Archeology has a lot to tell us about the potential behavior of materials and structures during a high-level waste repository's first 10000 years

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ARTIFACT TO ANALOGUE

Archeology of Arid Environments Points to Management Options for Yucca Mountain

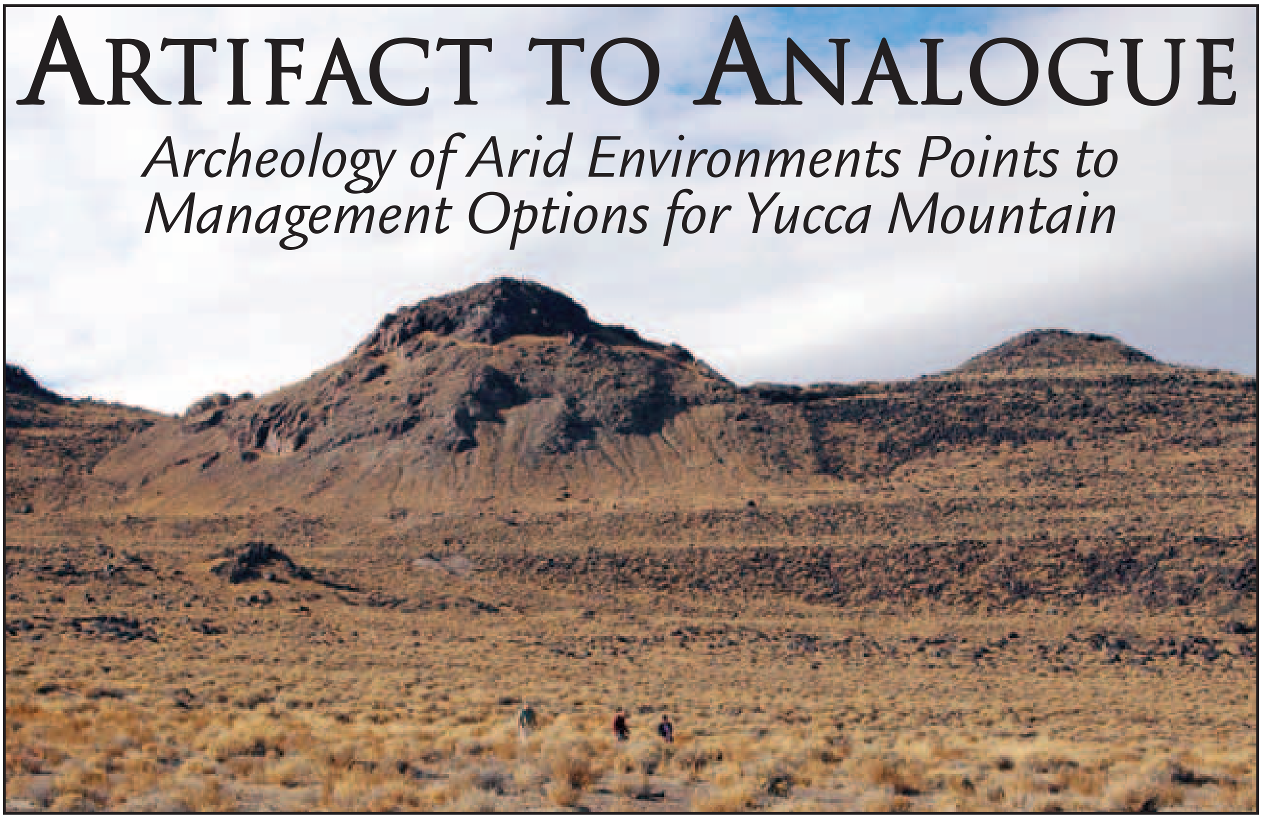

Fig. 1. Paleo-shorelines of ancient Lake Lahontan, northern Nevada.

Archeology has a lot to tell us about the potential behavior of materials and structures during a high-level waste repository's first 10 000 years.

By Neil Chapman, Amy Dansie, and Charles McCombie

As with all planned repositories for spent fuel, the critical period over which Yucca Mountain needs to provide isolation is the first hundreds to thousands of years after the fuel is emplaced, when it is at its most hazardous. Both the original and the proposed new U.S. Environmental Protection Agency standards highlight the central importance of this performance period by focusing on repository behavior during the first 10 000 years.

Archeology has a lot to tell us about the behavior of materials and structures over this time period. There have been numerous studies of archeological artifacts in conditions relevant to the groundwater-saturated environments that are a feature of most international geological disposal concepts but relatively few in arid environments like that of the Nevada desert. However, there is much information to be gleaned, not only from classic archeological areas in the Middle East and around the Mediterranean, but also, perhaps surprisingly to some, from Nevada itself.

Our recent study evaluated archeological materials from underground openings and shallow burial in arid environments relevant to Yucca Mountain, drawing conclusions about how their state and their environment of preservation could help to assess design and operational options for the high-level waste repository.

We compared materials from cultures in the arid regions of the ancient Middle East with the preservation of ancient materials in dry cave sites in the Great Basin desert area of Nevada. The specific reasons we studied objects from the Middle East are that the environments are similar to the Nevada sites and that these historical regions were home to cultures that used metals and glasses, whereas the ancient Nevada artifacts are mainly of organic materials. The preservation environments of materials that we considered are unsaturated and oxidizing; our emphasis has been on materials found in undisturbed underground openings such as caves and unbackfilled tombs.

In the Great Basin desert region of the United States, natural caves around the shoreline of the ancient (now long dried out) Lake Lahontan in northern Nevada (see Fig. 1) have been used as shelters or as burial sites for more than 10 000 years, with some containing almost perfectly preserved fabrics and textiles (e.g., Spirit Cave, Crypt Cave, and Horse Cave). Clearly, these predate the dawn of the ancient civilizations of the Middle East by many thousands of years (see Fig. 2). Detailed study of shelter caves also provides much information on how the interaction of natural ventilation, moisture ingress, and "natural backfill" (cave fill) affect materials preservation, as well as the overall stability of underground openings. The main timescales of interest in this study are from one to

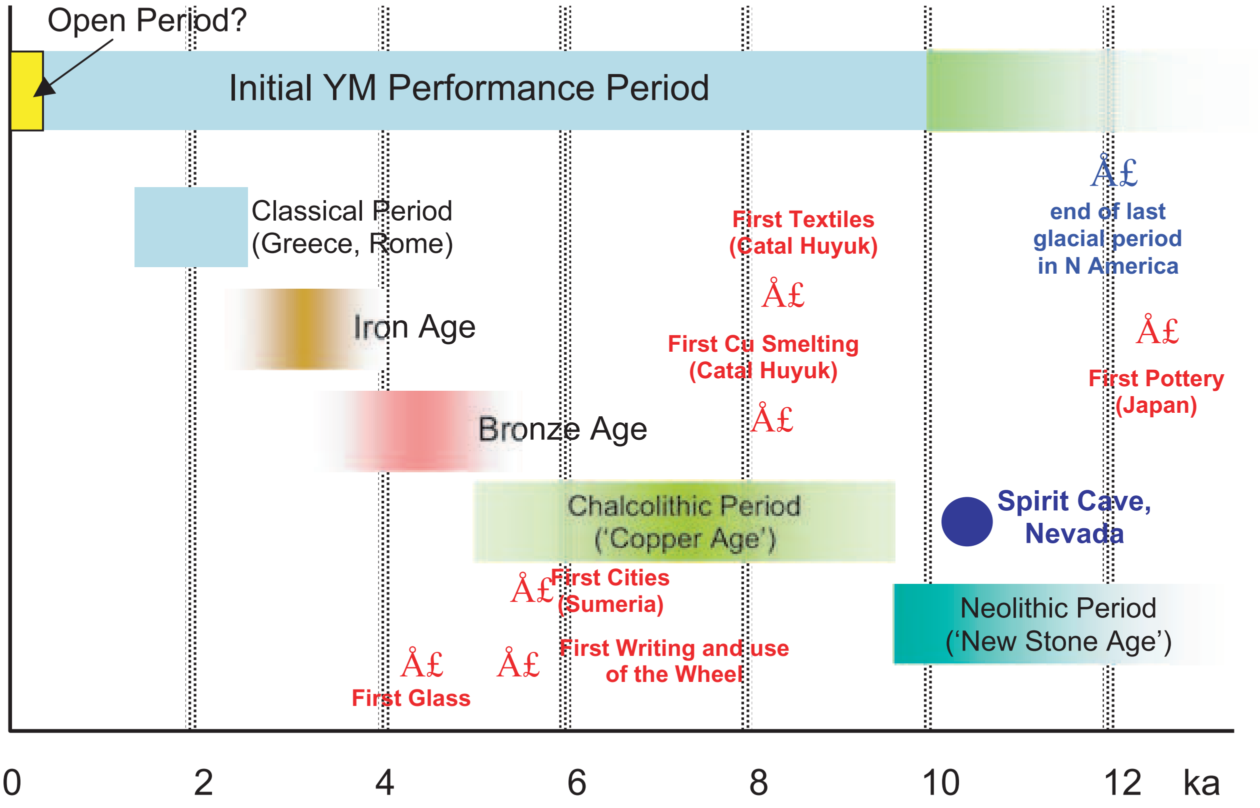

Fig. 2. Use of materials in past cultures in the Middle East and the Mediterranean area as a function of archeological time along with the age of one of the key dry cave sites in Nevada. The initial 10 000-year performance period for Yucca Mountain is shown on the same timescale.

several thousand years. However, combinations of archeological and paleontological evidence allow inferences to be drawn on preservation environments for the years back to 35 000 BP (before the present).

WHAT ARE WE LOOKING FOR?

The Yucca Mountain repository is currently planned to remain in an open, unbackfilled state for at least 50 years after spent fuel and vitrified HLW are emplaced. It is envisaged that this open period could extend to around 300 years. The first few hundreds of years are the most critical period for isolation and containment of the waste as the activity and radiotoxicity are at their highest, although declining rapidly. The radioactivity (and radiotoxicity) of the fission products in both spent fuel and vitrified HLW declines by a factor of about 100 000 within the first thousand years. For spent fuel, this is shown on a standard log-log plot in Fig. 3.

After a few thousands of years, the total radiotoxicity of HLW is similar to that of the uranium ore from which its precursor fuel was manufactured—for spent fuel (see Fig. 3), this "natural crossover"

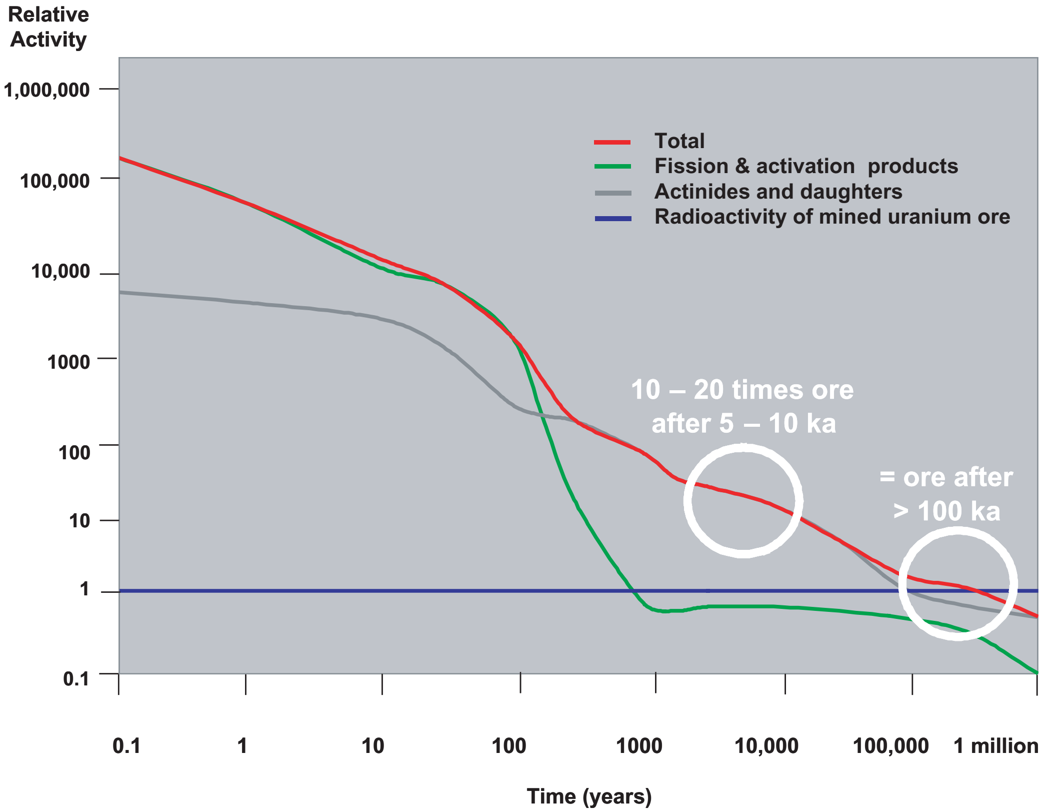

Fig. 3. Decline in radioactivity of spent fuel as a function of time out of the reactor, shown normalized to the activity of the uranium ore from which it was manufactured. Radiotoxicity follows approximately the same pattern.

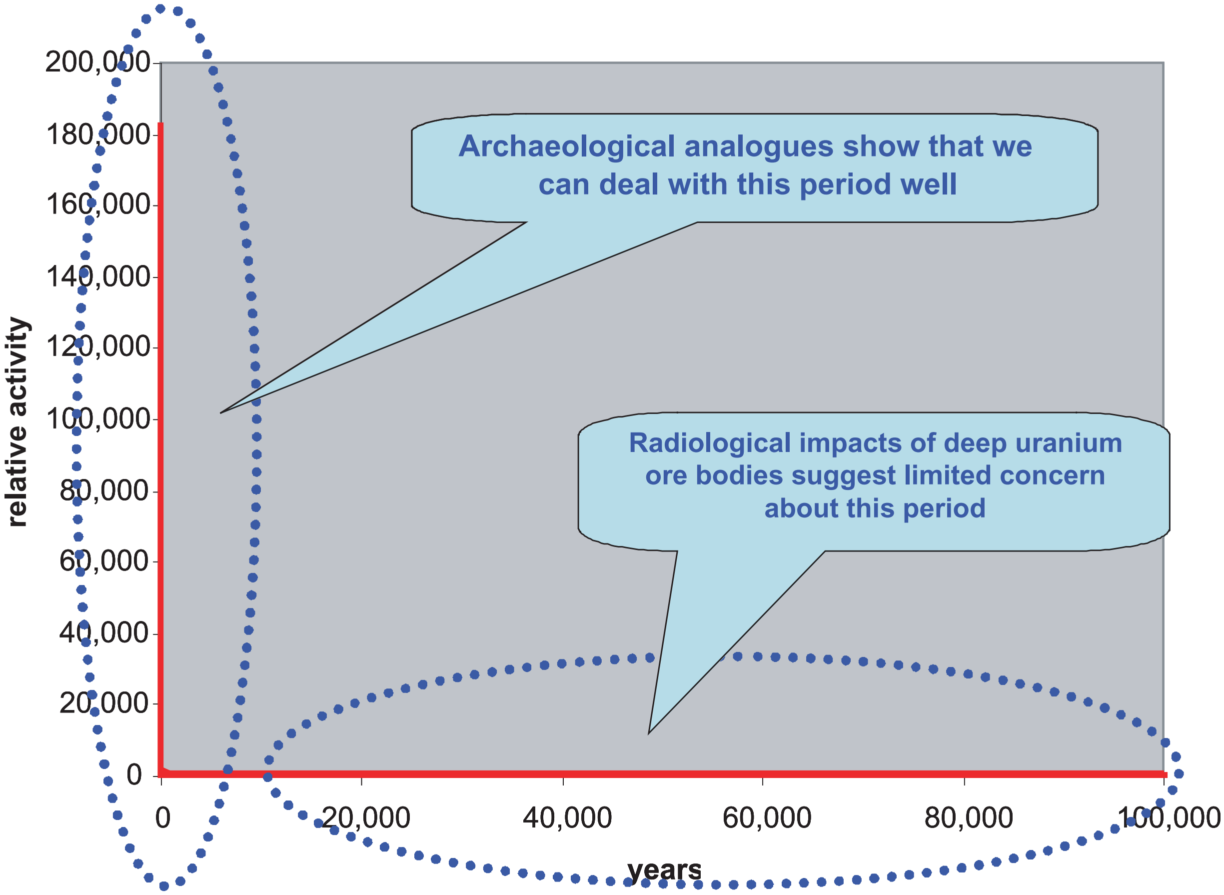

Fig. 4. Linear plot (red line) of the same relative activity decline for spent fuel as shown in Fig. 3.

time is longer—a few hundred thousand years. Nevertheless, at around the same time as the HLW crossover (a few thousand years), the radiotoxicity of spent fuel is only a few tens of times higher than that of the equivalent uranium ore.

The same information for spent fuel is shown on a linear plot in Fig. 4. The curve of Fig. 3 has been replaced by the two red lines clinging to the axes of the graph, and the dominance of the first few hundreds to thousands of years in reducing the hazard of the spent fuel is much more evident.

In terms of providing overall safety and isolation, we can see the following:

- Containment for around 1000 years brings immense benefits in terms of reduction in radiotoxicity for both waste forms.
- Containment for a few thousands of years brings both waste forms close to naturally occurring radioactive materials found in geological environments, and from natural analogues such as the Cigar Lake uranium deposit in Canada, we know that deeply buried ores can have essentially no radiological impact in some environments.

Consequently, having a high degree of confidence in the behavior of the engineered containment system over just a few thousands of years is an essential and valuable aspect of demonstrating repository safety.

This is where archeological materials and preservation environments offer the most direct and illustrative means of confidence building. Observations of materials preserved in parallel environments provide probably the most credible evidence that long-term containment is possible over these time periods (compared to predictions made from laboratory tests of materials).

LONG-TERM REPOSITORY CONDITIONS

The key to any analogue, geological or archeological, is the relevance of the analogue materials and environment. Neither can ever be exact, but a good analogue has sufficiently close similarities to give strong indicators, or sometimes even direct quantitative information, about long-term repository performance.

In the case of the Yucca Mountain repository, focusing on the early containment period of a few thousand years, we can make the following observations on analogue relevance:

- There are clearly no direct archeological analogues of the sophisticated nickel-chromium-molybdenum-tungsten and titanium alloys that are foreseen to be used for engineered barriers in the U.S. program. However, given that these materials have been selected for their corrosion resistance, it is possible to study analogous processes in other archeological “corrosion resistant” (but not noble) metals (copper and bronze) as well as in materials known to be much less resistant, such as iron and simple steels. If these materials show stability in similar environmental conditions, then it gives a measure of confidence that the metals specially selected for engineered barriers should also perform well. Much the same can be said about the analogy between HLW glass and archeological glasses, even though the compositional differences are pronounced.
- The repository is currently planned to remain open for decades to hundreds of years, with a representative relative humidity being about 40 percent. Following closure, humidity will rise to much higher values.

The specific reasons we studied objects from the Middle East are that the environments are similar to the Nevada sites and that these historical regions were home to cultures that used metals and glasses, whereas the ancient Nevada artifacts are mainly of organic materials.

● There is thus interest in looking at the behavior of materials in both well-ventilated underground openings (such as shallow caves) as well as closed underground openings such as tombs, where relative humidity is high, even in arid external conditions. Consideration of materials behavior in these varying conditions may give an indicator of alternative modes in which the repository might be managed during an extended open period and beyond.

With these points in mind, we sought locations where ancient metals and glasses could be found in underground openings, both closed and well ventilated. Our guideline was to look for the oldest examples possible and to concentrate on preservation in arid, desert environments, although tombs and burials in less arid conditions have also yielded valuable examples. Regions of the world displaying long periods of aridity during the Holocene as well as the presence of ancient cultures are clearly of most relevance—this points the focus principally to the ancient Middle East. In this region, from around 11 000 through 7000 BP, the climate was cooler and somewhat wetter than today. Mediterranean woodland existed in the uplands of the Sahara, and grasslands were found on its fringes and around its central massifs. For the last 7000 years, there has been a trend to increasing aridity—from about 3500 BP, becoming extremely arid in North Africa. A period of sudden aridity developed about 4170 BP in Mesopotamia. It is thought to have contributed to the collapse of the Akkadian empire, and its impacts can be seen in the evidence of windborne sands of that period.[1]

The southwestern United States has seen a similar trend toward drier conditions in the Holocene. In this region, Nevada contains many archeological sites where pretechnological human occupation materials (even delicate organic items, such as feathers and basketry) can be found in a state of almost perfect preservation in underground openings (open caves). Consequently, to make a link with the preservation of technological materials, we have also looked for direct parallels in Middle Eastern culture: similar open caves containing organic materials of similar age but, also, alongside glass or metal objects.

ANALOGUE SITES AND MATERIALS

The earliest use of metals and glass was in the ancient Middle East (e.g., Anatolia, Mesopotamia, Egypt, Kush, Syria, Palestine, Jordan, and Persia). In this region, exceptionally well-preserved glass, metal, and organic materials are found in the archeological record from sites that have been characterized by arid conditions for many thousands of years. Hoards of uncorroded copper objects as old as 5500 years BP (e.g., Nahal Mishmar) and an intact, 9-tonne (3.4- × 1.95- × 0.45-meter) block of more than 1000-year-old glass (Bet She'arim) are among some of the more remarkable items found concealed in natural or manmade underground openings in this region. Highly ornamental glass bottles survive intact from the earliest use of glass for containers across Mesopotamia and the eastern Mediterranean area from 3500 years BP. Iron and steel objects between 2500 and 3100 years old are also found in some locations.

In several cases, glass and metal artifacts are found together with well-preserved organic materials such as leather, bone, textiles, and matting. The preservation environments of materials considered in this study are unsaturated and oxidizing and include openings that have been either continuously open (caves) or sealed but not backfilled (tombs). Over periods of many thousands of years, glass and copper or bronze, sometimes also iron and steel, have been preserved in either extremely dry, well-ventilated conditions or in a humid atmosphere. Examples of the latter include ferrous metal objects preserved in periodically wetted sediments and copper and bronze objects from sealed Etruscan tombs, many excavated in volcanic tuffs.

LOCATIONS AND MATERIALS

Chalcolithic Hoards, Israel

Dry caves in the deserts of Israel contain some of the oldest copper objects, from around 5500 years ago, in the Chalcolithic Period (prior to the Bronze Age). A hoard of 429 artifacts was discovered in the so-called Cave of the Treasures at Nahal Mishmar in the 1970s.[2] These are mainly copper ceremonial items, plus a few objects of stone or ivory (see Fig. 5). The cave is extremely isolated, being located 50 m below the top of a cliff that drops 250 m to the bed of a canyon that descends through the Judean Desert to the Dead Sea.

The copper artifacts have highly variable levels of antimony and arsenic,[2] and a "natural alloy" of copper-arsenic-nickel also occurs in some artifacts. The hoard was found at a depth of approximately 2 m below the present cave floor, in a crevice in the cave wall. It was wrapped in a reed mat. Associated organic material, which provides a key link to the dry cave sites in Nevada with no metallic objects, in-

Fig. 5. Cooper objects, approximately 5500 years old, from a Judean desert treasure, Nahal Mishmar (Chalcolithic Period, second half of 4th millennium BCE). The white object in the background is ivory. Collection of Israel Antiquities Authority. (Photo copyright: The Israel Museum, Jerusalem.)

cludes artifacts of hippopotamus ivory, a wooden loom, pieces of woven linen and wool, wooden strainers, straw mats, ropes and basketry, and parts of a leather garment and a sandal.

Nahal Mishmar is not an isolated occurrence—a similar site was found recently at Peqi`in, in Upper Galilee.

Massive Bronze Objects

While small, delicate copper and bronze objects clearly testify to good preservation conditions, a more useful analogy to waste containers that weigh several tonnes is found in massive metal objects. The ancient world contains examples of measuring weights, sarcophagi, and other objects that may contain on the order of hundreds of kilograms of bronze such as the following:

- A large copper relief from the Ninhursaq temple at Tell al'-Ubaid, near Ur (modern Iraq) that dates from 4300 BP and is almost 3 m long. This is heavily corroded, which may be because it was buried in soil rather than in an opening (location: British Museum).
- Tin bronze weights in the shape of lions have been found in several locations. A typical example (see Fig. 6), from western Anatolia, weighs about 31 kilograms, is around 2500 years old, and represents a weight of one Babylonian talent (location: British Museum). A very similar Achaemenid (Persian) piece from Susa (Iran) is located in the Louvre Museum but is equivalent to 4 talents and weighs about 121 kg.
- A 2850-year-old massive bronze sarcophagus was found in 1989 at the ancient city of Nimrud (modern Iraq) within the inner chamber of a tomb located beneath the floors of a palace. Several tombs were untouched since the last burials took place. Hoards of gold, glass, and jewelry were found in some tombs. Some of the tomb chambers

Fig. 6. Persian (around 2500 BP) bronze lion weight (approx. 31 kg = 1 talent). A 121-kg (4-talent) equivalent also exists.

Fig. 7. Bronze and glass items found undisturbed in an Etruscan (2700 BP) tomb in central Italy.[3]

were found unfilled and "waterproof," apart from some soil that had seeped through gaps in the stonework. Presumably, the environment has had relatively high humidity for around 3000 years. A similar massive bronze coffin, dated at about 2350 BP, was found in Susa (Iran). It was found in a collapsed, brick-built vaulted tomb.

Etruscan Tombs, Central Italy

Undisturbed Etruscan tombs more than 2500 years old are found in parts of central Italy. Many of these, particularly those in Lazio and southern Toscana, have been constructed in volcanic tuff—partly hewn from the rock, partly constructed of worked masonry tuff blocks. The tombs were sealed, and bronze objects can be found as they were deposited[3] (see Fig. 7). These tombs also provide evidence that excavated underground openings can be stable, even in a region of Italy prone to significant earthquake activity, for thousands of years.

Iron and Steel

The earliest use of manufactured iron dates from about 3200 BP. Introducing carbon into the smelting process lowers the melting point to a temperature that was just about the limit of the temperature of ancient kilns (that could be used to melt copper). Iron with a low carbon content could be hammered but not melted completely (wrought iron). Semimolten carbon-rich iron can be cast (cast iron). Heat-treated steels (to remove impurities and some carbon) were made over much of the Old World from about 2500 BP.[4]

A set of well-preserved iron tools dating from the Assyrian occupation of Thebes (Egypt) in 667 BCE (before the Christian Era) was excavated by Sir Flinders Petrie from a brick chamber that may have been constructed in gravels close to the banks of the River Nile. Some of the tools contain small amounts of carbon and can be classed as steel.[5] One chisel with a fairly homogeneous composition consists of martensite, contains 0.2 percent carbon, and has been quench hardened. The preservation of iron in good condition for such a long period suggests that the burial location has remained essentially dry.

Somewhat older (about 3100 BP) steel anklets have been found in more closely relevant environments in cave burials in the Baq'ah Valley, Jordan.[6]

Core-Formed Glass Vessels

Core-formed potion bottles are the oldest known glass vessels, the earliest being found in Mesopotamia and dating from around 3500 BP. They are generally small (a few centimeters long) and highly colored, with some of the most beautiful pieces being produced in Egypt around 3300 BP. Residues of cosmetics and opium have been found in some samples. A bottle in the shape of a *bulti* fish (3350 BP), found in soil layers in the ancient Egyptian city of Tel el-Amarna, typifies the state of preservation of much early glass in these environments (see Fig. 8). Amarna was a center for glass production where current excavation and research is being undertaken on ancient glass technologies.

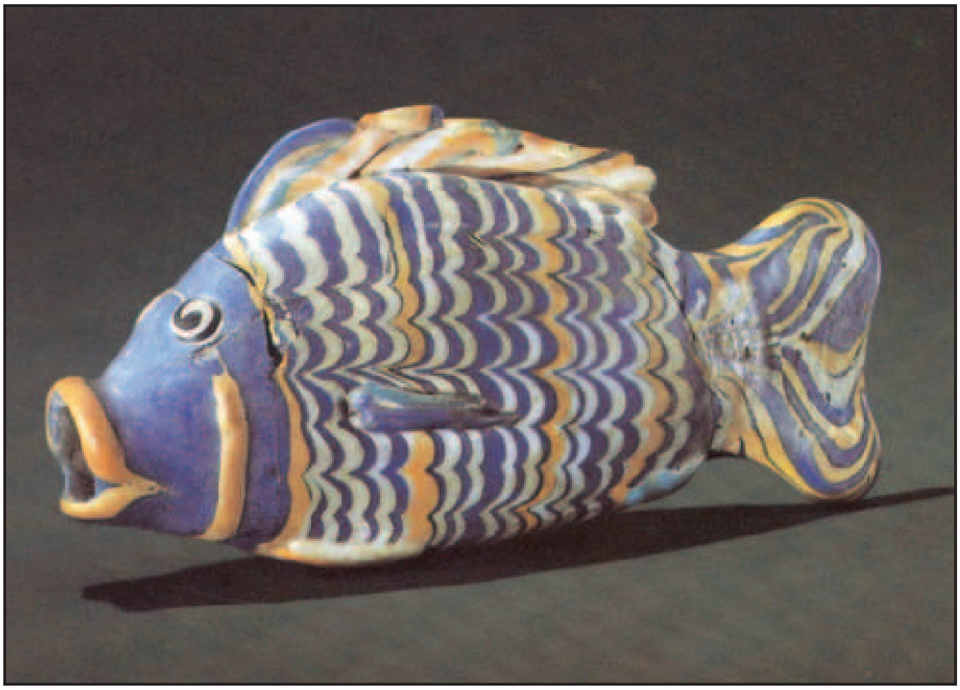

Fig. 8. Core-formed Egyptian glass cosmetic bottle from 3350 BP (Photo copyright: British Museum, London).

The Great Glass Slab

A massive, roughly 9-tonne (3.4- × 1.95- × 0.45-m) block of glass[7] (see Fig. 9) about 1100 years old was found in a cave at Bet She'arim in Israel. It is speculated[7] that it may have been cast underground as a secret compositional experiment that failed, as the calcium content was too high for glass working (high liquidus temperature). It was formed in a tank furnace, in situ in the cave, with about 11 tons of raw materials being heated to 1100°C and held at that temperature for 5 to 10 days. This block is considerably more massive than the vitrified HLW blocks intended for geological disposal.

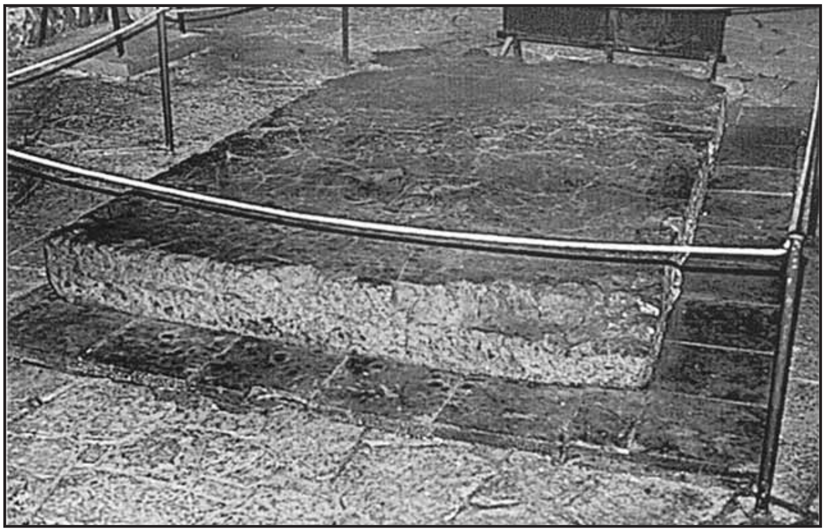

Fig. 9. The great glass slab (about 9 tonnes) of Bet She'arim—1100 BP, found in a cave in the desert.[7]

Organic Materials

As noted in the introduction, a special search was made for parallels to the dry caves of Nevada containing organic remains. Several examples are known where glass and metal artifacts are found together with well-preserved organic materials such as leather, bone, textiles, and matting. The copper hoard in the Cave of Treasures (described earlier) was wrapped in a Cyperus reed mat, bound with straw ropes. A contemporaneous grave (around 6000 years BP) in another dry cave site (the so-called Cave of the Warrior) contained well-preserved organic material but no metals.[8]. The grave objects include a plaited reed mat, textiles, a coiled basket-bowl, a wooden bowl, a bow and arrows, and leather sandals.

THE DRY CAVES OF NEVADA

More than a hundred dry cave sites that contain archeological remains are known of in Nevada. Most of these date back to about 6000 BP, a few back to 11 000 BP, and many contain packrat middens showing animal occupation back to 40 000 BP. No single archeological site is a direct analogue to Yucca Mountain, particularly because the archeological record does not include deep drifts, potentially affected by infiltration and seepage issues. All are shallow by comparison, but each has a suite of scientific data that when organized by repository variables can isolate a broad range of processes relevant to long-term preservation in a sheltered environment.

One of the best-documented sites contained a mummy burial that was discovered in 1940 but not dated until 1994. Originally thought to be about 1500 years old, the remains proved to be about 10 300 years old. Perfectly preserved textiles, leather, and other organic materials were found in a shallow burial in the cave floor, only a few meters from the cave entrance (a rock shelter rather than a deep cave). The textiles (see Fig. 10) were as pliable as if recently made.

Caves with burial materials of similar age (earlier than 10 000 BP) include Crypt Cave, Fishbone Cave, Hidden Cave, Chimney Cave, and Grimes Burial Shelter. Many of the burials are tightly wrapped in dry, absorbent textiles and placed under a thin layer of stones, soil, or sticks. Crypt Cave contained several human mummy burials and that of a dog (about 6300 BP), along with fine textiles including earlier than 9000 BP plain weave.

Many of the caves are in tufa or in tufa-cemented rock formations associated with the margins of pluvial Lake Lahontan. Tufa caves are extremely dry as they are generally protected from run-off permeation. Even caves that are less dry have sometimes provided high levels of preservation. For example, Smith Creek Cave contained wood shavings dated at earlier than 10 000 BP. However, moister conditions (e.g., caves with small openings and poor ventilation) generally have proved unfavorable to preservation of organic materials.

In the Nevada component of the study, we have sought evidence of the oldest cultural artifacts preserved in sheltered environments in the region of Yucca Mountain. Perishable artifacts greater than 10 000 years old are rare, and one of the questions is "Why are they so rare—is it poor material

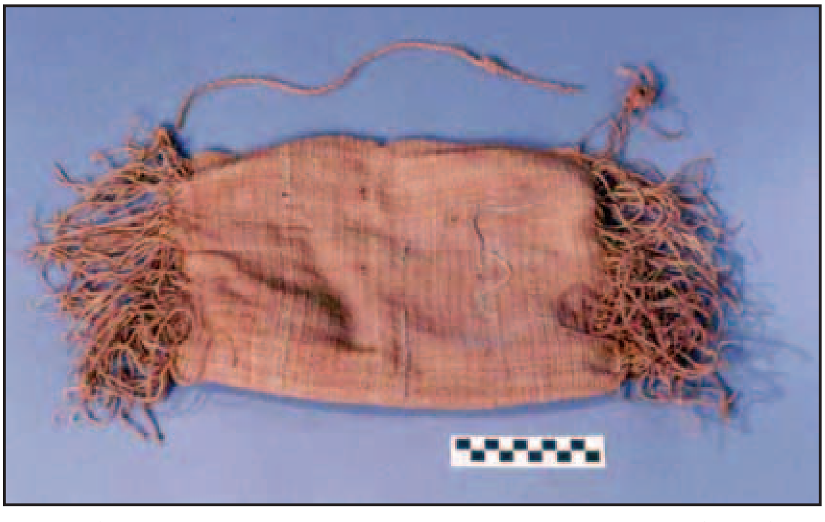

Fig. 10. Still pliable textile dated at earlier than 10 000 BP, from Spirit Cave, Nevada.

Preservation is best in openings that have been well ventilated (open caves), but good preservation is also found in sealed openings, with the best being in the driest sites (e.g., Egypt). Even under high-humidity conditions, openings can provide preservation of glass and copper/bronze for about 3000 years. Burial in soils, probably with periodically high pore-space humidity, can also give excellent preservations of metals.

survival or infrequent use of the shelters that makes the ancient evidence so rare?" Differential preservation and changing human settlement patterns are compared throughout the archeological record to evaluate long-term repository performance. Climate history has affected the preservation in some of the sites, which may offer clues to possible future climate effects on long-term storage, and provides the dynamic backdrop for the human adaptations represented by the archeological data.

In addition to seeking examples of ancient soft perishables, our analysis expands the archeological analogue concept to those sites that do not preserve material analogues for repository variables, using differential survival and other archeological data to demonstrate poor preservation conditions over time. This approach attempts to address a key question posed by Stuckless[9] regarding the continuum of preserved artwork and other analogues. Are we seeing all originally present analogues or have some been destroyed by environmental forces in the sheltered setting? This is an important question because Yucca Mountain is not likely to be completely dry due to normal infiltration of seasonal precipitation. The archeological record can show how much variation there is in the degree of long-term preservation and, in some cases, what causes the variation.

IMPLICATIONS FOR THE PROPOSED YUCCA MOUNTAIN REPOSITORY

Future decisions concerning the management of any geological waste repository cannot be preempted completely by today's society. Although project managers and regulators may stipulate, as part of planning and licensing, how a repository is to be operated and closed, the multidecade length of disposal projects means that the actual decisions will be taken by future generations on the basis of whatever drivers are important at the time. A clear example of how a new driver can radically affect a program is the possible impact of the Global Nuclear Energy Partnership on the waste forms that might be assigned to Yucca Mountain and how they will be managed. For example, the amount of spent fuel to be managed may be very significantly reduced, and it is even debatable whether spent fuel would be disposed of or simply stored until it can be reprocessed.

Uncertainties such as these will affect all the plans we may have today concerning open periods, retrievability, backfilling, closure, and sealing. With respect to Yucca Mountain, it is quite reasonable to envisage a long period (decades to hundreds of years) during which the repository could be managed as any one or more (i.e., sequentially) of the following:

- An open, ventilated, and managed long-term store.
- An open, unventilated long-term store.
- A sealed, ventilated disposal facility without backfill.
- A sealed, unventilated disposal facility without backfill.
- A sealed and backfilled disposal facility.

In these scenarios, the behavior and condition of repository materials over time frames of hundreds or a few thousands of years will be an important aspect of future decision making. As noted at the beginning of this article, this is the most critical period for the provision of containment.

Over the longer term, the climatic environment of Yucca Mountain is expected to vary significantly. It seems reasonable to assume that Nevada will either remain arid or will slowly return to wetter conditions but not for many thousands to some tens of thousands of years. For the next few thousand years, conditions are expected to remain rather similar to those of today.

Prior to closure, ambient atmospheric conditions will be warm and oxidizing, with medium-to-low humidity, depending upon the use and scale of ventilation. Following closure, the facility will remain warm for several hundreds of years, with increasing humidity and continuing oxidizing conditions. One can also envisage a facility that is closed and sealed (to access by people) but nevertheless equipped with natural ventilation to maintain lower humidity. Over hundreds of years, unless a tunnel support system has been emplaced and maintained, some parts of the facility may suffer from roof collapse, affecting local atmospheric conditions. In a backfilled system, the waste packages would be surrounded by unsaturated rock/soil

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but with relatively high-humidity air in the pore spaces.

It can be seen that the preservation environments of the archeological materials addressed in our study span all of these conditions. What, then, can be concluded with respect to the operation of Yucca Mountain?

IMPLICATIONS FOR DECISIONS

No analogue, natural or archeological, can match all aspects of the design, material, and future evolution of a waste repository. Nevertheless, it is possible to use our observations to draw conclusions of relevance to Yucca Mountain and to raise some interesting questions concerning the optimization of the design and the operational procedures.

Underground openings in arid regions are capable of providing exceptional preservation of glass and metals, like copper and bronze, for times that are *at least as long* as these materials have been known and used—their frequent perfect preservation suggests that they would actually survive very much longer.

Ventilated environments provide excellent preservation of delicate organic materials such as fabrics, basketry, leather, wood, and ivory—in the Middle East they are sometimes found with perfectly preserved copper items from 5500 BP, thus suggesting that the U.S. dry cave preservation of organics would also have preserved metals for at least 10 000 years.

Preservation is best in openings that have been well ventilated (open caves), but good preservation is also found in sealed openings, with the best being in the driest sites (e.g., Egypt). Even under high-humidity conditions, openings can provide preservation of glass and copper/bronze for around 3000 years. Burial in soils, probably with periodically high pore-space humidity, can also give excellent preservations of metals.

As well as small artifacts, massive and/or thick-walled glass and bronze/copper objects similar to waste blocks and waste containers also have well-preserved analogues. Archeological iron and steel artifacts are less well preserved in moist, oxidizing underground openings, although objects buried in tuff and in "dry" openings can maintain some integrity for about 2000 years.

Tombs excavated in native rock or built from stone and brick are generally in good structural condition, although some show soil and debris in-wash.

Analogues show that even a multicentury-scale interim storage/retrievable period is achievable without a need to repackage and possibly without a need for extensive repository refurbishment. The first centuries of interim, retrievable storage are of the most immediate importance, and the evidence from these analogues may indicate which materials are most demonstrably appropriate for retrievable waste packages.

Stuckless[9] observed that backfilling and sealing the Yucca Mountain repository "may not enhance its performance." If well-ventilated conditions would be valuable for management on a timescale of decades to hundreds of years, one can ask whether the repository can be designed so it can be sealed from human access but still have passive, very long term natural ventilation. This, in turn, has implications for decisions on drip shields and backfilling options. It also raises questions of how simpler container materials might perform under backfilled conditions (compared with C-22) with respect to releases occurring after about 10 000 years.

If preservation of generally corrosion-resistant materials over hundreds to thousands of years under the oxidizing conditions of the repository is considered important, then a well-ventilated system may enhance performance. If decade- or century-long retrievability is to be a feature of facility management, then a well-ventilated (forced or natural) design can be expected to keep corrosion-resistant materials in good condition—the analogous locations studied here have done this successfully for 6000 to 12 000 years, even for the most delicate organic materials.

Designs where good natural ventilation might be maintained even after closure and sealing (to prevent human access) may provide enhanced preservation well into the multithousand-year time frame, although this would obviously need to be evaluated in a full performance assessment. Information from closed tombs (e.g., Etruscan, Egyptian, and Assyrian) and artifacts buried in desert soils, where humidity has been elevated since burial, indicate that these conditions are less favorable; nevertheless, they show that bronze, and even iron, can remain extremely well-preserved for 2000 to 3000 years.

REFERENCES

1. B. P. deMenocal, "Cultural Response to Climate Change during the Late Holocene," *Science,* **292,** 667 (2001).
2. P. Bar-Adon, *The Cave of the Treasure,* The Israeli Exploration Society, Jerusalem, Israel (1980).
3. L. B. Dal Maso and R. Vighi, *Archaeological Zones of*

Latium: Southern Etruria, Bonechi Editions, Florence, Italy (1975).

4. P. T. Craddock, "Cast Iron, Fined Iron, Crucible Steel: Liquid Iron in the Ancient World," *Mining and Metal Production through the Ages,* P. Craddock and J. Lang, Eds., British Museum Press (2003).
5. A. R. Williams and K. R. Maxwell-Hyslop, "Ancient Steel from Egypt," *J. Arch. Sci.,* **3,** 283 (1976).
6. J. C. Waldbaum, "The Coming of Iron in the Eastern Mediterranean," *The Archaeometallurgy of the Asian Old World,* V. C. Pigott, Ed., University Monograph 89, University Museum, University of Pennsylvania, State College, Pennsylvania (1999).
7. I. C. Freestone and Y. Gorin-Rosen, "The Great Glass Slab of Bet She'arim, Israel: An Early Islamic Glassmaking Experiment?" *J. Glass Studies,* **41,** 105 (1999).
8. T. Schick, "The Cave of the Warrior: A Fourth Millennium Burial in the Judean Desert: The Chalcolithic Period, the Early Bronze Age, and the Middle Age," Israel Antiquities Authority Reports Series (1998).
9. J. S. Stuckless, "Archaeological Analogues for Assessing the Long-Term Performance of a Mined Geological Repository for High-Level Radioactive Waste," Open-file Report 00-181, U.S. Geological Survey (2000). ■

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