SALT DISSOLUTION IN OIL AND GAS TEST HOLES IN CENTRAL KANSAS

Part I: Salt Beds in the Subsurface in Russell,
Lincoln, Ellsworth, Barton and Rice
Counties, Central Kansas

Robert F. Walters
Walters Drilling Company
Wichita, Kansas

June 1975

This report was prepared by Robert F. Walters under Purchase Order Subcontract 78X-38283V with Union Carbide Corporation, Nuclear Division. The subcontract was administered by Oak Ridge National Laboratory.

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By Robert F. Walters

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SALT DISSOLUTION IN OIL AND GAS TEST HOLES IN CENTRAL KANSAS

PART I: SALT BEDS IN THE SUBSURFACE IN RUSSELL, LINCOLN, ELLSWORTH, BARTON AND RICE COUNTIES, CENTRAL KANSAS

ROBERT F. WALTERS

Wichita, Kansas

ABSTRACT

The Hutchinson Salt Member of the Permian Wellington Formation is described in a five-county study area of 4,000 square miles. The salt thickness map, prepared from original log sources, shows a median thickness of 250 feet northwestward from a reference section in a cored test hole near Hutchinson, Kansas (salt thickness 286 feet, Jones 1965) through Rice, Ellsworth, and Russell Counties. The salt is regionally thinner to the northeast in Lincoln County and regionally thicker to the southwest. Locally the salt is thin on anticlines coinciding with underlying oilfields and thicker in synclinal areas due to depositional variations. Depth to salt varies from 400 feet on the east to 1500 feet in southwestern Barton County.

Most of the 22,200 oil and gas test holes in the study area have been drilled with fresh water, causing dissolution of the salt during drilling, commonly resulting in borehole enlargement to three times the diameter of the drill bit. Some older rotary drilled holes have borehole enlargement to 10 feet in diameter.

After drilling ceases, no salt dissolution occurs in oil and gas test holes which

have properly cemented surface casing protecting all aquifers above the salt. This conclusion is valid regardless of how the hole is plugged, whether it is plugged at all, whether it is an otherwise uncased dry hole, or whether it is an abandoned producer with a stub of casing (plugged or unplugged) left in the place. This conclusion is based on a review study of the hydrology of central Kansas aquifers, the examination of cased hole logs some of which show shifts indicative of a fluid-air interface outside the casing, and a study of re-entered boreholes. Post-drilling salt dissolution does occur in holes abandoned with no surface casing left in place (illegal after 1935) as demonstrated by two re-entered holes, one with a calculated borehole diameter of 8-1/2 feet in the salt.

Rarely, salt dissolution in oil and gas test holes is so extensive as to cause collapse and subsidence of the land surface. Within the study area six such occurrences are known. For comparison, a well documented recent collapse and subsidence area totally unrelated to oil and gas activity is described. Excessive salt dissolution due to solution salt mining at the Cargill, Inc. plant, Hutchinson, Kansas caused a spectacular ground collapse in October 1974, disrupting operation of the main line of the Missouri-Pacific railroad, leaving the tracks suspended in midair for 300 feet.

Part II reviews the geology and hydrology of the 50-year old Gorham Oilfield, Russell County, in which two intensely investigated sink areas affecting Interstate Highway U. S. 70 are known to be due to inadvertent and extensive dissolution of salt in abandoned oil test holes resulting in collapse and surface subsidence.

Part III reviews geology and hydrology of the vast Chase-Silica Oilfield, Barton and Rice Counties (oil production over 250 million barrels at a depth of 3300 feet), in

which three surface sink areas are considered to be caused by salt dissolution in salt water disposal wells. Two sink areas subsided slowly but the third collapsed suddenly on April 24, 1959.

The conclusion is reached that extensive dissolution of the Hutchinson Salt in oil and gas test holes in central Kansas is a rare and unusual event in the 50-year history since the discovery of oil in Russell County in 1923. In only seven known instances (six of which are within the study area) did such dissolution lead to collapse and surface subsidence. With an estimated 72,000 holes drilled through the Hutchinson Salt Member within the State of Kansas, this is a ratio of approximately one occurrence for every 10,000 oil and gas test holes.

INTRODUCTION

This is Part I of a three-part research project concerning "Salt Dissolution in Oil and Gas Test Holes in Central Kansas." The research project was supported by the Oak Ridge National Laboratory (ORNL) of the United States Atomic Energy Commission (AEC) under Contract #78X-38283V. The three parts of the study are:

PART I	SALT BEDS IN THE SUBSURFACE IN RUSSELL, LINCOLN, ELLSWORTH, BARTON, AND RICE COUNTIES, CENTRAL KANSAS
PART II	SALT DISSOLUTION IN OIL AND GAS TEST HOLES IN THE GORHAM OILFIELD, RUSSELL, COUNTY, CENTRAL KANSAS
PART III	SALT DISSOLUTION IN OIL AND GAS TEST HOLES IN THE CHASE-SILICA OILFIELD - BARTON AND RICE COUNTIES, CENTRAL KANSAS.

The author assumes full responsibility for the investigation and conclusions of this report but wishes to acknowledge the indispensable help of others without whom the basic data could not have been gathered. In addition to the authors named in the references, the author expresses his thanks and indebtedness to the following, all of whom have furnished basic firsthand observation of data to the author:

Thomas H. Allan
N. W. Biegler
Virgil A. Burgat
Virgil B. Cole
O. S. Fent
F. G. Holl
C. L. Jones

Bruce F. Latta
R. P. Lehman
William J. Luck
Ralph E. O'Connor
Millard W. Smith
Gilbert J. Toman
Raymond A. Whorton
Frank W. Wilson

LOCATION OF AREA

Salt beds in the Hutchinson Salt Member of the Wellington Formation of Permian age occur in the subsurface of Kansas over an area of 27,000 square miles, as mapped in Figure 1 (after Schumaker 1966). These beds of water soluble rock salt (halite) do not occur at the surface. They are known from the records of an estimated 72,000 oil and gas test holes drilled through them. The area of this report, about 4,000 square miles as shown in Figure 2, includes many of the major oilfields of central Kansas, two of which, the Gorham and Chase-Silica oilfields, are described in Parts II and III. It constitutes a densely drilled area where the Hutchinson Salt Member is penetrated by 22,200 oil and gas test holes. The Hutchinson Salt has a thickness of zero to 350 feet, average near 250 feet. It is encountered at depths below the surface ranging from 400 feet on the east, near Hutchinson, Kansas, to about 1500 feet on the west in southwestern Barton County.

Fig. 1.--Map of Kansas. Contours indicate thickness of Permian Hutchinson Salt Member of the Wellington Formation in feet (after Schumaker 1966). The five-county area of this report, indicated by county outlines, is enlarged in Fig. 2.

Fig. 2.--Index map. For description of the 15 numbered localities, see text. Diagonal line approximates northeast boundary of densely drilled oilfield area (average 300 tests per 36-square mile township grid on map). Area northeast of line averages about three test holes per township.

The oil and gas test holes which are the subject of this investigation of salt dissolution are mapped on Plate 1, a large folded map. On it the Gorham Oilfield in Russell County and the Chase-Silica Oilfield in Barton and Rice Counties have been circled, and the location of a natural scale cross section A-B, Figure 3, is marked.

Plate 1.--Map of oil and gas test holes in the five-county, 4,000-square mile study area.

Fig. 3.--Cross Section A-B. Natural scale (no vertical exaggeration); length 1.7 miles. Wells and mine shafts 1-9 are listed in Table 1 and located on map, Fig. 4.

SUBSURFACE WELL CONTROL - OIL AND GAS TEST HOLES

Following the discovery of oil in western Kansas in November 1923 in the Fairport Field, Russell County, oil and gas test holes were drilled on close spacing (usually 10-acre well spacing, holes 660 feet apart) during the 1920's and 1930's. Drilling continued with wider spacing (20-acre well spacing, holes 660, 933 feet, or 1320 feet apart; and 40-acre spacing, holes 1320 feet apart) during the 1940's to 1970's. Drilling for oil and gas in the study area is still continuing. This 50-year period of oil and gas exploration resulted in the drilling of over 22,200 oil and gas test holes in the five-county study area of Russell, Lincoln, Ellsworth, Barton, and Rice Counties in central Kansas. Almost without exception these test holes have been drilled with fresh water dissolving the salt section during drilling until the drilling fluid becomes saturated with salt. Within the study area the oil producing portion comprises about two-thirds of the area and is defined in Figure 2 as southwest of the line bisecting Ellsworth County and continuing northward across Russell County. Within this oil producing portion of the study area comprising 2,668 square miles, 22,112 oil and gas tests have been drilled. This is an average drilling density of 8.3 test holes per square mile, or about 300 holes per township (the 36-square mile grid of Fig. 2). These test holes are widely dispersed as shown by the fact that within these 2,668 surveyed sections of land (normally one square mile each), 87-1/2 percent of the sections have been drilled for oil and gas with only 12-1/2 percent of the land sections totally undrilled. Drilling is even more widely distributed within the 900 square miles of Barton County, and the 720 square miles of Rice County where a total of only 142 sections of land, or less than 9 percent (.088)

of the land area on a one-mile grid is undrilled for oil and gas. The hole distribution is general enough that the average drilling density is meaningful. The Hutchinson Salt, which remained intact and undissolved for over 200 million years since Permian time, has been literally riddled with oil and gas test holes during the past 50 years.

Within the 1,296 square miles of the study area northeast of the line bounding the oil producing portion, Figure 2, drilling density is much less. There are only 126 oil or gas tests or a hole density of about one-tenth of a hole per square mile (.102857 holes per square mile), an average hole spacing of one hole every ten square miles, or 3.7 hole average per township (Fig. 2).

Outside of the five-county study area an estimated additional 50,104 oil and gas test wells have been drilled through the Hutchinson Salt Member in 22,820 square miles, bringing the total to an estimated 72,342 holes in 27,000 square miles penetrating the Hutchinson Salt within the State of Kansas to January 1, 1975.

Unfortunately these many thousand oil and gas test holes were drilled for purposes far removed from study of the salt section. The amount and quality of surviving information concerning the salt section is meager. The older cable tool holes, drilled principally before 1940, provide actual well cutting samples of the salt itself but in the form of channel samples of 5 to 20-foot runs. They provide almost no information on shale breaks and partings. Some valuable hydrological information is preserved on cable tool drillers' logs for aquifers above and below the salt.

Rotary drilling of more than 95 percent of the oil and gas test holes is commonly done with fresh water dissolving the salt hence cuttings show no salt. While the majority of holes have some sort of geological log or geophysical log preserved, the logs often cover the lower portion of the hole only and do not include the relatively shallow salt section.

Although the surviving data bank of geophysical well logs maintained in the library of the Kansas Geological Society is voluminous (61,000 logs), well organized, and easily available to the author, log suites diagnostic of the salt - usually requiring three curves - are unusual. Log data concerning the salt itself was commonly preserved only as a product of logging for other purposes. However, experience in a local area permits the geologist to fairly accurately infer the salt presence, thickness, and quality (presence of nonsalt units thicker than one foot) from incomplete logs such as those recording only one or two curves through the salt section. Data from diagnostic logs served as the rigid framework for the salt thickness map (Plate 2), supplemented by data from other less complete logs. Lithology logs prepared from samples of well cuttings and old drillers' logs were used only where no other control was available.

Plate 2, -- Thickness of Hutchinson Salt Member of Permian Wellington Formation.
Contour interval 50 feet. Prepared from original log data.

SUBSURFACE CONTROL - CORED SALT TESTS, ETC.

Within the study area there are underground salt mines both active and abandoned, solution salt mines, and storage of liquefied petroleum gases in salt. These projects provide additional subsurface control. The projects are located on Figure 2 by appropriate symbols numbered from 1 to 15. They are discussed briefly in the numerical sequence used on the map. By far the best information concerning the Hutchinson Salt is derived from five test holes specifically drilled for salt information (Fig. 2, No.'s 1-5). Complete cores of the entire salt section were cut, preserved, and studied. Extensive suites of geophysical logs were recorded. This work was done over a period of years for the United States Atomic Energy Commission (AEC) in conjunction with studies of the suitability of salt beds for use as a permanent underground repository for radioactive waste. The holes are located in Reno, Rice, and Lincoln Counties, Kansas. Reproductions of the geophysical logs from these test holes are included in the text of this report.

AEC Test Hole No. 1 (Fig. 2, No. 1). Salt core hole in Section 26, Township 19 South, Range 8 West, Rice County, Kansas. Cored with salt saturated brine in 1970, U. S. Corps of Engineers contractor. The salt is present in cores from 815.1 feet to 1084.1 feet, thickness 269.0 feet, halite 82 percent. The 6-inch diameter cores are stored at Kansas Geological Survey, Lawrence, Kansas.

AEC Test Hole No. 2 (Fig. 2, No. 2). Salt core hole in Section 35, Township 19 South, Range 8 West, Rice County, Kansas. Cored with salt saturated brine in 1970,

U. S. Corps of Engineers contractor. The salt is present in cores from 755.0 feet to 1002.5 feet, thickness 247.5 feet, halite 81 percent. The 4-inch diameter cores are stored at Kansas Geological Survey, Lawrence, Kansas.

AEC Test Hole No. 3 (Fig. 2, No. 3). Salt core hole in Section 22, Township 13 South, Range 8 West, Lincoln County, Kansas. Cored with salt saturated brine in 1972, Sterling Drilling Company contractor. The salt is present in cores from 816 feet to 973 feet, thickness 157 feet, halite 88 percent. The 3-1/2 inch diameter cores are stored at Oak Ridge National Laboratory, Tennessee.

AEC Test Hole No. 4 (Fig. 2, No. 4). Salt core hole in Section 9, Township 11 South, Range 10 West, Lincoln County, Kansas. Cored with salt saturated brine in 1972, Sterling Drilling Company contractor. The salt is present in cores from 1021 feet to 1187 feet, thickness 166 feet, halite 92 percent. The 3-1/2 inch diameter cores are stored at Oak Ridge National Laboratory, Tennessee.

Geotechnical Corporation HNAS Core Hole No. 1 (Fig. 2, No. 5). Salt core hole in Section 29, Township 24 South, Range 5 West, Reno County, Kansas. Located on the grounds of the Hutchinson Naval Air Station hence the name "HNAS". Cored with 30-degree gravity crude oil in 1958, contractor Geotechnical Corporation. The salt is present in cores from 426 feet to 712 feet, thickness 286 feet, halite 82 percent. The cores were quartered and are reported as shipped to Oak Ridge National Laboratory, Tennessee; Kansas Geological Survey, Lawrence, Kansas; Geotechnical Corporation, Dallas, Texas; and USGS, Washington, D.C. The cores from the test hole serve as a

reference locality for the Hutchinson Salt Member of the Permian Wellington Formation. They were described in detail by C. L. Jones (1965).

In determining the percentage of halite rock, Jones based his determination of the 286 feet of "salt" section as 82 percent halite rock, 3 percent anhydrite rock, 4 percent carbonate rock (dolomite magnesite), and 11 percent shale and siltstone on detailed lithology of units down to one-fourth inch in thickness. Comparable detail study is not available for AEC Test Holes 1 through 4 inclusive in which the percentage of halite is determined on the basis of measurement of beds at least one foot thick, which is the resolving power of the geophysical logs.

Carey Salt Company - Lyons Mine (Fig. 2, No. 6). Inactive underground salt mine. Shaft hand dug in 1889-1890 near the Center of Section 34, Township 19 South, Range 8 West, Rice County, Kansas. No salt mined since 1948. Depth to mine floor 1024 feet, ceiling 9 feet (except old "high ceiling area", 12 feet), room and pillar mining with mined area of approximately 200 acres. Current status: Accessible but not in use. The mine was under lease to the AEC from 1959 until 1973. Five new rooms mined in a salt bed 20 feet above the floor of the existing mine were the site for research known as "Project Salt Vault" (McClain 1973).

American Salt Corporation (Fig. 2, No. 7). Active underground salt mine. Shaft near the Center of the North Half (C N/2) of Section 3, Township 20 South, Range 8 West, Rice County, Kansas. Mine depth 993 feet, ceiling 9 feet, room and pillar mining with approximately 375 mined acres (Lomenick 1972).

Royal Mine (Fig. 2, No. 8). Abandoned salt mine, shaft plugged. Located in Section 30, Township 15 South, Range 7 West, Ellsworth County, Kansas, adjacent to the Crystal Mine with which it was connected underground. Mine floor 810 feet, ceiling 9 feet, room and pillar mine (Jewett 1956).

Crystal Mine (Fig. 2, No. 9). Abandoned salt mine with two shafts, both sealed. Locations are near the east edge of the city of Kanopolis in Section 25, Township 15 South, Range 8 West, and Section 30, Township 15 South, Range 7 West, Ellsworth County, Kansas. Mine floor 810 feet, ceiling 9 feet, room and pillar mine, closed in 1948 (Jewett 1956). The dirt filled east shaft in Section 30 was the site of sudden and dramatic collapse in January 1972 when the entire dirt fill disappeared down the shaft leaving an intact empty shaft. In March 1972 a crater formed with a calculated volume of four times the volume of the original mine shaft (N. W. Biegler, personal communication).

Independent Salt Company (Fig. 2, No. 10). Active underground mine. Shaft in the Center of the Northwest Quarter of the Northwest Quarter (C NW/4 NW/4) of Section 29, Township 15 South, Range 7 West, Ellsworth County, Kansas. Depth to mine floor 846 feet, ceiling 9 feet, room and pillar mine (Jewett 1956).

Little River Mine (Fig. 2, No. 11). Abandoned and closed underground mine. Shaft near the Northeast Corner (NE/Cor) of Section 18, Township 19 South, Range 6 West, Rice County, Kansas. Mine floor 798 feet, ceiling 11 feet, room and pillar mine. No salt mined after 1926. Closed 1937 or 1938. In 1963 the shaft of this mine was reported

as filled and sealed, then a hole was drilled into void space in the mined out area in an early effort by the Little River Co., Inc. to utilize the mined void space in the salt for LPG storage. The project was unsuccessful. In 1975 the project was reactivated and it was found that the shaft was not adequately sealed. Work is continuing (N. W. Biegler, personal communication) in 1975.

American Salt Corporation (Fig. 2, No. 12). Active solution salt mine. Located in Sections 14 and 15, Township 20 South, Range 8 West, Rice County, Kansas. Approximately 25 active "conventional" individual, separate, salt solution wells, depth near 1000 feet, with about the same number of abandoned interconnected solution wells. New salt wells are being drilled expanding the solution mining area eastward in Section 14. The holes are not cored and commonly not logged (Lomenick 1972).

Davis Mud & Chemical, Inc. (Fig. 2, No. 13). Inactive salt solution mine. Located in Section 28, Township 20 South, Range 15 West, Barton County, Kansas. Two wells, now temporarily abandoned, supplied salt saturated brine from depths of 1522 feet to 1732 feet and 1510 feet to 1710 feet. These wells produced about 262,000 tons of salt to October 1972, at which time they became inactive (Robert E. Davis, personal communication).

Northern Gas Products (Fig. 2, No. 14). Extensive active underground LPG storage project in dissolved salt voids. Located in Section 31, Township 17 South, Range 9 West, Ellsworth County, Kansas. Salt section occurs from about 950 feet to 1150 feet. Casing is commonly set at the base of a shale near 1072 feet, and the purer portion of

the salt from 1072 feet to 1150 feet is dissolved. More than 50 individual underground storage vessels for liquefied petroleum gases (LPG), ethane, propane, butane, etc. The holes are not cored but were logged immediately after drilling (and before solution enlargement), and also logged from time-to-time during use. The salt itself is not a product but is ultimately disposed as brine placed in deep Arbuckle salt water disposal wells. (Myers, Noah, Gries, 1972, illustrate brine cavities from this installation).

MAPCO Mitchell Storage (Fig. 2, No. 15). Underground LPG storage in four units in dissolved salt voids in the East Half (E/2) of Section 27, Township 19 South, Range 7 West, Rice County, Kansas. Constructed by Mid-America Pipeline System, a division of MAPCO, Inc., in 1973. Two additional similar units, developed capacity 100,000 barrels each, are being added in 1975. The salt itself is not utilized but is dissolved and transported as brine through a 14-mile pipe line eastward to the company's Arbuckle SWD well in the Southwest Quarter (SW/4) of Section 24, Township 19 South, Range 5 West, near their shallower large scale butane-propane LPG storage operation in salt voids at Conway, Kansas. The Mitchell LPG Storage was designed for ethane (vapor pressure 500 psi as contrasted with 100 psi for butane) requiring a rock overburden greater than 800 feet. The salt, encountered below 900 feet, is over 300 feet thick. (N. W. Biegler, personal communication).

NATURAL SCALE CROSS SECTION

A natural scale cross section (horizontal and vertical scales equal) 1.7 miles long, and almost one mile deep is shown as Figure 3. It serves to set the Hutchinson Salt in vertical perspective within the sedimentary rock section. Table 1 lists the control test holes and shafts. The general location of the cross section is shown on Plate 1. Greater detail concerning the location of the cross section near the city of Lyons, Kansas, is shown on Figure 4. The well numbers correspond with those on the cross section.

Table 1.--Wells and Shafts, Cross Section A-B, Fig. 4.

Fig. 4.--Index map showing location of cross section A-B, Fig. 3. Wells and mine shafts 1-9 are listed in Table 1.

Table 1

WELLS AND SHAFTS
CROSS SECTION A-B, FIGURE 4
(All in Township 19 South, Range 8 West, Rice County, Kansas)

1. Lyons Natural Gas, Oil,
and Mineral Co.
No. 1 Prospect
(or #1 Lyons Gas Well)

Cable tools - Drilled 1887
Total Depth 1230 feet

Section 34

C E/2 SW/4 SW/4

(South end of Block 18, Diamond Addition)

Elevation: 1693 Derrick Floor

Produced natural gas at a rock pressure of
67 lbs for a short while from Herrington
Limestone Chase Group. The first producing
well in the west ranges of Kansas. Discovery
well for salt in this area.

2. AEC Entry Shaft
Carey Salt Mine

Rotary drilled shaft, 1964
Total Depth 1060 feet

Section 34

C NE/4 SW/4

Elevation: 1699 Kelly Bushing

Drilled 9-7/8" diameter, and logged. Shown
on log as well X-15-40, Carey Salt Company.
Set 26" surface casing at 309'. Large diameter
casing set and cemented prior to developing
AEC mine rooms. Entry shaft for simulated
radioactive waste containers, Project Salt Vault.
Mine floor at 1000'. Coiling 15'.

3. Carey Salt Mine
Main Shaft

Hand dug 7' X 16'
in 1889-1890
Total Depth 1083.5 feet

Section 34

A few feet NW of Center of Section

Elevation of Shaft Collar: 1702

Salt 806' to 1068'

Mine ceiling 9'; older areas, 12'

Floor of mine 1024'

4. Woodman & Iannitti Drilling Co.
No. 2 Stockham

Rotary drilled, Nov. 1970
Total Depth 3466 feet in Simpson

Section 34

NE/4 NW/4 NE/4

Dry Hole

Table 1 - continued

WELLS AND SHAFTS
CROSS SECTION A-B, FIGURE 4
(All in Township 19 South, Range 8 West, Rice County, Kansas)

5. Western Petroleum Company
No. 1 Stockham	Section 34
C NE/4 NE/4
Elevation: 1721 Kelly Bushing
Rotary drilled, Nov. 1964
Total Depth 3493 feet in Arbuckle	Oil Well: Two producing zones
Kinderhook 3344'-3348'
Simpson 3398'-3418'
41 BOPD + 15% Water - Gravity 33 degrees
Production about 25,000 barrels of oil
6. Barnett Oil Company
No. 1 Wright	Section 35
Approx. C S/2 NW/4
810' from south line; 1150' from west line
Elevation: 1694 Kelly Bushing
Rotary drilled, 1971
Total Depth 3585 feet in Simpson
(Est. Arbuckle 3604'-1910')	Four aquifers (indicated by "W" on cross section)
were cored, then drill stem tested for water
information. Dry hole, 1971.
7. USAEC Test Hole No. 2	Section 35
30' North of C N/2
Elevation: 1704 Ground Level
Stratigraphic test hole
Rotary drilled, 1970 (6 1/4" diameter)
Total Depth 1215.6 feet in Chase
Group	Cored 739.9' to 1099.6', 4" cores. Salt
section 755.0' to 1002.5'. U.S. Corps of
Engineers rotary rig.
8. Atlantic Refining Co.
No. 1 Pulliam 'A'
Drilled 1936
Cable tools 0' to 3305'
Rotary tools 3305' to 4085 total depth
in Arbuckle. (Est. Precambrian 4121
or -2390)	Section 35
C S/2 N/2 NE/4
Elevation: 1731 Derrick Floor
Gas Well 1936 to 1945
41 Million cu. ft. gas per day
Plugged and abandoned in 1945
Re-entered and replugged in 1974

Table 1 - continued

WELLS AND SHAFTS
CROSS SECTION A-B, FIGURE 4

(All in Township 19 South, Range 8 West, Rice County, Kansas)

9. Kansas Petroleum Inc.
No. 1 Pulliam

Rotary drilled, 1962
Total depth 3541 feet
in Arbuckle

Section 35

C NE/4

Elevation: 1729 Kelly Bushing

Dry Hole

This test, drilled 17 years after the abandonment of the nearby Pulliam 'A'-1 penetrated the Arbuckle 300 feet with three drill stem tests in the Arbuckle showing water and a Simpson-Arbuckle drill stem test indicating 7 million cu. ft. per day of "sour" (H₂S) gas and salt water. Re-entered in 1974 by Northern Natural Gas Company and recompleted with 5½" casing set for use as a gas storage input-withdrawal well.

HUTCHINSON SALT, OVERVIEW

Viewed in the perspective of the regional index map, Figure 1, the Hutchinson Salt is seen as a laterally persistent but thin rock unit covering 27,000 square miles within the State of Kansas. The five-county study area is marginal to the salt basin, and viewed even more broadly the entire Hutchinson Salt area of Kansas is marginal to the great Permian Basin salt deposits of Oklahoma, Texas Panhandle, and southeastern New Mexico (Bachman and Johnson, 1973).

It has long been recognized that the west, northwest, north, and northeast edges of the Hutchinson Salt (Fig. 1) are depositional edges (Bass 1926), and that the updip east edge was solution-eroded. This has been confirmed in general by Kulstad's (1959) map of the salt beds in Kansas, prepared in the middle 1950's but not published until 1959, and by Schumaker's map (1966). It has been further verified by Dellwig (1963, 1971) in detailed studies of salt mines and cores. Considering the shoal water and basin margin environment of salt deposition, the lateral persistence of the Hutchinson Salt as a unit is remarkable. Within the outline of the salt area in Figure 1, no oil and gas test wells failed to penetrate salt, although thickness and quality vary. The fact that the salt is everywhere present is one of the "facts of life" for the oil and gas drilling industry in Kansas. The salt beds are characterized by very rapid penetration rate commonly as much as 180 feet an hour with modern rotary tools. The salt beds are routinely drilled with fresh water which is readily available (salt water is not as cheap or easily obtained). Drilling

mud programs are engineered for salt brine mud systems with the salt provided by dissolution of the Hutchinson Salt during drilling.

Although the Hutchinson Salt Member is remarkable for its wide lateral continuity as a unit, individual salt beds, separated by shale interbeds, and with shaley partings, commonly extend only a few miles. To quote Dellwig (1971), "the salt consists of a succession of layers. The area underlain by any single bed is small compared to the area underlain by the entire salt unit, indicating a continual shifting of the locus of deposition. Correlation (based entirely on logs) also indicated that individual strata are imbricate and have an oblique relationship to the upper and lower boundaries of the salt unit as a whole. Key beds can be correlated only for short distances. In studies of mine areas, correlation of key beds offers no problem but it is important to note that one should not expect to project local stratigraphic units from marginal areas (Hutchinson, Lyons, and Kanopolis mines; AEC holes) toward the basin center and anticipate an increase in thickness or improvement in quality of a salt unit . . ."

Perhaps even more remarkable than the lateral depositional extent of the Hutchinson Salt is the fact of the intact preservation of these water soluble halite beds over the time period of about 250 million years since Permian Leonardian time. This preservation is due to the "roof" of impermeable Permian Redbeds, shale and silty shale, immediately overlying the salt and to the location of the Hutchinson Salt beds in the stable heart of the North American Continent. These salt beds have been subject to no intense tectonic forces but only to gentle, vertical, epeirogenic movements for that time period. The protective "roof" of redbeds can be quite thin and still preserve the salt beds. Dellwig (1963) has published

a detailed cross section based on cores of salt encountered at depths just below 200 feet showing undissolved halite beds truncated by the overlying Permian shales, but "the contact between the salt and the overlying shale is clean and sharp and there is no indication of post shale-deposition solution of the salt and collapse of the overlying shale unit."

HUTCHINSON SALT, UPDIP EAST SIDE DISSOLUTION FRONT

Just east of the area where salt occurs at depths as shallow as 200 feet is the area shown on Figure 1 by the parallelism and convergence of the 200-foot and zero salt thickness lines which mark the solution truncated updip east edge of the Hutchinson Salt. For over 100 miles, the active dissolution front in which the Hutchinson Salt is being dissolved by ground water on its updip east edge is marked by the narrow and poorly mapped "Wellington lost circulation zone" of oilwell drillers. This is a zone of partial to total salt dissolution due to natural causes in which the void space created by salt removed has only partially been closed by gravity slumping, leaving a narrow conduit, brine filled, which is capable of either yielding large quantities of brine when pumped or of taking large quantities of fluid such as drilling mud. Penetration of this zone while drilling can cause "lost circulation" which at times leads to the loss of the hole. Redrilling sometimes only 50 feet distant may miss the zone. The "regional plumbing" of this narrow zone which extends along the salt front from near Wellington, in Sumner County, over 100 miles north to near Salina, Kansas, has been discussed by Fent (1971).

Along this updip east salt face occurs the only natural dissolution of the Hutchinson Salt. In Pleistocene time and continuing to the present, surface subsidence above the solution front resulted in sink and valley formation. A succession of such subparallel north-south valleys, now sediment filled, formed as the salt dissolved and the salt front receded westward. The study of these valley sequences and the dating of the Pleistocene

to Recent sediments filling them (often important fresh water aquifers) has enabled Fent (1971) to conclude that the westward retreat of the salt front due to natural dissolution occurred at an average rate of four miles a million years during early Pleistocene time and at a rate of about two miles a million years in late Pleistocene time, continuing to the present.

Except for this natural dissolution along the updip east edge of the Hutchinson Salt there are no instances of dissolution within the salt mass over hundreds of square miles prior to the advent of man's drilling oil and gas tests during the past 50 years, the effect of which is the subject of this investigation. In short, there has been no natural dissolution (or subrosion) of the Hutchinson Salt from its top downward.

LITHOLOGY OF THE HUTCHINSON SALT MEMBER

Because an evaporite sequence such as the Hutchinson Salt and the associated underlying massive anhydrites does not crop out on the surface in a humid climate such as Kansas had in Pleistocene time, there is no "type locality" for the Hutchinson Salt in the classical sense. The salt is named from the mines at Hutchinson, Kansas, ten miles south of the southeast corner of the five-county study area (Fig. 2). Although salt has been produced continuously at Hutchinson, Kansas since 1888, the mines themselves provide a poor type section. Underground mining of salt is usually confined to a single bed (thought to be approximately the same bed in all mines). Commonly the shaft which provides the only penetration of the entire salt section is cemented over, and indeed the shaft may not have been dug as deep as the base of the salt. Holes drilled with cable tools for salt and/or oil or gas from 1878 to the 1930's resulted in the recovery of actual samples of rock salt as well cuttings, but such samples are channel samples of the cable tool run commonly 10 feet, hence the shale breaks and partings are obscured. This situation prevailed when the AEC became interested in investigating the suitability of beds for a permanent underground repository for atomic waste. Accordingly a contract was entered into with the Geotechnical Corporation in 1958 for a test hole located south of Hutchinson, Kansas cored through the entire Hutchinson Salt Member of Permian Wellington Formation. The site was the former Hutchinson Naval Air Station hence the test hole is known as HNAS Core Hole No. 1 in the Southeast Quarter of the Northeast Quarter (SE/4 NE/4) of Section 29, Township 24 South, Range 5 West, Reno County, Kansas (Fig. 2, No. 5).

C. L. Jones (1965) published a detailed lithologic and petrographic description of the 286 feet of salt section and interbedded rocks present in these cores from 426 feet to 712 feet, together with gamma-ray and neutron logs of the hole. Because the importance of HNAS Core Hole No. 1 is a reference section for the Hutchinson Salt Member, and because the USGS Bulletin by C. L. Jones provides the only published details concerning lithology and mineralogy of a complete section of the Hutchinson Salt in Kansas, an error of omission in his published lithologic description is hereby corrected by use of photocopies he furnished of his original core description notes (C. L. Jones, personal communication July 9, 1974) from which the following additions (marked by asterisks) are abridged:

The Geotechnical Corporation
 HNAS Core Hole No. 1
 SE/4 NE/4, Sec. 29, T.24S, R.5W
 Reno County, Kansas

Addenda to core description by C. L. Jones (USGS Bulletin 1201-A, 1965)

520'-2"	525'-7"	5'-5"	Halite rock, description correct as published on page A-58.
*525'-7"	526'-9"	2'-2"	Clay shale, medium bluish gray cut by veins of orange halite.
*526'-9"	527'-4"	7"	Anhydrite rock. Has a 2" clay shale seam with orange halite veinlets.
*527'-4"	528'-5"	1'-1"	Halite rock, anhydritic and argillaceous; coarse grained ($\frac{1}{4}$ " to $\frac{3}{8}$ "), grayish color.
*528'-5"	531'-0"	2'-7"	Clay shale. Interlaminated medium bluish gray and gray. Prominent veins of amber halite, in part cut by anhydrite nodules.

*531'-0"	532'-0"	1'-0"	Halite rock. Interval incorrectly published but description correctly published at top of page A-59.
532'-0"	534'-2"	2'-2"	Halite rock. Description and interval correctly published on page A-59.

*Indicates additions to core log as published by C. L. Jones (1965).

The log of the HNAS Core Hole No. 1, published by Jones at a scale of 1" = 20 feet, is here reproduced at a scale of 1" = 50 feet as Figure 5 to facilitate comparison with the included logs of other key core holes. C. L. Jones (personal communication)

Fig. 5--Hutchinson Salt Member. Lithology from cores. Reprinted from Jones (1965).

correlates the 7-inch anhydrite seam near 647 feet with a similar anhydrite bed 2 to 4 feet below the mine floor in the Carey Salt Company underground mine at Hutchinson, and considers the salt cored from about 635 feet to 645 feet to be the bed mined. Likewise he considers the fossiliferous layer at depth of 698 feet ("F" on log) as very similar to a fossiliferous layer at the base of the salt 44 feet below the mine floor in the Carey underground salt mine at Lyons, Kansas.

In general the lithology of the Hutchinson Salt Member is described by Jones (1965, p. A-10) as "a saliferous sequence of evaporites and shales 286 feet thick that extends from a depth of 426 feet to 712 feet in the drill hole. "(HNAS Core Hole #1): He states,

"The sequence consists of an irregular alternation of relatively thick salt beds (halite rock) and thinner beds of clayey and silty shales, dolomite, magnesite, and anhydrite. The alternation of salt beds and shale, carbonate, and anhydrite beds, --- is repeated on a much smaller scale within the beds. As a consequence, virtually all the beds are lithologically complex and have different combinations of contrasting laminae or layers, such as shale and magnesite, magnesite and anhydrite, or other rocks. . The layering is rhythmic in character, and there is a regular order of succession. In general, a basal shale or siltstone gives place upward to carbonate rock (dolomite or magnesite), anhydrite, and halite rock. The carbonate and the anhydrite are ordinarily no more than a fraction of an inch thick, but the halite rock is almost everywhere several times as thick - often as much as 8 or 10 times as thick."

When the AEC wished to investigate the environs of the Carey Salt Mine at Lyons, in which they had been conducting experiments for almost a decade, it was again found that actual specific rock information concerning the subsurface salt (other than the one mined 9-foot bed), the Permian redbeds above the salt, and the anhydrites below was almost nonexistent. The AEC contracted the coring of two holes at Lyons, Kansas in 1970 designated as AEC Test Holes No. 1 and No. 2. Not until cores were recovered in 1970 was it relearned why miners laboriously hand digging a mine shaft in 1889 in search of salt would continue their shaft more than 200 feet below the top of the salt. Cores from AEC Test Hole No. 1 showed that the first 100 feet of salt section included 25 percent shale, measuring only beds one foot in thickness or more. In addition, thin shale partings were present in the dirty (clayey) salt. These cores confirmed what the old miners knew,

that the mined bed near the base of the salt, depth 1013 feet to 1024 feet in the Carey Salt Mine, was the cleanest and most mineable bed (free of shale partings) encountered. The same bed, and no other, is still being mined underground at the American Salt Company mine at Lyons, and is believed to be the same bed mined 30 miles north at Ellsworth. Even the bed which is mined because it is the "cleanest" salt, shows prominent light and dark banding or laminae ("Jahresringe", Dellwig 1963) of clay or anhydrite spaced 0.25 inches or more apart, with no regular spacing of the laminae, and the salt crystals show considerable variance in size. This is illustrated in Figure 6.

Fig. 6--Hutchinson Salt Member, Carey Mine, Hutchinson, Kansas, showing prominent light and dark banding. Photograph courtesy of Underground Vaults and Storage, Inc.

In the Carey mine at Lyons, the salt bed next shallower than that which was mined is more massive and appears cleaner (less clayey). It represents the maximum evaporative peak of the Hutchinson Salt cycle, but when five new chambers were mined in this bed for AEC research, it was found that the pinkish blebs in the wall were polyhalite, a potash mineral which is not a potash ore. Its presence made this salt bed undesirable for mining for table salt.

Figures 7 and 8 illustrate the gross lithology from field core descriptions for the AEC Test Hole No. 1. Also illustrated is the suite of wire line geophysical logs which have been redrafted, simplified, regrouped, and scaled to 50 feet to the inch for study and com-

parison with other logs. Comparable information for AEC Test Hole No. 2 is shown in Figures 9 and 10 following which there is a legend, Figure 11. The geophysical logs have been released and copies are available from the Kansas Geological Society, 303 Insurance Building, Wichita, Kansas 67202.

Fig. 7--AEC Test Hole No. 1, Section 26, Township 19 South, Range 8 West, Rice County, Kansas. Wire line geophysical logs, cored intervals, and lithology of Hutchinson Salt. For legend see Fig. 11. Logs are continued in Fig. 8.

Fig. 8--AEC Test Hole No. 1, continued from Fig. 7.

Fig. 9--AEC Test Hole No. 2, Section 35, Township 19 South, Range 8 West, Rice County, Kansas. Wire line geophysical logs, cored intervals, and lithology of Hutchinson Salt. For legend see Fig. 11. Logs are continued in Fig. 10.

Fig. 10--AEC Test Hole No. 2, continued from Fig. 9

Fig. 11--Legend for all illustrations which show geophysical logs.

Dellwig has published (1971) details of correlation of the salt section cored in AEC Test Hole No. 1 and AEC Test Hole No. 2 with the salt section in the Carey mine at Lyons, as shown in Table 2 on the following page. The still active underground mine of the American Salt Corporation is the same bed as that mined in the Carey mine with a floor at 1024 feet. At one time a joint mining project was commenced to connect the two mines underground for safety exits, but the project was not consummated and there is an

Table 2

**HUTCHINSON SALT - LYONS AREA
CORRELATIONS BY DELLWIG (1971)**

	<u>CAREY SALT MINE, LYONS</u>		<u>USAEC #1 Elev. 1745' Ground Rock Cores</u>	<u>USAEC #2 Elev. 1704' Ground Rock Cores</u>
	<u>AEC Shaft Elev. 1699' Kelly Bushing Gamma Log 19</u>	<u>Old Shaft Elev. 1702' Shaft Collar Log of Dug Shaft 1888</u>		
Top of Salt	785'	793'	815.0'	755.4'
Bed 17 - Roof of AEC Room	984'	987'	1016.0'	944.2'
Shale below floor of AEC Room Bed 18	1003'	1007'	1037.6'	965.6'
Salt Mine Floor of mine	1020'	1024'	1055.5'	983.3'
Shale below " Bed 19	1026'	1028'	1059.2'	987.9'
Base of Salt	-	1068'	1084.1'	1002.5'
Thickness of Salt	-	262'	269.1'	247.1'

unmined distance of 1500 feet (Lomenick 1972) separating the mines. No detailed petrographic study comparable to that of Jones from the HNAS Core Hole No. 1 has been made of the cores from AEC Test Holes No. 1 and No. 2 near Lyons, nor for AEC Test Holes No. 3 and No. 4 discussed later.

In order to obtain information as to the amount and quality of the Hutchinson Salt Member of the Wellington Formation in an area where the salt section was less densely drilled in connection with oil and gas exploration, the AEC contracted the drilling of two salt core holes in Lincoln County, Kansas. These holes are about 35 and 50 miles north of the Lyons area (Fig. 2; No.'s 3 and 4). They are designated as AEC Test Hole No. 3 and AEC Test Hole No. 4.

Figures 12 and 13 depict the section cored in AEC Test Hole No. 3. Figures 14 and 15 depict the section cored in AEC Test Hole No. 4. The same legend (Fig. 11) applies. No detailed lithologic or mineralogical study has been made of these cores and no exact correlations have been established with AEC Test Holes No. 1 and No. 2, with the HNAS Core Hole No. 1 or with the salt mines at Kanopolis, Lyons, and Hutchinson. The salt beds with a thickness of 157 feet gross (No. 3) and 166 feet gross (No. 4) were considered to be thinner than was desirable for future storage of radioactive waste although good quality salt was present.

Fig. 12.--AEC Test Hole No. 3, Section 22, Township 13 South, Range 8 West, Lincoln County, Kansas. Wire line geophysical logs, cored intervals, and lithology of Hutchinson Salt. For legend see Fig. 11. Logs are continued in Fig. 13

Fig. 13.--AEC Test Hole No. 3, continued from Fig. 12.

Fig. 14.--AEC Test Hole No. 4, Section 9, Township 11 South, Range 10 West, Lincoln County, Kansas. Wire line geophysical logs, cored intervals, and lithology of Hutchinson Salt. For legend see Fig. 11. Logs are continued in Fig. 14.

Fig. 15.--AEC Test Hole No. 4, continued from Fig. 14.

THICKNESS OF HUTCHINSON SALT

Plate 2 is a map of the thickness of the Hutchinson Salt, contour interval 50 feet. Thickness ranges from zero at the northeast corner of the map to over 350 feet along the south line. Two symbols for well control are used to emphasize the difference in quality of the well control. In the northeastern portion of the map open circles indicate the location of all oil and gas test holes from which salt thickness figures (of highly varying reliability) were obtained. In the central portion of the map small solid circles indicate the location of selected oil and gas test holes in which the salt thickness and salt quality could be measured. As previously indicated, the sparsely drilled northeastern area has an average of only 3.7 oil and gas test holes per township (36 square miles) whereas in the remainder of the mapped area control is two orders of magnitude greater, or an average of about 300 oil and gas test holes per township. Because of the enormous labor involved in reviewing hundreds of well records, mapping on a controlled quality basis is incomplete in Barton County.

By selective use of quality controlled well logs the principle was established that the salt is locally thinner over anticlinal structures and locally thicker in the intervening gentle synclines. The mapped areas of thin salt coincide with most of the major oilfields in the central portion of the map. The closed or narrow sinuous thick salt areas overlie "lows" separating oilfields.

Although exact bed-by-bed correlations cannot be carried across the several hundred square miles of area from log study with only five core holes, it can be shown that the salt

thickness varies due to some combination of:

- a. Loss of salt beds at base of salt section;
- b. Absence of salt beds in upper middle portion of the salt section;
- c. Loss of salt beds at the top of the salt section.

From available well logs it is relatively easy to accurately determine the top of the salt, but relatively difficult (and often impossible) to accurately determine the base of the salt section because a transition zone is present at the base of the salt section. For example, Dellwig (1971) identified fifteen lithological units, largely salt, in nine feet of core from 1077 feet to 1086 feet (base of the salt section 1084 feet) from AEC Test Hole No. 1 (Fig. 7) and specifically correlated each of the fifteen equivalent beds (largely devoid of salt) as all present in four feet of core from 1002 feet to 1006 feet from AEC Test Hole No. 2 (1-1/4 miles distant) in which the base of the salt was 1004.5 feet. Such fine discrimination requires cores studied by experts and is beyond the resolving power of even the best geophysical log suites. This example confirms the presence, recognized on a broader scale in log studies, of a variable basal transition zone sometimes salt bearing, sometimes not, with a thickness varying from zero to over 40 feet.

This basal transition zone indicates that anticlinal areas which were also gentle topographic highs were present in mid-Permian time during the deposition of salt in Kansas, with more and thicker salt beds deposited in the lows than on the highs.

The absence of salt beds in the upper middle portion of the salt section is associated with one or more disconformities marked by shale beds with a thickness from 1 to 10 feet.

In the upper 100 feet of the salt section beds of shale, each more than one foot thick, account for 25 percent of the interval thickness. The depositional environment of the Hutchinson Salt was a broad shallow embayment, perhaps with extensive tidal mud flats. Desiccation cracks, large scale polygons, and salt hopper crystals confirm the very shallow water environment (Dellwig 1971). The absence of salt beds, locally, in this part of the section may be due to redissolving the salt by incursions of muddy fresh water depositing the shale interbeds. Shale filled channels can be seen exposed in the walls of the Carey mine at Lyons. It is the present practice of operators dissolving caverns in the salt for LPG storage to set casing in or below a major shale zone about 100 feet below the top of the salt section. The upper salt section is left undissolved thus avoiding the shearing of tubing due to collapse of cantilevered shale partings as frequently occurred in early salt solution operations.

The local loss of salt beds at the top of the section may be due to nondeposition, but has been shown by Dellwig (1971) to be in part due to early post depositional truncation in Permian time, based on three core holes near Clearwater, Sedgwick County, Kansas. There is no evidence of thinning of the salt section by "subrosion" or natural dissolution of the salt from the top downward associated with the present land surface or with the land surface identified by the extensive pre-Cretaceous unconformity.

There is no direct evidence of thickening and/or thinning of salt beds by salt flowage. The beds are nearly horizontal with regional dips of only about 30 feet per mile ($1/3$ of 1°). It is thought that the maximum depth of burial in the 200+ million years

since deposition of the salt is less than 3000 feet. The present overburden thickness ranges from 400 feet to 1500 feet within the study area. These observations provide indirect evidence of the absence of salt flowage due to stable continental position, with a thin overburden and depth of burial too shallow to mobilize salt flowage on a regional basis. (Gera 1972).

RELATIONSHIP OF SALT THICKNESS TO OIL AND GAS FIELDS

By comparison of Plate 1, a map of oil and gas test holes drilled in the study area, with Plate 2, the salt thickness map, it may be seen that the locally thin areas of salt in the central portion of the map, where quality well control is available coincide in location with the underlying oilfields. The thick areas of salt whether in closed basins or in the narrow sinuous areas coincide with the gentle synclines between oilfields. This is not a mere coincidence. There is a generic cause and effect relationship. The principal time of migration of oil and gas into the prolific Arbuckle oil and gas reservoirs in central Kansas was in mid-Permian time, coinciding with the time of deposition of the Hutchinson Salt (Walters 1958). Long continued differential compaction of sedimentary beds forming the anticlines was followed by differential entrapment of oil and gas migrating deep underground during the time of salt deposition in Kansas. Examples of locally thin areas of salt which coincide closely with the location of underlying prolific central Kansas Arbuckle oilfields are provided by the Gorham Field in Russell County, Part II of this report, and by the Chase-Silica Field of Barton and Rice Counties, the subject of Part III of this report.

SALT DISSOLUTION IN OIL AND GAS TEST HOLES DURING DRILLING

Salt dissolution in oil and gas test holes during drilling can be measured by (1) study of caliper logs, (2) calculation of cement volume in holes in which casing is cemented through the salt section, or in the few unusual holes plugged with cement through the salt section, (3) by study of recorded geophysical logs, especially the neutron log which is highly sensitive to hole size and "washes out" (loses character) in enlarged sections of the hole, (4) by information from "fishing" operations opposite the salt, and (5) by recording and calculating volume and the increased salinity of the drilling fluid.

The first method, use of caliper logs, is by far the most important. In Figure 16 caliper logs from four holes drilled through the Hutchinson Salt with rotary tools were reproduced. The wells are identified in Table 3. These four logs provide examples of:

- A. Hole out-to-gauge with near zero alteration of the borehole by drilling;
- B. Carrot-shaped hole due to mechanical abrasion, no dissolution;
- C. Hole moderately enlarged by abrasion and by dissolution of salt;
- D. Extensive hole enlargement by dissolution of salt.

Fig. 16.--Caliper logs from four holes in Rice County, Kansas. Figures indicate hole diameter in inches and well depth in feet. Top and base of Hutchinson Salt indicated. Wells are identified in Table 3.

Table 3--Index to Boreholes 'A', 'B', 'C', 'D' of Figure 16, all in Rice County, Kansas.

For Borehole 'C' an approximate calculation of the hole enlargement during drilling can be made from the caliper log. The hole was drilled with a 7-7/8 inch bit. The average hole diameter above and below the salt measured about 10-1/2 inches. The average hole diameter through the salt section measures approximately 12-1/2 inches (maximum 13-1/2 inches). We may, therefore, calculate for the 277 feet of salt section a measured hole volume of 236 cubic feet, of which 94 cubic feet were cut away by the bit, 70 cubic feet of rock removed by mechanical abrasion including mud flow erosion, and the remaining 72 cubic feet removed by dissolution of the salt by the fresh water drilling mud. The measured hole is 2-1/2 times (251%) the volume of the cylinder drilled by the 7-7/8 inch bit. A total of 142 cubic feet of rock salt (or 60% of the measured hole volume) was removed by dissolution and/or abrasion. Borehole 'C' is not a typical borehole. It was drilled with a bentonite mud program (rather than clear water and native muds) which partially inhibited salt dissolution.

Borehole 'D' is representative of the usual borehole enlargement due to rotary drilling of the Hutchinson Salt with fresh water. This hole was drilled with a 7-7/8 inch bit. Average hole size above and below the salt is 9 inches. The caliper log illustrated recorded a maximum diameter of 15 inches. We may, therefore, calculate for the 287 feet of salt section a minimum hole volume of 333 cubic feet, of which 97

Table 3

Index to Boreholes 'A', 'B', 'C', 'D' of Figure 16
All are in Rice County, Kansas

BOREHOLE 'A'

USAEC Test Hole No. 2
Section 35, T.19S, R.8W
Drilled and cored by the U.S. Corps of Engineers 1970
Hutchinson Salt - 755.0 feet to 1002.5 feet
Cored from 737.9 feet to 1099.6 feet
Diameter of cores = 4" - Reamed to 6-1/4"
Caliper Log shows borehole out-to-gauge
Salt saturated brine and low water loss starch mud
Nine days spent coring and/or reaming from base of 8-5/8" surface pipe at 247.5' to 1216' T.D.

BOREHOLE 'B'

USAEC Test Hole No. 1
Section 26, T.19S, R.8W
Drilled and cored by the U.S. Corps of Engineers 1970
Hutchinson Salt - 815.1 feet to 1084.1 feet
Cored from 0 feet to 1300.8 feet
Diameter of cores = 6" - Cored with 7-3/4" core bit
Salt saturated brine and low water loss starch mud
Caliper Log shows hole is carrot-shaped due to abrasion
Twenty-five coring days from base of 8-5/8" surface pipe at 309.5' to 1300.8' T.D.

BOREHOLE 'C'

Barnett Oil Company, No. 1 Wright
Section 35, T.19S, R.8W
Drilled and cored in Oct. 1971
Hutchinson Salt - 758 feet to 1036 feet
Four cores and four drill stem tests of fluid
Drilled with 7-7/8" bit
Caliper Log shows maximum hole size 13-1/2"
Fresh water and starch mud
Fourteen drilling days from base of 8-5/8" surface pipe at 223' to 3583' T.D.

BOREHOLE 'D'

Woodman & Iannitti, No. 2 Stockham
Section 34, T.19S, R.8W
Drilled in Nov. 1970
Hutchinson Salt - 775 feet to 1062 feet
No cores. No drill stem tests
Drilled with 7-7/8" bit
Caliper tool fully extended at 15 inches
Clear fresh water and no mud additives
Six drilling days from base of 8-5/8" surface pipe at 179' to 3466' T.D.

cubic feet were cut away by the bit, 29 cubic feet of rock removed by mechanical abrasion, and the remaining 207 cubic feet removed by dissolution of the salt by the fresh water drilling mud. This figure is too low by an unknown amount but some order of magnitude approximations can be made. First, this log shows, midway through the salt section, two constrictions due to thin anhydrite beds. Second, a repeat caliper log with a maximum diameter of 16 inches (not shown) was run in connection with a density log. It confirmed the two anhydrite beds and indicated the tips of our additional thin shales and/or anhydrite beds in the extra inch of diameter measured, from which it may be inferred that the hole is only a few inches larger in diameter. Recalculation of the minimum volume on the basis of 16 inches maximum recording gives a hole enlargement of more than two diameters and a minimum volume of 372 cubic feet or a hole enlargement of nearly four times the drilled volume (383 percent) which is still too low by an unknown amount.

Occasionally older caliper logs recording to 36 inches maximum diameter are available. These logs were recorded with four independent legs probing the borehole, but with only the maximum reading recorded. Such logs dating in the 1960's to 1970's seldom record off scale measurements in normally drilled holes, but show frequent occurrences of holes in the 24 to 36 inch diameter range. The logs, rare in library collections because customers were loath to pay an extra log charge, were abundantly recorded quietly by the log engineers for their own personal use as they became aware of the sensitivity of the early neutron logs (the most common porosity tool then and now) to hole size corrections. Such logs indicate a common hole enlargement during rotary drilling of 7-7/8 inch holes or 9-inch

holes to the 24 to 36 inch diameter range or about three times the drilled diameter.

A second line of evidence comes from oilwell cementing experience. When cementing oil string casing through a salt section drilled with fresh water, an uncommon operation, cementers expect to use an additional 300 to 500 sacks of cement. Slurry volumes vary with types of cement and additives. Portland cement yields 1.18 cubic feet per sack, but with four percent bentonite (commonly used) yields 1.55 cubic feet per sack, or with eight percent bentonite (the maximum commonly used) yields 1.92 cubic feet per sack. For Borehole 'D' as a theoretical example, it can be assumed that the "additional" cement will be required for that part of the hole in excess of nine inches in diameter through the salt section. It can then be calculated that the hole size is within the following range; based on cementer's practical experience:

if filled with 300 extra sacks cement with 4 percent bentonite	19½" diameter;
if filled with 300 extra sacks cement with 8 percent bentonite	21½" diameter;
if filled with 500 extra sacks cement with 4 percent bentonite	24" diameter;
if filled with 500 extra sacks cement with 8 percent bentonite	26" diameter.

Similar calculations can be made for cement with salt added in varying amounts.

From these order-of-magnitude figures it may be estimated that the probable hole size in the salt section in Borehole 'D' is near 24 inches. If correct, this calculates as 902 cubic feet of salt removed, only 97 cubic feet of which were cut away by the bit, or a volumetric hole enlargement to about nine times the drilled hole volume due essentially to salt dissolution while drilling with fresh water during which the hole became enlarged

to a diameter about three times the bit size ($7\text{--}7/8$ inch bit $\times 3.17 = 25$ inches). These deduced figures are the right order of magnitude and give a good approximation of the usual hole enlargement by salt dissolution during modern rapid drilling with rotary tools in the 1960's and 1970's using fresh water and no mud additives as is the common practice in the study area.

The sensitivity of neutron logs to hole size provides a third line of evidence of hole enlargement during drilling of the salt section. An example is Borehole 'C' repeated in Figure 17. Even the measured small amount of hole enlargement from $7\text{--}7/8$ inches to a maximum of $13\text{--}1/2$ inches was sufficient to cause the neutron log to lose character through the salt section. This combination of gamma-ray, neutron, and resistivity logs, but without the caliper log, is the most commonly recorded log suite in oil and gas test holes in the study area. The flattening of the neutron curve in conjunction with low gamma and high resistivity readings on such logs provides evidence that salt was drilled and partially dissolved but does not provide useful quantitative evidence of the amount of hole enlargement due to dissolution of salt. See Figure 7 for neutron log in salt in out-to-gauge hole.

Fig. 17.--Wire line geophysical logs from Barnett Oil Company No. 1 Wright, Section 35, Township 19 South, Range 8 West, Rice County, Kansas. For legend see Fig. 11. Depth to top and base of Hutchinson Salt, in feet, are shown.

On occasion logging engineers running logs in hole after hole as for example in a salt solution well field, are able to approximately calibrate the sensitivity of their neutron log by comparison with known hole sizes from caliper or sonar surveys. One logging engi-

neer has determined that his 34-inch scintillometer-recorded neutron curve "washed out" completely at a hole diameter of 34 inches and his similarly recorded gamma-ray log "washes out" in holes larger than 36 inches in diameter. His experience with older Geiger-Muller counter tools indicated figures a little larger. He sometimes applies this aspect of log failure to locate "cavities" in cased salt solution holes. The neutron logs usually available to the writer do not permit quantitative hole measurement but record hole enlargement by salt dissolution.

"Fishing" operations give a fourth method of approximating hole diameter due to salt dissolution while drilling. During the period of slower drilling by rotaries, and less or no use of commercial mud additives, there are instances of great hole enlargement during drilling. Holes drilled by rotary in the 1940's had many "fishing jobs" to recover twisted off drill pipe. Drill pipe parted opposite the salt section (a common position) was difficult to recover because the "fish" leaned to the side of the hole back in the solution cavern under shale ledges, and could not be washed over. Fishing tools such as a "knuckle joint" which expanded outward as much as five feet were slowly rotated to sweep the salt cavern 360 degrees in a sometimes successful effort to "hook the fish" and move it to a vertical position centered in the well bore for recovery. Some salt washouts where the knuckle joint tool touched no iron were believed to be enlarged to more than 10 feet in diameter during drilling, an enlargement of over 13.3 diameters (9-inch bit) with a volume increase to over 178 times that of the cylinder but by the bit.

While method five, calculation of volume and salinity of the circulating fluid is routine in solution mining of salt, it is of limited applicability to oil and gas well drilling.

Commonly the hole is started with fresh water which becomes salt saturated during drilling but which is not then replaced with fresh water. Rather, as the hole is deepened and hole volume increases, more fresh water is added which in turn becomes salt saturated. An approximation of the amount of salt dissolved during drilling could be made if the volume of fresh water was accurately known. Such data is difficult to obtain, however, because water trucked to rotary rigs is billed on a trucking time basis, not a water volume basis. Often the water hauler will substitute a load of salt water (oilfield brine) if more easily available when roads are muddy, etc. hence this is not a meaningful source of data.

Instances of zero or near zero hole enlargement by salt dissolution during drilling are limited to the rare salt test holes drilled with brine and to old-time cable tool holes. The latter, though often of large drilled diameter in the salt section (18 inches or more), used small amounts of drilling water. Actual samples of the salt itself were recovered and the holes were not appreciably enlarged by salt dissolution during drilling.

In conclusion, salt dissolution in oil and gas test holes during drilling of oil and gas test holes may range from no dissolution (brine drilled rotary holes and cable tool holes) to extensive dissolution (more than 10 feet in diameter), but in modern rotary drilled holes such enlargement is commonly of the order of magnitude of three times the diameter of the drill bit or 9+ times the volume of the drilled hole as derived by the direct and indirect measurements discussed.

ESSENTIALS FOR ROCK SALT DISSOLUTION

Salt is dissolved during the rotary drilling of oil and gas test holes when the four essential conditions are all present. They are:

1. Salt;
2. Water;
3. Energy;
4. Brine outlet.

All of these basic elementary conditions must be present in a dynamic system (energy input) for rock salt dissolution to occur. In rotary drilling through the salt beds, dissolution continues only if the water in the drilling fluid is fresh or unsaturated. The energy input which moves the water past the salt is, of course, the motors on the pump. The brine outlet is provided by the return circulation of the drilling fluid upward past the salt into the pits. Elementary as it seems, if any one of the conditions is interrupted or absent, then dissolution ceases or does not occur.

The Hutchinson Salt Member of the Wellington Formation has been undissolved for over 200 million years because of its position sealed within an envelope of virtually non-permeable shales (condition 1, but not 2, 3, or 4). An abandoned salt mine, flooded with fresh water (conditions 1 and 2, not 3 and 4) loses a fraction of a millimeter from its walls and pillars by dissolution, but does not collapse. Indeed it is stronger waterfilled than airfilled. A brine solution mining well provides conditions 1, 2, 3, and 4, with resulting salt dissolution which is immediately discontinued when the pump motors are shut off (con-

dition 3, energy input, curtailed). Abandoned oil and gas test holes in Kansas (conditions 1, 2, 3, but not 4) penetrate salt below shallow aquifers where gravity can provide the energy to move fresh water down the borehole across the salt face, but absence of an outlet for saturated brine (condition 4) is commonly the limiting factor.

These general requirements for rock salt dissolution can be reviewed as applied to the specific example of a recent sink hole at the Cargill Salt, Inc. plant, Hutchinson, Kansas, where too much salt dissolution in connection with commercial salt mining caused sudden ground collapse.

CARGILL SALT, INC. SINK HOLE - HUTCHINSON, KANSAS

The dramatic ground collapse October 21, 1974 at the Cargill Salt, Inc. property in Hutchinson, Kansas, which occurred in the early morning hours, left three tracks of the Missouri-Pacific railroad suspended in air over a sinking area then 200 feet in diameter and growing larger as shown in the photograph (Fig. 18) taken early that afternoon. The

Fig. 18.--Photograph by The Hutchinson News, published October 21, 1974.

Sink hole in lower center is about 14 hours old, 200 feet in diameter, and still growing. View northward toward plant of Cargill Salt, Inc. Tracks of the Missouri-Pacific railroad are suspended in air and sagging as emphasized by their shadows on the water surface 21 feet below. The dark line is a temporary fence.

ground was still collapsing October 23, 1974 when the author talked with Melville W. Gray, Director of Environment, State of Kansas, Department of Health and Environment, at the site. The sink hole had then nearly stabilized. The vertical walled sink is about circular and nearly 300 feet in diameter (measured 285 feet by 291 feet by Walters, December 27, 1974). Volume of the collapsed sink hole is about 3 million cubic feet. Distance from the flat land surface to water was measured as 21.5 feet by Ralph E. O'Connor, Area Geologist, State of Kansas, Department of Health and Environment (personal communication), who also measured seven water depths on the nearly flat bottom (24', 24', 24', 25', 28', 33', 18'). Water depths average 25 feet but have a maximum of 33 feet near the center of the original collapse area, thought to be the location of abandoned salt solution well No. 9. The

minimum water depth of 18 feet is in a late collapse area on the east side where the ground was lowered by subsidence without tilting a large tree whose top branches are still visible above the water. Various buried pipe lines were uncovered, then parted, but the railroad tracks remained suspended in air, tilted and sagging, but unbroken until removed by railroad employees several days later. Figure 19 shows the sink hole in stabilized condition with the railroad tracks relocated.

Fig. 19.--Photograph by The Wichita Eagle, published November 16, 1974. Cargill Salt, Inc. plant in the foreground. View is toward the south. The stabilized sink hole is about 300 feet in diameter. Missouri-Pacific railroad tracks removed and relocated. The tree in the pit on the left (east) side was lowered from its position on the east bank in Fig. 18. Boxcars on siding are in same position in both photographs giving a visual measure of pit enlargement during the three days of active subsidence.

Location of the sink area in which active collapse occurred over about three days is at the south edge of the Cargill Salt, Inc. plant at the southeastern edge of the city of Hutchinson, in approximately the Center of the S/2 NW/4 of Section 19, Township 23 South, Range 5 West, Reno County, Kansas. Salt has been extensively and continuously solution mined at and under this plant for over 60 years. The plant is currently processing 500 tons of dissolved salt each day thus voiding 7,402 cubic feet each day.

Conditions leading to excessive salt dissolution followed by collapse included all of the essential factors: salt, water, energy, and outlet, together with a time factor of

60 years. The salt encountered below 400 feet has a thickness of 350 feet. The area is densely drilled with now-abandoned salt solution brine production wells which commonly had 5-1/2 inch production casing set near 480 feet in the salt. They have 8-5/8 inch surface casing set and cemented near 70 feet in the top of the bedrock, the Permian shale "redbeds". This casing protects the fresh waterbearing sand and gravel beds, thickness 50 feet, which are now visible in the pit walls. Salt was mined by pumping fresh water at a pressure of 150 psi down 2-inch tubing set within the salt at varying depths, commonly 550 feet but as deep as 770 feet near the base of the salt. Upon abandonment the tubing and production casing are salvaged when possible, but the surface casing is left cemented in place.

The location of one such abandoned brine production well, No. 9, falls within the sink hole where the water depth is the deepest, 33 feet, but the hole has not been located exactly, nor can its surface pipe be found. The history of well No. 9, one of many brine production wells, is that it was drilled in 1914 and used as a salt solution well until 1924. At that time so much salt had been dissolved that the underground void space became connected with adjacent brine wells and production from the gallery was inefficient. Well No. 9 was then repaired and used as a brine return well in this gallery until abandoned November 5, 1928. The area was redrilled with new brine wells on 300-foot centers located between the abandoned wells and these, too, were used as brine production wells until abandoned years later for the same reason - interconnection of void space from wall to wall to form large galleries, inefficient for salt brine pumping under pressure.

In salt plant operations there are waste solids, calcium sulfate, and magnesium chloride, etc. in the form of tiny crystals of gypsum, etc., produced with the dissolved salt in small percentages but considerable aggregate tonnage. For example, if the 500 tons of salt mined each day at the Cargill plant include only one percent such solid wastes, then five tons need to be disposed each day. This is done by returning such solids in plant "wash water" for slow settling in dissolved galleries. At the time of the sink collapse, four abandoned brine wells known to be in a connected gallery were being used for injection of plant waste disposal. Three of these interconnecting disposal wells, No. 34, No. 61, and No. 62, are located in a straight line starting with well No. 9 extending south-southwest for 900 feet. These wells, including No. 9, are on 300-foot spacing. A fourth well, No. 35, located 300 feet west of the line of input wells is pumped by air lift to return water to the plant, hence this waste disposal gallery was known as the "air lift" field.

The waste solids entered the gallery of the "air lift" field through wells by pumping at 150 psi at the time of collapse. During collapse the water in the sink was observed to have a rolling motion, but this ceased when pumping into the gallery was stopped, confirming interconnection between the sink and the wells of the "air lift" field. Samples of water in the sink hole taken on October 22, 1974 had a chloride content of 89,000 parts per million (ppm), as compared with 367 ppm chlorides, average of 39 water wells in the immediate vicinity, in water samples collected October 24-25, 1974.

Geologists with the State of Kansas, Department of Health and Environment (Ralph E. O'Connor personal communication), have discussed two possible causes for the sink hole

collapse, "piping" of sand downward or "stoping" upward, and prefer the first explanation. Both theoretical explanations are based on facts disclosed by their site investigations which established the intercommunication of the "air lift" gallery and the sink hole and which provide the analyses of 89,000 ppm chlorides in the sink hole lake at the time of subsidence (as compared with the 10 percent brine about 98,000 ppm for the wash water entering the gallery, and 367 ppm average for wells in the shallow aquifer breached by the sink hole). Under the "piping" concept they theorize that well No. 9 acted as a pipe or conduit for "piping" of loose sand and gravel downward by gravity into the salt gallery void space (hour-glass effect). Piping of loose sand below the surface would continue until the roof of the near surface cavity, formed in the sand and gravel, would not support itself. Collapse of this near surface cavity, they argue, would force a displacement of brine from the salt cavity upward and account for the high chloride brine in the sink hole October 22, 1974. Piping of large volumes of loose sediments into salt voids has been described by Fent (1971). Craters caused by piping are an occasional hazard in oil drilling operations, causing the drilling rig to tilt or overturn.

The same investigators have considered an alternative explanation (O'Connor personal communication) involving partial collapse of the Permian shale roof of the "air lift" gallery by what miners call "stoping". Such upward "stoping" or "chimneying" as a theory of sink hole formation has been described by Landes (1972) in connection with large scale brine cavity subsidence near Detroit, Michigan. Parts of the gallery roof spall or fall away in small amounts over extended periods of time undetected. Upward stoping continues in an inverted funnel shape until such time as the overlying roof shale cannot

remain self-supporting. Collapse occurs when the chimney undercuts the uppermost layer. Sink holes are usually dated from the time this plug drops breaching the surface and creating a crater or sink hole.

In any event, two cycles of commercial salt production plus "air lift" gallery operations, extending over a period of 60 years of salt mining dissolved a void space too large to be stable, resulting in collapse. The exact time and place of collapse may have been influenced by vibrations from the passage of trains on the Missouri-Pacific railroad. Well No. 9 is described in old company records as "in the southwestern corner of the intersection of (the eastward projection) Osborne Street and the Missouri-Pacific railroad tracks. Since the sink hole collapse, the "air lift" gallery has been abandoned because efforts to re-enter, log, and repair well No.'s 34, 35, 61, and 62 were unsuccessful. With solution mining and "air lift" operation discontinued, the energy input for continued salt dissolution has ceased. The stabilized sink hole is in the "dishing" phase in which the nearly vertical walls slowly erode to gentle slopes. The sink hole at the Cargill Salt, Inc. plant, here summarized as a current documented example of surface subsidence due to salt dissolution, is similar in size, depth, shape, and mode of origin to sink holes located in the Gorham Oilfield (Part II) and the Chase-Silica Oilfield (Part III) in this report, except that the boreholes involved were drilled for salt itself rather than for oil and gas.

SALT DISSOLUTION IN OIL AND GAS TEST HOLES AFTER DRILLING

GENERAL DISCUSSION

This subject is less difficult to investigate than one might assume on first impression. When information from abandoned holes re-entered years later plus information from cased hole logs is combined with knowledge of the hydrological principles involved, the conclusion is reached that, most commonly, no salt dissolution occurs after drilling ceases, shutting off that source of energy input. To understand why this is so, we must consider the four essential components - salt, water, energy, brine outlet - with the added factor of a 50-year time interval for extensive oil and gas test well drilling in the study area.

The salt itself has not changed - it is still in place where it has been for over 200 million years, but now with its protective shale envelope pierced by boreholes. Water, including fresh water, is usually present in Kansas in aquifers penetrated by the bit at depths more shallow than the salt. A constant natural energy source, gravity, is available to move the fresh water down the drilled hole past the salt section, unless prohibited by the well plugging materials or by cemented surface casing left in the hole (required in Kansas oil and gas test holes since 1935). Other aquifers (sometimes termed "salifers") below the salt contain brine in varying concentrations, but unsaturated as regards sodium chloride. Absent in most cases is the critical factor of a brine outlet hence post-drilling salt dissolution usually does not occur. Exceptions are old test holes with no surface pipe cemented through the shallow fresh water aquifers and seven instances of salt water disposal wells (high energy input, high volume of fluid flow) with corroded leaky casing where inadvertent extensive

salt dissolution has resulted in subsidence at the surface. Also excepted is approximately five percent of the study area including the Gorham Oilfield (Part II) where limited post-drilling salt dissolution is believed to be continuing at the present time.

To investigate post-drilling salt dissolution in oil and gas test holes we must briefly consider the hydrology of the aquifers drilled and their ability to flow from one to the other across the salt face through manmade borehole with only gravity as an energy source.

SALT DISSOLUTION IN OIL AND GAS TEST HOLES AFTER DRILLING

HYDROLOGY

To summarize the hydrology of multiple aquifers in a 4,000-square mile study area penetrated by 22,200 oil and gas test holes in a brief but meaningful way, we begin with a specific example, applicable in principal to 90+ percent of the area, then discuss the difference in the other 10+ percent of the area. In general, the aquifers drilled at depths less shallow than the salt are fresh water bearing; in general, the redbeds above and below the salt and the salt itself are nonaquifers or aquitards with very low transmissibility; and, in general, the multiple aquifers below the salt (some of which are oil and gas reservoirs) are brine bearing, but all brines are unsaturated as to sodium chloride at reservoir temperatures and pressures.

Cross Section A-B, Figure 3, in Rice County, Kansas shows in natural scale (vertical and horizontal scales equal) the relative position of the aquifers (indicated by the letter "W" on the cross section) here discussed as a specific example. Omitted from the cross section are the many shallow fresh water test wells drilled by the Kansas Geological Survey (Bayne and Ward, 1971). Drill stem test data from well No.'s 6 and 9, cable tool water information from well No. 8, and potentiometric surface data from shallow wells are combined in Table 4, next page.

Aquifer No. 1 of that table, "rain" was not entered to be facetious. In the Gorham Oilfield one abandoned (and apparently unplugged) oil well serves directly as a storm sewer

Table 4
EXAMPLE, AQUIFER DATA - RICE COUNTY, KANSAS

	<u>Aquifer Number</u>	<u>Depth (Base) Feet</u>	<u>Sea Level Datum</u>	<u>BHP psi</u>	<u>Pot. Surface</u>	<u>Sp. Gr.</u>	<u>Water Quality (ppm)</u> <u>Chlorides</u> <u>Total Solids</u>	
Surface water - rain	1	0	+1694	-	+1694	1.000	0+	0+
QUATERNARY								
Pleistocene - sand, gravel	2	50	+1644	-	+1680		71	445
CRETACEOUS								
Dakota - sandstone lenses	3	absent						
Kiowa - sandstone lenses	4	170	+1524	-	+1680		78	488
PERMIAN								
Nippewalla Group "redbeds"	aquitard							
Sumner Group "redbeds"	aquitard							
Hutchinson Salt Member	aquitard							
Chase Group								
Florence dolomitc limestone	5	1451	+ 243	435	+1249	1.162	155,000	270,000
PENNSYLVANIAN								
Wabaunsee Group limestone	6	2075	- 344	-	+1350 Est.	-	-	-
Shawnee Group								
Lecompton limestone	7	2604	- 910	1035	+1480	1.146	132,000	237,000
Douglas Group sandstone	8	2323	-1129	1150	+1527	1.145	132,000	234,000
Lansing-Kansas City Group limestone	9	3043	-1349	1167	+1346	1.135	127,000	195,000
CAMBRO-ORDOVICIAN								
Arbuckle Group dolomite	10	3526	-1783	1221	+1037	1.033	24,000	41,000

for rainwater runoff from Interstate Highway 90 draining a subsidence basin caused by salt dissolution. Aquifer No. 3, the Dakota sandstone, is absent in the cross section but widely present to the west as a shallow fresh water aquifer protected by surface casing. For the other shallow Quaternary and Cretaceous fresh water aquifers (No.'s 2 and 4 in Table 4) the potentiometric surface was measured directly in water wells drilled for that purpose by simply measuring the depth to water in the open hole and correcting for well elevation. For aquifer No. 6 the cable tool drillers' log of well No. 8 recorded "three bailers of water per hour at 2075 feet". All other aquifer data for brines below the salt section is derived from fluid recoveries and charts of bottom hole pressures recorded while using the drill pipe with one or more packers as temporary casing isolating the zone. Such a test, called a drill stem test (DST), gives accurate pressure information in pounds per square inch (psi) and provides recovery of the actual formation fluid, in part contaminated by the drilling fluid - or "mud". DST bottom hole pressures (BHP) are here converted to the potentiometric surface figure of hydrologists by dividing the BHP by .433 psi per lineal foot, the weight of a column of fresh water specific gravity 1.000; and correcting the answer to a sea level datum. For examples,

A. Chase Group, Florence Limestone, Aquifer No. 5

From an elevation of	1694 feet above sea level
at a depth of	1451 feet in the well bore
or a datum of	+243 feet above sea level
the BHP will support	1006-foot column of fresh water
	(435 psi/.433)
or a potentiometric surface of	+1249 feet above sea level.

B. Shawnee Limestone

From an elevation of	1694 feet above sea level
at a depth of	2604 feet
or a datum of	-910 feet below sea level
the BHP will support	2390-foot column of fresh water (1035 psi/.433)
or a potentiometric surface of	+1480 feet above sea level.

The resulting derived and measured potentiometric surface figures are graphed in Figure 20.

Fig. 20.--Graph showing static fluid levels (diagonal shading) for aquifers in central Kansas. Refer to Table 4 for identification of numbered aquifers. For brine aquifers No.'s 5-10 inclusive, the potentiometric surface, or calculated static fluid level for fresh water is dashed. Depths are in feet above or below sea level.

Hydrologists who are accustomed to working with fresh water in unconfined reservoirs find the simple concept of potentiometric surface adequate for much of their work as it is axiomatic that flow (by gravity downward) is from higher to lower values on the potentiometric surface. By simple inspection of Figure 20 it is apparent that aquifers 1, 2, and 4, all fresh water bearing and located above the salt will flow into any or all of aquifers 5 through 10, if a suitable borehole is available, with a "head" difference obtained by subtracting the potentiometric surface figures and such flow will be across the salt face if borehole conditions permit.

But as regards actual flow from one deeper aquifer to the other, the potentiometric surface can be misleading. Hydrologists working in the future with confined aquifers (or

"salifers") of varying salinity, will have to rely more on pressure data because in confined reservoirs the flow direction may be up, down, or sideways. For example, aquifer No. 9, Kansas City, has a higher potentiometric surface (+1346) than aquifer No. 5, Chase Group (+1249), but the actual flow direction is the opposite of that indicated by the potentiometric surface figures due to differences in the specific gravity of the contained brines.

The potential flow directions for aquifers 1 through 10, if interconnected, may be derived graphically. The construction of such a graph is shown in four steps. Figure 21 shows a graph of a DST of aquifer No. 5, Chase Group dolomitic limestone, with depths in feet and position relative to sea level as ordinate and BHP in psi as abscissa.

Fig. 21.--Graph of drill stem test (DST) data for aquifer No. 5, Chase Group dolomitic limestone showing derivation of pressure gradient curve.

The actual fluid fillup data is recalculated as a static fillup of brine (not rotary mud). The pressure gradient is then drawn. In the graph, Figure 22, the subsurface position of the salt is plotted and the position of three deeper aquifers is shown.

Fig. 22.--Graph showing subsea position of Hutchinson Salt relative to four aquifers. Top to bottom 5, 7, 8, and 9 of Table 4.

Figure 23 graphs the fillup data and pressure gradients for all four aquifers. Note that the four static fluid levels are all above or within the salt interval which means that if an underground salt operation inadvertently mined into an unknown abandoned and unplugged

Fig. 23.--Graph showing derivation of pressure gradients for four aquifers. Left to right, 5, 7, 8, and 9 of Table 4.

oil and gas test hole, the mine would be flooded (Lomenick 1972). Flow from one zone to another, if interconnected by a suitable borehole will be from higher pressure to lower pressure. Thus at the depth of the Florence Flint, aquifer No. 5, brine will flow from it into the borehole, down and into the Kansas City, aquifer No. 9. This flow is the opposite of that indicated by the simplistic potentiometric surface data, Table 4, used by hydrologists. Such flow, however, would occur only after flow from the Lecompton and Douglas, aquifers, No.'s 7 and 8, (in equilibrium with each other) had equalized with the brine in the Kansas City, aquifer No. 9. Common static level for all aquifers below the salt, No.'s 5, 6 (not shown), 7, 8, and 9, will be slightly higher than +864, but at a level within the salt section. This fact has been recorded on 100 or more cased hole logs in and near the Chase-Silica Oilfield by a pronounced shift in the neutron curve signaling an air-water contact outside the casing. Note that flow from zone to zone among these aquifers to equalize pressures does not involve flow across the salt face itself, hence no dissolution occurs even with borehole communication between all aquifers below the salt and above the Cambro-Ordovician Arbuckle dolomite, aquifer No. 10, which has by far the greatest capacity to either yield or take fluid.

The graph in Figure 24 repeats the previous four pressure gradients and adds a pressure gradient from four DST pressures in the Cambro-Ordovician Arbuckle dolomite in a nearby well, No. 9 (Fig. 3).

Fig. 24.--Graph of aquifer pressure gradients, central Kansas.

For all aquifers interconnected by a suitable borehole, flow direction can be read on the graph and will be from higher pressure (right) to lower pressure (left) until a common static level is reached. Flow from zone to zone to reach equalized static will occur at the aquifer depth level and there will be no flow across the salt face hence no dissolution of salt.

Note that the pressure data developed in the graphs, Figures 21-24, assume interconnected zones in an open borehole. They are, therefore, valid for all oil and gas test holes in the study area which have properly set surface casing "protecting" (isolating) fresh water aquifers as required by ruling of the Kansas Corporation Commission. This permits the conclusion that all oil and gas test holes, whether "dry holes" in which only surface pipe has been set, or oil wells cased to the pay zone, or abandoned oil wells with a shot off casing stub left in the hole, or salt water disposal wells, that ALL OIL AND GAS TEST HOLES HOWEVER PLUGGED OR EVEN NOT PLUGGED AT ALL WILL EQUALIZE FLUID at a permanent static level usually within, but sometimes above or below, the salt WITH NO FLOW ACROSS THE SALT FACE HENCE WITH NO SALT DISSOLUTION in oil and gas test holes after drilling, provided adequate surface pipe, internally plugged, is cemented in place through the near surface fresh water aquifers. This important conclusion applies to geological conditions over about 95 percent of the study area. It does not apply to 5+ percent of the area including the Gorham Oilfield where two additional aquifers, Cretaceous Cheyenne sandstone and Permian Cedar Hills sandstone occur above the salt and are not required to be "protected" by surface pipe because their contained fluid is brine. This situation can,

has, and will cause salt dissolution in oil and gas test holes as discussed in Part II, Gorham Oilfield.

Because of the critical importance of properly cemented surface pipe, as required of all operators, we will consider briefly the regulations covering the protection of fresh water. Surface casing is required for all oil and gas test holes, its amount is specified, and advance notice of intent to drill is required by the Kansas Corporation Commission. Violations are uncommon to nonexistent. The presence of surface pipe is easily monitored by cased hole logs. Final plugging of abandoned oil and gas test holes is under the direct field supervision of a "state plugger", and notarized well plugging reports showing surface casing are required and permanently filed. Such regulation of hole plugging, and concomitant surface pipe supervision by the state and well record file goes back to 1935. For the period prior to that there was limited supervision on a county-by-county basis to about 1930, prior to which there was no regulation, no protection of fresh water, and no supervised hole plugging. Drilling for oil, and earlier for salt within the study area extends back to 1888. There are instances, seldom documented, of uncased unplugged early oil and gas test wells in which post-drilling salt dissolution could and did occur. One such hole is described.

SALT DISSOLUTION IN OIL AND GAS TEST HOLES AFTER DRILLING

CASE HISTORIES - NO SURFACE CASING

An example of extensive post-drilling salt dissolution in an old test hole due to absence of surface pipe and lack of proper borehole plugging is provided by the Taylor No. 1, total depth 3552 feet in the Arbuckle dolomite, drilled from July 28 to October 10, 1934 in the Center of the NW/4 SE/4 of Section 25, Township 19 South, Range 8 West, Rice County, Kansas. This cable tool dry hole was abandoned prior to state regulation of well plugging and required protection of fresh water by surface casing. It is located just east of the abandoned Lyons Arbuckle gas field which Northern Natural Gas Company redrilled for use as an underground natural gas storage reservoir. To ensure proper plugging of old test holes to avoid leakage of valuable stored gas from the Arbuckle reservoir, they re-entered several abandoned holes in 1974 including the No. 1 Taylor on the south side of U.S. Highway 56 which was located without difficulty by use of 1938 aerial photographs. Discolored soil marked the location. Bulldozer excavation revealed the old cellar 12 feet deep which was followed downward in the manner of an archaeological dig. No surface casing at all was present. When the bulldozer was 17 feet down below the surface, it found a 48-inch hole empty and open. Before the contractor's rig could re-enter the hole it was necessary to set 18 feet of 48-inch conductor pipe, then to set 8-5/8 inch surface pipe at 134 feet. Even so, drilling was made more difficult by the presence of a Cretaceous sand from 170 to 190 feet, a fresh water aquifer, No. 4 of Table 4. At a total depth of 3495 feet 5-1/2 hours were required to circulate a sample of cuttings from bottom. Using this

information Bill Luck (personal communication), field superintendent for Northern, calculated that it required the pumping of 11,000 barrels of fluid to bring the cuttings to the surface. Using this as a minimum estimate of the volume of the old hole, Walters calculated an average hole diameter in the salt section from 800 feet to 1060 feet of 8.43 feet. Assumed in the calculation is the fact that hole enlargement is due to solution removal of salt. Any hole enlargement due to caving of an upper part of the hole would be compensated by filling a lower portion. This appears to be a documented example of an old hole with no surface casing at all, and no plug in the hole except by bridging the hole in the cellar with large concrete rig foundation blocks between which black topsoil was tamped.

The salt section in the Taylor No. 1 was drilled with a 15-inch cable tool bit, hence there was little or no solution enlargement during drilling. The estimated minimum diameter at re-entry, 8.43 feet, represents a post-drilling hole enlargement of about seven diameters, or of a removal of about 12,000 cubic feet of salt by post-drilling dissolution due to gravity flow from a fresh water aquifer down the borehole of an uncased unplugged oil and gas test hole unto the permeable Arbuckle dolomite which provided the needed brine outlet. It is thought that the hole partially plugged itself by bridging as a larger amount of dissolution could be expected in 40 years time with the available abundant fresh water supply.

A second example in the same area is the Pulliam No. A-1 in the Center of the S/2 N/2 NE/4 of Section 35, Township 19 South, Range 8 West, Rice County, Kansas, re-entered by Northern Natural Gas Company in 1974. The complete lack of surface pipe

in this abandoned gas well provided the first minor problem in re-entry for the reason that the well was actually drilled considerably south of its reported and staked location. After considerable bulldozer work, the old 6 ft X 6 ft cellar 10 feet deep was located. As excavation proceeded, the old sills and blocks were found to be in place at the bottom of the cellar. Below them was an open unfilled hole 48 inches in diameter to a depth of 28 feet. When this gas well was abandoned in 1945, it was adequately plugged in the Simpson and Arbuckle near 3200 feet, but all casing which could be removed was salvaged leaving no surface pipe at all and apparently no plugging of the old hole above the Arbuckle reservoir. No information is available as to the diameter of this hole in the salt section at re-entry in 1974.

A test hole in the same section only 150 feet south, in the Center of the NE/4 of Section 35, Township 19 South, Range 8 West, Rice County, Kansas, the Pulliam No. 1, re-entered by Northern Natural Gas Company, provides some information on hole enlargement in the salt, presumably in part due to post-drilling dissolution. The Pulliam No. 1, a dry hole, had surface pipe set at 204 feet with no casing below that point. It was drilled in 1962, fifteen years after the abandonment of the nearest gas wells. It was an easy hole to re-enter and had a deep penetration, 102 feet, in the Arbuckle, see Figure 3, cross section, well No. 9, and Table 4, aquifer No. 10. The author studied pressure and fluid recovery information from the drill stem tests and calculated equivalent specific gravity figures for three intervals. Figures were 0.996 (fresh water), 1.033 (equivalent 41,000 ppm), and 1.047 (equivalent 65,200 ppm). These calculations suggested leakage of water into the Arbuckle dolomite through older abandoned gas wells improperly plugged.

Northern set a new string of casing in the re-entered hole for use as an input-withdrawal gas storage well. From cementing information the author calculated the average hole size in the salt section, depth 777 feet to 1042 feet, as 37 inches average diameter. This amount is approximately 50 percent more hole enlargement than would be expected due to normal rotary drilling with fresh water.

These examples confirm the premise that absence of surface pipe isolating fresh water aquifers can cause post-drilling salt dissolution in unplugged or poorly plugged holes. Older holes drilled before 1935 are most suspect. Apparently these holes plug or partially plug themselves by bridging as there are no known examples of surface subsidence associated with these 40 to 50-year old holes.

SALT DISSOLUTION IN OIL AND GAS TEST HOLES AFTER DRILLING

CASE HISTORIES - SALT WATER DISPOSAL WELLS

Oil production in the study area dates from the discovery of the Fairport Oilfield in western Russell County in 1923. The underground reservoirs for the vast quantities of oil produced from the central Kansas oilfields in the study area over this 50-year period are the brine aquifers listed in Table 4. Oil in them is associated with reservoir brines which are produced in decreasing amounts in the solution drive reservoirs and in increasing amounts in the water drive Arbuckle dolomite reservoir as the wells become older. The Arbuckle dolomite, reservoir for perhaps 75 percent of the oil produced in the study area in the past 50 years, is an enormously large aquifer, hence Arbuckle oil reservoirs have a strong water drive. Wells producing from the Arbuckle Group (Walters 1958) are seldom abandoned because they run out of oil, only because it becomes no longer profitable to pump so much brine. Scores of Arbuckle wells in the Chase-Silica Oilfield each produced 500 barrels (42 gallons each) of salt water each day along with oil in amounts decreasing to 1 percent. One operator in the Gorham Oilfield is currently moving a submersible pump from one well to another well, profitably pumping 2,000 barrels of fluid per day with 99 percent brine and only 1 percent oil (20 BOPD). It has long been required in Kansas, under the supervision of the State of Kansas, Department of Health and Environment, that brine produced with oil be properly disposed usually by returning it underground. When disposed in aquifers other than the oil producing reservoir, or if 50 feet or more deeper in the same reservoir, the wells are known as salt water disposal wells (SWD). They are commonly completed in

the Arbuckle dolomite and take enormous amounts of brine by gravity flow. A single Arbuckle SWD well in the Tobias Oilfield of eastern Rice County, for example, disposes brine pumped by 50 Arbuckle oil wells, most producing over 100 barrels of brine each, or over 5,000 barrels of brine per day. The well takes water by gravity flow through approximately 3500 feet of plastic-coated 5-1/2 inch casing used as tubing. One can hear the roar of the falling water while standing many feet distant from the SWD well. The energy input into such a salt water system is enormous. Here 50+ large motors pump oil and water vertically 3350 feet, then the separated brine flows horizontally in a gathering system, followed by gravity drop of the combined brine through 3500 feet! This large daily volume of brine is unsaturated as to chlorides. The average of 33 Arbuckle brine analyses from the adjacent Chase-Silica Oilfield (Martin 1968) is 13,870 ppm chlorides. This figure is quite low as compared with 98,000 ppm chlorides for a 10 percent salt solution (common in drilling mud), or 210,000 ppm chlorides in a 20 percent salt solution, and approximately 260,000 ppm chlorides in a 26 percent saturated salt solution. There is tremendous capacity for this disposed "brine" to dissolve more salt. It is corrosive with a strong hydrogen sulfide odor. Here then is the potential for salt dissolution - high energy input, large volumes of water undersaturated as to chlorides, thick salt beds, and an enormous brine outlet in the Arbuckle dolomite, with corrosive fluid attacking the steel casing (plastic-lined or fiberglass tubing and plastic lead lines). This is the special situation which rarely has caused extensive salt dissolution in oil and gas test holes leading to surface subsidence in the seven known instances here listed.

Crawford No. 12
Crawford No. 16
Sec. 2, T. 14S, R. 15W
Twin wells in C NW/4 NW/4 SW/4
Gorham Oilfield
Russell County, Kansas

Witt No. 1
Sec. 3, T. 14S, R. 15W
C NW/4 NW/4 SE/4
Gorham Oilfield
Russell County, Kansas

Hodge No. 2
Sec. 25, T. 20S, R. 6W
C S/2 NW/4 NE/4
Welch-Bornholdt Oilfield
Rice County, Kansas

Hilton No. 6
Hilton No. 7
Sec. 6, T. 20S, R. 9W
C NW/4 NE/4 SW/4
Chase-Silica Oilfield
Rice County, Kansas

Berschedit Heirs No. 14
Sec. 6, T. 20S, R. 10W
C SW/4 SW/4 NW/4
Chase-Silica Oilfield
Rice County, Kansas

W. M. Panning No. 11
Sec. 2, T. 20S, R. 11W
C SW/4 SE/4 SE/4
Chase-Silica Oilfield
Barton County, Kansas

These twin wells, 50 feet apart, are the site of 20 feet of settling affecting the south (east bound) lane of U.S. 1-70. The Kansas State Highway Department drilled a test hole between these wells. The area is precisely surveyed, intensely studied (Burgat and Taylor 1972), (Taylor 1970), and affords conclusive evidence that subsidence is due to dissolution of salt in old oil and gas test holes.

The Witt No. 1 is next to the south right-of-way fence of U.S. 1-70. Subsidence of 10 feet around the well makes a gathering basin for rainwater which drains directly off the highway into the well bore, exposed in a gash gully.

There is a mature shallow dish depression with a small pond at this location. Gilbert Toman (personal communication) said this was due to settling of the ground around the old disposal well.

Twin SWD wells. Well No. 6 was used until October 1951 and well No. 7, a few feet distant, until June 1965. N. W. Biegler (personal communication) said that the subsidence area around these holes appears stabilized. There is a shallow fresh water lake in the gentle depression.

N. W. Biegler (personal communication) was present at the site during plugging of this Arbuckle SWD well in April 1972. The ground was then sinking and a pond had formed with water to the edge of the lease road.

On April 24, 1959 at 9:00 a.m. the landowner observed a cavity forming around this well. It developed into a pit 300 feet in diameter within a few hours time. At present the site is a fenced fresh water lake used as a game preserve with nesting Canada geese.

Daisy E. Pierce No. 5
Sec. 33, T. 23S, R. 4W
C NE/4 SE/4 NE/4
Burton Oilfield
Reno County, Kansas

Gilbert Toman (personal communication) said disposal into this shallow well caused about four feet of settling of the section line road. The well is 10 miles east and south of Hutchinson, Kansas, outside the study area of this report.

RECOGNITION OF SALT DISSOLUTION IN OIL AND GAS TEST HOLES

Discussed in this study are the subsurface methods of recognizing salt dissolution in oil and gas test holes in central Kansas. The list includes (a) the change from fresh water mud to heavy salty mud, (b) the calculation of salinity volume relations, (c) the probing with fishing tools, (d) caliper logs, (e) the interpretation of other wire line geophysical logs particularly the neutron log, and (f) cement volume calculations in the few cases where cement is placed behind casing opposite the salt section. At best, the subsurface measurement of salt dissolution in a borehole is an evasive and difficult subject. Once the hole is closed by abandonment and/or plugging, there are very few methods of monitoring subsurface conditions. Although many abandoned "dry holes" are routinely re-entered each year in central Kansas in search for overlooked hydrocarbons, such borehole re-entry work is done as quickly and cheaply as possible with little regard for the salt section. Only rarely is there a major re-entry program like that of Northern Natural Gas Company in the Lyons Gas Field where 18 holes were re-entered and carefully replugged at a cost of over \$600,000 in 1974. Three of the re-entered holes provided salt dissolution case histories for this study, the Taylor No. 1, Pulliam No. A-1, and Pulliam No. 1, pages 66-68. The presence of these unplugged oil and gas test holes was correctly suspected by Charles K. Bayne (Bayne and Ward 1971) who directed a detailed subsurface hydrological investigation of shallow aquifers in and near the immediate vicinity in 1970-1971. At that time the area was undergoing intensive investigation as to its suitability for long term (200,000 years) use as a repository for high level radioactive wastes. The groundwater study, funded by the United

States Atomic Energy Commission included the drilling by the Kansas Geological Survey of 36 shallow (100 feet+) water wells with its own drilling rig plus four deeper (300 feet) holes for hydrologic testing. The Survey's groundwater investigation disclosed a "pressure sink" in the potentiometric surface of the Cretaceous Kiowa aquifer (Table 4, aquifer No. 4) about which Bayne wrote with regard to their hole 2-S, ". . . . the anomalous hydraulic potential in this test hole can only occur if water is being or has been withdrawn either through a well pumping from the aquifer or being discharged downward through an old drill hole or fracture. There is no record present or past of water being pumped from this zone there is a strong argument for downward leakage of water. Several oil and gas test holes have been drilled within a few hundred yards of the site of test hole 2-S." This example indicates that when special needs justify funding the costly and time consuming effort, a detailed subsurface hydrological investigation of shallow aquifers by drilling and testing may provide pertinent information on uncased, unplugged oil and gas test wells which by inference may be the locus of salt dissolution.

Surface methods of detecting subsidence due to salt dissolution have been confined to the obvious in central Kansas. When the ground falls in during the night leaving main line railroad tracks suspended in midair, then the press flies over the site, runs front page pictures, and queries whether all Kansas is falling apart (the Chicken Little or Henny Penny approach to events - "the sky is falling down!"). Otherwise subsidence may well go unnoticed..

Downwarping detected at the surface by precise level surveys and cracking of the ground are two early surface indications of salt dissolution at depth. Ground cracks

show best in paving or solid material, but not at all in plowed ground. Precise level surveys are lacking; routine oil well elevations are accurate only to plus or minus one foot. The oilfields are located in an agricultural area where damage from subsidence is minimal. This is in contrast to the urban situation described by Landes (1972) where salt is mined near and under the city of Detroit. Many precise reference point elevations surveyed in units of 1/1000 of one foot are recorded, mapped, and graphed semi-annually or annually. Subsidence of 1/4th inch (0.021 feet) per year were considered acceptable in that area. In Kansas, slow subsidence of one foot may easily go entirely unnoticed. It is, however, unlikely that subsidence of two feet or more will go unnoticed because of interference with agriculture by ponding of water in the low spots, and because officials of the state regulatory agencies systematically inspect oil leases checking for infractions in water disposal, surface casing, and hole plugging. The author is indebted to officials of the State of Kansas, Department of Health and Environment (SWD installations, salt solution mining), the Kansas Corporation Commission (hole plugging, drilling permits, surface pipe), and the State Highway Department (highway construction, maintenance), for their on-site observations of surface conditions associated with salt dissolution.

CONCLUSIONS

As regards salt dissolution in oil and gas test holes in central Kansas, the conclusions are:

1. Salt dissolution occurs during drilling with borehole enlargement to about three times the bit diameter or about 9 times the drilled hole volume in the salt section.
2. Salt dissolution is known to have caused borehole enlargement to more than 10 feet in diameter in older holes drilled with rotary tools.
3. No salt dissolution occurs in boreholes after drilling ceases. This conclusion is valid for all oil and gas test holes which have properly cemented surface pipe opposite aquifers above the salt regardless of how the hole is plugged.
4. Post-drilling salt dissolution is known to have caused borehole enlargement to more than 8-1/2 feet in diameter in holes abandoned with no surface casing.
5. Salt dissolution resulting in collapse and surface subsidence is known in seven salt water disposal holes out of 72,000 boreholes penetrating the Hutchinson Salt.

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THICKNESS HUTCHINSON SALT MEMBER
CONTOUR INTERVAL 50 FEET

HUTCHINSON

FIG. 1

The Smithsonian Corp.
R. S. S. Corp.
Am. Mus. Nat. Hist.
Geol. Nat. Hist. Mus. of the
Smithsonian Institution

HUTCHINSON SECTION OF THE HUTCHINSON SALT MEMBER AND PART OF THE LOWER AND UPPER MEMBERS OF THE WELLINGTON FORMATION, HUTCHINSON NAVAL AIR STATION, RENO COUNTY, KANSAS

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Legend for all illustrations which show geophysical logs.

Gamma

Gamma Ray Log in API units. Radioactivity increases to the right.

Density

Gamma Gamma Log or Formation Density Log compensated for variations in hole diameter. Scale indicates bulk density in grams/cc. Commonly printed on the right side of multi-log prints, but here placed on the left near the gamma log to emphasize the similarity of the two logs (in shale and salt) and the dissimilarity (in anhydrite). Anhydrite commonly records as 2.9, halite as a little over 2.0 units.

Caliper Log

Measures the diameter of the hole in inches within limits of the "reach" of the logging tool. The caliper log is here presented twice as mirror image logs to give an image of the hole size and shape.

Neutron

Neutron Log in API units. This log is highly sensitive to hole size and is only effective in nearly out-to-gauge holes through the salt section. In enlarged holes (Fig. 16) this log loses character.

Laterolog

A resistivity log made with current focused. Measures electrical resistivity in ohms per square meter per meter (m^2/m), recorded on a logarithmic scale.

Guard Resist.

A resistivity log made with current focused (by the use of guards). Measures electrical resistivity in ohms per square meter per meter (m^2/m) recorded on two arithmetic scales.

BHC Sonic

Borehole Compensated Sonic Log, corrected for variations in hole size with interval transit time of sound recorded in microseconds per foot. Ideal travel time in halite is 67 and in anhydrite is 50 units. Also termed "Compensated Acoustic Velocity Log".

AEC No 3

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Figure 20

RF Mollers 1971

Figure 22

R F Walters 1971

Figure 23

RF Wallers 1971

Figure 24

RF Walters 1971