The Corrosive Well Waters of Egypt's Western Desert

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1757-O

Prepared in cooperation with the Arab Republic of Egypt under the auspices of the United States Agency for International Development

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By FRANK E. CLARKE

CONTRIBUTIONS TO THE HYDROLOGY OF AFRICA AND THE MEDITERRANEAN REGION

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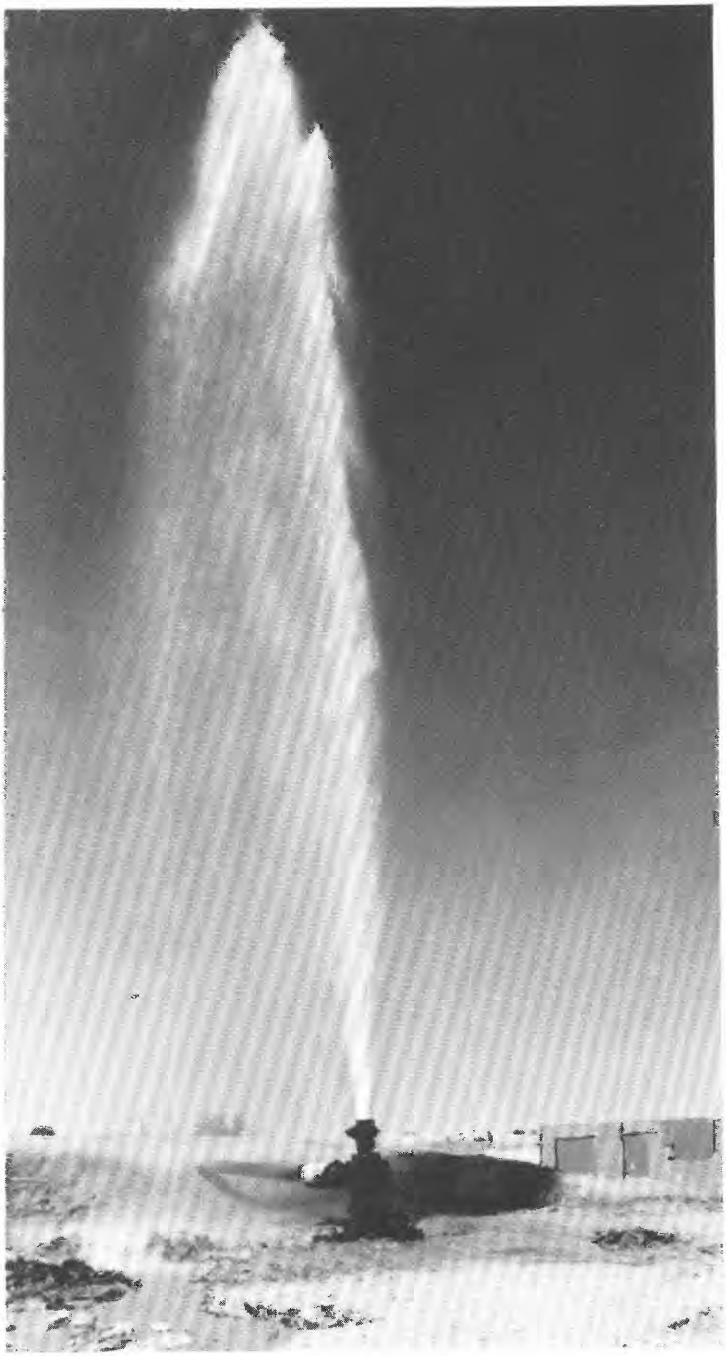

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CONVERSION FACTORS

Factors for converting from International System of Units (SI) to Inch-pound units are given below to three or four significant figures. However, in actual conversions, inch-pound equivalents should be determined only to the number of significant figures consistent with the SI counterparts.

SI UNIT	*MULTIPLY BY*	*= INCH-POUND*
millimeter (mm)	0.03937	inch (in)
centimeter (cm)	0.3937	inch (in)
meter (m)	3.281	foot (ft)
square kilomter (km^2)	0.3861	square mile (mi^2)
million cubic meters (Mm^3)	810.80	acre-feet (acre-ft)
cubic meters per day (m^3/d)	35.30	cubic feet per day (ft^3/d)
centimeter per second (cm/s)	0.0328	foot per second (ft/s)
degree Celsius (°C)	9/5(°C)+32	degree Fahrenheit (°F)
metric ton (t)	1.10	short ton, (2,000 lb)

CONTRIBUTIONS TO THE HYDROLOGY OF AFRICA AND THE MEDITERRANEAN REGION

THE CORROSIVE WELL WATERS OF EGYPT'S WESTERN DESERT

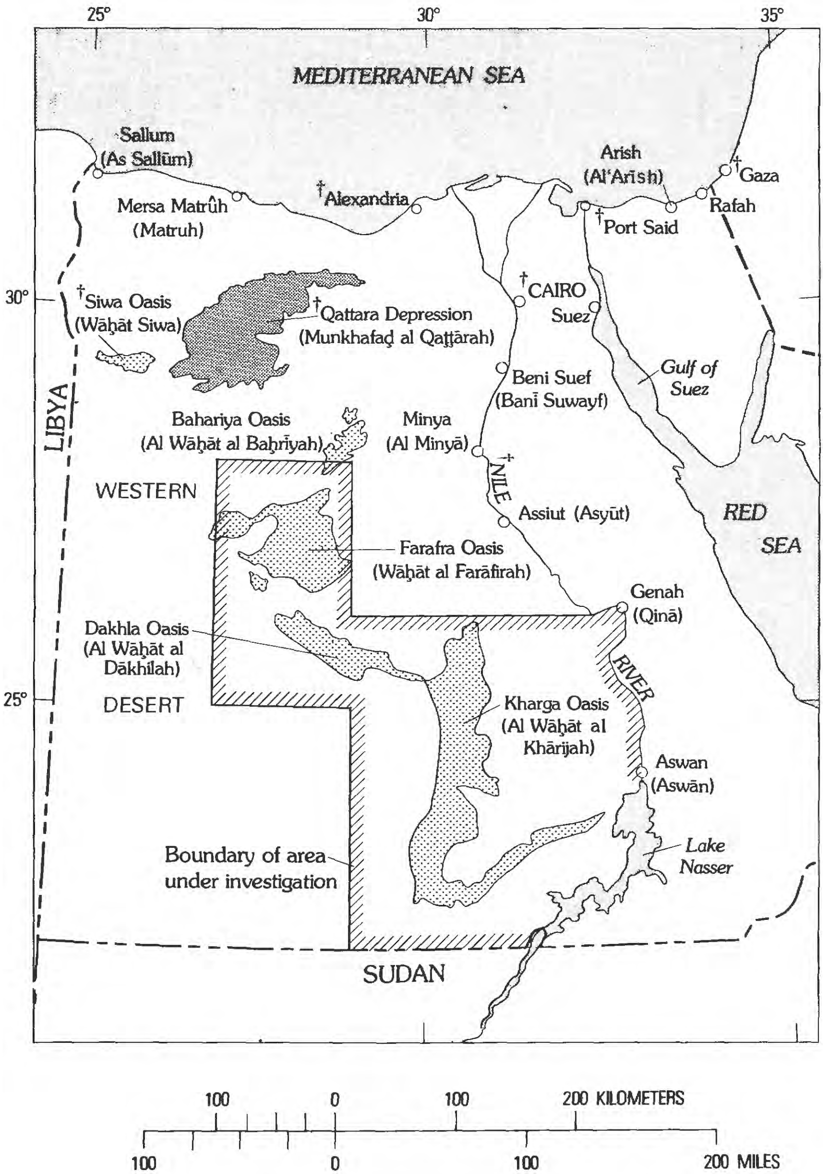
By FRANK E. CLARKE

ABSTRACT

The discovery that ground waters of Egypt's Western Desert are highly corrosive is lost in antiquity. Inhabitants of the oases have been aware of the troublesome property for many decades and early investigators mention it in their reports concerning the area. Introduction of modern well-drilling techniques and replacements of native wood casing with steel during the 20th century increased corrosion problems and, in what is called the New Valley Project, led to an intense search for causes and corrective treatments. This revealed that extreme corrosiveness results from combined effects of relatively acidic waters with significant concentrations of destructive sulfide ion; unfavorable ratios of sulfate and chloride to less aggressive ions; mineral equilibria and electrode potential which hinder formation of protective films; relative high chemical reaction rates because of abnormal temperatures, and high surface velocities related to well design.

There is general agreement among investigators that conventional corrosion control methods such as coating metal surfaces, chemical treatment of the water, and electrolytic protection with impressed current and sacrificial electrodes are ineffective or impracticable for wells in the Western Desert's NewValley. Thus, control must be sought through the use of materials more resistant to corrosion than plain carbon steel wherever well screens and casings are necessary. Of the alternatives considered, stainless steel appears to be the most promising where high strength and long-term services are required and the alloy's relatively high cost is acceptable. Epoxy resin-bonded fiberglass and wood appear to be practicable, relatively inexpensive alternatives for installations which do not exceed their strength limitations. Other materials such as high strength aluminum and Monel Metal have shown sufficient promise to merit their consideration in particular locations and uses. The limited experience with pumping in these desert wells leaves uncertainties concerning the durability of conventional pump designs.

Egypt's New Valley Project provides an excellent opportunity for continuing study of the corrosion problems that concern ground-water developers in many parts of the world.



Names and boundary representation are not necessarily authoritative. Asterisk (*) preceding name, name is not verified by BGN. Dagger (†) preceding name, name is conventional name form; name following in parentheses is native name form.

FIGURE 1.—Map showing principal features of Egypt's Western Desert and the boundary of the New York Valley Project, Modified from Ezzat (1969).

INTRODUCTION

Ground-water development in the New Valley Project of Egypt's Western Desert, like that in many other parts of the world, has been troubled by serious corrosion of metal casings, screens, pumps, pipes, and fittings. Over the years there have been numerous observations and investigations of this problem and various theories and remedies have been proposed in administrative documents, open-file reports, and other communications. This report summarizes such work to 1977, including that of the author during the period 1962–64. It discusses corrosion control in the light of theory and operational experience with the objective of providing useful background information for all who may have such problems. Although the observations were confined to wells in Kharga and Dakhla Oases depressions, corrosiveness is likely to be a problem in other parts of the Nubian aquifer underlying the Western Desert.

The site and well location maps (figs. 1 and 2) provide official translations from Arabic to English terms, as approved by the U.S. Board on Geographic Names (BGN). The official (BGN) name is shown in parenthesis. Names have been obtained from a variety of sources. Only the English terms are used elsewhere in the text, tables and illustrations, consistent with recent practice in U.S. Geological Survey publications dealing with Egypt. Names preceded by an asterisk (*) have not been verified by the Board on Geographic Names.

ACKNOWLEDGMENTS

The well-water studies discussed in this report were made in cooperation with the Egyptian General Desert Development Organization (EGDDO) under the auspices of the United States Agency for International Development (USAID). The references contain the names of many individuals of both organizations who provided valuable background information and assistance. General H. Sobieh, Hussein Idris, Mohammed Ezzat, Moussa Seddik, Hassan Mostafa, Mohammed Shaaban, and George Fahmy of EGDDO, and Herbert A. Waite, Raymond W. Sundstrom, the late Paul Bieber, Robert V. Cushman, and Joseph S. Gates of USGS/USAID, in particular, spent much time in field work or related discussions.

Valuable assistance in analysis of samples or data also was received from my associates William Back, Ivan Barnes, Edward J. Dwornik, Herman R. Feltz, Blair F. Jones, and James R. Jones all of the U.S. Geological Survey.

ENVIRONMENTAL SETTING

The Western Desert of Egypt extends from the northern margin of Qattara Depression and Siwa Oasis to the border of the Sudan and from the western edge of the Nile Valley to the Libyan border. Its area is approximately 685,000 square kilometers (km^2) or about 68.5 percent of Egypt's total area. As shown in figure 1, a series of topographic depressions, thought to be the combined effect of wind and water erosion, extend diagonally southeastward from Siwa Oasis just north of latitude 29°, through the Oasis of Bahariya, Farafra, Dakhla, and Kharga to near where the Nile River crosses the northern boundary of Sudan. The heads and flanks of these lows are bounded by escarpments which rise to 300 or 400 meters (m) above sea level. Their floors slope gently southeastward with subdepressions as low as 0.8 m above the sea. According to Ezzat (1974) mean daily temperatures in this southern part of the desert, known as the New Valley and covered by this study range, from 13°C in January to 31°C in July and temperatures may reach 49°C or more. Rainfall averages only 1 millimeter (mm) per year according to official records although infrequent intense storms are known to occur. Despite the arid climate, villages and supporting wells are scattered throughout the New Valley area as shown in figure 2.

The entire Western Desert is thought to be underlain by a thick sequence of waterbearing strata (aquifers) consisting of sand and sandstone, interbedded at places with shale, mudstone, and chalk. Loosely cemented angular sands like those of figure 3 constitute part of the sandstone. This series, collectively called the Nubian aquifer (Jones, 1967), rests on a Precambrian basement of granite and gneiss which outcrops on the east flank of the Ennedi, Erdi, and Tibesti Mountains at the southwest extreme of the desert, outside of Egypt. The Nubian aquifer slopes at a gradient of 1/2,000 to the northeast and is capped, except in the depressions, by shales, chalks, and limestones of upper Cretaceous, Paleocene, and Miocene ages. The sand and sandstone components, which constitute about 30 percent of the reservoir are nonfossiliferous and thus undated, but are thought to range from upper Cretaceous at the top to Cambrian at the bottom.

Thickness of the Nubian aquifers varies throughout the desert. It averages about 300 m in North Kharga Oasis and is as thick as 1,500 m in South Dakhla Oasis. The upper surface ranges from 50 m to several hundred meters below land surface, and artesian pressures as great as 157 m above sea level and 50 m land surface have been reported (Cushman and Gates, 1967). Numerous

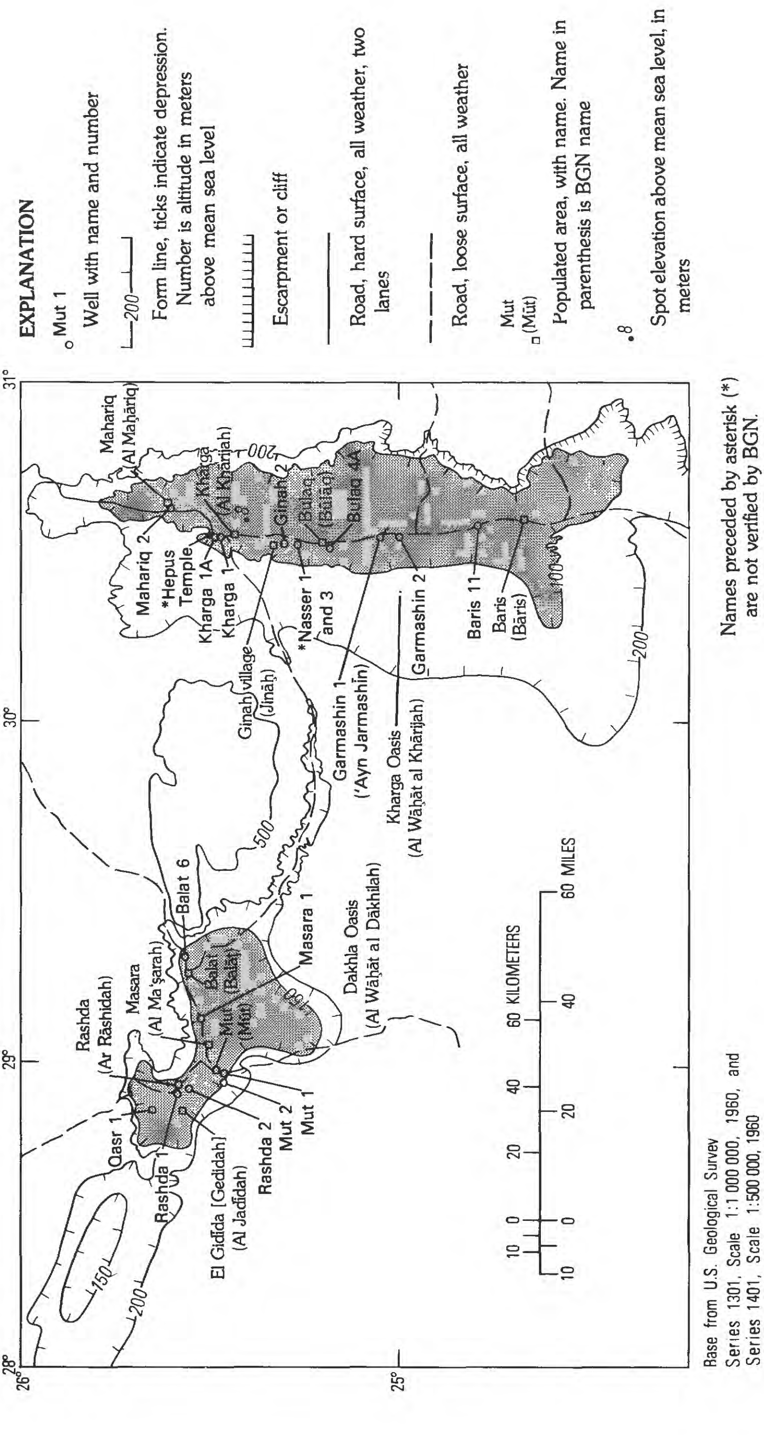


FIGURE 2.—Site and well location map, New Valley area, Egypt's Western Desert.

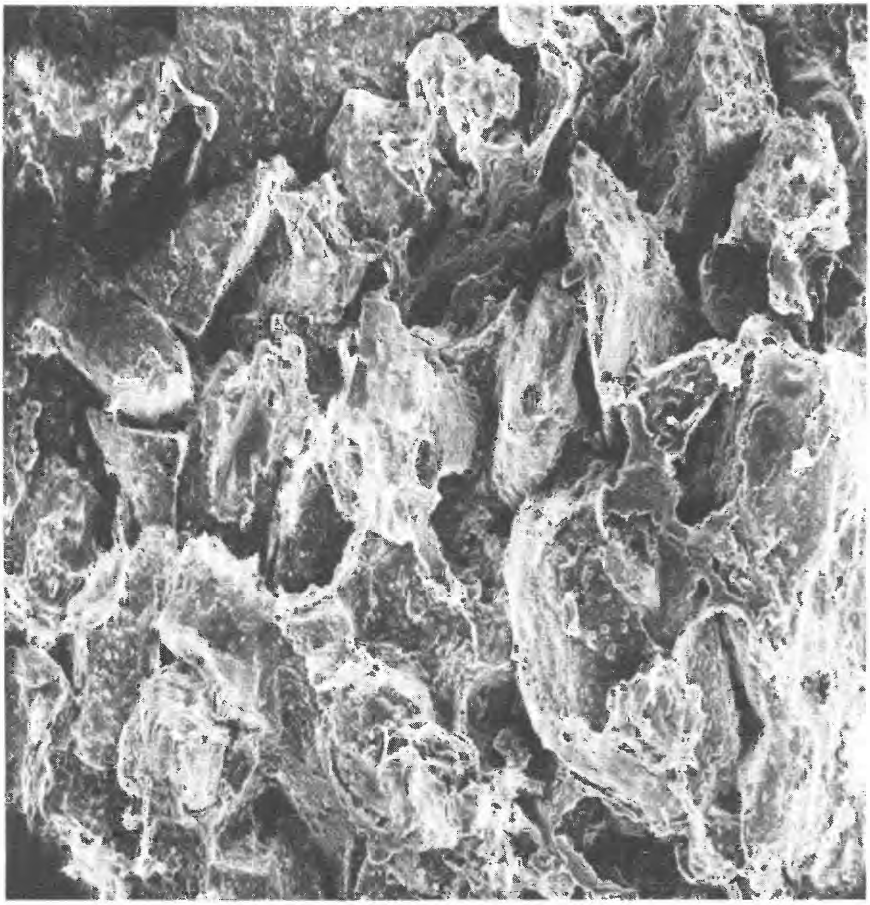
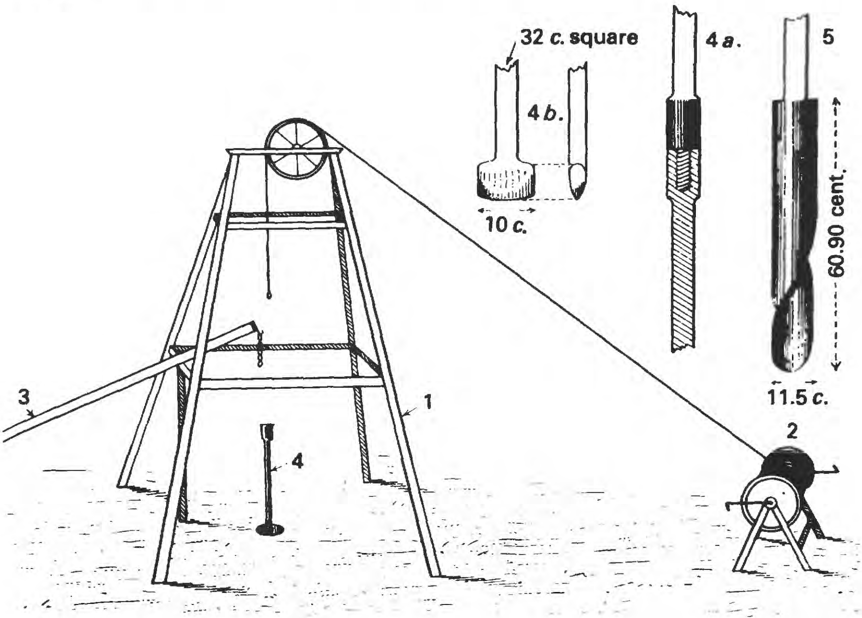


FIGURE 3.—Macrograph of Nubian sandstone showing loosely cemented angular grains, × 34.

opinions exist concerning the source and extent of recharge to this subsurface reservoir. However, it is generally agreed that, whatever the source, there is a vast amount of water. Hellstrom (1940) estimated water movement under Kharga and Dakhla at 15 m per year and concluded that at that rate it took 50,000 years to traverse the distance between the nearest rainfall areas and the oases, a period later confirmed reasonably well by carbon dating that indicated 25,000 years "travel time" for Dakhla Oasis and 50,000 years for Siwa Oasis. Ezzat (1974) calculated the rate of water movement to be 156 m per year and concluded that the storage beneath Kharga and Dakhla Oases is sufficient to provide 1,280 million cubic meters (Mm^3) of water annually for 200 years. He also concluded that the rate of movement through the entire Nubian section is 27 m per year. Burdon and Pavlov (1959) estimated the annual infiltration rate and practicable yield at 17,000 Mm^3, a virtually inexhaustible supply in the kinds of development likely to be undertaken the Western Desert. Even if recharge and natural movement are insignificant there obviously is a great amount of water available in such a large amount of water-bearing earth material. The latest estimate is that 2,500 Mm^3/yr can be withdrawn at practicable pumplift (Ezzat, 1978).

There is evidence that humans have inhabited the desert depressions and utilized water from the Nubian aquifer and other sources over a great period of time. Waite (1962) discussed sedimentary evidence of a post-Pleistocene lake which covered some of the Kharga Oasis depression and may have stood at 65 to 70 m above sea level when Darius II revised Hepus Temple about 423 B.C. near the present village of Kharga. Ball (1900) mentioned a spring of perched water which still exists 260 m above sea level on the scarp to the east and 180 m above the village of Baris in South Kharga Oasis. Inscriptions nearby suggested that this spring was used by the Coptic Christians who migrated to the desert during the fifth century A.D. Nubian ground water probably discharged at occasional natural springs coincident with geologic faults; perhaps the flow amounted to the several tens of thousands of m^3/d suggested by Cushman and Gates (1967). Although there is no longer any physical evidence of such natural leaks, it is clear that desert cultures expanded around them. The Roman Admiral Scylox is reported by LaMoreaux (1962) to have developed extensive irrigation in Kharga Oasis including underground transfer systems (kanats) some 2,500 years ago near Hepus—"city of the plow." Ball (1900) states that Bishop Nestorius practiced irrigation in the Christian settlement in Kharga Oasis in the early 400's A.D.

The exact manner of constructing the earliest Western Desert wells is unknown but it seems likely that the ancient method described by Beadnell (1901), and others was used from the time of the Roman occupation to the appearance of relatively modern percussion drilling machinery in the desert about 1860. This consisted of a palm log frame 2 m square sunk by hand 50 m or more to the bottom of the surface clay and a central acacia wood casing of similar depth and 35 centimeter (cm) inside diameter. The two members were separated by a tightly packed filling of earth material. In later years the depth of the frame and upper casing were reduced to about 30 m and a smaller water conducting pipe made of hemicylindrical sections of palm or acacia was sunk to the base of the surface clay. How the deeper drilling was accomplished in the early days is unknown; however, Beadnell's report illustrates drilling equipment which must have been quite similar to that used. (fig. 4). The same kind of native drilling rigs and casings of unknown age (fig. 5) were observed by the writer in 1962.



Parts of boring-plant used in Dakhla Oasis

1. Heavy timber framework with pulley wheel
2. Windlass
3. Beam for lifting and dropping whole length of rod during boring
4. Rods. 4 a. Enlarged junction of two (not to scale.) 4 b. Cutter
5. Auger

FIGURE 4.—Sketch of native well drilling equipment. From Beadnell (1901).

Improvements in drilling techniques ineviably led to construction of more wells, sometimes to well interference and the loss of some flowing wells and productive land. Early investigators of these problems (for example, Ball and Beadnell) correctly surmised that deeper wells might tap other, perhaps more productive aquifers. Such studies eventually led to modern drilling, steel well components, and an increasingly troublesome problem—corrosion.

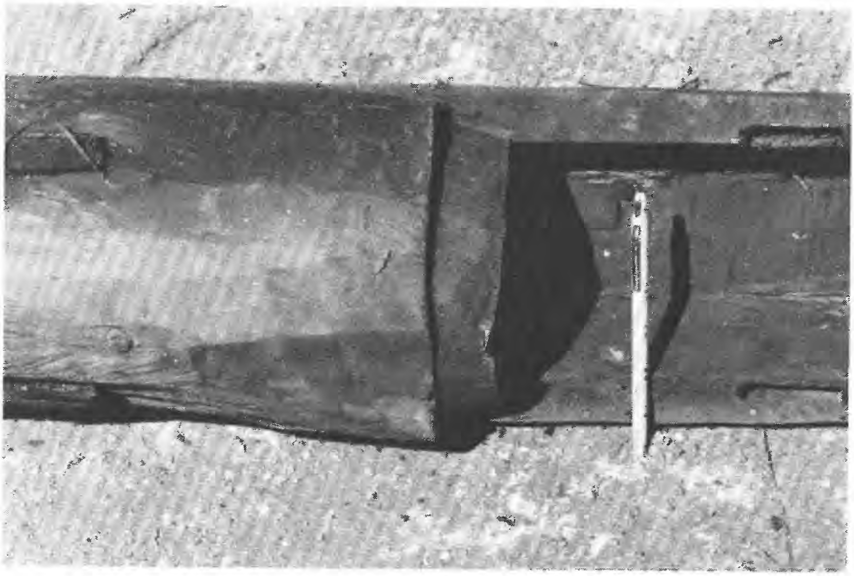


FIGURE 5.—Acacia wood casing from native well, Kharga Oasis.

EVOLUTION AND DESIGN CHARACTERISTICS OF WESTERN DESERT WELLS

Although Beadnell (1901) mentioned 162 new wells in Dakhla Oasis, his report, like that of Ball (1900), indicates little improvement during the 19th century in either boring equipment or well design over primitive practice. More advanced percussion drilling equipment and metal well components, in lieu of wood, were introduced during the first half of the 20th century. Little and Attia (1942), mentioned the reported presence of a rig in Kharga Oasis capable of drilling to 750 meter depths, presumably in search of deeper water. The same report expressed views on the increasing use of steel casing and the corrosion problems likely to follow.

It would appear from a discussion of well collapse by Paver and Pretorius (1954) that early steel-cased wells were constructed without external cementing. More recent deep wells in the desert have casings which are cemented above the water-bearing formation and a down-hole construction sequence which includes 15 m of 12¾ to 14¾ in. (31–36 cm) diameter surface casing, 8⅝ to 9⅝ in. (21–23.6 cm) intermediate casing to screen height and 6⅝ in. (16.25 cm) screen (filter pipe). Boreholes are sufficiently large to provide annuli of 2.5–7.5 cm for cementing around the casing. Of the 255 screened wells studied by Cushman and Gates in 1967, 131 had screens of mild steel, 56 of aluminum, 36 of stainless steel, 12 of wood, 5 of fiberglass, 3 of unreinforced plastic; and 30 were operating with no screens at all. Screen pattern and openings included horizontal-slotted wood, fiberglass and plastic, drilled and bridge-slotted mild steel and aluminum, and both wire-wrapped and louvered stainless steel. It is common practice to use christmas-tree well heads, like those employed in the oil industry, together with concrete sumps and weirs.

Although some of the desert wells initially yielded more than 14,000 m^3/d and flowed considerably above ground level, it is generally agreed that their relatively small diameters are not ideal for optimal production. In fact, Cushman and Gates (1967) found that efficiencies ranged from 20 to 50 percent of that theoretically obtainable. Small diameters increase linear velocity in the casing and screens with attendant adverse effects discussed later in the report.

Over the years there have been recurrent reports of declining pressure and yields in the desert wells as drilling progressed and these effects have been more pronounced since intensive development started in 1959.

CORROSION–OBSERVATIONS AND INVESTIGATIONS

The general corrosiveness of Western Desert well waters has been known for a very long time and reported either directly or indirectly by virtually everyone who studied the oases since the turn of the century. There is consistent reporting of iron stains in discharge channels and of the odor of hydrogen sulfide even in ancient wells. Both indicate anaerobic water and suggests its capacity for converting iron components of aquifer materials to soluble form. The reports of Beadnell (1901), Little (1926 and 1931) and Little and Attia (1942) indicate that inhabitants of the desert have been aware of the water's corrosiveness since ancient times. The following account by an unidentified investigator, Buckley (1908), in the report by Little and Attia (1942) would appear to indicate that this knowledge stems in part from experience with early well maintenance problems:

> It seems to be doubtful whether the employment of metallic tubes as casings would be advisable. The natives declare that any piece of iron used in the wells invariably becomes corroded in a very short time. At one period they began to strengthen their casings by binding them with hoop irons such as those used in making up cotton bales but they had to abandon this on

account of the excessive oxidation of the iron. They declare that rods which have been left in a well for a few months have become corroded; that any iron nails driven into the casings perish almost immediately and that it is for this reason that they are obliged to fix the two halves together by means of timber dowels. (See fig. 5.)

In the report which contained the quotation cited above, the view was expressed that corrosion problems would be encountered in using ordinary steel casings.

Paver and Pretorius (1954), who appear to have been the first to study desert well corrosion in any detail, mention serious metal loss in the upper casings of Gina well 2 of Kharga Oasis after only 6 months of operation and stated that significant attack was apparent in a pipe used for cleaning Qara well 1 in Dakhla Oasis after only one week of immersion. They described the mode of attack on steel accurately as the formation of a black film on the metal surface and development of a deposit which gradually eats into the metal, flakes it off, and yields serious pitting. These same effects were observed by the author and pictured in his report of 1963 (fig. 11). Paver and Pretorius attributed the collapse and obstruction of certain desert wells to perforation of metal casings and resulting intrusion of formation materials or erosion of the casings by high pressure leakage. They apparently made no measurements to determine how much corrosion and obstruction contributed to the observed reductions in flow. They did, however, make self-potential logging measurements on a number of obstructed and unobstructed wells, including some cased in whole or in part with wood, by observing the difference in electrical potential between a nonpolarizing electrode in "a fixed ground position" and a movable electrode within the well. The resulting data in table 1 show values above what they termed normal ground potential of 140 millivolts (mV) for all but the wood-cased holes. From this they concluded that the steel tubes were corroding over their entire lengths. Although such measurement between a nonpolarizing electrode near the well and a sliding electrode within the casing is primarily an indication of external corrosion potential, their conclusion that serious corrosion was in progress was sound.

Fahmi (1956), who approached the problem primarily from theoretical considerations based on knowledge of water quality, also concluded that plain mild steel would corrode rapidly. He accurately predicted that aluminum, stainless steel and Monel Metal would be significantly more resistant. On the basis of this assessment he recommended aluminum and galvanized steel as

TABLE 1.—*Well obstruction and self-potential data*

[Modified from Paver and Pretorius, 1954.]

Well designation	Completion date	Percentage decline in flow *	Depth to obstruction, (m)	Casing depth (m)	Self-potential (mV)
Deep wells:					
Kharga Oasis (steel casing)					
Ginah 2	1952	Nil	No obstruction	200	740
Bustan	1950	62	248	457	850
Faruqiya	1939	69	350	470	910
Qara	1939	77	412	507	770
Borg	1940	41	348	497	800
El Mahariq	1947	40	432	492	760
Dakhla Oasis (steel casing)					
Budkhulu	1941	100	42	240	800
Qara 1	1947	58	2	Unknown	---
Qara 2	1943	64	2	221	---
Gedidah	1940	66	110	259	800
Qalamun	1940	84	118	249	820
Faruqiya	1940	69	Collapsed	233	---
Ismant 1	1951	Nil	No obstruction	208	830
Shallow wells:					
Dakhla Oasis					
El Adion (wood casing)	----	---	---	80	140 **
Abdl Latif (wood casing)	----	---	---	35	140 **
Abdl Latif (steel casing)	----	---	---	125	600

* Combined effects of corrosion and other hydrologic factors.
** Normal ground potential.

practicable alternative construction materials. Burdon and Pavlov (1959) also were aware of the waters' serious corrosiveness and stated that a solution to the problem must be found before large-scale well development began in the oases.

Sudrabin (1962), an American corrosion consultant to the New Valley Project, examined a number of wells in Kharga Oasis and reported after examination of corroded steel screen parts and discharge pipes that damage is more severe on internal surfaces and that hydrogen sulfide and carbon dioxide are the principal corrosive agents, the latter's effect possibly being increased by gas release due to pressure drop across the screen openings. Sudrabin

TABLE 2.—*Redox potential (Eh) and geotrode data, Kharga wells*

[From Sudrabin, 1962.]

Well designation	Eh (mV)	Potential of discharge pipe against copper sulfate electrode, (mV)
El Kharga 1	+ 16	− 811
El Kharga 1A	+ 12	---
Baris 2	+ 76	− 774

stated, on the basis of water data compiled by the Desert Institute, particularly for the carbon dioxide, iron, and calcium carbonate saturation values, that more corrosion might be expected in Dakhla than in Kharga Oasis, a view also expressed by Paver and Pretorius (1954). Tests performed during the Sudrabin survey by Dr. Gregory Jann, Fulbright professor at Ein Shams University, showed no evidence that hydrogen sulfide was resulting from active bacterial sulfate reduction within the wells.

Sudrabin measured electrical potentials between an inert platinum electrode and a copper sulfate reference electrode immersed in certain Kharga Oasis well discharges and between the same copper sulfate electrode and a probe (geotrode) contacting the submerged internal surfaces of the discharge pipes. The first measurement, when corrected for reference-electrode potential, indicates voltage differentials in terms of the standard hydrogen electrode and is commonly referred to as the Eh value. The second, which is read directly without reference-electrode correction, also indicates oxidizing or reducing environment and therewith a probability for either retention or destruction of protective oxide films. The data in table 2 indicate reducing conditions which would promote metal loss.

As final checks, Sudrabin measured long-line potentials produced by coupling both nearby and remote buried copper sulfate reference-electrodes with the well heads. He also performed well-casing polarization tests by applying a series of increasing currents (that is, amperage) to well heads and measuring residual potential against a copper sulfate electrode after interruption of each successive current application.

From the long-line current data (table 3), he concluded that aluminum screen as well as iron casing was udergoing corrosion, the former because of direct coupling to the iron. He interpreted the polarization data as indicating more than one transition in electro-chemical process within the casing. This study, like earlier ones, pointed to the need for better construction materials.

TABLE 3.—*Long-line current data, Kharga wells*

[From Sudrabin, 1962.]

Well designation	Potential against nearby copper sulfate electrode (mV)	Potential against remote (160 m) copper sulfate electrode (mV)
El Kharga 1	— 700	— 717
El Kharga 1A	---	— 650
Baris 9		---
(150 m depth)	— 860	— 861 *
Baris 9		
(600 m depth)	— 777	— 827
Baris 2	— 752	---

* This value in excess of — 850 said to indicate galvanic attack at junction of steel casing and aluminum screen.

During 1962, 1963, 1964 the author continued the field studies of corrosion started by Sudrabin and extended them to Dakhla Oasis, using corrosion monitoring equipment and special field test-

FIGURE 6.—Perforated elbow, Mut well 1, Dakhla Oasis.

ing for unstable water-quality parameters likely to influence the corrosion process. His first examination of Kharga and Dakhla wells in June of 1962 confirmed the observation of Sudrabin concerning serious internal corrosion of well screens and well head equipment and provided additional information concerning the sulfide-bearing black corrosion deposits which are common to many of the steel-cased wells. He concluded that perforation of a Dakhla well head elbow (fig. 6) on its outer curve indicated the combined effect of high linear velocity and corrosive water and suggested that observed separation of relatively thick bridge pieces from the steel screens (fig. 7) was the result of preferential attack at stress points. The photograph of a corroded discharge line (fig. 8) from a Kharga Oasis well is evidence of the aggressiveness of the water.

The first corrosion test specimens installed in March 1962 in Kharga well 1A on the recommendation of Sudrabin and examined by the author in late June of the same year are shown in figure 9. They consisted of wood-slat insulated 30 cm screen lengths of bitumastic-coated bridge-slotted steel, mild steel casing drilled with 1.5 cm holes, bridge-slotted 61SW aluminum, and wire-wrapped Type 304 stainless steel. After the three months exposure, these four large specimens were covered with the thick slimy black deposit characteristic of desert well interiors. The organic coating had disappeared from much of the bridge-slotted steel specimen, and the mild-steel drilled specimen was heavily etched. Both of these steel sections contained numerous pits ranging from 0.25 to 0.75 mm deep, the deepest on the coated specimen. Neither the aluminum nor the stainless steel specimens showed evidence of attack after this short exposure, even when examined with a low power microscope.

Following this initial inspection, the same four specimens were returned to the discharge line of Kharga well 1A along with a sample of fiberglass tubing and a Type 347 stainless steel stress corrosion test specimen of the type shown in figure 10. The fiberglass was drilled with 2 mm holes to simulate well-screen openings and to serve as indicators of swelling or delamination in such critical passages. All six specimens were examined again by the author and by USAID and EGDDO personnel in May 1963, 14 months after the original installation, and again in March 1964 after the four older specimens had been exposed for two years.

The later examination substantiated the corrosive effect of Kharga Oasis well water on mild steel. Both the bridge-slotted and the drilled steel specimens had severe general etching and local-

FIGURE 7.—Severed screen bridge, Kharga well 1A, Kharga Oasis, × 4.6.

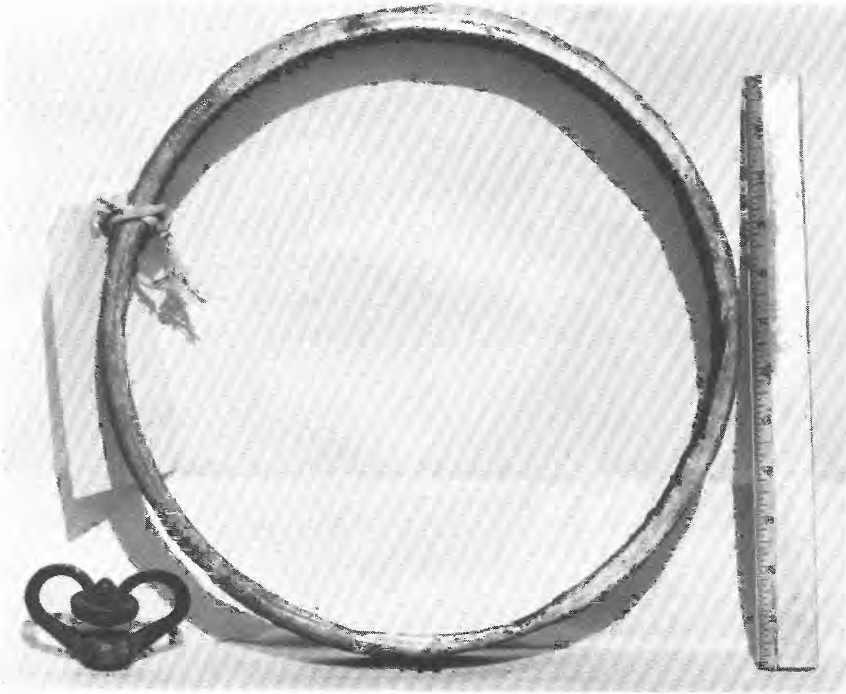


FIGURE 8.—Corroded discharge line, Kharga well 1A, Kharga Oasis.

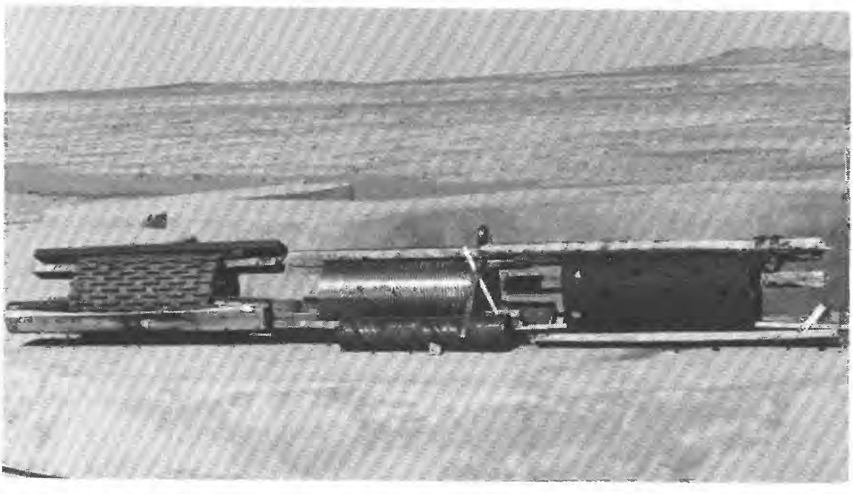


FIGURE 9.—Surface line corrosion specimens, Kharga well 1A, Kharga Oasis.

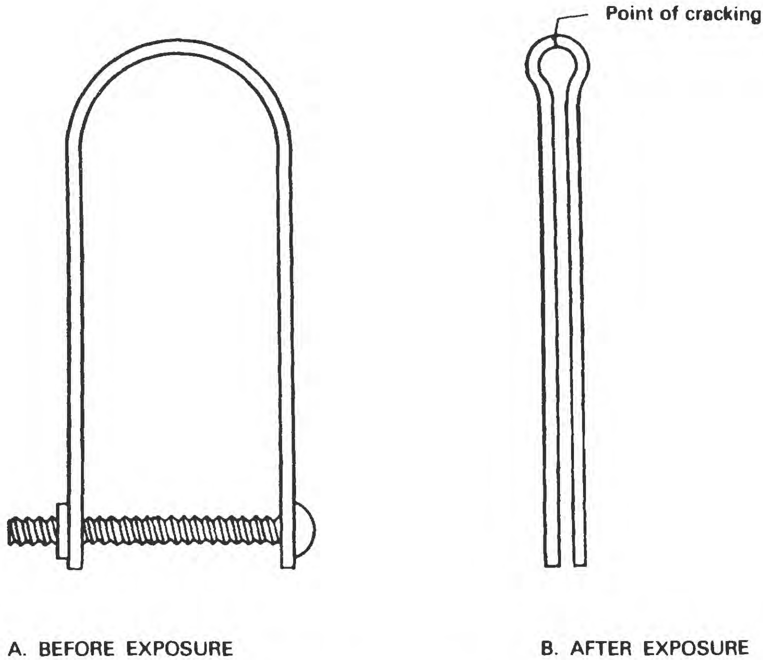


FIGURE 10.—Stainless steel stress corrosion specimen used in Kharga well 1A.

ized pits to 1.5 mm depth. On casual examination, however, the damage was difficult to detect. But surfaces which retained original mill marks and saw scratches flaked away to reveal deep subsurface penetration of the type described by Paver and Pretorius and illustrated in figure 11. The corrosion deposit was heavy and relatively brittle. The aluminum specimen had developed white corrosion tubercles but had only insignificant etching on cut edges (fig. 12). The stainless steel screen specimen retained original mill marks and there was no evidence of corrosion.

The final inspection showed that two years of exposure had increased the overall metal loss in both mild steel specimens although the maximum depth of pitting was still about 1.5 mm. Damage of the type shown in figure 13 was concentrated on the convex surfaces of the slot bridge as evidence that stress from cold working was contributing to local attack. Analysis of the brittle black corrosion deposit showed it to contain iron sulfide (Fe_9S_8), in addition to the more common black hydrated iron oxide. The aluminum and stainless steel specimens endured the two-year exposure with no significant damage. Except for a superficial coating of iron corrosion products, small white tubercules

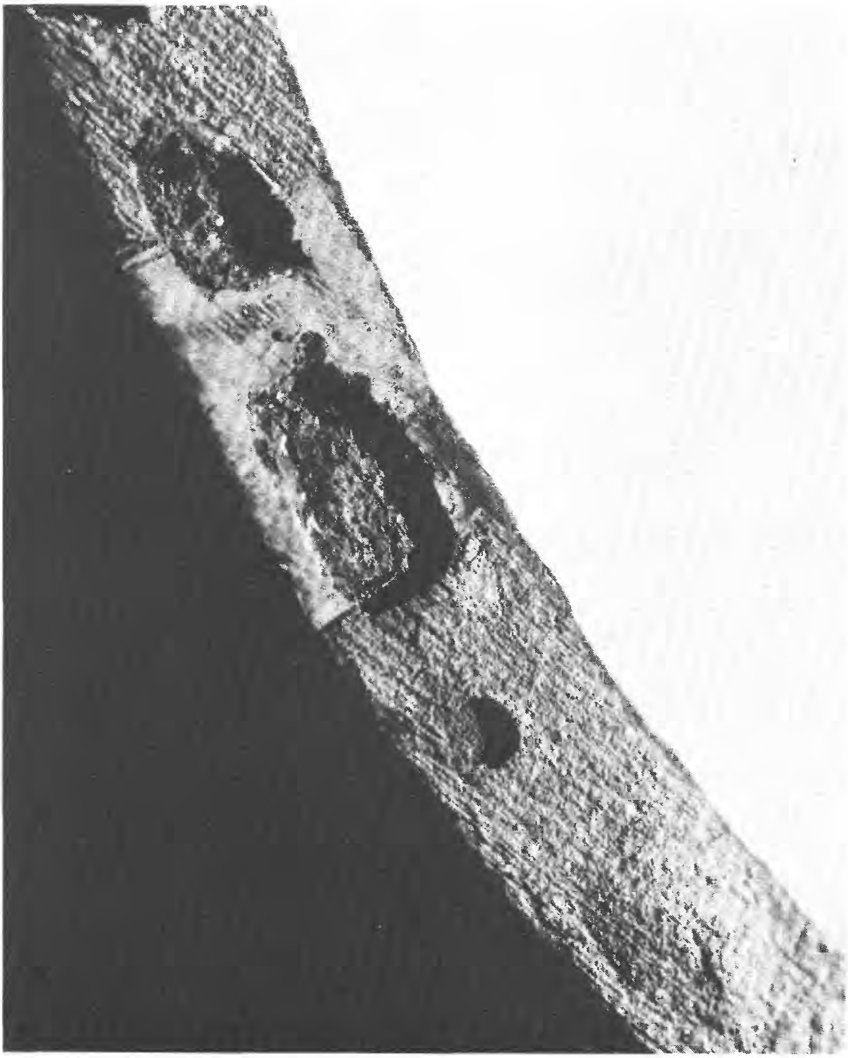


FIGURE 11.—Subsurface pitting, Kharga well 1A, × 5.

of hydrated aluminum oxide ($Al_2O_3.3H_2O$), and slight etching on cut ends of aluminum pieces, both types of specimens appeared to be in original condition. There was no evidence of corrosion attack on the wire-wrapped stainless steel and no intergranular attack on the stressed specimen of stainless steel. The fiberglass tubing also appeared to be in essentially original condition after 22 months of exposure, with no swelling and no seperation of laminates except in one small area of a sawed edge.

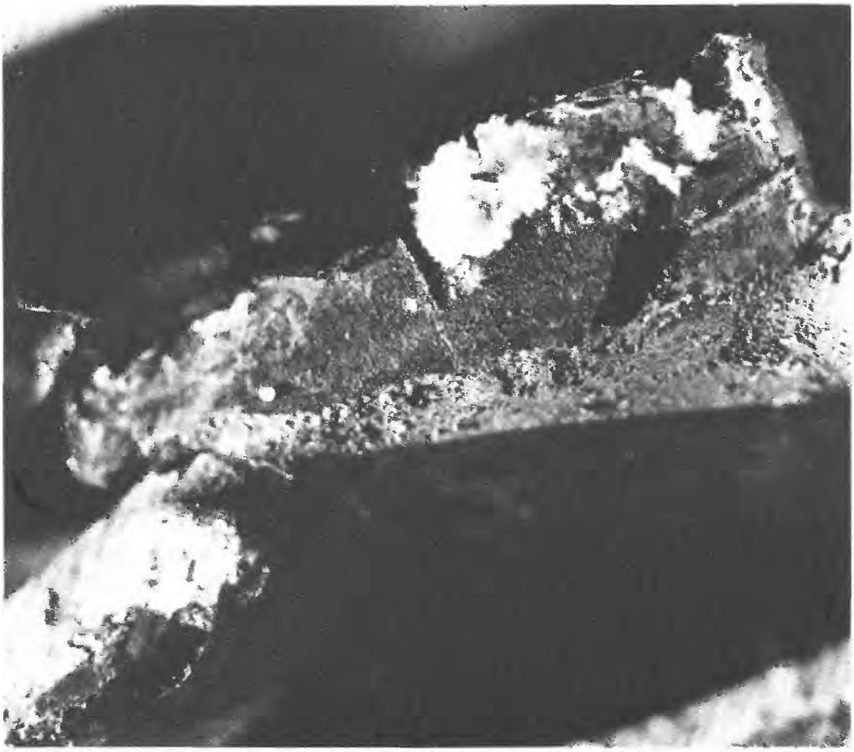


FIGURE 12.—White corrosion tubercles, aluminum specimen, Kharga well 1A, × 7.

Similar surface line specimens of mild steel, aluminum, and stainless steel were installed in Mut well 1 of Dakhla Oasis in December 1962 and examined in May 1963, replaced with new specimens and examined again in March 1964. In April 1963 down-hole specimens consisting of weighted, rubber-insulated cylinders or flattened screen sections made variously from mild steel, aluminum, stainless steel, Monel Metal and Incoloy 800, also were suspended together on stainless steel cable in Mut well 2 just above screen height and 340 m below the surface. This specimen string was examined during the final inspection. The assembly is shown in figure 14.

As reported by early observers, the deep well water of Dakhla Oasis proved to be more destructive to steel than that of Kharga Oasis. After only 4 months' exposure, steel specimens were severely damaged on slot bridges and on the peripheries of holes

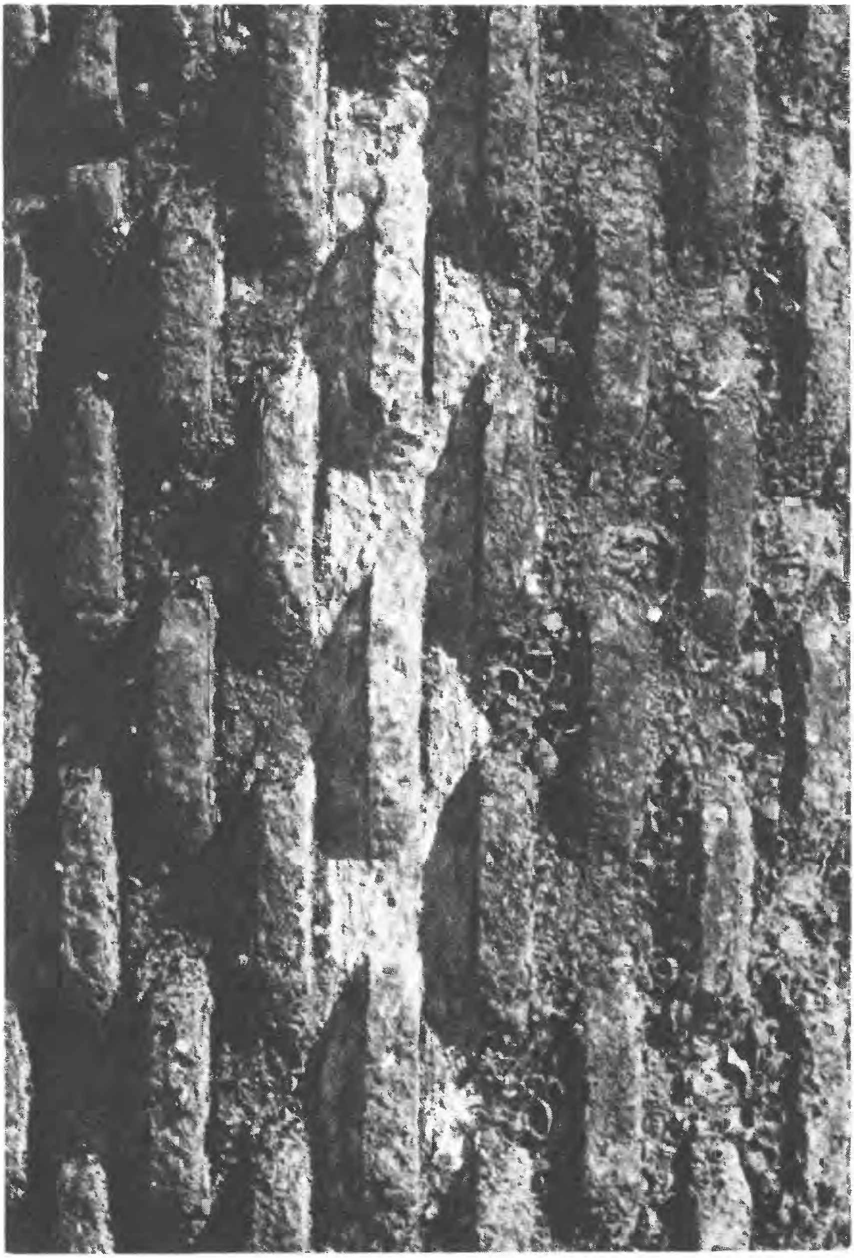


FIGURE 13.—Corroded bridge-slotted screen, after 2-year exposure, Kharga well 1A.

FIGURE 14.—Downhole corrosion specimen string, Mut well 2, Dakhla Oasis.

drilled in the specimens. Many bridge pieces had been completely penetrated by pitting. The drilled casing appeared to have lost about 25 percent of its average wall thickness and its 6 mm wall had been perforated in some places. All corroded areas were relatively clean with only superficial films of nonadherent deposits as shown in the macrograph (fig. 15). Final inspection in March 1964 showed similar severe damage on mild steel surface line specimens installed one year earlier and on the down-hole specimens mentioned above. In the latter exposure, the bridge-slotted specimen has been reduced to approximately 50 percent thickness

FIGURE 15.—Deep, deposit-free corrosion, steel specimen, Mut well 1, Dakhla Oasis × 7.

overall and had lost its bottom half entirely, dropping the drilled casing specimen and the tension weight (fig. 16).

As in the Kharga Oasis test, the resistance of aluminum specimens to Dakhla Oasis well water was much better than that of steel specimens, but there was evidence of significant attack. After four months' exposure in Mut well 1, the bridge-slotted aluminum specimen was speckled with scattered white corrosion tubercles covering shallow corrosion pits up to about 0.125 mm

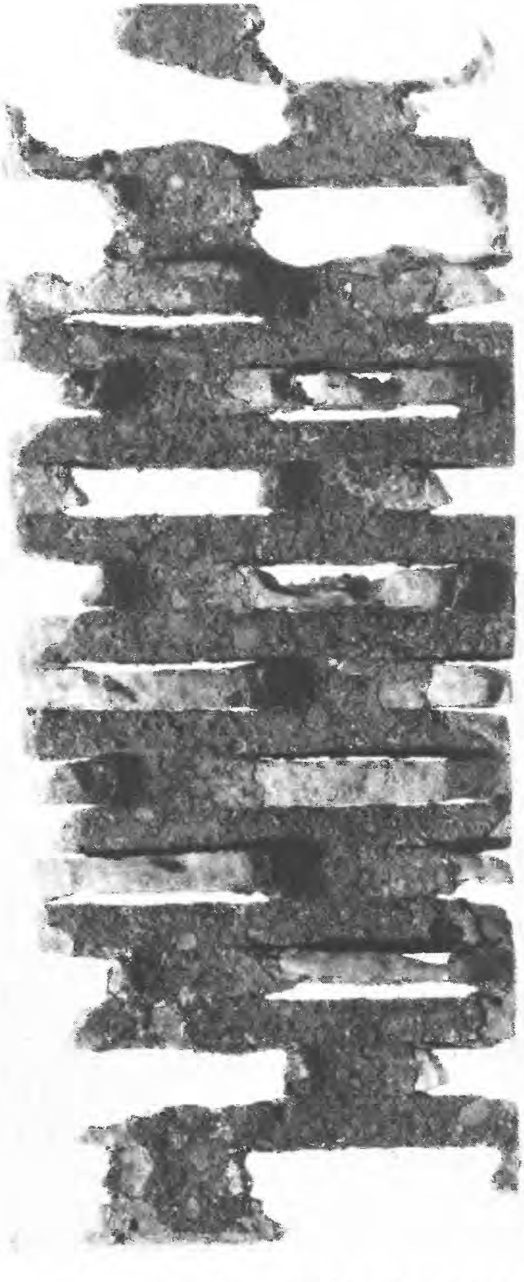


FIGURE 16.—Severely corroded bridge-slotted steel specimen from down-hole string, Mut well 2.

in depth. Effects on down-hole wire-wrapped and bridge-slotted specimens were even more pronounced after a year's exposure in Mut well 2. White corrosion tubercles of the type shown in figure 17 covered 25 percent of their surfaces and underlying these were pits which penetrated up to 10 percent of the total wall thicknesses. Surfaces between the tubercles were covered with thick deposits of black iron oxide.

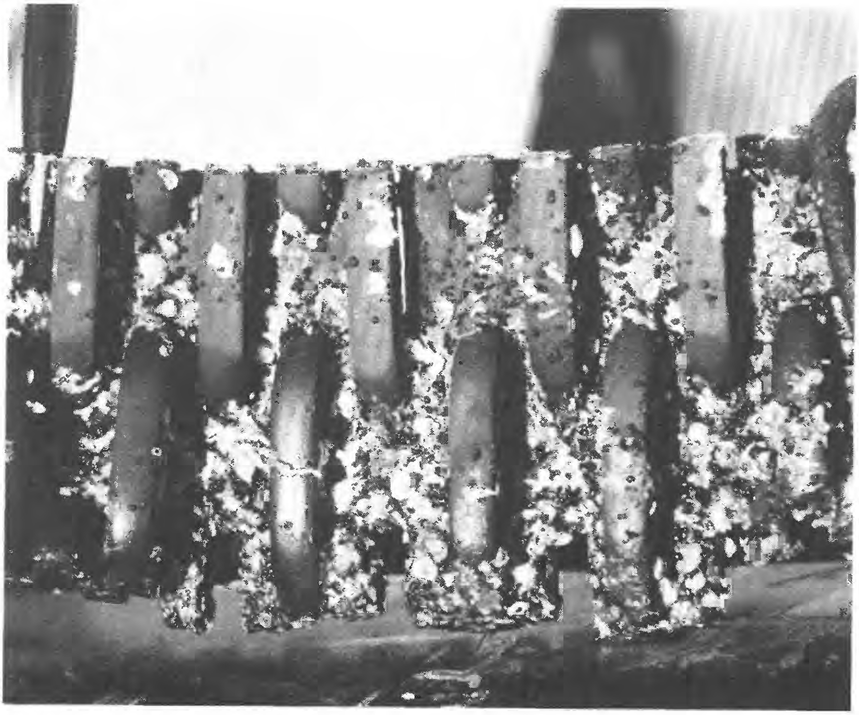


FIGURE 17.—Corroded, aluminum specimen from down-hole string, Mut well 2.

The Type 304 stainless steel specimens installed in Dakhla Oasis wells showed no evidence of corrosion except for superficial brown films of iron oxides on the surface line specimen (fig. 18) and somewhat heavier films on the down-hole specimens. This alloy was in original condition as far as could be determined by microscope inspection at the end of the test period. The same was true of the specimen made from a special chromium-nickel steel alloy (Incoloy 800) that was suspended in Mut well 2. The performance of a down-hole specimen of 27–68 copper nickel

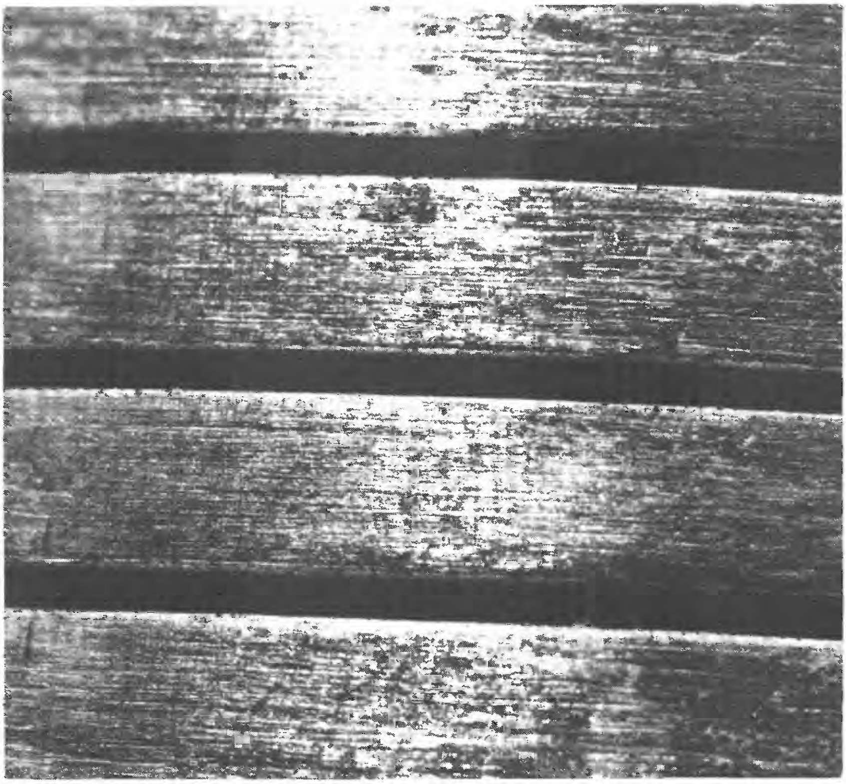


FIGURE 18.—Undamaged stainless steel screen specimen, surface line, Mut well 1, × 5.

(Monel Metal) also was good. Although its surface was mottled blue, gold, and brown as evidence of selective nickel solution and there was overall etching and minor uniform metal loss (fig. 19), there was no localized pitting of the sort that occurred on mild steel.

In addition to these corrosion tests with relatively massive metallic specimens, the authors, with the help of USAID and EGDDO personnel, made a series of corrosion probe studies in Kharga and Dakhla Oases well waters, using the corrosometer shown in figure 20. These corrosometer probes consisted of loops of 1-mm diameter wire that were installed through the surface casing above ground level by means of suitable bushing-shield assemblies (fig. 21). A portion of the wire loop representing one leg of a Kelvin resistance bridge is protected with water proof coating so that it senses and compensates for water temperature

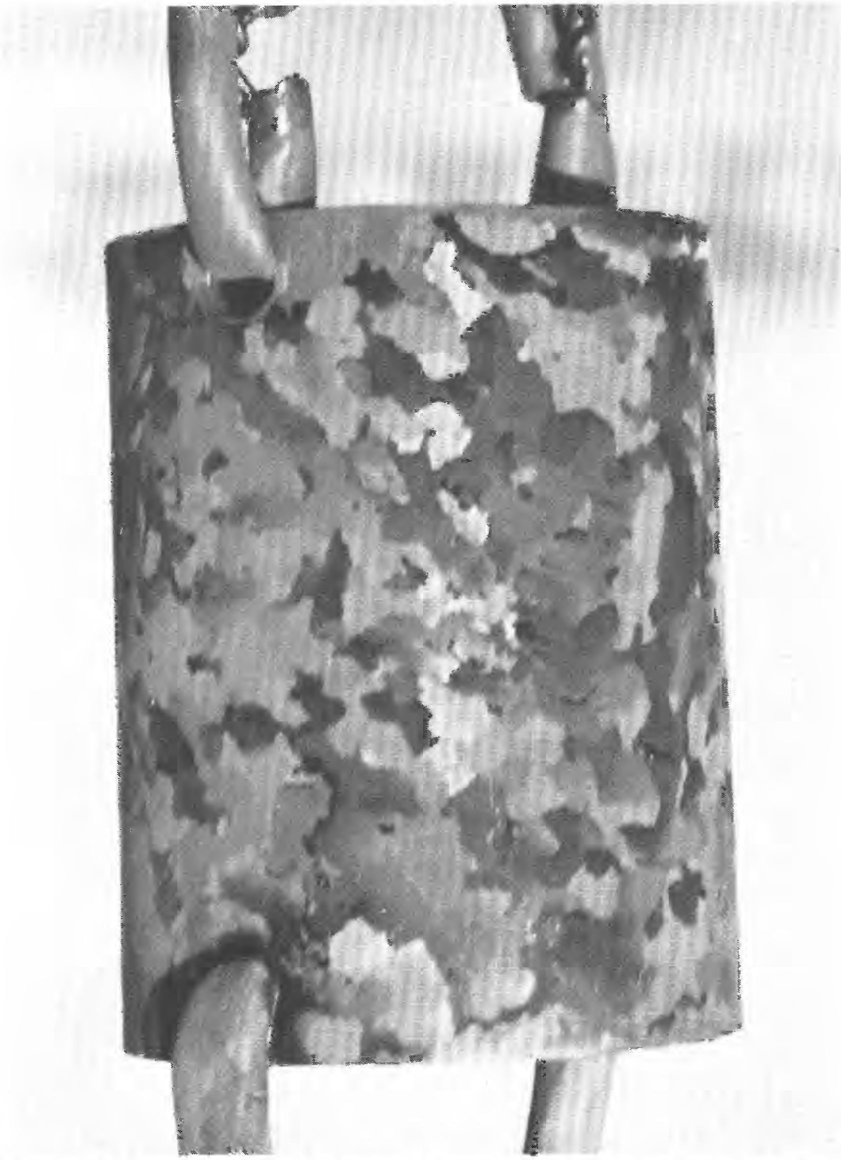


FIGURE 19.—Slightly corroded Monel Metal specimen, down-hole string, Mut well 2.

but is not affected by corrosion. A battery powered meter is used to compare electrical resistances in the exposed to that in the reference leg of the resistance bridge. Resistance change due to

FIGURE 20.—Mohammed Shaaban, Egyptian General Desert Development Organization, operating a corresometer, Kharga well 1.

metal loss of the exposed leg is converted to average metal penetration by the equation:

$$\text{mm } PY = \frac{D}{T} \times 0.09271$$

where: mm PY = millimeter penetration per year
D = change in instrument dial reading (electrical resistance change) between data points
T = exposure time in days between data points
0.09271 = a factor for converting diameter change of the W 40 probe wire to millimeters penetration per year (mm p/yr), using a probe multiplier of 10.

Such readings average corrosion rate over the entire specimen.

The relative severity of attack is judged by these criteria:

Extent of damage	Penetration (mm/yr)
Insignificant (mild)	Less than 0.05
Moderate	0.05 to 0.5
Severe	0.5 to 1.25
Extreme	Greater than 1.25

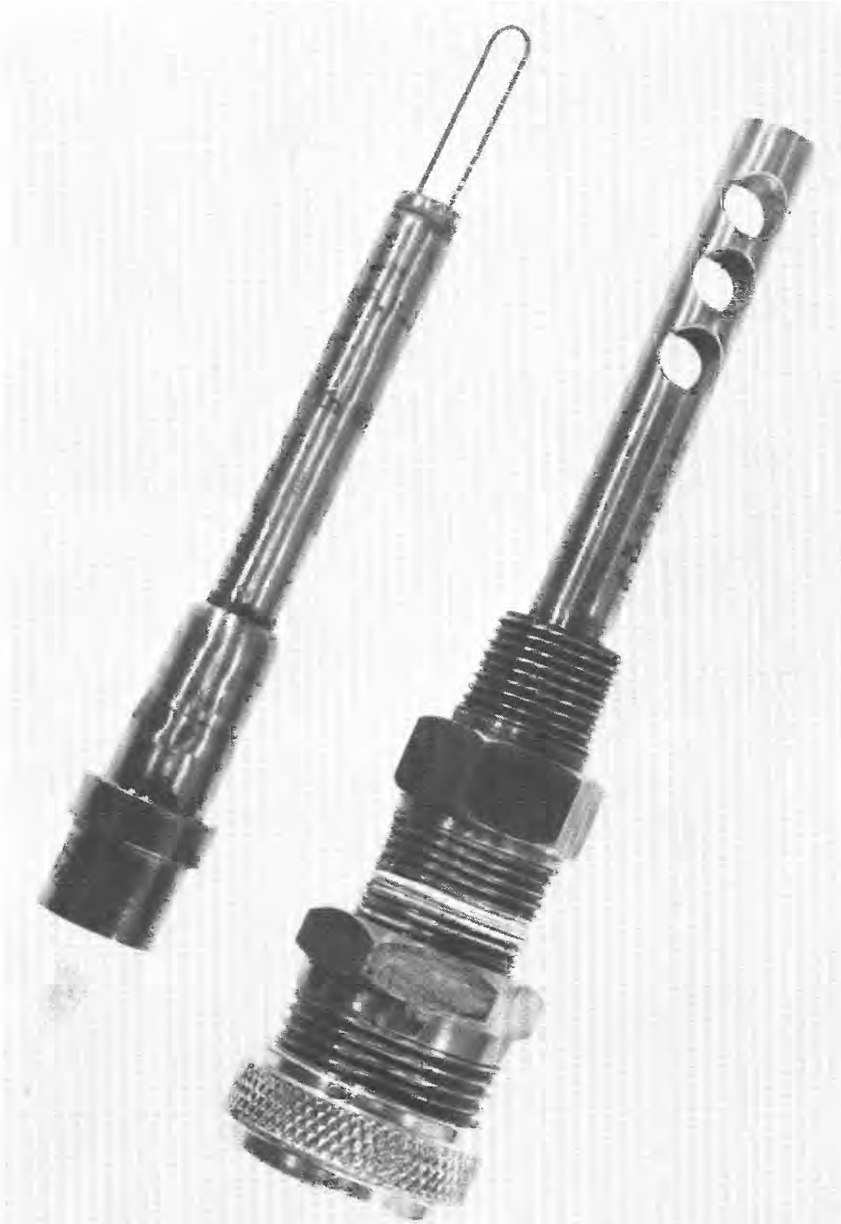


FIGURE 21.—Corrosion probe and shield.

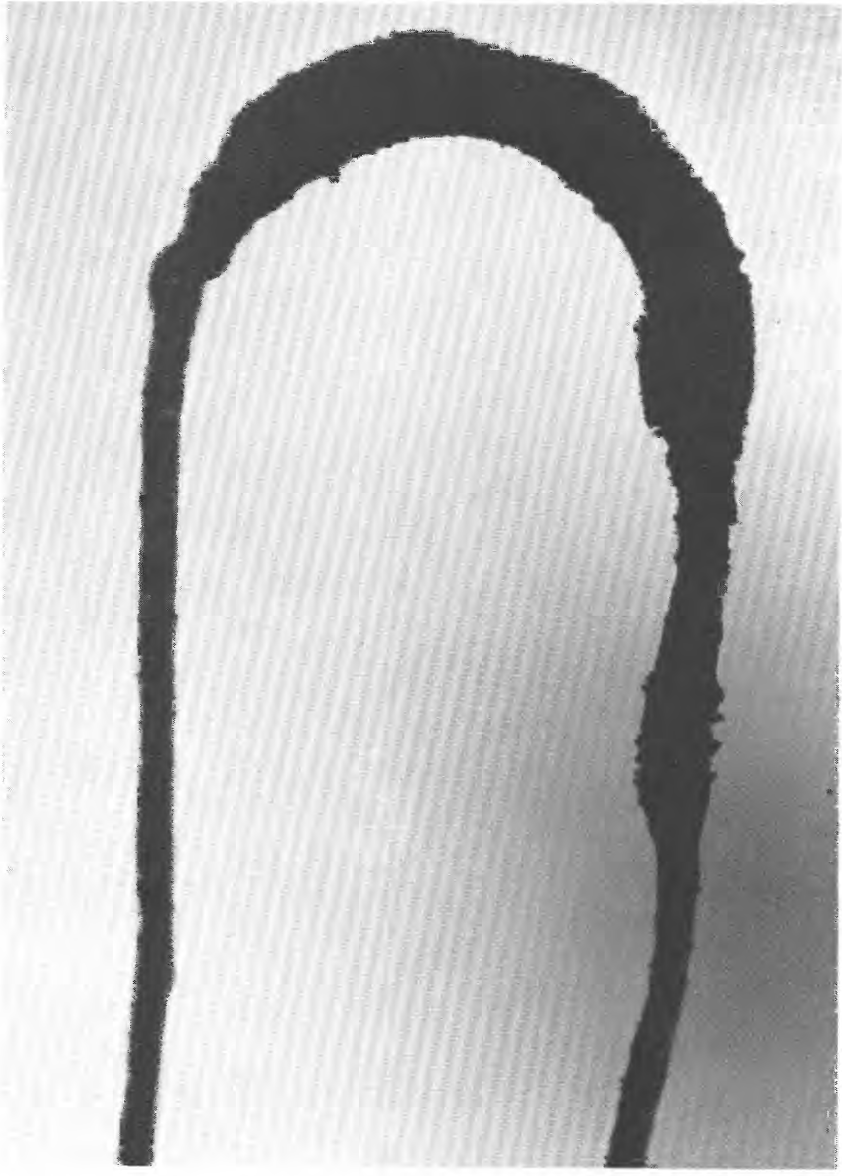


FIGURE 22.—Corroded steel probe wire, Baris well 11, Kharga Oasis, $\times$ 12.

Data obtained in corrosion probe studies of Kharga and Dakhla Oases wells were in general agreement with those obtained on actual well-screen specimens exposed in the corresponding well discharged lines. Except for the test in Nasser well 3, all steel probes exposed in Kharga Oasis wells corroded rapidly during a large part, if not all, of the test periods and developed heavy corrosion products and occasional deep localized pitting as in the more massive specimens (fig. 22). Steel probes in Dakhla Oasis wells corroded more rapidly and exhibited the same clean, uniformly wasted surfaces as in the counterpart screen specimens. Figures 23 and 24 show corrosion rate curves for Kharga and Dakhla respectively. In each figure, the shaded area indicates severe attack in terms of the aforementioned accepted engineering criteria. The erratic corrosion rate curves obtained for steel in Kharga well 1A and Nasser well 1, and the exceptionally low corrosion rate for the steel probe in Nasser well 3 are evidence that great care must be taken in interpreting data obtained on the mixed discharges from a multizone aquifer system.

The data obtained with aluminum probes also were generally consistent with the behavior of actual screen specimens exposed in flowing water of Kharga and Dakhla Oasis wells. Except for Masara well 1 in Dakhla Oasis where the aluminum probe corroded almost as rapidly as steel, aluminum corrosion rates (0.0005–0.05 mm/yr) were well within the engineering limits for long-term performance. Despite this generally favorable quantitative performance, there were significant qualitative differences and evidences of local effects which did not appear in corrosion rate curves. Some aluminum probes, like that exposed in Kharga well 1A (fig. 25), developed uniform light etching under the black surface deposits of iron corrosion products. Others, like that exposed in Nasser well 1 (fig. 26), exhibited scattered white tubercles covering pits up to 20 percent of the probe wire diameter. This variation in mode and extent of attack on aluminum again points to probable differences attributable to qualitative variation in the water-bearing zones or to differences in hydraulic characteristics of the wells.

The effects of Monel Metal probes exposed in the two oases were essentially identical to those on specimens of Monel tubing suspended just above the screen in Mut well 2 of Dakhla Oasis. Both the probes and the tubing were mottled blue, gold, and brown in color as evidence of nickel loss and corrosion on both types of specimens consisted of separation of extremely thin concentric layers of metal. The performance of the alloy from a

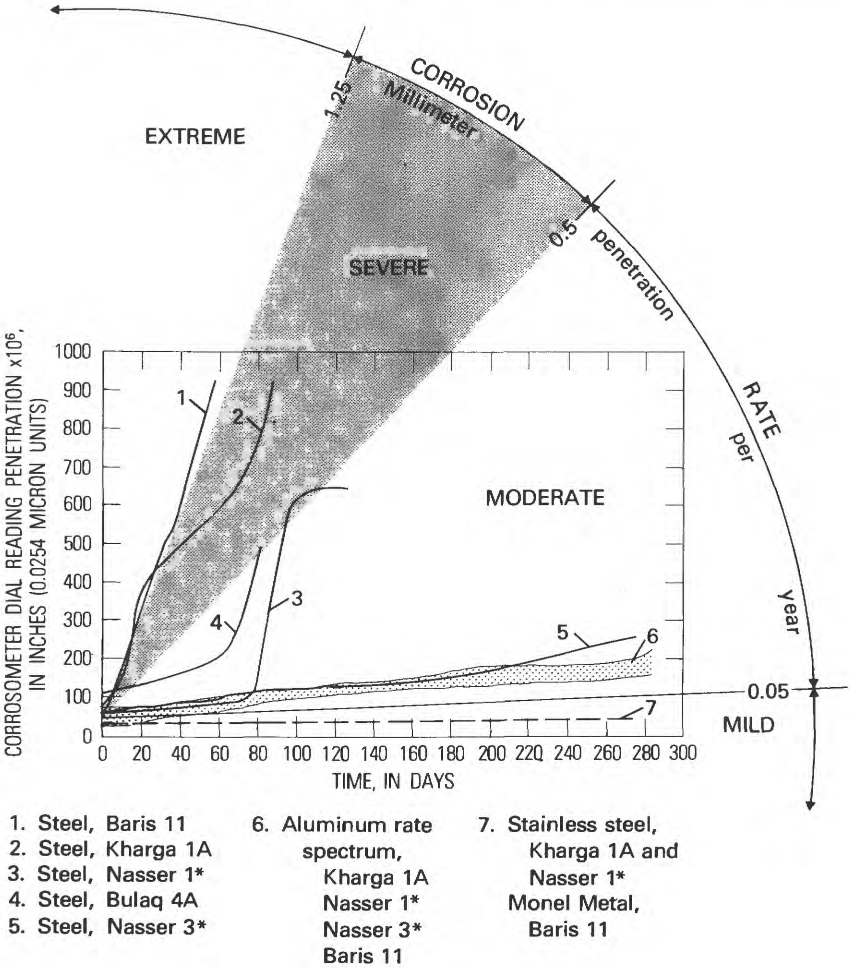
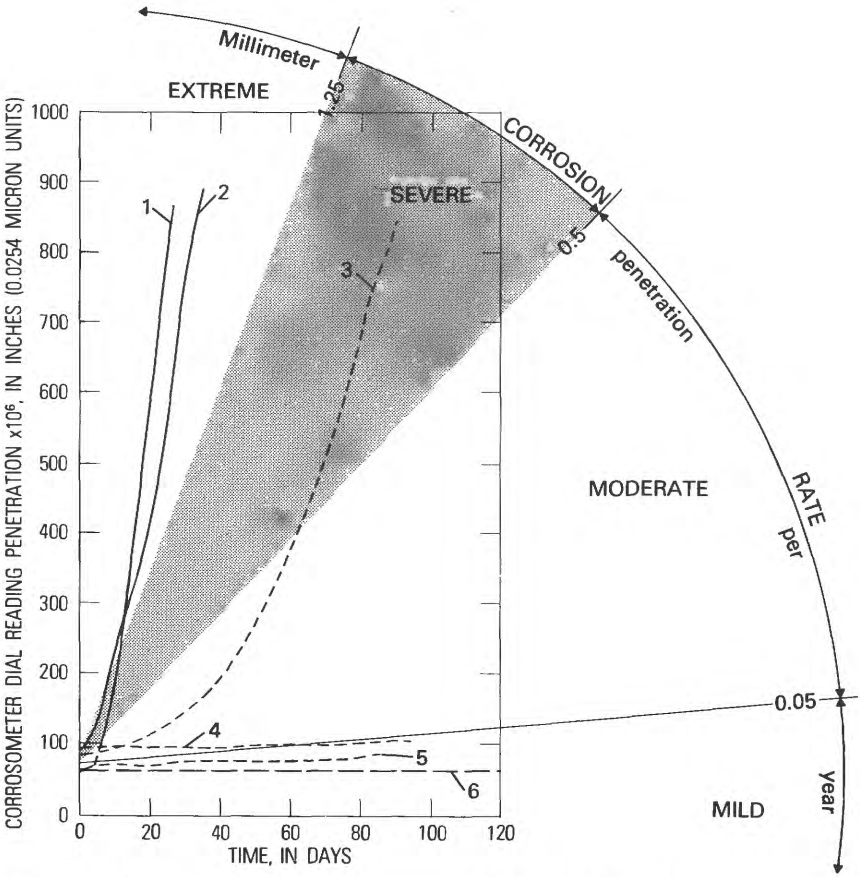


FIGURE 23.—Corrosion rate curves, Kharga Oasis wells.

quantitative standpoint was excellent. Corrosion rated ranged from 0.005 to 0.032 mm/yr. Such performance equals that of the best aluminum probes and approaches the superior performance of stainless steel.

Both the Type 304 stainless steel and the Incoloy 800 probes proved to be almost completely resistant to corrosion in both Kharga and Dakhla Oasis well waters. This corresponds to the similar excellent performance of surface-line and bottom-hole specimens of the same materials discussed earlier in this report.

Although some differences in corrosion effects between these



1. Steel, Masara 1
2. Steel, Balat 6
3. Aluminum, Masara 1
4. Aluminum, Balat 6
5. Aluminum, Rashda 2
6. Incoloy, Masara 1 Stainless steel, Balat 6

FIGURE 24.—Corrosion rate curves, Dakhla Oasis wells.

small probe wires and actual well parts could be expected because of differences in geometry, surface velocities, residual stresses, resistance to fatigue and other contributing factors, the probe data appear to distinguish durable materials from those which are questionable or a poor risk.

QUALITY CHARACTERISTICS OF NEW VALLEY WELL WATERS

Pertinent water-quality observations concerning wells in Kharga and Dakhla Oases extend back at least to the turn of the

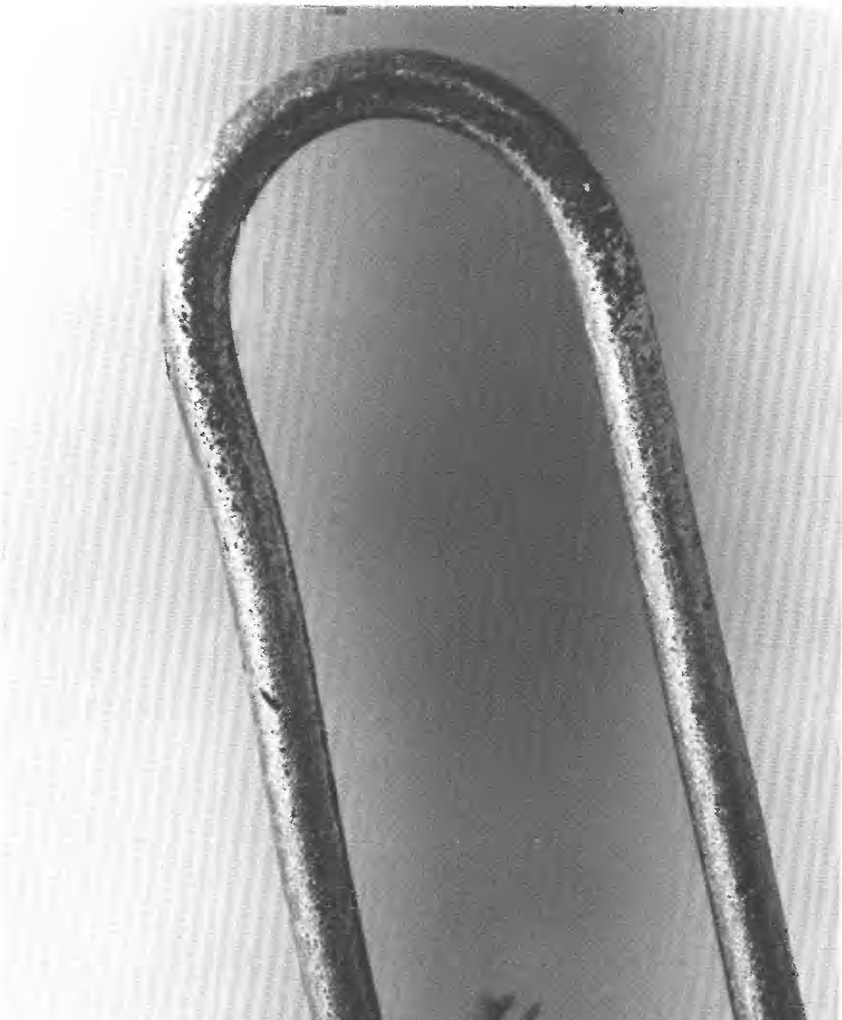


FIGURE 25.—Etched aluminum probe, Kharga well 1A, × 10.

Century. Ball (1900), Beadnell (1901), Little (1926, 1931), Little and Attia (1942), and Paver and Pretorius (1954) all reported iron stains in discharge channels, including those in wood-cased wells, in addition to the odor of sulfide, effervescing gas, and relatively high temperatures. Beadnell concluded that most of the well-water temperatures in Dakhla Oasis are higher than would

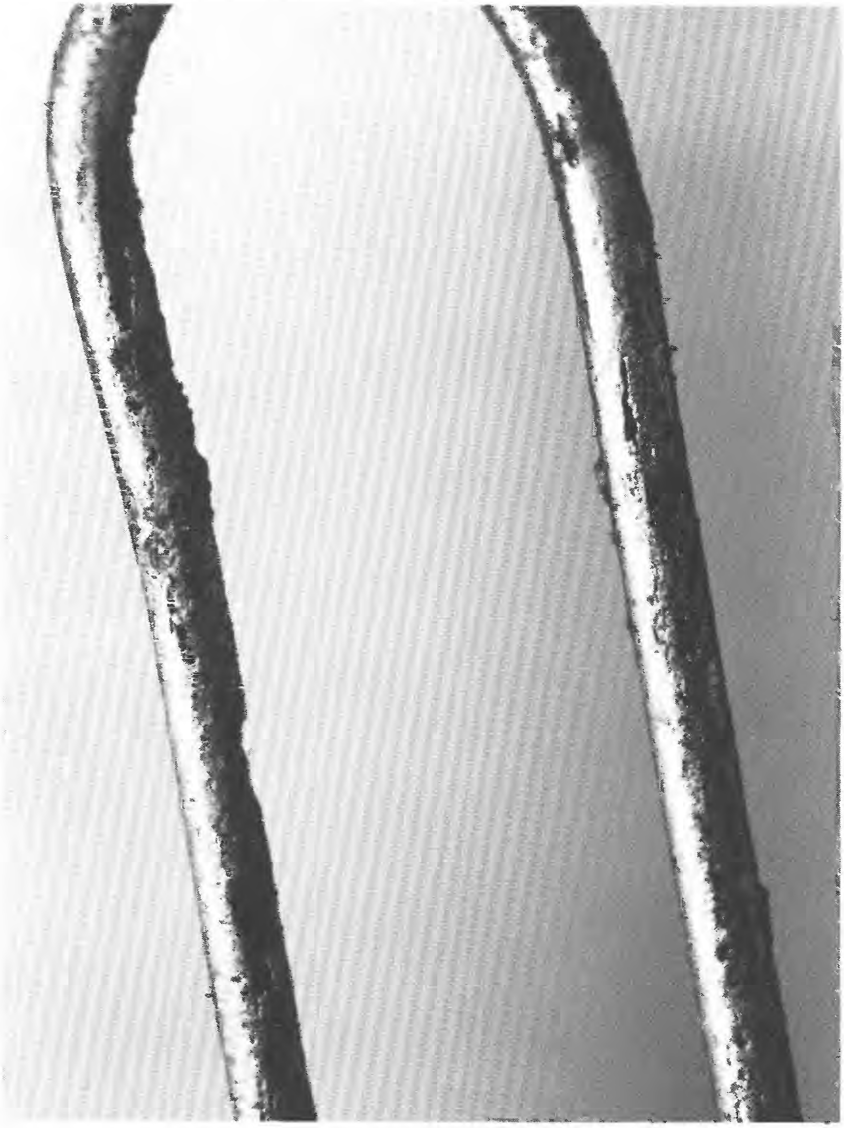


FIGURE 26.—Corroded aluminum probe, Nasser well 1, × 11.

otherwise be expected from well depth and average ambient conditions and attributed this to deep circulation of the water before it reaches the wells. Little and Attia mentioned a pH of 6.6 in Bir Faruqya near Mut in Dakhla Oasis, but did not state how it was measured.

FIGURE 27.—Hassan Mostafa (right), Egyptian General Desert Development Organization, and the late Paul Bieber, U.S. Geological Survey, measuring bicarbonate ion in water from a Kharga Oasis well, 1962.

Later investigators, including those of the Nasr Oil Company, the Egyption Desert Institute, and the EGDDO extended water-quality information with gas analysis and mineral analyses made of samples transported to laboratories in Cairo and other locations. Unfortunately, analyses at distant laboratories did not permit accurate measurement of unstable constituents and characteristics such as pH, oxidation potential (Eh) bicarbonate ion, and dissolved gases. To overcome this problem, both field tests for unstable parameters and laboratory analyses for the stable ones were included in the author's investigation reported here. Field tests were made for pH and bicarbonate ions by the methods of Barnes (1964), using an electronic pH meter with a glass-calomel electrode system both for measuring pH and for detecting the equivalence point in the bicarbonate titration (see fig. 27). Electrode potential was measured by the method of Back and Barnes (1961), using the pH meter as a potentiometer and a platinum-calomel electrode system in the flow cell shown in figure 28. Iron and sulfide ion were determined in the laboratory on samples

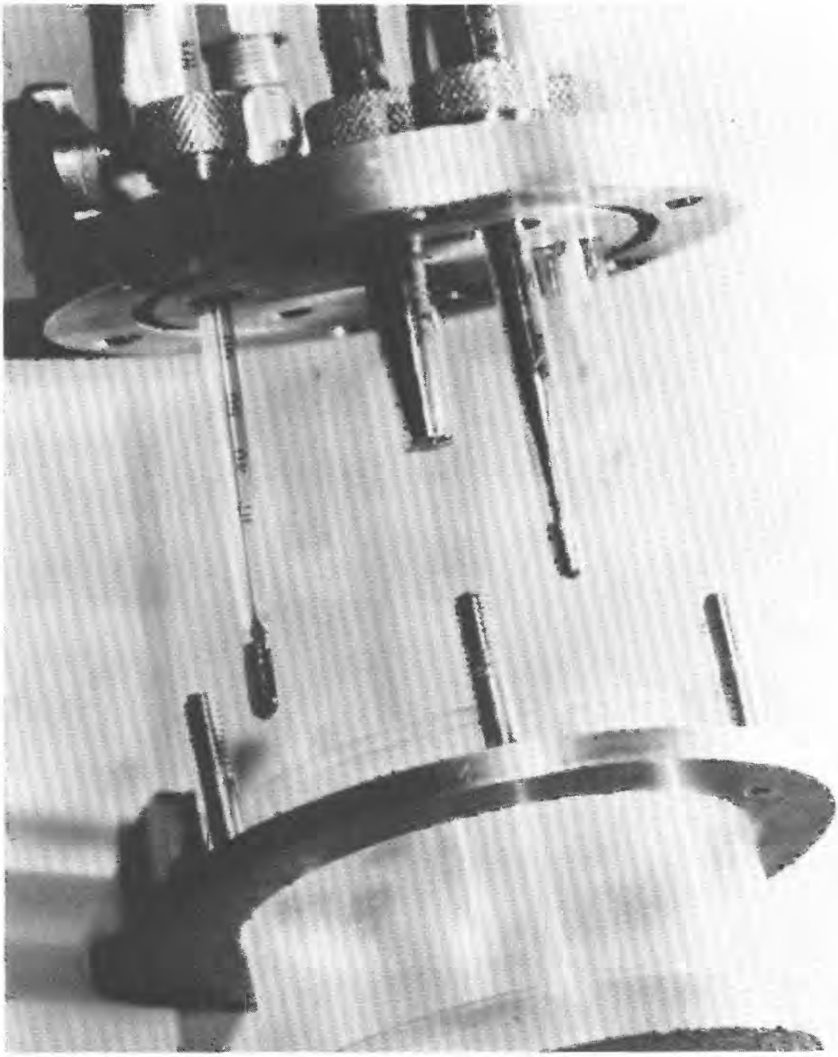


FIGURE 28.—Flow cell for measuring Eh.

treated at the wells with acid and zinc acetate, respectively. All other analyses were made in the laboratory using untreated samples.

Because it is difficult to make reliable field tests under desert conditions, a relatively small number of such analyses have been made and not all of them included every measurement of interest. However, the resulting data contained in tables 4 and 5 are con-

TABLE 4.—*Water-quality data, selected New Valley wells*

Well designation	Field tests					Ionic analysis (mg/L)							
						Cations							
	Temperature 0°C	CO_2 (from HCO_3) mg/L	Eh (mV)	pH	Maximum & minimum corrosion rates (mm/y)	Calcium Ca	Magnesium Mg	Sodium Na	Potassium K	Aluminum Al	Iron Fe	Manganese Mn	Copper Cu
Kharga Oasis													
Baris 11	36	--	---	-	2.0	25	12	48	25	zero	2.4	0.07	zero
					1.7								
Bulaq 4A	34	--	---	-	0.4	66	31	77	31	0.1	5.1	0.34	zero
Garmashin 1	36	17.4	−141	7.0	-	31	17	40	28	0.1	2.7	0.17	0.04
					2.0								
El Kharga 1A	39	32.8	− 3.4	6.9	1.0	14	4.9	22	27	zero	2.6	0.03	zero
El Mahariq 2	38.5	89.5	+125	6.6	-	19	8.8	77	24	zero	1.0	zero	zero
					2.0								
Nasser 1	33	31.7	− 21.8	6.7	0.4	34	28	36	38	0.1	4.2	0.48	zero
Nasser 3	38	24.5	− 28.4	6.9	0.05	18	11	27	27	zero	2.1	0.31	0.05
Dakhla Oasis													
Balat 6	37	30	---	6.4	3.4	11	8.3	23	16	zero	5.8	0.07	0.04
					2.1								
Masara 1	36	32	---	6.3	4.1	25	9.7	26	5.3	zero	5.9	0.28	0.06
Mut 1	*31	42.6	+ 99.7	6.33	-	20	7.5	25	8.6	zero	0.24	0.28	zero
Rashda 1	34	36	+ 64.7	6.38	-	23	8.8	25	6.5	zero	5.8	0.45	0.04
Rashda 2	36	32.4	---	6.3	-	29	9.5	28	5.1	zero	5.8	0.07	zero

* Questionable value

Well designation	Ionic analysis (mg/L)						Other data				
	Anions										
	Carbonate CO_3	Bicarbonate HCO^3 **	Sulfate SO_4	Chlorine Cl	Nitrate NO_3	S^{-2}	Conductivity μmho/cm, 25°C	Total Dissolved solid (mg/L)	SiO_2 (mg/L)	Langelier Index, $pH-pH_s$	Ryznar Index $2\,pH_s-pH$
Kharga Oasis											
Baris 11	--	---	52	102	zero	0.85	583	321	12	-	--
Bulaq 4A	--	---	133	225	zero	1.36	1120	664	12	-	--
Garmashin 1	--	104.5	31	117	0.1	1.36	625	361	13	—0.9	9.2
El Kharga 1A	--	104	12	34	0.3	2.2	304	177	15	—1.2	10.0
El Mahariq 2	--	205.5	27	65	0.2	1.36	607	346	14	—0.7	9.2
Nasser 1	--	89.5	111	116	0.1	1.7	748	463	12	—1.2	9.6
Nasser 3	--	110	11	59	zero	0.9	405	223	14	—1.0	9.8
Dakhla Oasis											
Balat 6	--	27	49	42	zero	2.39	323	181	13	—2.4	12.1
Masara 1	--	24.5	56	62	0.1	0.17	389	223	12	—2.3	11.4
Mut 1	--	55.5	47	45	zero	zero	338	209	14	—2.0	11.2
Rashda 1	--	53	53	62	0.1	0.34	377	217	12	—1.9	10.7
Rashda 2	--	39.4	64	70	0.1	0.34	430	246	12	-	--

** Field Determination

TABLE 5.—*Gas composition, selected New Valley wells*
[Data from Mostafa Salem, Nasr Oil Co.]

Well designation	Percentage of gaseous components		
	Hydrogen sulfide H_2S	Carbon dioxide CO_2	Nitrogen N_2
El Kharga 1	Trace	3.1	96.9
El Kharga 1A	0.1	1.4	98.5
El Mahriq 2	Trace	4.0	96.6
Nasser 1	Trace	1.5	98.5
Mut 1	Trace	2.9	97.1

sidered to be generally reliable. Together with computer analyses of pertinent geochemical factors by the method of Plummer and others (1976), these data form the basis for generalizations concerning water-quality characteristics and their contributions to metallic corrosion. The data agree with earlier conclusions that well waters of Kharga and Dakhla Oasis are abnormally high in temperature and relatively high in iron, sulfide ion, and dissolved gas. Reliable temperatures range from 33° to 39°C in the test wells and are up to 6°C above expected values for some of the shallow wells according to Cushman and Gates (1967), although they found the thermal gradient with depth to be less than expected.

Despite the significant variation in water quality from well to well and from Dakhla Oasis to Kharga Oasis, as judged from samples taken at the surface, all waters tested fall into a category characterized by relatively low dissolved solids content, low pH and Eh values, and relatively high temperatures and gas contents, particularly nitrogen and carbon dioxide. The pH values are significantly lower and the Eh values significantly higher in Dakhla Oasis than in Kharga Oasis. The trilinear diagrams in figure 29 also show significant differences between waters of the two oases. In these percentage plots of principal ions and ionic combinations, Dakhla Oasis waters are consistently sulfochloride types and except for Balat well 6, have more alkaline earth (Ca and Mg) than alkali species (Na and K). The Kharga Oasis waters do not group as consistently. Garmashin well 1 and Nasser well 1, like the Dakhla Oasis wells, are sulfochloride types relatively high in alkaline earths, and Nasser well 3 is a marginal sulfochloride type, whereas Kharga well 1 and Mahariq well 2 are alkaline bicarbonate types.

There is little doubt and some analytical evidence that quality varies appreciably between certain ground-water horizons and that bottom-hole qualities are different from those measured in

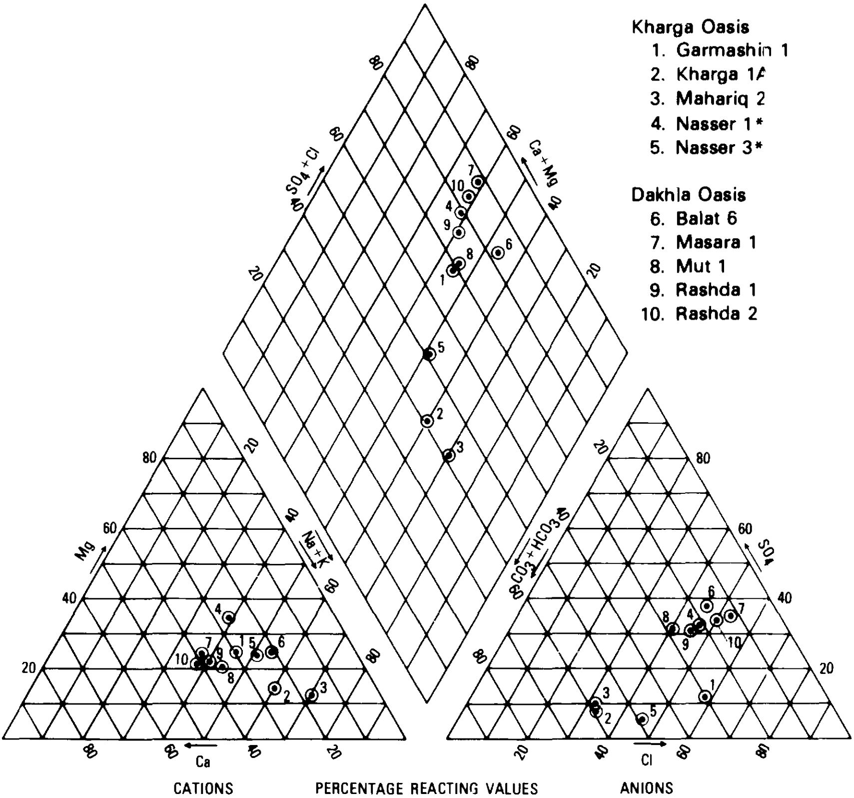


FIGURE 29.—Trilinear diagram showing ionic balances of New Valley well waters.

the mixed waters at the well heads. There also is evidence that dissolved gas content varies with depth. Cushman and Gates (1967) conducted borehole pressure tests which indicated gas separation starting above the screened sections in certain deep wells. Considerably more work would be required to relate quality characteristics to the various geographic locations and water-bearing zones.

CAUSES OF CORROSION

Corrosion of iron and steel in aqueous media is an electrolytic process involving innumerable anodic and cathodic areas on the metal surfaces that are caused by differences in stress (for example, from cold working), surface films, metallic inclusions, and other nonuniformities. Long-line electrolytic currents resulting from differences in solute concentrations, temperature, flow rates, or other characteristics from one part of the metallic system to another (for example, top to bottom of a well casing) may be superimposed upon and markedly influence local corrosive action. Direct coupling of dissimilar metals such as steel and aluminum can cause local electrolytic (galvanic) attack.

In its simplest form the electrolytic corrosion of steel involves solution of iron in anodic areas to form ferrous ion and release electrons which pass through the metal to cathodic areas where they react with hydrogen ions in the water and cause atomic hydrogen to form upon and protect (polarize) metal surfaces. Loss of protective hydrogen through combination with dissolved oxygen, lowering of pH or involvement in bacterial reduction processes depolarizes the cathode and allows corrosion to proceed.

In natural waters a variety of quality characteristics tend to influence electrolytic reactions. If the water contains sufficient calcium bicarbonate, calcium ion attracted to the cathodic areas will react with hydroxyl ion to form concentrated calcium hydroxide which, in turn, will react with bicarbonate ion to precipitate protective calcium carbonate scale on the metal surface. Sodium chloride, on the other hand, yields nonscaling sodium hydroxide at the cathode which increases pH of the cathode in relation to that of the anode thereby increasing reaction rate (corrosion). Chloride ion attracted to anodic areas has no corrosion-inhibiting power and actually tends to increase solubility of the metal. If dissolved oxygen is present, the resulting iron solution will convert to ferric chloride and this will hydrolize to hydrochloric acid, a very corrosive agent.

Water of particularly low pH reacts as acid solution by dissolving metal and liberating a chemically equivalent amount of hydrogen gas. For a weak acid, such as a solution of carbon dioxide in water (carbonic acid), this attack may be significant at a pH value of 6 or more and it is markedly influenced by temperature, doubling in rate for each 10°C temperature increase.

Interaction of these factors is expressed by the Langlier and Ryznar indices. The Langlier which equals the actual pH minus the pH of calcium carbonate saturation (pH_S), yields either positive or negative values as evidence of the water's ability or lack of ability, respectively, to form protective carbonate deposit. The Rynar index, which equals $2pH_S$–pH, yields only positive numbers and there is some agreement that values below 7 indicate increasing tendency to deposit calcium carbonate, whereas higher numbers indicate increasing tendency to corrode. It is significant that New Valley waters appear to be nonprotective (corrosive) by these criteria. See table 4.

Solubility of metal and related protective films also is influenced by the pH–Eh relationship which determines stability of mineral species and by the concentrations (degree of saturation) of various solutes in the aqueous solution. The nature and rate of water movement across metal surfaces can be important factors in corrosion, depending upon the type of metal and corrosion process involved. Whatever the process, increasing electrical conductivity in the solution (for example, by increasing dissolved mineral) tends to intensify its effects. In most natural waters, chemical interactions are so complex that it is difficult to determine which of the several contributing factors is primarily responsible for the damage observed.

Data collected on the well waters of Kharga and Dakhla Oases show that they combine a number of characteristics which could be expected to cause corrosion. The trilinear diagrams in figure 29 indicate that none of the predominantly sulfochloride waters has a calcium carbonate content high enough to precipitate protective calcium carbonate scale, a fact confirmed by EGDDO's saturation index studies. Such waters could be expected to promote the corrosive chloride electrode processes discussed above, with the resulting effects generally more pronounced in Dakhla Oasis than in Kharga Oasis. This has been confirmed by the limited number of corrosion observations made thus far and is consistent with the correlation of corrosion rate and combined percentage of sulfate and chloride ions in sulfochloride type waters (fig. 30).

The relatively high carbon dioxide and hydrogen sulfide contents of certain wells and the high temperatures of all waters in both oases undoubtedly are contributing very significantly to corrosion processes. The nature of attack in Kharga well 1A (fig. 11) is evidence that sulfide ion is combining directly with the iron to generate relatively cathodic iron sulfide, which increases the corrosion potential, and hydrogen which penetrates and apparently embrittles the metal surface. Chloride and sulfate concentrations are known to increase and pH to decrease under such deposits, thus increasing corrosion (Baylis, 1926). Less than a part per million of sulfide ion can be very destructive in this process.

The pH values of Dakhla Oasis ground water collected at the well heads are in the range where direct attack of the metal by carbonic acid would be expected and it is likely that much lower

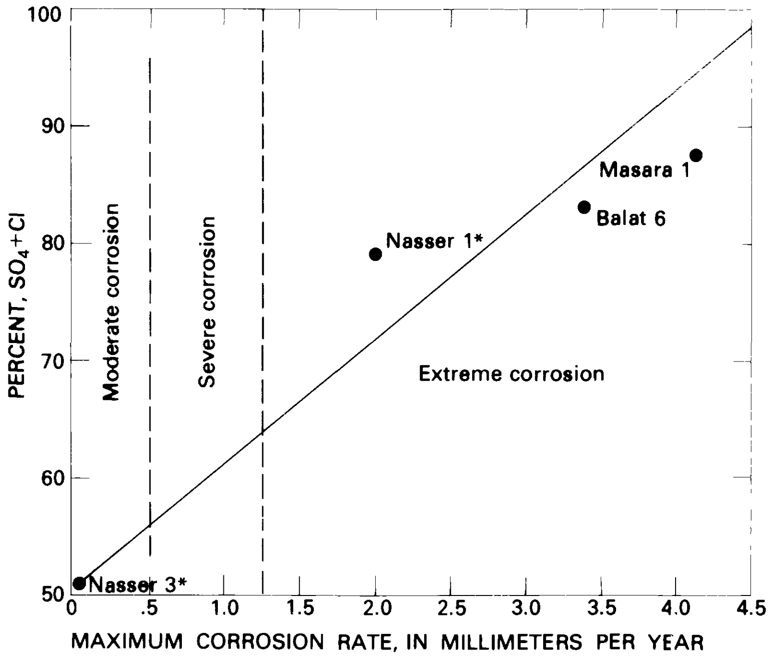


FIGURE 30.—Relation of sulfochloride concentration to corrosion rate.

pH values exist in the carbonic-acid rich envelopes of carbon dioxide bubbles that contact the metal surfaces. Even in Kharga well 1A where the pH was significantly higher than in Dakhla Oasis wells, the deep relatively uniform corrosion noted in the discharge pipe is evidence of acid attack. These unfavorable reactions are being intensified both by the high temperatures that characterize all the well waters and by the relatively high surface velocities that result in part from well design. The temperature abnormalities observed by Cushman and Gates (1967) would be significant in corrosion reactions controlled by hydrogen liberation (for example, carbonic acid attack) where doubling of rate occurs with each 10°C rise in temperature. The maximum surface velocity of 335 cm/s which the author estimated for flow at Rashda well 2 in 1962 on the basis of the well's discharge of 11,000 m^3/d is far above the 90 cm/s recommended limit for steel exposed to corrosive water.

Innate corrosiveness of the New Valley well waters also is indicated by the Eh–pH relationships shown in figure 31. In this stability field diagram, plotted according to Hem and Cropper (1959), the segmented central line separates oxidized species

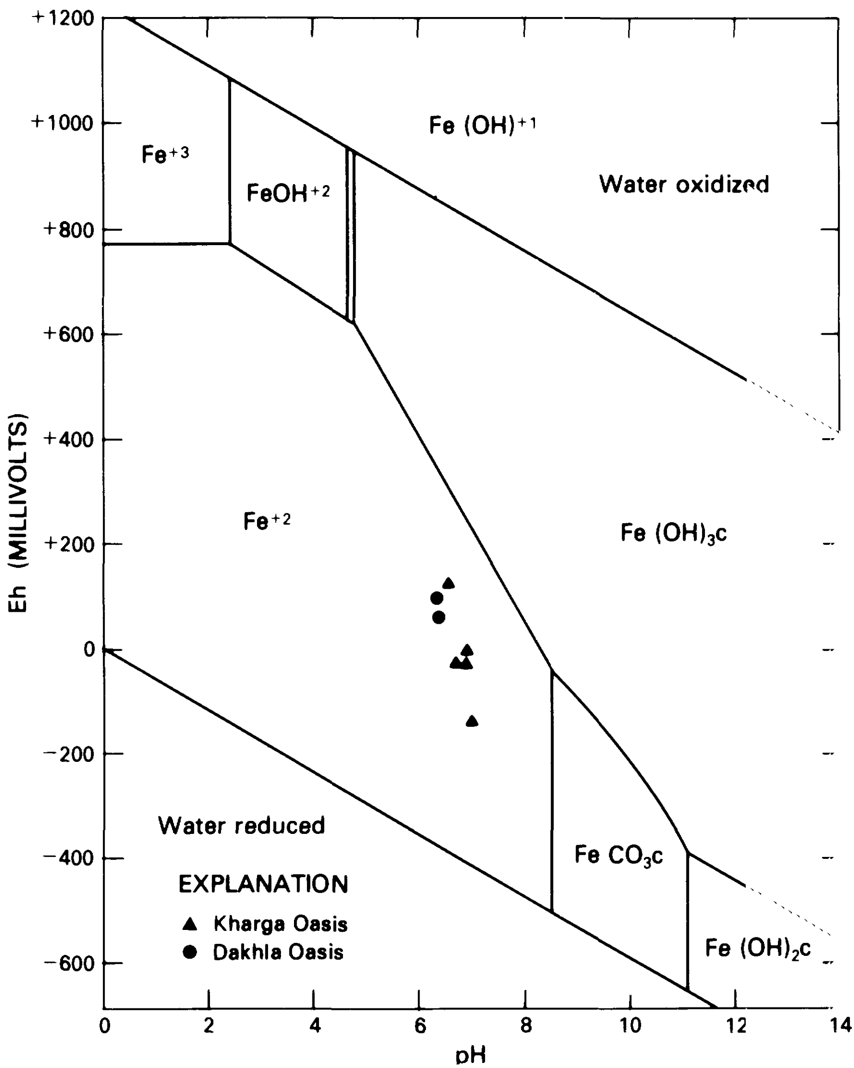


FIGURE 31.—Stability field diagram, ferric and ferrous species, assuming 2×10^{-7} molal activity of iron and based on $Fe(OH)_3$.

above from reduced species below. Vertical lines which separate the various species are determined from equilibrium constants. The Eh–pH values which intersect in reducing areas of the diagram, particularly in the ferrous ion (Fe^{+2}) stability field, indicate waters capable of dissolving iron from either geologic formations or the steel in well components. Those which plot in areas of oxidation, particularly in the ferric hydroxide [$Fe(OH)_3$]

field, represent less aggressive solutions which may actually inhibit corrosion of steel.

All the well waters tested by the author plot in the ferrous ion field (fig. 31) as evidence of their abilities to take iron into solution. This is consistent with the fact that dissolved iron is common in native desert wells which contain no metal parts.

Additional information concerning tendency for corrosion to occur can be obtained by comparing the observed concentration of calcium carbonate, a protective mineral species, with its equilibrium concentrations in the same environment. Such comparisons made by the computer method of Plummer and others (1976) are plotted against corrosion rates in figure 32 where the dark horizontal line separates oversaturation (protection) above from undersaturation (lack of protection) below. The fact that all the well waters included in the plot are far below calcium carbonate saturation agrees with their observed high corrosion rates. The degree of undersaturation (that is, distance of point below the saturation line) correlates reasonably well with observed maximum corrosion rates despite the fact that other corrosion control

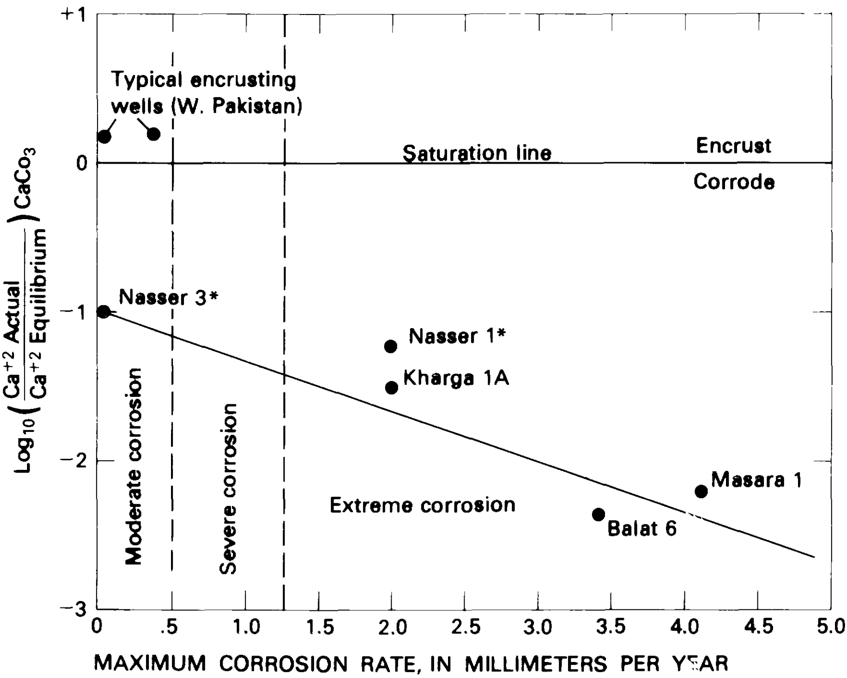


FIGURE 32.—Relation of calcium carbonate equilibrium to corrosion rate.

mechanisms are involved (for example, sulfide, chloride, and carbonic acid processes).

Taken together, the characteristics described in the preceding text show the New Valley well waters to be anaerobic media with considerable capacity for reduction (solution) of protective iron compounds; with ionic ratios known to promote corrosion rather than inhibit it (for example, chloride to bicarbonate), and with minor solutes, such as carbon dioxide and sulfide ion, which are particularly destructive to steel. Sudrabin's long-line potential data (table 3), which range from −700 to −861 mV and suggest corrosion of steel in an anaerobic environment, agree with these conclusions. Concentration of damage in certain parts of the system can be attributed to cold-work stresses, such as those in the formed bridge slots of screen sections, and to velocity effects, like those evident in the elbow from Mut well 1 (fig. 6), or other pecularities of construction or operation which intensify effects of the basically corrosive waters.

CONTROL OF CORROSION

A variety of treatments are commonly used for controlling corrosion of steel in aggressive aqueous solutions, including surface coatings, soluble inhibitors, impressed electrical currents and sacrificial electrodes of more active metals. Unfortunately, none of these treatments is practicable for use in water wells of the New Valley. Even the best surface coating provides little protection at sharp edges like those in screen slots, and coatings are liable to damage in transit and installation with resulting severe corrosion in the damaged area. Similarly, down-hole chemical treatment with corrosion inhibitors is impracticable and incompatible with the intended water use. Cathodic treatment with impressed current requires precise control which cannot easily be achieved in remote desert locations and it protects only external surfaces, not the interiors of screen slots and casings where serious damage is known to occur. Proper positioning and maintenance of sacrificial electrodes also would be difficult and costly in these desert wells and even the best installations would not prevent corrosion of casing exteriors and inner surfaces of screen openings.

Because of the limitations of conventional treatments, one must depend upon selection of materials and well design to minimize the kinds of corrosion damage discussed in this report. Several investigators suggest operation with open-hole construction instead of conventional screen wherever the characteristics of the water-bearing formations favor such design since it would eliminate the problem of rapid deterioration of steel screens. Continuation of the present practice of externally cementing steel casing above filter (screen) sections should prevent formation erosion in case of casing failure and overcome the problem of well collapse described by Paver and Pretorious (1954). Using optimal screen lengths and openings and increasing diameters of well screens and casing to reduce surface velocities and accommodate larger pumps, where pumping is required, also should significantly reduce corrosion problems and increase hydraulic efficiency, but the cost-benefit aspects of such design changes obviously are an important consideration. Designing well-head equipment for long life or easy replacement, even if down-hole corrosion of steel parts occurs, is desirable.

Corrosion problems which cannot be handled practicably by design changes must be overcome through the use of alternative construction materials that are inherently more resistant to attack by the desert ground waters. The corrosion data already discussed show that high strength aluminum is significantly more resistant than steel in most Western Desert locations. However, because of aluminum's relatively high cost (about 2.5 times that of steel), and its unpromising behavior in certain tests, particularly down-hole exposure, it is a questionable substitute for steel in wells which are intended for long-term trouble-free service and when durability of down-hole metal parts (for example, screens) is an important consideration. The excellent performance of Type 304 stainless in all tests shows that it would be durable screen material for long-term service in any location which requires screening rather than open-hole operation. Such material could be used in conjunction with cemented mild steel casing with or without an electrically insulated joint, but such insulation would be an additional safeguard against possible galvanic attack. The relatively high cost of stainless steel (4 to 6 times that of mild steel, depending on design), is its only disadvantage. That cost must be weighted against the cost and practicability of replacing less durable screen materials' as well as the feasibility of open-hole operation.

In recent years considerable progress has been made in fabricating epoxy-bonded fiberglass and wood tubing for use as both casing and filter pipe (screen) for well construction. Modern fiberglass products, which are essentially corrosion proof, will withstand tensile loads of 45 metric tons (t) or more; and the overall strength of fiberglass is approximately equal to that of red brass tubing of similar dimensions. Even where strength is reduced by saw-slotting, fiberglass filter pipe is considered to be strong enough for well depths to over 300 m. Great progress also has been made in quick coupling design for rapid assembly of fiberglass tubing. The key-lock joint shown in figure 33 proved

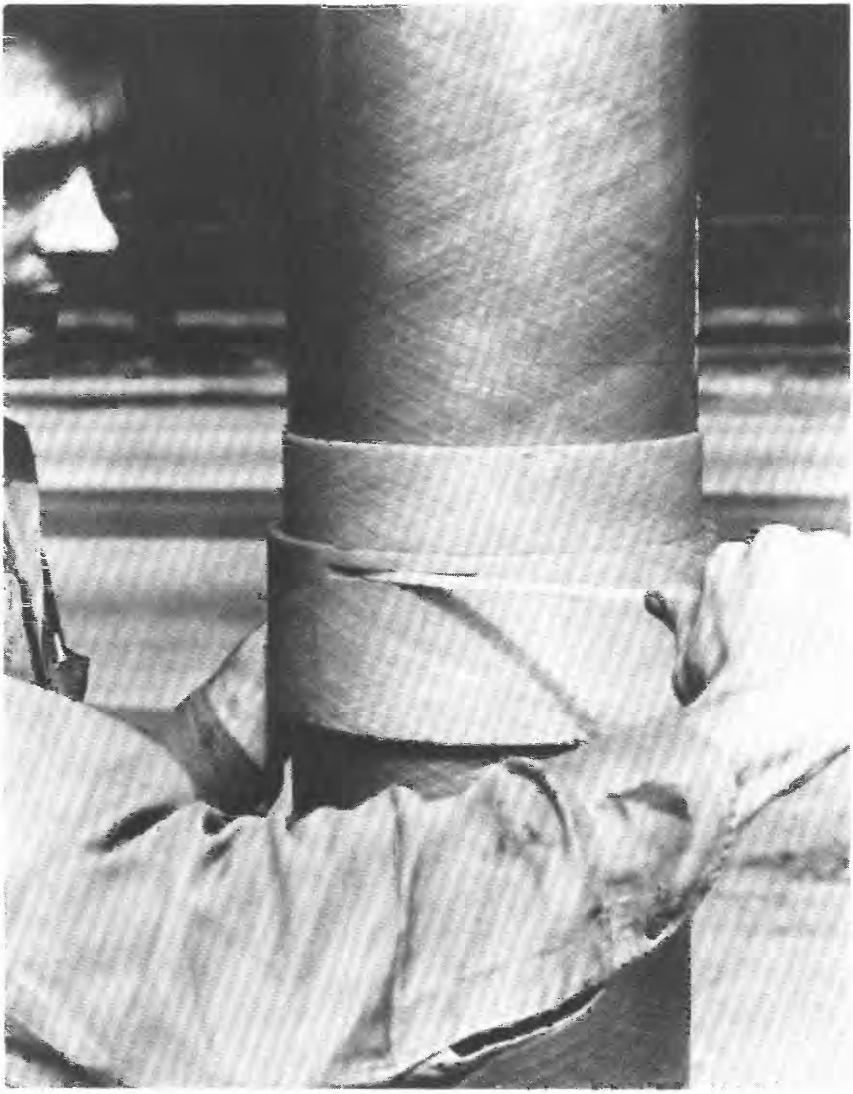


FIGURE 33.—Key-lock joint, fiberglass well pipe.

to be quite practicable and durable in well-field development in the Indo Gangetic plains (Indus Plains) of West Pakistan.

Although fiberglass tubing costs about 2.5 times as much as mild steel tubing of the same size, the lower cost of transporting and installing it makes it a close competitor from the standpoint of installed cost. For this reason it should be economically practicable to use fiberglass for either filter pipe or casing wherever its strength is adequate for the particular installation.

As with all new products, we currently have limited information concerning the long-term durability of laminated wood and fiberglass in water well service. Recent down-hole camera observations of fiberglass installations in West Pakistan wells showed no evidence of encrustation or deterioration after several years of service but well performance tests showed some evidence of sand clogging of filter pipe slots. Similar observations on fiberglass and modern wooden screen installations in the Western Desert would provide additional useful information on these alternative construction materials.

Tests with corrosion probes showed Monel Metal to be very resistant to waters of the Western Desert. Although this material, which as approximately as expensive as stainless steel, probably would not be as durable as stainless if used for well screens, it might be a practicable alternative for special components, such as well-head valves.

PUMPS AND THEIR PROBLEMS

The need to lift or otherwise gain access to water which once flowed freely to the desert surface has been recognized for a very long time. Near the old village of Kharga there are remains of a kanat (ancient underground tunnel) once used to tap a declining well below the surface and convey its water to a lower part of the oasis (fig. 34). Beadnell (1901) mentioned the use of native water-lifting devices in Dakhla Oasis in 1896, and Ball suggested in 1900 that these saqiyas (waterwheels) and shadufs (sweeps) could be used to good advantage in revitalizing a number of desert wells which had ceased to flow because of expanded and indiscriminate drilling. Despite this growing need Paver and Pretorius reported only a small number of water-lifting devices in the Western Desert in 1954.

Rapid development of deep wells, starting with the New Valley Project in 1959, caused a relatively rapid decline in artesian pres-

FIGURE 34.—Kanat at nonflowing well, Kharga Oasis.

sures and increased the need for lifting water by mechanical devices. By 1967, according to Cushman and Gates, there were about 200 saqiyas operating in Kharga and Dakhla Oases with a maximum unit discharge of 800 m^3/d and an average of 255 m^3/d.

The need for modern pumping and the possibility of troublesome pump maintenance problems were both recognized by those involved in New Valley Project planning and water-quality investigations. Pump experiments to assess corrosion problems were recommended by the author in 1962 and experimental pumps were obtained for this purpose the following year. According to Cushman and Gates, 60 pumps of approved design had been acquired for desert use by 1967 and some later were installed in Kharga Oasis.

Table 6 shows information provided by Idris and Ezzat (1976) concerning the pumps in use around Kharga Oasis. It is apparent from this summary that while modern pumping had not yet started in Dakhla Oasis, it is relatively common in the north and south of Kharga Oasis. The diesel-operated, shaft-driven pumps in use were obtained from the United States, India, and Denmark. All have cast-iron bowls, but shafts include water-lubricated mild steel, water-lubricated stainless steel, and oil-lubricated mild steel. Impellers are made of either bronze or stainless steel and discharge lines and couplings of plain carbon steel.

TABLE 6.—*New Valley wells being pumped, 1976*

GOVERNMENT WELLS, KHARGA OASIS		
Sherka 1A	West Kharga	Garmashin 2A
Sherka 3	El Sajaha	Garmashin 6
Sherka 34	Hepus	Garmashin 16
Sherka 2	El Bustan 1C	Garmashin 2A replacement
El Mahariq 2	El Bustan old	
El Mahariq 7	Genah 2A	Garmashin 4 replacement
El Kharga 1	Genah 1A	
El Kharga 1A	Genah 3A	Baris 1
El Kharga 2	Genah 3B	Baris 12
El Kharga 10	Garmashin 1	Baris 15
El Kharga 12	Garmashin 2	Baris 18
NATIVE AND VILLAGE WELLS, KHARGA OASIS, BARIS AREA		
Baris Village and Baris El Qasr	Rajda	El Oeum
El Maks	Om Saeda	El Gaba
Doush	Salm and Fakhara	Badran
OTHER LOCATIONS		
Sherka Native	Genah Village	

NOTE: There are no pumping wells in Dakhla.

According to Idris and Ezzat (1976), corrosion occurs primarily in the plain steel shafts, couplings, and discharge lines, which is not surprising in view of the relatively high carbon dioxide contents and the change from velocity head to pressure head in passing through the relatively small diameter, high speed pumps. Significant corrosion of pump bowls is reported to occur in only 10 percent of the installations and average pump life is estimated by Idris and Ezzat to be 6 to 8 years. However, Parkinson and Worts (1977) mention failure of well parts, including pumps, in as little as 6 months of service. In such aggressive waters 6 to 8 years would be surprisingly good performance for iron pumps.

It seems likely that damage to discharge lines and couplings could be reduced significantly and perhaps economically through the selection of alternative materials. Relatively large pumps are known to be operating with plastic discharge lines in other corrosive well waters (for example, in Australia).

OPPORTUNITIES FOR FURTHER STUDY

To make the best of Western Desert experience in planning new wells for Egypt or well fields elsewhere in the world, it would be desirable to make additional observations when circumstances permit. Down-hole camera observations of the several kinds of metallic and non-metallic filter pipe materials installed since 1959 would provide positive evidence of their performance and allow better predictions in the future. Similar observations would show whether or not open-hole construction is practicable and shed some light on the relative merits of various filter pipe designs.

Ability to predict corrosiveness on the basis of water-quality data also could be improved by measuring the qualities of the individual water-bearing strata rather than by measuring their mixed discharges at the well heads. Such data would also aid in understanding the Nubian aquifer system. Advances in techniques for sampling and analysis since initiation of the New Valley Project should simplify these tasks. There is little doubt that the technical community would be eager to see the results of such studies.

SUMMARY

The observations and investigations reported here confirm the extreme corrosiveness of well waters in the New Valley area of Egypt's Western Desert. Relatively low pH and Eh values together with the relatively high water temperatures, high carbon dioxide contents, and high concentrations of sulfide, sulfate, and chloride ions account for the severity of the attack.

Use of corrosion-resisting metals such as stainless steel or high strength epoxy-resin bonded fiberglass or wood appears to be the most practicable solution to maintenance problems in deep wells which require long-term service from screens and casings. However, high strength aluminum should provide significantly better service than plain steel in most locations.

Better information on the specific quality characteristics of the several water-bearing horizons and on the performance to date of the various kinds of well screen materials would simplify the choice among alternative construction materials.

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