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MICROCLIMATE STUDY OF KARTCHNER CAVERNS, ARIZONA

ROBERT H. BUECHER
7050 E. Katchina Court, Tucson, Arizona 85715 USA

A detailed two-year study of the microclimate in Kartchner Caverns determined that the most significant problem in maintaining the microclimate of the cave is the potential for drying out due to increased airflow. Two factors—a small, hypothesized upper second entrance and a slight geothermal warming of the cave—control natural airflow and increase the amount and intensity of winter air exchange.

The average amount of water reaching the cave is 7.9 mm/yr, only twice the amount lost by evaporation from cave surfaces. Kartchner Caverns has an average relative humidity (RH) of 99.4%. Useful measurement of RH required a dewpoint soil psychrometer rather than a sling psychrometer. Moisture loss from cave surfaces is proportional to relative humidity, and small changes in RH have a dramatic effect on evaporation from cave surfaces. A lowering of RH to 98.7% would double the evaporation rate and start to dry out the cave.

The volume of air exchange in the cave was estimated from direct measurement, changes in CO_2 concentration, and temperature profile models. All of these methods are consistent with a volume of 4,000 m^3/day entering the cave during the winter. During the summer, the direction of airflow reverses and the volume of air leaving the cave is much smaller than during the winter months. Surface air is almost always drier than cave air—only during the summer months when rain occurs does outside air contain more moisture. However, the rate of air exchange is greatly reduced during the summer, which minimizes any potential effect of increased outside moisture.

Radon concentrations in the cave are high enough to be of concern for long-time employees but not for the general public. Radon^{222} concentrations average 90 pCi/L and radon daughters average 0.77 Working Levels (WL) in the main part of the cave. During the winter, radon levels in the Echo Passage are up to six times higher than the rest of the cave due to the passage's stable microclimate and limited air movement, which greatly reduces radon removal by plateout. Natural removal by ventilation is only a minor factor in determining radon levels in the rest of the cave.

Arizona Conservation Projects, Inc. (ACPI) performed comprehensive pre-development baseline studies of Kartchner Caverns from 1989 to 1992 for the Arizona State Parks Department (Buecher 1992). This paper presents results from the microclimate portion of those studies organized into two sections: (1) general surface weather conditions at the park; and (2) microclimate within Kartchner Caverns. The cave microclimate study was designed to provide data necessary for determining the nature and magnitude of microclimate changes that may result from the development of the cave.

Maintaining the existing moisture conditions is the most important consideration in development of the cave because the small, historic entrance allows relatively little air exchange with the surface. However, development of the cave for public viewing will greatly increase evaporation due to multiple entrances, induced airflow, and increased heat from visitors and lights. Drying of the cave can result in permanent damage to many of the features that make Kartchner Caverns so attractive. This has been observed in many other show caves, but in Kartchner, the arid Arizona climate aggravates the problem.

SURFACE CLIMATE

Surface climate monitoring provided a record of external variations that frequently drive microenvironmental changes within the cave. The Ozark Underground Laboratory (OUL) initiated the surface climate monitoring program at Kartchner Caverns. ACPI performed instrument installation, maintenance, and additional measurements. The analysis and interpretation of the collected climatological data was also performed by ACPI.

A surface weather station, including a thermograph, hygrograph and microbarograph, was placed in a standard instrument shelter on the south side of Guidani Wash, ~165 m southeast of the natural entrance. A recording rain gauge was also installed near the weather station. Surface climate data was collected continuously from June 1989 to June 1991. The mean surface temperature measured over this 24-month study period was 16.9°C (62.4°F). For the year-long period from June 1989 through May 1990 a total of 288 mm (11.34 in) of precipitation was recorded. In the second year of the study from June 1990 through May 1991, a total of 607 mm (23.90 in) of precipitation was measured.

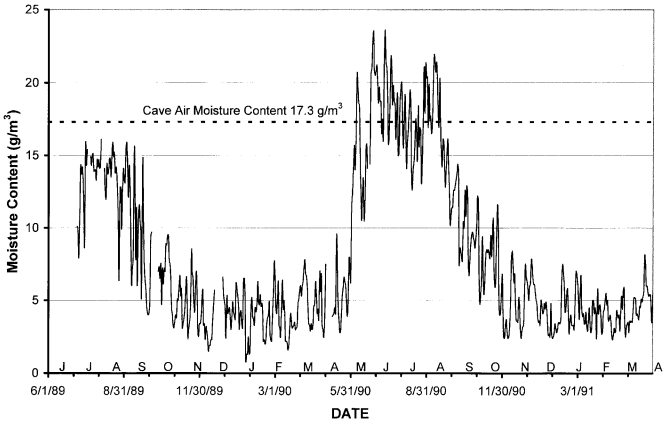

Figure 1. Average daily surface air moisture content of outside air is almost always less than the moisture content of air inside the cave.

From this climatological information, the moisture content of the air was computed for each day. The difference in moisture content between surface air and cave air is a measure of the potential airflow drying the cave. Figure 1 is a plot of the surface daily average air moisture content determined from the relative humidity (RH) and temperature. During the 24-month study period, the mean daily moisture content of the surface air was less than cave air for all but 3 months in the summer of 1990.

In order to ensure that the data collected over 24 months at the park was truly representative, a comparison was made with long-term records for two nearby surface weather stations at approximately the same elevation-Tombstone and Sierra Vista (Sellers & Hill 1974). Based on the long-term mean temperatures from Tombstone 17.3°C (63.2°F) and Sierra Vista 16.6°C (61.9°F), the average annual temperature at the park is estimated at 17.1°C, which agrees well with the measured mean temperature of 16.9°C (62.4°F).

The precipitation record for the park during this period also was compared with the Tombstone (352 mm/yr) and Sierra Vista (391 mm/yr) records to determine the probable long-term average precipitation. From the Tombstone and Sierra Vista records the average precipitation at the park was calculated at 419 mm/yr. This compares well with the park average of 448 mm/yr (17.62 in/yr) for the 24 months of study.

CAVE MICROCLIMATE STUDY

Microclimate studies at Kartchner Caverns measured:

1. Moisture balance of the cave, water reaching the cave, evaporation from cave surfaces, and RH distribution;
2. Air and soil temperature annual variations and distribution throughout the cave;
3. Rate of air exchange between the cave and surface;
4. Concentrations of the trace gases carbon dioxide (CO_2) and radon^{222}.

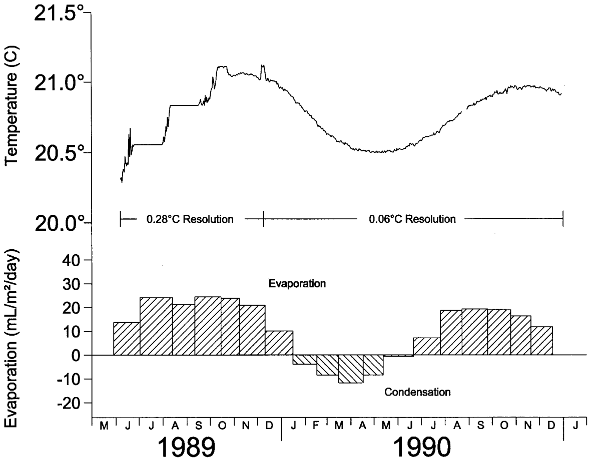

Figure 2. Typical data collected at monitoring station #13 in the Big Room. Shaded areas represent evaporation or condensation rates. Temperatures are daily averages of hourly measurements.

Twenty-two environmental monitoring stations were installed throughout the cave. Locations were chosen to represent general conditions and also areas of particular interest, such as near the entrance or in areas where a cave passage is near the surface.

Each station was equipped with the following apparatus: a 23 cm (9 in) diameter water evaporation pan with overhead drip shield, a PVC pipe stand to hold thermometers, an air temperature sensor, and a soil temperature sensor. In the front portion of the cave, each monitoring station was cabled to a computer datalogger system that recorded wet bulb, dry bulb, and soil temperatures each hour. In the back portions of the cave, temperatures were measured with a digital thermometer that stored both high and low temperatures.

Each station was visited approximately once a month and additional air, soil and water temperatures were taken with a portable thermometer to verify in-cave instruments. Also, pan evaporation, relative humidity, alpha radiation, and carbon dioxide measurements were taken at the same time. Table 1 summarizes these measurements, and Figure 2 shows typical air temperature measurements made with the datalogging system and evaporation pan.

CAVE MOISTURE

Kartchner Caverns is a moist cave, pools of water remain only during an unusually wet year. Thus, the supply of moisture to the cave is just barely adequate to maintain the moisture balance. The amount of water reaching the cave from the surface was estimated by monitoring the drip rate at eight locations throughout the cave. For each drip station the rate of dripping, volume of dripping water, and water conductivity was measured. The average volume of a single drip was found to be 0.08 mL.

Table 1. Environmental Monitoring Station Data Summary.

#	Station	Evaporation mL/m²/day	RH	Temperature (°C) Water	Air	Soil
1	Crow's Nest Rock	6.0±3.9	99.07%±0.76	18.6±0.24	18.7±0.22	18.8±0.27
2	Pirate's Den	7.1±5.0	99.19%±0.71	18.5±0.09	18.7±0.13	18.6±0.17
3	Sue's Room	2.1±0.8	99.38%±0.57	20.1±0.11	20.2±0.14	20.2±0.18
4	Mushroom Passage	16.8±7.3	99.38%±0.64	19.3±0.14	19.6±0.23	19.6±0.32
5	Granite Dells	4.5±3.1	99.28%±0.51	18.7±0.18	18.9±0.26	18.8±0.36
6	Pyramid Room	5.8±2.1	99.27%±0.80	19.4±0.29	19.6±0.27	19.5±0.21
7	Cul-de-sac	2.1±1.6	99.52%±0.45	20.6±0.07	20.7±0.12	20.7±0.17
8	Rotunda Room	5.8±2.1	99.48%±0.52	19.8±0.10	19.8±0.13	19.9±0.18
9	Echo Passage (end)	1.8±1.0	99.30%±0.56	20.4±0.07	20.6±0.12	20.5±0.07
10	Echo Passage (start)	3.1±2.9	99.38%±0.52	20.4±0.15	20.6±0.15	20.5±0.17
11	Tarantula Room	27.2±20.9	98.43%±0.91	20.4±0.38	20.7±0.36	20.7±0.35
12	Mud Flats	9.4±9.9	99.15%±0.58	20.2±0.22	20.2±0.27	20.3±0.19
13	Sharon's Saddle	6.8±13.9	99.30%±0.68	20.4±0.29	20.6±0.27	20.5±0.28
14	Main Corridor	17.8±19.9	98.80%±1.67	19.9±0.29	19.9±0.32	19.9±0.31
15	Scorpion Passages	15.2±13.4	98.80%±1.18	18.8±0.24	18.9±0.24	19.0±0.21
16	Grand Central Station	47.4±43.2	97.00%±3.80	18.6±0.48	18.8±0.36	18.7±0.45
17	Lower Throne Room	8.9±1.8	99.40%±0.51	19.6±0.12	19.7±0.12	19.7±0.13
18	Throne Room Overlook	2.4±1.0	99.55%±0.40	19.7±0.08	19.8±0.13	19.9±0.16
19	Lover's Leap	1.3±5.5	99.50%±0.50	20.2±0.15	20.4±0.22	20.3±0.20
20	Mud Trench	3.7±1.6	99.33%±0.69	19.4±0.14	19.6±0.17	19.5±0.12
21	Big Room Overlook	4.7±2.9	99.39%±0.69	20.7±0.16	20.9±0.21	20.9±0.23
22	Kartchner Towers	9.2±3.4	99.30%±0.67	20.5±0.22	20.6±0.25	20.6±0.24
	AVERAGE	9.50	99.15%	19.74	19.88	19.86

Environmental Station Data From June 1989 to May 1991
Stations 1, 2, 3, 4, 6 & 20 From June 1989 to August 1990

A lower limit on the amount of moisture reaching the cave was determined by surveying the whole cave for active drips. In each room we listened and counted the number of drips in a fixed length of time. This single "whole cave" drip rate was then adjusted to the average annual drip rate by using the 8 monitored drips as an index of conditions at the time of the "whole cave" survey. Using the average drip volume, an overall influx of drip water was determined to be equivalent to an accumulated depth of 4.3 mm/yr.

Another estimate of drip water was made by placing 23 cm (9 in) diameter pans in random locations and measuring the amount of water collected. This volume was corrected for evaporation loss and then converted to an annual average by again using the 8 monitored drips as an index. This method resulted in a slightly higher estimate of 6.9 mm/yr of drip water reaching the cave.

An upper limit on the amount of water reaching the cave was estimated by determining the evaporation rate in areas of the cave that dry out during the winter. A series of evaporation pans placed in the entrance passages shows that cave surfaces completely dry out at evaporation rates of 12.4 mm/yr, which means that moisture must be supplied at a rate less than 12.4 mm/yr (0.49 in/yr).

From these three approaches the amount of water reaching the cave in the form of dripwater was estimated to be 4.3 mm/yr, 6.9 mm/yr and 12.4 mm/yr. The average, 7.9 mm/yr is used as a reasonable estimate for the average amount of water entering the cave in the form of drips. Thus, of the 448 mm of annual precipitation, less than 2% reaches the cave.

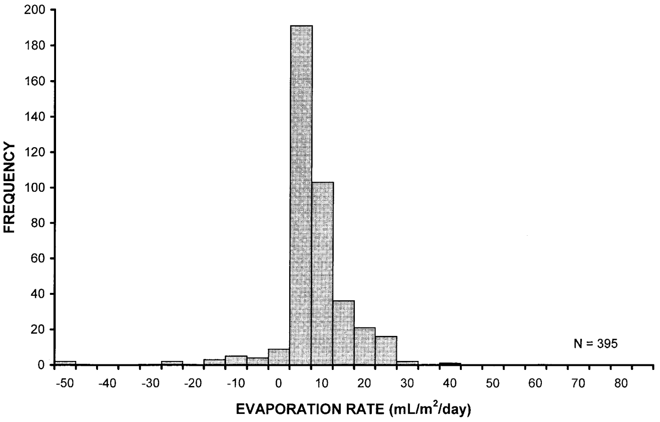

Figure 3. Distribution of monthly pan evaporation rates.

EVAPORATION

Evaporation rates at floor level were measured at each of the 22 environmental monitoring stations on a monthly basis and at several other locations close to the natural entrance. At each station, a 23 cm (9 in) diameter aluminum pan (surface area 382 cm²) was filled with exactly 750 mL of distilled water by using volumetric flasks. The volume of water necessary to restore the 750 mL volume was carefully measured each month and the evaporation rate in mm/day was determined from the volume lost divided by the pan area and number of days between measurements. Using these methods, evaporation rates could be determined with an accuracy of ±1 mL/m²/day. The distribution of these measurements is shown in Figure 3. Average evaporation in the cave is 9.4 mL/m²/day. Values less than zero represent a gain in the volume of water in the pan due to condensation onto the water surface. Evaporation measurements indicated that most areas have evaporation rates near zero. Figure 2 shows that rates of evaporation and condensation at this location follow the shape of the air temperature curve. As air temperature falls, moisture in the air condenses onto cooler surfaces. As air temperatures rise, evaporation increases.

RELATIVE HUMIDITY

Relative humidity is defined as the percentage of moisture contained in the air compared to the maximum amount of moisture that the air can hold at a given temperature. Most caves have high relative humidity, often approaching 100%. At 100% relative humidity, the air contains the maximum amount of moisture it can hold at that temperature and is said to be saturated. The amount of moisture contained in a volume of air can be computed from the relative humidity and temperature (Zimmerman & Lavine 1964).

A relative humidty (RH) decrease of a few percent will have a major impact on moisture conditions within the cave as the rate of evaporation is largely determined by the relative humidity. Higher humidity results in lower evaporation. For example, if the relative humidity changes from 99.5% to 99.0%, the evaporation rate will double.

Initially RH measurements in Kartchner Caverns were per-

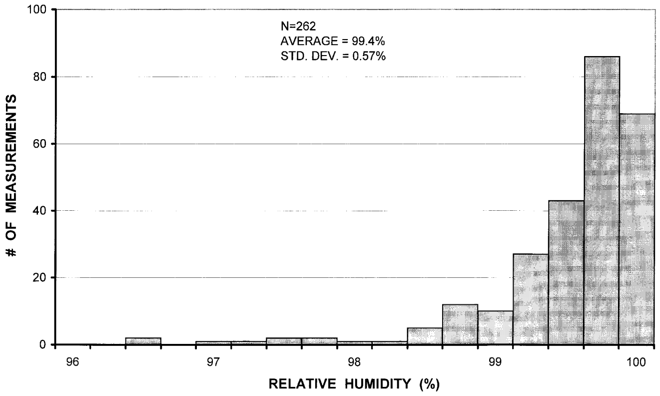

Figure 4. Distribution of precise relative humidity measurements.

formed with hand-held sling psychrometers. These instruments have a maximum accuracy from ±0.7% to ±2.5% at high humidity levels. Experience showed that this method is not accurate enough to assess moisture conditions and flux within the cave. Sling psychrometers almost invariably measure the RH at 100% even in areas where there are obvious changes in moisture conditions. Therefore, a switch was made to a dewpoint microvoltmeter to precisely measure RH. This instrument, typically used for measuring soil moisture content, is capable of measuring the relative humidity and dewpoint temperature with a accuracy of ±0.05% RH. Throughout the cave, 318 measurements were taken with the dewpoint meter. RH varied from 96.32% to 100.00%, averaging 99.42% (Fig. 4). The distribution is highly skewed toward relative humidities approaching 100%.

High RH also means that only a very small drop in air temperature is needed to condense water out of the air. For the majority of conditions observed within the cave, a temperature drop of <0.1°C will bring the air to saturation, and any additional cooling of the air will cause condensation to occur. A rise in air temperature has the opposite effect, lowering the RH and increasing the evaporation rate.

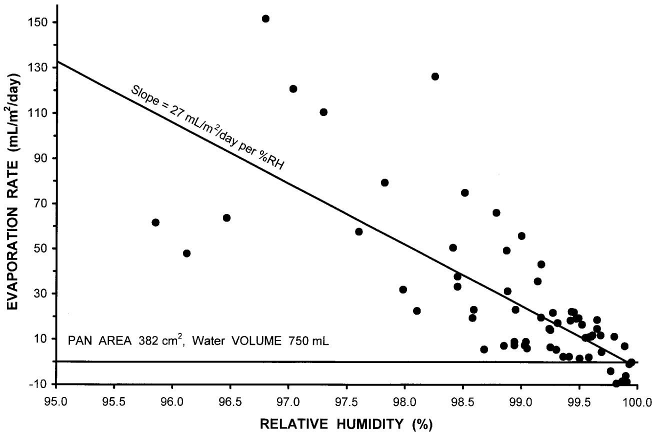

Figure 5. Pan evaporation rates versus average precise relative humidity.

A significant amount of moisture can be lost from a cave by evaporation and air exchange with the surface (McLean 1971; 1976). Due to the arid Arizona climate, the outside air almost always contains less moisture than the cave air. As a consequence, exchange of outside air for cave air will usually result in drying out the cave.

The greatest numbers of precise relative humidity measurements were taken at five monitoring stations in the Big Room. Evaporation decreases with increasing RH, although there is considerable scatter (Fig. 5). A straight-line fit of the data has a slope of 27 mL/m²/day of evaporation for each 1% RH change below 100%. As mentioned previously, cave surfaces become dry at an evaporation rate of >12.4 mm/yr. Using the above relationship, this evaporation rate corresponds to a RH of 98.7%. Thus, an apparently small change from 99.4% RH to 98.7% would allow the cave to dry out.

EVAPORATION FROM CAVE SURFACES

The total amount of evaporation from all surfaces within the cave can be estimated based on the measured values from the environmental stations. The surface area and volume of the cave was determined from the survey data and passage cross sections. Total evaporation estimates were made for the two regimes: (1) the cave entrance area where evaporation rates are high; and (2) remote areas where evaporation rates are much lower.

The entrance area includes the entrance passages, Grand Central Station, Main Corridor, Mud Flats, and the Tarantula Room (Fig. 6). The floor area of these passages totals 3,710 m². The annual average evaporation rate in this area is 23 mL/m²/day which is equivalent to 8.4 L/m²/yr. The floor of remote areas of the cave is 25,100 m². The evaporation in this

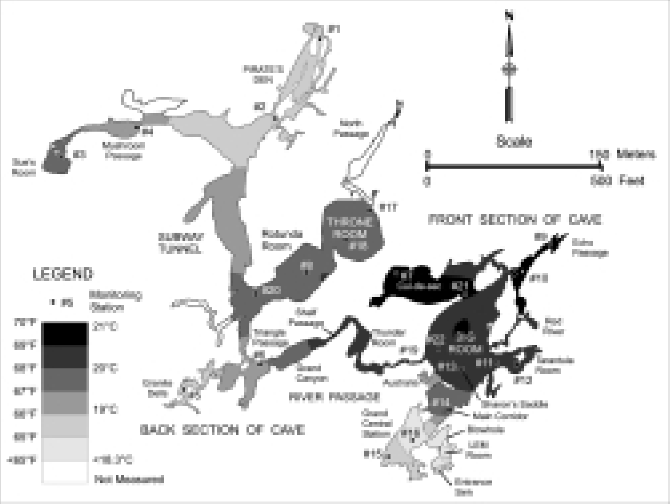

Figure 6. Map of the distribution of soil temperatures in Kartchner Caverns.

area is estimated at 5.8 mL/m^2/day, equivalent to 2.1 L/m^2/yr.

The area of effective evaporation is assumed to be twice the area of the floor to account for the irregular nature of the floor and walls. Evaporation from the ceiling is assumed to be zero as moisture enters at the ceiling and RH is higher in the less dense air. Potential total evaporation is calculated as follows:

entrance areas	8.4 L/m^2/yr · 3,710 m^2 · 2 = 62,300 L/yr
deep cave	2.1 L/m^2/yr · 25,100 m^2 · 2 = 105,000 L/yr

While the above estimation for the entrance area is potentially 62,300 L/yr, evaporation cannot exceed the available moisture supply. Since the amount of moisture reaching the cave has been estimated to be 7.9 mm/yr, over the area of the entrance passages (3,710 m^2), this amounts to 29,300 L of available water. Thus, evaporation in the entrance passages will be limited by the available moisture supply to 29,300 L/yr. Total evaporation from the entire cave based on measured evaporation rates and available moisture supply is estimated as 135,000 L/yr. The total average amount of water which reaches the cave is 7.9 mm/yr or a total of 230,000 L/yr. Thus, in an average year the cave receives less than twice as much moisture as it can lose by evaporation. Therefore, a succession of several dry years would begin to dry the cave out.

These calculations were made to illustrate how a small opening, such as the natural entrance, can dramatically increase evaporation in a large portion of the cave. Creation of another opening of similar size, such as an artificial entrance, would cause enough additional evaporation to use up the available moisture supply unless evaporation control measures are implemented.

CAVE TEMPERATURE

The temperature of a large cave is generally considered the same as the mean local surface temperature at the cave's elevation (Moore & Sullivan 1978). A comparison of measurements made in 54 Arizona caves (Buecher 1977) indicates that the temperature of a cave at Kartchner's elevation (1420 m) should be about 15.4°C

Kartchner Caverns does not have a constant temperature but varies from 20.9°C (69.7°F) to 18.6°C (65.5°F) throughout the cave. Temperatures at all locations inside the cave are always 1.7°C (3.0°F) to 4.0°C (7.2°F) higher than the mean surface temperature (Fig. 7). The mean temperature of the whole cave is 19.8°C as compared with 16.9°C for outside the cave. Why these differences in mean cave and surface temperatures?

The most likely reason is geothermal heating. The 1982 Geothermal Resources Map of Arizona (Witcher *et al.* 1982) indicates that the San Pedro Valley east of the cave is an area of geothermal water. Near Tombstone, heat flow from the earth ranges from 74 to 85 mW/m^2, equivalent to a thermal gradient that would increase the cave temperature by 2.8°C at a depth of 30 m.

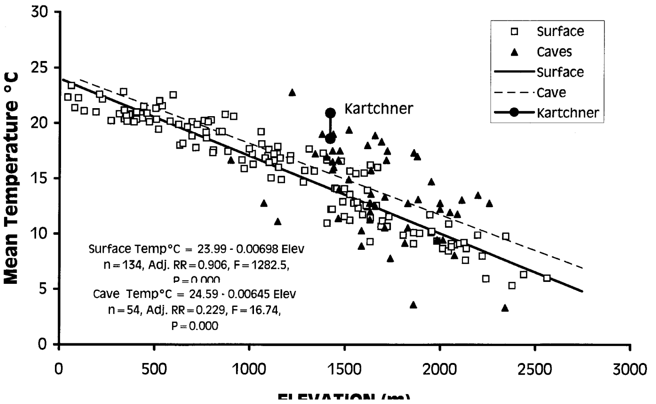

Figure 7. Arizona cave and surface station temperatures versus elevation.

A temperature profile log of a nearby water well (Graf 1999) provides further evidence that geothermal heating causes the elevated temperature in Kartchner Caverns. In measurements conducted in July and November 1991, temperature asymptotically approached 19.6°C just above the water level, ~15 m below the surface. Figure 8 shows the measured temperature profiles and the mean surface temperature of the Kartchner well (Cropley 1965; Lee 1965; Whitaker 1977). The maximum well temperature of 19.6°C is 2.7°C (4.9°F) warmer than the mean surface temperature. This well temperature at 15 m depth is exactly the mean temperature of Kartchner Caverns, 19.6°C. Other wells on the park also show slightly elevated water temperatures (Graf 1999, Table 1).

While geothermal heating explains why the cave is warmer than expected, it does not explain the variations in temperature in different sections of the cave. The warmest part of the cave is the Big Room at 20.9°C. The coldest parts of the cave are in the Back Section (18.6°C) and in the entrance passages (averaging ~17.8°C). Temperatures in the entrance passages

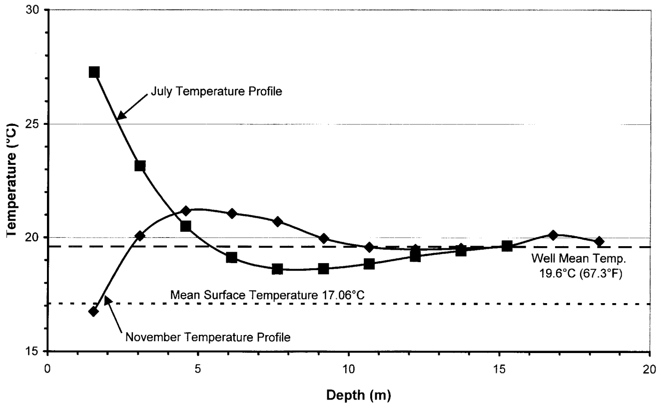

Figure 8. Temperature profiles of the Kartchner well in June and November converge to a stable temperature of 19.6°C, 2.6°C above the mean surface temperature, at a depth of 15 m.

are almost the same as the mean surface temperature due to air exchange. Why the other two areas of the cave have such different temperatures is more problematic. Flooding of the cave during the winter months provides the most likely reason for the cold temperatures in the Back Section. Although flooding does not occur every year, when it does flood, there is apparently insufficient time for the Back Section to completely return to the ambient temperature. The pattern of depressed soil temperatures appears to match the flooded area.

Warmer temperatures in the Big Room may result from air stratification. Cool dry surface air entering the cave remains near the Big Room floor while warmer air rises towards the ceiling. A thin layer of condensation fog forms at the interface between these two masses of air. This fog is frequently seen along the Main Corridor during the winter months. Condensation releases heat which warms the overlying air mass (the upper areas of the Big Room), and condensation droplets fall into the cooler, drier air near the floor. The droplets evaporate, further cooling the incoming air while raising the relative humidity of that air. Condensation-corrosion weathering and the popcorn "line" on the walls leading into the Big Room is evidence of this stratification effect.

ENTRANCE PASSAGE TEMPERATURE AND HUMIDITY

The existing natural entrance to Kartchner Caverns is the only known connection to the surface. Early observations indicated that the natural entrance has a profound influence on conditions throughout the cave, prompting an intensive program of data collection. Seven dry and wet bulb temperature probe stations were connected to a computer data logging system. Temperatures were recorded each hour from March 1989 to June 1990. Relative humidity was calculated from the difference between the unventilated dry and wet bulb temperatures. Figure 9 shows the temperature measurements and calculated RH in the LEM Room, which is located 25 m from the entrance.

It is clear from these plots that temperature and RH follow an annual cycle. The temperatures at even this short distance into the cave do not mimic those on the surface but rather have a sawtooth shape. The peak temperature in the LEM Room occurs during late September and early October, indicating a lag of 3 months behind the surface. The lowest temperatures are in December, January and February and occur at approximately the same time as low temperatures on the surface. The annual cycle is markedly asymmetric. Temperatures rise from March to September (7 months) and fall from October to January (4 months). The rise in air temperature is much slower than the decline.

The annual cycles of RH in the LEM Room reveal a pattern where RH is highest from mid-June to mid-September when it is typically at or near 100%. During this time RH stays remarkably constant. The remaining months of the year show numerous short periods of RH fluctuations as dry, high-pressure weather systems move through the region. The lowest relative humidity occurs during December, January and February. The lowest RH was recorded between 10-16 December 1989 and this very low RH allowed nitrocalcite cotton to form in the entrance passages (Hill 1999).

The annual patterns of temperature and relative humidity can be explained partially by the predominant direction of airflow observed in the entrance passages. During the winter months, cold dry air flows into the cave. This quickly lowers the temperature in the entrance passages. Large fluctuations occur because storms and short-term surface weather changes cause reversals in airflow direction. During the summer, from mid-June to mid-September, the airflow reverses and warm, moist air blows out of the natural entrance. Because the deep-interior cave temperature is at a near-constant temperature, air from the interior maintains this uniform temperature in the entrance when air is blowing out of the cave. Likewise, the high RH results from air moving from the interior of the cave. Slight cooling of this air in the entrance passages further raises the RH. The uniform rate of temperature rise and steady flow of air out of the natural entrance during the summer months maintains a constant high relative humidity. In summary, the entrance passages operate under two distinctly different seasonal modes.

SOIL TEMPERATURE

Soil temperatures taken on a monthly basis at each of the monitoring stations were identical to the air temperature (Table 1). In order to determine how temperature varies between the stations, a comprehensive survey of soil temperatures throughout Kartchner Caverns was conducted during April 1990. Temperatures were measured approximately every 15 m to 30 m along the trails throughout the cave to provide detailed information between monitoring stations. The results of the survey (Fig. 9) show a surprisingly large variation in soil temperature throughout the cave.

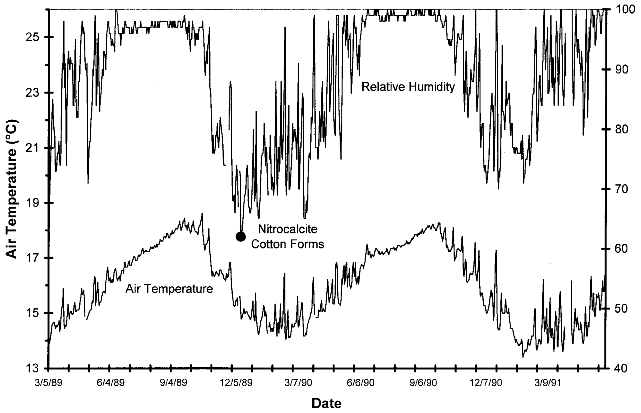

Figure 9. Average daily temperature and relative humidity in the LEM Room, ~25 m from the cave entrance. Temperatures show a sawtooth pattern that peaks in October. RH has a flat plateau near 100% during the summer months.

The purpose of the survey was to: (1) determine the temperatures of those areas poorly represented by the environmental monitoring stations; and (2) identify areas of anomalous temperature. Areas of unusually high or low temperatures can be indicative of outside air entering or leaving the cave. The average of 119 individual soil temperature measurements was 19.3°C. The areas near the natural entrance are unusually cool and bias this average. A better representation of the true interior temperature of the cave obtained by averaging all areas of the cave exclusive of the entrance passages is 19.6°C.

Wigley and Brown (1971) developed a mathematical model of temperature and RH profiles at cave entrances. An important aspect of this model is the use of the relaxation length, X_0, to describe these profiles.

Relaxation length (m) = $X_0 = 100r^{1.2} V^{0.2}$
where r = passage radius in meters and V = air velocity in m/min.

The relaxation length is a measure of the rate of exponential damping of temperature differences as one proceeds deeper into conduit, in this case a cave. Temperatures should remain constant year-round a distance of 4 to 5 times the relaxation length. The model predicts the relaxation length under assumptions of uniform air velocity and passage geometry where passages are considered to be essentially circular pipes with moist walls. Air entering the passage gradually comes to thermal equilibrium with the walls through conduction, and gain or lose of water by evaporation or condensation.

Based on known entrance passage geometry and measured airflow rates in Kartchner Caverns, the anticipated relaxation length was calculated using an airflow of 10 m/min and passage areas of 0.30 m² and 1.0 m². Calculated relaxation lengths are 39 m and 80 m, respectively. Based on the soil temperatures measured in April 1990, a relaxation length of 44 m provided the best fit to the measured temperatures (Fig. 10). The profile of soil temperatures in the entrance passages shows an exponential decay, and the observed relaxation length is in good agreement with that predicted by the Wigley-Brown model. The best fit to the measured profile is a small average passage cross-section and daily air volume of 4,300 m³.

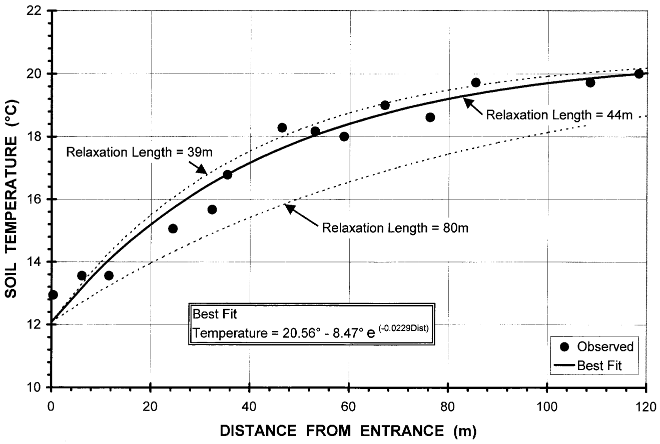

Figure 10. Profile of soil temperatures near the natural entrance in April 1990. An exponential curve fit to the temperatures has a relaxation length of 44 m.

The soil temperature survey shows that the natural entrance has the largest horizontal temperature gradient of any area in the cave. The effect of the natural entrance on soil temperatures extends for at least 120 m from the entrance (Fig. 10). Approximately 100 m from the entrance, a temperature gradient of 0.018°C/m exists. Examining the soil temperature map for large horizontal temperature gradients should identify areas of the cave that are near even a small entrance. Other than the entrance passages, only the Pyramid Room/Granite Dells area have temperature gradients in excess of 0.018°C/m. The steep gradient in this area is more likely the result of cooling by floodwater than from entrance airflow. The lack of high soil temperature gradients in other areas of the cave indicates that it is unlikely there are additional entrances that draw appreciable outside air into the cave. However, there may be other small openings where air is being expelled from Kartchner Caverns.

CAVE AIRFLOW

Air exchange to the surface causes moisture loss from the cave. Controlling the air exchange rate is one of the most important concerns in commercial cave development. Airflow is also strongly related to other processes within the cave, such as the concentration of carbon dioxide and radon gas. Management of these gases may contradict the most effective means of controlling cave moisture. Increasing air exchange rates would lower gas concentrations but also would increase evaporation, drying of the cave, and potentially damage the beauty of the cave. A knowledge of how these three parameters- evaporation rate, carbon dioxide concentration, and radon concentration- relate to airflow facilitates predicting the likely effect of development.

The most reliable method for determining the rate of air exchange is by directly measuring the quantity of air entering and leaving the cave. Unfortunately, the entrance passages are in a breakdown complex with many small (inaccessible) openings, so that air follows many different paths. Furthermore bats entering and leaving the cave during the summer use these passages, restricting the time for winter measurements. Thus, no single passage in the front part of the cave seems appropriate. Airflow measurements at a few locations can only give us a lower limit on the rate of air exchange.

The equipment used to measure airflow consisted of a sensitive hotwire anemometer, airflow direction indicator, wet and dry bulb temperature sensors, and an atmospheric pressure sensor, all connected to a datalogger. One-minute averages of each parameter downloaded to a computer. Airflow was measured at the interior end of the Blowhole crawlway and at the entrance to the River Passage. Airflow was measured 22 times, yielding a total of 22.7 days worth of data.

Selected data from the Blowhole provided an understanding of airflow near the entrance of Kartchner. Measurements taken during the winter of 1989 and 1990 were selected because they represent a nearly continuous record of airflow over several days (Table 2). The Blowhole area at the measurements station has a cross-sectional area of 0.47 m². Using the average of the measurements in Table 2, the volume of air that entered the cave averaged 4,000 m³/day during the coldest part of the winter. But the Blowhole is not the only known route for airflow. Air also enters through the Babbitt Hole and other small openings in the LEM and Crinoid Rooms. Based on the cross-sectional area of these other openings, the roughly estimated total airflow is about three times that entering through the Blowhole, or 12,000 m³/day.

Table 2. Airflow Measurements at Blowhole.

Start Date	Sample Duration	Air Movement*	Airflow Rate/Day
12/23/89	0.44 days	3,288 m (IN)	7,470 m/day
12/27/89	0.26 days	2,069 m (IN)	7,956 m/day
12/29/89	0.35 days	3,383 m (IN)	9,666 m/day
12/31/89	0.18 days	3,453 m (IN)	19,185 m/day
01/12/90	1.74 days	14,552 m (IN)	8,363 m/day
01/14/90	1.39 days	9,261 m (IN)	6,662 m/day
01/16/90	1.71 days	15,612 m (IN)	9,130 m/day
TOTALS	6.07 days	51,616 m (IN)	8,503 m/day

A minor amount of air moved out of the cave during these measurements. The total airflow out was 1,788 m or 3.4% of the inflow.

The most surprising finding of the airflow measurements is that during the winter months, the direction of airflow is overwhelmingly (97%) into the cave. Direct observations of airflow direction confirm that air is moving almost exclusively into the cave at the Blowhole during the winter. The simplest explanation for this airflow pattern is that the cave functions as a "chimney". During the winter, colder, denser air enters at the natural entrance, becomes warmer, and rises out of openings at a higher elevation. The naturally induced airflow into the lowest entrance is strongest in the winter, weakening and reversing direction during the summer. The airflow measurements provide strong evidence that other small entrances to the cave exist at elevations higher than the natural entrance. No higher, second opening has been found, but the inferred opening must be smaller than the natural entrance to create the observed pattern of air movement. Such an opening may be comprised of several smaller openings or be covered by loose soil.

CAVE AIRFLOW PATTERNS

The pattern of airflow through the cave was mostly deduced by two methods. Airflow direction can be felt in constricted passages if there is sufficient air movement (Fig. 11). An indirect method is to observe the growth patterns of certain cave deposits (speleothems) known as "popcorn". The growth,

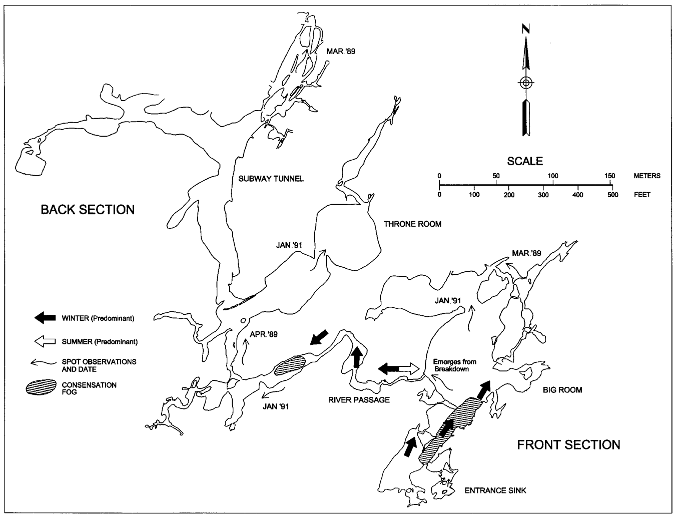

Figure 11. Observed airflow direction in Kartchner Caverns.

orientation, and type of popcorn are influenced by long term patterns of airflow (Fig.12). Using these methods, the following pattern of winter airflow is hypothesized.

The natural entrance is the only (known) point where air enters the cave. In the Anticipation Room, air entering the cave divides, part going into Main Corridor and the remainder going to Grand Central Station (Fig. 11). Outside air that enters the cave is cooler, drier and denser than the cave air so it flows along the floor. This displaces the warmer, more humid air in the Big Room and results in the stratification of air with the warm, moist cave air forming a layer starting about 1 m above the floor. The air that enters Grand Central Station flows under the breakdown of the Big Room and exits at the start of the River Passage. During the winter, a steady breeze

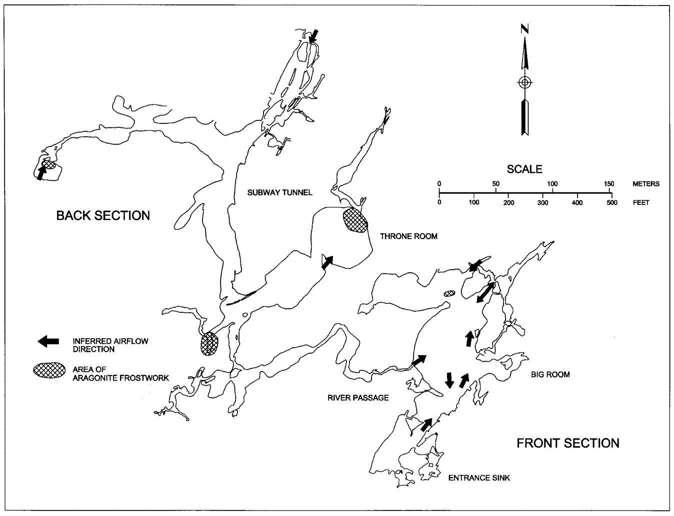

Figure 12. Airflow pattern deduced from the orientation of popcorn speleothems.

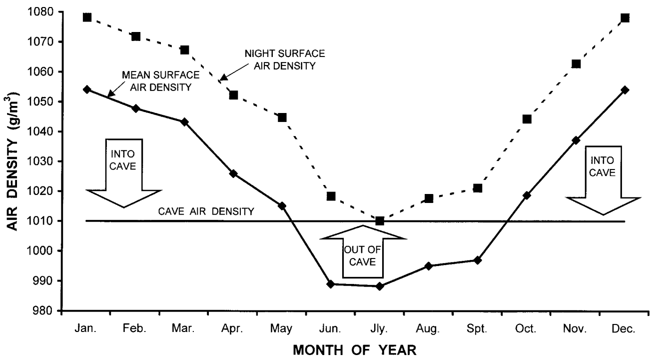

Figure 13. Direction of airflow estimated from mean monthly surface air density.

can be followed along the River Passage to the Grand Canyon Passage. A continuation of this airflow is seldom noticeable in the crawlway at the west end of Grand Canyon. Condensation fog is also frequently visible in the Grand Canyon. The bedrock in the Grand Canyon passage is quite fractured. It is not difficult to envision small cracks and fissures continuing to the surface. In the summer, the airflow pattern appears to stagnate or perhaps weakly reverse. Moist air frequently flows out of the natural entrance but this pattern is not as strong or consistent as the dry air that enters in the winter. Infrequently, airflow has been felt in the Triangle Passage crawl blowing into the cave toward the Subway Passage. Airflow has also been observed entering the Throne Room from the Rotunda Room. The observed popcorn growth is consistent with this airflow pattern (Fig. 12), as popcorn grows into the direction of dry, cool air movement (Hill & Forti 1997).

The annual pattern of air exchange can be quantitatively understood by comparing the density of surface air and cave air (Fig. 13). During winter months, surface air is colder and denser than cave air and therefore flows into the cave. During the summer, the surface air is warmer and less dense than air in the cave and so air would tend to flow out the natural entrance. Two other effects complicate this simple relationship. First, as discussed previously, the cave is several degrees warmer than the average surface temperature. As a result the density difference driving winter air exchange is twice as great as it is during the summer. The geothermal warming also lowers the air density in the cave causing the summer airflow out of the cave to last for only 4 months. This asymmetric pattern of airflow creates the second effect. Air will move along a gradient of decreasing air density, as shown in the winter profile of Figure 14. But because a greater volume of air enters the cave during the winter, the entrance passages become quite chilled. In the summer, air moving out of the cave is cooled as it approaches the entrance. This creates a pocket of cool dense air that partially blocks the summer airflow out of the natural entrance.

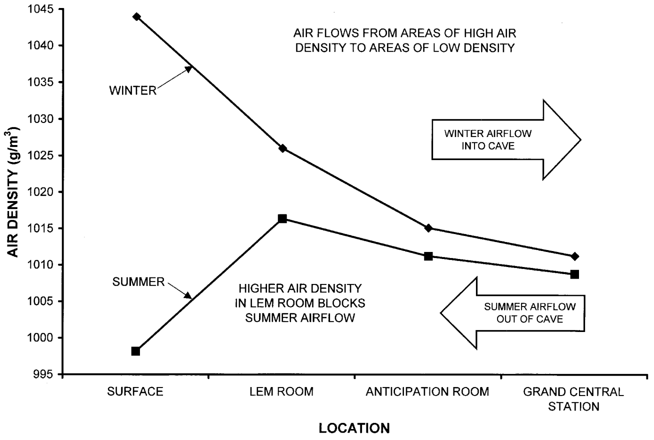

Figure 14. Winter and summer air density profile of entrance passages. In the summer, air in the LEM Room has greater density than air at the surface or deeper in the cave, thus restricting airflow.

CARBON DIOXIDE

Measurement of carbon dioxide concentrations consisted initially of collecting "grab" samples in a number of locations throughout the cave. Then, beginning in the summer of 1990, CO_2 was intensely monitored on a monthly basis at two locations - the Throne Room and the Big Room at Sharon's Saddle. The results of these measurements are given in Table 3. CO_2 concentrations are highest during the summer and can reach 5400 ppm.

Table 3. Monthly CO_2 Measurements.

DATE	Upper Throne Room	DATE	Sharon's Saddle
07/18/90	2910	07/26/90	3610
08/26/90	3925	08/23/90	4680
09/30/90	5400	09/27/90	4100
10/30/90	4935	10/23/90	2220
11/24/90	3827	12/05/90	1130
12/19/90	3296	12/19/90	1132
01/15/91	2430	01/17/91	852
02/14/91	1690	02/21/91	1147
03/24/91	2620	03/31/91	1190
05/05/91	2167	04/23/91	1746
05/29/91	1660	05/29/91	1190
06/11/91	2650	06/10/91	2130

Measurements in ppm by Drager diffusion tubes, corrected to 854 Mb pressure.

The measurement of CO_2 is important for a number of reasons. First, high levels of CO_2 in Kartchner Caverns during late summer and autumn raise some concerns regarding the levels that may be present after the cave is open to the public. Visitors to the cave will add more CO_2 to the air, possibly raising it to unacceptable levels (Cabrol 1997). Second, the concentration of CO_2 is an important parameter in determining if the water percolating into the cave will deposit or dissolve calcite. The growth of carbonate speleothems (such as helictites) depends on the concentration of CO$_2$ entering the cave via vadose seeping dripwater and equilibrating with the cave air (Hill & Forti 1997).

Third, changes in the concentration of CO$_2$ gas in the cave air can be used to approximate the rate of air exchange between the cave and the surface. The outside air contains approximately 300 ppm CO$_2$. Within the cave, CO$_2$ concentrations vary seasonally from approximately 1000 ppm in late winter to over 5000 ppm in late summer. The amount and rate of CO$_2$ entering the cave follows an annual cycle, being dependent on the rate of drip water entering the cave and the biologic activity in surface soils. The measured concentration of CO$_2$ in Kartchner Caverns varies by a factor of 3 to 5 over the course of a year. If we make two simplifying assumptions that the rate at which CO$_2$ enters the cave is constant, and that ventilation with outside air is the primary method of removal, we can make a simple estimation of the ventilation rate. The equation for the time-dependent concentration of a tracer being removed at a constant rate is:

$$\text{Concentration} = \text{Starting Concentration } \exp^{(-Kt)}$$

Where: K = flow rate/ Volume (air exchanges per day)
t = time (days)

For the Throne Room measurement station, CO$_2$ levels decreased from 5400 ppm on 9/30/90 to 1690 ppm on 2/14/91, a period of 137 days. For this station K was determined to be 0.0085; the reciprocal is the time for a complete air exchange, or 118 days. For the Big Room at Sharon's Saddle, CO$_2$ levels decreased from 4100 ppm on 9/27/90 to 1130 ppm on 12/5/90, a period of 69 days. For this station K was determined to be 0.0187 and the ventilation rate 54 days. These ventilation rates (118 and 54 days) are equivalent to air exchange rates of 1,100 to 2,400 m^3/day, respectively.

RADON

Radon^{222} gas is an intermediate product in a chain of radioactive decays that begins with uranium and ends with lead. Radon gas is present in caves as a result of the liberation of radon from low concentrations of uranium in bedrock or sediments. Radon is an inert gas and, unlike all other uranium-series decay products, does not form chemical bonds. As a result, radon atoms can move freely through the pore spaces of porous materials like bedrock or sediments without bonding to other substances. Radon^{222} has a half-life of 3.82 days, and decays into a series of atomic-sized particles known as radon decay products or radon daughters. A few seconds after formation, the daughters may become attached to airborne dust and condensation particles in cave air. If the radon daughters are inhaled, their further disintegration by radioactive decay releases a high-energy alpha particle that can be injurious to healthy lung tissue. It is important to measure radon in caves for two reasons: (1) at high levels radon decay products have been shown to cause increased incidence of lung cancer, and (2) it is useful as a natural tracer gas in understanding the movement of air.

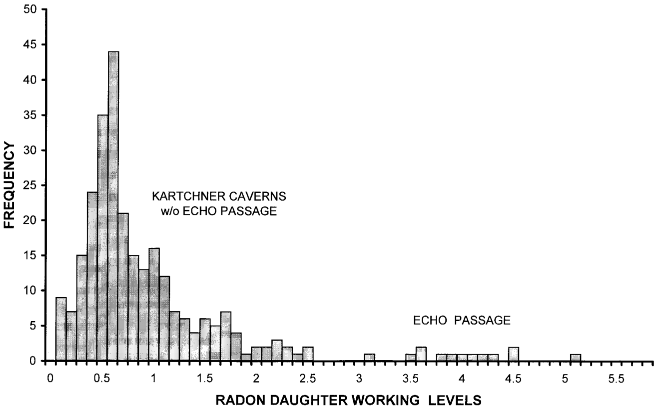

Figure 15. Distribution of radon daughter "Working Level" measurements. All of the measurements above 3 WL are in the Echo Passage during the winter.

Radon^{222} gas is measured in picoCuries per liter of air (pCi/L) but its decay products, radon daughters, are commonly reported in "Working Levels" (WL), a unit of exposure. Under ideal conditions 1 pCi/L of radon^{222} will decay and produce a total exposure of 0.01 WL from radon daughters. This conversion is only approximate since we are comparing radon gas with the sum of the decay products, some of which may have been removed from the air prior to measurement.

Radon daughters in Kartchner Caverns were first measured by OUL during September and December of 1989, (Aley 1989, 1990). These measurements demonstrated that alpha radiation levels from radon daughters were high enough to possibly be of concern for the long-term health of employees spending a lot of time in the cave. However, the OUL measurements were taken only twice and did not provide an adequate picture of radon variations over an entire year. Nor were the OUL measurements sufficiently detailed so as to be useful in characterizing the reasons for the variations found in different areas of the cave.

ACPI followed up with a more comprehensive study. This study included measurements on:

(1) Radon Working Levels,
(2) Radon^{222} gas, and
(3) Individual radon daughters.

The distribution of all 275 radon daughter measurements by ACPI and OUL is shown in Figure 15. The most of the measurements (263) are below 3 working levels and average 0.77 Working Levels. A second group of 12 measurements clusters at higher values, averaging 3.96 Working Levels. These measurements all came from near the start of the Echo

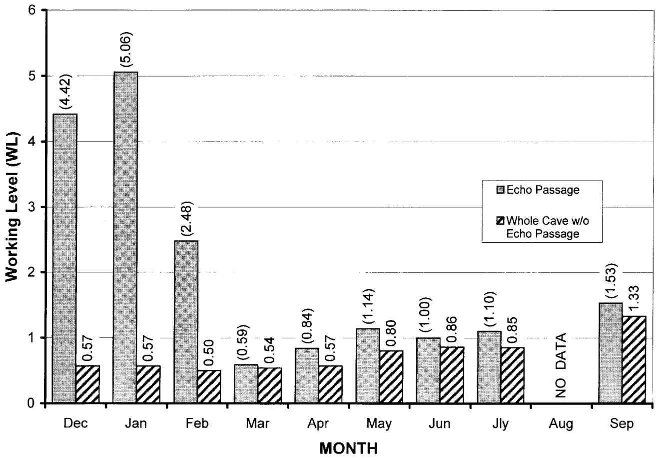

Figure 16. Average monthly radon daughter "Working Levels" for all of Kartchner Caverns excluding the Echo Passage, and for only the Echo Passage.

Passage during the winter months. Measured radon daughter concentrations in the cave appear to exhibit a seasonal pattern, with lower levels in the winter and higher levels in the late summer (Fig. 16). The Echo Passage has the largest variation, ranging from a high of 5.09 WL in January to a low of 0.59 WL in March. The rest of the cave varies from a high of 1.33 WL in September to a low of 0.50 WL in February.

A series of radon^{222} gas measurements were made utilizing alpha track detectors that maintain a high degree of sensitivity even at high humidity levels. The detector is a small plastic film that is damaged by the track of a particle of alpha radiation. By counting the number of alpha tracks and knowing the length of exposure, the average radon gas concentration was determined. Detectors were left in the cave for three to four weeks. These tests gave a long-term average of the radon gas concentration in the cave. The results of the alpha track radon measurements are given in Table 4. While only a limited number of measurements were made, these show that in the Big Room the concentration of radon^{222} is highest in summer and decreases by a factor of 2.5 during the winter. In the Throne Room, which is far from the natural entrance, the concentration of radon dropped 11% from summer to winter. The Echo Passage was found to have the highest concentration of radon gas in the cave.

Table 4. Alpha Track Radon Gas Measurements.

Location	Start Date	End Date	Radon (pCi/L)
Big Room near Bishop	05/05/89	07/10/89	162.0
Big Room near Bishop	03/07/90	03/31/90	66.0
Throne Room EMS 18	05/05/91	05/29/91	58.5
Throne Room EMS 18	12/19/90	01/15/91	52.1
Echo Passage EMS 10	12/05/90	12/18/90	368.7
Average (all)			141.5 ±135
Average (w/o Echo)			84.7 ±52

A total of 17 additional measurements were made in order to determine the concentration of three of the individual radon daughters; radon A (Po^{218}), radon B (Pb^{214}), and radon C (Bi^{214}). The method used was the modified Tsivoglou method (Harley 1988; Nazaroff & Nero 1988). The results of these measurements are shown in Table 5. The average concentration for the first radon daughter, Radon A, was 101 pCi/L. Radon A has a short half-life of approximately three minutes. Because of the short half-life, it is likely to be in equilibrium with the parent radon gas. The fact that the average Radon A (101 pCi/L) is within the range of measured radon gas concentrations reinforces this conclusion. The second radon daughter, Radon B, has a half-life of 27 minutes. The average concentration of Radon B was found to be 73 pCi/L. The third radon daughter, Radon C, has a half-life of 20 minutes. The average concentration of Radon C was found to be 60 pCi/L.

Table 5. Individual Radon Daughter Measurements.

Date	Location	Sample #	Radon-A pCi/lp	Radon-B Ci/l	Radon-C pCi/l	Comments
3/31/91	Echo Passage	2	208	219	210	Equilibrium
3/31/91	Big Rm-Kartchner Towers	3	66	61	61	Equilibrium
2/24/91	Big Rm-Main Corridor	5A	39	32	40	Equilibrium
2/24/91	Big Rm-Overlook	1	59	48	51	Equilibrium
2/24/91	Big Rm-Mud Flats	1	61	62	64	Equilibrium
5/29/91	Throne Rm-Upper	1A	57	53	40	Equilibrium
3/24/91	Big Rm-River Passage	4	46	35	33	Non-equilibrium
3/31/91	Big Rm-Traverse	1A	62	43	38	Non-equilibrium
3/31/91	Throne Rm-Lower	2A & 3A	84	58	50	Non-equilibrium
5/5/91	Big Rm-Bat House	2	143	118	97	Non-equilibrium
5/16/91	River Passage-Grand Cny	2	84	60	49	Non-equilibrium
5/16/91	Big Rm-Fallen Shield	5	83	51	36	Non-equilibrium
5/29/91	River Passage-Grand Cny	2	99	61	42	Non-equilibrium
5/29/91	River Passage-Thunder Rm	1	241	153	93	Non-equilibrium
6/25/91	River Passage-Grand Cny	2	175	66	33	Non-equilibrium
5/16/91	Grand Central	1	66	53	43	Outside Air Dilution
6/21/91	Entrance Passages-Pop-up	5A	147	63	34	Outside Air Dilution

If air exchange or other processes remove none of the radon daughters, then the concentration of each radon daughter will be in equilibrium with the parent and all should be equal. This is true in the case of six of the measurements. This indicates that for some areas of Kartchner there is little or no removal of radon daughters other than by radioactive decay. The remaining measurements for other areas of the cave show that the concentration of each successive daughter is generally smaller than the preceding daughter. This indicates that some process is actively removing the successive radon daughters from these areas. Two mechanisms that can remove radon daughters are air exchange and attachment to surfaces. In order for air exchange to be a significant factor in removing radon daughters, the exchange rate must be relatively large compared to the half-life of the radon. Because the half-life of each radon daughter is less than half an hour, the air exchange rate must be greater than once per hour to remove a significant quantity of radon daughters. High rates of air exchange have been found only in the entrance passages and may account for the reduction in radon daughter concentrations in two of the samples. For the remainder of the samples, it appears that the individual radon daughters are being removed by plate-out onto aerosols or cave surfaces.

CONCLUSIONS

(1) The amount of water reaching the cave from surface precipitation is estimated to be 7.9 mm/yr. This is less than 2% of the annual precipitation at Kartchner Caverns State Park.

(2) The average rate of evaporation for the whole cave is 9.4 mL/m²/day, while areas of the cave far from the natural entrance have a rate of evaporation as low as 3 mL/m²/day. Evaporation rates are highly skewed toward very low rates that approach no evaporation at all.

(3) Relative humidity averages 99.4% for the whole cave. The distribution is highly skewed toward RH values above 99.5%.

(4) Comparison of RH and evaporation rates shows that, as expected, the rate of evaporation is proportional to the RH difference from 100%. Evaporation increases by 27 mL/m²/day for each additional 1% RH below 100%.

(5) Using the measured evaporation rates, the amount of moisture being lost from cave surfaces is estimated at 134,700 L/yr. This represents over half of the 7.9 mm of water that infiltrates into the cave. During a dry year the cave will lose more moisture by evaporation than is resupplied by surface precipitation.

(6) The soil and air temperatures in the cave are in equilibrium. The temperatures within the cave are always above the mean surface temperature. This is due to regional geothermal heating. The slightly warmer cave temperatures have a profound influence on the air exchange rate.

(7) Annual temperature and RH measurements in the entrance passages of Kartchner indicate that during the winter cold air enters the cave, and during the summer warm moist air is expelled.

(8) A profile of the cave soil temperature from the entrance shows that the influence of the small natural entrance extends 120 m into the cave. This profile agrees well with theoretical predictions and is supporting evidence for the volume of air entering the cave.

(9) Measurement of airflow near the cave entrance shows that during the winter the direction of airflow is overwhelmingly into the cave. This is taken to be evidence that the cave has unidentified small openings at a higher elevation than the natural entrance. The volume of air that enters the cave during the coldest part of the winter is estimated to range from 4,000 to 12,000 m³/day.

(10) Seasonal fluctuations in CO_2 concentrations collected in the fall in two areas of the cave were used to make independent estimates of the ventilation rate. These measurements indicate that air was moving into the cave at 1,100 to 2,400 m³/day.

(11) High radon levels in the cave were found to be a possible health concern for long–time workers in the cave. Radon levels are not high enough to cause concern for the viewing public. $Radon^{222}$ concentrations average 90 pCi/L and radon daughters average 0.77 WL in the main cave. The Echo Passage has radon levels that are as much as seven times higher than this during the winter. This is due to the stable microclimate and limited air movement in this passage. Natural removal of radon daughters occurs predominantly by plate-out onto cave surfaces or aerosols, while removal by ventilation seems to be a minor factor.

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