Memorandum

• State Parks •

To: Jean Emery
Chief of Resources Management

From: Rick Toomey
Cave Resources Manager
Kartchner Caverns State Park

Date: April 11, 2002

RE: Kartchner Caverns 2001-2002
Annual Report

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I have been employed by Arizona State Parks as the Cave Resources Manager for approximately one year. During that time, I have been involved in a variety of activities related to improving the environmental protection of Kartchner Caverns. These activities relate to 1) assessing the environmental state of the cave; 2) developing improved methods of monitoring the cave, cave resources, and related surface environments; 3) analyzing threats to the cave environment and recommending mitigation or avoidance strategies; and 4) improving our interpretation of the cave.

Although it is impossible to cover the full range of cave protection and operations issues on which I have worked over the past year, I will try to highlight some of the most important and far-reaching ones in the attached report, Kartchner Caverns Cave Resources Manager's Annual Report 2001-2002 and Supplement. In particular, I have addressed aspects of cave environment and climate, scientific oversight and advising, bat usage of the cave and park, algae and bacteria growth, surface land use issues, Big Room development and planning, and inter-agency outreach and cooperation. Because this report follows only my first year, many of its conclusions are preliminary and many of the projects to improve monitoring are still under development. However, I feel that it is important to provide you with even preliminary interpretations, in order to begin discussion of potentially important issues. Likewise, I am including descriptions of on-going projects so you can see the directions my efforts are taking.

As you might anticipate, each of the major areas with which I will be dealing in this report is complex. The information provided in this report is a fairly simple and generalized treatment of each subject. Full treatment is beyond the scope of this report. I would be happy to prepare individual reports on these or additional issues, if the Board would like.

Overall, the environmental health of the cave is very good for a show cave; this is the best we can reasonably hope to achieve. Development and tourism almost always results in significant alteration of the cave environment. Kartchner Caverns is not an exception to this, although the degree of alteration is lower than is often seen. We must continue to work to guarantee the changes we have made do not interfere with the natural functioning of the cave any more than is necessary.

Although issues that raise concerns for the cave come up constantly, ASP staff (at KCSP, in the regional office, and in Phoenix) also work constantly to address these concerns. I have been very pleased with the level of support that I have had in working to protect and conserve Kartchner Caverns. I believe that we will make progress on addressing existing areas of concern. I look forward to another successful year and hope to report next year that the cave remains in good environmental health.

Enc.

CAVE RESOURCES MANAGER'S ANNUAL REPORT 2001-2002

Rickard S. Toomey, III, Ph.D.
Cave Resources Manager
Arizona State Parks

April 18, 2002

During the past year since joining Arizona State Parks as Cave Resources Manager for Kartchner Caverns State Park, I have been involved in numerous activities devoted to monitoring the environmental condition of Kartchner Caverns. These responsibilities have included establishing data collection procedures, analyzing such data, and providing expertise on issues related to the operation and continuing development of Kartchner Caverns as an Arizona State Park.

This report summarizes those activities under the following topics:

- Cave Environment and Climate – Data Collection and Analysis
- Measures taken to inhibit undesirable Algae and Bacteria Growth
- Bats in the Cave and on the Park
- Establishment of a Scientific Oversight and Advisory Committee
- Continuing Development of the Big Room portion of the Cave
- Providing Expertise on Surface Land Issues Potentially Impacting Cave Resources
- Exploration of Interagency Outreach and Partnering Opportunities

Because I have been on staff for approximately one year, many of the efforts outlined below are still in their infancy. Correspondingly, scientific conclusions based on the collected data are at best preliminary, and in some cases premature. Analysis continues as monitoring and management measures stabilize and take hold.

Cave Environment and Climate

Measures undertaken in 2001-2002:

- **Installed approximately 50 temperature data loggers to monitor temperature and humidity in cave and tunnels**
- **Completed digitization of monitoring data from existing stations**
- **Identified source of more sophisticated cave environmental monitoring system and continue to negotiate plan for installation of a custom system**
- **Initiated program for upgrading surface weather monitoring stations at the Park**
- **Began installing meters to quantify energy input into cave**

- **Instituted plans to re-establish former deep cave data logger stations**
- **Provided assistance in radon licensing process**
- **Continued monitoring and assessment of cave carbon dioxide levels**
- **Conducted daily, ongoing analysis of collected data**

The following paragraphs set out in somewhat more detail the measures undertaken this year to improve and upgrade data collection and analysis of the cave's microclimate. A summary analysis of the data itself and my preliminary observations about the significance of the data appears at the end of this report in the Supplement.

- **<u>Installation of New Data Loggers</u>**

Environmental monitoring at the cave has been upgraded during the past year in several ways. Approximately 20 HOBO and 30 Thermochron data loggers have been installed throughout the cave and tunnels to supplement the 13 existing environmental monitoring stations. These temperature data loggers are small electronic thermometers attached to computer chips. They can be programmed to measure temperature at set intervals and store the data for extended periods of time, reducing the number of visits to a station by Park personnel. The loggers make possible more frequent (up to once a minute, but more often once every 10 minutes) monitoring of conditions and the collection of data from more sites than is possible with hand collection. They have been installed at many of the existing environmental monitoring stations, permitting more frequent, precise temperature data at those sites. They are also being installed in less accessible areas where environmental monitoring stations are impractical.

Several of the data loggers have been dedicated to shorter-term, specific temperature-related issues, such as measuring temperatures around certain lights or in electrical rooms. For comparison purposes, temperature data loggers have been installed in one of the small caves on the Park, in a cave on the Coronado National Forest, and in the bat roost in the bridge over Guindani Wash on the Park.

- **<u>Digitization of previously existing data</u>**

During the past year, records from the existing environmental monitoring stations and weather station have been transferred entirely to electronic media and the data has been quality-checked. In addition, new databases have been created to facilitate improved monitoring of certain specific environmental variables and indicators, and the tracking of trends.

- **<u>Higher-precision monitoring system</u>**

Because of the great need for a more sophisticated, higher-precision monitoring system, I have investigated developing the specifications for such a high-precision, high-accuracy, data logging environmental system to track temperature, humidity, barometric pressure, and air movement in the cave. I have located a source of a possible custom system and we have initiated discussions about the Park's data requirements and the cost and functionality of such a system.

- **<u>Surface Weather Stations</u>**

  An agreement is being finalized with the University of Arizona (as part of the advisory process) to install a modern surface weather station at the Park to aid in the tracking of surface climate. Surface weather data is important because cave climatic conditions are intimately tied to surface conditions.

- **<u>Reestablishment of Remote Monitoring Stations</u>**

  Temperature and evaporation monitoring is being re-established at several of the environmental monitoring stations located in the more distant locations of the cave. These stations, for instance, at Sue's Room and Pirates Passage **(Figure 1)**, were removed after the pre-development studies partially in response to concerns that the monitoring of these stations required repeated staff travel through wet, muddy areas of the cave and carried significant long-term impact. With the reduced in-person collection requirements of the newly installed data loggers, these stations can be re-established without frequent, damaging trips. Data from these stations will be useful in assessing whether development changes remain localized or can be noted in the more distant reached of the cave.

- **<u>Installation of energy monitors</u>**

  Reducing excess energy input into the cave is one approach to minimizing the impacts of development and visitation. As a component of quantifying the energy added to the cave, ASP has contracted to install electrical usage monitors in the cave. These monitors will document energy inputs in certain areas, providing the basis for identifying areas where such energy inputs can be reduced. I am also working on modeling other factors that input energy into the cave and their contribution to the cave energy balance.

- **<u>Radon licensing</u>**

  In 2002, the Arizona Radiation Regulatory Agency issued a radon license to ASP for the duration of the development of the Big Room. The University of Arizona Radiation Control Office worked with ASP to develop a radon monitoring program and has agreed to oversee ASP's radon monitoring activities. Under the radon program, radon decay products are measured daily in several areas of the cave (both tour and development sections).

- **<u>Monitoring Carbon Dioxide Levels</u>**

  Elevated carbon dioxide levels can affect the cave health by increasing dissolution of calcite, by slowing deposition of speleothems, and by encouraging growth of algae. Carbon dioxide (CO_2) levels in Kartchner vary greatly in space and time. Current data remains comparable to that obtained in the pre-development studies and data collection remains ongoing.

Algae and Bacteria Growth

Measures undertaken during year:

- **Established database to improve monitoring of algae growth and treatment**
- **Continued to limit algae growth through diligent control with bleach**
- **Tested hydrogen peroxide as a possible replacement for bleach as potential algae control agents**
- **Reduced potential for algae growth by minor modifications of lights and misters**
- **Working with development to take algae control in to account when placing lights in Big Room**
- **ISA with Dr. Maier for study of slime producing bacterial colonies associated with fiberglass fixtures**

Algae growth is a widespread, and serious, problem among lighted show caves. Algae grow well in warm, humid, high carbon dioxide places such as caves. Normally, an essential element for algae growth is lacking--light. But when light is added to a cave to allow visitor tours, algae may "bloom" in an uncontrolled manner. This problem is so widely known that it has been given a name: "lampenflora."

Precautions were taken during the development of Kartchner to minimize algae growth. The cave lighting design permits limited use of the lights only for brief periods during each tour, inhibiting the type of growth that would occur if the lights were left on for hours. In spite of this, small amounts of algae growth have been found in the cave. In the tunnel, where lights do remain on continuously during tour hours, somewhat more algae growth has been observed. Any such observations are immediately addressed by cleaning the area affected by algae with a weak solution of bleach. To reduce the potential for either initial growth of algae or re-growth where it has been found, a program to modify lights, misters, and camouflaging methods to eliminate situations conducive to algal growth has been instituted.

This year, a database was devised to record all algae observations and control measures taken by the cave unit. Studies have also been initiated to determine if solutions other than bleach are more effective in controlling growth.

A similar, but not related problem to that of algal growth, is the growth of slime-producing bacterial colonies on some fiberglass surfaces in the cave. This problem does not appear to be related to lights, and the bacteria do not need light to grow. Instead, it appears that the bacteria are able to grow more vigorously (and produce slime) on some of the moist fiberglass pieces that have been used to hide man-made features along the Rotunda-Throne tour route. ASP has commissioned a research study by Dr. Raina Maier, an environmental microbiologist in the Department of Soil, Water and Environmental Sciences of the University of Arizona, to characterize the bacteria colonies, determine whether the problem is related to the fiberglass, the paint used to disguise the fiberglass, or other factors, and assist in designing solutions that will not promote growth of the bacterial colonies and will control growth on existing surfaces. The study should be completed in 2002.

Bats in the Cave and Park

Notable activities and observations:

- **Bats continue to use cave despite on-going Big Room development**
- **Drafted and sought peer review of formal protocols for determining Big Room closure dates**
- **Improved monitoring and archiving of bat sightings on Park**
- **Identified several significant bat roosts on Park and off**
- **Begun temperature study of Guindani Wash bridge roost**

The bats at Kartchner Caverns are vital to the cave's continued environmental health. They provide the guano that is the basis for the cave's internal ecosystem. As is well-known, the cave serves as an important maternity roost for the cave *Myotis* (*Myotis velifer*).

The Big Room in the portion of the cave currently under development is the primary maternity roost area for the cave *Myotis.* With development nearing completion and the approach of the Big Room's opening to public tours, we have drafted a protocol for determining when the Big Room should close and re-open for tours due to the presence of the bat maternity colony. The draft protocol has been reviewed by a number of biologists including Ronnie Sidner, Katy Hinman, Bob Steidl, and Sherry Mann. Their comments are being incorporated into the final protocol.

In addition to the maternity colony of cave *Myotis*, several other bat species occupy the Park, including a small colony of Mexican long-tongued bats, a moderate-sized colony of Mexican free-tailed bats, a small colony of pallid bats, and a few individual big brown bats. Bat colony monitoring has been expanded in the Park to provide data on areas within the Park used by these bats.

Scientific Oversight and Advising

Key accomplishments for year:

- **Established basis for oversight and advising committee**
- **Solicited interested faculty and staff at University of Arizona**
- **Initiated Interagency Service Agreement Process to legally form Committee**
- **Finalized Interagency Service Agreement for bacterial slime research study**
- **Drafted and sought peer review of bat protocols**

- **Cooperated with committee members in identifying desirable research projects**

During the past year, we have facilitated the formation of a scientific oversight and advising committee comprised of faculty and research scientists primarily from the University of Arizona. The Science, Education, and Research Advisory Committee ("SERAC") will provide expertise in a variety of scientific fields relevant to the continued stewardship of Kartchner Caverns, including hydrology, geology, soil and water sciences, renewable natural resources, and microbiology. An interagency service agreement has been drafted formalizing the relationship between ASP and the University. It is currently under review by the representative authorities.

The Committee has already formally met and members have, on a more informal basis, begun providing assistance and advice on various issues. One such example is the development of a research study, to be conducted by Dr. Raina Maier, to understand the bacterial slime growth that occurs on fiberglass in the cave and develop ways to eliminate this problem. Dr. Paul Brown has assisted in understanding local climate data and in developing a plan for improving the park's weather stations. Drs. Bob Casavant and Karl Glass have provided important geologic information on the park. Dr. Casavant has also developed several educational programs relating to geology that have already proved beneficial to the Park and provided research opportunities for his university students. Dr. Bob Steidl has helped review draft protocols for determining the dates of closure of the Big Room due to bat usage. Drs. Julia Cole, Jonathan Patchett, and Warren Beck are developing proposals to study recent and past climate change as well as cave processes.

Big Room Development and Planning

Key accomplishments for year:

- **Provided scientific assistance in development decisions relating to the opening of the Big Room**

During the past year, I have been involved with numerous projects and meetings regarding the development of the Big Room for public tours. This has included working with the development unit in construction and lighting decisions, and assisting the Big Room committee working to develop a workable tour schedule, appropriate tour size, and proper interpretation.

Surface Land-Use Issues

Key activities:

- **Provided evaluation of potential impacts of proposed Whetstone Springs resort development**

- **Consulted with outside experts regarding potential impacts of proposed resort development**
- **Worked with U.S. Forest Service regarding wild fire issues that might affect cave**
- **Work with ASP staff on land use and operations issues that might affect cave.**

In June 2001, ASP learned of a request to rezone a parcel of land on Kartchner Caverns State Parks northeast boundary. The rezoning would permit development of a large, luxury resort complex. Upon analysis, it was concluded that the resort would be constructed on the same geologic formation, the Kartchner Block, occupied by the cave, and the potential hydrological connection could have adverse impacts on the amount, distribution, or quality of the water entering the cave. Any of these modifications could cause great harm to the cave environment. An outside consultant retained by ASP to analyze the situation concluded that a hydrologic connection between the parcel of land to be developed for the resort and the caverns was more likely than not. Based on this assessment, the Arizona State Parks Board authorized the filing of an eminent domain suit on the 159.99 acres of land on the park's northeast boundary. The action is currently pending in Cochise County Superior Court.

Wildland fires and associated fire-fighting activities could impact Kartchner Caverns, in particular, the potential contamination of the cave by air-dropped fire retardants and foams by way of a direct drop on the cave area or through watershed runoff. I have been in consultation with the U.S. Forest Service to assist in developing a fire management policy in the Kartchner Caverns area.

Inter-Agency Outreach and Cooperation

Key activities for year:

- **Working with numerous governmental and non-governmental groups to improve management and protection of Kartchner Caverns and its resources.**
- **Working with numerous governmental and non-governmental groups to improve management and protection of other caves, cave resources, and bats.**

During the past year, I have initiated and encouraged cooperative and collaborative efforts with other governmental and non-governmental groups working on cave and bat issues. These include hosting field trips for cave management seminars and meetings, participating in professional conferences, and meeting with representatives of federal and state agencies on numerous cave protection issues.

The Coming Year

Plans for 2002-2003 call for the continuing collection and analysis of data. As data from the additional data loggers accumulates and with the hoped for installation of the custom monitoring system in the next year, trends may be discerned and measures will be taken to address problems. Concentrated efforts will continue to reduce energy inputs, such as the modification of lights and lighting durations. The formation documents for SERAC will be finalized and ASP and the Committee will move forward to review and develop needed research projects. Observations of bat occurrences will continue and a protocol for operation and management of the Big Room relating to the cave's bat colony will be put in place. ASP will continue to seek scientific advice and consultation on issues relating to protection of the Kartchner Caverns resource.

SUPPLEMENT

CAVE CLIMATE CONDITION:
A PRELIMINARY ANALYSIS OF COLLECTED DATA TO DATE

Cave Climate

The data collected from the cave since 1988 indicates that changes in the cave microclimate have occurred and are continuing to occur. While some of these changes appear to be tied to the development of the cave, sorting out the various contributing causes to these changes is difficult. Some of the factors are anthropogenic (human-caused); others are the result of natural processes. And some of the changes are probably the result of the intersection of natural and anthropogenic factors. This report presents a summary of some of the data collected during the past year, and when appropriate, suggests some possible interpretation of that data.

Different areas of the cave show different patterns of cave climate change. The differences may relate to differences in the development and use of various areas of the cave. They may also be the result of inherent differences in areas, such as air and water flow patterns in the cave. To illustrate the difficulty in reaching one overall assessment of the cave climate and to provide the broadest cross-section of results, this report outlines the data from three environmental monitoring stations in the cave: Echo Passage, Cul De Sac, and Lower Throne. Their locations are shown in **Figure 1**. Echo Passage is an undeveloped area of the cave; Cul De Sac is an area currently under development; and Lower Throne has been developed and is open to public tours. Cave climate data has been collected at each of these stations from 1988 to the present.

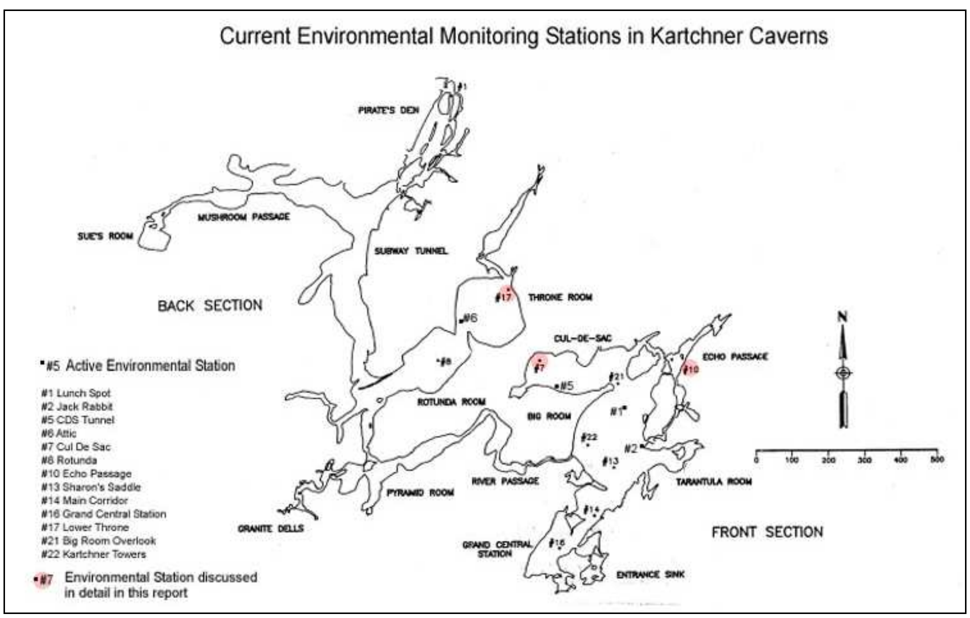

Figure 1 -- *Map of Kartchner Caverns showing locations of the currently active environmental monitoring stations. The stations that are discussed in detail in this report are marked in red. This map is modified from the ACPI final report.*

Discussions of cave climate focus generally on measures of cave temperature and moisture. The temperature measure used here is air temperature, while the moisture measure is relative humidity. **Figures 2, 3,** and **4** summarize the temperature and moisture histories at three stations. Each graph shows the air temperature at an environmental station (small beige diamonds), a five-reading moving average of the air temperature (red line), the relative humidity at the station (small blue squares), and a five-reading moving average of the relative humidity (blue line). Because the individual data vary from reading to reading, the moving averages provide the most straightforward tracking of temperature and humidity.

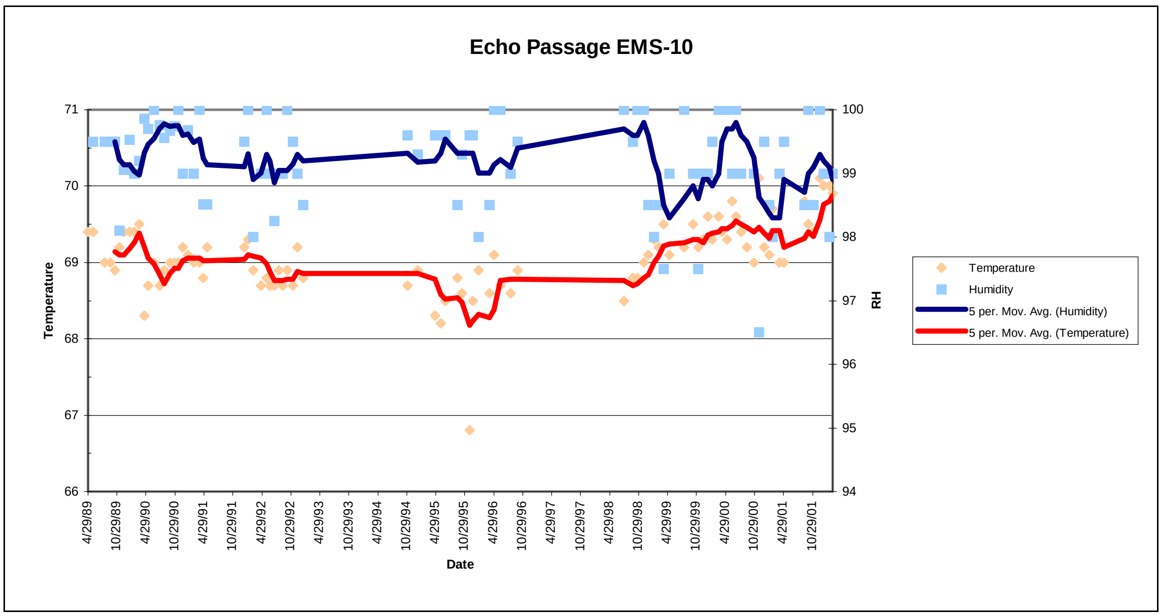

Figure 2 -- *Temperature and relative humidity data and trend at the Echo Passage environmental monitoring station (EMS-10).*

Echo Passage

Figure 2 shows the climate data from the environmental monitoring station in Echo Passage. This station is the existing deep-cave station that is furthest from current development impacts or visitor tours (**Figure 1**). The data suggest a small change in temperature or humidity has occurred in this area. The temperature during the development phase (October 1998 to present) shows a small increase (about 0.5-1°F compared to pre-development temperatures). The humidity shows a small but statistically significant decrease during the period of development (from a mean relative humidity of 99.3% from 1989-1998 to a mean of 98.9% from 1999 to the present; unpaired, one-tailed, heteroscedastic, t-test probability p = 0.016), and it shows somewhat greater variability in humidity from reading to reading (1989-1998 standard deviation 0.57 to 1999-2002 standard deviation 0.88). However, overall this station shows relatively little change in temperature and relative humidity from pre-development to the present.

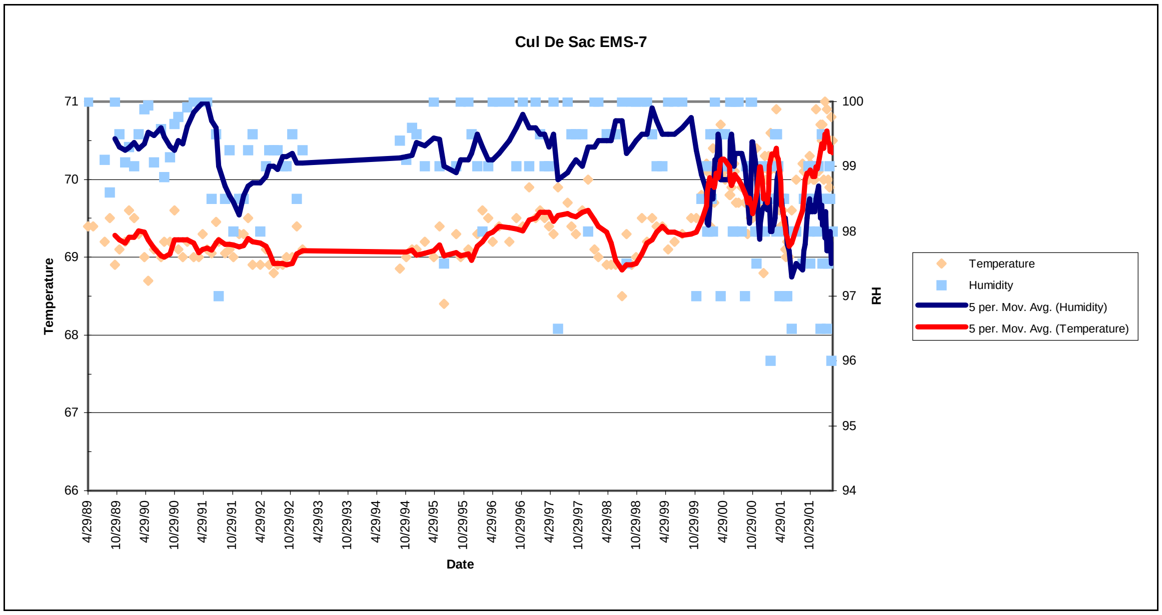

Figure 3 -- *Temperature and relative humidity data and trend at the Cul De Sac environmental monitoring station (EMS-7).*

Cul De Sac

The Cul De Sac environmental monitoring station shows a somewhat larger change in temperature and humidity (**Figure 3**) than seen at Echo Passage. This station is near the trail being developed in the Big Room complex, a portion of the cave not yet open to public tours. This station is experiencing cave activities associated with development (development lighting and personnel levels, construction, concrete pours), but not with tours (tour style lighting and visitation levels). The data from Cul De Sac shows an approximate 1°-Fahrenheit rise in temperature since the beginning of 1999. The trend of generally rising temperature reversed for a period in the spring of 2001. This reversal is discussed further below.

An important difference between the Cul De Sac and Echo Passage trends is that the temperature change in the Cul De Sac is accompanied by a larger change in humidity as well. Between 1989 and the end of 1998, the humidity at the station had a mean of 99.28% (standard deviation 0.73%). Since the beginning of 1999 the humidity at the station has been generally lower and more variable (mean 98.5%; standard deviation 0.97%). The decrease in relative humidity at this station between these periods is statistically significant (unpaired, one-tailed, heteroscedastic, t-test probability $p = 6.0x10^{-9}$). Another environmental monitoring station with similar temperature and humidity trends to the Cul De Sac station is Kartchner Towers. The stations at Sharon's Saddle, the Big Room Overlook, and Main Corridor show trends somewhat between those of the Echo Passage and Cul De Sac stations.

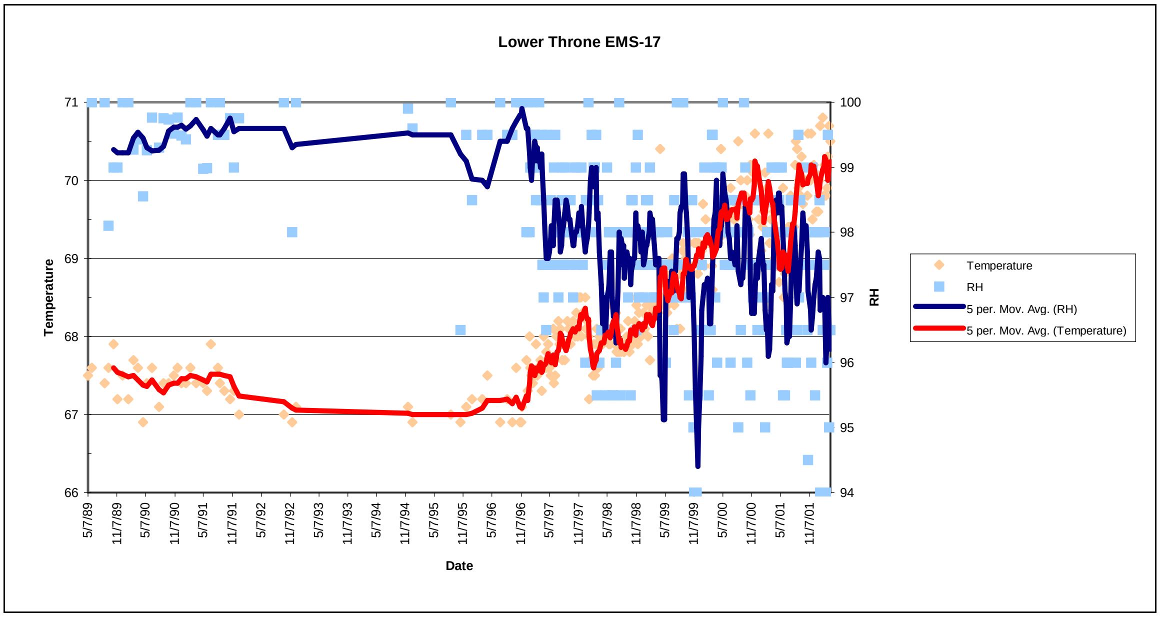

Figure 4 -- *Temperature and relative humidity data and trend at the Lower Throne environmental monitoring station (EMS-17).*

Lower Throne

The Lower Throne environmental monitoring station shows notably larger changes in temperature and humidity (**Figure 4**). This station is in the Rotunda-Throne section of the cave, an area of the cave that has been developed and open for tours since November 1999. This station has been subject to changes associated with development (development lighting and personnel levels, construction, concrete pours), and those impacts associated with tours (lighting and visitation levels). The graph of the data from Lower Throne shows an approximately 3° Fahrenheit rise in temperature since the beginning of 1997. The trend (like that of the Cul De Sac temperature data) shows several reversals, notably during the first half of 2001. Accompanying the temperature increase at this station is a decrease in humidity. Between 1989 and the end of 1996 the humidity at the station had a mean of 99.43% (standard deviation 0.71%); between the beginning of 1997 and the present the humidity at the station was generally lower and more variable (mean 97.63%; standard deviation 1.30%). The difference between the humidity during the two periods is highly significant statistically (unpaired, one-tailed, heteroscedastic, t-test probability $p=2.4x10^{-28}$). The station in the Rotunda shows a similar record of environmental change to that shown for Lower Throne station. The temperature rise at the Rotunda station since the beginning of 1997 is approximately 4° Fahrenheit; this rise is slightly larger than that at the Lower Throne station. However, humidity change is less pronounced in the Rotunda than in the Throne Room (1989-1996 humidity mean 99.26%, standard deviation 0.87; 1997-2002 humidity mean 98.55%, standard deviation 1.31). The humidity difference in the Rotunda between these two periods, although smaller, is still highly significant statistically (unpaired, one-tailed, heteroscedastic, t-test probability $p=2.1 \times 10^{-6}$).

Analysis of factors contributing to temperature change

The data indicate recordable and statistically significant climate change in portions of the cave that can be correlated to the beginning of development and the opening of the cave to tours. At this point, the change appears to be relatively localized; that is, the areas with the most development and tour-related activity show relatively larger changes than in those areas more peripheral to these activities.

To understand the meaning of the temperature changes observed in the data, it is necessary to identify the factors that contribute to temperature rise. Not surprisingly, a major contributor to temperature rise appears to be heat energy added to the cave environment by development activities and human presence. Development activities such as concrete pours (due to heat produced by hydration of Portland cement), lighting (lights needed for construction activities and as part of visitor tours), and having people in the cave (visitors or workers; people produce metabolic heat that they release to the cave atmosphere) add substantial amounts of heat energy to the cave. The excess energy added to the cave can raise the temperature of the air and walls in the area where the heat is added, can be transported to other areas of the cave through air movement (raising temperature in other areas of the cave as well), and/or can evaporate additional water and increase the amount of moisture in the air (although this process will not necessarily raise the humidity). Likely the heat input at Kartchner is doing all of the above; however, the balance of impacts vary from place to place and over time.

The largest change in temperature and humidity has occurred in the Rotunda and Throne Rooms, two areas that have probably experienced the greatest amount of heat input through development and tours. In addition, airflow from these areas to other areas of the cave is apparently extremely limited. Air movement in the cave appears insufficient to transport heat from the Rotunda and Throne Rooms to other portions of the cave to large degree.

The added heat from development and tour activities is not the only possible contributor to temperature increases. Because the extra heat can also evaporate available water (rather than raise the temperature), the amount of water available for evaporation is an important component of an analysis. If there is an excess of water available, added energy will go to evaporating that excess, rather than to increasing temperature. Thus, cave temperature and moisture are affected by available moisture. The amount of moisture available in the cave relates to a large extent to external or surface moisture conditions.

External climate conditions

The relationship between available moisture and temperature can be seen when the temperature history of the Lower Throne station is compared to the moisture history of the area around the cave (**Figure 5**). The moisture history is expressed as the Palmer Drought Severity Index for the southeastern area of Arizona (Cochise, Santa Cruz, and Graham Counties. The Palmer Drought Severity Index is a meteorological index that uses rainfall, temperature, and soil moisture to express the moisture state of an area (from extremely wet to extreme drought). Negative numbers indicate dry conditions and anything less than about -3 means a severe drought. Positive numbers indicate wet conditions and anything over 4 is extremely wet. In October 2000 the moisture conditions in southeastern Arizona changed from a severe drought to extremely wet. At that time, the cave flooded and more water became available to be evaporated. The cave monitoring data show a corresponding reversal of the warming trend. This could be attributed to the excess heat being expended in the evaporation of available water rather than to keeping the temperature elevated. When the extra water was largely exhausted, the temperature again began to rise. A similar, but smaller reversal accompanies moist conditions in the beginning of 1998. In general the Lower Throne temperature record suggests that moist regional conditions are accompanied by lower temperatures in the cave.

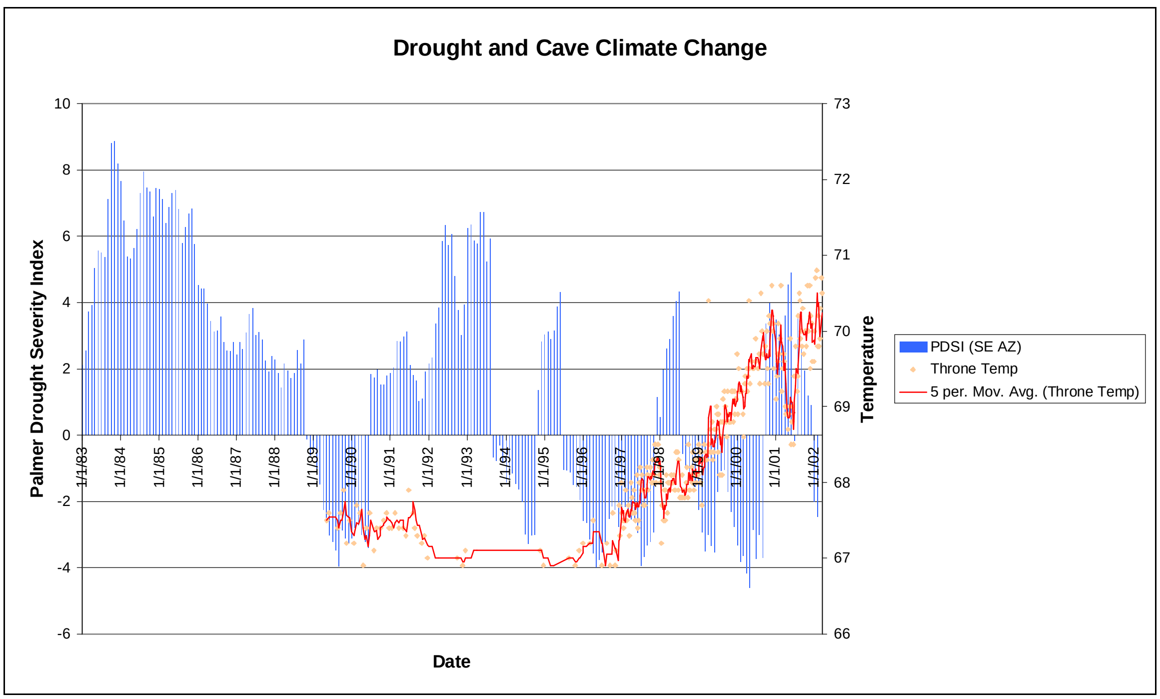

Figure 5 – *Regional moisture (as measured by the Palmer Drought Severity Index for Southeastern Arizona) compared to the temperature trend at the Lower Throne environmental monitoring station*.

The larger temperature and moisture changes seen in the Rotunda and Throne Room appear to be the result of the interaction of the increased energy being put into the system and reduced amounts of moisture in the cave due to drought conditions. If the cave contained abundant water, the additional heat energy could evaporate more water, the temperature would go up, and there would be more moisture in the air (and relative humidity would remain near 100%). If no extra energy came into the cave, the reduced moisture (from drought) would still likely be enough moisture to keep the cave moist (near 100% relative humidity). However, at present, the cave contains additional heat energy and drought conditions exist externally, contributing to an elevation of cave temperatures where the heat-producing activities are most profound. The same factors are likely causing the temperature and moisture changes in the Big Room complex (Cul De Sac, Sharon's Saddle, Kartchner Tours, and Big Room Overlook). Because the energy inputs have been smaller (less concrete, work has proceeded for less time, no tour lights, and fewer visitors) and the overall volume of the rooms is larger, the temperature and moisture changes have been smaller. Another factor that may mitigate temperature rises in the Big Room complex is the closer proximity of the cave entrance to the room itself, permitting some of the excess energy to be transported out of the cave via airflow through the entrance.

The effect of the excess moisture is important in evaluating the pre-development studies as well. The period from the beginning of 1983 to the end of 1988 is the longest moist period on record for the area. That means that when the pre-development studies occurred, the cave was almost certainly storing as much moisture as at any time in recent history. Unfortunately, significant drought during the 1990, as well as cement curing and extra energy inputs, has probably used most all of that stored water.

In my estimation, the moisture changes in the cave are due to a combination of lower input of moisture into the cave (caused by drought conditions outside the cave) and increased temperatures in the cave (resulting in lower effective moisture, e.g. relative humidity, with the given amount of moisture). Others have suggested that perhaps the cave is losing moisture through or around the tunnels (through small cracks). I have not found evidence that supports that contention; however, it is a possible condition. Additional monitoring and airflow studies are being developed to directly assess this possibility.

Significances of Cave Climate Change

The increase in temperature in both the areas being toured and the areas under development is not surprising. Indeed, the ACPI final report predicted cave air and wall temperature increases of between 1° and 3° Fahrenheit based on the added energy input they predicted from lights and visitors. At this point, the temperature change in the Rotunda and Throne Rooms is slightly above the upper end of predicted climate change; the Big Room area stations indicate temperature change at the lower end of the predicted range.

The fact that temperature change has been approximately that predicted in the pre-development report may or may not indicate that there is no problem with the observed temperature rise. If the pre-development studies are correct, the observed temperature increase, if stable, may not result in negative long-term consequences for the cave. However, the fact that the observed temperature rise is near that predicted in the pre-development studies may not indicate that the rise is entirely benign. One reason that it may not mean that the change is benign is that the predictions from the report are based on the final development and visitor predictions. In some areas, we are above the upper end of predictions prior to the final development and tour effects. Another reason is that it is not clear at this point whether the climate changes have stabilized in the Rotunda and Throne Rooms or whether these areas are undergoing further climate change. An additional complication for evaluating the predictions is that the extra stored water that was probably in the cave during the pre-development studies provided an extra measure of protection that may not be available for the long term.

The significance of the changes in temperature and moisture in the cave are the focus of continuing examination. A critical aspect of this is reaching an understanding of whether the temperature and moisture changes in the Rotunda and Throne Rooms have stabilized, or will continue to trend upward. Until this can be determined, the effect of development of the cave cannot be adequately evaluated. Understanding the long-term significances of the observed cave climate changes, although challenging, is a high priority.

Radon Monitoring

The Occupational Safety and Health Administration Permissible Exposure Limit for radon is 4.0 working level months per year. Exposure is calculated using the average amount of radon decay products a person may be exposed to (such as the data shown in the graph above) along with the duration of the exposure to decay products. In 2001, the highest exposure level by a development worker at the cave was 2.283 working level months and the highest exposure level by an operations worker was 1.812 working level months.

Figure 6 shows the measured level radon decay products in the Imaginary Passage (on the current tour route) as an example. These levels are similar to those observed in pre-development studies.

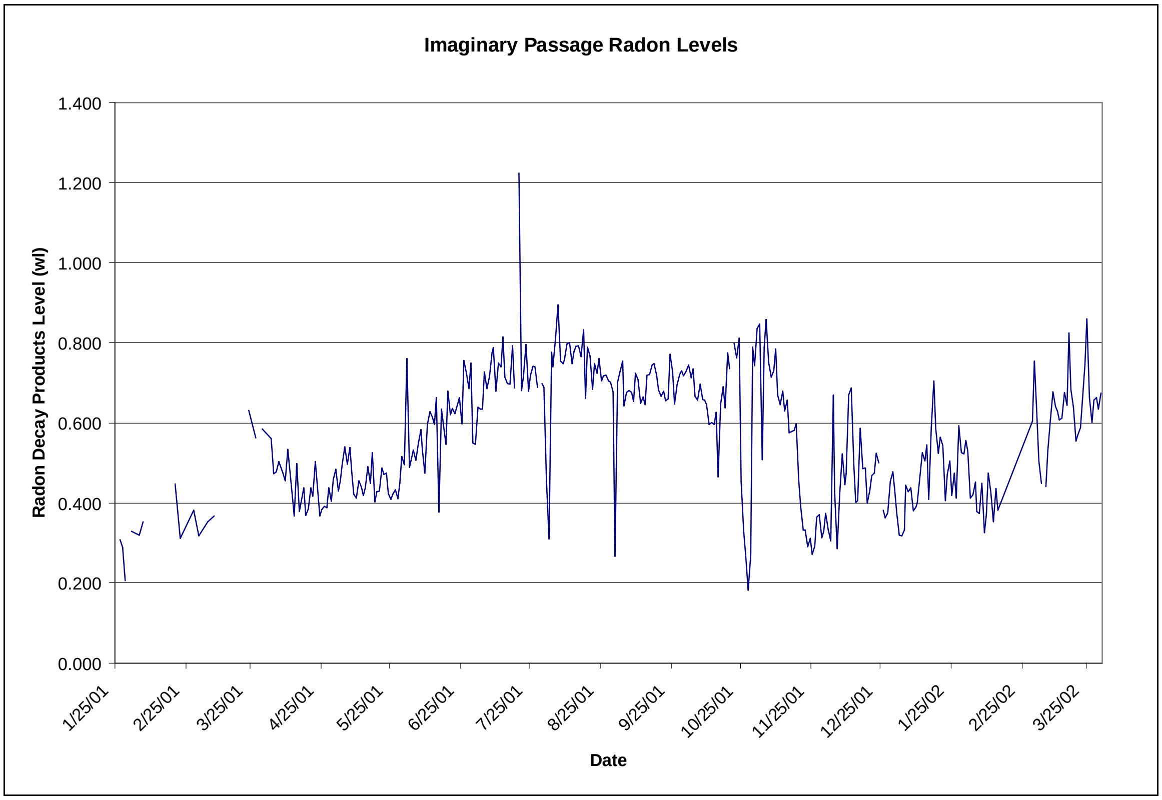

Figure 6 – *Morning radon decay products levels, expressed in working levels, in the Imaginary Passage, Kartchner Caverns*.

Carbon Dioxide Levels

Using the Throne Room as an example, carbon dioxide levels, in general, are highest in the late summer and lowest in the winter and early spring (**Figure 7)**. The reason for this is that the source of carbon dioxide in the cave is the soil overlying the cave. During the months that plant growth is limited (winter and early spring), less CO_2 occurs in the soil, and thus less is transported into the cave. Conversely, when plants are more active (late summer and early fall) more CO_2 is in the soil and is transported into the cave.

Development and tourism in the cave may also cause a rise in the level of CO2 in the cave, as a result of the exhalation of CO_2 from people working in or touring the cave. This exhaled CO_2 might theoretically cause an eventual long-term rise in CO_2 in the cave. However, data from predevelopment studies and present monitoring shows only a negligibly small increase in CO_2 levels in the Throne Room. Limited pre-development measurements showed the area to have a mean CO_2 level of 3125 parts per million (ppm) (range 1660-5400; standard deviation 1196 ppm); measurements during development and tours provide a mean of 3300 ppm (range 1000 – 6100 ppm; standard deviation 1595 ppm). The observed rise is not statistically significant (unpaired, one-tailed, heteroscedastic, t-test probability p=0.69) and is much smaller than the potential rise predicted in ACPI studies. If data from during development are ignored (comparing only pre-development with tours), the rise is slightly more pronounced (tour mean 3684 ppm; range 2000-6100 ppm; standard deviation 1461 ppm). However, this rise is also not statistically significant (unpaired, one-tailed, heteroscedastic, t-test probability p=0.21). Although the data from other areas of the cave are much sparser, they too suggest no demonstrable rise in the CO_2 levels due to development and tours. Even the highest levels of CO_2 found in the cave are not considered harmful for people, based on NIOSH guidelines (10,000 ppm for 8-hour exposure and 30,000 ppm for 15-minute exposure).

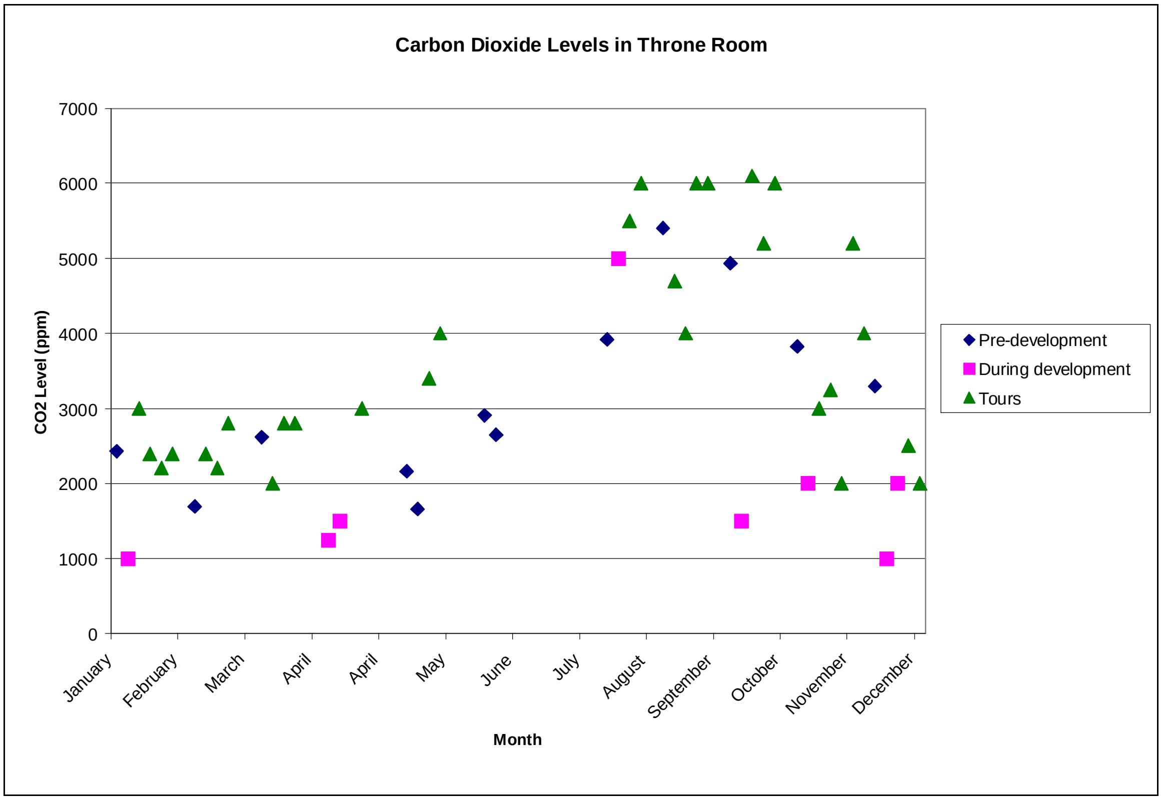

Figure 7 – *Measured carbon dioxide levels in the Throne Room by month.*

Bat Populations

Figure 8 shows the peak bat counts for each of the last 13 years. This past year was a fairly good for bats at the park with the peak cave *Myotis* count of 885 occurring on June 5, 2002. The graph shows both the peak early in the summer (late May to early July, when the young have not been born or are not flying) and the peak later in the summer (mid August, when the young would be flying as well).* Although the early peak count for 2001 was down from those in 1998-2000, it is in line with the 13-year average (934 bats). Careful monitoring of bat populations will continue.

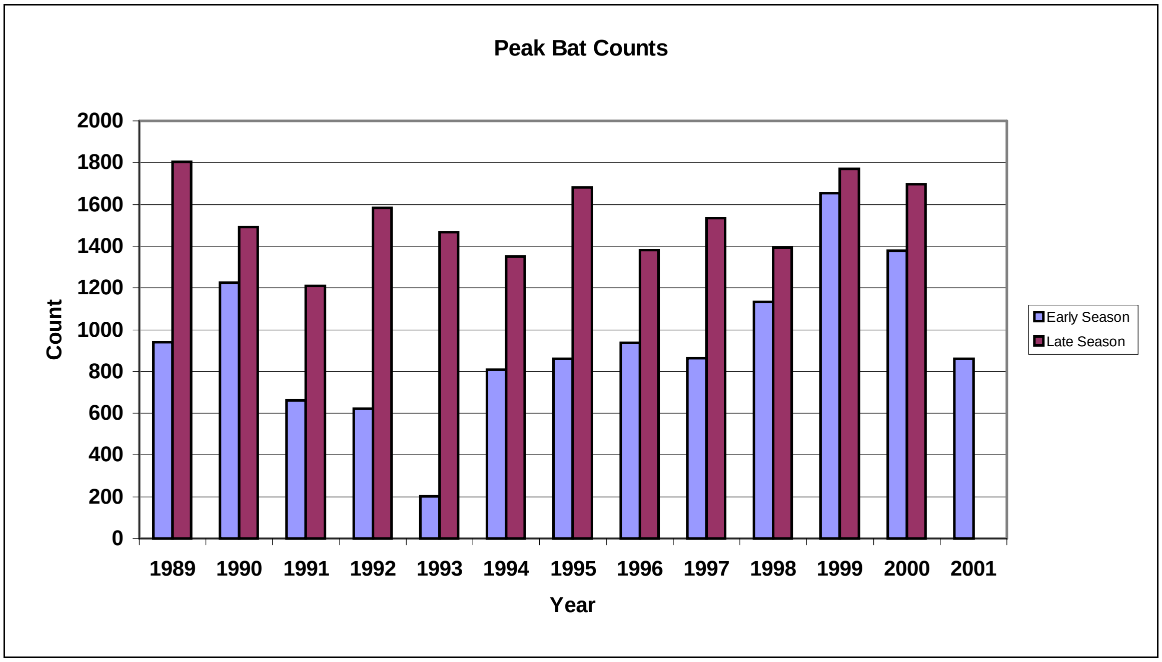

Figure 8 – *Kartchner Caverns peak bat counts early (June) and late (August) in the season.*

CONCLUSIONS

The issues involving cave climate (and climate change) are very complex, and it is difficult to address them fully in this type of report. Recordable changes have occurred in the cave microclimate since the beginning of development and the opening of the cave to the public. Identifying the contributing causes of these changes is difficult. It is unclear whether these changes have stabilized in the developed area or will continue to trend upward. Significant steps have been taken during the past year to improve our data collection and analysis processes so that sound science provides the basis for implementing effective mitigation measures.

* Last summer's very active monsoon's hampered bat counts for that period after the young began flying, so no reliable count on the peak after the young were flying is available.