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DRAFT

**RESOURCE PROTECTION STUDIES ASSOCIATED WITH
RE-LIGHTING OF A PORTION OF THE HISTORIC TOUR ROUTE,
MAMMOTH CAVE, KENTUCKY.**

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**An investigation and report for Mammoth Cave National
Park prepared under purchase order PX553080450.**



EXECUTIVE SUMMARY

This report is divided into three major sections:

- 1) Exotic plant growth.
- 2) Re-lighting strategies.
- 3) Restoration techniques and guidelines.

The exotic plant growth section of the study included a substantial literature review of plant growth in caves with particular emphasis on methods of control. Plants which have been identified in Mammoth Cave include moss protonema, 21 species of green algae, at least 21 species of cyanobacteria, 2 species of Euglenoids, 1 species of Dinoflagellates, 1 species of yellow-green algae, at least 5 species of diatoms, and 3 species of red algae. Green algae, cyanobacteria, and moss protonema are the most common components of the exotic flora found in Mammoth Cave.

Exotic plant growth should be prevented to the extent reasonable. The most effective strategy for plant growth prevention is careful control of light intensity reaching moist or wet cave surfaces. In general, light intensities on moist natural cave surfaces should be kept at less than 7.5 foot-candles to the greatest extent possible. Essentially all plant growth can be prevented if light intensities on moist sites is kept below 2.3 foot-candles. Greater light intensities on moist cave surfaces are acceptable if needed for interpretive or safety reasons. However, such intensities will result in some plant growth and will require periodic plant control work. Control of exotic plants can best be conducted through the use of 5.25% sodium hypochlorite solutions applied as a mist to the vegetation.

Guidance for the re-lighting of the cave should comply with the following strategies. In general, a light should either illuminate the trail or else a cave feature; most lights cannot ideally serve both functions. Lights must be effectively shielded from direct view both for esthetic reasons and to maintain night vision in visitors. Light intensity must be carefully controlled and balanced so as to prevent the creation of unduly bright spots. The quality of cave lighting tends to increase with an increase

in the number of light fixtures. The greater the number of lighting fixture, the lower the wattage should be in each individual light. The distance between trail lights should be shorter on steps and around obstructions than is the case on straight and unobstructed portions of cave trails. It is better to reduce the distance between trail lights than to increase the wattage of the lights.

Restoration techniques and guidelines are focused on the control of exotic plant growth, the removal of "clay worms", removal (or reducing the visibility) of graffiti, clean-up of soot deposits and related debris from kerosine torches, lint removal, removal from natural cave surfaces of rock and sediment debris placed during trail construction, and major work on cave trails. Most of the trails in Mammoth Cave provide little protection for those cave resources present on the floor of the cave. In general, trails should be narrowed; they should be paved with concrete rather than constructed of compacted cave sediment; and unused trail segments and other similar facilities should be removed when they are no longer of use.

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INTRODUCTION

This report deals with resource protection studies which accompanied test re-lighting of a portion of the Historic Tour in Mammoth Cave, Mammoth Cave National Park. There were seven task items identified in the purchase order under which this work was conducted.

The first step in the studies was to determine light intensities which would minimize the growth of moss, moss protonema, algae, and cyanobacteria in the portions of the cave to be re-lighted. Data on exotic plant growth are included in the next section of this report; these data are relevant to Tasks 1, 2, and 3.

Much of the work conducted under this purchase order focused on assisting National Park Service personnel in re-lighting work in the cave. Both Tom and Cathy Aley spent several days in the cave with National Park Service personnel in identifying unlighted or obscure features of particular significance which needed to be lighted. This work also identified presently lighted features which needed to be de-emphasized by decreasing the amount of light they received; many of these features were obvious graffiti which possessed little if any historical significance. This represented Tasks 4 and 6. The narrative portion of this work, which we have titled "Re-lighting Strategies", is limited because of the nature of the work.

Task 5 involved the development of restoration techniques and guidelines for the area to be re-lighted. The techniques and guidance were to focus on removal of exotic plant growth, identification and removal of unnatural "clay worms" (vermiculations), techniques for removing or diminishing the visibility of graffiti, and techniques for identifying and removing inappropriate unnatural coatings or materials on cave surfaces. The section of this report entitled "Restoration Techniques" deals with these investigations and recommendations.

Task 7 consisted of data analysis and reports; this report satisfies the requirements of this task.

EXOTIC PLANT GROWTH

Scope of Work

The purchase order for these investigations included three tasks related to identification of exotic plant growth in Mammoth Cave and determination of light intensity constraints useful for minimizing such plant growth. The specific tasks were described as follows:

Task 1. Develop light intensity constraints for the new lighting system.

Determine light intensity values below which exotic algal and other plant growth in the electrically lighted portion of Mammoth Cave is prevented or minimized. Use light intensity values to identify areas where exotic plant growth is likely to be a problem with a particular light installation and determine the best light placement, installation, or shielding to minimize the problem.

Task 2. Identify exotic species of algae and mosses found around lights in Mammoth Cave.

In particular, identify those species of algae associated with the unnatural development of vermiculations (clay worms) which create ideal substrates for unnatural plant growth, and give the cave a highly unnatural appearance.

Task 3. Identify cave features where light intensity must be minimized to protect features.

Determine cave features where exotic plant growth could occur and thereby destroy the features. Develop light intensity values that will prevent or minimize the destruction of such features.

Growths that occur in caves include fungi, cyanobacteria (formerly called blue-green algae), algae, mosses, ferns, and lichens. For the purposes of our discussions we will view all of these growths as "plants".

This section of the report begins with a literature review of plant growth in caves, with particular emphasis on growth associated with electric lighting. The purpose of this review is to provide the reader with a good understanding of plant growth in caves. The review gives special attention to light intensity constraints developed from studies in other electrically lighted caves. The review also includes detailed information on the role of substrates in plant growth in caves and on methods which have been used to kill exotic plant growth in caves.

A section of this report entitled "Plant Growth in Mammoth Cave" follows the literature review. This section specifically relates to Task 2 identified earlier. Plants which have been identified in Mammoth Cave include moss protonema, 21 species of green algae, at least 21 species of cyanobacteria, 2 species of Euglenoids, 1 species of Dinoflagellates, 1 species of yellow-green algae, at least 5 species of diatoms, and 3 species of red algae. Clay worms (vermiculations) are important in the establishment of visible growths of many of these plants and are particularly important in the establishment of the floristic components that were most abundant in the Frozen Niagara area of the cave in 1974.

A very helpful study (which exists only in manuscript form) was conducted by Van Hoff (1974) in the Frozen Niagara section of Mammoth Cave. Van Hoff was a student at Western Kentucky University and conducted the study as part of his college work; he was assisted by Dr. Gary Dillard of the Department of Biology. This 1974 study was conducted prior to the start of any plant control work in this part of the cave; it therefore provides data on conditions which had developed after years of uncontrolled plant growth. Van Hoff (1974) collected and identified plant growth at 53 individual sites within the Frozen Niagara Area; he also made light intensity measurements at each of these stations. We have made substantial use of the raw data developed by Van Hoff (1974) in our report.

Information related to Task 1 begins in the section entitled: "Important floral components in lighted portions of Mammoth Cave" and continues in the following section entitled: "Relationship of plant growth to light intensity". The report section entitled: "Recommendations for light intensities to minimize plant growth" is relevant to both Tasks 1 and 3. The report section entitled: "Areas where exotic plant growth is likely to be a problem" is in response to Task 3.

Literature Review

The growth of fungi, cyanobacteria, algae, mosses, ferns, and lichens on speleothems and other cave surfaces is a common situation in electrically lighted show caves. Such growth is generally considered to be a problem because it detracts from the natural appearance of the cave and damages the natural integrity of caves and their features. Cubbon (1976) comments on Akiyoshi-do, a show cave in Japan with an extensive green plant flora around artificial lights. This cave is unusually rich in fauna, and some of the animals are believed to depend upon the plant growth resulting from the artificial lights for their sustenance.

Plant growth in caves can seriously damage speleothems and other cave features (Aley and Aley, 1984; Aley, 1976; Cubbon, 1976). Cubbon (1976) discusses the formation of eucladioliths. Eucladioliths are tufa-like deposits of calcium carbonate which have formed by calcareous seepage of water depositing upon growing mosses. As the moss grows (toward the light) more calcium carbonate is deposited on the older parts, and a speleothem builds up around the plant. Eucladioliths can also be found in artificially lighted portions of caves where mosses have been permitted to flourish and where suitable drippage or seepage water exists. The authors of the present study have noted that exotic plant growth in the Frozen Niagara Section of Mammoth Cave prior to its control in the 1980's resulted in appreciable deterioration of outer layers of some of the large speleothems.

Aley, Aley, and Rhodes (1985) noted that surfaces of some speleothems in Carlsbad Caverns had been turned to a jello-like substrate by algal and cyanobacterial attack, and that other speleothems had been discolored. Aley and Aley (1986 and 1991) reported upon extensive fungal growth in the Snowball Dining Room area of Mammoth Cave. The fungal growth (which includes some algae, sediment particles, lint, and carbon particles) has blackened the surfaces of gypsum crystals and limestone surfaces in the Snowball Dining Room. Approximately 15,000 square feet of surface area in the Snowball Dining Room and adjacent passages has been noticeably affected by this fungal growth.

Went (1969) found fungal hyphae commonly associated with the tips of soda straws, but not associated with helictites. These observations were made in Lehman Caves, Nevada. Went (1969) suggested that the fungal hyphae might serve to orient soda straws so that they would grow downward. While this is an interesting possibility, Hill and Forti (1986) suggest mineralogical differences between helictites and soda straws. Moonmilk, another cave speleothem, is thought by some workers to be formed as a part of the life cycle of microorganisms (Hill and Forti, 1986); these microorganisms include bacteria, fungi, and algae. However, these microorganisms may not be present in all moonmilk (Hill and Forti, 1986). While scientific debate exists about possible interactions between biological activity and speleothem deposition, it must be recognized that such relationships may exist.

We generally presume that none of the "green plants" grow in unlighted caves. This is not quite accurate. Vandel (1965) notes that algae such as Chlorella, Sce-nedesmus, and Pleurococcus are able to manufacture chlorophyll in complete darkness, and that this has been known since about the turn of the century. With at least some algae, the formation of chlorophyll and carotenoid pigments is greater in cultures kept in the dark than in illuminated cultures (Vandel, 1965). Furthermore, pigments of the symbiotic algae entering into association with fungi in lichens, can also develop in the absence of light (Vandel, 1965). Cubbon (1976) concludes that

it is unlikely that the algae-fungal partnership would hold together in total darkness, yet he notes that a number of lichens have been found in South Wales caves in light intensities as low as about 5 lux (0.5 foot-candles).

Vandel (1965) also notes that greenish or reddish beds formed by Protococcus and Haematococcus algae are found in unlighted caves. Since the phenomenon of photosynthesis cannot occur in total darkness, Vandel (1965) concludes that the development of these algae must depend upon the presence of organic matter. Cubbon (1976) reports that a cyanobacterium Synechococcus elongatus has been isolated from moonmilk in the dark zone of a cave in South Wales, and concludes that this organism must have been utilizing alternative metabolic pathways to the normal photosynthetic ones it employs in the light. Cubbon (1976) further notes that:

A related alga Gleocapsa sp. was isolated together with certain bacteria...from a Norwegian cave deposit of the moonmilk type, and it is worth noting that Gleocapsa magma has been isolated from the dark zone of Baridge Cave, as well as the threshold zone of Pulpit Hole and Ogof Fflnnon, all in South Wales...Moonmilk formation was also observed in Lascaux Cave at the time of the "Maladie Verte"...[Note 1: Gleocapsa sp. was a common cyanobacteria found in the Frozen Niagara area by Van Hoff (1974)]. [Note 2: The *Maladie Verte* was the name given to the plant attack on the prehistoric paintings in Lascaux Cave in France].

Claus (1962) reported that approximately 200 species of chlorophyll-containing algae species, representing all algal divisions (including Cyanobacteria) except for the Phaeophyta, have been found living in caves in Hungary. Nagy (1965) reported a member of this latter group from a dark region of Crystal Cave, Kentucky; thus all major groups of the fresh water algae have been found in unlighted caves. These algae have been found as live tissue, not merely as spores or in some other dormant stage. Jones

(1964) reported 27 species in Mammoth Cave, Kentucky. Nagy (1965) reported seven species from Crystal Cave (which is physically connected with Mammoth Cave); only one of these species was found by Jones (1964) in Mammoth Cave. Williams (1967) found 30 algal species in caves in South Wales. Most of the algae found within the dark portions of caves are diatoms, green algae, or cyanobacteria.

Although many species of algae or cyanobacteria may be present in a cave, light indeed seems to be the limiting factor for luxuriant algal growth (Jones, 1964). Kol (1967) selected strains of a number of algal species found in dark portions of caves and exposed them to a control period of 268 days of total darkness. Kol (1967) found that most of the algal strains survived this long period of darkness, retained their green color, and many of them even showed satisfactory growth. However, some of the strains died while in some other cases, although the strain survived, its color changed from green to brownish or yellowish-green. Kol (1967) reported that in those strains which retained their green color some apparently actively grew, while in other cases only the original inoculum survived.

After the 268 day period of total darkness, Kol (1967) exposed the algae samples to 150 days of light in the laboratory. He found that as much variation occurred in the reactions of the algae to the 150 days of light as to the 268 days of darkness. Some of the algae developed with great intensity in the light, a few strains which had barely survived in the darkness underwent a vivid growth during this 150 days, a good number of the strains which had just survived the rigors of darkness did not improve in the light and some even perished. A few particularly interesting strains which had shown some development during the first part of the experiment quit growing in the light as though the light itself were actually a restraining factor (Kol, 1967).

Kol (1967) concluded that light requirements for growth, or the ability to survive the lack of it, is not so much a characteristic of a species as it is of a single algal strain. In some species, some strains showed quite

satisfactory growth in darkness while others died. During the course of Kol's study, out of a total of 95 strains of algae, 14 showed significant growth and 12 died. As a generalization, Kol (1967) reported that some algae strains which showed only a small development or remained barely alive in the cave when placed in the light showed an excellent growth thereafter. In general, however, the strains which developed well in the cave retained their developmental intensity when exposed to light.

The studies by Kol (1967) and others upon algae found in totally dark caves are helpful in understanding plant growth in electrically lighted caves. First, algae and cyanobacteria commonly exist within the caves prior to the introduction of electric lights. Claus (1962) and Kol (1967) both suggest that at least portions of the cave algal and cyanobacteria "floras" are not derived from recent introductions, but instead are floras from pre-lighting conditions. If this is the case, then we must presume that components of the cave algal floras are adapted to the cave environment, or are at least very compatible with the cave environment. Studies by Kol (1967) have shown that the introduction of light will result in the rapid growth of some algal strains in a cave. Those strains which are able to both survive cave conditions and grow well when light is added represent a serious threat to the integrity of the cave. Major problems can result if such strains are permitted to propagate and then be spread through the cave system.

The studies by Kol (1967) indicate that the absence of light, even for substantial periods of time, will not necessarily kill or even damage particular strains or species of algae or cyanobacteria. If the algal and cyanobacteria strains growing in the cave are indeed floras from pre-lighting conditions, it is reasonable to assume that most of them will be tolerant to highly tolerant of long periods of darkness.

With regard to algae and cyanobacteria growing in dark portions of caves, it should be noted that the growths are typically not detectable without microscopic examination of scrapings from cave surfaces or cultures. For practical purposes, problems with plant growth in caves

are confined to lighted portions of the caves. Although the amount of plant growth tends to increase with both the intensity and duration of light (Aley and Aley, 1984; Aley, 1976; Sheps, 1972), plant growth in caves can be found at surprisingly low light intensities. Sheps (1972) working in Lehman Caves, Nevada, found algae growing in lighted portions of that cave where light intensities were as low as 12 foot-candles. Aley and Aley (1984) found algae growth in Carlsbad Caverns growing in alcove sites at intensities as low as 0.6 foot-candles. Aley and Aley (1985) found threshold light intensities necessary for plant growth in Oregon Caves, Oregon to be approximately 2.5 foot-candles, and that light intensities between 28.4 and 164 foot-candles were routinely correlated with maximization of plant growth.

Sheps (1972) reported that in Lehman Caves, Nevada, mosses were generally limited to sites with light intensities greater than 20 foot-candles. Algae were found in Lehman Caves at light intensities below 20 foot-candles (Sheps, 1972). Cubbon (1976) reported on vegetation inside cave entrances. As one progresses deeper into the cave, light intensities decrease, which in turn results in a distinct zonation of the plants present (Cubbon, 1976). On a transect taken from the cave mouth into the darker regions of the cave, flowering plants and ferns disappear first, followed by the mosses and liverworts. Algae and cyanobacteria are the most resistant to low light intensities, and are thus found deeper into cave entrances than are other plants (with the exception of the fungi). Fungi can grow in total darkness.

Aley, 1972 and 1976) reported that mosses were found growing closer to lights than were algae in Blanchard Springs Caverns, Arkansas. Most mosses were within a meter of light fixtures; most algae were within seven meters of light fixtures. The reason for this zonation was believed to be differences in light intensity requirements; mosses require greater light intensities than do algae. Similar conditions were noted in Oregon Caves by Cordero (1977).

Plant growth in electrically lighted caves can be extensive and sometimes luxuriant. Aley and Aley (1984) found plant growth in Carlsbad Caverns to be associated with 43% of the lights inspected. The plant growth in Carlsbad Caverns is approximately 70% cyanobacteria, 20% green algae, and about 10% moss protonema. In addition, there are diatoms present in about 25% of all of the clusters of algae and cyanobacteria in Carlsbad Caverns (Aley and Aley, 1984).

Oregon Caves, Oregon, is a much "wetter" cave than is Carlsbad Caverns. Aley and Aley (1985) found plant growth associated with all fixed lights in Oregon Caves. There was no plant growth associated with the only non-fixed light in the cave (a spotlight which the guide used to point out various features in a large chamber). In Oregon Caves, about 15% of the areas covered by visible plant growth supported mature moss; another 10% supported moss protonema. About 40% of the areas covered by visible plant growth supported cyanobacteria, and about 35% of the areas support green algae. Diatoms, which are very small and do not cover large areas, are present in about half of the samples of algae and moss protonema from Oregon Caves (Aley and Aley, 1985).

Photoperiod effects may be important in determining the magnitude of plant growth in electrically lighted caves (Aley, 1976). Circadian rhythms of plants have been shown to consist of a light (or photophil phase) during which light is stimulating, and a dark (or scotophil phase) during which light is inhibiting to growth (Went, 1962). Sheps (1972) worked with the moss Camphyllum chrysophyllum in Lehman Caves, Nevada and found that when this moss was given a 12 hour period of light it showed 3.5 times more growth than when it was grown under intermittent lighting as normally associated with cave tours. Unfortunately, Sheps (1972) did not document the number of hours per day that lights were on under normal tour conditions nor the number of times that lights were switched on and off.

Many operators of show caves have noted that the extent of plant growth increases with the amount of time since the cave was first opened. Sheps (1972) reports that this situation exists at Lehman Caves, Nevada, and provides the following information:

The importance of time in the establishment of cave communities is shown by the sparse vegetation in the Talus Room, which has been lighted for only 9 years, compared with the considerably greater abundance and variety in the remainder of the cave which has been lighted for 30 years. Thus, of 15 lights surveyed in the former, only 13.3% had algae and none had mosses; whereas in the latter, of 146 lights, 45.2% had vegetation, 43.2% with algae and 15.8% with mosses. Note: Sheps (1972) viewed cyanobacteria as algae.

Cubbon (1976) reports that the prehistoric painted cave of Lascaux operated as a show cave for about 20 years before experiencing "the green sickness" (maladie verte). The green sickness of Lascaux was due to a heavy growth of a green algae, Palmellocooccus sp., which threatened to completely overgrow the prehistoric paintings.

Cubbon (1976) concluded that the growth of algae in Lascaux was made possible because of very heavy contamination of the cave due to a large number of visitors who deposited both organisms and organic materials derived from the human body and clothing in the cave. Cubbon (1976) further concluded that with time, sufficient proliferation of micro-organisms (chiefly bacteria) occurred, and this enriched the substrate to the point where the algae could begin its rapid spread. From the literature (Cubbon, 1976; Lefevre and Laporte, 1969) it appears that the spread of the algae in Lascaux was extremely rapid.

Stark (1969) reported that limited amounts of soil, low light intensity, and possibly a deficiency of nitrogen and other elements was preventing the establishment of higher plants near lights in Lehman Caves, Nevada. Many

of the "microecosystems" in Lehman Caves identified by Stark (1969) included lint and other materials transported into the cave by visitors.

Aley and Aley (1985) noted that new algal and moss protonema growth in Blanchard Springs Caverns, Arkansas was often on and adjacent to pellets of bat guano. Bat guano contains appreciable amounts of nitrates, phosphates, and carbon; these are all recognized contributors to algal growth.

Aley (1976) in a study at Blanchard Springs Caverns, Arkansas, also commented that plant growth in caves tended to increase with time. He suggested that organic matter from visitors and accumulated plant growth due to the lighting of the cave were factors probably implicated in the problem of increased rates of plant growth. Appreciable plant growth in this cave became quite noticeable within about three years of the introduction of electric lights. Plant growth problems in Blanchard Springs Caverns became severe during the show cave development phase of the project.

Aley and Aley (1984) conducted a 110 day growth plot study in Carlsbad Caverns using six selected substrates. The substrates were:

- 1) Lint and minor amounts of associated sweepings from within the cave
- 2) Yellow cave silt
- 3) Red cave mud
- 4) Crushed gypsum
- 5) Limestone pebbles
- 6) Trail washings.

Plant growth occurred on all substrates, but was more rapid and more extensive on the lint and minor associated sweepings than on any other substrate. The substrate which developed the smallest amount of plant growth was the red cave mud. The authors suggested that, since most detergents contain phosphates, residual phosphates should be anticipated on lint. Phosphates are notorious for causing excessive algal growth in streams and lakes. Aley

and Aley (1984) suspected that the excessive growth on the lint substrate in Carlsbad Caverns was a result of appreciable phosphates present on the lint.

Aley and Aley (1985) conducted an 80 day growth plot study in Oregon Caves using eight selected substrates. The substrates were:

- 1) Lint and hair
- 2) Trail debris which included lint and hair
- 3) Cave sediment with lint added to the surface
- 4) Clean cave sediment without lint
- 5) Fresh broken marble with lint added to the surface
- 6) Fresh and clean broken marble without lint
- 7) Calcite with lint added to the surface
- 8) Clean calcite without lint.

The greatest plant growth occurred on the trail debris which included lint and hair. The second greatest amount of plant growth occurred on the lint and hair substrate. The third greatest amount of plant growth occurred on the fresh broken marble with lint added to the surface. The least growth was on the lint-free substrates. The amount of plant growth in the Oregon Caves growth plot study was appreciably less than that developed on the Carlsbad growth plots. This was due, in part, to the fact that the Oregon Caves study lasted for only 80 days while the Carlsbad Caverns study lasted 111 days. Aley and Aley (1985) suggested that the warmer cave temperatures in Carlsbad Caverns (approximately 58 degrees F. at the study plot location) were also implicated in the more rapid growth noted at this cave. The cave temperature at the study plot location in Oregon Caves was 42 degrees F. (Aley and Aley, 1985).

Sheps (1972) reported that cultures of cave plant species grew less well under apparently more optimal controlled laboratory conditions than in the cave (Lehman Caves). In fact, based upon 12 hour photoperiods, plant growth in Lehman Caves was seven times greater than that observed under "controlled" laboratory conditions. The "controlled" laboratory conditions did not include control over carbon dioxide concentrations in either air or water,

nor controls over other plant nutrients such as phosphates and nitrates. Furthermore, there were no controls over bacteria which might be associated with plant growth.

Aley and Aley (1984 and 1985) noted that "soft" substrates in both Carlsbad Caverns and Oregon Caves routinely developed more extensive plant growth than did "hard" substrates. Soft substrates include sediment and assemblages of weathered speleothems, inactive coral, and moonmilk. Hard surfaces include rock and firm-surface speleothems. The authors suggested that the soft substrates were capable of holding more moisture than hard substrates, and could thus better supply moisture for plant growth during drier periods of the year.

Aley and Aley (1985) reported that substrates exert major influence upon the extent of plant growth in Oregon Caves, and listed the following generalizations:

A) Plant growth generally is greater on wet or very wet surfaces than on damp or nearly dry surfaces. Most surfaces in Oregon Caves are at least damp for at least part of the year.

B) Plant growth generally is greater on weathered speleothem surfaces and on surfaces coated with moonmilk than on firm speleothem surfaces.

C) Plant growth generally is greater on muddy speleothems and muddy marble than on clean and solid speleothems and marble.

D) Plant growth generally is greater on lint "globs" and clay worms (vermiculations) than on adjacent surfaces which are free of lint and clay worms. This difference is most noticeable on clean and solid speleothems and marble.

E) Plant growth generally is greater on relatively flat surfaces than on steeply inclined surfaces, and generally is greater on steeply inclined surfaces than on cave ceilings.

F) Plant growth generally is greater on broken margins of trail materials than on firm trail surfaces.

A number of management strategies and different plant control agents have been tried at various show caves. The following discussion is illustrative of these.

The "green sickness" at Lascaux Cave in France was discussed earlier. Cubbon (1976) reports that the algae were controlled by application of formalin solutions to kill the algae, following a treatment with a mixture of antibiotics to kill the bacteria which were thought to be enriching the nutrients available to the algae on the walls. Unfortunately, the control strategy has not been able to control plant growth, protect the paintings, and permit continued visitation. Access to the cave is now by appointment only, and is restricted to a relatively small number of people for only a short period of time. The major cave paintings have been reproduced in a museum adjacent to the cave so that the general public can view them.

Formalin solutions would undoubtedly kill the algae. Formalin is commonly used for preserving algae for later study. Formalin solutions produce odors that many people associate with zoology laboratories. Formaldehyde (which is in formalin solutions) is one of the indoor air pollutants which has received regulatory attention in recent years; it is liberated from some of the foam insulations.

Aley (1972) used hot water steam to kill plants growing in Blanchard Springs Caverns, Arkansas. The control work was slow, it added appreciable heat to the cave, and the treatment was not effective on plants growing between resolution crystals on calcite speleothems. Furthermore, the treatment caused physical damage to some surface crusts on some inactive speleothem surfaces.

Blaisdell (1974) reported on plant control studies in Oregon Caves, Oregon Caves National Monument. Germicidal lamps, which emit short wave ultra-violet light, were found to kill both moss and algae either in the presence or absence of other lights. The lights were employed for

many hours before kills occurred; based upon the data available from Blaisdell's (1974) study, it appears that about 450 hours of operation was required to kill mosses and that about 4,000 hours of operation was required to kill algae. Aley and Aley (1984) conducted a limited study with a 15 watt germicidal lamp in Carlsbad Caverns and found that about 200 hours of exposure to ultraviolet light was necessary to produce an apparent kill of all visible algae.

Blaisdell (1974) also reported on chemical control experiments on plants in Oregon Caves, Oregon Caves National Monument. The chemicals tested were as follows:

- 100% ethanol
- 10% DCMC (Diuron) herbicide in an alcohol solution
- Undiluted Chlorox (5.25% sodium hypochlorite solution)
- 10% copper sulfate in water
- 10% Zepherin antiseptic in water
- Ortho brand antimildew preparation

In addition, it is possible that some testing was done with Thimerasol Elside #91. This is a methyl mercury compound and should be expected to cause adverse environmental impacts.

Blaisdell (1974) concluded that moss was best controlled with Diuron and that the recommended chemical for algae was copper sulfate. He also recommended installation of green fluorescent tubes or green plastic sleeves over daylight fluorescent tubes, and installation of germicidal lamps where possible. Sodium hypochlorite (Chlorox) solutions were found to quickly kill plants, however, Blaisdell (1974) was concerned about chlorine fumes and the possibility that chlorine and water would form a weak hydrochloric acid. In reality, these concerns are trivial. Potential problems with other control agents (such as Diuron and copper sulfate) received no attention in the study in Oregon Caves (Blaisdell, 1974).

Lynn (1976) applied a number of herbicides to algae and moss in Lehman Caves, Nevada. The herbicides tested had the following trade names; in the following listing, we have incorporated Lynn's (1976) evaluation of the effectiveness of the herbicide:

Linuron. Moss and algal kill extensive.

Solar. Kill extensive, but some recovery evident.
Banvel D. Kill extensive, but overgrowth of revegetating flora was very extensive.
Atrazine. Kill excellent, regrowth minimal to nonexistent.
Monuron. Good original kill, but recovery rate high.
Fenuron. No effect on blue-green algae (cyanobacteria), but moss kill effective.
Datahy. Kill extensive, but recovery high.
Cutrine. Algae initially killed but recovery appeared to be total.
Weedtrine. Excellent algal and moss kill, little apparent recovery.

Lynn (1976) concluded that only Weedtrine appeared to be highly promising as a control chemical. Lynn (1976) also tested Round-Up herbicide, and generic 2,4-D and 2,4,5-T. He noted that samples from the in situ treatments when returned to the laboratory failed to regenerate although viable algal material was isolated from the treated substrate which grew well when transferred to media devoid of herbicide. Lynn (1976) was concerned that under conditions of the cave environment, a dilution effect from seepage and condensation would limit the effective control. From the Lynn (1976) discussion, it is apparent that herbicides first kill the plants and then high enough residual concentrations of herbicides persist to sterilize the substrate for algae and moss growth for some period of time.

Aley (1976) developed a plant control strategy for Blanchard Springs Caverns. The strategy basically involved a reduction of lighting intensities, shielding of lights that created "hot spots", and routine control of plants with 5.25% sodium hypochlorite (bleach) solutions. The bleach was found to effectively kill both mosses and algae when applied in 5.25% concentrations; lesser concentrations were markedly less effective, and greater concentrations were not needed for effective kills of plant growth (Aley, 1976).

Aley (1976) also experimented with hydrogen peroxide, but found it to be ineffective in killing algae and moss. Aley (1976) noted that hydrogen peroxide is sometimes formed by plants during their growth, and plants have a mechanism for breaking down this chemical and thus preventing damage to the plant. Even 30% solutions of hydrogen peroxide did not kill the tested algae (Aley, 1976).

Aley and Aley (1984) conducted an extensive problem-solving investigation on plant growth problems in Carlsbad Caverns. The plant control strategy which was recommended emphasized both prevention of plant growth and then frequent control of the growth which did occur. Aley and Aley (1984) found that maximum light intensities reaching moist alcove surfaces should be less than 0.9 foot-candles if plant growth is to be largely prevented in such sites. They also found that maximum light intensities reaching moist non-alcove surfaces should be less than 2.8 foot-candles if plant growth is to be largely prevented.

Aley and Aley (1984) concluded that copper sulfate, hydrogen peroxide, commercial solutions of hydrogen peroxide and phosphoric acid, and calcium hypochlorite solutions should not be used for plant control work in Carlsbad Caverns. The only plant control agent which they recommended was sodium hypochlorite solutions in concentrations ranging between 4.2 and 5.25% sodium hypochlorite. Chlorox is an example of a 5.25% sodium hypochlorite solution suitable for plant growth control in Carlsbad Caverns.

Harris (1979) studied plant control approaches in artificially lighted portions of Mammoth Cave, Kentucky. Harris (1979) commented that nuisance plant growth dramatically increased with the introduction of fluorescent sources of light in cave systems, but offered no evidence that fluorescent light produces either more or less plant growth than incandescent lights. Blaisdell (1974) presumed that fluorescent lighting in Oregon Caves would result in less plant growth than incandescent lights, but also offered no evidence in support of this presumption. Blaisdell (1974) apparently believed that fluorescent

lights would cause less plant growth than incandescent lights because they produce less heat than do incandescent lights. However, increases in heat output tend to desiccate surfaces; this discourages plant growth. At least some of the personnel at Blanchard Springs Caverns believe that incandescent lights produce less plant growth than would fluorescent lights because incandescent lights can be carefully focused, and sensitive areas can be shielded from too much light. Fluorescent lights provide a more general lighting of a cave than do incandescent lights.

The light spectrum from various types of lights can potentially affect the extent and magnitude of plant growth in caves. In general, incandescent lights produce a spectrum which is probably more conducive to plant growth than fluorescent lights, but as Harris (1979) notes, the "cool-white" fluorescent lights offer a wide range of light in the visible spectrum which is especially conducive to the photosynthetic mechanisms of green plants. Harris (1979) studied plant growth in test plots in Mammoth Cave which were illuminated with the following six types of fluorescent lights: red, pink, gold, green, blue, and cool-white. Harris (1979) found that plant growth was most extensive around cool-white lights. Red and blue lights produced less plant growth than cool-white lights, but had more growth than pink, gold, or green lights. Pink and gold lights produced about equal amounts of plant growth, and green lights produced less plant growth than any of the other lights tested. It should be noted that all of the lights tested by Harris (1979) produced at least some plant growth.

Both Blaisdell (1974) and Harris (1979) recommended use of green fluorescent lights or green filters for fluorescent lights in the caves which they studied. Harris (1979) commented that the human eye quickly adjusts to green colors, and that green light would soon become relatively unnoticed. In contrast, many show-cave operators believe that visitors prefer the "warmer" colors (the reds and yellows), and generally dislike the "cooler" colors (such as the blues, greens, and many fluorescent lights).

A deficiency in the studies of Harris (1979) and Blaisdell (1974) was the absence of light intensity data associated with the various colors of lights. Aley and Aley (1984) noted that colored lights produce lesser light intensities than do the white lights. Their data from Carlsbad Caverns suggested that when moisture was not limiting, it was generally light intensity, rather than light wavelength or light type, which best correlated with the extent of plant growth.

Aley, Aley, and Rhodes (1985) found visible plant growth in Carlsbad Caverns associated with 43% of the 277 lights they inspected. Visible plant growth was associated with 56% of the fluorescent lights, with 18% of the incandescent lights, and with 19% of the mercury vapor lights. These authors noted that there were three possible reasons which could help explain these differences. First, plant growth might be more commonly associated with fluorescent lights than with incandescent or mercury vapor lights because of the pattern of lighting. Fluorescent lights produce a more dispersed and more even intensity of lighting than is produced by incandescent lights. The dispersed and more even intensity of fluorescent lighting commonly has the effect of putting more cave surfaces "at risk" for plant growth than would be the case with the more highly focused incandescent lights. Incandescent lights can be focused and shielded much more readily than can fluorescent lights. Secondly, the differences might be associated with substrate moisture conditions. Incandescent lights produce more heat and thus more substrate desiccation than fluorescent lights. If moisture were only marginally adequate for plant growth, the sites which experienced the least desiccation would tend to be the sites most likely to have plant growth. Thirdly, there are differences between the general objectives of the different types of lights. The objective of the fluorescent lights in Carlsbad Caverns is to provide a general lighting of the cave; the incandescent lights are used primarily to highlight features; the mercury vapor lights are primarily used to illuminate distant ceilings. Comparison of the extent of plant growth

associated with different types of lights must recognize the differences amount the objectives of the various types of lights.

Aley and Aley (1984) recommended the following light intensity guidelines for fixed lights in Carlsbad Caverns:

Maximum light intensities reaching moist alcove surfaces should be less than 0.9 foot-candles if plant growth is to be largely prevented in such sites. Maximum light intensities reaching moist non-alcove surfaces should be less than 2.8 foot-candles if plant growth is to be largely prevented. Where this value is undesirable for interpretive or other reasons, plant growth can be minimized and often prevented by keeping light intensities reaching moist surfaces at less than 3.6 foot-candles.

Aley and Aley (1985) recommended the following light intensity guidelines for fixed lights in Oregon Caves:

Light intensities reaching moist surfaces should not exceed 4.2 foot-candles. For ideal plant growth prevention, sensitive cave features should receive light intensities of not more than 2.5 foot-candles.

Plant Growth in Mammoth Cave

Our use of the term "plant" includes all mosses and moss protonema, all algae, and the cyanobacteria (formerly called the blue-green algae). Our listing does not include any fungi present in the cave; fungi are particularly significant in causing the black coatings on gypsum in the Snowball Dining Room (Aley and Aley, 1986; Aley and Aley, 1991).

Harris (1979) developed a list of algae (and cyanobacteria) found in association with electric lights in the Frozen Niagara Section of Mammoth Cave. Van Hoff (1974) also identified a number of algae in the Frozen Niagara Section; his work (which is available only in manuscript form and includes substantial raw data) was particularly valuable since he collected light intensity values at each of 53 collection sites. The work by Van Hoff (1974) pre-dated exotic plant control work in the Frozen Niagara Section, and thus reflects the types of plant growth which can develop in Mammoth Cave in the absence of routine exotic plant control work. Jones (1964) identified a number of algal species in Mammoth Cave; most of these were found in unlighted portions of the cave. Nagy (1965) identified a number of algae from Floyd Collins Crystal Cave; many of these were also found in unlighted portions of the cave. Based upon the four references above we have compiled a list of identified "plants" known from Mammoth Cave.

Our list of plants includes both those found in association with electric lights and those found in total darkness. While there may be differences between plants found in total darkness and those associated with electric lights, it appears that many of the plants able to exist in total darkness ultimately do well under electric lights and become components of the unnatural flora associated with the lights.

Identification of Plants Known from Mammoth Cave

Moss protonema

The presence of mosses and moss protonema was recognized by Van Hoff (1974). Moss protonema cannot be identified to genus. Our observations in Mammoth Cave indicate that moss protonema can be important components of the cave flora, particularly if routine exotic plant control work is not conducted.

Green Algae

Ankistrodesmus falcatus (Jones, 1964)
Asterococcus superbus (Jones, 1964)
Cladophora kuetzingianum (Harris, 1979)
Chlorella ellipsoidea (Harris, 1979)
Chlorella vulgaris (Jones, 1964)
Chlorococcum humicola (Van Hoff, 1974)
Chlorococcum sp. (Harris, 1979)
Chlorosarcina consociata (Harris, 1979)
Coccomyxa dispar (Jones, 1964)
Diogenes sp. (Harris, 1979)
Harpochytrium hyalotheca (Jones, 1964)
Kirchneriella lunaris (Jones, 1964)
Nannachlorella bacillaris (Harris, 1979)
Neochloris minuta (Nagy, 1965)
Oocystis lacustris (Jones, 1964)
Planophila laetevirens (Jones, 1964)
Protococcus viridis (Harris, 1979)
Scenedesmus abundans (Jones, 1964)
Scenedesmus brasiliensis (Nagy, 1965)
Tetrachloris inconstans (Jones, 1964)
Ulothrix tenerrima (Jones, 1964)

Cyanobacteria (Blue Green Algae)

Anacystis sp. (Van Hoff, 1974)
Aphanothece gelatinosa (Van Hoff, 1974)
Beggiatoa alba (Jones, 1964)
Chamaesiphon gracilus (Nagy, 1965)
Chroococcus sp. (Van Hoff, 1974)
Gleocapsa sp. (Van Hoff, 1974)
Gomontiella magyariana (Jones, 1964)
Hydrocoleum homeotricum (Harris, 1979)
Lynqbya contorta (Harris, 1979)
Lynqbya pusilla tenuior (Jones, 1964)
Microchaete tenera (Harris, 1979)
Microcystis stagnalis (Jones, 1964)
Nostoc minitissimum (Jones, 1964)
Oscillatoria subtilissima (Jones, 1964)
Oscillatoria neglecta (Jones, 1964); (Nagy, 1965)
Oscillatoria animalis (Jones, 1964)
Oscillatoria clausiana (Jones, 1964)
Oscillatoria sp. (Van Hoff, 1974); four unidentified species which may or may not include those identified by Jones (1964) and Nagy (1965)
Phorium cebennense (Jones, 1964)
Phormidium subtruncatum (Jones, 1964)
Phormidium automnale (Harris, 1979)
Synechococcus aeruginosus (Van Hoff, 1974)

Euglenoids

Phacus pleuronectes var hyalinus (Jones, 1964)
Trachelomonas verrucosa (Jones, 1964)

Dinoflagellates

Gymnodium tenuissimum (Nagy, 1965)

Yellow-green Algae

Chrysococcus klebsianus (Jones, 1964)

Diatoms

Several species of Pennalean diatoms (Harris, 1979)
Cocconeis sp. (Van Hoff, 1974)
Fragilaria sp. At least two species recognized. (Van Hoff, 1974)
Melosira sp. (Van Hoff, 1974)
Navicula mutica var. nivalis (Nagy, 1965)
Navicula sp. (Van Hoff, 1974). May or may not be species identified by Nagy (1965)

Red Algae

Asterocytis smaragdiana (Nagy, 1965)
Lemanea torulosa (Jones, 1964)
Rhodochorton sp. (Harris, 1979)

Important Floral Components in Lighted Portions of Mammoth Cave.

Many of the algae from the Frozen Niagara Area identified by Van Hoff (1974) were found in four samples or less. Table 1 identifies all floral components which were identified in at least 5 of the 53 samples collected by Van Hoff (1974). These common floral components are listed in order of increasing mean light intensity reaching the collection sites.

The data in Table 1 demonstrate that the most common floral components in the Frozen Niagara Area in 1974 were Chlorococcum humicola (a green alga), Lyngbya sp. (a cyanobacteria), and moss protonema. Other green algae and cyanobacteria were also commonly found. Diatoms were also common, however, they are very small and do not generally produce the luxuriant growth associated with the green algae, cyanobacteria, and moss protonema.

Table 1. Floral components present in at least 5 of the 53 samples from the Frozen Niagara Area and mean light intensity where it was found. Floral components are listed in order of increasing mean light intensity. Data derived from Van Hoff (1974).

Component	Type *	Percent of samples in which found	Foot-candles
Aphanothece gelatinosa	Cy	9	14.0
Moss protonema	Moss	57	23.8
Lyngbya sp.	Cy	60	25.6
Diatom 1 (not to genus)	D	25	25.9
Melosira sp.	D	15	25.9
Oscillatoria sp. #2	Cy	23	36.5
Chlorococcum humicola	G	70	36.6
Navicula sp.	D	13	37.0
Oscillatoria sp. #1	Cy	13	39.2
Gleocapsa	Cy	11	39.4
Minute green alga; not identified to genus	G	26	41.7
Fragilaria sp. #1	D	9	58.8

* Cy = Cyanobacteria; G = Green Alga; D = Diatom.

Clay worms (also called vermiculations) are curving and rather tubular-like clay deposits which are scattered about on many surfaces in Mammoth Cave and in many other caves. They are typically less than an inch long. The source of the clay worms is generally airborne dust which has deposited on cave surfaces. We suspect that the particles comprising the clay worms are electrically charged, and that they accumulate into the worm-shaped structure when the surface on which the particles are attached becomes moist. The moisture may facilitate sediment transport; it may also lessen frictional forces and permit particle movement in response to electric charges.

Chlorococcum humicolum was the most common floral component in the Frozen Niagara area. An unidentified species of this same genus was a common component of the exotic flora of lighted portions of Oregon Caves, Oregon Caves National Monument (Aley and Aley, 1985). In Oregon Caves it was associated with mud-covered marble, lint "globs" on marble, firm and smooth flowstone, and cave coral with moonmilk. In Oregon Caves it was associated with light intensities between 0.79 and 16.0 foot-candles.

Stark (1969) reported C. humicolum in lighted portions of Lehman Caves, Nevada. Williams (1967) reported this same species from soil and moonmilk in caves in South Wales; it was found growing in total darkness in these caves. C. humicolum and C. infusionum were reported growing in total darkness in Peace Cave, Hungary by Claus (1962). Kol (1967) reported C. humicolum, C. infusionum, and an unidentified species of Chlorococcum in total darkness in Baradla Cave, Hungary; Claus (1964) also reported C. infusionum in this cave. Aley and Aley (1984) did not find this genus in studies at Carlsbad Caverns.

Lyngbya sp. was the second most common floral component in the Frozen Niagara area. Three species of Lyngbya were found in electrically lighted portions of Carlsbad Caverns (Aley and Aley, 1984); they were most commonly associated with alcove sites with low light intensities. Lyngbya was not found in electrically lighted portions of Oregon Caves (Aley and Aley, 1985), nor in Lehman Caves (Stark, 1969).

Moss protonema were the third most common floral component in the Frozen Niagara area. In electrically lighted portions of Blanchard Springs Caverns moss protonema are the dominant plant material (Aley, 1976). Aley and Aley (1984) estimated that 10% of the "alga-like" plant growth in Carlsbad Caverns was actually moss protonema. Aley and Aley (1985) reported that moss protonema were a significant part of the exotic plant growth in Oregon Caves; they found the protonema in approximately 1/3 of their sampling stations. Typical substrates where moss protonema were found in Oregon Caves included fairly dry sediment, rocks in flowing water, smooth flowstone, weathered flowstone and moonmilk, "clay worms" with lint, and flowstone and marble coated with small amounts of sediment.

Aphanothece gelatinosa was found in 9% of the samples from Mammoth Cave. The same species was found in lighted portions of Oregon Caves (Aley and Aley, 1985) where it was associated with lint "globs" on bedrock surfaces.

With the exception of Gleocapsa sp., all of the other genera shown in Table 1 as being common in the Frozen Niagara portion of Mammoth Cave (Oscillatoria, Melosira, Fragilaria, and Navicula) were also found in lighted portions of both Carlsbad Caverns (Aley and Aley, 1984) and Oregon Caves (Aley and Aley, 1985).

The above discussion indicates that the composition of the flora found in Mammoth Cave (and particularly in lighted portions of the cave) is generally similar to that found in other studied caves. Every cave has its own collection of flora, and some caves may contain unique or unusual species. However, exotic plant growth in electrically lighted portions of American show caves commonly consists primarily of moss protonema, several species of cyanobacteria, a few species of green algae, and several species of diatoms. This is clearly what is present in Mammoth Cave.

Relationship of Plant Growth to Light Intensity

Van Hoff (1974) conducted his algal survey of the Frozen Niagara area of Mammoth Cave prior to exotic plant control actions by the National Park Service in this area. His work included the collection and identification of algae, and an assessment of the presence of moss protonema, in 53 samples where plant growth was visible. At each of these sampling sites he measured the light intensity reaching the growth area.

Figure 1 provides a graph of the cumulative percent of visible plant growth vs. light intensity in the Frozen Niagara area in 1974 (the data are from Van Hoff, 1974). The lowest light intensity at which Van Hoff (1974) collected samples was 5 foot-candles. As can be seen in Figure 1, approximately half of the sampling sites where plant growth was visible received light intensities of 15 foot-candles or less.

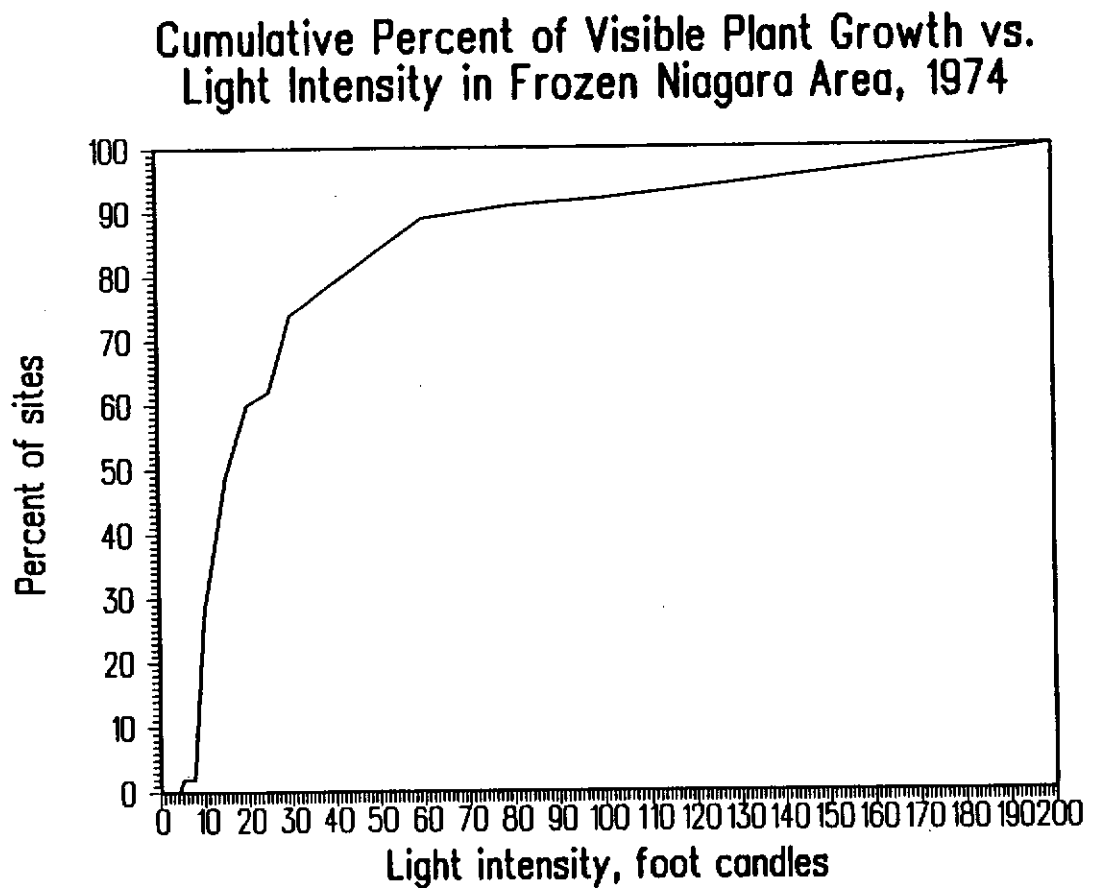
During our restoration studies we made a series of light intensity measurements at plant growth sites along the Historic Tour Route. The results are summarized in the following paragraphs.

The light intensity at points with maximum plant growth was measured at 12 sites; the mean value was 47.6 foot-candles; the standard deviation was 35.1 foot-candles. The range of values was from 11.3 to 116 foot-candles.

The minimum light intensity resulting in plant growth was measured at 43 points. The mean value was 7.51 foot-candles; the standard deviation was 3.65 foot-candles. Values ranged from 2.3 to 20.0 foot-candles. The associated plant growth was algae and moss protonema.

The minimum light intensity resulting in mature moss growth was measured at 3 points. The mean value was 27.7 foot-candles; the values ranged from 22.7 to 32.0 foot-candles.

Figure 1. Cumulative percent of visible plant growth vs. light intensity in the Frozen Niagara area of Mammoth Cave, 1974. Data from Van Hoff (1974).



Recommendations for Light Intensities to Minimize Plant Growth

Based upon light intensity measurements at plant growth sites, we have the following guidance for Mammoth Cave:

1) Light intensities on moist natural cave surfaces should be kept at less than 7.5 foot-candles to the greatest extent possible.

2) Essentially all plant growth can be prevented if light intensities on moist sites are kept below 2.3 foot-candles. Light intensities on the majority of moist cave surfaces should be at or below 2.3 foot-candles.

3) Greater light intensities on moist cave surfaces are acceptable; such intensities will result in some plant growth and will require periodic plant control work. Greater light intensities may be locally necessary, however, light intensities should not routinely exceed the limits indicated above.

4) Higher light intensities can be permitted on dry cave surfaces. There are substantial areas in Mammoth Cave where there is not enough moisture on cave surfaces to support establishment of exotic plant growth. However, it should be remembered that respiration from visitors and seasonal airflow patterns may result in condensation of water on cave surfaces; such condensation is sometimes sufficient to support the establishment of plant growth. Additionally, and particularly in the case of the cyanobacteria, less moisture is required to maintain growth than to establish it.

5) In summary, even on apparently dry surfaces, light intensities should be minimized to the greatest extent possible consistent with interpretation of the cave and visitor safety. Light intensity reaching most natural cave surfaces should be equal to, or less than, 2.3 foot-candles. Light intensities of up to 7.5 foot-candles are acceptable on localized areas, particularly if the sites are not moist. Greater light intensities are acceptable for highlighting some particular feature, but such intensities should be the exception rather than the routine situation. The greatest attention to light

intensities is needed on moist or wet surfaces, and particularly those that are difficult to reach for plant control purposes.

Areas Where Exotic Plant Growth Is Likely to Be a Problem

Within Mammoth Cave moisture is the most common factor limiting the extent of plant growth. Most of the cave is overlain by sandstone units which permit very little water to move downward into the cave. In localized places the overlying sandstone has been breached and water is able to percolate or flow downward into the cave. Vertical shafts and calcium carbonate speleothems are common in these areas. Most plant growth in Mammoth Cave is associated with vertical shafts and/or areas with calcium carbonate speleothems.

There are some areas where water enters the cave yet solution has not been sufficient to create vertical shafts and deposition has not created calcium carbonate speleothems. However, if there is moisture in these areas there can be plant growth.

Respiration by visitors may provide some moisture for exotic plant growth. However, if this were particularly important in the area being re-lighted we would expect appreciable plant growth in the vicinity of the rest area in Great Relief Hall. There is essentially no plant growth in this area.

Areas near entrances where outside air moves into the cave during times when surface temperatures are warmer than cave temperatures are seasonally characterized by water condensation on cave surfaces. Plant growth can occur in these areas. Areas where air saturated with moisture moves into a cooler portion of the cave will also experience condensation that can result in adequate moisture for plant growth.

Plant growth along the Historic Route is primarily found in the following areas:

- 1) Passage between the main entrance and the Rotunda.
- 2) Passage from the Wooden Bowl Room to the start of Fat

Man's Misery.

3) All areas with vertical shafts and/or calcium carbonate speleothems.

Plant growth causes more resource damage on speleothems than on bedrock or sediment surfaces. Plant growth is most significant on speleothems when the following conditions are met:

- 1) The surface is commonly moist.
- 2) Light intensities are in excess of 2.5 foot-candles. Major plant growth is likely when light intensities are in excess of 7.5 foot-candles. Maximum plant growth is most likely to occur when light intensities are between about 12 and 83 foot-candles.
- 3) Plant growth is allowed to remain in place for weeks or months after it initially becomes visible.
- 4) Moonmilk is present on the speleothem, or the speleothem is coated with even small amounts of sediment or lint. Vermiculations (often called "clay worms") consist of sediment and lint; they are routinely the sites where plant growth begins.

Some areas are difficult to reach and therefore are difficult to treat if plant growth occurs. Very careful control of the intensity of light reaching these areas is obviously important.

RE-LIGHTING STRATEGIES

Scope of Work

The purchase order for these investigations included two tasks related to re-lighting of a portion of Mammoth Cave. The tasks were described as follows:

Task 4. Identify cave features which should be emphasized by the new lighting system.

The lighting of these features must emphasize:

1. Safety considerations
2. Protection of cave resources
3. Interpretation
4. Aesthetics
5. Installation and maintenance convenience

Task 6. Assist those individuals who are selecting lighting fixtures, designing the lighting system, installing the lights, and conducting restoration work to insure that the new lighting system maximizes safety, resource protection, resource restoration, and interpretative values.

Introduction

Most of the work on these two tasks was accomplished by spending several days working in Mammoth Cave with NPS personnel involved in the re-lighting project. The work progress through the following three fundamental steps:

1) We first spent several hours with NPS personnel examining and discussing how the old lighting system functioned; this was contrasted with how we wanted the new lighting system to function.

2) Next, the Ozark Underground Laboratory staff and NPS personnel were all involved in identifying and discussing features which should be illuminated and features which should be avoided to the greatest extent possible in the new illumination.

3) Finally, we installed and shielded selected lights. This was the "how to" phase of the work. Selected lights included those where we could demonstrate techniques for

shielding lights, trail lights in areas with steps, and lights typical of common trail and feature lights. Techniques were demonstrated for building shields out of metal, rock, and plastic soil cement.

The three steps are discussed in the following paragraphs. We would ask that the reader understand that it is difficult to explain in writing things which can (and were) best demonstrated and practiced in the cave.

Comparison of the Old and New Lighting Systems

The old lighting system in the study area of the cave primarily relied upon fluorescent lights with tubes at least four feet long. One commonly encounters fluorescent lighting in offices, shops, and businesses because it provides a broad, diffuse lighting of large areas. In contrast, the new lighting system relies primarily upon incandescent lights.

Part of the rationale for the old fluorescent lighting system in the re-lighting portion of Mammoth Cave was the mistaken belief that fluorescent lights caused less exotic plant growth than did incandescent lights. Aley and Aley (1984) examined this issue in detail in Carlsbad Caverns and concluded that, in the presence of adequate moisture, light intensity was the primary factor limiting exotic plant growth. The spectrum of the emitted light (unless it was green) made essentially no difference; the intensity of the light reaching suitable growth substrates was the controlling factor.

Incandescent lighting in caves enhances those features with "warmer" colors (the red and yellow hues). The "warmer" colors are common in cave sediments in Mammoth Cave. Fluorescent lighting enhances those features with "cooler" colors (the blue and green hues); these are uncommon in Mammoth Cave. Since caves are naturally dark, neither type of light is more or less "natural" than another. Slight enhancement of colors which naturally exist in the cave would seem to be desirable, yet it should be recognized that some people might prefer the color balance associated with the fluorescent lights over that associated with the incandescent lights.

Light intensities from point to point vary much more with typical incandescent lighting than they do with typical fluorescent lighting systems. As a useful generalization, fluorescent lighting in caves tends to light chambers; incandescent lighting tends to light specific features. Prevention of the "spilling" of light onto surfaces which one does not want to illuminate is much easier with incandescent lighting than with fluorescent lighting.

The old fluorescent lighting system often lighted the trail by aiming the lights at the ceiling or at walls and reflecting light onto the trail. Cave walls and ceilings are poor reflectors, so it was often necessary to apply abundant light to such surfaces in order for there to be enough light to safely illuminate the trail. In the new incandescent light system we identified lights as either trail lights or feature lights. In a few cases one light may adequately do both jobs. However, in most cases, separate lights are needed for the best performance of separate functions.

The human eye adapts rather quickly to low light intensities. This adaptation to relatively low light intensities tends to be slower in older people than it is in younger people. Lights which shine into a visitors eyes, or very brightly lighted spots, significantly reduce the quality of a person's night vision. These conditions created major problems with the old fluorescent lighting system for several reasons. First, the fixtures were large and often difficult to conceal. Secondly, many of the lights had not been carefully shielded. Finally, the large lights and the strategy of reflecting light for the trails off the walls and ceilings frequently created very bright spots in the cave.

In the new lighting system we adopted the following strategies for light placement:

- 1) In general, a light should either illuminate the trail or else a cave feature; most lights cannot ideally serve both functions.

2) Lights must be effectively shielded from direct view both for esthetic reasons and to maintain night vision in visitors.

3) Light intensity must be carefully controlled and balanced so as to prevent the creation of unduly bright spots.

4) The quality of cave lighting tends to increase with an increase in the number of light fixtures. The greater the number of lighting fixture, the lower the wattage should be in each individual light.

5) The distance between trail lights should be shorter on steps and around obstructions than is the case on straight and unobstructed portions of cave trails. It is better to reduce the distance between trail lights than to increase the wattage of the lights.

Features to Illuminate and Features to Avoid

The portion of the Historic Tour selected for re-lighting experienced many years of heavy use. Graffiti (some of which may have some minor historical interest) is extensive at many points in this area. The cave floor has been extensively modified by piles of rock and sediment debris from trail construction and by people having walked on essentially every accessible surface. At present, the cave is clearly not in a near natural condition.

The unnatural conditions in the cave were particularly visible under the old fluorescent lighting system since the lighting system tended to illuminate the entire chamber and everything in it. The strategy used in positioning incandescent lights was to illuminate features of natural significance and to avoid lighting unnatural features. Much of the graffiti in the cave is difficult to see at low light intensities, so it was often possible to greatly de-emphasize the graffiti while still permitting visitors to see the general nature and outline of the chambers.

In our training of NPS personnel we identified a number of features which should be lighted with the new lighting system. Primary emphasis was placed on lighting features which were characteristic of the portion of the cave being traversed. We emphasized that it was very important to

light features which displayed common features uncommonly well. It is also important to light uncommon or unique features. One example within the segment being lighted was a joint controlled passage; joints only rarely control passage orientations in Mammoth Cave.

We did not make lists of features which should be lighted or which should not be emphasized in the lighting. Instead, we felt the better approach was to help NPS personnel understand the strategy of the new lighting system. We believe this was adequately accomplished by the several days we spent in the cave with the NPS personnel who were doing the lighting.

Installation and Shielding of Lights

Our recommendations relative to the re-lighting program in Mammoth Cave were included and summarized in a letter to Superintendent Dave Mihalic dated November 13, 1988. Important recommendations were as follows:

1) Various test equipment is needed for any re-lighting program. The equipment includes extension cords, various shields, diffusers, focusing aids, and a range of bulbs and fixtures. One simply cannot plan everything in advance; there must be substantial "try it and see if it works" involved. The lighting must be a creative and innovative effort.

2) All lights must ultimately be anchored so that they cannot be accidentally moved or moved on a whim. There needs to be a tag on each light indicating the type and wattage of the light; future light replacement must be in conformance with the tag.

3) A written documentation should be made for each light. The documentation should indicate the intent of the light and its general positioning. It should also include the type and wattage of the light and any other relevant information.

4) Colored lights are amber and blue. Blue lights will seldom be useful. We are not after "special effects"; instead, we are trying to provide a true depiction of the natural character of the cave. Colored lights are

potentially appropriate only to the extent that they assist in the true depiction of the natural character of the cave.

5) Lights which can be used should be specified at the discretion of the lighting team. They should include, but not necessarily be limited to, the following:

A) Incandescent bulbs of 15, 25, 40, 60, and 100 watts; most should be frosted, but some could be clear.

B) 100 watt flood lights (predominantly white, but including, at the discretion of the lighting team, a few amber and perhaps some blue lights).

C) 100 watt white spot lights.

D) Quartz lights in the Temple of Karnak area.

We strongly emphasize that other types of lights and related fixtures can be used as appropriate.

Without adapters, the present fixtures will not adequately accept standard 15, 25, or 40 watt bulbs. This limitation needs to be overcome since there is a distinct need for some smaller wattage bulbs. It is worth noting that at Carlsbad Caverns there were 26 different kinds of lights used.

6) The final decision on the number of lights and their placement must lie with the lighting team and be a reflection of the needs of interpretation and resource protection. In one of our sessions Larry Compdon told the group that the electrical system has sufficient capacity to provide essentially total flexibility for a lighting system. This flexibility should be used.

7) Metal screen wire (such as the aluminum wire commonly used for house screens) can be placed in front of bulbs to act as a diffuser and to reduce light intensities. This is an excellent way to balance light intensities and fine-tune the lighting system. The screens do not necessarily need to regulate all light from a particular fixture.

A series of light intensity measurements were made at the Ozark Underground Laboratory to quantify the effects of the screen wire on light intensity. One thickness of screen wire will reduce the light intensity reaching cave surfaces by approximately 25%. This 25% reduction applies

regardless of the distance from the light bulb. A second piece of screen wire, aligned so that the wires are offset from those in the first piece, results in a further light reduction of 25% of the light passing through the first piece of wire. Therefore, two pieces of screen wire, one on top of the other and with the wires offset, will reduce the light intensity reaching particular points by approximately 44% (75% of the light passes the first screen and then 75% of this passes the second screen; $.75 \times .75 = 0.56$ of the initial light intensity passes through both screens; $100\% - 56\% = 44\%$ light intensity reduction).

We also made a series of light intensity measurements where the distance from the bulb to the screen (or screens) was varied. Other than the size of screen necessary, it makes no difference how far the screen is from the bulb. At any given measurement point, the presence of one screen reduces light intensity by 25% over the intensity without a screen.

8) The mortar mix for constructing shields should be a plastic soil cement mix consisting of about 5 parts cave soils to one part Portland cement. The mix should be adjusted as the amount of clay and silt in the cave soils varies until the mix has a color similar to cave colors. Workers should use cave soils which contain as little sand as possible. The intent is to have a mix which blends with the cave colors while also having adequate strength; strength is not commonly a problem.

9) Some shields, or portions of shields, can be constructed of hardware cloth covered with plastic soil cement. We constructed an example of such a shield during our work in the cave. Rocks can be placed in front of bulbs to reduce light intensities reaching particularly sensitive points. However, unless these rocks are firmly anchored they are likely to be moved when bulbs are changed; such movement changes the lighting and is undesirable.

10) Based upon measurements of light intensities at plant growth sites, we have the following guidance for minimizing exotic plant growth:

A) Light intensities on natural cave surfaces should be kept at less than 7.5 foot-candles to the greatest extent possible.

B) Essentially all plant growth can be prevented if light intensities on moist sites are kept below 2.3 foot-candles. Light intensities on the majority of cave surfaces should be at or below 2.3 foot-candles.

C) Greater light intensities are acceptable; such intensities will result in some plant growth and will require periodic plant control work. Greater light intensities may be locally necessary, however, light intensities should not routinely exceed the limits indicated above.

To avoid confusion on light intensity recommendations, it is our recommendation that the light intensity on most natural cave surfaces be equal to or less than 2.3 foot-candles. Intensities of up to 7.5 foot-candles are acceptable on localized areas, particularly if the sites are not moist. Greater light intensities are acceptable for highlighting some particular feature, but such intensities should be the exception rather than the routine situation. The greatest attention to light intensities is needed on moist or wet surfaces.

11) Personnel doing cave lighting should have authorization to dig small excavations as needed for proper siting and installation of the lighting.

12) Good lighting can assist guides in maintaining good contact with, and control of, their parties. A sequential interpretive lighting program (controlled by the guide) should be considered for the Mammoth Dome-Ruins of Karnak area. It could be used at times when tour party size does not exceed the carrying capacity of the cave. Such programs are used very effectively at Blanchard Springs Caverns and elsewhere.

13) Studies should be conducted to establish a carrying capacity for the Historic Route. As noted above, exceeding the carrying capacity can affect the operation of the lighting system.

14) Tours on the Historic Tour Route should always be one-way; they should move from River Hall toward Mammoth Dome. While it is possible to have trail lights and limited interpretive lighting which permits two-way travel, good lighting to depict the cave must be designed and installed for a single direction of travel.

On September 10, 1988, we reviewed the re-lighting efforts that had been conducted up to that time. Our suggestions and observations were detailed in a letter to Mr. George Gregory dated September 19, 1988, and were as follows:

1) Light intensities in most of the smaller passages which have been re-lighted were well below those which would result in exotic plant growth. If necessary or desirable, light intensities could be increased somewhat without appreciable increases in plant growth. This is particularly true in the drier passages.

2) The rock light shields are undoubtedly the best approach for some installations. Where particularly careful lighting is needed, construction of shields made of galvanized quarter-inch hardware cloth and plastic soil cement is recommended. The hardware cloth provides the basic framework for the plastic soil cement; holes in the shields are cut where needed.

The plastic soil cement is made of 5 parts cave soil (of an appropriate color) and 1 part of Portland cement. Sufficient water is added to make a workable material which is rather like a very sticky mortar. The material is mixed in a fashion similar to that used for mixing mortar (although the plastic soil cement is more difficult to mix because it is so sticky). The resulting plastic soil cement has a color very similar to the cave soil; it adheres very well to the hardware cloth structure even in overhanging situations. We typically work the plastic soil cement with our hands (we wear rubber gloves); it is difficult to remove from a trowel. Portions of shields can be added on simply by using the plastic soil cement to attach another piece of hardware cloth. The resulting shields are made in the cave, and each one is different.

Slits and holes can be left in the shields to provide the desired pattern of lighting on trails and cave surfaces. With careful construction, lights will not shine in visitors' eyes. A light which shines in visitors' eyes will degrade their night vision for varying periods; the periods are greater for older visitors than for younger people.

3) The general reliance upon small lights is very nice. Keep in mind that the smaller the light, the more individual light fixtures will be needed. There were several places in the re-lighted portions of the cave where we felt the need for additional light fixtures; the need seemed to be greatest in areas where the trail made bends.

4) There are some fine scallops on cave walls and ceilings in the area before Mammoth Dome. We were disappointed that these were not better depicted by the preliminary lighting. Perhaps this short-coming can be overcome by use of plastic soil cement shields.

5) We were very impressed with how much better the fluting in the vertical shafts is depicted by the incandescent lights than was the case with the fluorescent lights. Shadows are a great tool in incandescent lighting.

6) The incandescent lighting also makes the graffiti in this portion of the cave far less noticeable. Conditions will be improved further when graffiti is removed.

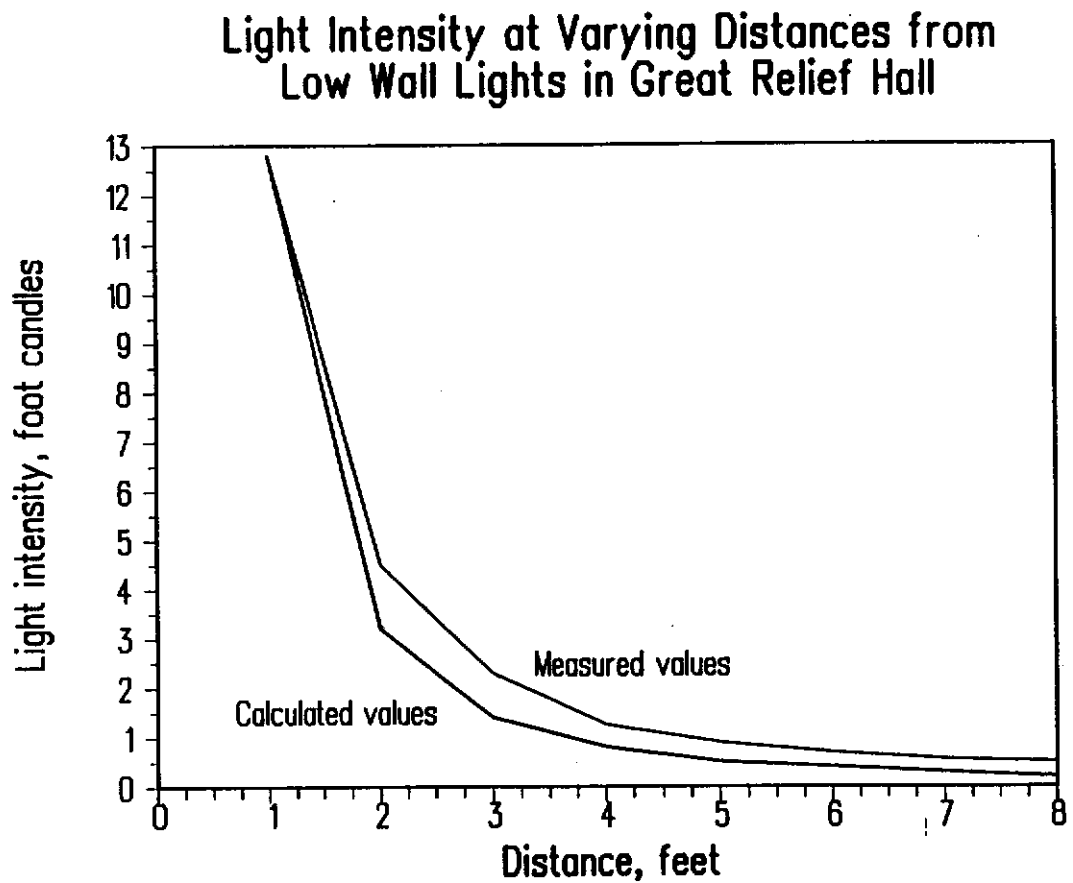
7) There is a need for some opaque and/or translucent shields in Mammoth Dome. There were several places where excessive amounts of light were "spilled" on surfaces near the lights. This condition creates undesirable resource and visual effects; in some places the lighting tends to decrease the night vision of visitors.

8) There are places (such as near the top of Mammoth Dome) where interpretation may be benefitted by light intensities which could cause exotic plant growth. You should consider use of sound-activated lights, or some similar device, to reduce the duration of the lighting in these areas.

On February 3, 1990, we inspected new trail lights installed in a low masonry wall in Great Relief Hall. The bulbs used in the light fixtures were 60 watt frosted incandescent lights. Light intensities were measured on the floor at varying distances from the lights. The results are shown in Figure 2. Calculated values are based upon the relationship that light intensity varies with the square of the distance from the light source. It will be noted that ^{calculated} measured values are consistently slightly larger than measured values. The explanation for this is that one measures some light from adjacent lights as he moves away from an individual light.

An earlier discussion indicated that essentially all plant growth could be prevented if light intensity reaching moist surfaces was less than 2.3 foot-candles. Figure 2 indicates that light intensities of less than 2.3 foot-candles occur at all points more than three feet from one of the trail lights installed in the low masonry wall.

Figure 2. Light intensities at varying distances from low wall lights in Great Relief Hall.



RESTORATION TECHNIQUES AND GUIDELINES

Scope of Work

The purchase order for these investigations included one task related to re-lighting of a portion of Mammoth Cave. The task was described as follows:

Task 5. Develop restoration techniques and guidelines for the area to be re-lighted.

This work involves the following sub-tasks:

1. Removal of exotic plant growth
2. Identification and removal of unnatural "clay worms"
3. Techniques for removing or diminishing the visibility of graffiti.
4. Techniques for identifying and removing inappropriate unnatural coatings or materials on cave surfaces.

Removal of Exotic Plant Growth

Our recommended approach for removing exotic plant growth is very similar to the methods outlined for restoration work in the Snowball Dining Room (Aley and Aley, 1991). Fungus (and some algae) comprised much of the black coatings in the Snowball Dining Room; the restoration approach was to oxidize the fungus and algae with a 5.25% sodium hypochlorite solution. This solution works extremely well on algae, cyanobacteria, and moss proto-nema. We have made extensive studies of exotic plant growth and appropriate control approaches in Carlsbad Caverns (Aley and Aley, 1984) and in Oregon Caves (Aley and Aley, 1985); our recommendations for control approaches in Mammoth Cave are consistent with the findings of these previous investigations.

Treatment Approach

1. Apply a mist of bleach (5.25% sodium hypochlorite) to the area affected by visible plant growth. This is the standard bleach usually sold in grocery stores. For small areas the application can be made with a small spray bottle. For larger areas the application can use a pump-up tank type sprayer with a wand at least three or four feet

long. The sodium hypochlorite should be applied at a rate heavy enough to moisten the surface being treated; however, the application rate should be light enough to minimize drippage from the treated surface. Some drippage will occur and is expected. All drippage and all rinse waters must be collected and removed from the Cave.

2. Treated areas which are rock or flowstone should be rinsed with clean water after the first treatment with the sodium hypochlorite solution. We recommend that treated areas not be rinsed for at least one week after treatment. This allows time for fungus to become established on the dead algae, cyanobacteria, and moss and moss protonema. This fungal development makes it much easier to wash off all dead plant material.

3. Cave sediments should be treated with the sodium hypochlorite solution but not subsequently rinsed.

4. Re-treat areas with the 5.25% sodium hypochlorite solution as necessary. Re-treatment is not routinely needed unless excessive amounts of plant growth have become established between treatment cycles.

5. Cave resources are best protected and treatment time is minimized if areas prone to exotic plant growth are inspected monthly and treated anytime plant growth is visible.

6. Rubber clothing and a full-face respirator appropriate for chlorine gas environments will be required for each person doing the exotic plant control work. Rubber gloves must be worn. All workers must understand that bleach can damage the lungs and other body tissues. Label instructions on bleach bottles must be followed.

7. Worker safety can be insured by a good treatment protocol and by good training and supervision of workers. Additionally, safety equipment such as respirators and goggles must be both effective and comfortable. It has been our experience that some of the less expensive respirators and goggles are extremely uncomfortable for extended use. Uncomfortable or awkward safety equipment provides an unwarranted incentive for workers to dispense with the equipment.

Discussion

Calcium hypochlorite solutions must not be used. Calcium hypochlorite is not as strong an oxidizing agent as is sodium hypochlorite. As a result, more calcium hypochlorite must be applied to attain results comparable to those with sodium hypochlorite. Finally, calcium hypochlorite applications in Carlsbad Caverns (Aley and Aley, 1984) resulted in unnatural calcium chloride deposits on speleothems.

The use of sodium hypochlorite will create unnatural odors in the cave. The odors will decrease over a period of a few hours to a day or so. Small applications on several days is a better approach than a large application on a single day. Odor problems, and many other problems, can be minimized by the use of a small treatment team which is well trained and well supervised. Damage to the cave can be minimized by having the same team do all of the treatment work; most damage is likely to occur as people get the "feel" of the work.

Aley and Aley (1984) conducted studies on the impacts of repeated treatments of 5.25% sodium hypochlorite solutions on calcite speleothem colors in Carlsbad Caverns, New Mexico. They color indexed speleothems and then subjected them to 25 cycles of 5.25% sodium hypochlorite immersion. Some of the test speleothems were rinsed between treatments; others were not. Aley and Aley (1984) were unable to detect any changes in the color index values of any of the test speleothems.

Aley and Aley (1985) conducted a 480 day study to determine if repeated treatment of calcite speleothems with 5.25% sodium hypochlorite solutions impacted subsequent speleothem deposition. They found no apparent impacts.

In summary, there is no technical literature to indicate that the recommended restoration work, if it follows the outlined procedure, will result in any significant adverse impacts upon Mammoth Cave.

Identification and Removal of Unnatural "Clay Worms".

Clay worms (which are also called vermiculations) are curving and rather tubular-like clay deposits which are scattered about on many surfaces in Mammoth Cave and in many other caves. They are typically less than an inch long. The source of the clay worms is generally airborne dust which has deposited on cave surfaces. We suspect that the particles comprising the clay worms are electrically charged, and that they accumulate into the worm-shaped structure when the surface on which the particles are attached becomes moist. The moisture may facilitate sediment transport; it may also lessen frictional forces and permit particle movement in response to electric charges.

Dust and other particulate matter is "stirred up" by visitors and becomes airborne. One can readily demonstrate this by shining a bright light down a cave passage both before and after the passage of a tourist party. Steps which can be taken to minimize this include paving of all areas where people walk and periodic washing of trails to remove particulate matter. Trails in Mammoth Cave are not routinely washed.

We believe that all of the vermiculations found along the Historic Route in Mammoth Cave are due to the impacts of human visitation. The vermiculations retain moisture and lint from visitors; the lint contains nutrients which enhance exotic plant growth. Because of the moisture and nutrients, the vermiculations are good substrates for exotic plant growth and are often the first points upon which exotic plant growth can be seen.

We believe that all vermiculations in lighted, or formerly lighted, portions of Mammoth Cave should be viewed as unnatural features. If there is no visible plant growth associated with a group of vermiculations they can be removed simply by spraying them with a small amount of water. If there is visible plant growth associated, the area should first be treated with a 5.25% sodium hypochlorite solution to kill the plant growth.

After approximately one week the vermiculations and associated dead plant material can be removed by spraying with a small amount of water.

Techniques for Removing or Diminishing the Visibility of Graffiti

Initials, names, and other defacements are scratched, carved, lipsticked, pencilled, smeared, and painted onto cave surfaces throughout Mammoth Cave. The graffiti is particularly abundant along the Historic Tour Route. In the past (and perhaps still in the case of some of the guides) the graffiti has been interpreted as part of the history of the cave. Such interpretation, combined with the presence of extensive existing graffiti, probably results in the creation of additional graffiti.

We recommend that a historian identify any writing on cave features which is of historical significance. This work should be conducted prior to major restoration work. Such historical assessment work should document the location and describe the significance of any identified feature deemed to have historical significance. It is clear that the vast majority of the graffiti is of no historical value and is, in fact, totally inappropriate defacement of natural features of a National Park.

Many of the cave surfaces along the Historic Tour Route are weathered rock. One of the principal modes of weathering is from carbon dioxide dissolved in the water vapor of the cave air. During our studies we tested a small representative area near the rest room and found that much of the graffiti could easily be removed with water and a nylon bristle scrub brush. The brush left marks on the wall, but these marks were easily removed by spraying the rock surface with a fine mist of water from a small spray bottle. The scrubbing and washing basically re-distributes the weathered rock and obscures the graffiti in the process. One should not overlook the fact that much graffiti can often be removed with water even without scrubbing.

Mr. W.T. Austin of Horse Cave, Kentucky, has told us that Dr. E.R. Pohl (former Mammoth Cave geologist) reported that during the 1930's CCC crews scrubbed the cave walls from the Historic Entrance to at least the Rotunda. The purpose of this work was to remove smoke coatings from saltpetre workings and other former activities in the cave. Scrubbing to remove graffiti accumulated along the entrance passage since this previous restoration work would not be likely to affect anything of historical value.

The scrubbing and rinse approach for removing graffiti is recommended for many of the cave wall and ceiling surfaces. It is particularly recommended for the graffiti-rich areas in Great Relief Hall.

Scratches in firm rock or speleothems can be made substantially less visible by treating them with vinegar. This "ages" the scratches. We suspect that fresh graffiti provides an encouragement to other visitors to add their own defacement; treating the scratches will reduce this encouragement. Some smoked or painted graffiti can be removed with vinegar; this works particularly well with gypsum substrates.

A water slurry of five or more parts of cave sediment to one part of Portland cement will closely approximate the color of many cave surfaces. Other cave materials, such as powdered fragments of broken gypsum, can also be used in slurry preparation. The slurry can then be applied, with an artist's paint brush, on scratches and carved letters. The slurry should not be applied to unscarred surfaces. After drying, the treated area is sprayed with vinegar and then rinsed with water. Control over color balances can be attained by using Munsell color charts for soils to obtain the color of the marred surface. With standard mixes of sediments, cement, etc., one can appropriately match color tones and do a good job of restoring deeply marred surfaces.

Solutions of 5.25% sodium hypochlorite will remove some foreign substances adhering to cave surfaces. Peanut oil will "lift" some lipsticks from cave surfaces. A Water-Pik is a particularly useful tool for washing off

graffiti; it tends to be less destructive to sensitive surfaces than brushes, although an assortment of brushes (including tooth brushes) have their place in graffiti removal work.

Hydrochloric acid can be used in locations where other methods do not adequately remove graffiti. Hydrochloric acid can be purchased in weaker concentrations as muriatic acid in building supply stores; it is routinely used to remove waste mortar from new masonry. Stronger concentrations can be purchased through laboratory supply houses. Hydrochloric acid should never be used in cave restoration work at concentrations where there is any visible fuming of the acid. The acid can be diluted by pouring hydrochloric acid into distilled or demineralized water; never pour water into the acid.

Muriatic acid sold for removing waste mortar generally can be used without dilution, but there may be variations in the acid concentrations between suppliers. Furthermore, the acid concentration needed may vary somewhat among areas of the cave and types of graffiti. Personnel doing the restoration work should have the flexibility to try, and then select, different acid concentrations for different tasks and applications in the cave. We have found that solutions of 5% to 10% hydrochloric acid are quite adequate for cave restoration work. Such dilute acid solutions minimize the creation of chlorine gas and instead tend to form calcium chloride (a salt which will be removed during the clean water rinse).

Hydrochloric acid is best applied to graffiti with a small spray bottle. The acid works well in removing lamp soot, pencil, mud, and chalk from both limestone and speleothem surfaces. It will also remove paint that was applied to wet, muddy, or dusty walls. It is the best method for removing remnants of waste mortar and concrete from old lighting fixtures. In the case of mortar and concrete, the acid should be used after the majority of the mortar or concrete has been chipped away with a chisel. Work with the chisel should not be allowed to scar any natural cave surface.

The acid works by dissolving the contact between the soot, pencil, mortar, etc. and the underlying natural cave surface. Repeated treatments with hydrochloric acid are typically needed to remove all of the unnatural material. After the treatment has been completed the area should be rinsed with clean water. A nylon bristle scrub brush sometimes helps in the cleaning.

All of the safety precautions found on hydrochloric acid labels must be followed. These include the wearing of rubber gloves and goggles. Clean water should be available anytime acid is being used. A package of baking soda should be readily available in the event that acid is spilled on clothing or skin. An appropriate respirator should be used anytime treatment is more than minor and very localized; a respirator should always be used in enclosed spaces with little air exchange.

Techniques for Identifying and Removing Inappropriate Unnatural Coatings or Materials on Cave Surfaces.

Kerosine Torch Debris

Cotton rags soaked in kerosine have been used in the past in lighting displays in various parts of Mammoth Cave. They produced large amounts of smoke which contains substantial amounts of particulate matter ("soot") which was transported through the cave by air currents. There are many soot deposits in the cave as well as unburned remnants of torches.

Areas with heavy soot deposits can be washed to restore the natural integrity of the cave surfaces. Unburned torch fragments can be picked up; some of the soot in the vicinity of the torch fragments can be collected with a portable vacuum cleaner. Some soot deposits may require treatment with hydrochloric acid.

Soot from Indian torches and fires occurs along portions of the Historic Tour Route. These materials should not be removed. A limited amount of kerosine torch debris should also be left in selected portions of the cave for historical reasons.

Lint

Visitors to the cave add large amounts of lint, hair, and other foreign material. Substantial accumulations of these materials can be found in various places in Mammoth Cave. Caves are enclosed spaces unwashed by rains; like buildings, they are not self-cleaning. Collection and removal of lint from show caves is a component of the normal "house-keeping" of such facilities. Soft brushes and soft whisk brooms, plus substantial hand work, are typically required for lint collection and removal.

Disturbed Cave Floors

Floors of show caves are yet another surface which needs, yet seldom receives, management attention. Most cave floors within toured (or formerly toured) portions of Mammoth Cave have been extensively disturbed and often substantially modified. Rock and sediment debris from trail construction (let's call this material "rubble") has typically been piled or thrown on cave surfaces. This material needs to be removed from the cave or else it should be moved to a point where it can be incorporated in the trail. For logistical reasons, it may be necessary to cache rubble in a few spots within the cave. The "rubble problem" is found throughout National Park Service caves; it is also found in some private show caves. Within the National Park System major efforts have been conducted at Oregon Caves National Monument to remove such rubble; lesser efforts have been conducted at Wind Cave and Carlsbad Caverns to deal with this situation.

Rubble removal requires careful, well supervised work to insure that underlying cave surfaces are not damaged. Generally, it is not particularly difficult to distinguish between rubble and natural cave surfaces. Tools needed for the final phases of rubble removal should include garden trowels and whisk brooms.

Cave trails should enhance visitor enjoyment of a cave while protecting cave resources. Most of the trails in Mammoth Cave provide little protection for those cave resources present on the floor of the cave. Many trail segments within Mammoth Cave are not of "trail" dimensions;

instead, they more nearly approximate the width of county roads. Trails need to be narrowed to protect more of the natural resources found on the cave floors. Some of this work was conducted in Great Relief Hall as a component of the re-lighting work; the NPS staff who conducted this work did an excellent job.

Many of the trails in Mammoth Cave (including some on the Historic Tour Route) are constructed of packed earth rather than concrete. Such trails cannot be washed; as a result of this, and the wearing away of the trail by foot traffic, tours put substantial amounts of particulate matter into the cave air. Cave trails should be made of concrete rather than sediment. Cave trails should not be paved with asphalt as it has deleterious impacts on cave features.

Unused trail segments, old rest room walls, and other similar facilities should be removed when they are no longer of use. There are "monuments" found in portions of the cave; they date from periods when guides would encourage visitors to pick up rocks and stack them as part of cave "development". While a few of the monuments might have some historical interest, the majority are simply inappropriate human modifications of cave features. Most of the "monuments" should be torn down and the rocks restored to a more nearly natural positioning.

SUMMARY AND RECOMMENDATIONS

This report was divided into three major sections:

- 1) Exotic plant growth.
- 2) Re-lighting strategies.
- 3) Restoration techniques and guidelines.

Exotic Plant Growth

The exotic plant growth section of the study included a substantial literature review of plant growth in caves with particular emphasis on methods of control. Plants which have been identified in Mammoth Cave include moss protonema, 21 species of green algae, at least 21 species of cyanobacteria, 2 species of Euglenoids, 1 species of Dinoflagellates, 1 species of yellow-green algae, at least 5 species of diatoms, and 3 species of red algae. Clay worms (vermiculations) are important in the establishment of visible growths of many of these plants and are particularly important in the establishment of the floristic components that were most abundant in the Frozen Niagara area of the cave in 1974. Green algae, cyanobacteria, and moss protonema are the most common components of the exotic flora found in Mammoth Cave.

Exotic plant growth should be prevented to the extent reasonable. The most effective strategy for plant growth prevention is careful control of light intensity reaching moist or wet cave surfaces. Based upon light intensity measurements at plant growth sites, we recommend the following guidance for Mammoth Cave:

- 1) Light intensities on moist natural cave surfaces should be kept at less than 7.5 foot-candles to the greatest extent possible.
- 2) Essentially all plant growth can be prevented if light intensities on moist sites is kept below 2.3 foot-candles. Light intensities on the majority of moist cave surfaces should be at or below 2.3 foot-candles.
- 3) Greater light intensities on moist cave surfaces are acceptable; such intensities will result in some plant growth and will require periodic plant control work.

Greater light intensities may be locally necessary, however, light intensities should not routinely exceed the limits indicated above.

4) Higher light intensities can be permitted on dry cave surfaces. There are substantial areas in Mammoth Cave where there is not enough moisture on cave surfaces to support establishment of exotic plant growth. However, it should be remembered that respiration from visitors and seasonal airflow patterns may result in condensation of water on cave surfaces; such condensation is sufficient to support the establishment of plant growth. Additionally, and particularly in the case of the cyanobacteria, less moisture is required to maintain growth than to establish it.

5) In summary, even on apparently dry surfaces, light intensities should be minimized to the greatest extent possible consistent with interpretation of the cave and visitor safety. Light intensity reaching most natural cave surfaces should be equal to, or less than, 2.3 foot-candles. Light intensities of up to 7.5 foot-candles are acceptable on localized areas, particularly if the sites are not moist. Greater light intensities are acceptable for highlighting some particular feature, but such intensities should be the exception rather than the routine situation. The greatest attention to light intensities is needed on moist or wet surfaces, and particularly those that are difficult to reach for plant control purposes.

Not all exotic plant growth can be prevented; some plant control work is necessary. Plant growth causes more resource damage on speleothems than on bedrock or sediment surfaces. Plant growth is most significant on speleothems when the following conditions are met:

- 1) The surface is commonly moist.
- 2) Light intensities are in excess of 2.5 foot-candles. Major plant growth is likely when light intensities are in excess of 7.5 foot-candles. Maximum plant growth is most likely to occur when light intensities are between about 12 and 83 foot-candles.
- 3) Plant growth is allowed to remain in place for weeks or months after it initially becomes visible.

4) Moonmilk is present on the speleothem, or the speleothem is coated with even small amounts of sediment or lint. Vermiculations (often called "clay worms") consist of sediment and lint; they are routinely the sites where plant growth begins.

Removal of exotic plant growth should be conducted as follows:

1) Apply a mist of bleach (5.25% sodium hypochlorite) to the area affected by visible plant growth. For small areas the application can be made with a small spray bottle. For larger areas the application can use a pump-up tank type sprayer with a wand at least three or four feet long. The sodium hypochlorite should be applied at a rate heavy enough to moisten the surface being treated; however, the application rate should be light enough to minimize drippage from the treated surface. All drippage and all rinse waters must be collected and removed from the Cave.

2) Treated areas which are rock or flowstone should be rinsed with clean water after the first treatment with the sodium hypochlorite solution. Treated areas ^{should} not be rinsed for at least one week after treatment to allow time for fungus to become established on the dead algae, cyanobacteria, and moss and moss protonema. This fungal development makes it much easier to wash off all dead plant material.

3) Treated areas which are cave sediments should be treated with sodium hypochlorite solution but not subsequently rinsed.

4) Re-treat areas with the 5.25% sodium hypochlorite solution as necessary. Re-treatment is not routinely needed unless excessive amounts of plant growth have become established between treatment cycles.

5) Cave resources are best protected and treatment time is minimized if areas prone to exotic plant growth are inspected monthly and treated anytime plant growth is visible.

6) Rubber clothing and a full-face respirator appropriate for chlorine gas environments will be required for each person doing the exotic plant control work. Rubber gloves must be worn. All workers must understand that bleach can damage the lungs and other body tissues. Label instructions on bleach bottles must be followed.

7) Worker safety can be insured by a good treatment protocol and by good training and supervision of workers. Additionally, safety equipment such as respirators and goggles must be both effective and comfortable. It has been our experience that some of the less expensive respirators and goggles are extremely uncomfortable for extended use. Uncomfortable or awkward safety equipment provides an unwarranted incentive for workers to dispense with the equipment.

Re-Lighting Strategies

The following strategies were identified and recommended for light placement:

- 1) In general, a light should either illuminate the trail or else a cave feature; most lights cannot ideally serve both functions.
- 2) Lights must be effectively shielded from direct view both for esthetic reasons and to maintain night vision in visitors.
- 3) Light intensity must be carefully controlled and balanced so as to prevent the creation of unduly bright spots.
- 4) The quality of cave lighting tends to increase with an increase in the number of light fixtures. The greater the number of lighting fixture, the lower the wattage should be in each individual light.
- 5) The distance between trail lights should be shorter on steps and around obstructions than is the case on straight and unobstructed portions of cave trails. It is better to reduce the distance between trail lights than to increase the wattage of the lights.

A series of 14 recommendations were made for the installation and shielding of lights. These recommendations are discussed in detail in the section of the report entitled "Installation and Shielding of Lights" and will not be repeated here.

Restoration Techniques and Guidelines

This section identifies a number of restoration problems and identifies appropriate restoration techniques and guidelines. Principal findings and recommendations are as follows:

1) Clay worms (vermiculations) consist of dust and other particulate matter. We believe that all clay worms in lighted or formerly lighted portions of Mammoth Cave are due to the impacts of human visitation and should be viewed as unnatural features. They provide good substrates for exotic plant growth and should be removed by first treating any plant growth which may be present and then simply washing them off the cave surface.

2) A series of techniques for removing or diminishing the visibility of graffiti are identified. We recommend that a historian identify any writing on cave features which is of historical significance prior to major restoration work. Such historical assessment work should document the location and describe the significance of any identified feature deemed to have historical significance. It is clear that the vast majority of the graffiti is of no historical value and is, in fact, totally inappropriate defacement of natural features of a National Park.

Graffiti related restoration can be accomplished by a number of site-specific approaches. These include scrubbing with water and brush; treatment with vinegar; application in deeply carved areas of a slurry comprised of water, cave sediment, and Portland cement; treatment with a 5.25% sodium hypochlorite solution; and treatment with hydrochloric acid.

3) Areas with heavy soot deposits from kerosine torch debris can be washed to restore the natural integrity of the cave surfaces. Unburned torch fragments can be picked

up; some of the soot in the vicinity of the torch fragments can be collected with a portable vacuum cleaner. Some soot deposits may require treatment with hydrochloric acid. Soot from Indian torches and fires occurs along portions of the Historic Tour Route. These materials should not be removed. A limited amount of kerosine torch debris should also be left in selected portions of the cave for historical reasons.

4) Lint should routinely be collected and removed as a part of normal "cave-keeping".

5) Rock and sediment debris from trail construction should be removed from natural cave surfaces. The removal of such rubble requires careful, well supervised work to insure that underlying cave surfaces are not damaged. Generally, it is not particularly difficult to distinguish between rubble and natural cave surfaces.

6) Cave restoration work should include major work on cave trails. Most of the trails in Mammoth Cave provide little protection for those cave resources present on the floor of the cave. In general, trails should be narrowed; they should be paved with concrete rather than constructed of compacted cave sediment; and unused trail segments and other similar facilities should be removed when they are no longer of use.

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