Evaluation and Control of Corrosion and Encrustation In Tube Wells of the Indus Plains, West Pakistan

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1608-L

Prepared in cooperation with the West Pakistan Water and Power Development Authority under the auspices of the U.S. Agency for International Development

Slotted fiber-glass well casing, Indus Plains, West Pakistan. Courtesy Koppers Company, Organic Materials Division.

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By FRANK E. CLARKE *and* IVAN BARNES

CONTRIBUTIONS TO THE HYDROLOGY OF ASIA AND OCEANIA

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EVALUATION AND CONTROL OF CORROSION AND ENCRUSTATION IN TUBE WELLS OF THE INDUS PLAINS, WEST PAKISTAN

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ABSTRACT

Seepage from rivers and irrigation canals has contributed to waterlogging and soil salinization problems in much of the Indus Plains of West Pakistan. These problems are being overcome in part by tube-well dewatering and deep leaching of salinized soils. The ground waters described here are anaerobic and some are supersaturated with troublesome minerals such as calcium carbonate (calcite) and iron carbonate (siderite). These waters are moderately corrosive to steel. Some wells contain sulfate-reducing bacteria, which catalyze corrosion, and pH-electrode potential relationships favorable to the solution of iron also are rather common. Corrosion is concentrated in the relatively active (anodic) saw slots of water-well filter pipes (screens), where metal loss is least tolerable. Local changes in chemical properties of the water, because of corrosion, apparently cause deposition of calcium carbonate, iron carbonate, and other minerals which clog the filter pipes. In some places well capacities are seriously reduced in very short periods of time. There appears to be no practicable preventive treatment for corrosion and encrustation in these wells. Even chemical sterilization for bacterial control has yielded poor results. Periodic rehabilitation by down-hole blasting or by other effective mechanical or chemical cleaning methods will prolong well life. It may be possible to repair severely damaged well screens by inserting perforated sleeves of plastic or other inert material.

The most promising approach to future well-field development is to use filter pipes of epoxy-resin-bonded fiber glass, stainless steel, or other inert material which minimizes both corrosion and corrosion-catalyzed encrustation. Fiber-glass plastic pipe appears to be the most economically practicable construction material at this time and already is being used with promising results.

ACKNOWLEDGMENTS

The water-well studies which yielded the data and led to the conclusions of this report were made in cooperation with the West Pakistan Water and Power Development Authority under the auspices of the United States Agency for International Development (USAID). The references contain the names of many individuals of USAID, the Water and Power Development Authority of West Pakistan (WAPDA), and the Water and Soils Investigation Division of WAPDA

(WASID), who provided valuable technical help and background information. The references also acknowledge the excellent technical assistance of U.S. Geological Survey employees, Norman H. Beamer, Herman R. Feltz, Pauline J. Dunton, Blair F. Jones, Roger G. Wolff, and Mary E. Mrose.

Tipton and Kalmbach, Inc., Technical Consultants to WAPDA, made very important contributions to the investigation by providing information on well construction and performance, and on the company's development research and field studies on well maintenance, methods, and improved well construction materials, particularly fiberglass plastic pipe. The company's technical staff also provided valuable assistance with the field tests described here.

Acknowledgment is made here to George C. Taylor, Jr., for his interest, advice, and support throughout the period of study; to Joan V. Mouer and Mary J. Burks, who helped type the manuscript; and to Norma C. Grube for manuscript work, technical editing, and constructive criticisms of composition and format. All are employees of the U.S. Geological Survey.

HYDROLOGIC SETTING

The area known as the Indus Plains of West Pakistan is approximately 900 miles long and is as much as 400 miles wide. As shown in figure 1, it stretches from the Arabian Sea at the southwest to the foothills of the Himalayas in the northeast, with Afghanistan on the west, and India and Kashmir on the east. It appears to lie at least in part in a structural trough formed by deep crustal subsidence related to upthrusting of the Himalaya and other bordering mountain ranges. The 125,000-square-mile area is underlain by unconsolidated sediments of Tertiary and more recent age, which extend to depths of a few thousand feet. The sediments consist primarily of sand, silt and clay but sandy sediment is most prevalent. Much of the deposit is water saturated to within a few feet of the land surface. Significant salt deposits occur in the northwestern margin bordering the Salt Range.

In the northern part of the plains, the Sutlej, Rāvi, Chenāb, Jhelum, and Indus Rivers converge in a fan-shaped pattern to form a single channel—the Indus, and to give the area its name, Punjab, from the native words "paunch ab," which mean five waters. From this point of convergence the Indus flows alone southwest through the Sind to the Arabian Sea.

The climate of the Indus Plains ranges from relatively humid in the mountainous northeast, where rainfall may exceed 30 inches per year, to semiarid in the central part, and to near desert conditions in the southern Sind, where annual precipitation is likely to be less than

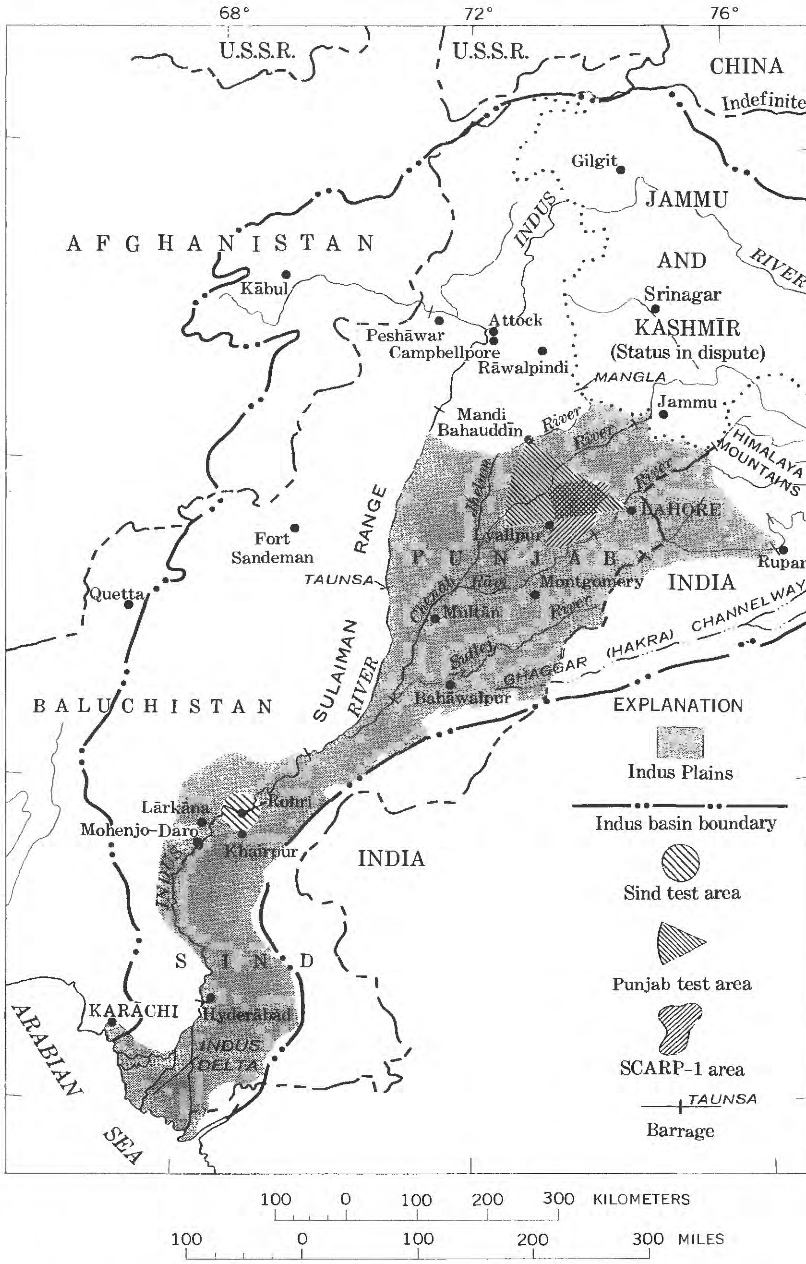

Figure 1.—Map of Indus Plains showing approximate test areas.

4 inches. Generally speaking, the 15-inch precipitation line which passes through the city of Lyallpur (see fig. 1) divides the south from the north and the arid from the semiarid region. The plains' gentle slope of 1 to 1½ feet per mile results in rather sluggish drainage of whatever water falls upon them. During the dry season (Rabi) almost all of the rain which falls is lost by evaporation. Even during the wet season (Karif) the loss by evaporation is about 75 percent. Hence, leakage from the perennial rivers, canals, and natural drains plays a major role in sustaining the ground-water level.

Man has lived upon and irrigated the Indus Plains with waters from its rivers and shallow flood-plain ground waters since the dawn of history. The Harappa civilization (2300 to 1500 B.C.), centered in the north near Montgomery and in the south at Mohenjo-Daro near the present town of Lārkana, apparently flourished despite the limited rainfall. At first all irrigation depended on natural river flooding, called "sailab," during the monsoon season (July and August) or primitive mechanical water lifts, such as the shaduf, the mote, and the Persian wheel (fig. 2). Near the end of the 17th century inundation canals were dug from the rivers inland to spread water further into the doabs which separated them, thereby extending the benefits of monsoon flooding. About the middle of the 19th century low barrages constructed on the rivers (fig. 3) and networks of canals stemming from them made perennial irrigation feasible for the first time on a relatively large scale. These canals covered more of the flat Punjab

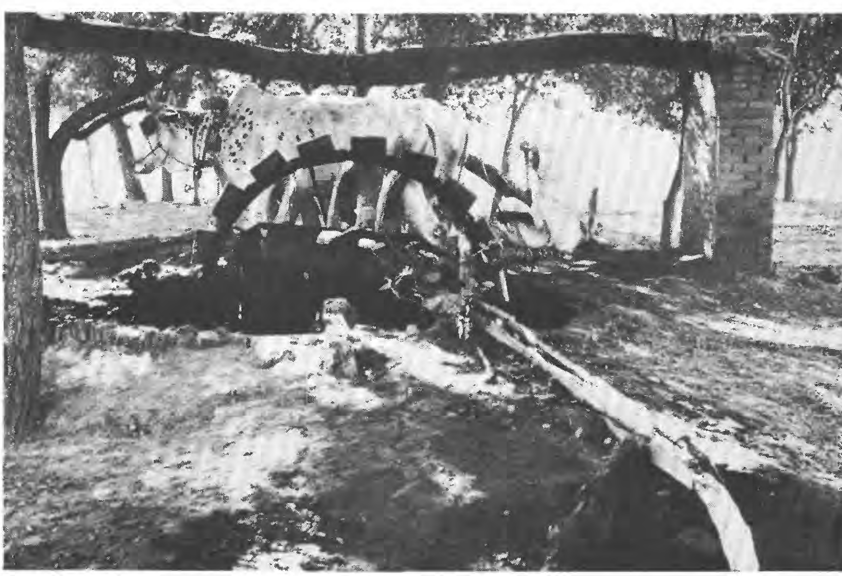

FIGURE 2.—Persian wheel in shallow well.

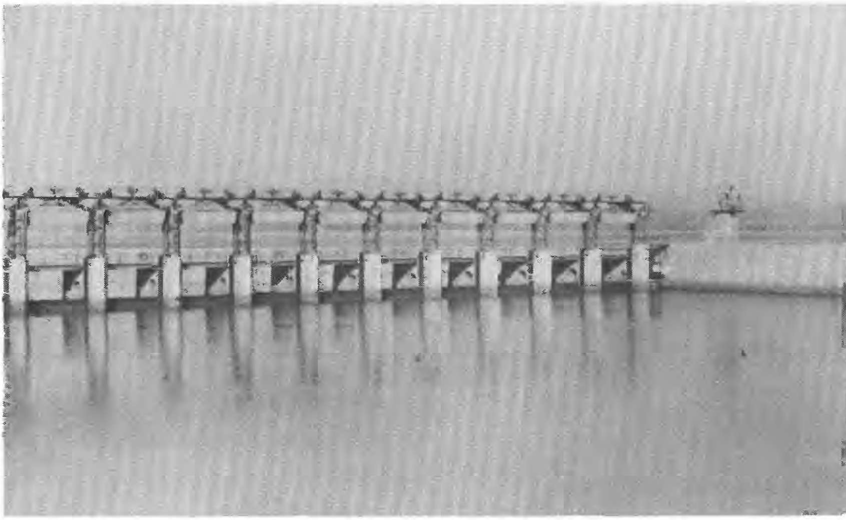

FIGURE 3.—Irrigation barrage, Jhelum River.

area with water and markedly increased infiltration through porous alluvial deposits into the ground-water system (Carlston, 1953). As a result, ground-water levels once 30–90 feet below the surface rose steadily in heavily irrigated areas of the Punjab and eventually caused waterlogging, soil salinization from near surface evaporation, and crop destruction. The compressed-scale diagram in figure 4 shows the change in ground-water level in the Punjab during the first half of the 20th century. Typical effects of waterlogging and salinization are shown in figures 5 and 6.

Attempts to control the rising water table by pumping ground water back to major canals was started during the 1940's in Chaj and Rechna Doābs with rows of wells approximately a quarter of a mile apart on both sides of the canals. The first wells were installed about 60 feet from the water's edge and were later constructed 100 feet away in an effort to improve results. The 1,800 "Rasul" wells, named for the hydroplant which powered them, had little beneficial effect partly because of inadequate pumping capacity and partly because some electrical power originally intended for their operation was necessarily diverted to other uses. By 1960 the water table in Rechna Doāb had risen as much as 90 feet, thus exceeding river level and reversing the hydraulic gradient (Malmberg and Ataur Rahman, 1966). More promising reclamation projects were started during the 1950's in several areas of central Rechna Doāb. The Chuharkana project started in 1952, and originally planned to benefit about 9,000 acres, included 24 centrifugally-pumped tube wells which supplied ground water to canals for

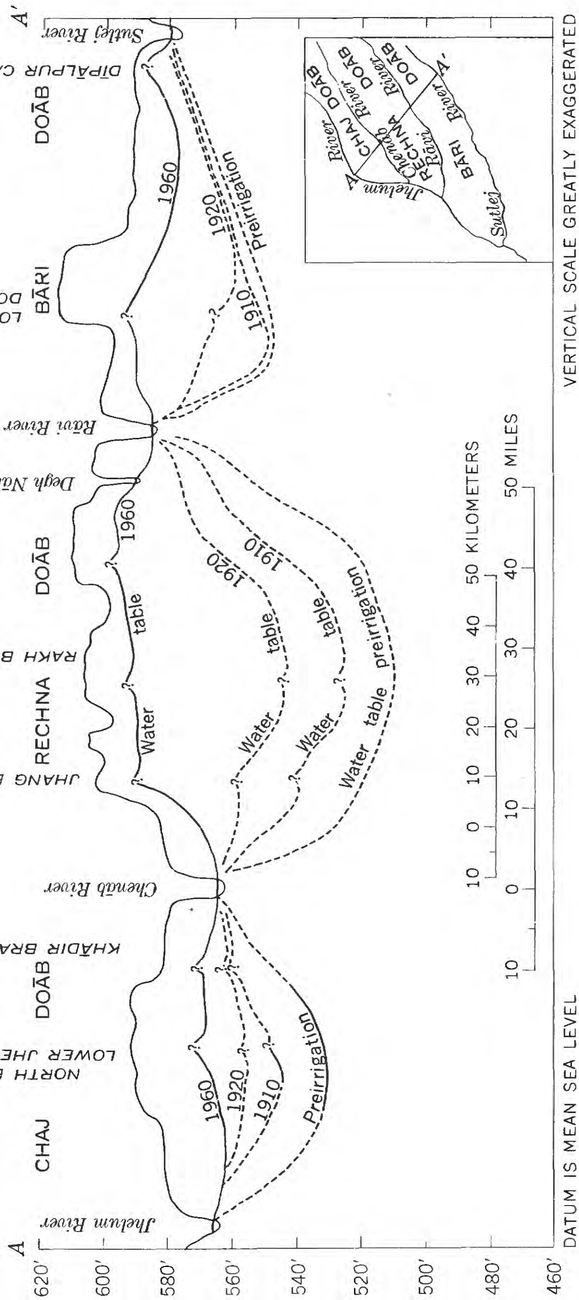

FIGURE 4.—Change in ground-water level.

FIGURE 5.—Waterlogging.

FIGURE 6.—Salinized soil.

irrigation water while lowering the water table. Here too pumping capacity failed to prevent waterlogging from canal leakage and monsoon floods. Three other reclamation projects, Jaranwala, Pindi Bhattian, and Chichohi Mallian, involving 178 wells and 105,000 acres followed during the years 1954 and 1960. These later were incorporated in the present Salinity Control and Reclamation Project 1 (SCARP–1) which started in 1959 and now includes a total of 12 reclamation projects with 2,000 wells covering 1.3 million acres.

The principle of tube-well dewatering is relatively simple, although it involves extensive hydraulic testing and well construction. It is less costly than any kind of horizontal drainage and is more effective under favorable geologic conditions such as those in the Indus Plains. Sufficient water is pumped to establish a new hydraulic condition in which ground-water levels are low enough to prevent serious water-table evaporation and consequent salt concentration in the root zones. Usable ground water is pumped back into the surface irrigation system from which it can be spread onto the land for irrigation, salt leaching, and soil reclamation. Salty water is pumped to drains or to rivers or large canals for dilution. Because much of the water pumped from the underground system is lost by surface evaporation during irrigation, ground-water levels can be lowered significantly in relatively short periods of time provided wells are properly spaced and perform at rated capacities. According to Malmberg and Ataur Rahman (1966), dewatering operations during the past 4 years has lowered ground-water levels in the SCARP–1 area 1–8 feet and an average of 6 feet. Depth to water now ranges from 10–20 feet in this region. Some salty areas like the one shown in figure 6 have been reclaimed and are productive agricultural lands.

Continuing success of ground-water dewatering operations in the Indus Plains depends on the continuing effectiveness of pumping. Loss of well capacity already has proven to be an unexpected and costly problem in parts of the Punjab. Exploratory studies by several investigators have shown corrosion and related mineral encrustation of water-well components, particularly the latter, to be major contributing factors. These observations led to the work reported here, which was conducted in the shaded areas shown in figure 1 and was aimed at understanding corrosion and encrustation processes involved in order to determine the preventive and corrective treatments best suited to tube wells of the Indus Plains. Earlier work is discussed in open-file reports (Clarke and Barnes, 1964 and 1967).

GENERAL WATER-QUALITY CHARACTERISTICS OF GROUND-WATER SYSTEMS

Data reported by Swarzenski (1968) show that five rivers of the Punjab contain waters with dissolved solid contents of only 200–300 mg/l (milligrams per liter), particularly during the period from April to October when the rivers are sustained partially by snowmelt from the mountains and by monsoon rains, both of which dilute the higher base-flow concentrations resulting from irrigation return. The river waters are calcium-magnesium bicarbonate types, but this surface water is converted to sodium bicarbonate type as it seeps from the river channels to form narrow belts of relatively shallow fresh ground water beneath the flood plains. Deeper water and water farther inland beyond the range of this fresh-water source generally have higher salt concentrations and sodium chloride contents.

The data shown in table 3 are reasonably representative of ground-water quality in the Punjab, where tube-well dewatering and irrigation is being practiced or planned. The data represent a rather wide range of dissolved-solid concentrations and ionic balances. Most of the waters with dissolved-solid contents below 1,000 mg/l are primarily sodium bicarbonate types because of base exchange. Occasionally sodium sulfate or calcium sulfate solutes are found to predominate. Sodium chloride predominates only in water with concentrations above 1,000 mg/l, and occasionally sodium sulfate predominates in this concentration range. Much of the water is anaerobic, and much of it contains significant concentrations of ferrous and sulfide ions, which are relatively common in air-free ground-water systems. Generally speaking, concentration of ground-water solutes tends to increase down doābs toward river junctions. However, this is not a consistent pattern, and more than one center of high salt concentration may occur within the doāb boundaries as shown in figure 7. Water-table evaporation at depths of 50 feet or more has been suggested as the primary cause of salt concentration (Greenman, Swarzenski, and Bennett, 1967). Flow of saline water from the Salt Range in the northwest of the Punjab also has been proposed as a possible source of saline water (H. E. Skibitzke, oral commun., 1967). However, it is doubtful that the Salt Range supplied saline ground water to the southern plains (Sind)

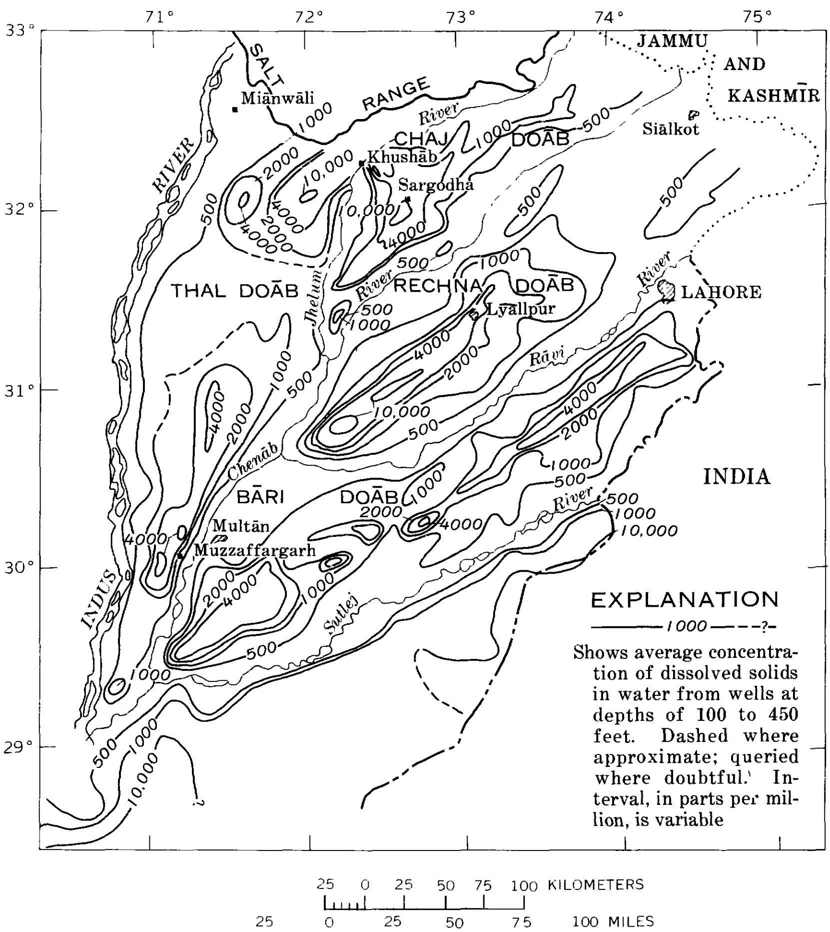

FIGURE 7.—Mineral content of native ground water in Punjab area.

where it is even more prevalent and troublesome. Increasing aridity from north to south would be expected to intensify evaporation and to increase salt concentration in both surface water and ground water in a downstream direction.

Vertical movement of surface salt to pumping depth and its lateral movement to the wells will take considerable time. Because of this and the small amount of direct return flow to the rivers from irrigation projects, local changes in ground-water quality are not likely to be rapid except in marginal zones separating fresh and saline ground-water bodies. Here, continuous pumping can be expected to cause up-coning and lateral intrusion of saline water and noticeable changes in water-quality patterns. General inoculation of the aquifers by bacteria, such as sulfate-reducing organisms, introduced through water wells is also possible, but water-quality effects of such organisms probably will be concentrated in the boreholes rather than spread throughout the aquifers. One would expect areal variations in water quality to be more significant than variations of quality with time at a particular location. However, Malmberg and Ataur Rahman (1966) report that significant quality changes already have been observed in some of the tube wells and that changes in quality with time can be detected by plotting isograms periodically for pertinent solutes.

TUBE WELLS OF THE INDUS PLAINS

The term "tube well" is used to describe relatively small-diameter boreholes which penetrate the ground-water formation and yield water by artesian flow or pumping. Tube wells of the Indus Plains generally are 10 inches or less in diameter and seldom exceed a depth of 500 feet except in exploratory boreholes. Many wells are privately owned and of relatively simple design. Some of these are constructed by percussion drilling and are cased with plain carbon steel pipe from 6–8 inches in diameter. Many wells are equipped with coir filter pipes (screens) consisting of central cylindrical grids or cages of uniformly spaced vertical steel rods or bars held in place by circumferential steel bands and wrapped spirally with closely-spaced small diameter coconut-hull (coir) rope (fig. 8). Wells with coir screens generally are relatively shallow and are equipped with centrifugal pumps of local design which are relatively inexpensive, easy to install, and rather trouble free. Yields are limited by well design and pump capacity to 1 cfs (cubic foot per second) or less. Cost of constructing coir wells is said to be approximately one-fifth that of an all-steel well with saw-slotted filter sections.

Better quality private wells and certain wells constructed and operated by government agencies are cased with steel tubes and equipped with saw-slotted plain yellow brass filter pipes ("screens").

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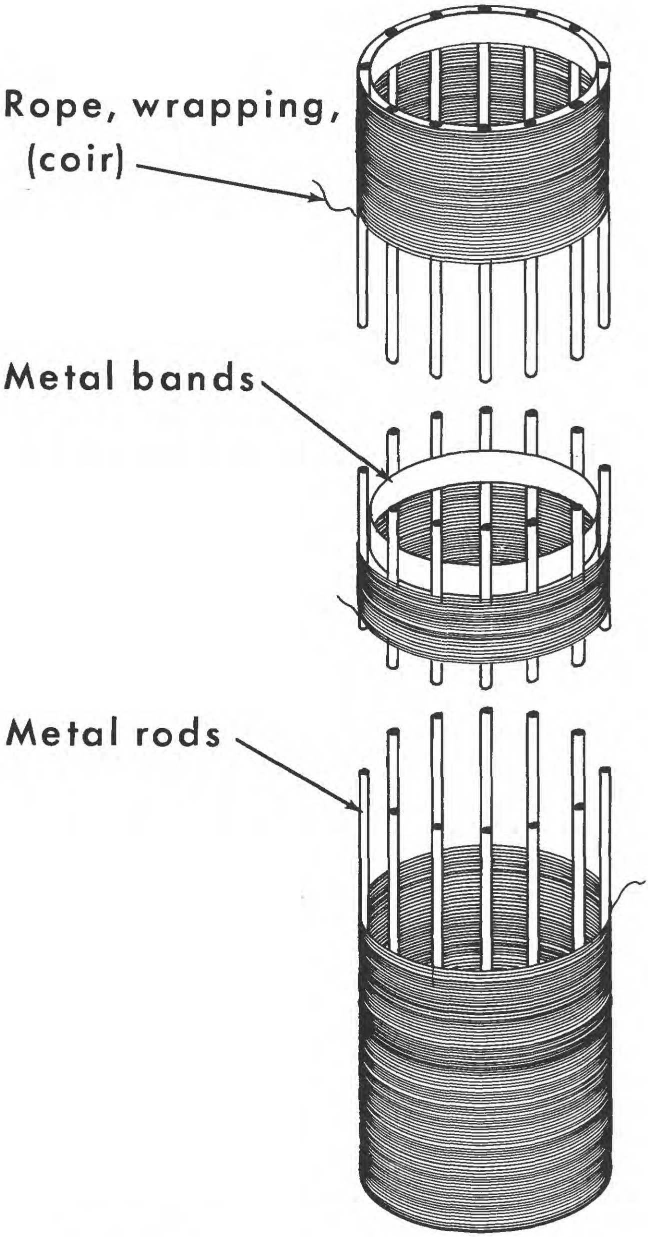

FIGURE 8.—Diagrammatic sketch of coir well screen.

These wells generally are gravel packed and may be equipped with either centrifugal or multistage turbine pumps, the latter capable of discharging up to 5 cfs of water. The brass filter pipe is made locally, with slots about $\frac{1}{32}$ inch wide. Construction with brass pipe is significantly more costly than all steel construction because of the higher cost of the brass. However, brass filter pipes have proven to be less troublesome than those made of steel.

Modern tube wells installed under direction of the Water and Power Development Authority (WAPDA) in the SCARP projects are designed for 8-inch- to 10-inch-diameter casing and are constructed by reverse rotary drilling. Most wells have steel casings, slotted steel filter pipes, and multistage turbine pumps which discharge 3–5 cfs; all are gravel packed. Filter pipes are slotted in the pattern shown in figure 9, with slots approximately $\frac{1}{16}$ inch wide and 3 inches long. This pattern provides from 6 to 8 percent opening, which is calculated to be adequate for the aquifers involved.

A few hundred wells with less conventional construction materials (such as fiber-glass plastic) are in use as a result of the investigations reported here and are discussed later in the text. Figure 10 shows a typical tube well.

More than 30,000 private tube wells are now operating in the Punjab. The 12 schemes of SCARP–1 area include approximately 2,000 modern high capacity wells. About 1,500 modern high capacity tube wells already have been constructed in SCARP–2 area. These, plus the 2,000 in SCARP–1 and new wells to be completed in SCARPs 2, 3, and 4, will bring the total to about 4,900 wells serving more than 3 million acres before the end of 1968 (Tipton and Kalmbach, Inc., 1967).

Because of basic similarities in water quality, all wells are likely to be subjected to conditions similar to those responsible for the corrosion and encrustation problems observed in wells of SCARP–1. Severity of effects can be expected to vary because of significant differences in water quality, well design, operational factors, and sensitivity of well construction matrials, particularly the last.

NATURE AND PATTERN OF WATER-WELL PROBLEMS

Tube wells of the Punjab often are completed and developed with pumps powered by portable electric generators before permanent electrical power is available for continual pumping. Such wells may stand idle for a year or more before final acceptance testing. Wells constructed and developed in this manner using slotted steel filter pipes occasionally suffer serious losses in specific capacity during the idle period between initial development and start of service.

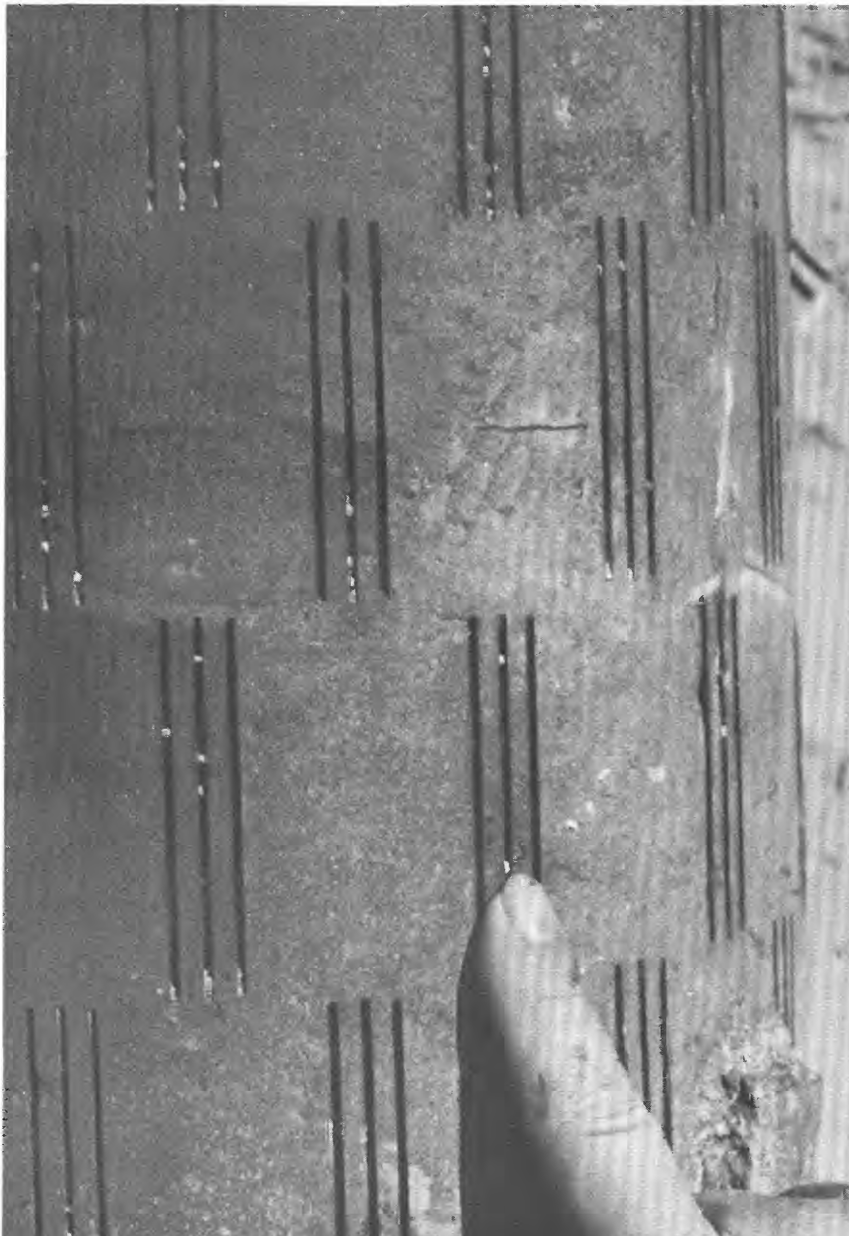

FIGURE 9.—Slotted steel filter pipe.

FIGURE 10.—Typical tube well.

These losses suggest clogging of openings in the gravel pack (shrouding) or filter pipe, presumably by mineral encrustation, formation particles or corrosion products. Specific capacity losses as high as 80 percent have occurred in unused waterwells, and losses of 30 percent are rather common. After pumping starts, wells generally continue to decline in capacity, and in some the rate of decline is so rapid that rehabilitation is required in 3 years or less. Rehabilitated or replaced wells commonly follow the same die-away pattern. The performance curves in figure 11 for typical troublesome steel wells in SCARP–1 show the rates and extents of capacity changes after start of pumping.

Well-clogging problems vary considerably from one area to another because of the variation in water quality. Only 10–15 percent of the modern tube wells in SCARP–1 had proven to be very troublesome at the time of this study, but most of these had been in operation for 5 years or less. A much larger percentage showed evidence of gradual decline, which could markedly affect their usefulness within a decade. Some areas, such as parts of the Shāhkot project in SCARP–1, appear to be relatively free of serious tube-well deterioration problems, whereas others, like much of the Shādman project, require frequent attention. The fact that all areas contain examples of relatively good and relatively poor performers, sometimes located rather close together and operating in waters with very similar general characteristics,

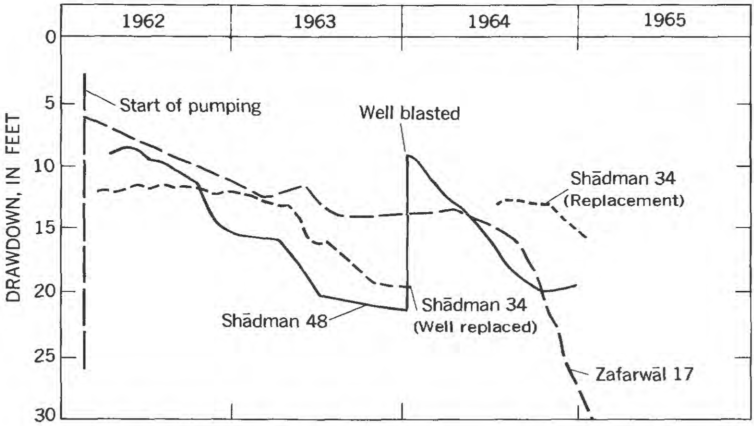

FIGURE 11.—Performance record, troublesome steel wells, SCARP–1.

presents a particularly challenging situation to the investigator. It suggests marginal water quality where kinetic factors and catalytic effects have a marked bearing on troublesome reactions.

FIELD AND LABORATORY STUDIES OF WATER-WELL PROBLEMS

Conventional laboratory analyses of water samples alone are of little value in determining subtle quality characteristics responsible for spotty well performance of the kind observed in West Pakistan. The field and laboratory studies used in the investigation described here involve a number of tests and analyses which generally are not made in studies of ground-water quality. These included well-head tests for hydrogen ion (pH); electrode potential reading (called Eh for convenience); ferrous, sulfide, and bicarbonate ions; and short-term measurements of corrosion rates with special test equipment. These measurements relate to unstable properties or components which can be expected to change during transit of water samples to the laboratory. Results obtained, together with field observations of affected well parts and data from conventional laboratory analyses for more stable water components and mineral deposits, were subjected to rigorous thermodynamic studies in an effort to understand observed behavior. The field tests have been described in detail in an earlier open-file report (Clarke and Barnes, 1964). Brief descriptions are presented here for convenience of the reader.

Tests for pH and bicarbonate ion were made by the methods of Barnes (1964). In these methods, an electronic pH meter with glass-calomel electrode system is used both for measuring the pH and for detecting the chemical equivalence point in the electrometric titration for bicarbonate ion. Electrode potential was measured by the method of Back and Barnes (1961) using a platinum-calomel electrode system in a special flow cell (figs. 12 and 13), together with the above-mentioned pH meter, which served as a potentiometer. Ferrous ion was determined colorimetrically with bipyridine reagent, and sulfide ion was determined by iodometric titration, as described by Clarke and Barnes (1964). Short-term corrosion rates were measured with an electrical-resistance type wire-loop probe inserted in the well water and monitored with a portable Kelvin Bridge circuit (corrosometer). This senses resistance changes in the test loops as evidence of change in diameter of the metal test specimens. The meter's dial reading represents an average value over the entire specimen, and therefore the reading is easily converted to metal penetration in inches per year (ipy) or any other convenient unit of metal loss. The type and size of wire corrosion specimens are selected to provide various rates of testing and sensitivity to corrosion. Such corrosion data in themselves are not quantitative indications of well life; however, they provide an excellent means for comparing performance of a particular metal in a variety of ground waters, or the effects of a particular ground water on various construction materials. Corrosometer tests provide useful data for correlating well performance records and water-quality data. A corrosion probe with its guard removed to show the wire loop specimen is illustrated in figure 14.

FIGURE 12.—Measuring electrode potential.

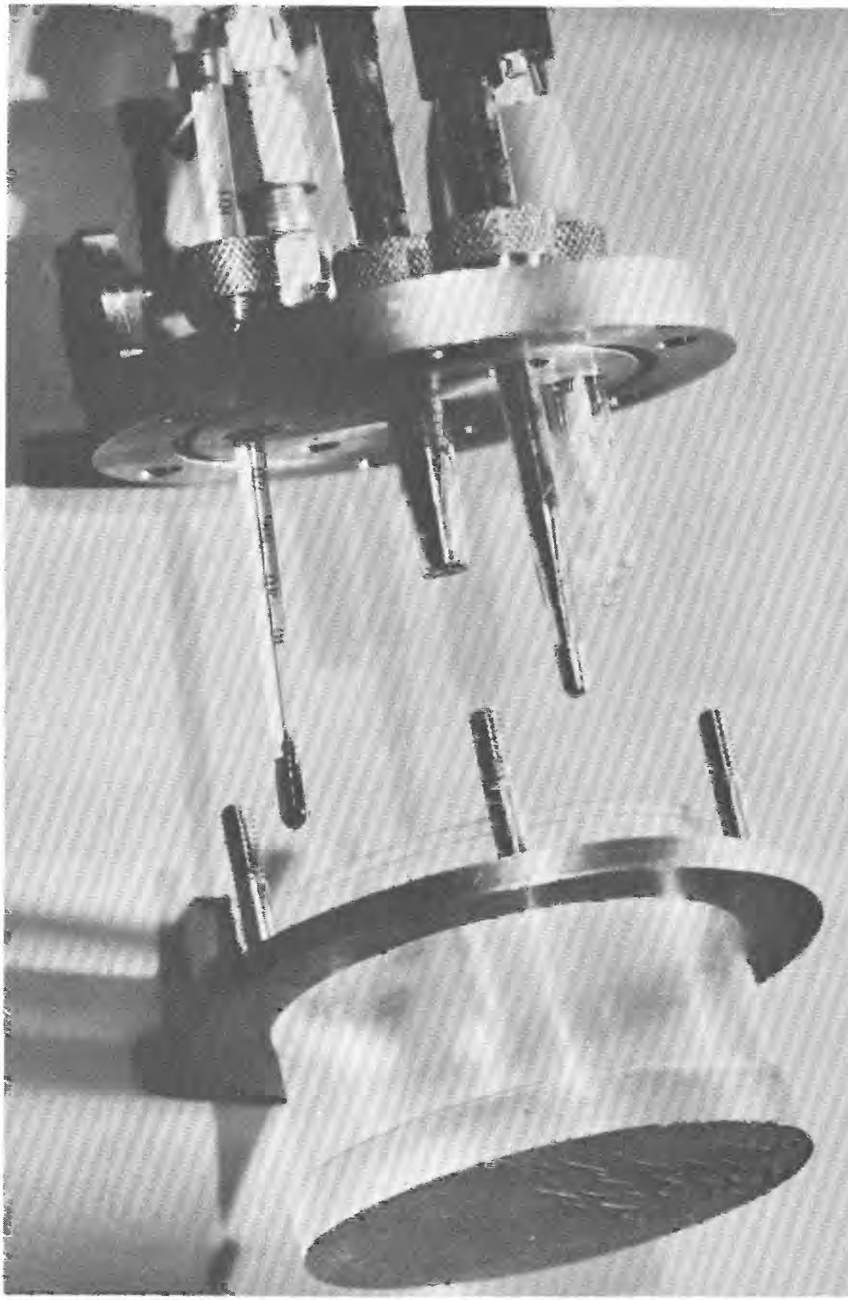

FIGURE 13.—Platinum-calomel flow cell for measuring electrode potential.

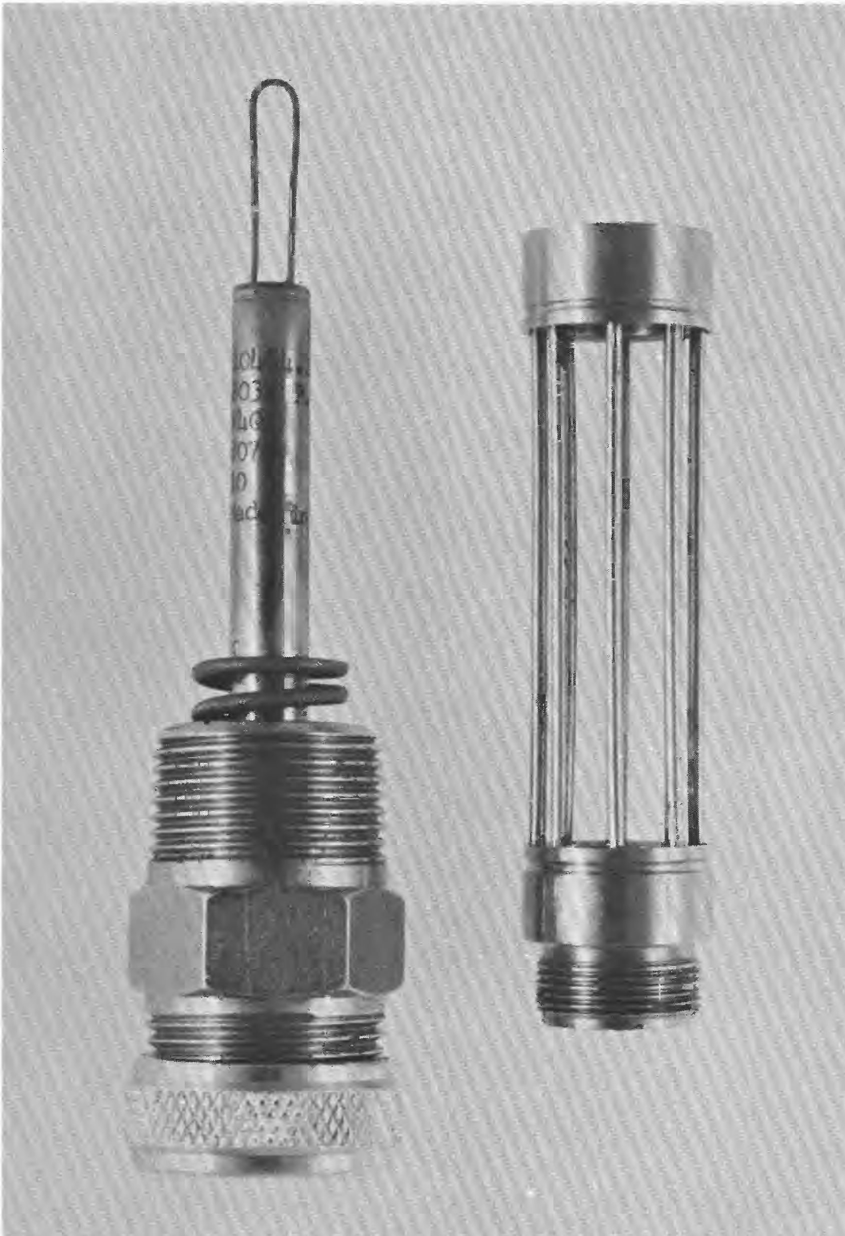

FIGURE 14.—Corrosion probe with guard removed to show element.

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Long-line corrosion current studies were made on selected SCARP–1 wells by the standard procedure of burying a copper sulfate reference electrode at various distances from the well, connecting it to the well head through a potentiometer, and measuring well-casing potential against the reference (fig. 15). This reveals differences in electrical potential between upper and lower portions of the casing filter pipe assembly. Results of the tests have been discussed by L. P. Sudrabin (written commun., 1964). Such surveys are useful in detecting massive corrosion cells caused by differences in concentrations of air or salt dissolved in the water at various levels in the underground system.

Actual corrosion and encrustation effects on water-well components were determined by optical and microscopic examination of well screens and casings and by laboratory analyses.

In addition to the special field tests, complete laboratory analyses were made on all water samples. Water-formed deposits were examined by microscopic, X-ray diffraction, X-ray fluorescence, and spectrographic methods.

Both field and laboratory data are needed to determine states of reactions among minerals and a variety of ground-water solutes before the probable behavior of the water can be predicted. The calculations involved and results obtained in such analyses are discussed later in this report.

FIGURE 15.—Measuring long-line potential, SCARP–1 well.

ON-SITE INTERPRETATIONS OF DATA

Certain of the field data can be interpreted immediately in terms of effects of ground water on well parts. Presence of ferrous ion, a common solute in West Pakistan wells, is positive evidence that the water has dissolved iron from subsurface geologic formations, ferrous well parts, or both. Electrode potential readings below 200 mv (millivolts), which are common in the Indus Plains, show that the environment is favorable to sulfate-reducing bacteria which are likely to cause corrosion. When plotted on a stability field diagram (fig. 16) of the type

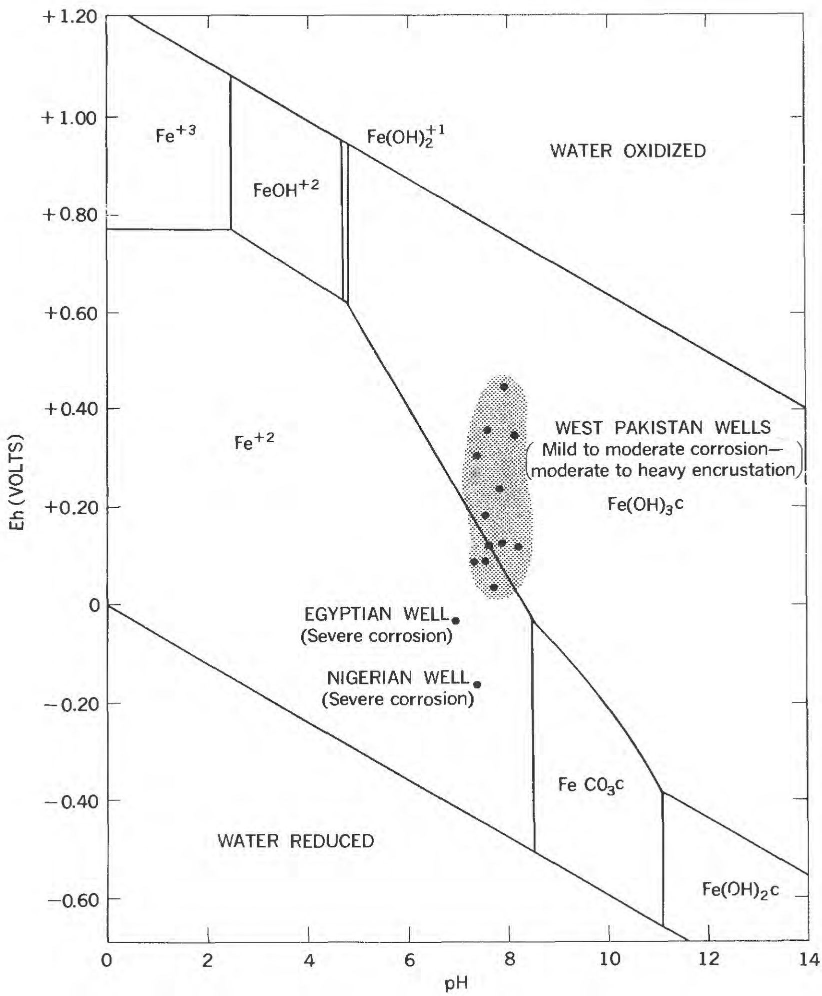

FIGURE 16.—Stability field diagram, ferric and ferrous species, assuming 2×10^{-7} molal activity of iron and based on $Fe(OH)_3$.

published by Hem and Cropper (1959), Eh–pH relationships give useful information regarding probable intensity of corrosion. In this diagram, the central curved line is fixed by the Nernst equation, and it separates the oxidized species above the line from the reduced species below. The vertical lines which separate the species are determined from related equilibrium constants. Corrosive waters like the Egyptian and Nigerian examples plot within the ferrous ion field (reduced). This may be because the reducing environment prevents retention of protective films on steel well parts. Those waters which plot near the boundary between ferrous ion and ferric hydroxide have marginal qualities and are likely to cause both mild corrosion and related encrustation. Those which fall in the ferric hydroxide field are more likely to cause encrustation problems than corrosion problems. Ground waters of the Indus Plains belong to the last two classes.

PATTERN AND NATURE OF WATER-WELL ENCRUSTANTS

Mineral encrustation is prevalent and troublesome in Pakistan wells. Deposits include minerals precipitated directly from the ground water, as well as corrosion products resulting from reactions between the water and well-construction materials. Examination of wells which have lost pumping capacity invariably shows a majority of casing slots to be clogged with mixed mineral deposits. It is not uncommon to find in the same well adjacent sections of slotted pipe with markedly different amounts of deposit. For example, one side of a casing may be heavily encrusted, whereas the opposite side is almost completely clean (fig. 17). Whenever there is limited encrustation, the deposits are concentrated around the slots of the filter pipe, as shown in figure 18. Regardless of the intensity of external encrustation, the insides of casings and filter pipes always are rather clean, with no more than eggshell thickness of mixed corrosion products and mineral deposits. Pumps and column pipes also appear to be free of troublesome deposits. Encrustation is known to have extended into the gravel shrouding for several inches, as shown in figure 19. There is some evidence that use of calcareous gravel is at least partially responsible for this effect.

The compositions of SCARP–1 encrustants are as variable as their depositional patterns, but calcium and iron are the major elements. External crusts are predominantly iron carbonate (siderite) with much smaller amounts of calcium carbonate (calcite) and heavy metal constituents. Deposits removed from the casing slots, like the one shown in figure 20, generally are complex, multilayer, sandwichlike plugs consisting of the original slot filling plus several layers of corrosion products on either side of it. This layering appears to be the result of continually changing depositional patterns, which are presumably the result of catalytic effects of successive deposits. The structure of the slot filling is shown in figure 21.

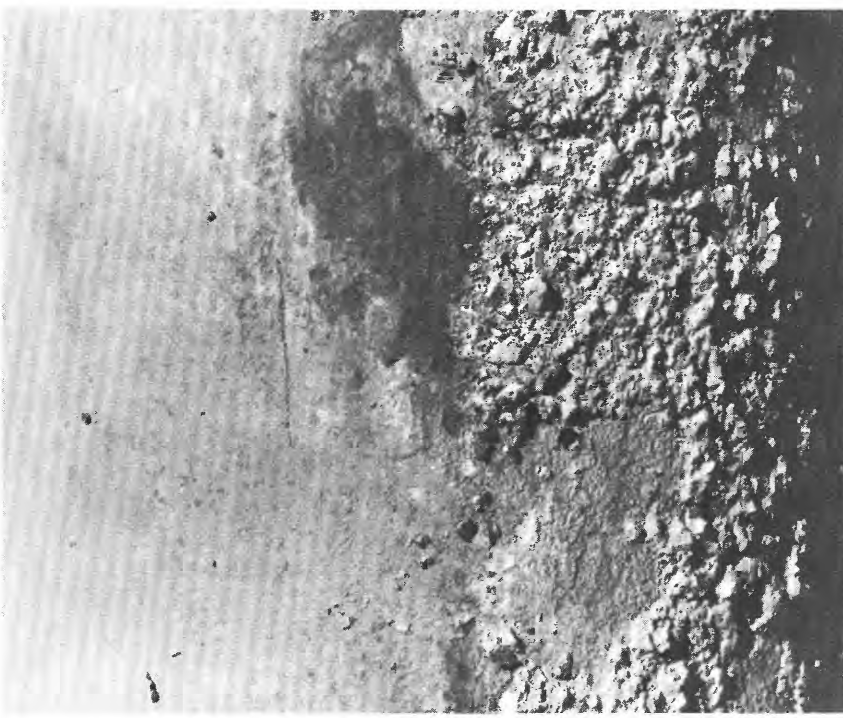

FIGURE 17.—Preferential encrustation of steel casing (× 1½), Shādman well 34, SCARP–1.

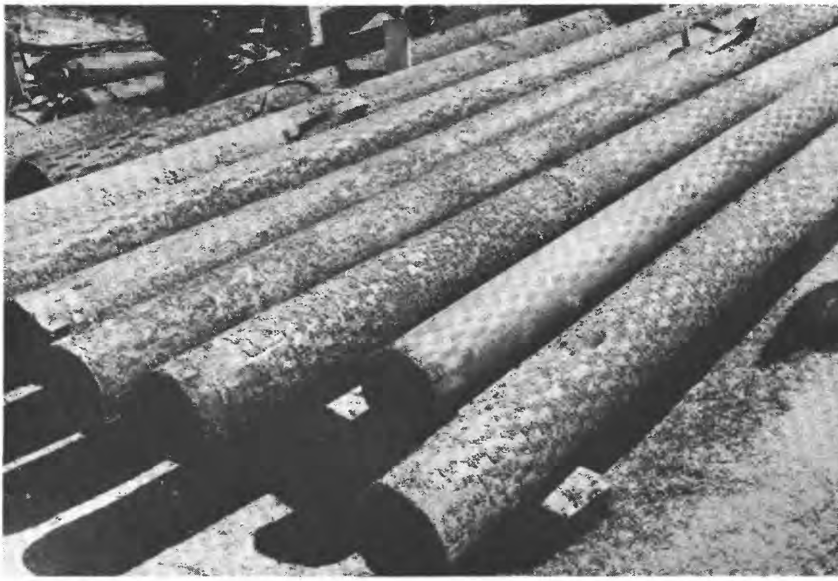

FIGURE 18.—Localized encrustation of casing slots, Shādman Well 34, SCARP–1.

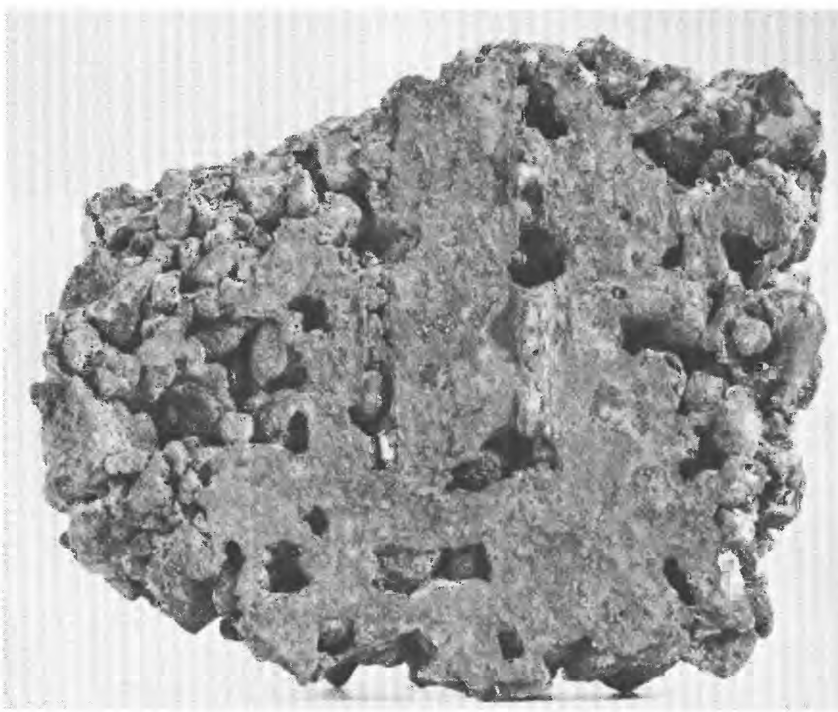

FIGURE 19.—Encrusted gravel pack (× 3), well TW2, Sind area.

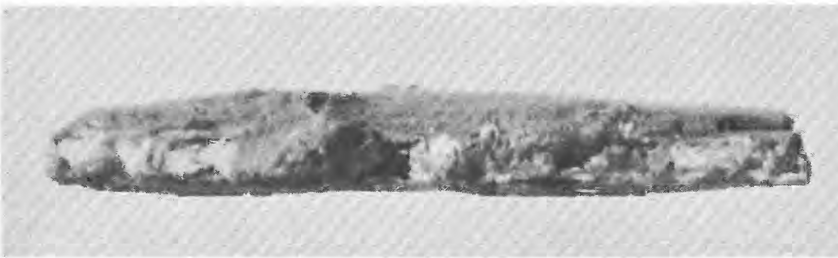

FIGURE 20.—Mineral deposit from casing slot (× 4), Shādman well 34, SCARP–1.

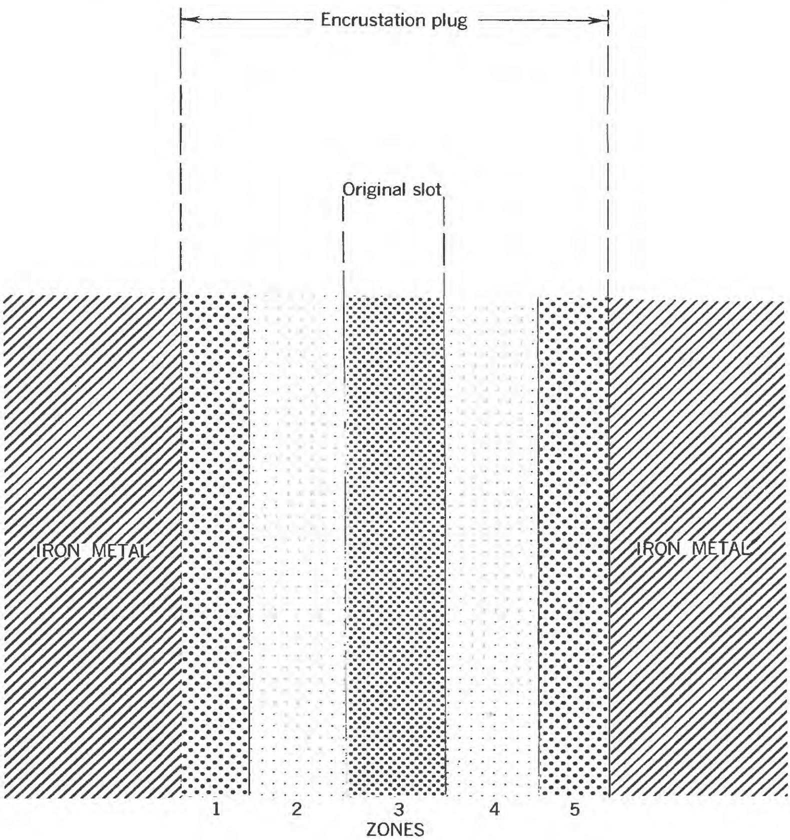

FIGURE 21.—Structure of slot deposit, Shādman well 34, SCARP–1. Numbers correspond to zones of encrustation in table 2.

The analytical data, obtained by emission spectrography, X-ray diffraction, and X-ray fluorescence are presented in tables 1 and 2.

TABLE 1.—*Composition of deposits, in percent, from Shādman well 34*

[Sulfur was determined quantitatively by X-ray fluorescence; other determinations were made semiquantitatively by emission spectrography. Analyses by Pauline Dunton, U.S. Geological Survey. Samples 1 and 2 represent separate deposit plugs removed from casing slots of Shādman well 34]

Element found	Pump suction side	Casing interior	Casing exterior	Casing, slot plug, metal side		Casing, slot plug, central part		Casing, slot plug intermediate layer
				Sample 1	Sample 2	Sample 1	Sample 2	
Iron (Fe)	15	32	37	34	48	16	27	44
Calcium (Ca)	10	.1	.5	.1	----	5	----	----
Manganese (Mn)	.3	.1	.5	.5	.5	.1	.1	.1
Cobalt (Co)	----	.007	.01	.03	.03	.009	.003	.007
Copper (Cu)	.003	.1	.5	.7	1.0	.03	.05	.05
Chromium (Cr)	----	.01	.07	.05	.1	.003	.007	.007
Nickel (Ni)	.005	.03	.3	.3	.3	.005	.005	.03
Sulfur (S)	----	14	3	----	4	----	18	----

TABLE 2.—*Minerals identified in deposits from Shādman well 34*

[For photograph and diagram of casing slot plug structure, see figs. 20, 21. Identification by Roger Wolff and Blair Jones, U.S. Geological Survey]

Slot filling: Zones 1 and 5	Slot filling: Zones 2 and 4	Slot filling: Zone 3	Crust from outside slotted pipe	Crust from inside slotted pipe
Siderite ($FeCO_3$)	$Cu(OH)_2$	Quartz (SiO_2)	Siderite ($FeCO_3$)	$Cu(OH)_2$
Mn_3O_4 (spinel)	Mackinawite (FeS)	Calcite ($CaCO_3$)	$Cu(OH)_2$	Mackinawite (FeS)
$Cu(OH)_2$	Quartz (SiO_2)	Siderite ($FeCO_3$)	Mn_3O_4 (spinel)	Siderite ($FeCO_3$)
Hausmanite (Mn_3O_4)	----	Mackinawite (FeS)	Calcite ($CaCO_3$)	$Mn(OH)_2$?
Magnetite? (Fe_3O_4)	----	Mica?	----	----
Maghemite? (Fe_2O_3)	----	Feldspar?	----	----

They show the original slot filling to be primarily quartz (SiO_2) from the geologic formation (sand particles) held in a deposited matrix of siderite ($FeCO_3$), with smaller amounts of mackinawite (FeS, tetragonal), mica, and feldspar. The outermost surfaces of the plug, which contacted the corroding steel (fig. 21, zones 1 and 5) contained siderite ($FeCO_3$), spinel (Mn_3O_4), copper hydroxide [$Cu(OH)_2$], hausmannite (Mn_3O_4, tetragonal), magnetite (Fe_3O_4), possibly maghemite (Fe_2O_3), and detrital quartz and mica. The intermediate layers between the original slot fillings and the outermost layers, which deposited as corrosion proceeded (fig. 21, zones 2 and 4), contained copper hydroxide [$Cu(OH)_2$] and mackinawite (FeS, tetragonal), as well as quartz, but there was no carbonate. This depositional pattern suggests complex interactions between corrosion and encrustation processes in the steel system. Slot plugs in brass filter pipes were found to be far less complex and consisted mostly of calcite. They were confined primarily to the original slot opening because of the very limited metal loss in filter pipe constructed from this alloy.

NATURE AND SIGNIFICANCE OF CORROSION DAMAGE

From the limited amount of well parts available for examination, it would appear that significant corrosion damage in water wells of the Punjab is concentrated almost entirely in the saw slots of the filter sections, although occasional corrosion in threads of steel casings jointed with cast iron couplings has been observed. The interiors and exteriors of blank (unslotted) casings generally show little evidence of metal loss; and pump parts, including the bowls, impeller blades, and shafts, also are free from significant corrosion damage. Even the relatively sensitive pump column pipes (above the pump bowls) show little damage in SCARP–1 wells.

In the saw slots of the filter pipes it is sometimes difficult to determine the extent of damage by casual inspection. Metal attack starts on the sawed slot faces and proceeds so gradually that metal is replaced by corrosion products with little evidence that conversion of the metal to friable reaction product has occurred. Only when a deposit is dislodged from the slot or eroded away is the extent of damage clearly evident. Figure 22 shows slots which were seriously corroded and eroded by local concentration of flow in an otherwise almost completely encrusted section of filter pipe. In some wells corroding slots develop into relatively large holes of the type shown in figure 23.

Both forms of localized damage are typical effects of relatively moderate corrosion, which concentrates attack on the most active (anodic) surfaces of the electrochemical system. Most of the ground waters examined in the Indus Plains can be described as mildly or moderately corrosive, and they fall into a class which would not be considered intolerably aggressive to steel tube wells, if it were not for the loss of critical dimension in the abnormally sensitive casing slots and troublesome interactions between corrosion and encrustation processes. The corrosion curves in figures 24–27, obtained with the electrical-resistance type corrosometer probes, agree with the moderate corrosion revealed by visual inspection of damaged casings.

The fact that corrosion of steel is moderate and concentrated primarily in the casing slots does not reduce its seriousness from the standpoint of well maintenance. Slot dimensions control well performance. Enlarging them, either through gradual metal wasting or by periodic removal of corrosion products to restore capacity, defeats

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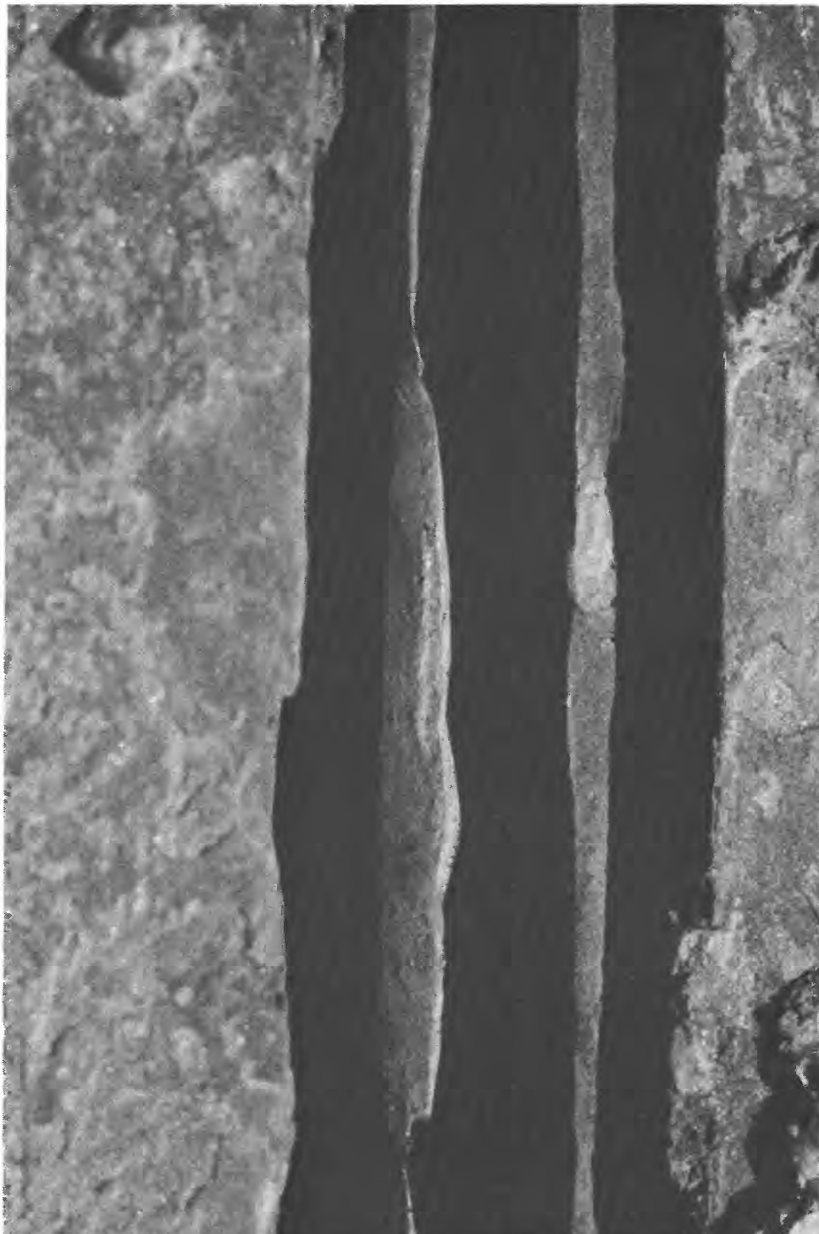


FIGURE 22.—Casing slot damaged by corrosion and erosion (approximate magnification, × 4), Shādman well 34, SCARP–1.

FIGURE 23.—Localized corrosion hole (approximate magnification, × 2), Shāhkot well 198. Courtesy of David Greenman, Tipton and Kalmbach, Inc.

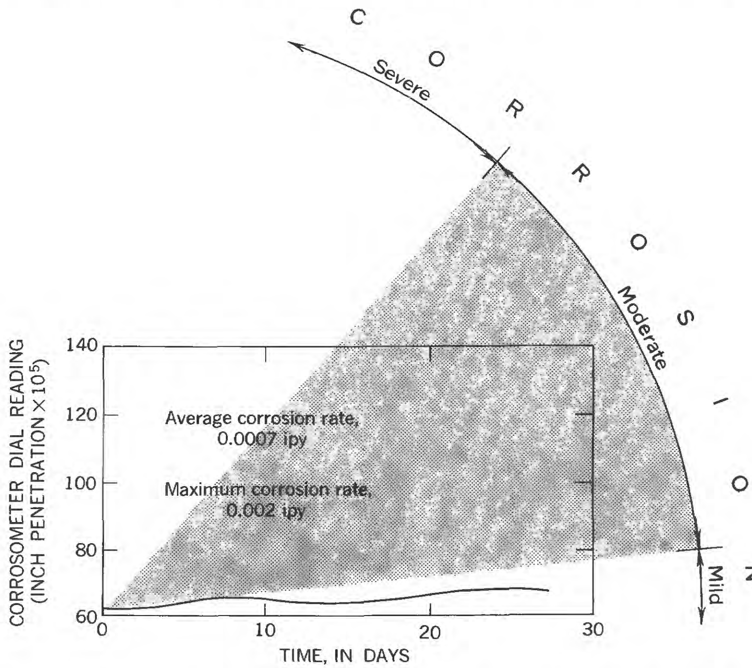


FIGURE 24.—Corrosion curve, mild steel, Shādman well 27.

their original design purpose—stabilization of the gravel pack and aquifer sand while admitting water to the borehole. Clogging the slots with mixtures of corrosion products and related mineral encrustants is equally intolerable because of reduction in capacity. For these reasons, corrosion of steel is a significant, and, in some cases, an intolerable problem in water wells of the Indus Plains, although the corrosion rates observed would be considered rather insignificant by quantitative standards.

CAUSES OF CORROSION

All corrosion in aqueous media is electrochemical in nature, whereby solution of iron in anodic areas forms ferrous ion and releases electrons which flow to cathodic areas where they neutralize hydrogen ion and cause atomic hydrogen to plate out on the metal surface. The reactions eventually become blocked (polarized), because of metal ion concentration in the system and hydrogen plating on the cathode areas, unless depolarizing processes, such as combination of dissolved oxygen with hydrogen or scouring away of reaction products, occur. Surfaces of active metals, such as steel, are covered with innumerable microscopic anodes and cathodes resulting from slight differences in composition or physical characteristics of the metal surface. In the

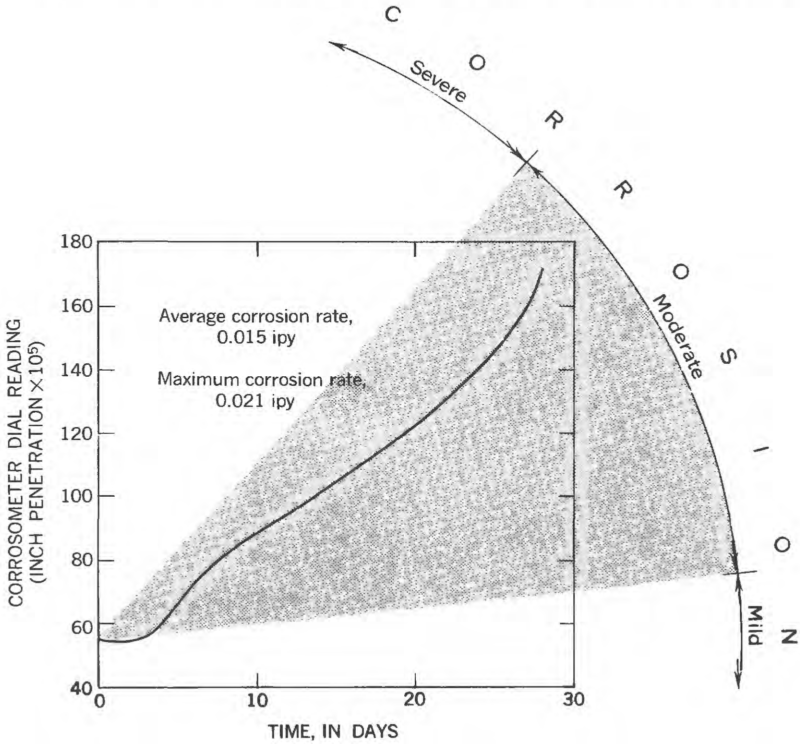


FIGURE 25.—Corrosion curve, mild steel, Shādman well 47.

mildly corrosive ground waters of the Indus Plains these areas are likely to be clearly defined and to serve as sites of localized corrosion (pitting). In very corrosive systems, surface features change continuously because of rapid metal loss, and general corrosion is likely to obscure local effects.

In water wells of West Pakistan, corrosion damage is concentrated on faces of saw cuts of slotted pipe because sawing coldworks the metal near the cut surfaces, imparts abnormal energy to it, and makes it more active and more anodic than adjacent metal. Gradual enlargement of casing slots indicates effective and continuing depolarization despite the apparent absence of dissolved oxygen in the wells. This means that long-line electrical currents, anaerobic bacterial activity, or other processes are serving as depolarizing mechanisms. The analytical data (table 3) show Eh values to be favorable for sulfate-reducing bacteria, and sulfide, the reduction product, is a relatively common component in water wells of SCARP–1. Several positive tests for sulfate-reducing organisms have been made in this area. Bacterial sulfate reduction is a common depolarizing process in anaerobic

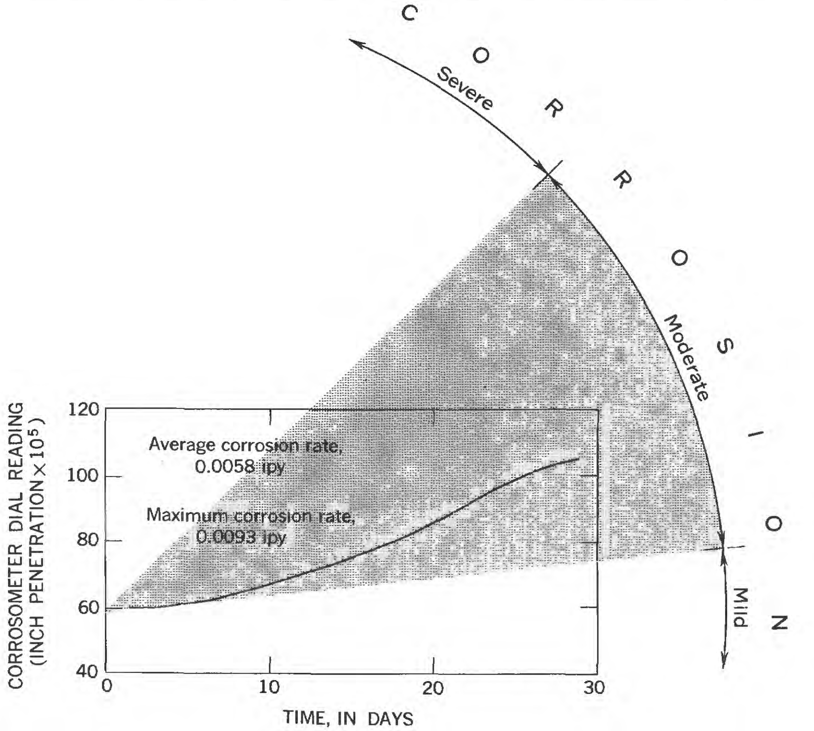
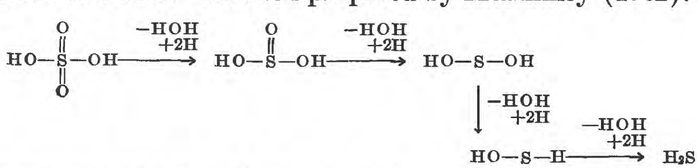


FIGURE 26.—Corrosion curve, mild steel, Shāhkot well 251.

environments. Details of the process are uncertain, but the stepwise reaction shown below has been proposed by McKinney (1962).



In this process sulfate-reducing organisms do not actually attack the metal. Instead, they catalyze the combination of atomic hydrogen with sulfate (SO_4) ion and thereby remove the protective layer of hydrogen from the cathode and allow corrosion to continue. The reaction has a troublesome secondary effect of combining sulfide ion with iron to form ferrous sulfide (FeS), which is cathodic to steel and is therefore likely to establish galvanic corrosion cells. The presence of sulfide compounds in deposits both inside and outside the casings and the screens and deep in multilayer slot plugs (fig. 20) suggests that sulfate reduction is a pertinent aspect of ground-water corrosion and encrustation processes in West Pakistan wells (Clarke and Barnes, 1964). The small quantities of deposit available for laboratory study did not allow confirma-

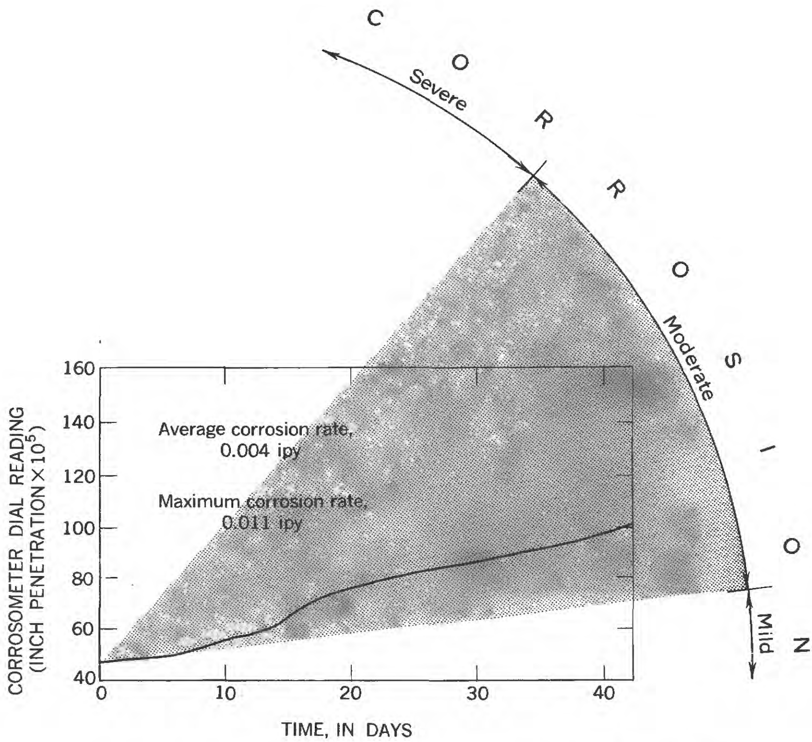


FIGURE 27.—Corrosion curve, mild steel, Shāhkot well 252.

tion of the 3 $Fe(OH)_3$/1 FeS structure which characterizes deposits involving such bacterial activity.

Evidence of long-line current flow also was found in the Indus Plains. This flow undoubtedly provides some depolarization which otherwise would have to be supplied by local processes. Well-head measurements using remote copper sulfate electrodes (fig. 15) on a number of SCARP–1 wells yielded electrical potentials of the order of −500 mv, rather than the −850 mv potential expected for an anaerobic aqueous system containing iron or steel (L. P. Sudrabin, written commun., 1964). A potential of −500 mv is typical of steel corroding in aerated water and indicates that local corrosion cell effects in the screen slots probably are being intensified by superimposed long-line currents flowing from deep anodic surfaces to cathodic areas of casings surrounded by aerated soil near the land surface.

In most of the West Pakistan wells the EH–ph relationships favor mild or moderate corrosion. They are marginal environments between the stability fields of ferrous ion and ferric hydroxide (fig. 16), so that both removal of protective films and solution of iron would be expected.

TABLE 3.—*Water quality data,*

Well name and number	General determinations						
				Mg/l			
	pH	Eh, mv (all values positive)	Temp (° C)	CO_2	SiO_2	Total Fe	Total solid by evaporation at 180°C
Khaipur 12	7.33	82.5	28.5	13.7	23	1.70	10,200
Khāngrā Dogran 71	7.79	90.5	23	5.0	21	.22	244
72	7.58	88.5	29.5	12.0	24	.22	431
73	7.54	119	29.5	15.0	25	.20	394
Lyallpur 54	7.58	103	25	22.3	29	2.00	5,340
Mona 53	7.65	61.5	25	12.7	24	.90	928
83	7.58	96.5	27	23.2	25	.30	3,430
113	7.88	240	23	2.4	20	.80	2,200
Phālia 65	7.7	[1] 84	24	10.8	17	1.80	342
66	7.45	56	23	22.5	18	1.80	341
81	7.6	181	25	12.1	21	0	359
88	7.4	[1] 149	24.5	23.1	20	.50	725
89	8.02	[1] 177	25.5	4.1	19	0	342
101	8.11	[1] 216	26	3.7	20	0	475
Sāngla Hill 2	7.98	441	22	2.3	15	.20	316
Shādman 16	7.56	89.5	27	14.4	21	.30	407
17	7.58	79.5	26.5	14.5	20	.75	483
27 (1964)	7.7	41	27	7.8	22	.80	578
27 (1965)	7.69	58	28	7.6	23	.22	278
34	7.49	87	28	16.2	20	.40	398
40	7.55	46.5	28	10.2	--------	.50	404
45	7.45	76.5	27	20.0	20	.80	770
46	7.55	61.5	28	14.2	19	.50	674
47	7.5	81.5	27	16.4	20	.70	696
48	7.4	61.5	28	25.3	19	1.00	966
50	7.5	85.5	27	18.0	20	.75	481
81	7.7	31.5	28	7.5	--------	.30	530
Shāhkot 16	7.55	353	28	16.9	24	.15	910
20A	7.47	303	29	24.5	25	.10	1,100
213A	7.48	391	28	36.2	25	.02	1,510
251	8.12	118.5	21	1.5	14	.22	189
252	8.12	339.2	22	1.5	10	0	163
Zafarwāl 1	7.67	36.2	32	9.8	21	.52	687
4	7.55	93.8	29	15.0	23	.45	607
6	7.7	55.2	32	9.4	21	.67	653
7	7.7	65.5	29	11.1	22	.52	746
11	7.52	38.2	28	17.6	20	.75	626
16	7.38	68.5	29	24.2	20	.95	680
17	7.56	58	27	16.1	19	.75	708
27	7.53	66.2	27.8	20.1	20	1.30	1,530
121A	7.33	129.5	27	26.1	23	0	898
142	7.56	37.6	27.5	20.0	20	1.00	974
159	7.55	53.8	28.5	15.6	23	.60	660
367	7.85	156.5	27	6.8	20	0	515

[1] Corrected value based on Zobell's solution calibration.

ENCRUSTATION MECHANISMS AND EFFECTS

Rigorous thermodynamic analysis of well-water data collected throughout this investigation showed that departure from equilibrium of certain mineral species apparently has a marked bearing on the rates of corrosion and encrustation. This report compares observed concentrations of pertinent ionic species (for example, iron and carbonate)

Indus Plains wells, West Pakistan

Cations (mg/l)								Anions (mg/l)				
Al	Ca	Mg	Na	K	Fe^{++}	Mn	Cu	Cl	HCO_3	CO_3	S^{--}	SO_4
0.9	344	415	2,350	42	1.7	0.26	0	3,000	265	0.5	--------	3,220
0	28	16	35	4.8	.2	.12	0	3.6	183	.57	0.65	32
0	39	23	84	4.3	.2	.12	0	20	306	.64	.75	64
0	39	23	76	6.7	.2	.12	0	9.3	321	.57	1.15	75
.5	60	106	1,500	28	.7	.13	.26	1,490	678	2.4	2.1	1,150
.3	41	44	103	3.8	.9	.12	.17	39	394	1.1	--------	116
.6	89	52	825	6.2	.3	.42	.35	460	690	2.3	1.0	874
.5	63	37	600	6.7	.1	0	.20	925	131	.8	.6	181
0	50	21	62	3.4	1.8	.4	0	13	341	.91	1.25	44
.1	47	27	48	5.3	1.8	0	0	8	333	.46	1.1	44
0	26	12	88	3.5	0	.02	0	11	327	.68	.7	44
0	70	38	130	6.1	.5	.04	0	79	407	.52	.35	209
.1	18	10	98	1.7	0	.02	.02	6.1	295	1.6	.7	52
0	14	11	140	2.6	0	.02	0	15	328	2.2	.4	99
.4	29	13	19	3.6	.1	.14	.47	3.5	138	.8	.1	29
0	47	13	88	3.1	.3	0	0	26	366	.64	.9	60
0	55	17	110	3.1	.75	.05	0	32	388	.76	.97	92
.2	46	15	44	4.8	.8	.24	.12	16	271	.8	.25	22
0	42	16	35	5.0	.22	.10	.04	13	259	1.7	1.1	18
.01	62	27	61	3.1	.4	.12	.04	23	357	.7	.5	45
--------	37	25	56	--------	.5	--------	--------	12.6	266	.6	.2	912
.5	58	23	95	4.9	.7	.27	.25	26	399	.8	.6	56
.3	43	16	98	6.7	--------	.19	.15	22	359	.8	.4	49
.3	53	18	77	3.4	.2	.22	.16	22	366	.8	.9	56
.1	62	17	150	4.1	1.0	.34	.09	41	459	.8	.5	104
0	56	20	120	4.4	.75	.05	.02	36	404	.59	.7	92
--------	34	10	66	--------	.3	--------	--------	12.6	142	.9	--------	130
.5	35	21	155	6.0	0	.10	.26	32	432	1.1	--------	121
.5	36	26	190	6.2	0	.05	.21	40	536	1.2	.45	267
.1	16	40	496	9.1	0	0	.02	145	810	1.15	1.0	380
0	27	10	19	4.3	.22	.10	0	6.8	126	1.8	.5	42
0	28	9	15	3.8	0	0	0	3.8	123	1.8	0	28
0	38	20	200	3.2	.52	.09	.22	108	344	1.2	1.1	111
.1	54	19	138	5.0	.45	.09	0	60	387	1.0	.75	117
.2	43	17	166	4.5	.67	.11	0	96	354	1.4	.5	126
0	40	19	202	4.5	.52	.11	0	74	408	1.5	0	187
0	49	14	158	4.5	.75	.11	0	56	420	1.0	.1	115
0	62	17	155	4.4	.95	.11	0	69	425	.7	.65	141
0	52	15	185	3.8	.75	.11	0	86	421	1.1	.5	142
0	75	28	453	5.8	1.3	.11	0	448	514	1.4	.5	230
.1	69	26	195	6.3	0	0	0	159	289	.27	1.0	260
0	58	17	280	5.5	1.0	.08	0	185	533	1.4	.95	153
0	54	18	150	6.5	.6	.09	0	81	402	1.0	1.0	110
0	27	18	135	3.6	0	.04	0	38	340	1.15	.5	97

with calculated equilibrium concentrations of the same species in the same environment. The degree of undersaturation or supersaturation determined by this analysis is an indication of the driving forces in pertinent chemical processes. Such calculations do not indicate chemical effects on well components in a quantitative way because such effects also are influenced by kinetic and catalytic factors.

To compare observed cation concentrations with their concentrations at equilibrium, the activities of various probably dissolved species were calculated using the relation:

$$\alpha_i = m_i \gamma_i$$

where

α_i is the activity of the ith species,
m_i is the molality of the ith species, and
γ_i is the activity coefficient of the ith species.

Molality m_i was determined by direct analysis of the well water, and the activity coefficient of each species was computed from the Debye-Hückel equation in the form used by Clarke and Barnes (1968).

In comparing actual composition of well water with equilibrium composition for the same solution, activity (α) is defined in terms of chemical potential differences between the actual and equilibrium states by the relation

$$RT \ln \alpha_i = \mu_i - \mu_i^{\circ}$$

where

R is the gas constant,
T is the temperature in degrees Kelvin, and
μ_i and μ_i° are chemical potentials of the actual and standard states, respectively.

The difference in the sum of chemical potentials between the actual solution and the solution at equilibrium with a particular postulated phase is expressed as follows:

$$\Delta\mu_R = \left(\sum^{i}\mu_{i_{\text{products}}} - \sum^{j}{}_{j_{\text{reactants}}}\right)_{\text{observed}} - \left(\sum^{i}\mu_{i_{\text{products}}} - \sum^{j}{}_{j_{\text{reactants}}}\right)_{\text{equilibrium}}.$$

For a reaction of the type $aA + bB = cC + dD$, which is controlled by mass action, the actual composition is expressed as the product of observed activities (activity product, AP) in the equation

$$AP = \frac{(\alpha_C)^c (\alpha_D)^d}{(\alpha_A)^a (\alpha_B)^b}.$$

Comparison of actual solution composition (well water) with equilibrium state can be made in terms of the difference in sums of chemical potentials by substituting the above definition of activity to yield the expression

$$\Delta\mu_R = RT \ln \frac{AP}{K}$$

where K is the equilibrium constant and $\Delta\mu_R$ is the difference in the sum of the chemical potentials between the actual and equilibrium states.

A similar calculation made for oxidation-reduction reactions, which are directly related to corrosion processes, uses

$$\text{EhTC} = \text{E}^\circ_{(T)} + \frac{RT}{n\mathfrak{F}} \ln \frac{(\alpha_C)^c(\alpha_D)^d}{(\alpha_A)^a(\alpha_B)^b}$$

where

$\text{E}^\circ_{(T)}$ is the standard electrode potential,
n is the number of electrons involved,
$\mathfrak{F}$ is the volt equivalent (calories per volt gram equivalent), and EhTC is the electrode potential calculated for the observed temperature.

The EhTC is the electrode potential the solution (well water) should have if the postulated oxidation-reduction reaction is controlling the observed or measured Eh (Ehm), recorded in the well-water data of table 1. This equilibrium case (EhTC) is compared with the observed electrode potential (Ehm) by the relation

$$\Delta\mu_R = n\mathfrak{F}(\text{EhTC} - \text{Ehm}).$$

The mass action and the oxidation-reduction relationships described above assume that steady-state conditions exist in the well waters during testing, a requirement that was met reasonably well in these studies, because well-head tests yielded essentially constant results during repeated sampling.

Because only the difference in the sum of the chemical potentials ($\Delta\mu_R$) has thermodynamic rigor, there is no sound theoretical justification for interpreting well-water data of these kinds in terms of significance of a single compositional variable, such as pH or ferrous ion. However, such interpretations have practical value when the variable selected is known to have major significance in the system being studied (for example, Fe^{++} in a steel cased well), and when the results obtained by such calculations correlate favorably with observed effects on water-well components.

Comparison of observed and equilibrium states for the great variety of mineral species which might influence corrosion or encrustation can be done practically only by a computer method, such as that described by Barnes and Clarke (1969).

The usefulness of such studies in assessing water-well problems of the Indus Plains is evident in figures 28–34, where equilibrium data

$$\left[\log\left(\frac{\text{actual concentration}}{\text{equilibrium concentration}}\right)\right]$$

for particularly significant minerals are plotted against measured cor-

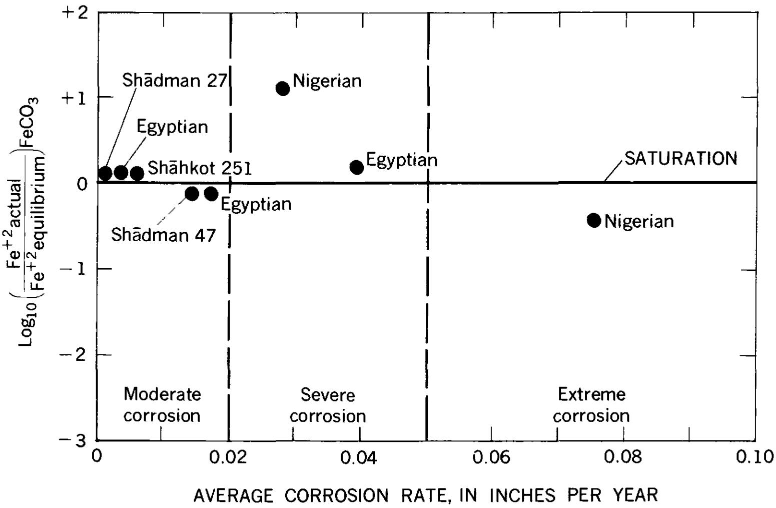


FIGURE 28.—Relation of corrosion to equilibrium state, $FeCO_3$.

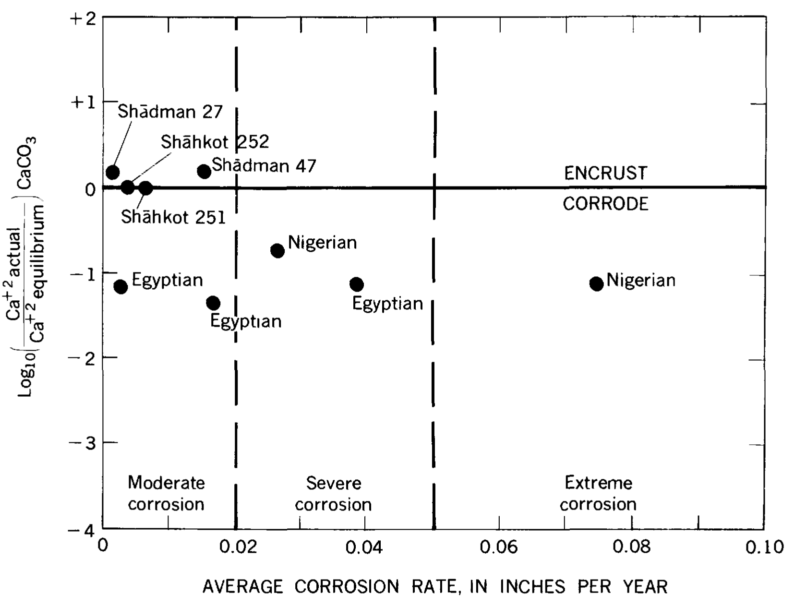


FIGURE 29.—Relation of corrosion to equilibrium state, $CaCO_3$.

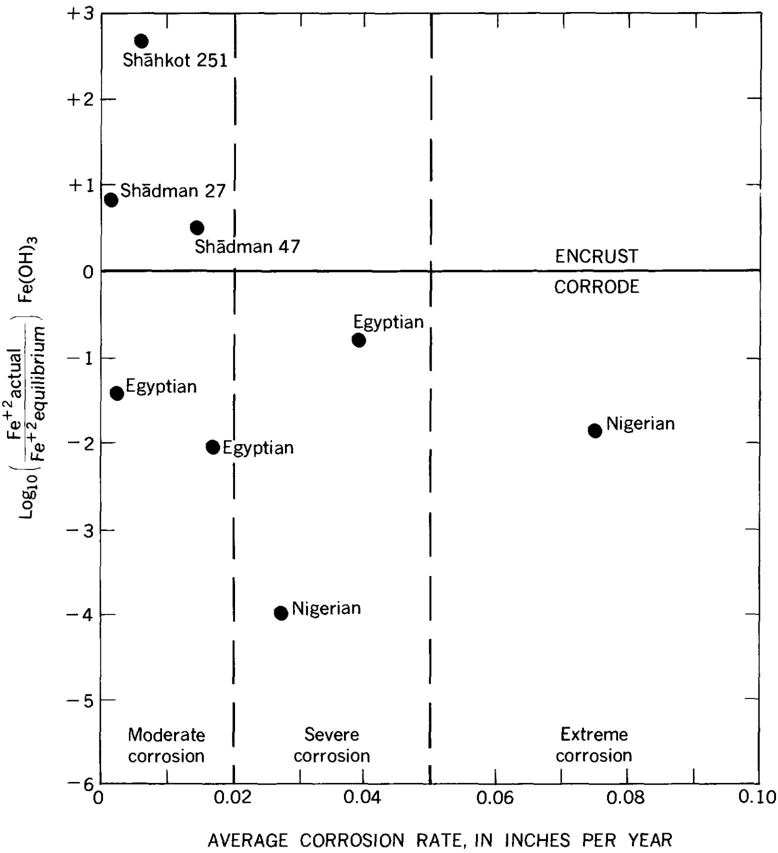


FIGURE 30.—Relation of corrosion to equilibrium state, $Fe(OH)_3$.

rosion rates in steel parts of the corresponding wells. Similar data from troublesome well fields in the Western Desert of Egypt and the Chad Basin of Nigeria are included for comparison. The corrosion ranges, marked by vertical dashed lines and representing moderate, severe, and extreme damage, are those normally accepted by corrosion engineers. In each case the heavy solid horizontal line represents equilibrium concentration (saturation) for the mineral species identified on the ordinate. Plotted points above and below this line represent well waters supersaturated and undersaturated, respectively, with this species. Positive correlation between severity of corrosion and degree of saturation with both $Fe(OH)_3$ and $CaCO_3$ is evident in these plots. However, tests in other well fields suggest that the $CaCO_3$ relationship is the more consistent one. There appears to be no consistent relation between corrosion rate and degree of saturation with iron carbonate

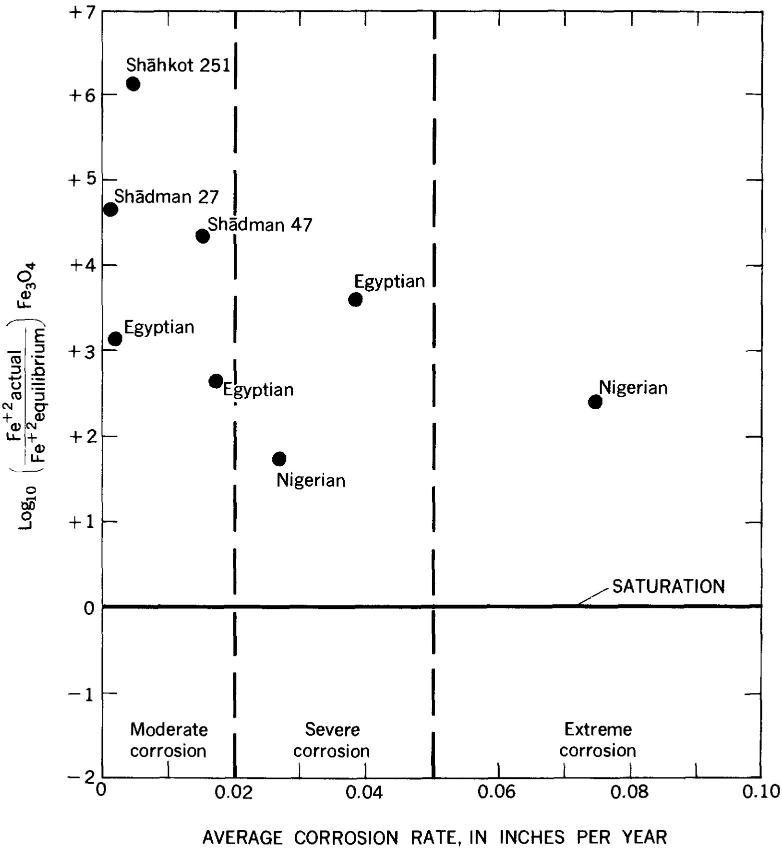


FIGURE 31.—Relation of corrosion to equilibrium state, Fe_3O_4.

($FeCO_3$), although this is a troublesome encrustant in steel-cased water wells, and particularly so in the Indus Plains.

Other interesting relationships between ground-water qualities and effects on steel well parts also are evident in equilibrium data of table 4. From the standpoint of corrosion, it is significant that virtually all anaerobic waters represented by the diagram in figures 28–34 are undersaturated with ferrous hydroxide [$Fe(OH)_2$], a primary product of corrosion of steel, and iron metal, the material undergoing solution in steel systems. Undersaturation with ferrous hydroxide and iron metal indicate capacity of the water for dissolving iron, and one would expect corrosion in such an environment unless there are inhibiting processes. All waters were supersaturated with Fe_3O_4 and unsaturated with Mn_3O_4—the highest concentrations occurring in the least corrosive wells in each case. The fact that waters slightly supersaturated

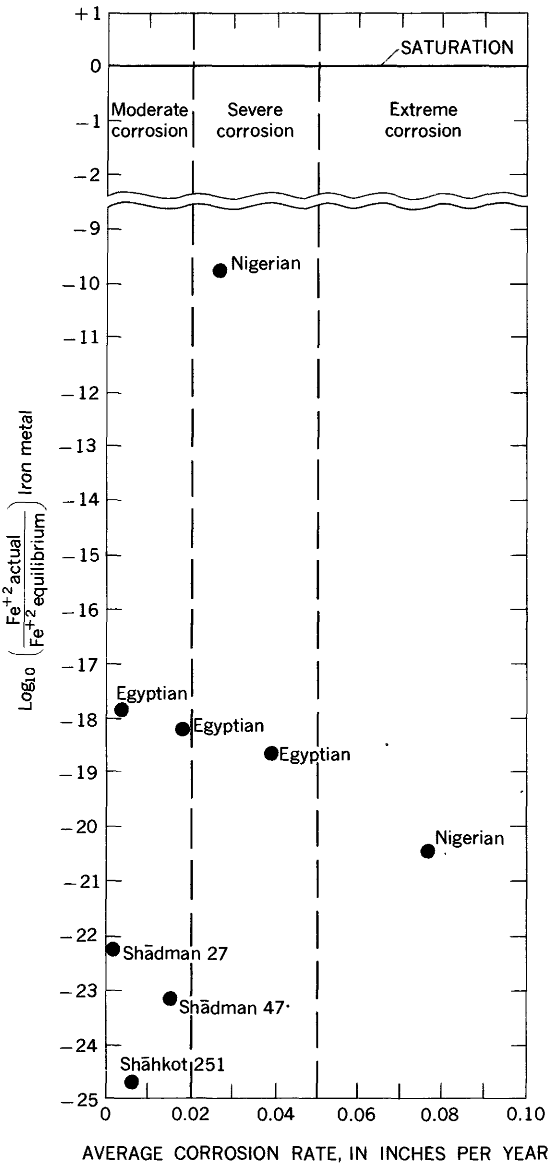


Figure 32.—Relation of corrosion to equilibrium state, Fe.

with ferric hydroxide [$Fe(OH)_3$], as judged from analysis of well-head samples, cause relatively mild corrosion of steel, whereas much more serious damage occurs in waters undersaturated with this species,

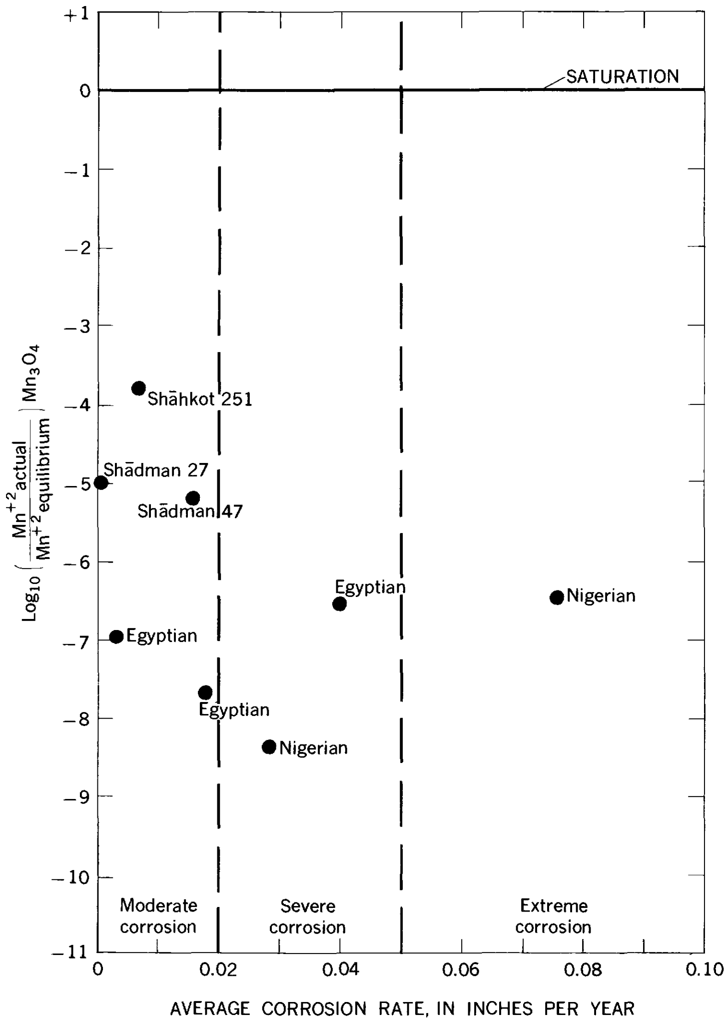


FIGURE 33.—Relation of corrosion to equilibrium state, Mn_3O_4.

probably is significant. However, the true relationship of this metastable phase to corrosion processes has not yet been determined.

It is evident in table 4 that practically all waters tested in SCARP–1 were supersaturated with siderite and calcite—the supersaturation factors of these materials range from 1.08–12.16. Field experience suggests that supersaturation above a factor of 2 is likely to cause mineral deposition, either spontaneously or in combination with some reaction that serves as a catalyst. The relative rates of deposition from waters with various levels of supersaturation are unknown because catalytic

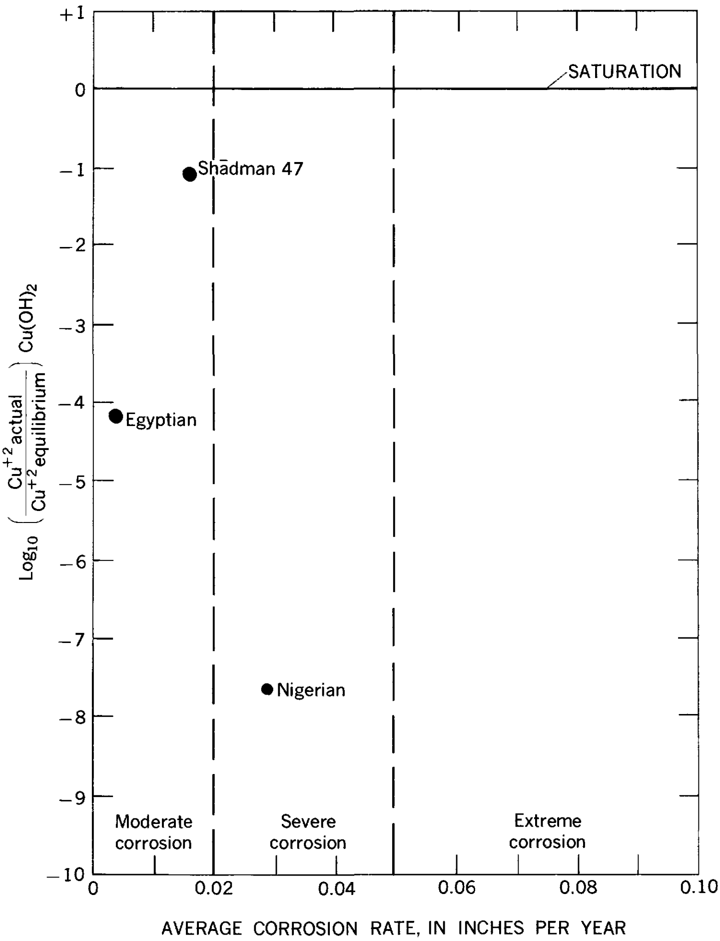


FIGURE 34.—Relation of corrosion to equilibrium state, $Cu(OH)_2$.

and kinetic factors still are poorly understood. However, it is well established that both siderite and calcite are troublesome encrustants in the Indus Plains.

It is probably significant that thermodynamic analysis showed only one stable phase (calcite) to behave as predicted from stable equilibrium considerations. All other solids found as precipitates in the Pakistan wells are metastable phases. In other words they are not the least soluble phases possible in the chemical system studied. Siderite ($FeCO_3$) and ferric hydroxide [$Fe(OH)_3$] appear to behave approximately as would be predicted from equilibrium considerations, but both are metastable, and the presence of neither would be expected if

TABLE 4.—*Equilibrium data, selected*

Well name and No.	Measured cation concentration / Cation concentration at equilibrium = cation ratio		
	$CaCO_3$	Iron, Fe	$Fe(OH)_2$
Khaipur 12	2.1831	3.4338×10^{-23}	3.6049×10^{-4}
Khāngrā Dogran 73	1.3614	5.9539×10^{-25}	2.6568×10^{-4}
72	1.4204	6.1772×10^{-24}	3.1960×10^{-4}
71	8.1153×10^{-1}	2.2996×10^{-24}	4.1210×10^{-4}
Lyallpur 54	2.0313	2.2453×10^{-24}	3.8965×10^{-4}
Mona 53	1.6977	1.1416×10^{-22}	1.0814×10^{-3}
83	4.0306	2.4334×10^{-24}	2.4445×10^{-4}
113	1.0305	2.6527×10^{-30}	2.2103×10^{-4}
Phālia 65	2.2398	3.6698×10^{-23}	2.5658×10^{-3}
66	1.2910	2.8369×10^{-22}	7.1126×10^{-4}
81	9.0021×10^{-1}		
88	1.5441	6.1496×10^{-26}	1.7011×10^{-4}
89	1.5343		
101	1.5884		
Sāngla Hill 2	9.6410×10^{-1}	1.0944×10^{-36}	4.4690×10^{-4}
Shādman 16	1.7436	6.0579×10^{-24}	3.2303×10^{-4}
17	2.1215	2.9641×10^{-23}	8.0622×10^{-4}
27 (1964)	1.8475	7.1861×10^{-22}	1.7170×10^{-3}
27 (1965)	1.6741	6.1218×10^{-23}	5.1472×10^{-4}
34	1.9612	1.1097×10^{-23}	3.4715×10^{-4}
40	7.9397×10^{-1}	2.6473×10^{-22}	4.8150×10^{-4}
45	1.7583	3.7583×10^{-23}	4.4195×10^{-4}
46	1.6019		
47	1.6983	7.4560×10^{-24}	1.6248×10^{-4}
48	1.9266	1.8853×10^{-22}	5.4601×10^{-4}
50	1.8897	1.9762×10^{-23}	5.8672×10^{-4}
81	1.3500	6.1822×10^{-22}	7.0617×10^{-4}
Shāhkot 16	1.4670		
20A	1.5036		
213A	7.7976×10^{-1}		
251	1.0762		
252	1.1688		
Zafarwāl 1	1.9598	1.0818×10^{-22}	1.5179×10^{-4}
4	2.1122	6.3399×10^{-24}	4.3309×10^{-4}
6	2.4461	1.5397×10^{-22}	1.0522×10^{-3}
7	2.2377	3.8583×10^{-23}	5.9821×10^{-4}
11	1.8537	4.5795×10^{-22}	3.8267×10^{-4}
16	1.7545	1.1779×10^{-22}	5.2677×10^{-4}
17	2.0059	1.6004×10^{-22}	7.4707×10^{-4}
27	2.8341	1.4138×10^{-22}	1.0730×10^{-3}
121A	1.4103		
142	2.7010	1.0405×10^{-21}	1.0006×10^{-3}
159	2.1242	2.1868×10^{-22}	6.9496×10^{-4}
367	1.7723		

minerals, West Pakistan wells

Measured cation concentration / Cation concentration at equilibrium = cation ratio—Continued			
$Fe(OH)_3$	$FeCO_3$	Fe_2O_3	Fe_3O_4
5.4924	1.6152	1.8528×10^{6}	3.8835×10^{4}
2.7384×10^{1}	1.0434	9.0502×10^{6}	1.0026×10^{5}
1.1217×10^{1}	1.0886	3.7071×10^{6}	5.8812×10^{4}
2.1079×10^{1}	8.7524×10^{-1}	7.9809×10^{6}	1.1194×10^{5}
2.1169×10^{1}	3.5682	7.6818×10^{6}	1.0552×10^{5}
1.3726×10^{1}	5.6111	4.9807×10^{6}	1.1108×10^{4}
1.0896×10^{1}	2.0393	3.7916×10^{6}	5.5595×10^{4}
4.8678×10^{3}	2.4698×10^{-1}	1.8431×10^{9}	3.4233×10^{6}
8.5178×10^{1}	1.2158×10^{1}	3.1570×10^{7}	5.1123×10^{5}
4.3032	7.4655	1.6293×10^{6}	4.6552×10^{4}
-----	-----	-----	-----
3.6205×10^{1}	1.6618	1.3278×10^{7}	1.1572×10^{5}
-----	-----	-----	-----
-----	-----	-----	-----
3.3201×10^{7}	5.0260×10^{-1}	1.2843×10^{13}	1.5912×10^{9}
1.0490×10^{1}	1.6705	3.6504×10^{6}	5.9484×10^{4}
1.8351×10^{1}	4.3458	6.4528×10^{6}	1.1839×10^{5}
1.1802×10^{1}	4.8228	4.1071×10^{6}	1.1230×10^{5}
6.8893	1.3141	2.3482×10^{6}	5.1399×10^{4}
8.9623	1.8960	3.0548×10^{6}	5.3715×10^{4}
2.9975	1.6253	1.0217×10^{6}	2.8863×10^{4}
6.7395	3.1852	2.3453×10^{6}	4.9168×10^{4}
-----	-----	-----	-----
3.3728	9.6191×10^{-1}	1.1737×10^{6}	2.2202×10^{4}
4.2892	4.6563	1.4620×10^{6}	3.8221×10^{4}
1.4216×10^{1}	3.7988	4.9472×10^{6}	8.8881×10^{4}
3.4838	1.7955	1.1874×10^{6}	3.6250×10^{4}
-----	-----	-----	-----
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-----	-----	-----	-----
9.6116×10^{-1}	3.8352×10^{-1}	3.0194×10^{5}	8.4700×10^{3}
1.7146×10^{1}	2.0478	5.7252×10^{6}	8.7267×10^{4}
1.4705×10^{1}	2.5589	4.6193×10^{6}	9.9527×10^{4}
1.1283×10^{1}	2.0921	3.7674×10^{6}	7.3527×10^{4}
1.6147	2.2675	5.5036×10^{5}	1.7700×10^{4}
5.3362	4.0214	1.7818×10^{6}	4.2780×10^{4}
7.1778	4.3425	2.4978×10^{6}	6.1083×10^{4}
1.3543×10^{1}	7.3636	4.6354×10^{6}	1.0347×10^{5}
-----	-----	-----	-----
4.4457	6.9841	1.5311×10^{6}	4.8409×10^{4}
5.8257	3.5336	1.9653×10^{6}	5.0269×10^{4}
-----	-----	-----	-----

only the most stable phases were considered. Why metastable phases precipitate in these wells, and by what route stable phases eventually would be formed, cannot be explained on the basis of present data. Regardless of this fact, the data do provide an explanation for the presence of siderite and calcite encrustants and thus provide a plausible explanation for the observed clogging of screens.

CHEMICAL INTERACTIONS

Chemical interactions undoubtedly are largely responsible for water-well problems in the Indus Plains. Corrosion processes alter the composition of aqueous films covering the cathodic and anodic areas of corrosion cells, and these changes probably are sufficient to cause mineral precipitation from water which is at or near saturation with calcite, siderite, or other troublesome encrustants. Precipitated minerals, in turn, cause differences on the metal surfaces by shielding some areas while leaving others unprotected, thereby creating new electrolytic cells. Interactions of this kind are likely to be most significant in mildly corrosive waters like those of the SCARP-1 wells, where concentrations of troublesome minerals are at or above saturation, and metal loss by corrosion, even in the most susceptible areas, is too slow to prevent adherence of solids precipitated by electrode reactions and other processes. Rapid encrustation of idle wells between the period of delevopment and the period of approval testing undoubtedly is the result of catalytic effects of corrosion. Figure 35 shows reason-

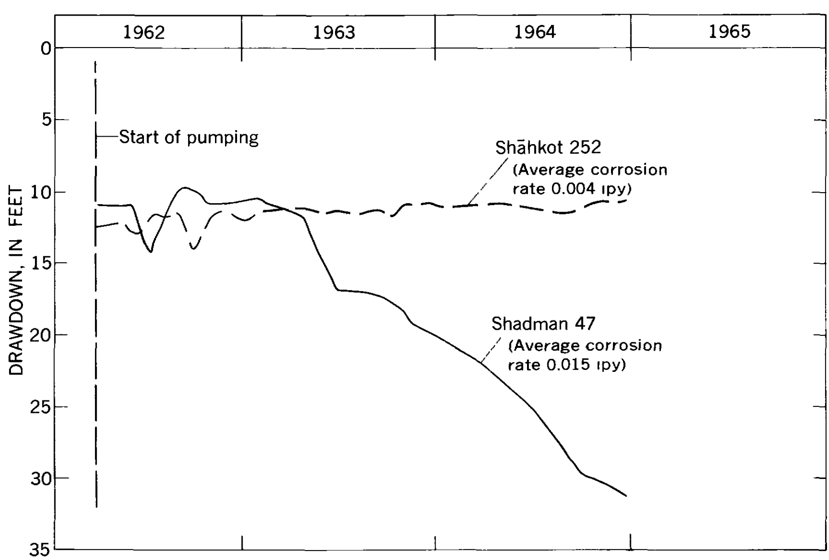

FIGURE 35.—Performance record of corrosion test wells, SCARP-1.

ably good correlation between performance records and corrosion data for two wells checked with corrosion probes. Preferential corrosion of the casing slots is the most probable cause of heavy mineral encrustation in these areas, where it is least tolerable. The fact that both corrosion and mineral encrustation are far more prevalent on the relatively stagnant exterior of the casing than on the interior surfaces can be explained on this basis. Inert surfaces, such as stainless steel or plastic, are less likely to encrust because chemical interactions are minimized. Performance data in table 5 show that steel wells in certain areas lose as much as 80 percent of original capacity during a few months of idleness between development and performance testing, whereas fiber-glass wells generally retain approximately their original capacities under similar conditions. Apparent increases in these capacity data resulted from change of datum point due to well-house construction. The marked variations in performance among the test areas indicates the importance of slight quality differences and kinetic factors.

CORROSION CONTROL TREATMENTS

Corrosion of steel can be controlled by protecting the metal surface with an inhibiting chemical or impervious coating; by eliminating depolarizing agents from the system; by counteracting corrosion current with an external current source (cathodic protection); by providing a sacrificial anode, which corrodes in preference to the steel well part; or by minimizing effects of dissolved carbon dioxide and unfavorable Eh-ph relationships through addition of an alkaline chemical. These treatments are not very practicable for a water well, and they are not considered promising for corrosion control in ground-water systems of the Indus Plains. Surface coatings, such as bitumastic paint, enamels, and epoxy resins invariably provide very poor coverage of the sharp edges of filter pipe openings, where corrosion is likely to be most severe and corrosion damage least tolerable. Even the best coating is subject to damage during transport and installation of well parts, and corrosion is concentrated and accelerated in damaged areas unless secondary protective treatment, such as cathodic protection, is available.

Theoretically, cathodic protection is capable of counteracting the total electrolytic current generated by local and long-line corrosion sells. However, no practical use has been made of the process in these wells because theoretical considerations and experience show that it will not prevent corrosion within the screen slots. Also, overcharging because of improper current control would increase pH in cathodic areas and could accelerate encrustation. Placing sacrificial electrodes inside the well casings involves high cost and difficult engineering problems.

Chemical treatment with film-forming inhibitors, such as sodium silicate, and neutralizers, such as lime, would not be economically feasible for irrigation wells of this type. Down-hole injection of chemicals involves expensive pumping equipment, and the cost of chemicals alone probably would exceed the cost of well replacement in only a few years of operation.

Sterilization with chlorine, hypochlorite, formaldehyde, copper sulfate, or other bactericide to eliminate sulfate-reducing bacteria and their depolarizing effects is not very promising. With the exception of copper sulfate, these treatments are not expected to have lasting effect, and even the copper treatment has proved to be of little or no value in West Pakistan. If sulfate-reducing bacteria introduced through well openings invade the aquifers, reinfection of wells may occur soon after the sterilizing chemical has been flushed away.

For these many reasons, corrosion control is far less promising than reliance on rehabilitation and use of materials other than steel which are less susceptible to corrosion and encrustation.

MAINTENANCE AND REHABILITATION

Approximately 10 percent of the water wells in SCARP–1 area of the Indus Plains have deteriorated rapidly enough that rehabilitation has been required to maintain adequate productivity. Both blasting (fig. 36) and chemical cleaning have been tried, and only the former has been effective. Blasting is effected by suspending explosive rope (primacord) in the well and detonating it with an electric spark so that an exposion occurs simultaneously throughout the slotted part of the well casing. This is intended to blast out the slot plugs, leaving in their places the enlarged openings resulting from whatever metal wasting occurred since installation or the last rehabilitation treatment. Blasting sometimes restores capacity to near that of the original well; however, its effectiveness may be quite temporary, as shown in figure 37, and capacity decline after blasting is common. Repeated blasting can be expected to lead to abnormal openings in the filter section, collapse of gravel shroud, and sand pumping problems.

Both hydrochloric acid and sulfamic acid have been tried without success in chemical cleaning of encrusted water wells in SCARP–1. In every case the acid component has been poured into and mixed with the water of the well at ambient temperature, which always is far below the optimum temperature for maximum effectiveness of chemical cleaning. In at least one case serious frothing of the well occurred, and capacity after treatment was even less than before.

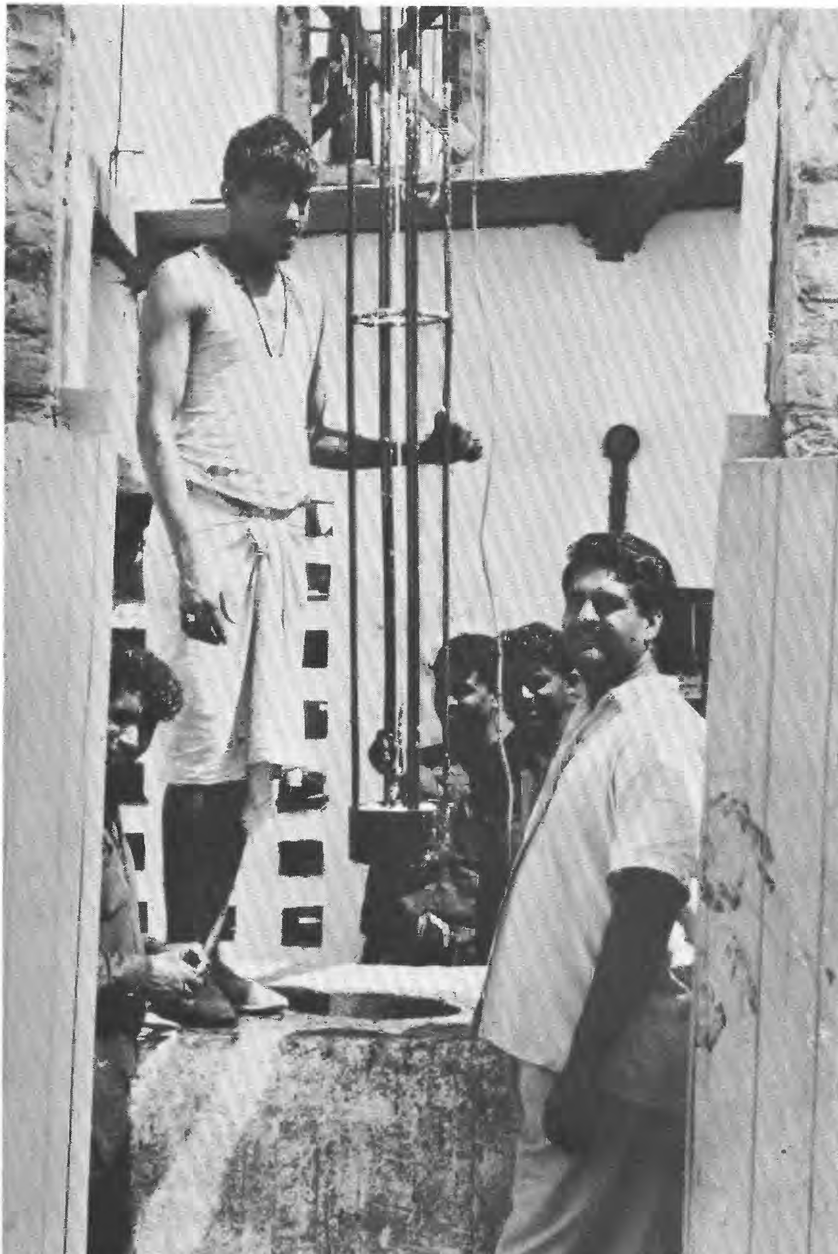

FIGURE 36.—WAPDA personnel installing primacord to blast encrusted well.

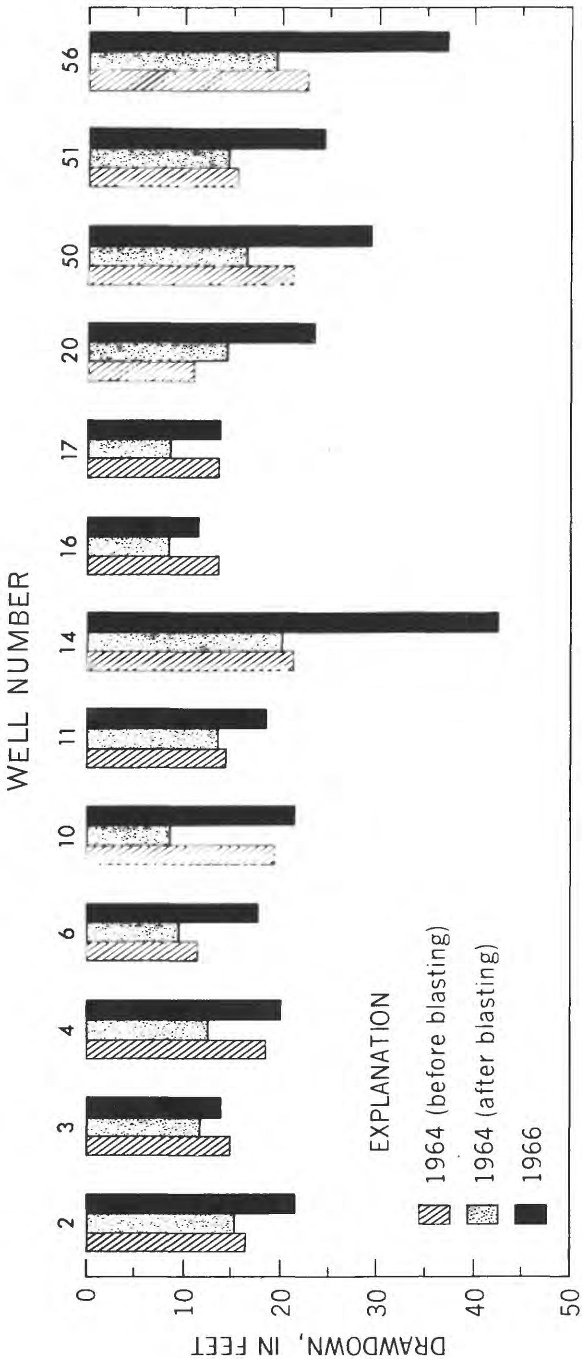

FIGURE 37.—Effect of blasting on well performance, Shadman wells, SCARP-1.

To improve the effectiveness of chemical cleaning, it would be necessary to maintain higher well-water temperatures, either with downhole immersion heaters or by recirculating the cleaning solution in a heated surface tank, as discussed by Clarke and Barnes (1964). In either case the well water must be analyzed periodically to insure maintenance of sufficient concentration of acid for effective chemical reaction. Such treatment is difficult and expensive in a remote well site. For this reason mechanical rehabilitation of some kind always is likely to be more practical. Other mechanical treatments, some already tried, include high frequency vibration, high pressure surging, and mechanical hammering. These have not proven to be as practicable and as effective as primacord blasting in West Pakistan. The bore holes are too small to accept the high energy packages recommended for effective high frequency treatment. High pressure surging of the long filter sections requires installation of packers which considerably increases the time and cost of cleaning.

Regardless of the rehabilitation method employed, gradual deterioration of steel-casing slots eventually will lead to poor screening and related troubles. Problems of this kind have been overcome in other parts of the world (for example, the Chad Basin of Nigeria) by inserting noncorrodible plastic casings and corrosion-resisting screens within the damaged well. In the water wells of West Pakistan it may be possible to use the same method by first perforating the damaged screen with a down-hole cutter and then inserting slotted fiber glass, slotted polyvinyl choride plastic, or other noncorrodible filter section. The success of a rehabilitation method of this kind depends upon opening enough area in the original screen to prevent rapid resealing of the openings with encrustants. In other words, the cutter must produce large holes.

Leakage of the gravel shroud and aquifer sand into the annulus between the original casing and the insert may not be a problem if clogging of openings in the original steel casing does not occur. However, there is the possibility that corrosion catalyzed encrustation may spread from the old steel member into gravel both inside and outside the original casing and thereby reduce flow. Thus, practicability of the method should be determined on an experimental basis before large-scale repair by this method is attempted.

IMPROVED MATERIALS OF CONSTRUCTION

Because of sensitivity to both aerobic and anaerobic environments, steel is seldom the best choice for well construction material where critical dimensions must be maintained for long periods of service. The tendency of corrosion to catalyze encrustation reactions makes it a particularly undesirable construction material for well screens in Pakistan, where ground waters are supersaturated with several troublesome mineral species. A number of alternate alloys are more resistant than plain carbon steel to corrosion in the waters involved, but most of them have little advantage when all factors, including cost, are considered. Aluminum, common yellow brass, red brass, manganese-silicon bronze (Everdur), and cupronickel alloys, such as Monel, range from 2–10 times the cost of plain carbon steel, depending on component design and availability of the alloy at the point of use. High copper alloys, such as the red brass, Everdur bronze, and cupronickel, are attacked rather readily by free carbon dioxide and sulfide ion, but should be adequate for use in the Indus Plains, if it were not for their high costs. Aluminum would be much more durable than steel, but some pitting would occur because of traces of copper, which are rather common in the ground-water system. Yellow brass, a locally available product, has adequate corrosion resistance for long-term service, but it undergoes mild corrosion and some encrustation of screen slots—a problem which has been intensified by the relatively narrow slots used in local filter pipe constructed from this material. Resin-bonded hydraulic plywood casing and slotted filter pipe is being used on an experimental basis in the Indus Plains. Cost of the experimental pipe is 4–5 times that of mild steel filter pipe. Joints are cumbersome and the rather thick wall tends to promote clogging. Durability is not yet known.

Of all materials considered, stainless steel (chromium-nickel steel) and epoxy resin-bonded fiber glass are the most attractive for use in ground waters of the Indus Plains. Both resist corrosion and corrosion-catalyzed encrustation. Stainless steel has greater strength. Its blank-pipe cost is approximately equal to that of fiber glass at the time of this reporting, but installed cost of stainless filter pipe may be several times that of installed fiber glass because of differences in filter-pipe design and handling costs.

Type 304 stainless-steel well screen containing approximately 18 percent chromium and 8 percent nickel has an excellent history of reliable performance in aggressive ground water in many parts of the world. In recent years a less expensive stainless steel with 11.5 percent chromium and 4.5 percent nickel has shown considerable promise in corrosive ground-water service. Wire-wrapped stainless-steel screens like the one shown in figure 38 are undergoing tests in the Sind area of West Pakistan.

Since 1964 Tipton and Kalmbach, Inc. (Technical Consultants to West Pakistan) has conducted and encouraged extensive development research on fiber-glass pipe to improve it for use as a water-well con-

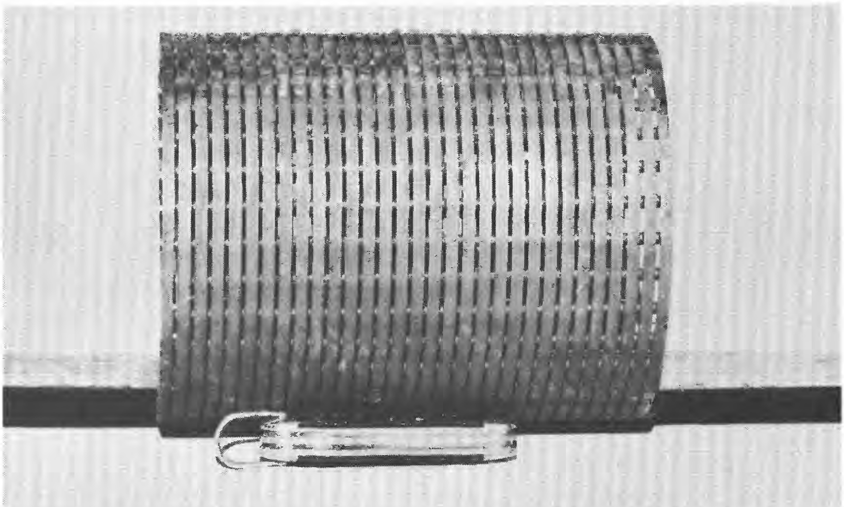

FIGURE 38.—Wire-wrapped stainless-steel well screen. Test specimen supplied by UOP-Johnson Division.

struction material. The product is available in two principal types, centrifugally-cast and mandrel-wrapped. However, only the latter has been used in water wells of West Pakistan. In centrifugal casting, resin is injected into a rotating mold lined with layers of glass fiber. Centrifugal force drives resin and fiber against the mold to form a plastic pipe. The desired wall thickness is obtained by varying the thickness of fiber layers and the quantity of resin. In the mandrel-wrapped variety, glass cloth generally is spiralled around the mandrel, first in one direction and then in another, to provide a crisscross pattern. However, some recent designs combine longitudinal and circumferential fibers in order to minimize loss of fiber strength in saw slotting of filter pipe. Pipe joints can be made with conventional threaded couplings, with epoxy cemented couplings, or with specially-designed key locks of the type shown in figure 39. O-ring seals can be added to key-locked joints if complete absence of leakage is desirable. Coupling with threaded fitting and epoxy-bonded joints is relatively slow and plastic threads are easily jammed and damaged by debris. The lock joint specifically designed for the West Pakistan wells is strong and easily assembled. Ten-inch-diameter pipes coupled in this fashion have withstood 50,000–60,000 pounds of tensile load, and recent laboratory tests suggest that similar assemblies can be made to withstand tensile loading of 100,000 pounds or more.

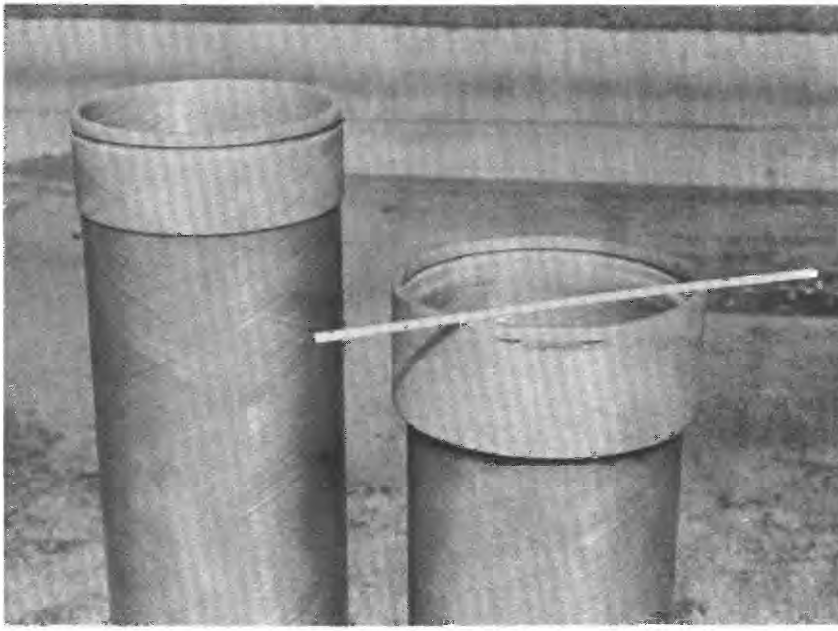

FIGURE 39.—Fiber-glass well casing with key lock. Courtesy Koppers Co., Organic Materials Division.

Physical testing of fiber-glass pipe in uncut form by Tipton and Kalmbach, Inc., Denver, Colo., using sand presses and other conventional equipment, shows that its collapse strength in 0.18-inch wall thickness is adequate for use in water wells of West Pakistan (up to 400 ft deep). Saw-slotting longitudinally or transversally in a pattern similar to that shown in figure 40 reduces crushing strength significantly, sometimes by as much as 25 percent, but such pipe still is sufficiently strong for use in the relatively shallow wells of the Indus Plains.

As supplied by the mill in uncut form, fiber-glass pipe is very resistant to water as well as to a great variety of aqueous solutions. Extensive boiling water tests and hydraulic pressure tests made by Tipton and Kalmbach and fiber-glass manufacturers have not disclosed any significant weakness attributable to saw slotting (excessive water adsorption or exfoliation). More experience with field installations like those in West Pakistan will be required to demonstrate its expected durability in ground-water environments. Detailed information on development, testing, and use of fiber-glass pipe in West Pakistan wells has been prepared by Tipton and Kalmbach, Inc. (1967).

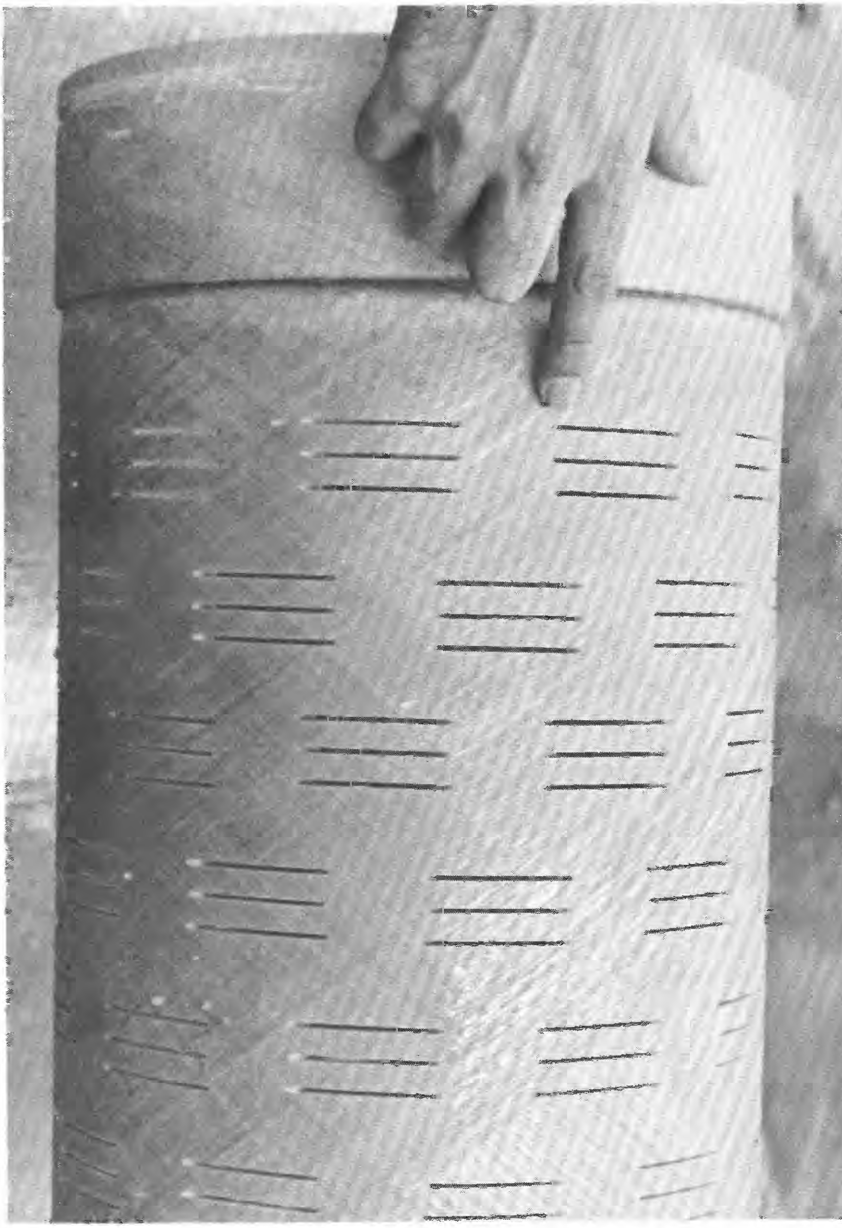

FIGURE 40.—Saw-slotted fiber-glass well casing. Courtesy Koppers Co., Organic Materials Division.

The basic cost of casing for the 800 10-inch-diameter fiber-glass wells installed in West Pakistan from 1964 to the time of this report was approximately 2.5 times that of mild steel casing. However, because of the ease of handling and the speed with which fiber-glass pipe can be assembled and the wells completed, the actual cost of new well construction using slotted fiber-glass fitter pipe is approximately equal to that of construction with steel. Thus, fiber glass appears to be competitive with mild steel for future well-field developments in West Pakistan provided it proves to be durable.

As stated earlier in this report, experience with fiber-glass well pipes to date suggests that the inert surface of this material is resisting mineral encrustation as well as corrosion, presumably by minimizing catalytic effects and surface effects. In some areas, where both fiber glass and mild steel have been installed, idle fiber-glass wells have retained approximately original capacities whereas idle mild steel wells show significant capacity losses (see table 5). Whether fiber glass will continue to resist encrustation when pumping begins remains to be seen. If corrosion, rather than pressure reduction, is the principal triggering mechanism for encrustation, which could be the case, the use of fiber-glass plastic or other inert construction materials should markedly improve long-term well performance and greatly reduce the need for continuing rehabilitation of wells.

TABLE 5.—*Effects of ground water on idle water wells, Upper Jhelum subproject, West Pakistan (1965–66)*

[Well designation: PH, Phalia unit; SO, Sohawa unit; BS, Busal unit. S, steel well; F, fiber-glass well. Number of idle months is period between development and acceptance testing with portable generator equipment. Specific capacity in gallons per minute per foot of drawdown. No steel wells were tested in the Busal unit]

Well	Material	Number of months idle	Specific capacity		
			When developed	When tested	Percentage of retention
PH–4	S	16	30.4	20.3	66.8
PH–7	S	17	39.2	11.7	29.8
PH–10	S	16	42.6	26.1	61.3
PH–14A	S	18	42.5	32.6	76.7
PH–16	S	18	56.1	30.5	54.4
PH–20A	S	18	38.5	15.2	39.5
PH–24	S	19	102.1	20.5	20.1
PH–24A	S	18	62.2	20.1	32.3
PH–33	S	17	32.0	16.1	50.3
PH–33A	S	18	57.6	31.6	54.9
PH–34	S	18	44.7	15.3	34.2
PH–35	S	18	75.1	27.6	36.8
PH–36	S	18	94.0	80.5	85.6
PH–37	S	16	106.5	34.8	32.7
PH–49	S	19	100.3	33.6	33.5

TABLE 5.—*Effects of ground water on idle water wells, etc.*—Continued

Well	Material	Number of months idle	Specific capacity		
			When developed	When tested	Percentage of retention
PH-75	F	5	75. 4	78. 7	104. 4
PH-76	F	6	57. 5	64. 4	112 0
PH-77	F	7	70. 9	78. 9	111. 3
PH-78	F	6	52. 8	55. 4	104. 9
PH-78A	F	6	79. 0	80. 1	101. 4
PH-79	F	6	55. 2	56. 5	102. 4
PH-80	F	7	57. 3	60. 9	106. 3
PH-82	F	6	81. 1	85. 4	105. 3
PH-82A	F	6	77. 3	84. 1	108. 8
PH-85	F	6	73. 8	78. 6	106. 5
PH-86	F	6	69. 4	117. 7	169. 6
PH-90	F	6	61. 0	60. 8	99. 7
PH-91	F	6	74. 6	74. 5	99. 9
PH-92	F	6	86. 0	76. 7	89. 2
PH-94	F	5	101. 8	103. 7	101. 9
PH-180	F	6	117. 7	119. 0	101. 1
PH-181	F	6	149. 0	153. 4	103. 0
PH-182	F	6	157. 7	153. 0	97. 0
PH-183	F	6	127. 7	129. 4	101. 3
PH-184	F	6	141. 0	147. 7	104. 8
PH-198	F	5	111. 5	105. 9	95. 0
PH-199	F	5	111. 8	121. 0	108. 2
PH-200	F	4	145. 6	153. 7	105. 5
PH-201	F	5	121. 9	122. 9	100. 8
PH-202	F	5	146. 1	157. 8	108. 0
PH-203	F	4	152. 5	159. 5	104. 6
PH-205	F	4	113. 3	121. 7	107. 4
PH-207	F	4	115. 0	118. 4	103. 0
PH-210	F	5	121. 4	126. 5	104. 2
PH-211	F	4	130. 8	142. 5	108. 9
PH-212	S	7	96. 2	108. 3	112. 6
PH-214	S	8	117. 2	110. 6	94. 4
PH-215	S	8	121. 1	131. 1	108. 3
PH-216	S	8	103. 2	107. 3	104. 0
PH-217	S	8	101. 3	104. 2	102. 9
PH-218	S	8	139. 3	138. 6	99. 5
PH-220	S	7	118. 9	118. 6	99. 7
PH-221	S	8	129. 3	141. 7	109. 6
PH-222	S	8	110. 7	127. 9	115. 5
PH-223	S	8	152. 5	167. 5	109. 8
PH-224	S	8	89. 5	95. 3	106. 5
PH-227	S	8	163. 3	167. 3	102. 4
PH-228	S	7	145. 6	150. 3	103. 2
PH-230	S	8	101. 7	114. 6	112. 7
PH-231	S	8	110. 7	119. 4	107. 9

TABLE 5.—*Effects of ground water on idle water wells, etc.*—Continued

Well	Material	Number of months idle	Specific capacity		
			When developed	When tested	Percentage of retention
SO-8	S	12	86. 9	64. 4	74. 1
SO-8A	S	11	77. 3	53. 7	69. 5
SO-9	S	11	72. 5	54. 2	74. 8
SO-20A	S	8	48. 5	32. 8	67. 6
SO-21	S	15	47. 8	36. 4	76. 2
SO-21A	S	6	39. 2	30. 8	78. 6
SO-23	S	7	55. 3	36. 0	65. 1
SO-23A	S	7	48. 3	35. 7	73. 9
SO-24	S	4	62. 0	43. 7	70. 5
SO-25	S	11	77. 2	66. 1	85. 6
SO-26	S	14	53. 9	36. 2	67. 2
SO-27	S	8	80. 2	44. 2	55. 1
SO-27A	S	8	65. 7	47. 2	71. 8
SO-29	S	7	97. 6	59. 9	61. 4
SO-30	S	7	74. 8	72. 4	96. 8
SO-30A	S	9	73. 3	70. 2	95. 8
SO-41	S	11	101. 7	104. 5	102. 8
SO-42	S	12	94. 0	94. 9	101. 0
SO-43	S	11	113. 9	73. 1	64. 2
SO-44	S	8	97. 5	96. 5	99. 0
SO-45	S	13	60. 9	64. 0	105. 1
SO-46	S	8	74. 7	73. 8	98. 8
SO-47	S	10	58. 8	48. 6	82. 7
SO-48	S	8	65. 4	50. 6	77. 4
SO-49	F	13	68. 7	64. 5	93. 9
SO-50	F	7	65. 8	70. 6	107. 3
SO-51	S	9	52. 9	52. 1	98. 5
SO-53	S	13	59. 7	50. 3	84. 3
SO-56	F	10	59. 3	59. 1	99. 7
SO-57	F	9	77. 4	78. 0	100. 8
SO-58	F	14	74. 4	75. 8	101. 9
SO-59	F	8	83. 3	82. 5	99. 0
SO-60	F	9	52. 0	57. 0	109. 6
SO-61	F	10	48. 9	48. 6	99. 4
SO-62	F	10	85. 3	84. 8	99. 4
SO-64	F	10	58. 7	59. 8	101. 9
SO-65	F	10	61. 1	52. 3	85. 6
SO-66	F	9	103. 1	109. 5	106. 2
SO-67	F	10	105. 3	115. 2	109. 4
SO-68	F	9	84. 6	91. 0	107. 6
SO-69	F	10	92. 9	83. 5	89. 9
SO-70	F	12	102. 3	102. 4	100. 1
SO-71	F	10	68. 2	72. 4	106. 2
SO-73	F	9	82. 0	79. 8	97. 3
SO-74	F	9	100. 5	97. 8	97. 3
SO-75	F	9	111. 0	108. 8	98. 0

TABLE 5.—*Effects of ground water on idle water wells, etc.*—Continued

Well	Material	Number of months idle	Specific capacity: When developed	Specific capacity: When tested	Specific capacity: Percentage of retention
SO-76	F	10	74.6	68.1	91.3
SO-77	F	10	130.9	123.7	94.5
SO-78	F	10	118.2	100.0	84.6
SO-80	F	10	54.5	56.6	103.9
SO-81	F	12	73.0	79.8	109.3
SO-82	F	9	63.8	64.4	100.9
SO-83	F	9	69.1	73.1	105.8
SO-84	F	9	136.1	135.0	99.2
SO-85	F	10	61.7	59.3	96.1
SO-85A	F	10	70.9	79.5	112.1
BS-1	F	9	130.3	145.0	111.3
BS-2	F	9	178.9	205.7	115.0
BS-3	F	11	142.6	158.5	111.2
BS-4	F	11	128.8	156.8	121.7
BS-5	F	13	124.4	125.8	101.1
BS-40	F	11	138.2	156.5	113.2
BS-42	F	9	152.5	169.2	111.0
BS-43	F	9	103.6	115.8	111.8
BS-44	F	9	81.3	87.6	107.7
BS-45	F	9	103.3	113.7	110.1
BS-81	F	10	91.4	97.6	106.9
BS-82	F	10	129.5	145.2	112.1
BS-83	F	8	150.8	169.5	112.4
BS-94	F	5	100.4	150.8	150.2
BS-95	F	5	109.2	123.0	112.6
BS-149	F	5	118.9	132.8	111.7
BS-150	F	9	87.8	89.4	101.8
BS-151	F	9	128.3	132.5	103.3
BS-152	F	9	119.7	121.2	101.3
BS-154	F	8	132.7	139.2	104.9
BS-191	F	6	104.9	112.6	107.3
BS-192	F	6	101.4	112.0	110.5
BS-193	F	6	107.8	122.9	114.0
BS-194	F	6	86.9	100.0	115.1
BS-195	F	6	99.3	115.0	115.8
BS-223	F	8	75.0	119.0	158.7
BS-224	F	8	110.7	115.7	104.5
BS-225	F	8	107.2	120.6	112.5
BS-226	F	8	116.8	126.3	108.1
BS-227	F	9	148.6	159.5	107.3

SUMMARY

Ground water of the Indus Plains varies considerably in solute concentration and ionic balance, but much of it is supersaturated with troublesome minerals, such as calcite, siderite, and ferric hydroxide. Most of the wells covered by this report are anaerobic (air free), and sulfate-reducing bacteria and their products, sulfide ion and metallic sulfide compounds, are rather prevalent. The waters tested so far are corrosive enough to cause objectionable changes in dimensions of mild steel casing slots and to encourage mineral encrustation, but are not corrosive enough to cause intolerable damage on blank casings and pumps.

High cost, engineering difficulties, and probability of adverse chemical reactions make it impracticable to overcome corrosion and encrustation problems through the use of protective coatings, chemical treatments, or cathodic protection, and chemical sterilization for minimizing bacterial attack has not yielded promising results. Theoretical considerations and short-term experience suggest that construction of slotted filter pipes and screens from corrosion-resisting materials, such as fiber-glass plastic and stainless steel, will minimize encrustation as well as corrosion, and use of fiber-glass plastic appears to be the most economically feasible alternative at present. Some encrustation is likely to occur regardless of the construction material used, and both corrosion and encrustation will continue to plague existing steel-cased wells. These problems must be overcome by mechanical or chemical cleaning and either repair or periodic replacement of wells. The water-quality tests now in use are capable of identifying the areas which are most likely to be tolerant to steel-cased wells—those with high Eh and pH and with low CO_2, sulfide, and ferrous ions. The same tests are adequate for systematically monitoring areal changes in water quality as dewatering continues and for providing data against which to compare performance of alternate construction materials. Periodic removal and examination of slotted fiber-glass pipe is the best means of assessing long-term performance of this new and promising product.

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