PRE-DEVELOPMENT STUDIES AT KARTCHNER CAVERNS

Robert H. Buecher
Arizona Conservation Projects, Inc.

ABSTRACT

Kartchner Caverns is a beautiful limestone cave in pristine condition, considered by experts to be the premier cavern in Arizona. It will be protected and displayed to the public as the 25th Arizona State Park. The cavern was discovered in 1974 by two Tucsonans, Gary Tenen and Randy Tufts. They kept the cave secret for fourteen years to protect it from vandalism and to maintain it in its original condition. It is located approximately 8 miles southwest of the town of Benson on the west side of State Highway 90. The park site is 550 acres in size and is situated at an average elevation of 4700 feet.

The cavern is over two miles long with spacious rooms, one of which is as long as a football field, (Figure 1). It is a wet, 'live' cave into which water still percolates from the surface and whose calcium carbonate features are still growing. It contains an unusually wide variety of multicolored cave formations – stalactites, stalagmites, flowstone, shields, helictites and soda straws - some of which are among the best examples in the U.S . It is also a summer home to a colony of approximately 1200 bats. The contrast between the moist interior of the cave (over 99% relative humidity) and the dry desert above makes Kartchner Caverns particularly vulnerable to damaging changes. Changes in airflow, temperature, or humidity caused by improper development could quickly dry out the cave, halt speleothem growth, and diminish the cave's beauty.

To prepare for the public opening of Kartchner Caverns in an environmentally sensitive manner, Arizona State Parks has contracted for a two year pre-development study of the cave with Arizona Conservation Projects (ACPI). This report presents the preliminary results of that 24 month study. The studies focus on four main aspects of the cave environment: (1) cave microclimate and meteorology, (2) hydrology, (3) geology, and (4) biology.

CAVE MICROCLIMATE AND METEOROLOGY

Maintaining the moist conditions within the cave has been identified as the most important consideration in developing the cave. Drying of the cave can result in permanent damage to many of the features which make the cave so attractive. There is a marked contrast between the surface conditions and the interior of the Kartchner Caverns. The surface is a semi-arid desert while the cave is a moist stable environment. On the surface, temperatures fluctuate by 85°F over the course of the year. Deep inside the cave the annual temperature change is less than 1°F. The difference between evaporation on the surface and in the cave is even more dramatic. Outside, the yearly evaporation can exceed 65 inches, inside the cave it is less than 0.08 inches. The rate of evaporation outside is 800 times greater than inside the cave. If outside air were allowed to freely enter the cave it would deplete the entire annual supply of moisture to the cave in only three days.

The cave receives moisture from percolating rain water and infiltration from surface washes. Significant infiltration from washes is sporadic and occurs only during years with above average precipitation. It is, however, the largest source of water for the cave when it does occur. The influx of water from the washes is very important in maintaining the microclimate of the cave. Precipitation and the subsequent percolation of water into the cave is highly variable from year to year. It is still the most reliable source of moisture for the cave. Water is lost from the cave by a system of natural drains and by direct percolation through the floor of the cave. Evaporation from cavern surfaces and the removal of the moist air from the cave by air exchange with surface air is presently responsible for only a small fraction of the moisture loss. However, development of the cave will unavoidably increase the air circulation within the cave resulting in increased evaporation. Surface climate measurements indicate that because of the desert environment, the exchange of outside air with cave air will always have a drying effect on the cave.

An analysis of the moisture balance of the cave indicates that air exchange is the only parameter which can be effectively managed. Increased airflow from development will unavoidably remove additional moisture from the cave. Minimizing the potential for increased air exchange should be a primary consideration of the cave development in order to maintain the moist microclimate of the cave.

Environmental Monitoring Program

The environmental monitoring system is designed to provide data necessary for determining the nature and magnitude of microclimate changes which will likely result from the development of the cave and the construction of one or more man-made entrances. The program of environmental monitoring was initially outlined by the Ozark Underground Laboratory (OUL) with instrument installation, maintenance and data collection performed by ACPI. Approaches suggested by OUL have been modified by ACPI as necessary in order to obtain useable data

The microclimate studies at Kartchner Caverns have measured the following parameters:

- Air Temperature
- Soil Temperature
- Relative Humidity
- Evaporation Rates
- Air Trace Gasses
- Airflow

ACPI has installed a total of 22 environmental monitoring stations (EMS) distributed throughout the cave. The locations were decided on after consultation with Tom Aley of Ozark Underground Laboratory (OUL). The majority of these stations are placed in pairs. One is located as close as is practically possible to the location of a potential entrance. The second station is located one hundred or more feet into the cave and acts as a reference station. The distribution of the monitoring stations is not uniform nor was the original intent of the system to provide uniform coverage of the interior portions of the cave. These stations have been placed so that the existing and future impact of an entrance or proposed entrance on the microclimate of the cave could be assessed.

At each EMS, the following equipment was placed: a 9" diameter water evaporation pan, a PVC pipe stand to hold thermometers, an air temperature sensor and a soil temperature sensor. In the back portions of the cave, temperatures are also taken with a digital thermometer which stores the high and low temperatures. In the front of the cave, each EMS is wired into a computer data logger which records a wet bulb, dry bulb and soil temperature each hour.

Approximately once a month, each station is visited and additional independent air, soil and water temperatures are taken with a portable thermometer. The volume of water lost by evaporation is also measured at this time. Other measurements of relative humidity, alpha radiation levels and carbon dioxide are usually taken at the same time.

In addition to the manual temperature measurements taken at each station on a monthly basis, two computer systems record temperatures on an hourly basis. Gathering temperature data by computerized data loggers has several advantages:

- More measurements can be taken.
- Simultaneous measurements can be taken at different locations.
- Probes have come to equilibrium.
- There is no interference from the presence of the observer.
- Readings can be taken without disturbing the bats.

Two separate systems have been installed in Kartchner Caverns. In March 1989 a data logger and seven probes were installed in the entrance passages. Two of the probes measure unventilated wet bulb temperatures. These allow an estimate of relative humidity to be made.

A second, more elaborate computer data logger system was installed in the Big Room in May 1989. Initially this system had 30 temperature probes. Three temperature probes were connected to each of the ten environmental monitoring stations around the Big Room. At each station, a probe measures air temperature, wet bulb temperature and soil temperature . The initial system measured temperatures with a resolution of 0.5°F. In October and December 1989, the system was expanded to 40 probes and the temperature resolution increased to 0.1°F. See Figure 2 for a graph of the average daily temperature and monthly evaporation rate for one of the stations in the Big Room.

Temperature

The temperatures of large caves are generally considered to be at the same temperature as the mean surface temperature. At Kartchner Caverns State Park the surface weather station has a mean surface temperature of 62.5°F. This agrees well with temperatures based on correlations of the Kartchner temperatures with nearby weather stations.

Inside the cave temperatures vary from 69.7°F to 65.5°F with a mean temperature of 67.7°F for the whole cave. The discrepancy between the range of temperatures inside the cave and the mean surface temperature is the result of three processes.

1) Temperatures in Kartchner Caverns are elevated primarily because of regional geothermal heat flow. The above average heat flow over much of Arizona is responsible for an increase in cave temperatures of 2.4°F to 6.5°F above the mean surface temperature. This indicates that the temperature of Kartchner Caverns should be in the range of 64.9°F to 69.0°F.

2) Flooding of the cave during the winter is the cause of the cold temperatures in the Back Section. While flooding does not occur every year there is insufficient time for the Back Sections to completely return to equilibrium temperature.

3) Stratification of air in the Big Room during the winter causes this part of the cave to become the warmest area in the cave. Cool, dry air from the surface flows along the floor through parts of the Big Room and into the River Passage. At the interface between the cool air on the floor and warmer air above, a condensation fog forms. Condensation releases heat which warms the overlying air.

Evaporation

The moisture content of the air within the cave can become a critical management issue. At the present time, evaporation from cave surfaces is the major source of moisture in the air. The rate at which water evaporates within the cave is expected to be very low. On the surface the energy required to evaporate water comes from the sun, differences in air and soil temperatures and the relative humidity of the air. Inside the cave, temperatures are relatively constant, there is little or no wind and the relative humidity is almost 100%. The rate of evaporation within the cave is largely determined by the relative humidity of the air. It is important to understand that evaporation is proportional to the difference in relative humidity from 100%. If the relative humidity changes from 99.5% to 99.0%, the evaporation rate will double! This means that very small changes in the relative humidity could have major impacts on the moist conditions in the cave.

Precise relative humidity (RH) has been measured with a dewpoint microvoltmeter at each of the monitoring locations. This instrument is capable of measuring the relative humidity and dewpoint temperature with an accuracy of 0.05%. The relative humidity ranges from 96.32% to 100.00% RH. The average relative humidity for all measurements is 99.42% but is highly skewed toward the higher values.

Evaporation rates have been measured at each of the 22 environmental monitoring stations on a monthly basis and at a number of other locations adjacent to the natural entrance. At each location a 9" diameter aluminum pan (surface area 59.2 square inches) is filled with a volume of 750 ml of distilled water. The volume of water can be carefully measured and the evaporation rate determined with an accuracy of 0.05 ml per day. The average evaporation rate for all stations is 0.36 ml per day (0.14"/year).

Because a large proportion of the evaporation occurs near the natural entrance evaporation rates have been divided into two categories. 1) Those stations which are located near the natural entrance and have higher evaporation rates (0.91 ml per day (0.34"/year)) due to cool dry air entering the cave. 2) Stations distant from the natural entrance and which have lower (0.22 ml per day (0.08"/year)), more consistent evaporation rates.

The relationship between evaporation rates and relative humidity has been approached in two ways. Correlating precise relative humidities with pan evaporation for those stations with the most data gives the relationship of 1.0 ml/day per %RH below 100%. A larger sample of evaporation and relative humidity measurements was evaluated by a purely distributional comparison. This yields an estimate of evaporation to be 0.65 ml/day per %RH below 100%. A value of 1.0 ml/day per % RH below 100% is considered to best fit to the data.

Under present conditions evaporation plays a minor role in removing moisture from the cave. This is because the present entrance is quite small and there is relatively little air exchange with the surface. Development of the cave for public viewing can greatly increase the amount of evaporation. Poorly located or constructed entrances can induce a strong airflow pattern which in turn will greatly increase the evaporation. This has been observed in many other developed caves. These problems can be lessened by care in locating or enlarging entrances and connecting tunnels. Steps can also be taken to control the airflow entering the cave. Entryway doors can be constructed to act as airlocks and prevent the entry of outside air. Developing the cave so as to prevent increased airflow and evaporation is the most easily controllable part of the moisture balance.

DRIP WATER MEASUREMENT

Water which percolates into the cave directly from precipitation falling on the limestone surface of the hill is an important source of moisture for the cave. Understanding the moisture balance of the cave requires that we make a reasonable estimate of the quantity of water which enters the cave in this manner. Additionally we need to understand how various patterns of precipitation affect the amount and rate of water percolating into the cave. In order to understand these processes, a program of collecting and analyzing drip water was established.

A series of 8 drip water monitoring locations were established by ACPI throughout the cave. Once a month drip water was collected, with additional samples frequently taken during other trips into the cave. A total of 292 samples were taken during the study. For each sample the rate of flow was determined by measuring the volume of water collected in a known length of time. Samples were taken from the cave and later measured to determine the specific conductivity of the water. The conductivity of the water is related to the total dissolved solids.

When the measured conductivity of drip water samples is plotted by date, a consistent pattern emerges. Conductivity is slightly higher during the summer and early fall than at other times of the year. During the winter the conductivity is at its lowest values. The most obvious interpretation for this seasonal variation is that it is a reflection of the level of biologic activity in the soil. Carbon dioxide is produced by this biologic activity. Higher concentrations of carbon dioxide in the soil allow rain water to dissolve greater amounts of limestone which increases the conductivity of the drip water.

Levels of carbon dioxide in cave air have been periodically measured. When drip water conductivity is plotted against carbon dioxide levels it is apparent that the two are related. For each of four drip water stations in areas where CO_2 has been measured, drip water conductivity increases at a rate proportional to the increase in CO_2. From a nomograph in Palmer's "Origin and morphology of limestone caves" it is possible to estimate the change in conductivity due to a change in CO_2. This works out to be 18 uMHOS per 1000 ppm CO_2, only slightly higher than the observed. This may also indicate that most of the variation in conductivity observed in the other drips is due to changes in CO_2 concentrations within the cave rather than changes in CO_2 production in the soil. While the concentration in CO_2 within the soil undoubtedly increases during the summer, the amount of water percolating through the soil also increases. The increased flow appears to maintain a relatively uniform concentration of CO_2 while it is moving within the limestone. The increase in CO_2 observed within the cave during summer months is due more to increased drip water flow than to changes in CO_2 concentrations in the drip water.

Water which enters the cave from the surface drips from the ceilings creating the numerous formations in the cave. A significant amount of water enters the cave in this way. Unfortunately the amount of water entering the cave as drips is difficult to estimate. Drips are randomly spaced throughout the cave and many are inaccessible. The flow rate is also highly variable and dependent upon surface precipitation. Several approaches have been devised to estimate the quantity of water entering the cave as drips.

The source of drip water is precipitation which falls on the surface of the limestone hill above the cave. Water which is not lost to evapotranspiration and direct runoff percolates down into the limestone. The quantity of water which does reach the cave can be estimated by determining the excess moisture available after accounting for evapotranspiration. A general approach for determining the excess soil moisture is the Thornthwaite Method. In this method excess soil moisture is determined from the mean daily temperature, precipitation, time of year, geographic location and soil moisture capacity.

We can estimate what the long term excess soil moisture is by assuming that Sierra Vista is similar to Kartchner Caverns State Park. Both sites have the same elevation, mean temperature and average yearly precipitation. Based on an analysis of weather records for Sierra Vista from 1955 to 1990, the average excess soil moisture is 1.70" per year. The excess moisture is partitioned between direct surface runoff and water which percolates into the limestone bedrock. A rough guess is that only one third will percolate into the cave, or approximately 0.60" per year.

The amount of water which actually reaches the cave has been estimated by three methods.

1) By counting the number of drips. Frequently when drip water samples were collected, the rate of dripping was also recorded. From this data a general correlation has been found between the number of drips per minute and the flow rate for stalactites in Kartchner Caverns. The flow rate in ml per hour is found to be 4.75 times the number of drips per minute. Therefore, by counting the number of drips per minute in a given area, it is possible to estimate the quantity of water entering that area of cave. This method estimates that 0.17" of water that enters the cave each year.

2) By drip water collection in randomly placed pans. A set of 10 empty, 9" evaporation pans were placed randomly about the Big Room. During this period (145 days) the volume of water, if any, was measured and the pan emptied. After each measurement the pan was moved to a new location. This experiment yielded estimates of the amount of water reaching the cave that range from 0.07 to 0.13 inches per year. This rate must be corrected for the amount of evaporation which occurred. Adding the estimated evaporation to the amounts collected in the pans gives an estimated 0.24" to 0.30" of water reaching the floor of the cave.

3) By evaporation rates in dry areas. There are very few areas that can be found in the cave where the floor and walls are actually dry. Only portions of the entrance passages up to Main Corridor and the Tarantula Room have a dry floor during winter months. The evaporation rate at these areas must exceed the moisture supply. By comparing the evaporation records of monitoring stations in this area we can determine the evaporation rate that will just balance the drying of the cave.

Data from stations near the natural entrance were examined to determine average evaporation rates during those months when drying is known to occur. Based on these measurements it was estimated that 1.3 ml per day of evaporation an area of cave would dry it out within a few months. This corresponds to 0.49 inches of evaporation per year. Since these areas do dry out the moisture supplied must be supplied at a rate less than 0.49" per year. This sets an upper boundary on the moisture influx into the cave by percolating surface water of 0.49" per year.

The three estimates of the annual drip water influx are:

> Drip count estimates 0.17" per year.
> Random collection pans 0.24" to 0.30" per year
> Dry areas 0.49" per year.

The average of these estimates is 0.3" of water per year entering the cave in the form of drips (60,000 gallons per year).

Hydrology

Two off-site drainage areas, Guindani Wash and Saddle Wash have been shown to be the source of the water which sporadically floods the back portions of the cave. Two flooding events occurred during the course of our study. In August, 1990 the back section of the cave was flooded. This was our first indication that combinations of intense, localized summer thunderstorms could produce enough surface runoff to cause flooding. The flooding was not observed but was determined to be rather slow, taking a week or more to flood the cave. The cave was also found to respond slowly to runoff on the surface. The adjacent washes must flow for several weeks before water begins to enter the cave. This indicates that rapid flooding of the cave is highly unlikely. By observing the rate at which flood water left the cave we were able to determine that the drains are very small and inefficient. It took over two months for the flood water to completely disappear. Because the flooding was not discovered until after the peak had passed, it was difficult to determine the points at which water entered the cave. A small flowing stream was found entering the cave at Sue's Room. The source of this stream was determined to be Saddle Wash by dye tracing.

The second flooding event occurred in the winter of 1991. Once again the back sections of the cave flooded. This time the whole sequence of flooding was closely observed. We were able to measure the amount of water being lost from the surface stream and identify the areas where infiltration is taking place. Water was found to be entering the cave at Granite Dells. This confirmed that only a small amount of water enters the cave at Sue's Room. By measuring the rate at which the interior water level changes, the quantity of water reaching the cave was determined. Approximately $^2/_3$ of the water which disappears from the surface stream reappears in the cave. Positive proof of the connection was made by dye traces from the surface stream into the cave at Granite Dells.

These two surface streams appear to be one of the most significant sources of water for the cave. Changes in land use within these drainage areas can directly affect the quantity and quality of water entering the cave. These watersheds are located on Coronado National Forest lands. Arizona State Parks will be taking steps to see that the cave is adequately protected from detrimental changes in these watersheds.

An analysis of weather records at nearby surface stations has allowed us to develop a correlation between flooding of the cave and precipitation patterns. This indicates that while flooding of the cave has been rare in recent years, historically it is a common occurrence. Flooding of portions of the back areas of the cave has a 67% chance of occurring in any given year. A majority of the flooding events will occur during the winter months. Because the winter runoff which floods the cave is cold water, it has a lasting impact on the microclimate of the cave. The areas of the cave which are flooded have temperatures which are several degrees below that of the adjacent areas of the cave. This creates a zone of cold, dense air which has a controlling influence on air flow patterns in the cave.

Understanding the response of the cave to the heating and cooling from flooding has been useful in predicting the post-development temperatures in the cave. Flooding of the back portions of the cave can have two different effects on the rate of evaporation in the cave. If the flood waters are warmer that the cave temperature, as they were in August, 1990, then the water acts as a moisture source and decreases the rate of evaporation in the cave. Warm moist air rises from the water, when this air comes into contact with the walls and other cave surfaces which are cooler, water condenses onto the surfaces. A decrease in evaporation was observed at several of the monitoring stations in August, 1990. If the floodwater is colder than the cave temperature, then the water will act as a sink for moisture in the cave, increasing the rate of evaporation in adjacent areas of the cave. Air which is in contact with the water is cooled sufficiently to cause condensation on the surface of the water. The net effect is to produce a gradient of relative humidity. Near the cool water, the relative humidity will be 100%. Further away, moisture will move toward the cooler water and thus increase the rate of evaporation in areas adjacent to the water. Increased evaporation was noted at several monitoring stations during and after the winter, 1991 flood.

Carbon Dioxide and Ventilation Rates.

The quantity of carbon dioxide (CO_2) gas contained in the cave air has been used to approximate the rate of air exchange between the cave and the surface. The outside air contains approximately 300 ppm CO_2. The chief advantage of CO_2 as a tracer is that it is predominantly removed from the cave by ventilation. The primary source of the carbon dioxide is thought to be the CO_2 produced in the overlying soil and brought into the cave dissolved in drip water and by air exchange through small cracks in the ceiling. A small amount of CO_2 may be produced by the decomposition of bat guano, bat respiration and tree roots which enter the cave. Most, if not all, of the CO_2 is removed from the cave by the naturally occurring ventilation of the cave with surface air.

Carbon dioxide concentrations have been measured in the cave at two locations on a monthly basis. The upper Throne Room location has an annual average of 3125 ppm ± 1200 and a range of 1660 to 5400 ppm CO_2. At Sharon's Saddle, the annual average is 2095 ppm ± 1320 and ranges from 852 to 4680 ppm. CO_2 concentrations vary seasonally from a minimum in late winter to a maximum 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 the surface soils.

A relatively simple model of CO_2 concentrations in the cave can be constructed from a knowledge of the cave volume, the rate at which CO_2 enters the cave and the ventilation rate. The volume of the cave is reasonably well known from the survey data. The airflow rate has been measured primarily during the winter at the natural entrance. The rate at which CO_2 enters the cave is not known.but we can make a few educated guesses based on the rate of rise and decline of the CO_2 measurements. For the model, the rate at which CO_2 enters the cave is considered to be proportional to two other parameters, the rate at which drip water enters the cave and the biologic activity in the soil. These two parameters are used to index the rate at which CO_2 enters the cave.

The proper values for the ventilation rate and rate of CO_2 introduction which most closely fits the observations has been determined by trial and error. The measured ventilation rate and inferred CO_2 influx were used as starting points. The final model is based on an influx rate of CO_2 that varies from 20 ppm/day in winter to 80 ppm/day in summer. The measured CO_2 concentrations reasonably fit a ventilation rate of 170,000 to 36,000 ft^3/day. The good overall fit indicates that the range of ventilation rates is reasonably well known.

Air Exchange

Air exchange between the cave and the surface has been identified as one of the major routes by which moisture is lost from the cave. For this reason controlling the rate of air exchange is one of the most important tasks in developing the cave. Airflow is also strongly related to other processes within the cave such as the concentration of carbon dioxide and radon gas. Unfortunately the concentrations of these trace gases is also an important management issue. Increasing rates of air exchange would lower the concentrations of these gases but would also result in increased evaporation, drying of the cave and potentially irreparably damage the beauty of the cave. A knowledge of how these three parameters, evaporation, carbon dioxide and radon, are related to airflow is necessary in order to predict the likely effect of development. The maximum concentrations of both of these gases is determined by the air exchange rate. Estimates of the rate at which air is exchanged have been made by several different approaches. These range from direct measurement of airflow to estimates based on concentrations of trace gases, and models of air exchange. No one method has given a clear cut picture but together they give a consistent overall estimate of the air exchange rate.

The pattern of airflow through the cave can be deduced by several different methods. First, the airflow direction can be sensed in constricted passages if there is sufficient air movement. In larger passages and rooms the air velocity is too slow to be observed directly.

A second method is to observe the growth patterns of the cave formations. Sustained patterns of airflow for long periods of time can influence the growth, orientation and type of speleothems.

A third method involves the measurement of the properties of the air. The amount of alpha radiation particles, relative humidity and CO_2 in the air are all indications of how long the air has been in the cave and how frequently it is exchanged with outside air. A final method is by examining the rate at which soil temperatures change throughout the cave. Areas near existing connections to the surface will have large horizontal temperature gradients. The size of the area influenced by an entrance is dependent on the size of the opening and predominant direction of air movement.

The volume of air entering the cave has been measured by ACPI at the Blow Hole and start of the River Passage for a total of 6.07 days. The average volume of air measured entering the cave is 140,000 ft^3/day. Airflow is also thought to be entering the cave through other small openings in the entrance passages than those measured. Based on the estimated areas of these passages, the total volume of outside air entering the cave is estimated to not exceed three times the observed airflow, or 420,000 ft^3/day.

During all periods of measurement, the direction of airflow was overwhelmingly into the cave (97%). The simplest explanation for this would be the existence of another opening(s) at an elevation above the natural entrance. No evidence of such an opening has been found within the cave. It is thought that the upper opening(s) is either very small or partially blocked by rubble. It appears that the size of this upper opening is what controls the volume of air entering the natural entrance.

The annual pattern of air exchange can be qualitatively understood by computing the density of the surface air and the cave air during winter and summer. Assuming that a higher opening exists, the cave will then act as chimney. During the winter, surface air is denser than air in the cave and flows into the cave. During the summer, surface air is less dense and air flows out the natural entrance. This simple relationship is complicated by two other effects. First, the cave is several degrees warmer than the average surface temperature. This increases the density difference during the winter and decreases it during the summer. As a result, winter air exchange is twice as great as summer and summer air flow out of the cave lasts for only 4 months. This asymmetric reversal of airflow creates the second effect. Because more winter air, which is cooler, enters the cave, the entrance passages become quite chilled. This in turn creates a pocket of cool dense air which partially blocks the summer airflow out of the natural entrance.

ALPHA RADIATION

Alpha radiation levels in all caves are elevated and Kartchner Caverns is no exception. While the level is higher in Kartchner Caverns than in most developed caves, it must be emphasized that it is not a hazard for the public visiting the cave. The levels are high enough to be of concern for employees who may work in the cave for many years.

ACPI has researched the available literature regarding guidelines for permissible exposure levels for the general public. The following statement is taken from "Air Exchange and ^{222}Rn Concentrations in the

Carlsbad Caverns", M.H. Wilkening and D.E. Watkins, Health Physics, Vol 31, pp 139-145.

> "Although there are no explicit guidelines for exposure of the general public to radon and its daughters, both the International Commission on Radiation Protection and the National Committee on Radiation Protection have recommended that individuals in the general public be limited to exposures at levels one-tenth as high as those for occupational exposure. Also for a suitably large sample of the general population, the general guideline is another factor of three smaller."

The average radon daughter level in Kartchner Caverns is approximately one Working Level. Applying the above guidelines would allow the general public to spend up to 22 hours and 40 minutes within the cave based on a permissible standard of 4 working level months for employees. A tour of the cave is anticipated to take less than 2 hours. It would appear that the visitors to the cave would experience less than one-tenth of the guideline exposure.

The radon levels within Kartchner Caverns average approximately 100 pCi/l and vary by a factor of two on a seasonal basis. Radon daughters resulting from the radioactive decay of radon average approximately 0.8 Working Level. These concentrations are high enough to be of concern to those who will work within the cave. Prolonged exposure to radon daughters for many years has been linked to increased rates of lung cancer. Radiation exposure to human lung tissue results from inhalation of radioactive radon-decay products that adhere to lung tissue or to airborne particles that become trapped in the lungs. Due to inhalation of these products, the lungs of most people receive more radiation than any other body organ.

Health consequences of radon exposure to underground miners are the primary basis for determining health risk to people exposed to lower, more common radon levels in houses and other buildings. Most estimates of lung-cancer risk due to low-level radon daughter exposure in homes and buildings use a linear extrapolation from high exposure rates experienced by some groups of underground miners. In a linear extrapolation, exposure and risk are proportionally related; for example, half the exposure would constitute half the risk.

There is some question about whether the exposure rates determined for miners are applicable to the much lower exposures encountered in homes and most caves. Mines typically contain large amounts of dust and exhaust from equipment and miners are not a representative sample of the general population. Despite these differences most risk assessments are based on studies of uranium miners.

The Environmental Protection Agency (EPA) has used the risk coefficients determined for uranium miners to project lung cancer rates at lower exposure levels. EPA has determined lifetime risk coefficients that range from 2.4 to 9.4×10^{-4} per WLM. Other studies have generally recommend somewhat lower risk estimates. A comparison of risk estimates from 7 studies compiled by Nazaroff gives an average lifetime risk coefficient of 2.1×10^{-4} per WLM. The lowest risk coefficient cited in any study was approximately 1×10^{-4} per WLM.

If we use the NPS proposed guidelines of 3.5 WLM per year and a lifetime maximum of 105 WLM as reasonable maximum exposure estimates we can calculate the lifetime lung cancer risk. This is between 2.5% and 9.9% based on EPA risk coefficients and 2.2% based on the average of other studies.

We can compare these estimates with other risks commonly faced by workers in other industries. The rate of fatal accidents in American industry is about 1.1 per 10,000 workers per year. Based on 30 years of work, the risk is about 0.33%. The riskiest industry is mining with a fatal accident rate of 6 per 10,000 workers per year. Based on 30 years of work, the risk is 2.0%. The estimated range of risk associated with radon daughter exposure can be the same as or greater than that of jobs that are commonly perceived of as being risky.

For comparison, the low end of the estimate (2.2%) is slightly greater than the risk of dying in an auto accident. The high end of the estimate (9.9%) is comparable to the risk associated with cigarette smoking. These comparisons indicate that exposure to the levels of radon daughters expected to be found in the cave can be a significant risk for those working in the cave for many years. Exposure and risk to the general public is very much smaller because they will be in the cave for a very short period of time. Based on a one and a half hour tour length, the risk to the public is approximately the same as that associated with a 60 mile automobile trip.

The nature of the radioactive decay sequence provides three approaches to mitigating the problem. First, it is necessary to understand that radon gas and radon daughters have very dissimilar properties. While radon daughters are the actual health risk, radon gas is the direct source of radon daughters. Radon gas has a much longer half life than radon daughters (by a factor of over 100.). If radon gas is eliminated or reduced, then the radon daughters will also be eliminated or reduced. The three approaches can be categorized as follows:

- Control of Radon Gas
  - Removal of radon source
  - Removal of radon gas from the air
  - Ventilation to remove radon gas
- Control of Radon Daughters
  - Ventilation to remove radon daughters
  - Air circulation to increase radon daughter plateout
  - Filtering air to remove radon daughters
  - Passive filtration of air to remove radon daughters
- Protection of the individual employee
  - Personal protection methods
  - Manage the length of employee exposure

Many of the processes that allow high levels of radon and carbon dioxide to accumulate in the cave are also those which maintain the moist cave environment. Valuable insight into the operation of the cave's microclimate can be gained by modeling the behavior of radon within the cave. An additional benefit is the ability to make generalized predictions of the consequences of developing the cave for public viewing. Two models of radon and radon daughter concentrations have been considered. One considers those factors which create the individual radon daughters and effect the removal processes. The other model considers the rate at which radon enters the cave and is removed by decay and ventilation.

In 1972, Jacobi published a mathematical model for predicting the concentrations of airborne radon daughters under the influence of various sources and removal processes. The initial model was formulated for use in uranium mines, but the same processes are active inside caves. The model is generally referred to as the Jacobi Model.

Application of the model is dependent on knowing the rates at which the various radon daughters are created by radioactive decay and removed by various processes. The rates at which the individual daughters are created by radioactive decay are well known physical constants. The rates at which the daughters are removed by ventilation, deposition and attachment is quite variable but has been studied extensively in recent years. Five additional parameters are needed to describe the deposition and removal processes.

1) Ventilation rate
2) Aerosol attachment rate.
3) Unattached plateout rate.
4) Attached plateout rate.
5) Probability of recoil detachment.

Once the model has been calibrated on the undeveloped cave, the effect of development of the cave on alpha radiation levels can be estimated. Several important parameters of the model will change after development. The principal change will be an increase in air circulation caused by convective heating from lights and visitors. This will result in a more uniform mixing of cave air and bring the air into more frequent contact with cave surfaces. This will increase the rate at which radon daughters will plate out. The number of condensation nuclei will also increase. These will be produced by visitors and condensation of water vapor near cooler surfaces.

The Jacobi model results predicts that alpha radiation measured in Working Levels will decrease by approximately 15% as a result of development. Application of the Jacobi Model indicates that development of the cave will tend to decrease alpha radiation levels.

Radon enters the cave from the walls of the cave and from cave sediments. As radon is an inert gas there are only two ways in which it is removed from the cave. The primary mechanism is by radioactive decay into the daughter products. The half-life of radon is 3.82 days and if it were not constantly entering the cave, 99% would have decayed within 25 days. The second process which removes radon from the cave is air exchange with the surface. A simple model of radon levels within the cave can be constructed based on these two processes. The only parameters are the rate of radon entry and the ventilation rate. The model must also be consistent with the following general conditions which have been observed inside the cave.

- Average Radon gas concentration is 100 pCi/l.
- Peak radon gas concentrations of 400 pCi/l.
- Radon daughter concentrations and presumably radon gas concentrations vary by a factor of two on an annual cycle, being lowest in the winter and highest in the summer.
- Air exchange rates are at least 140,000 cubic feet per day but are less than 1,000,000 cubic feet per day.

The model has been set up as a steady state system with the influx of radon and ventilation rate being constant for a period that is long compared to the removal rates. The cave is also treated as a lumped system which assumes that radon levels are uniform throughout the cave and surface air is well mixed with cave air. Neither of these assumptions is likely to be correct and so we can only expect the model to predict the gross behavior of the cave.

The influx of radon is first estimated to be 0.45 pCi per square meter per second. This is a general average for most materials. Based on the surveyed volume and estimated surface area, this corresponds to 0.92 pCi/l per hour inside the cave. The decay constant for radon can be determined from the half-life and is precisely known.

We can first solve the model to determine the ventilation rate which would allow radon to build up to the observed average level of 100 pCi/l and determine the likely annual variations caused by changes in the ventilation rate throughout the year. The results of the model run are contained in Figure 3.

The fact that radon levels are significantly different in various areas of the cave indicates that radon influx rate is also variable throughout the cave. The model shows that variations in the influx rate are directly proportional to the maximum radon concentration.

The impact of various ventilation rates can also be examined with the aid of the model. The air on the surface has a very low radon content compared to the air in the cave. Surface air brought into the cave will dilute and transport radon out of the cave, resulting in lower radon concentrations. The model can be used to assess the importance of ventilation in determining the radon concentration and also to investigate the effect of artificially increasing the ventilation to control radon.

The model indicates that ventilation has little effect on the radon levels within the cave until the ventilation rate is less than 30 days. It would be necessary to completely change all of the air within the cave every 5.5 days in order to reduce the radon level by 50%. Such a high ventilation rate would certainly destroy the existing moist conditions within the cave.

SURVEY OF THE INVERTEBRATE CAVE FAUNA

Invertebrates, especially arthropods, make up the majority of all known cave organisms. If development of the cave is to minimize disturbance to all cave organisms and their habitat, the invertebrate species present and their significance must be assessed. With this information the Arizona State Parks Department can prevent the extinction, and/or reduction of species during and after development of Kartchner Caverns. After development, the information gathered on the invertebrate fauna can be used as a baseline for monitoring cave species and for interpretive programs.

Preliminary work indicates there are several new species of cave adapted invertebrates, including at least one new species of cave isopod and a new mite species. The study of Kartchner Caverns is a unique opportunity for an extensive baseline study of the invertebrate cave fauna before development that will allow future follow up studies to determine the effect of development on the cave fauna.

Thirty three invertebrate species were found in Kartchner Caverns during this study. Of the 33 species, 5 (15%) are considered to be obligate cave dwellers (troglobites) and 16 (48%) are facultative cave dwellers (troglophiles). The camel cricket, Ceuthophilus pima, is a trogloxene because they leave the cave to feed. The remaining 11 (33%) species are either accidentals (10) or obligate parasites (1).

All of the troglobites and troglophiles in Kartchner Caverns are dependent on organic material from the surface. Most of this organic material is deposited as Myotis velifer bat guano every summer. Small amounts of organic matter carried into the cave by periodic flooding of the Back Section provide a limited food supply in that area. The camel crickets are the only cave arthropod that is not dependent on organic material carried into the cave.

Few invertebrates were found in the Back Section (Pyramid Room, Rotunda Room, Mushroom Passage, Throne Room, Subway Tunnel, Pirate's Den, and Sue's Room) of Kartchner Caverns. The Throne Room, Sue's Room and the upper portion of the Rotunda Room are without invertebrates.

The Granite Dells area is biologically interesting. The presence of C. pima, a surface spider, and a lepidopteran indicates a direct connection to the surface. Even with a connection to the surface there were few individuals and species in this area due to lack of available organic material at the Granite Dells level.

The area between the Pyramid Room and Big Room (River Passage, Bathtub Room, Grand Canyon, Thunder Room) is a transition zone between the two parts of the cave. No invertebrates were regularly found in this area.

The Front Section (Big Room, Cul-de-Sac Passage, Echo Passage, Red River Passage, Grand Central Station, Main Corridor, Tarantula Room, Scorpion Room, LEM Room and entrance area) is the biological center of the cave with more than 13 invertebrate species in some areas.

In the Big Room and Cul-de-Sac there are a number of Myotis velifer guano piles of different sizes and ages that serve as the primary food source for most of the invertebrate cave fauna. The bats currently roost in two main areas, near the Lunch Spot and on the west side of Sharon's Saddle.

The area from the Pop-up Junction to the entrance is very different from the rest of the cave. There is a significant seasonal fluctuation in temperature and humidity and organic input is primarily limited to scattered guano pellets and occasional surface material carried in by rodents. The dominant cave arthropod is the camel cricket, C. pima. The other fauna in this area varies seasonally with moisture, but includes many of the accidental species found in the cave.

The invertebrate cave fauna and cave community of Kartchner Caverns is unique. Although the cave fauna of Arizona is not well known, some comparisons can be made. There are significant differences in the cave fauna of Kartchner Caverns and other caves in the Huachuca, Santa Rita, Catalina and Whetstone Mountains . Most notable is the absence in Kartchner Caverns of several relatively common arthropods (a troglophilic opilionid, a carabid beetle, and a dipluran) found in other southern Arizona caves .

There are two possible explanations for the absence of these cave forms. One is that they were present at one time, but for an unknown reason they became extinct in Kartchner. Another possibility is that Kartchner Caverns was only available for colonization when the climatic conditions were such that these cave forms were not able to colonize the cave. Additional information on the climatic history of the area and more detailed study of fauna in other caves may help to understand the differences in the cave fauna.

Based on work with the cave fauna there are currently only two openings from Kartchner Caverns to the surface. One is the current entrance used by the bats, humans and arthropods, while the other is in Granite Dells. The Granite Dells entrance is too small for anything other than arthropods and small rodents. The presence of more than an occasional camel cricket has been found to be a reliable indicator of a direct connection to the surface.

The invertebrate fauna of Kartchner Caverns is unique with several new species that may be endemic to Kartchner Caverns. Every effort should be made to keep disturbance of the cave soil to a minimum.

Development of Kartchner Caverns must be scheduled in a way to preserve the bat population in the Big Room. The loss of the bats from the Big Room in Kartchner Caverns would result in the extinction of most of the arthropod fauna in the cave. Development in the Back Section, especially the Throne and Rotunda Rooms would have the least impact on the cave fauna.

Care must be taken during construction and subsequent tours to insure the cave environment remains unchanged and exotic species are not introduced into the cave. A change of the environment and/or the introduction of surface species could result in the disruption of the cave community and eventually the loss of cave species.

BATS

Bat studies at Kartchner Caverns have been performed under the direction of Ronnie Sidner of the University of Arizona. The purpose of this study was to obtain a biological inventory of bats at baseline level prior to the development of Kartchner Caverns. The acquisition of such data before the population has been impacted by much major disturbance provides a vehicle to study the effects of future activities on the population. This purpose has been paramount in the activities carried out thus far concerning bats at Kartchner Caverns State Park.

Among its many other values, Kartchner Caverns is important because it is a natural refuge for a large colony of bats. From May to mid-September of each year, the cave is home to 1000 to 2000 Myotis velifer, a species of insectivorous bat. These bats, primarily pregnant females , return each year to Kartchner Caverns to rear their young. These bats provide an important link between the ecosystem of the cave and the surface. The bat guano introduces a rich food source for Kartchner's cave limited organisms. During the summer, bats are usually found roosting together in a small cluster on the ceiling of the Big Room. Accumulations of bat guano in other parts of the Big Room indicate that they may occasionally use different parts of the room. There is no indication that bats presently use any other part of the cave.

The importance of the bats to Kartchner Caverns State Park is three-fold. For the Arizona State Parks, they are an exciting educational experience for the park visitor. The public has become increasingly aware of the many benefits provided by this often misunderstood animal. Cave parks such as Carlsbad Caverns fill an amphitheater on summer evenings for a natural history talk about bats during the bats' nightly emergence. The bats also act as a natural insecticide for the park property. A conservative estimate indicates that the bats roosting in Kartchner devour approximately one-half ton of insects every summer. The third benefit of a healthy bat roost within Kartchner Caverns is its introduction of excrement (guano) below the roost. This bat guano is the primary source of food for the permanent organisms of the cave.

At this point, we have garnered much information about the bats with minimal disturbance to the population and only little disturbance to some individuals. For species of bat which are readily identifiable at a distance, low-disturbance techniques achieve identification with high confidence. This has been the case with our observations of Plecotus townsendii and Choeronycteris mexicana which occur in small numbers in outer areas of the cavern. On the other hand, a species of Myotis is not so easily identified, and other measures must be employed. We have not netted the bat population in residence in the cavern, however, because of the potential risks that disturbance within a roost can cause. Fortunately, it has been possible to patiently gather much evidence with other low-disturbance techniques to identify the bats in residence. During the study, trips into the cave during the summer were greatly reduced or taken during the night while the bats were out of the cave feeding. Head lamps, with red filters, were used whenever work was performed near the bat roost.

Additional low-disturbance techniques have included examination of bone material and carcasses inside the cavern for species identification; handling only a couple of isolated bats within the cavern for species identification; noting changes in the guano after bats have exited at night to determine which areas are utilized by bats; observing the presence of non-volant juveniles after adults have exited at night to determine maternity use; banding animals outside and away from the roost to confirm cavern use by these individuals when the reflective tags were observed while bats flew from the entrance during the evening exit ; and netting bats outside and away from the roost in order to determine events in the reproductive cycle of the population. Using these techniques a number of bat species have been identified from the interior of Kartchner Caverns. These identifications are based upon observations of live bats and collection of preserved material.

From observations of live animals:

- Myotis velifer
- Plecotus townsendii
- Choeronycteris mexicana
- "small bat" species (small Myotis spp. or Pipistrellus)

Bone specimens:

- Myotis spp.
- Myotis velifer
- Myotis occultus
- Leptonycteris sanborni
- vespertilionid bat bones

The number of bats using the cave has been estimated by careful counts of individuals during the exit flight. Due to the constricted passages near the entrance, bats are forced to leave in small groups which are easily counted. The results of numerous counts made in past three years is shown in Figure 4. The increase in estimated population size from April through August is partially due to the summer birth rate and to recruitment of volant juveniles or adults from other roosts. However, other roosts are not known in the area.

From both public-interest and scientific viewpoints, Kartchner Caverns is even more exciting as a bat roost because it houses a maternity colony. This means also that continued responsible and knowledgeable management is necessary for the bats. From our observations in the cavern and at the cattle tank, we know the period from mid-June to early August is the time when females are in late stages of pregnancy, parturition, or lactation, and juveniles are developing and fledging. This is the critical period of time when the bats require non-disturbance to assure healthy behavior, and in turn, successful reproduction and continued population growth.

In 1990 a BCI bat house was installed on a pole below the main roost site to see if it would be used if available. A temperature probe was also installed and hooked up to the data logger. This allowed us to determine if the bat house was being used from the temperature record. Apparently the bats never used the bat house. We felt that the reason bats did not use the house was that it was much lower than the ceiling and also was attached to a pole which might interfere with flying. In the spring of 1991 the original bat house was removed and two new ones were installed on the ceiling near the roost site. One of these was a new BCI wooden bat house similar to the one previously installed. The second bat house was constructed from two large plastic flower pots, nested together and hung upside down. A temperature probe was installed in the BCI bat house. Both bat houses were washed with a mixture of water and bat guano from the cave to provide a familiar "lived in odor". Preliminary results indicate that neither of these bat houses were occupied during the summer of 1991. This indicates that it is unlikely that attempts to relocate the bats to other areas of the cave would be successful.

The presence of a healthy bat population in Kartchner Caverns provides much potential for scientific interest. For a state park, however, what is perhaps more important is that the bat population provides opportunity for public eduction about these increasingly popular animals and about the exciting and interesting ecology of a subterranean ecosystem. This will require that development of the cave not disturb the bats or drive them from the cave. Options for maintaining the bat population after development are:

- Limit visitor use of the Big Room while bats are present.
- Attempt to entice the bats to use another portion of the cave.
- Mitigate the impacts of development on the bats by trail alignment, low level lights and providing a bat house on the ceiling.

The first option is clear but would limit visitation to the Big Room from May to mid-September. The second and third options have never been successfully implemented in any other cave. The preliminary results from the bat houses placed in Kartchner indicate that there is little reason to expect that the bats could be successfully relocated.

GEOLOGIC STUDIES

The geologic study was conducted to provide a detailed understanding of the geologic setting of Kartchner Caverns and the surrounding area. The objectives of the surface and subsurface geological investigations are twofold: (1) to provide geological engineering information critical to the evaluation of potential visitor access points and (2) to provide a detailed understanding of the geological setting and speleogenesis of the cave.

The geological studies include investigations of the surface geology, subsurface geology, speleothems (cave decorations), mineralogy, sediments, speleogenesis and geophysical explorations to identify unknown extensions to the cave.

The detailed geologic database referenced above provides geological engineering information critical to the evaluation of potential visitor access points. It also provides geological interpretations essential for the understanding of how meteoric water enters the cave--along faults, fractures, and as perched aquifers on top of impermeable marker beds. This understanding should ultimately allow better management of the delicate cave resources.

The surface geology of the entire Kartchner Caverns State Park was mapped by Dr. Kenneth C. Thomson as part of the initial geologic study. The geologic mapping of the Kartchner Caverns State Park revealed a highly faulted and fractured block of Paleozoic limestones. These limestones, consisting of Pennsylvanian Horquilla Limestone, Pennsylvanian Black Prince Limestone, Mississippian Escabrosa Limestone, Devonian Martin Formation, and Cambrian Abrigo Limestone, have a general dip to the west ranging from 10 to 45 degrees. The fractures or joints have been solutionally enlarged near and at the surface. These minor fractures were probably formed in conjunction with the major normal faults which cut through the limestone with displacements up to several hundred feet. The rock units have been covered in many places by unconsolidated sediments of varying ages from very recent back to Late Tertiary/Quaternary time. This outlying block of limestone has both an east bounding fault (revealed by geophysics) and a west bounding fault.

A more detailed map of the geology of the cave and surface geology of the area overlying the cave was performed by David H. Jagnow. His study focused in greater detail on the structural geology and subdivisions within the Escabrosa Limestone block that contain Kartchner Caverns.Kartchner Caverns is contained entirely within a highly faulted and fractured block of Escabrosa Limestone. The detailed mapping focused on the key marker beds within the Escabrosa Formation, and the associated structures. Identification of key marker beds allowed the surface and interior geology to be closely correlated by projecting surface features into the cave.

The majority of faults cutting Kartchner Caverns are high-angle normal faults that trend northeast from 20° to 60°. Most of these faults are either vertical or dip steeply to the southeast from 90° to 75°. The displacement on these faults is usually less than 10 feet, being down-thrown on the southeast side--a typical normal fault. There are occasional reverse faults, where the fault plane is dipping to the southeast, yet the southeast side is upthrown.

The present study has identified no less than 60 faults that cut or bound the Kartchner Block. The vast majority of these faults are high-angle normal faults that trend NE. Where the displacement and dip of the fault plane is known, there are only 5 known high-angle reverse faults. There are three low-angle faults (dipping 40° to 45°), of which two are normal, and the third shows reverse displacement. There do not appear to be any true thrust faults cutting the Kartchner Block.

The most complexly faulted portion of the Kartchner Block is directly over the Big Room. The high concentration of faults in this area is probably responsible for the increased solubility that formed the Big Room. The majority of faults cutting Kartchner Caverns are high-angle normal faults that trend northeast from 20° to 60°. Most of these faults are either vertical or dip steeply to the southeast from 90° to 75°. The displacement on these faults is usually less than 10 ft., being down-thrown on the southeast side--a typical normal fault. There are two reverse faults, where the fault plane is dipping to the southeast, yet the southeast side is upthrown.

During the course of this study, particular attention was paid to the unstable or potentially dangerous areas throughout the cave. A separate map was prepared locating geologic hazards. These were classified into three categories:

A) Structurally Hazardous Areas
B) Hazardous Ceiling Blocks
C) Incompetent Beds

Geophysics Studies were performed by Arthur L. Lange and Phillip A. Walen of The Geophysics Group. More complete results of their investigations are included in a separate paper in these proceedings.

Geophysical investigations have been performed to map the sub-surface and to detect the presence of auxiliary caverns. Electromagnetics were employed to map near-surface groundwater levels, while a natural-potential survey over the entire Park identified zones of infiltration in the valley alluvium and likely cavern targets in the carbonate outcrop. A gravity survey delineated range-front faults and resulted in a map of depth-to-bedrock beneath the valley alluvium. Although the gravity survey could not resolve the carbonate/schist boundary, it portrayed the regions of shallow bedrock that control ground-water flow and storage. The gravity survey also produced significant anomalous lows over two of the three main cavern sections and identified sites likely underlain by cave galleries not yet discovered.

MINERALOGY

An assessment and inventory of the cave minerals and sediments of Kartchner caverns was performed by Carol Hill. The mineralogy of Kartchner Caverns is both diverse and significant. It is diverse in that six different chemical classes are represented by the cave mineralogy: the carbonates, nitrates, oxides, phosphates, silicates and sulfates. It is significant for a number of reasons:

1. World's longest soda straw 21'-2".
2. Largest and most massive column in Arizona - 58 foot high Kubla Khan.
3. First reported occurrence of nontronite and rectorite as cave minerals.
4. First cave occurrence of "birdsnest" needle quartz. This type of quartz is known only from Jeffrey Quarry, Arkansas.
5. Rare occurrence of nitrocalcite as a cave mineral. First modern description of this mineral.
6. One of the most extensive occurrences of brushite moonmilk in the world.
7. First reported occurrence of "turnip" shields."

The diverse and interesting mineralogy of Kartchner is due to an unusual set of circumstances. Unlike most limestone caves, Kartchner Caverns is located near igneous terrain. Alaskite granite borders the Escabrosa Limestone along fault zones to the west, and the Pinal Schist underlies the cave. The dry Arizona desert supplies another condition: the low relative humidity causes the efflorescence of nitrocalcite in the entrance zone of the cave. Bats add the third ingredient, phosphates and nitrates. In setting and mineralogy, Kartchner Caverns most nearly resembles the caves of the Transvaal, South Africa, where a hot and dry climate combined with an igneous rock-bat guano source of cations and anions has produced an unusual cave environment in which a number of minerals can form (Hill and Forti, 1986).

The carbonate mineralogy of Kartchner Caverns is relatively simple, consisting almost entirely of calcite, $CaCO_3$. While mineralogy is simple, the number of carbonate speleothem types and subtypes is extensive.

Kartchner Caverns is distinguished in that it has the longest known soda straw in the world - "The Soda Straw" in the Throne Room measured at 6.45m (21.16 ft) long. This length beats the previous world of 6.24 m (20.47 ft) in a western Australian cave (Hill and Forti, 1986).

Columns form where a stalactite and stalagmite grow together. Kartchner Caverns has the tallest, and probably most massive, column in Arizona - the 58 foot tall Kubla Khan in the Throne Room.

Nitrocalcite. ($Ca(NO_3)2 \cdot 4H_2O$) is a deliquescent mineral, efflorescent only under very low humidity conditions (around 50% or so for a normal range of cave temperatures (Hill and Forti, 1986). In Kartchner Caverns, nitrocalcite occurs as cave cotton growing from sediment in scattered areas along the Entrance Passage (e.g. Babbitt Hole, LEM Room) where cold, dry winter air flows into the Entrance Passage from the surface. The growth of nitrocalcite in the Entrance Passage correlates with episodes of low relative humidity in the winter months.

Two phosphate minerals have been identified in Kartchner Caverns: Brushite, $CaHPO_{4 \cdot 2H2}O$, and hydroxylapatite, $Ca_5(PO_4)_3(OH)$. Both are common cave minerals which derive from bat guano (Hill and Forti, 1986).

Four silicate minerals have been found in Kartchner Caverns: illite, nontronite, rectorite and quartz. The last of these, quartz, occurs as vein deposits within fault zones or as needle crystals in or near fault zones. The first three are all phyllosilicate $[(Si, Al)_4O_{10}]$ clay minerals which are found as floor sediment or as clay material filling fault zones.

Potential Entrances

At the present time there is only one entrance into Kartchner Caverns, the original discovery entrance. To reach the main rooms of the cave, one must crawl for several hundred feet through small passages. To develop the cave, a new entrance will need to be constructed. The preferred access point must lead conveniently to the part of the cave people will see, dovetail into a planned traffic pattern, accommodate the number of people that the cave can carry, be amenable to microclimate controls, structurally stable, able to be excavated, and accessible to security supervision. A total of 10 different locations for constructing a new entrance into the cave were investigated. For each location, three schematic designs were considered: a wheelchair-accessible ramp, a flight of stairs and an elevator. For each of these 30 combinations, an assessment was made of the potential for disrupting the microclimate of the cave. Preliminary results from the microclimate study indicate that the potential for increasing airflow and subsequent moisture loss is the most important issue to be considered. Other factors included in the assessment were impacts on the supply of moisture to the cave and impacts on the biota. The biota is not only an important feature of the cave but also provides a sensitive indicator of the conditions within the cave. In the analysis of the potential entrances, a number of severe impacts to the cave were found. These are impacts associated with a particular entrance configuration which would jeopardize the integrity of the cave if that entrance were to be constructed. Three types of severe impacts were identified.

- Entrance tunnels which would disrupt the infiltration of water from the adjacent washes.
- Identification of portions of the cave which are subject to frequent flooding. Such flooding would prevent visitors from entering the cave for several months.
- Entrances which impact a known active bat roosting site or which would result in visitors conflicting with the bats' flight out of the cave.

Potential entrances were also evaluated in regard to development considerations. These include distances to major cave features, length and slope of access tunnels and distance from potential visitor center locations.

Based on a weighted point system, the following three potential entrance locations were judged to be the most favorable.

- Tarantula Room
- Echo Passage
- Throne Room

Future detailed studies will focus on the geology of these locations. Additional studies should be performed to determine a suitable trail system for the interior of the cave based on these entrances.

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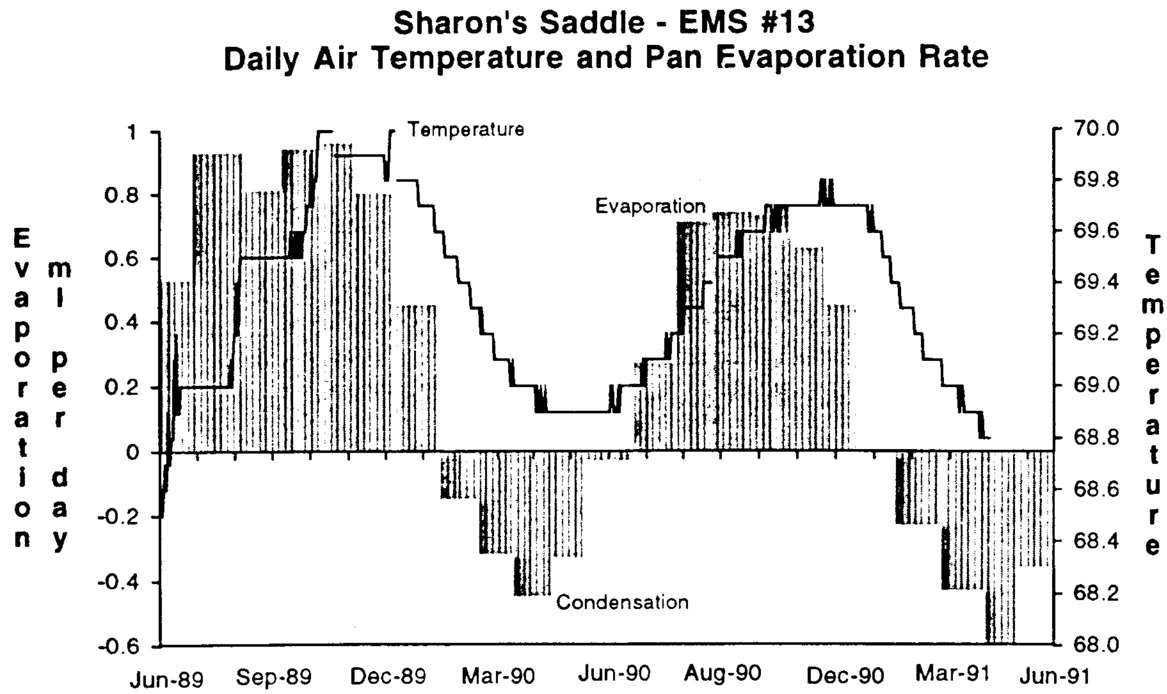

Figure 2. 24 month record of temperature and evaporation from one of the 22 monitoring stations. One ml per day of evaporation is equal to 0.38 inches per year.

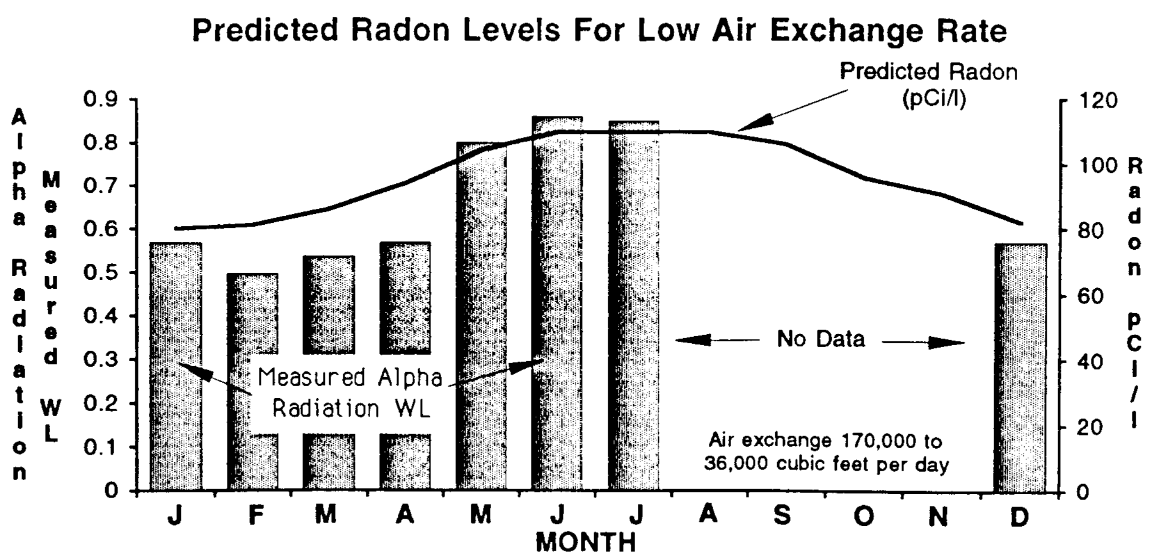

Figure 3. Annual variation in radon gas concentration modeled by ventilation. Note that no conversion factor is implied between radon gas and Working Level.

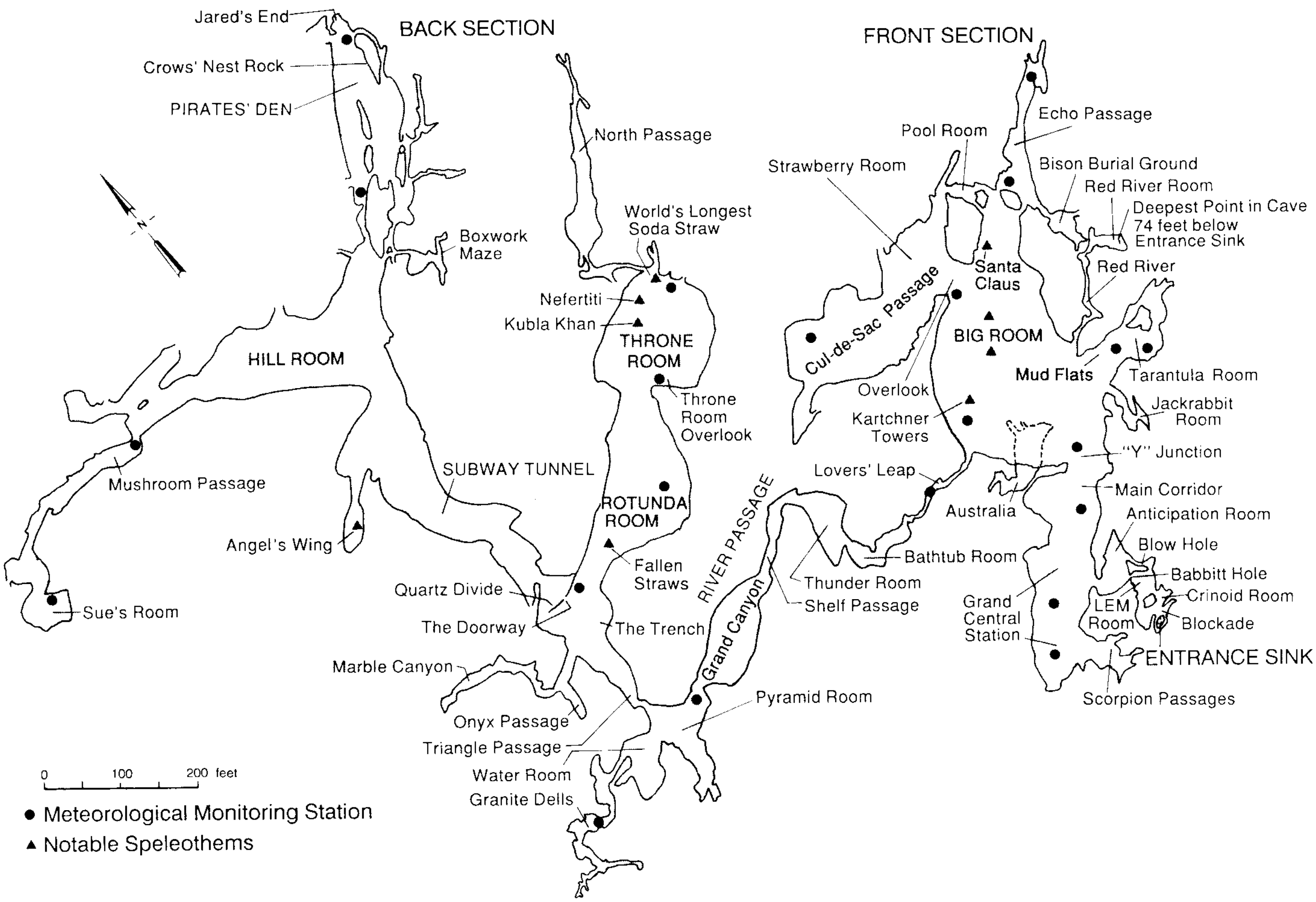

Figure 1. Outline map of Kartchner Caverns. Reprinted from Graf, 1990

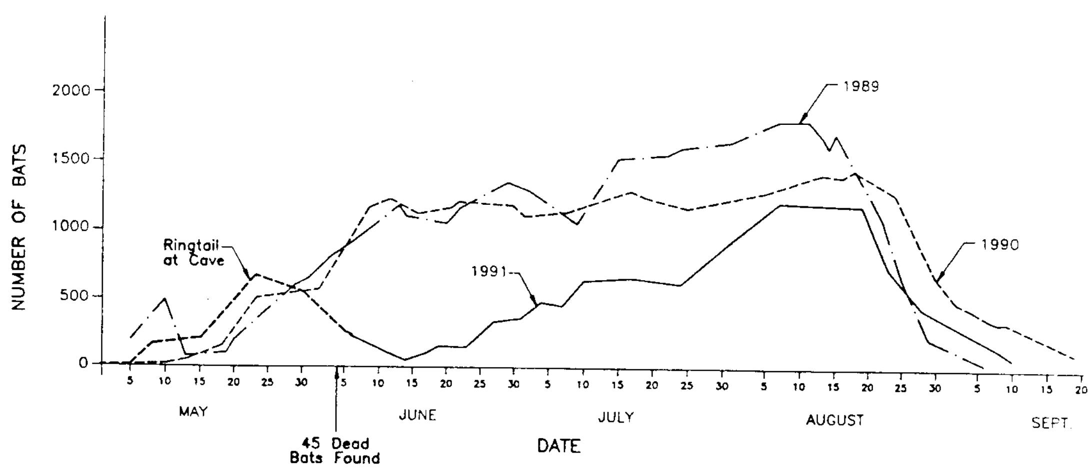

Figure 4. Number of bats utilizing Kartchner Caverns from 1989 to 1991 as determined by exit flight counts.

1991
National Cave Management Symposium Proceedings

Bowling Green, Kentucky
October 23 - 26, 1991

Hosted By:

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National Speleological Society
The Nature Conservancy
Richmond Area Speleological Society
U.S. Fish and Wildlife Service
U.S. Forest Service

Symposium Program Chairmen:
David G. Foster and Ronal C. Kerbo

Designed and Produced by
The American Cave Conservation Association
Horse Cave, Kentucky

Senior Editor: Debra L. Foster
Associate Editors: David G. Foster, Mary M. Snow, Richard K. Snow