CAUSES AND EFFECTS OF HUMIDITY IN MONUMENTS IN DESERT REGIONS

There may appear to be a degree of contradiction in the title given to this lecture, since it is known that the desert is dry, and yet our lecture deals with the effects of humidity on monuments situated in desert regions. Actually, there is not so, much contradiction as at first appears. The climate of the desert is usually continental, and in the daytime, when the temperature is high, the relative humidity becomes low or even very low; but at night the temperature falls greatly, and accordingly the relative humidity increases to such an extent that it may reach saturation. If it falls still further, water droplets will condense to form a dew on anything the desert may contain, including monuments. Humidity is, therefore, a factor affecting the state of preservation of monuments in the desert. It may be added that although rainfall is somewhat rare in a desert, it is not a possibility to be completely excluded, and this means another potential cause of humidity.

The effect of humidity on monuments will be illustrated by reference to the monuments of Ancient Egypt, since all of us are better acquainted with these; moreover, they are comparatively ancient, and hence the effects of humidity on them will be more apparent.

Before going into detail, I would like to mention two important facts. The first is that it is not humidity itself that affects the monuments in the desert; it is the variation in relative humidity which brings about most of the effects which we shall be mentioning. The second fact is that humidity does not always adversely affect the monuments; it is sometimes beneficial, depending on the other factors associated with it, as will be explained.

Type of monument found in the desert.

The monuments to be found in the Egyptian desert are mostly pyramids, temples and tombs. Some are free standing buildings, while others are carved into the rock. The larger pyramids are all built of limestone blocks. The temples are mostly built of limestone, as is the case with those of Abydos, and the temples of Amenemhêt III and Amenemhêt IV at Madinet Madi in Fayum, or else of granite, as in the case of the Valley Temple of Khefren at Giza, or of sandstone, as in that of the temples of Kalabsha and Dakka in Nubia. There are also temples carved into the rock, such as the temple of Deir El-Bahari at Thebes, which is mostly of limestone, and the two temples at Abu Simbel, which are carved in the sandstone mound on the border of the Nubian Desert. The tombs other than the pyramids are mostly cut into the limestone hills of the Eastern and Western Deserts; such are the Beni-Hassan tombs, the tomb of Nefertari and the tombs of the Valley of the Kings at Thebes, etc.

In addition to the monuments made of the above materials, there has also been found, in the Giza Desert, a huge boat made of wood which will be discussed as an example of a monument made of this material.

Effects of humidity.

The effects of humidity on monuments located in desert areas depend upon the other conditions associated with it. Thus, under certain conditions humidity may cause deterioration of the monument, while under others it may lead to its improved conservation and stability. Accordingly, we may classify these effects under two categories, namely :-

I . Effects leading to deterioration
II. Effects leading to conservation and improved stability.

EFFECTS EADING TO DETERIORATION.

Humidity - or, to be more accurate, variations in the relative humidity of the air in the desert - can lead to the deterioration of monuments in two completely different types of circumstances, i.e. :

1. n the presence of salts
2. n the absence of salts.

Deterioration caused by humidity in the presence of salts.

If the stone of the monument contains salts, humidity will cause it to deteriorate considerably. The extent of the deterioration, however, will depend upon the kind of stone. If the stone is comparatively porous (sandstone or limestone, for example), the deterioration will be more acute, since the moisture will dissolve the salts present, and the solutions thus formed will migrate through the pores towards the drier parts of the surface where evaporation is greatest, and so act on this surface as to cause it to decay. The decay will depend on the kinds of salts present, and may be divided into three different types : -

1. Deterioration due to humidity in the presence of freely soluble efflorescent salts : These are the salts most commonly to be found in the monuments. They may have contaminated the sedimentary rock during its formation, or have found their way into it from the soil on which the monument was built, or from the débris which has covered it, partly or completely, through the ages. Such salts are composed mainly of sodium chloride or sodium sulphate, or both, and may contain a small proportion of calcium sulphate, as is shown in the following analyses :

	Tomb of Hsw-wr (Kom El-Hesn) XIIth Dyn. %	Stele from Mataria XIXth Dyn. %	Zawyet Asiout Coptic %
Acid-insoluble salts (mostly silica)	18.90	40.95	5.92
Sodium sulphate	74.00	-	89.48
Sodium chloride	3.20	45.94	0.58
Calcium sulphate....	5.40	1.01	3.84
Aluminium and ferric oxides....	-	4.38	-
Calcium carbonate...	-	7.05	-
Total	101.50	99.33	99.82

In wet conditions, these salts dissolve and migrate to the surface, where they crystallize as efflorescent salts, which are extruded from the pores; such efflorescence subsequently conceals most of the surface details. Since these salts occupy a greater volume than can be contained in the pores of the stone - for example, calcium carbonate occupies a volume 1.7 times that of calcium carbonate - they will impose so much strain on the stone that the surface will be broken and will disintegrate, causing complete destruction of the principal reliefs or paintings. It sometimes happens that the surface of the stone has for some reason or other become almost non-porous; in such a case, the salts will crystallize under the surface to form a cryptoflorescence, causing considerable pressure and stresses in the course of time, and finally pushing the surface outwards, perhaps even causing it to fall away completely. Of such deterioration caused by humidity in association with efflorescent salts we may mention the following examples:

1. The Osirian at Abydos : This building dates back to the Nineteenth Dynasty (about 1300 - 1223 B.C.). It is built of limestone and stands on the border of the Western Desert, very near to the Nile Valley. With the annual rise in the level of the Nile, water has infiltrated its way in, and thus appears in it every year, especially at flood time. The level of the water infiltrating subsides, however, during the winter and spring seasons, and all water completely disappears from the Osirian. At the same time, huge amounts of débris containing much salt have collected behind the walls of the Osirian and reach almost to the top. It is clear, therefore, that

all the factors of decay are present, namely, high relative humidity during summer and autumn and low relative humidity during winter and spring, associated with large quantities of salt which have impregnated the stone from the débris behind the walls. Thus, the wide variations in the R.H. have caused formation on the walls of thick deposits of crystalline salts, almost wholly composed of sodium chloride, and damaged the beautiful reliefs and important inscriptions which used to decorate these walls.

2. The tomb of Nefertari at Thebes : This tomb belongs to Nefertari, wife of Rameses II of the Nineteenth Dynasty (1290 - 1223 B.C.). It is carved in the limestone hill in the Valley of the Queens, to the west of Thebes, bordering the desert; its walls used all to be coated with gypsum plaster bearing very beautiful painted reliefs. The relative humidity inside this tomb was found to be lower than the R.H. outside, even during the daytime; thus, on 4th and 5th March, 1958, for example, the R.H. inside was almost constant at about 28%, while outside it was 40 - 43% at 10 o'clock in the morning, and naturally much higher at night. Unfortunately the limestone of the hill contained little sodium chloride, and under such conditions the salt migrated towards the drier side, i.e. towards the inside of the tomb, where either it crystallized behind the painted plaster layer (in which case the crystals gradually forced the latter out of place), or else it passed through the plaster layer and crystallized in its pores, causing disintegration. Thus many parts of the painted plaster layer have fallen away, especially where it was rather thin.

The low relative humidity inside the tomb has also caused damage of a different type. The blue and green paint on the walls of the tomb was applied by using a mixture of blue or green frit and an organic adhesive, most probably animal glue. These frits are artificially-made pigments, prepared in the same way as glass, and then ground. Acdordingly, they were somewhat coarser than the other natural pigments, and necessitated admixing with a greater proportion of glue in the process of painting. The low humidity inside the tomb caused the glue to dry up and shrink, and thus the green and blue paints have suffered and most of them have either fallen away or cracked very badly.

3. The Pyramid of Pepi II as Saqqara : This pyramid dates back to the end of the VIth Dynasty (ca. 2350 - 2280 B.C.) and is situated a few kilometres south of Saqqara in the Western Desert. The limestone walls of its inner chambers are inscribed with Pyramid texts. Here there is a new factor of decay, namely, wrong restoration, which, in the presence of humidity, has caused decay of the stone. The pieces of the walls which had fallen away were stuck back in their original places with gypsum mortar more than forty years ago. The gypsum mortar was composed of calcium sulphate, which is slightly soluble in water, and contained some sodium chlo-

ride as an impurity. These two water-soluble salts, in conjunction with the variation in relative humidity, have had the usual effect and caused the surface of the stone to disintegrate in the restored parts and around them.

B. Deterioration due to humidity in the presence of slightly soluble gypsum mortar : The Ancient Egyptians knew gypsum and used it as a mortar from the Third Dynasty (2778-2680 B.C.) onwards. Since gypsum is composed of hydrated calcium sulphate, which is slightly soluble in water (0.202%), the presence of moisture will partly dissolve it and the solution will pass through the porous stone, where it will crystallize on the surface, causing disintegration of the latter. We shall mention the following example as an illustration :

The Valley Temple of Sneferu at Dahshur : This temple lies in the Western Desert, about 10 kilometres to the south of Saqqara. It dates back to the beginning of the Fourth Dynasty (ca. 2680 B.C.). It is built of fine-grained limestone; its walls are very thick and consist of two or more rows of limestone blocks held together with gypsum mortar. When discovered, in October, 1951, the walls were found encrusted in some places with an efflorescence mainly composed of hydrated calcium sulphate (gypsum) and containing a small amount of sodium chloride. These efflorescent salts were removed partly by mechanical means and partly by washing. About two months later I was told that salts had appeared again. They were composed of feathery crystals, which were found to consist wholly of hydrated calcium sulphate containing no sodium chloride. They were very easily removed, mechanically. After about two further months, the same thing happened again, and continued to recur. It is clear that the efflorescence of calcium sulphate formed here was due to the presence of the mortar with which the blocks were held together, and some means must therefore be found for separating the walls and isolating them from the mortar.

C. Deterioration due to humidity in the presence of deliquescent salts : Some of the desert monuments were found partly or wholly covered with débris which contained organic animal matter. The organic proteinic substances had in the course of time become converted into nitrates, generally calcium nitrate, which is deliquescent. These nitrates, being very soluble in water, had penetrated, together with some other salts found in the débris, through the porous sandstone monuments to a great depth. When the débris covering such monuments was removed, these salts, being highly deliquescent, caused many parts of the surfaces of the sandstone to appear consistently damp and darker in colour. Such highly deliquescent salts do not crystallize on the stone surface; nevertheless, they make these parts much softer and more friable. It was noticed that birds ate away the stone in these areas and built their nests in the hollows thus formed. Moreover, some kinds of algae may grow in these hygroscopic areas.

Such cases have been observed in the Abu Simbel temples, in the Temple of Madinet Habu at Thebes, and even in some other temples among these in the valley. Some of these salts were extracted from the façades of the two temples at Abu Simbel, and chemical analysis showed the following probable composition:

	Salts from façade of the Great Temple %	Salts from Small Temple %
Calcium sulphate . . .	3.14	1.09
Calcium nitrate . . .	75.11	60.45
Magnesium nitrate . .	3.97	-
Calcium chloride . . .		11.02
Magnesium chloride. .	5.89	8.97
Potassium nitrate. . .	0.54	
Potassium chloride . .	-	3.89
Sodium chloride . .	2.85	10.37
Chemically-combined water-content (by subtraction)	8.56	4.21
Total	100.00	100.00

The fact that most of the constituents of these salts are highly deliquescent explains the observation that however low the R.H. of the air the areas impregnated with them always remain humid and darker in colour thant the adjacent salt-free areas.

Deterioration caused by humidity in the absence of salts.

This action has been more specially observed in the case of granite monuments. In the red granite Valley Temple of Khefren at Giza, for example, the surface layer is seen to have been forced off and has even scated off in many parts, although no soluble salts could be detected in the stone. The same thing is also observed in the granite stele of Thotmes IV, which stands between the fore feet of the Sphinx at Giza. It seems that such deterioration may be due to dimensional changes in the surface layer of the rock, as a result of the continental climate of the desert; the temperature sometimes falls to below 0°C, and the R.H. increases, to saturation point, the dew formed changing to ice and thus exerting a pressure below the surface, causing its partial extrusion.

Humidity also causes alteration of some of the mineral constituents of granite; felspar, mica and biotite minerals change into kaolin and chloritic minerals, which are soft, and the other components of the granite, such as quartz, become loose and leached, either mechanically or by the action of rain water; the final result is the disintegration of the surface.

FFECTS LEADING TO CONSERVATION AND IMPROVED STABILITY

Two examples will be given here to illustrate the beneficial action of humidity and its rôle in preserving monuments :

1. "Desert varnish".

It has been noticed that many stone monuments in the desert acquire a brown, dark brown or black colour which strongly adheres to the surface and cannot be easily rubbed off. This colour or patina develops naturally on the surface of the stone through the effect of humidity, and is known an "desert varnish". It is observed on the surface of many of the stones of the three pyramids at Giza, on the Dahshur pyramids, on the façades of the two Abu Simbel temples in Nubia, and on many other monuments in desert areas.

Such patina or varnish has formed in the following manner, as a result of variations in R.H. The limestone or sandstone usually contains traces of iron compounds, such as ferrous carbonate. If rain falls, or the R.H. becomes very high at night, water, coupled with carbon dioxide from the air, passes through the porous stone and will convert some of the ferrous carbonate into soluble ferrous bicarbonate, which is brought to the surface by capillarity, especially when the weather turns dry. The ferrous bicarbonate decomposes very quickly into ferrous carbonate, which decomposes in its turn, and is oxidized on contact with the air, to produce ferric oxide, which is deposited on the surface. The process is repeated thousands of times, and a distinct layer of crystalline adherent ferric oxide is formed. This explains the formation of the brown "desert varnish" .

If the stone contains manganese carbonate, black manganese dioxide is formed on the surface in the same way, by the action of humidity and carbon dioxide. This explains the formation of the black varnish. If both ferrous and manganese salts are found in the stone, the varnish will be dark brown.

The mechanism of the formation of the "desert varnish" shows that humidity plays the principal rôle. Since this varnish affords a certain degree of protection to the stone, the humidity in this case leads to improved stability for the monument.

2. The Cheops Boat at Giza.

This is a special case which has occurred in the desert at Giza, and therefore I mention it only as an example of an interesting phenomenon connected with humidity which has taken place in the desert, though it could have happened in any other place and is not characteristically a desert phenomenon.

On May 26th, 1954, a huge wooden boat was discovered in a rectangular pit cut in the rock, a few metres to the south of the Great Pyramid of Cheops at Giza. The pit was originally covered with much desert sand under which lay a further covering of 41 huge limestone blocks. The blocks were stuck together with gypsum mortar, and the ancient builders had taken all possible precautions to make the pit completely air-tight. After plant fibres constituting the mats and ropes buried with the boat started to dry up, but the moisture could not escape out of the air-tight pit. The drying-up of the contents of the pit continued only for a short time, until the atmosphere in it became almost saturated with moisture. An equilibrium was established between the moisture in the atmosphere of the pit and the moisture-content of the wood. Actually the R.H. inside the pit before it was uncovered was found to be 88%. As a result of this equilibrium and the high R.H., the wood of the boat did not suffer much drying, and accordingly most of it remained well preserved and reached us in a comparatively good state.

From these examples it is apparent that humidity has played an important rôle in the preservation or deterioration of monuments even when situated in the desert. But, to be fair, it should be stated that humidity is not always responsible for the deterioration usually attributed to it; in most cases it must be associated with other factors. In a few instances it has proved helpful in protecting and preserving some of the monuments which we now possess.

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