equation for the 3 m pans was developed by performing a regression analysis on the weekly averages of the weather and the pan evaporation data:

$$LD = -0.255 + 0.000108(R)(A) + 0.0182\,T \qquad (2)$$

where LD = level drop in centimeters per day; R = radiation in Watt-hours per day per M^2; A = brine activity; T = average ambient temperature; R^2 = 0.898 (an indicator of the reliability of the regression). Number of observations = 646.

The addition of such terms as wind run or absolute humidity had very little effect on improving the correlation. This is not surprising because the weather at the salar is very consistent from year to year with wind run and humidity roughly following the same sine wave as solar radiation. However, ambient temperature peaks after solar radiation, as does the water pan evaporation (see Fig. 2). Bonython (1968) calculated that the order of importance is radiation, ambient temperature, water vapor pressure in the air, and finally wind.

In Equation (2) it can be seen that the activity term acts as an efficiency factor on radiation. Also, this equation indicates that evaporation from a brine is a first-order function of brine activity. Since the brine activity does not have a straight line relationship with brine concentration, then evaporation does not have a straight line relationship with brine concentration when magnesium plus lithium is used as a concentration indicator and a broad range of concentrations are considered.

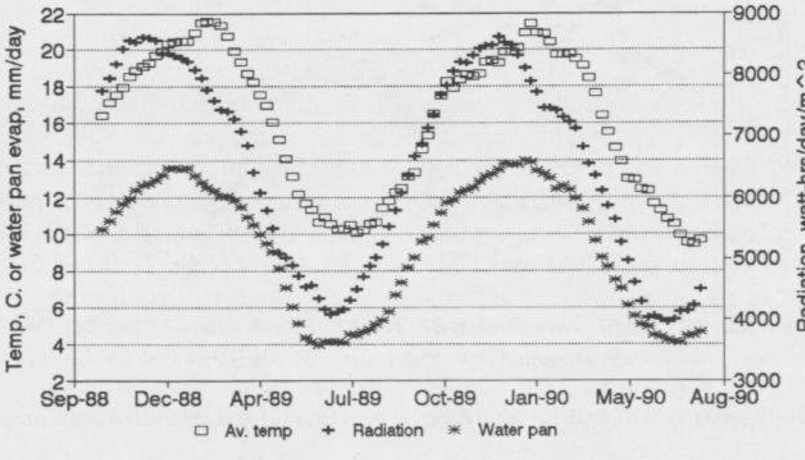

Fig. 2. Salar de Atacama: 5 week average of radiation, water pan evaporation, and average ambient temperature.

Water pan evaporation accumulates all of the weather inputs into one output which summarizes the effect of these inputs on the evaporation of water. Further, water pan evaporation is a simple measurement that does not have the calibration problems associated with other measurements in a remote location.

Two equations were developed for the 3 m pans using water pan evaporation as the weather input plus brine activity. Initially, a first-order with respect to brine activity was calculated because of the results obtained with the radiation equation. However, the first-order water pan equation did not have good results at the extremes of activity. Therefore, a second regression was calculated which included a second order activity term. The result was:

$$LD = (WP)(A)[1.098 - 0.4124(A)] \quad (3)$$

where LD = level drop in cm per day; WP = water pan level drop in cm per day; A = brine activity; R^2 = 0.895 (an indicator of the reliability of the regression). Number of observations = 526.

The results of applying Equations (2) and (3) to individual 3 m pans are shown in Tables 2 and 3 respectively. The average measured level drop for each pan ranged from 93 to 105% of the average values calculated by Equation (2). When Equation (3) provided the calculated values, the average ratio of measured to calculated level drop was 96–104% of the ideal value of 1.

Figures 3–6 illustrate the typical performance of the two level-drop equations over time for two of the pans. The water pan correlation, Equation (3), indicates that the pan factor between the brine pan and the water pan is not dependent on the time of the year.

TABLE 2

Radiation–temperature equation applied to 3 m pans

Pan no.	Mg + Li as Mg (%)	Pan brine activity	Ratio measured/calculated
5023	8.73	0.37	0.99
5523	7.96	0.42	0.95
5022	7.80	0.44	0.93
5021	7.19	0.49	0.99
5522	7.13	0.49	0.99
5521	5.69	0.58	1.02
5508	4.41	0.64	1.03
5507	3.64	0.67	1.05
5506	3.12	0.69	0.96
5730	2.81	0.70	0.96

TABLE 3

Water pan equation applied to 3 m pans

Pan no.	Mg + Li as Mg (%)	Pan brine activity	Ratio measured/calculated
5023	8.72	0.37	1.01
5523	7.68	0.44	0.99
5022	7.73	0.44	0.96
5021	7.02	0.50	0.98
5522	6.85	0.51	1.00
5521	5.58	0.58	1.03
5508	4.48	0.64	1.04
5507	3.69	0.67	1.06
5506	3.17	0.69	1.03
5730	2.81	0.70	0.96

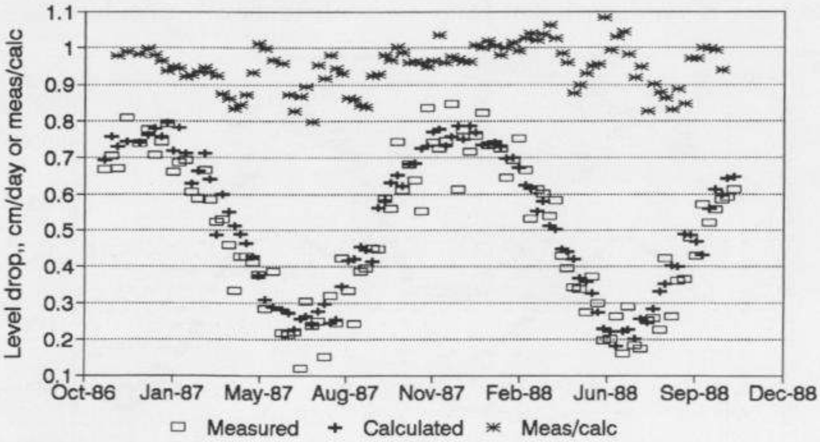

Fig. 3. Three meter pan 5506, activity 0.67 to 0.72: level drop by equation (2) and measured level drop. Measured/calculated is 5 week average.

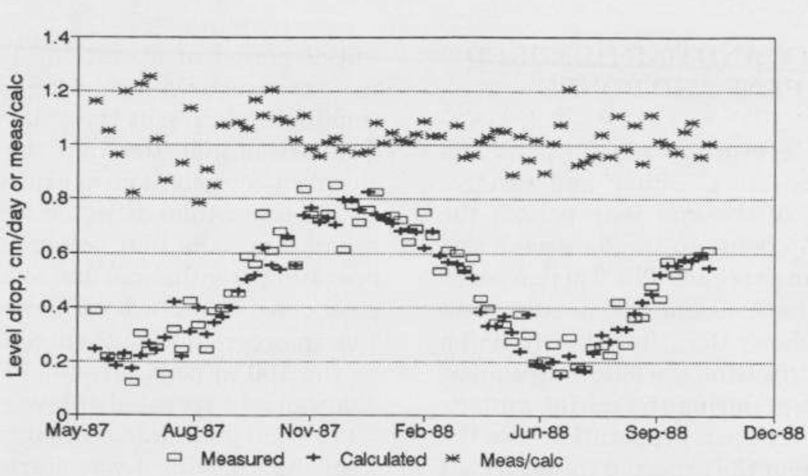

Fig. 4. Three meter pan 5506, activity 0.68 to 0.72: level drop by equation (3) and measured level drop. Meas/calc is 5 week average.

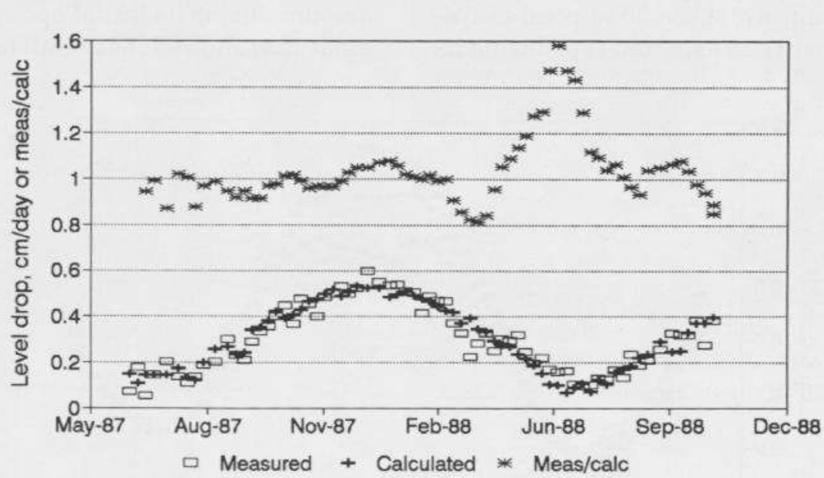

Fig. 5. Three meter pan 5523, activity 0.39 to 0.44: level drop by equation (2) and measured level drop. Meas/calc is 5 week average.

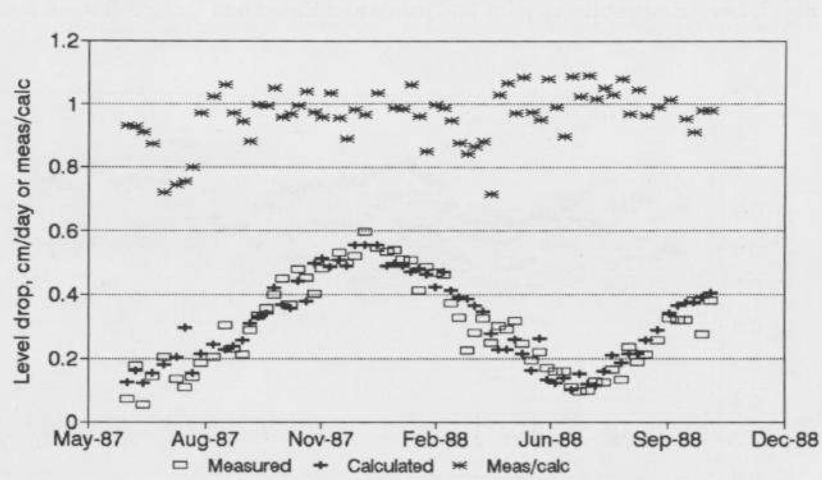

Fig. 6. Three meter pan 5523, activity 0.39 to 0.44: level drop by equation (3) and measured level drop. Meas/calc is 5 week average.

THREE, NINE, FIFTY, AND ONE HUNDRED METER SCALE-UP PANS AND PONDS

Figure 7 plots the level drops for the pans and ponds at the scale-up sites, Elmer and Omega. During the first half of the one year period, the difference in level drop between the four pans and ponds was smaller than expected. The 3 m pan continued operating after the 9, 50, and 100 m units were shut down. Figure 7 shows that the 3 m pan had a higher evaporation rate during the following winter, indicating some problem during the initial winter's operation. The higher 3 m pan evaporation rate the following winter was near the expected value for that time of year. Figure 8, which contains the relative level drop of the pans and ponds at the scale-up sites, also shows that the performance of the 9 m pan was similar to the 3 m pan, while the 50 m pond evaporated at a much higher than expected rate during its initial period of operation. Table 4 compares the ratio of measured level drop to calculated by Equation (3) level drop at the scale-up sites. The Table 4 comparison indicates that the 100 meter pond had the most consistent comparative results.

The lower than expected evaporation rate for the 3 and 9 m pans that occurred during the first few operating months was due to allowing these pans to cook down to a low level during their initial operation in order to keep their concentrations the same as the 100 m pond. These small pans had a 60 cm sidewall and operated at levels as low as 30 cm. The 50 m pond got a late start due to troubles with the liner. As a result, it was started when the evaporation rate was low, which required some time to cover the black liner with a layer of salt. In addition, it was suspected that the 50 m pond was leaking a small amount during its initial operation. Liner tests were made that showed that small leaks salt up with time.

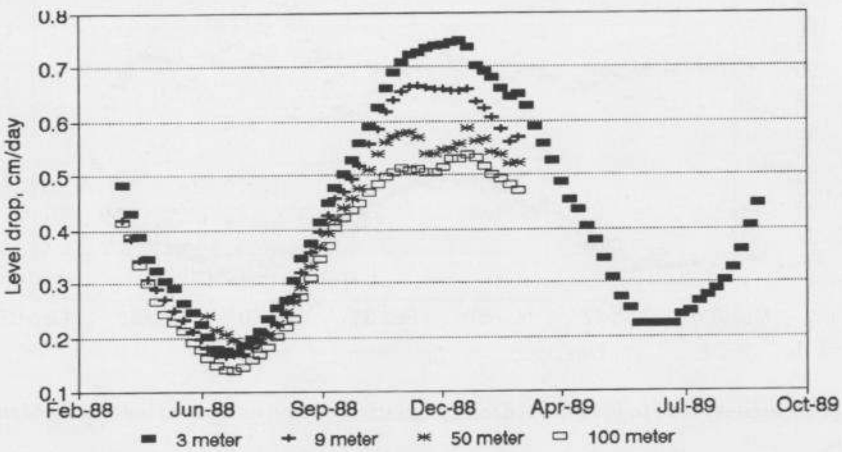

Fig. 7. Level drop: scale-up pans and ponds and Elmer and Omega: 5 week average.

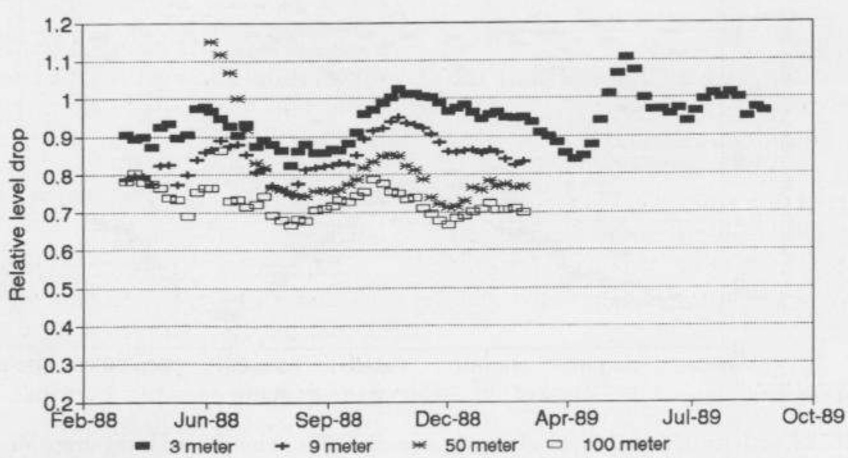

Fig. 8. Relative evaporation of the scale-up pans and ponds: measured divided by calculated per equation (3): 5 week average.

TABLE 4

Water pan equation applied to the scale-up site.

Pan size (m)	Periods of operating date	Brine activity	Water pan equation measured/calculated
3	March 15, 1988 to March 15, 1989	0.71	0.94
3	March 15, 1988 to October 1, 1988	0.72	0.89
3	October 1, 1988 to March 15, 1989	0.70	0.97
9	March 15, 1988 to March 15, 1989	0.71	0.85
9	March 15, 1988 to October 1, 1988	0.72	0.81
9	October 1, 1988 to March 15, 1989	0.70	0.88
50	May 23, 1988 to March 15, 1989	0.71	0.79
50	May 23, 1988 to October 1, 1988	0.72	0.85
50	October 1, 1988 to March 15, 1989	0.70	0.77
100	March 15, 1988 to March 15, 1989	0.71	0.72
100	March 15, 1988 to October 1, 1988	0.72	0.74
100	October 1, 1988 to March 15, 1989	0.70	0.71
The next line below covers the total steady state period of the 3 meter scale-up pan.			
3	October 1, 1988 to September 1990	0.70	0.96

Based on these results, it was decided that the total year would be used to determine the pan factor to be applied to the equations to estimate the level drop to be expected from a 100 m pond. For estimating the relative evaporation rates between the other pans and ponds at the scale-up sites Elmer and Omega, the second half of the one year period would be used. The results of these conclusions are summarized in Table 5.

GENERAL COMMENTS

The class A water pan operating at the Salar de Atacama is painted white. This deviation from the class A standard of monel or galvanized construction probably resulted in lower readings due to the white paint reflecting radiation. Therefore, if Equation (3) is applied to other locations, a 10–15% safety factor should be included.

It is estimated that Equation (2) should not be applied to locations that have markedly different weather from the Salar de Atacama. This is particularly true in other locations that have a higher humidity along with a higher ambient temperature. Absolute humidities at the Salar de Atacama average about 5 mm of mercury, while the average ambient temperature is about 15°C.

TABLE 5

Scale up pan factors

Pan size (m)	Reference	Brine activity	Pan factor pan evap/reference pan
9	Relative to the 3 m pan at Elmer	0.70	0.91
50	Relative to the 3 m pan at Elmer	0.70	0.80
100	Relative to the 3 m pan at Elmer	0.70	0.74
100	Relative to equations (2) and (3)	0.70	0.71
3	Relative to equations (2) and (3)	0.70	0.96

CONCLUSIONS

At the Salar de Atacama it is possible to predict evaporation of brine using radiation, average of the high and low ambient temperatures, and the brine activity. The brine activity acts as an efficiency factor on radiation over a broad range of activity.

Correlations developed using water pan evaporation and brine activity indicated that an equation with a second order activity term provides a method of predicting brine evaporation on a year round basis.

The effect of pond size on the evaporation rate relative to a 3 m diameter pan was 0.91 for a 9 m diameter pan, 0.80 for a 50 m pond, and 0.74 for a 100 m pan. The pan factor that should be applied to the two 3 m pan equations is 0.70 when estimating a 100 m pond level drop.

Pan factors applied to a class A water pan are essentially the same in summer or winter.