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HYDROGEOLOGIC CHARACTERISTICS OF THE WASTE GATE FORMATION, A NEW SUBSURFACE UNIT OF THE POTOMAC GROUP UNDERLYING THE EASTERN DELMARVA PENINSULA

by
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THE WASTE GATE FORMATION, A NEW SUBSURFACE UNIT OF THE POTOMAC GROUP UNDERLYING THE EASTERN DELMARVA PENINSULA

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ABSTRACT

The Lower Cretaceous Waste Gate Formation (Hansen, 1982) is a new name proposed for a subsurface unit of the Potomac Group occurring beneath the eastern Delmarva Peninsula; the top of the unit occurs at depths ranging from about 3,500 feet at its up-dip edge to 5,670 feet at the Coast. It consists chiefly of unconsolidated to moderately lithified, light gray to whitish, arkosic to subarkosic sandstones and drab, often finely laminated silty shales (or clays). It ranges up to 1,500 feet thick at the Coast with sand percentages characteristically 50 to 70 percent. The unit is tentatively dated Neocomian (Berriasian to Hauterivian (?)) on the basis of limited palynological data. An apparent absence of *Clavatipollenites* and other Zone I (mid-Barremian to early Albian) palynomorphs implies that the Waste Gate Formation is older than the Patuxent Formation, which comprises the basal beds of the outcropping Potomac Group.

Sandstone porosities of the Waste Gate Formation, estimated from geophysical logs, range between 19 and 27 percent. Analysis of production test data for a Waste Gate sandstone in the DOE Crisfield Airport No. 1 well yielded permeabilities in the 75 to 118 millidarcy (3 to 5 gallons/day/foot^2) range. The formation waters of the Waste Gate are of the sodium-calcium chloride type. The Crisfield Airport well produced salty water with a chloride concentration of 42,000 mg/l (71,000 mg/l total dissolved solids). Elsewhere on the Peninsula, geophysical log estimates of NaCl salinity range from 53,700 mg/l to 97,000 mg/l. Below 3,000 feet Waste Gate fluid pressures increase under a hydrostatic pressure gradient of about 0.44 to 0.46 psi/foot. Temperature gradients appear to fall between 1.3° and 1.75° F/100 ft. Waste Gate formation temperatures range from about 124° F in up-dip areas to about 172° F near the base of the formation at the Coast; temperatures as high as 190° F are possible, but are less likely.

Possible utilization of the Waste Gate aquifers include extraction of chemical commodities from brines, low-temperature geothermal heat production, and disposal of liquid wastes.

INTRODUCTION

The Lower Cretaceous Waste Gate Formation that underlies the eastern portion of the Delmarva Peninsula is a newly erected subsurface unit of the Potomac Group (Hansen, 1982). Until recently, the hydrogeologic characteristics of the Lower Cretaceous sediments underlying the Peninsula were poorly understood and were inferred largely from the stratigraphic descriptions of three deep oil test wells drilled in the 1940's (Anderson and others, 1948). In 1979 the completion of a deep (5,562 feet) geothermal test well located near Crisfield in Somerset County, Maryland, provided new information bearing on the stratigraphy, petrophysics, and interstitial water of the Waste Gate Formation (e.g., Hartsock, McCoy, and Radford, 1980). With the availability of these data, a modern reappraisal of the hydrogeologic characteristics of the deeper Potomac Group units became possible.

ACKNOWLEDGEMENTS

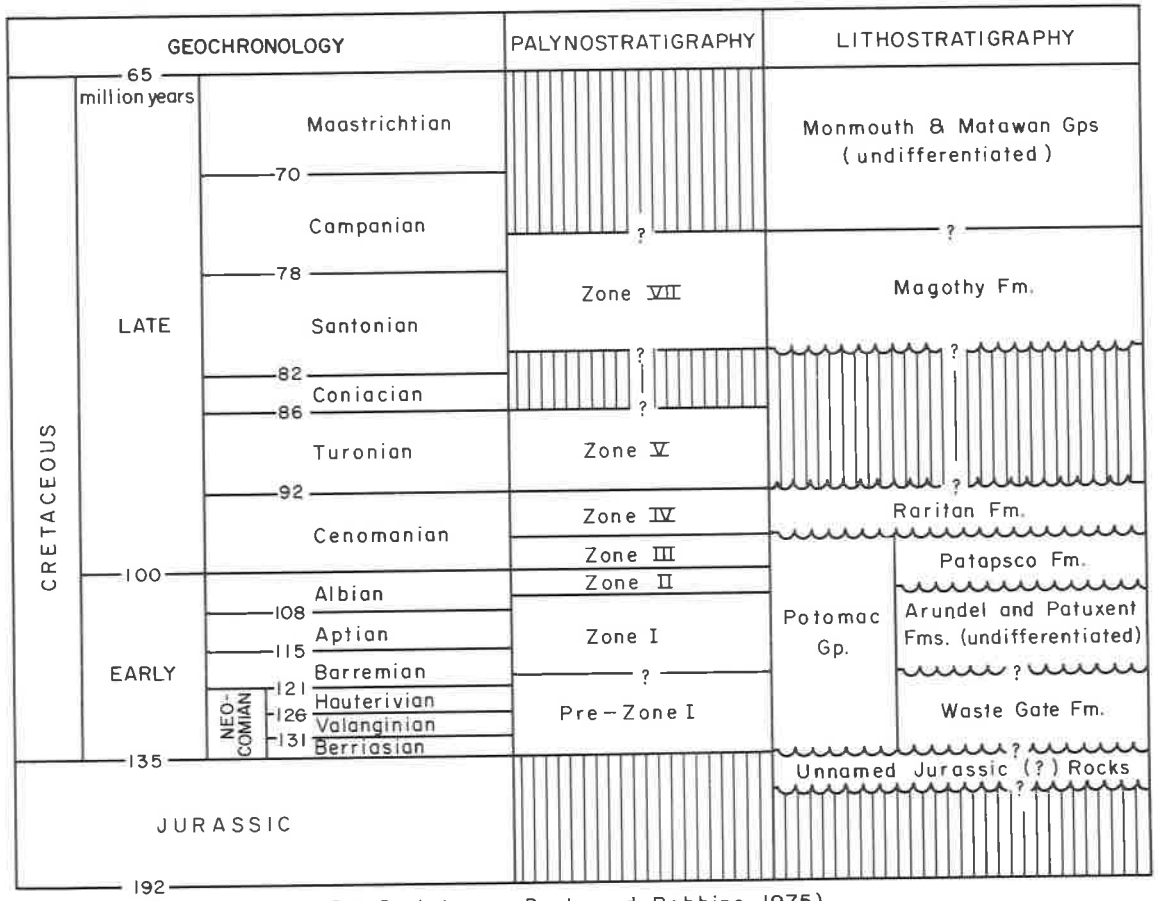
The palynological data cited in this report were provided by Gilbert J. Brenner, State University of New York (New Paltz) and James A. Doyle, University of California (Davis). Chemical analyses of Waste Gate Formation water were made by the U.S. Geological Survey (Water Resources Division).

POTOMAC GROUP

The Potomac Group underlying the Eastern Shore of Maryland (Maryland portion of the Delmarva Peninsula) is a largely non-marine fluvio-deltaic complex of interbedded sands and silt/clays which exceeds 5,200 feet in thickness at the Atlantic Coast. The unit is chiefly Early Cretaceous to Cenomanian in age, but may include Upper Jurassic beds at its base. The basal beds of the Potomac Group thin up-dip by onlap with their age younging westward from Berriasian (or older) at the Coast to Barremian at their type locality in the Baltimore-Washington corridor. In its type area the Potomac Group is subdivided into the Patuxent and Arundel Formations of Middle Barremian to Early Albian age and the Patapsco Formation of Albian age. Elsewhere the formations are less distinct lithologically and the Potomac Group is often treated as an undivided unit. The toplapping upper beds of the Potomac Group are erosionally truncated by Santonian age sediments (Magothy Formation), which mark the beginning of a major cycle of marine sedimentation.

The areal distribution of individual sands within the Potomac Group is very complex and usually allows only local delineation, well

Table 1. Proposed stratigraphy of the Potomac Group beneath the eastern Delmarva Peninsula



(modified from Am. Assoc. Pet. Geol., in prep.; Doyle and Robbins, 1975)

control permitting. Informal groups of sands can often be correlated more widely and may define a hydraulically continuous aquifer system extending over two or three counties. In vertical profile the Potomac Group sands frequently exhibit fining upward cycles characteristic of meandering stream deposition (Hansen, 1969). Blocky profiles suggestive of braided or stacked channel sand deposits are also common and may dominate locally. Eastward, the fluvio-deltaic complex becomes increasingly distributary (Robbins, Perry, and Doyle, 1975, p. 64) and includes, rarely, marginal marine elements. The thickness of individual sand beds varies widely, but usually does not exceed 150 feet without a significant (10 ft.) clay/silt break.

Potomac Group sands along the inner margin of the Maryland Coastal Plain are characteristically light-colored and quartzose, unconsolidated and porous (>35 percent). Field hydraulic conductivities are generally in the 20 to 250 ft/day range. Downdip the Potomac Group thickens by the addition of basal onlapping units like the Waste Gate Formation. In contrast to the outcropping Potomac Group in Maryland the Waste Gate sands are typically feldspathic and often partially cemented with kaolinite or calcite, forming friable sandstones. Average porosities are significantly lower (19 - 24 percent), with sandstone permeabilities perhaps two to three orders-of-magnitude less than the shallower Potomac Group aquifers currently in production.

None of the several deep test wells drilled in the area have shown any traces of oil or natural gas. Although the Potomac Group (or older Mesozoic rocks) may contain commercial quantities of hydrocarbons, the general consensus is that production, if it occurs, will be off-shore along the outer edge of the continental shelf (Maslowski, 1983, p. 4). Thus, any future onshore utilization of the brine aquifers of the Potomac Group will probably be focused on low-temperature geothermal heat or liquid waste injection.

WASTE GATE FORMATION

Stratigraphy

Nomenclature: The Waste Gate Formation is a new stratigraphic name introduced to identify a correlative sequence of subsurface beds underlying the eastern Delmarva Peninsula (tab. 1). These beds were previously included in the Potomac Group (undivided) (e.g., Robbins, Perry, and Doyle, 1975) or, if given formation rank, assigned to the lower part of the Patuxent Formation (Anderson, and others, 1948). Because, however, this stratal sequence differs significantly in age, lithology, and petrophysics from the Patuxent Formation at its type locality, a new stratigraphic ranking is warranted. The Ohio Oil Com-

pany L. G. Hammond No. 1 (Wi-Cg 37*) located in central Wicomico County (N 38° 20′ 48″, W 75° 29′ 13″), near the cross-roads of Waste Gate, is designated the type well for the Waste Gate Formation. At this site, the Formation is 615 feet thick and was penetrated between 4,745 feet and 5,360 feet K.B. (Altitude: +70 feet) (fig. 1). The Hammond well was drilled in 1944 and cored continuously through the Waste Gate section with good recovery. The core descriptions and electric logs were published by Anderson and others (1948). A small archival collection of the Waste Gate core remains in the Maryland Geological Survey sample library. Additional core material is stored at the Academy of Natural Sciences in Philadelphia, Pennsylvania.

Lithology: The Waste Gate Formation consists largeiy of an unconsolidated to moderately lithified sequence of interbedded light gray to white arkosic to feldspathic sandstones and drab to occasionally mottled, silty shales (or clays), often finely laminated with carbonaceous material. Anderson (1948, p. 14) reports that the sandstones (sands) are relatively poorly sorted, ranging from fine to very coarse-grained with an occasional pebbly bed. The feldspars are often strongly kaolinized, resulting in a pervasive, clayey matrix sufficiently binding to form friable sandstones in places. The more indurated sandstones are associated with occasional occurrences of calcareous cement. Core descriptions provided by Anderson and others (1948, p. 408-412) indicate that about 27 percent of the arenaceous footage is sufficiently lithified to be called "sandstone", a figure perhaps representative of the Waste Gate Formation elsewhere in Maryland.

The Waste Gate Formation in the Hammond well is about 70 percent sandstone (sand); however, each unit is relatively thin and rarely exceeds 100 feet in thickness. In profile the self-potential (S.P.) signatures of the arenaceous beds (fig. 1) do not exhibit the well-defined fining upward cycles generally ascribed to deposition by meandering streams. Rather they have a blocky aspect suggestive of braided or stacked sand channel deposition, perhaps associated with a higher energy alluvial complex (Robbins, Perry, and Doyle, 1975, p. 62).

Age and Biostratigraphy: In the earlier studies of Anderson and others (1948) and Spangler and Peterson (1950), the Waste Gate beds were lumped into the Patuxent Formation and dated Early Cretaceous without biostratigraphic evidence. Later work by Maher (1971, p. 39) tentatively placed the beds in the Trinitian (?) or Aptian (?) stage of the Lower Cretaceous based on regional correlations with a deep well at Cape Fear, North Carolina. Brown, Miller, and Swain (1972, pl. 35), again largely on the basis of regional correlations, placed the Waste Gate beds in the lower part of their Unit H. Although Unit H of Brown, Miller, and Swain (1972, pl. 2) included beds as young as

*Well number assigned by the Maryland Geological Survey.

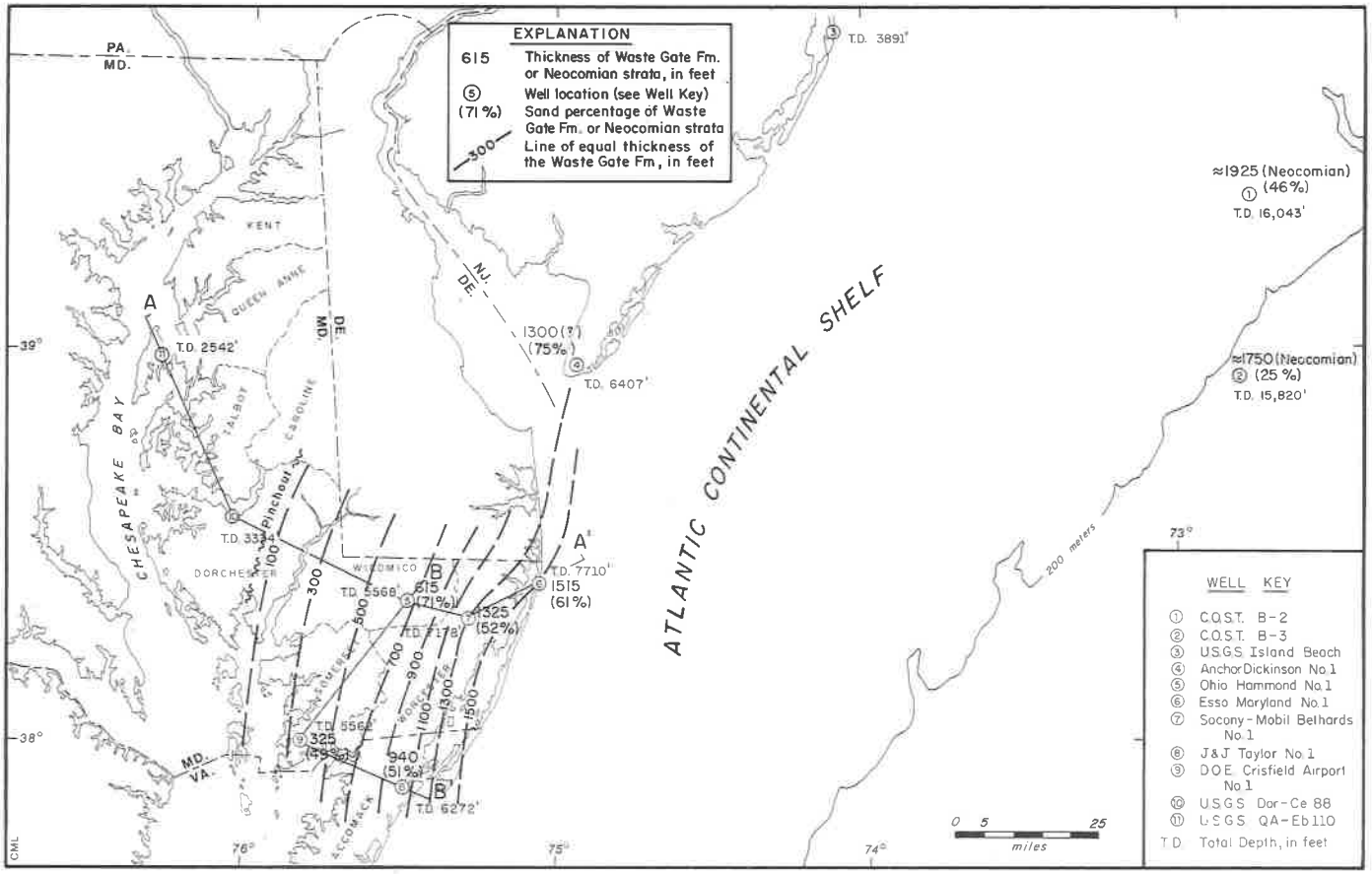


Figure 2. Well location map showing total sand thickness and cumulative sand percentage of the Waste Gate Formation beneath the Delmarva Peninsula and vicinity

Aptian, the lower part was probably older and may have included strata of Barremian/Neocomian age. The first palynological study of the Waste Gate section of the Potomac Group in Maryland was undertaken by Robbins, Perry, and Doyle (1975). Using core material from the Ohio L. G. Hammond No. 1, the Socony-Mobil J. B. Bethards No. 1 (Wor-Ce 12) and the J and J Enterprises E. G. Taylor No. 1-G (from neighboring Accomack County, Virginia), they established an Early Cretaceous age for the Waste Gate beds (figs. 1, 2). Furthermore, they strongly suggested that the beds were pre-Barremian (i.e., pre-Palynozone I of Brenner, 1963) based on the absence of *Clavatipollenites hughesii* and other Zone I palynomorphs found in the outcropping Patuxent and Arundel Formations.

Habib (1977) reviewed Robbins, Perry, and Doyles' work and considered their pre-Palynozone I beds to correlate with his *Ephedripites multicostatus* Zone of Berriasian to Hauterivian (Neocomian) age. More recent work on the DOE Crisfield Airport No. 1 well by J. A. Doyle (1982) and G. J. Brenner (per comm., 1981) confirms a pre-Barremian age for the Waste Gate beds. In a study of core samples between 4,121 feet and 4,148 feet Doyle reported that the schizaeaceous and verrucate spores correlate with mid-Berriasian assemblages reported by Norris (1969), Hughes and Croxton (1973), and Doring (1965).

Brenner (*in* Hansen, 1982, p. 15) made a preliminary evaluation of two core samples from the Crisfield Airport No. 1 well. He reported that for sample 4,139.5 to 4,140 feet the most conservative evaluation of the age would be Late Berriasian to Hauterivian (?). Typical Barremian forms such as *Clavatipollenites* were not found in this sample. Nor were they found in a second core (4,121.6 feet to 4,122.1 feet) from the Crisfield Airport well or in a core from the Socony-Mobil Bethards well (5,612 - 5,628 feet) (fig. 1). Brenner dated the latter sample pre-Zone I, conservatively placing it between the Berriasian and the lowermost Barremian. Although the available palynological data strongly suggest that the Waste Gate Formation is largely of Berriasian to Hauterivian (?) age, Brenner (*in* Hansen, 1982, p. 15a) also reported the presence of *Peromenoletes peroreticulatus,* an early angiosperm type common in Palynozone I in a core (4,927 - 4,933 feet) from the Ohio Hammond No. 1 well (fig. 1). This evidence retains the possibility that the upper beds of the Waste Gate Formation may extend into the early Barremian.

Areal Distribution, Thickness, and Lithofacies: The Waste Gate Formation is a subsurface unit on the Delmarva Peninsula. It is known to occur beneath parts of Somerset, Wicomico, and Worcester Counties, Maryland, and Accomack County, Virginia (fig. 3). The Waste Gate probably underlies a portion of Sussex County, Delaware, and based on the correlations of Brown, Miller, and Swain (1972, pl.

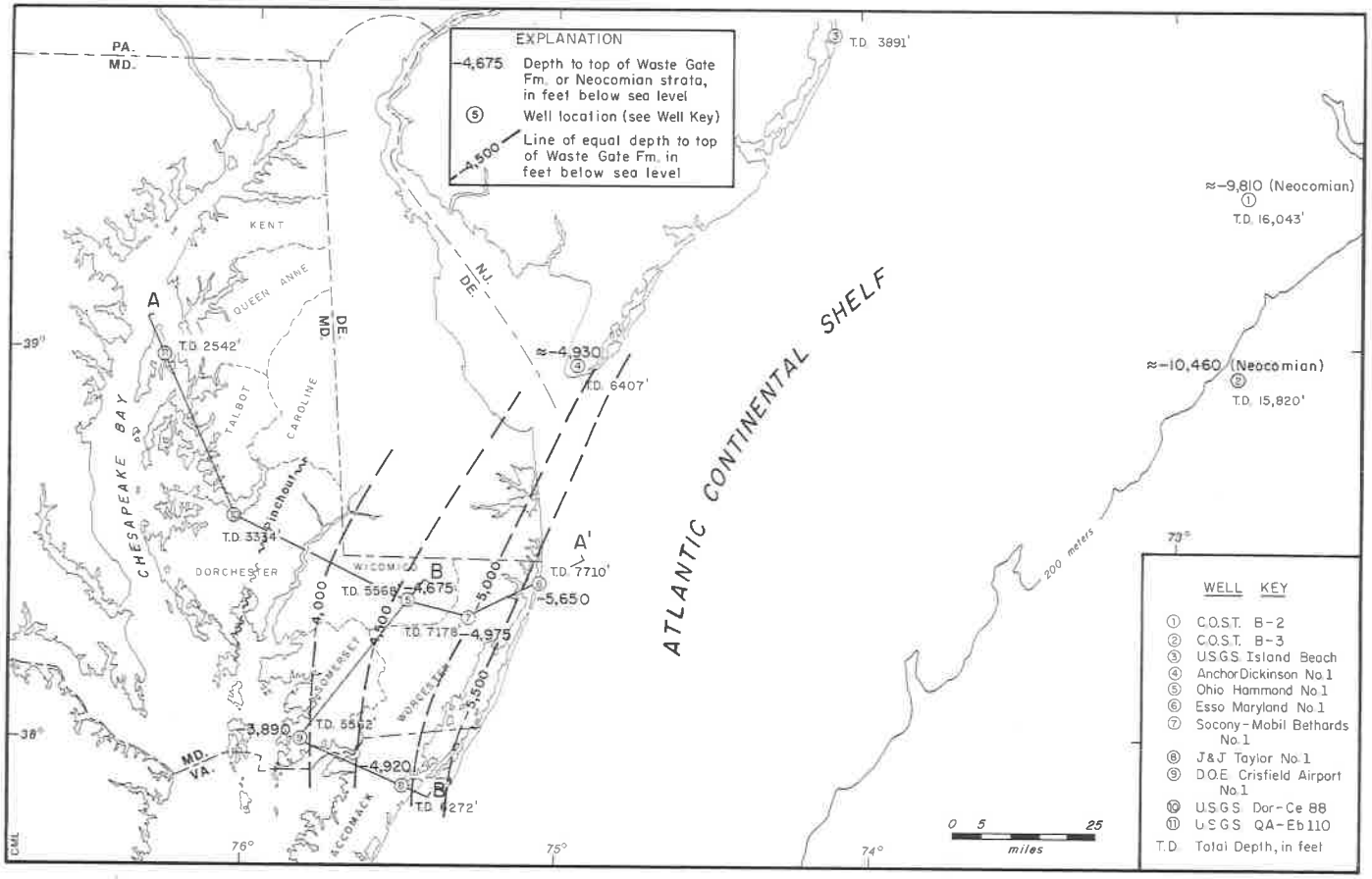


Figure 3. Contour map showing altitude of the top of the Waste Gate Formation beneath the Delmarva Peninsula and vicinity

54), and Maher (1971, pl. 9) may extend at least as far north as the Anchor Dickinson No. 1 at Cape May Point, New Jersey.

Offshore of New Jersey, partially coeval Berriasian to Hauterivian beds have been identified by Scholle and others (1980, figs. 23, 24) in both the COST B-2 and COST B-3 wells (figs. 2, 3). In the COST B-2 well drilled about 91 miles east of Atlantic City on the outer continental shelf these strata are nonmarine, except for a mid-shelf Berriasian section. On the continental slope 32 miles south of B-2, however, COST well B-3 penetrated an uninterrupted marine Berriasian to Hauterivian section.

In Maryland, the Waste Gate Formation has been penetrated in only four wells; two in Worcester County and one each in Wicomico and Somerset Counties (figure 2). At the Coast, the unit is about 1,515 feet thick in the Esso Maryland No. 1. Although correlation of the Waste Gate Formation into the COST B-2 and B-3 wells is tentative, the Berriasian to Hauterivian section appears to show only a modest increase in thickness offshore (1,925 feet and 1,750 feet respectively) (Scholle and others, 1980, p. 48-49). Up-dip the Waste Gate Formation thins relatively rapidly by onlap. It is, for example, only 615 feet thick in the Ohio Hammond No. 1 and even thinner, 325 feet, in the DOE Crisfield Airport No. 1. The up-dip feather-edge of the unit is poorly defined because of a lack of data. It was not encountered, for example, in Dor-Ce 88 which logged typical Patuxent Formation lithologies immediately overlying gneissic basement rock (figs. 1 and 3). The occurrence of gneissic basement rock at this site, however, provides a feldspar-rich source terrane for the Waste Gate sandstones in eastern Maryland.

The Waste Gate Formation in Maryland is a nonmarine alluvial sequence of interbedded arkosic to feldspathic sandstones (sands) and shales (clays). The sands are poorly sorted ranging from fine to pebbly. The unit is characterized by high sand percentages (49% to 71%), particularly the northern wells that are nearer the depositional axis of the Salisbury embayment (fig. 2). The Waste Gate Formation in Maryland contains both carbonaceous laminae and calcareous sandstones, but does not exhibit coaly seams or limestones. Although rare occurrences of marine or brackish water fossils have been noted, the evidence generally favors a high-energy, alluvial setting dominated by fluvial channel facies proximal to the Early Cretaceous Fall Line.

The COST B-2 well also penetrated a dominately nonmarine Neocomian section dominated by feldspathic sandstones and shales. But the presence of coaly seams, calcareous shales, and occasional limestones coupled with rare dinoflagellate occurrences suggest a lower (distributory) deltaic setting with perhaps intermittent marine incursions (Scholle, 1977, p. 19, 33, 42). On the other hand equivalent strata in the COST B-3 well contain inner to mid-shelf foraminifera

and calcareous nannofossils in association with limy sandstones, marine shales, and limestones (Scholle, 1980, p. 22, 76).

Thus, the Waste Gate Formation and its off-shore equivalents include three first order facies: 1) Upper deltaic fluvial facies (onshore wells), 2) Lower deltaic distributory facies (COST B-2), and 3) marine shelf or delta-front facies (COST B-3). Because the onshore and offshore wells are widely separated it remains possible, however, that more than one deltaic sequence is represented.

Petrophysics

Information regarding the petrophysics of the Waste Gate Formation is largely based on geophysical logs. A fairly complete suite of logs is available for the DOE Crisfield Airport and the J and J Taylor wells. The Ohio Hammond, Socony-Mobil Bethards, and Esso Maryland wells were drilled in the 1940's and only self-potential and multi-point electric resistivity logs are available (fig. 1). In addition, drawdown-recovery pumping tests were conducted on several Waste Gate aquifers in the DOE Crisfield Airport well.

Porosity and Permeability: Representative sandstone porosities computed from compensated formation density logs range between 21 and 27 percent in the DOE Crisfield Airport and J and J Taylor wells. To estimate porosity values in the Hammond, Bethards, and Esso Maryland wells, a graphical method described by Pirson (1963, p. 94) using the short-normal (16″) curve was used. For old wells lacking a modern suite of logs, it is a useful method to establish first approximations. In the Hammond well Waste Gate sandstones largely yielded invaded zone porosities of about 23 to 27 percent. In both the Bethards and Esso Maryland wells, estimated porosities were somewhat lower (19 to 24 percent).

The only pumping tests (drawdown-recovery tests) of the Waste Gate Formation conducted to date were for the DOE Crisfield Airport well (Hartsock, McCoy, and Radford, 1980, p. 10-26). Eighty-six feet of casing were perforated between 3,901 and 4,032 feet. This zone yielded about 118 gallons per minute during a 48-hour test. Bottom hole pressure declined 121 psi from an initial value of 1,718 psi (water density=1.031). Analysis of the straight part of the pressure build-up curve using the van Everdingen method gave a slope of 51 psi/cycle and a permeability of 75 millidarcies (Hartsock, McCoy, and Radford, 1980, p. 12-46). Achmad (per comm., 1979) analyzed the same drawdown and recovery data using standard ground-water techniques (Jacobs semi-log method). Over one time cycle (100-1,000 minutes) the drawdown was 29.9 psi which yielded a transmissivity of 430 gallons/day/foot and a hydraulic conductivity of 5 gallons/day/foot^2 at field

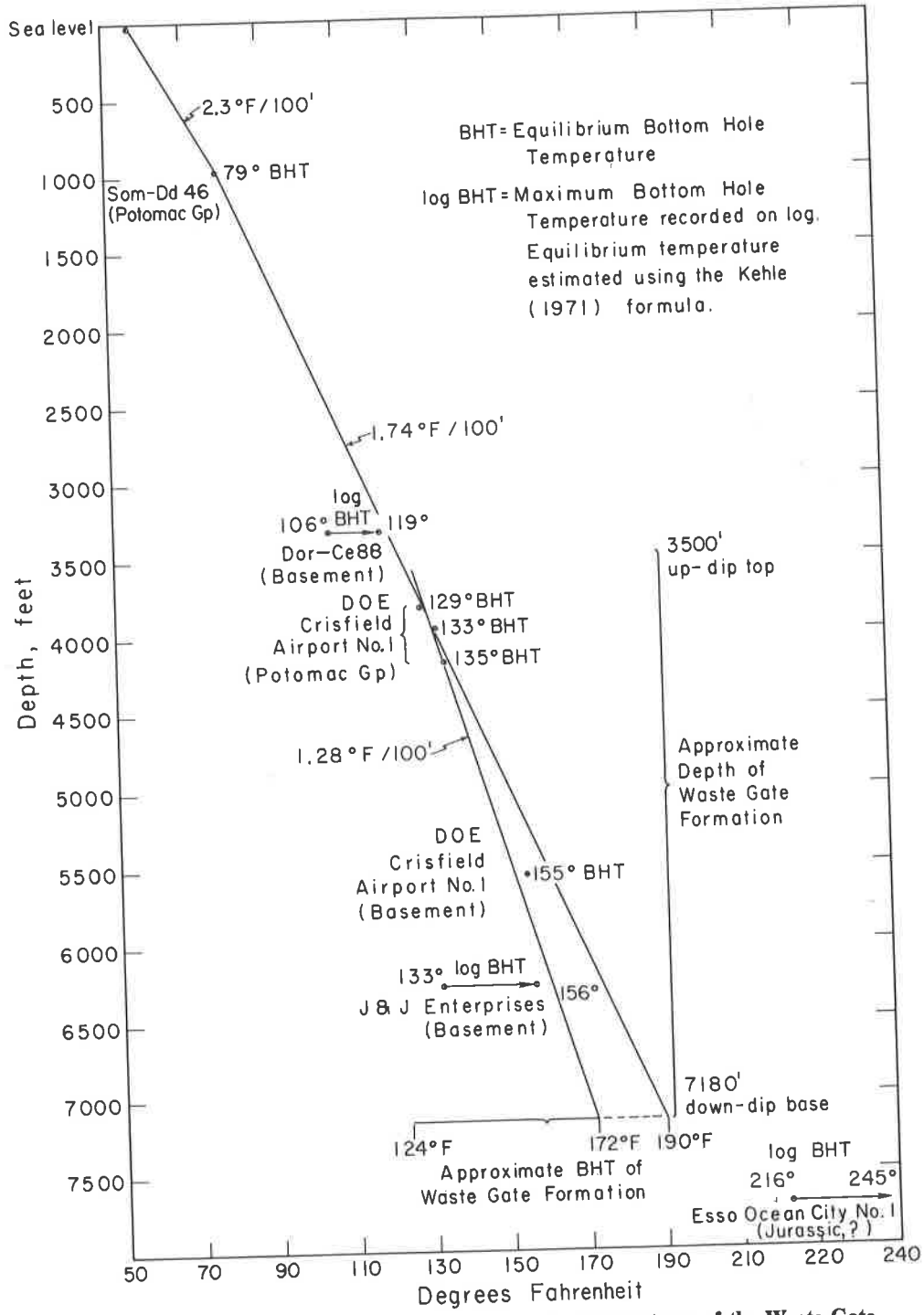


Figure 4. Graph showing estimated bottom-hole temperatures of the Waste Gate Formation between 3,500 feet and 7,180 feet

temperature (135° F). Analysis of the pressure recovery data using a plot of time versus extended drawdown minus residual drawdown yielded a calculated recovery of 38 psi over one time cycle (100-1,000 minutes). Transmissivity and hydraulic conductivity values of 340 gallons/day/foot and 4 gallons/day/foot^2 were calculated from these data. These data converted to oil-field units suggest formation permeabilities in the range of 93 to 118 millidarcies.

Pressure and Temperature: At present on the Delmarva Peninsula only one well, the DOE Crisfield Airport No. 1, has been completed in the Waste Gate Formation and systematically tested for bottom hole pressures and temperatures. To estimate regional gradients for these parameters, the Crisfield Airport well data was supplemented by other, less reliable information. Evidence at hand suggests that with increasing depth normal hydrostatic pressures prevail (0.44 to 0.46 psi) and that the geothermal gradient is probably within the expected range (1.3° to 1.75° F per 100 feet) for the Coastal Plain area (Hansen, 1982).

Based on temperatures reported by Dashevsky and McClung (1979, p. A22-29) the average temperature gradient at Crisfield between 965 feet and 4,180 feet is approximately 1.74° F/100 ft. (fig. 4), significantly lower than the average gradient above 965 feet (2.3° F/100 ft.). The Crisfield Airport well was drilled through the base of the Coastal Plain and penetrated several hundred feet of basement rock, reported by Gleason (1979, p. A-5) to be a grey-green, fine-grained metamorphic rock. An equilibrium bottom-hole temperature of 152.5° F was measured at 5,553 feet. Also plotted on figure 4 is the log bottom-hole temperature for the J and J Taylor No. 1 located in Accomack County, Virginia. A recorded temperature of 133° F at 6,271 feet was adjusted using Kehle's formula (Bebout, Loucks, and Gregory, 1978, p. 74) for converting Gulf Coast log temperatures to equilibrium temperatures. This results in an adjusted temperature of 156° F, a useful but approximate value at best. A trend line through these points yields a geothermal gradient of about 1.28° F/100 ft. between 3,816 feet and 6,217 feet. What appears to be an anomalously high log bottom-hole temperature was recorded for the Esso Maryland No. 1. An uncorrected temperature of 216° F was logged at 7,710 feet. The gradient could be steeper in the Ocean City area, but the possibility of an unreliable temperature reading cannot be ruled out. Temperature logs run in the COST B-2 well (16,043 feet T.D.) 26 to 31 hours after cessation of mud circulation recorded a geothermal temperature gradient of about 1.5° F/100 ft. without any noteworthy anomalies (Smith and others, 1976, p. 23).

The anticipated range of bottom-hole temperatures through the Waste Gate section beneath the Delmarva Peninsula is shown in figure 4. The values range from about 124° F in up-dip areas where the

Table 2. Chemical analyses of three water samples from the Waste Gate and lower Patuxent (?) Formations, Crisfield, Maryland

Well Number	SOM Dd 47	SOM Dd 47	SOM Dd47
Sample Date	6/23/79	6/28/79	7/5/79
Aquifer	Waste Gate	Waste Gate	Patuxent (?)
Sampling Depth (Ft.)	4,148-4,200	3,901-4,032	3,798-3,846
Elevation of Land Surface Datum (Ft. NGVD)	3.50	3.50	3.50
Temperature (Deg. C)	42.0	52.0	36.0
Density (Gm/ml at 20° C)	1.043	1.042	1.040
Agency Analyzing Sample (10/16/79)	U. S. Geol. Survey	U.S. Geol. Survey	U. S. Geol. Survey
Color (Platinum-Cobalt Units)	80	290	150
pH (Units)	6.7	6.3	6.7
Carbon Dioxide, Dissolved (Mg/l as CO_2)	16	40	---
Alkalinity (Mg/l as $CaCO_3$)	41	41	29
Nitrogen, Nitrite Total (Mg/l as N)	.02	.00	.01
Chloride (Mg/l as Cl)	42,000	42,000	41,000
Sulfate (Mg/l as SO_4)	870	820	1,000
Fluoride (Mg/l as F)	.8	.7	.5
Silica (Mg/l as SiO_2)	16	17	15
Arsenic (µg/l as As)	0	0	1
Barium (µg/l as Ba)	100	100	500
Beryllium (µg/l as Be)	0	0	20
Boron (µg/l as B)	9,200	8,600	1,000
Cadmium (µg/l as Cd)	0	0	0
Chromium (µg/l as Cr)	7	7	7
Cobalt (µg/l as Co)	0	0	0
Nitrogen, Nitrate Total (Mg/l as N)	.08	2.7	.05
Nitrogen, NO_2 + NO_3 Total (Mg/l as N)	.10	2.6	.06
Phosphorus (Mg/l as P)	.01	.01	.01
Hardness (Mg/l as $CaCO_3$)	20,000	20,000	19,000
Hardness, Noncarbonate (Mg/l as $CaCO_3$)	20,000	20,000	19,000
Calcium, (Mg/l as Ca)	7,200	7,100	6,900
Magnesium (Mg/l as Mg)	490	510	470
Sodium (Mg/l as Na)	18,000	21,000	26,000
Sodium Adsorption Ratio	55	65	82
Sodium Percent	66	70	75
Sodium-Potassium (Mg/l as Na)	18,000	21,000	---
Potassium (Mg/l as K)	62	60	120
Strontium (µg/l as Sr)	270,000	270,000	260,000
Zinc (µg/l as Zn)	3,800	410	800
Lithium (µg/l as Li)	670	590	600
Selenium (µg/l as Se)	0	0	0
Solids, Residue at 180° C. (Mg/l)	70,300	68,900	65,100
Solids, Sum of Constituents (Mg/l)	69,000	71,900	75,800
Specific Conductance (Micromhos)	90,000	90,000	---
Iodide (Mg/l as I)	.01	.00	.02
Mercury (µg/l as Hg)	1.0	1.0	.8
Copper (µg/l as Cu)	4	29	3
Iron, Suspended Recoverable (µg/l as Fe)	0	16,000	9,300
Iron, Total Recoverable (µg/l as Fe)	25,000	23,000	18,000
Iron, Dissolved (µg/l as Fe)	25,000	7,200	8,700
Lead (µg/l as Pb)	0	0	1
Manganese, Suspended, Recoverable	1,000	0	1,000
Manganese, Total Recoverable (µg/l as Mn)	12,000	13,000	13,000
Manganese, Dissolved (µg/l as Mn)	11,000	13,000	12,000
Molybdenum (µg/l as Mo)	0	0	0
Nickel, (µg/l as Ni)	3	---	0
Silver (µg/l as Ag)	0	0	---

unit is overlapped to about 172° F near the base of the Formation near the Coast. Temperatures as high as 190° F are possible, although less likely.

Salinity: Although regional studies have suggested the occurrence of brines in the Waste Gate Formation (Manheim and Horn, 1968; Meisler, 1980), the only water samples thus far collected for analysis are from the DOE Crisfield Airport No. 1 (tab. 2). Formation water from two Waste Gate aquifers contain chloride concentrations (42,000 mg/l) exceeding twice that of ocean water (18,980 mg/l). Elsewhere electric log-derived equivalent NaCl concentrations were computed. Values range from 53,700 mg/l in the Ohio Hammond well to 97,400 mg/l in the Socony-Mobil Bethards well.

The Ca/Cl ratio of formation water is significantly greater than the equivalent ocean water ratio, a condition more commonly associated with deep aquifer brines. The composition of the water is characteristic of Back's (1966, p. 13) sodium-calcium cation facies with Ca+Mg totalling 32 percent (expressed as equivalents per million) of the major cations. Although the mechanisms involved are incompletely understood, most observers agree that chloride brines, typically with a relatively high proportion of calcium, do not necessarily require an evaporite association to develop (White, 1965, p. 344). Increase in the Ca/Cl ratio requires a calcium source, which in the case of the nonmarine Waste Gate Formation might be calcic feldspar grains or interstitial calcite.

In summary, Waste Gate formation waters increase in salinity with depth and are of a calcium/sodium chloride type that is typical of deep subsurface waters in many areas (Dickey, 1966). These waters are at normal hydrostatic pressure and exhibit very lethargic to stagnant flow systems. As in the case of the Waste Gate Formation, which is overlapped by younger units of the Potomac Group, brines of this type are isolated by confining beds from sources of meteoric or ocean water. Because the system is essentially at hydrostatic pressure, hydraulic gradients across the confining beds are small, precluding the transport of large volumes of water into or out of the stagnant zone. Over geologic time, fluid migration within the stagnant zone is largely controlled by the amount of subsidence and compaction occurring in the basin. As Jones (1981, p. 113-114) points out, "the overall water movement is into the basin and downward, rather than out of the basin and upward". As subsidence occurs, the formation waters move downward into higher temperature and pressure zones, but upward stratigraphically. It is probable that this flux mechanism, active at least since the Cretaceous, has contributed to the downward concentration of salty water in the Waste Gate Formation.

Potential Utilization

On the Delmarva Peninsula potential utilization of the Waste Gate Formation will be in one of three areas: commercial brines, low to moderate temperature geothermal applications, and/or repositories for liquid waste disposal.

Commercial brines: Mineral commodities extracted commercially from brines or sea water include bromine, calcium, chloride, iodine, lithium, and magnesium (Fulton, 1975, tab. 1). Commercial brines of the NaCl type generally have salinities close to saturation (>300,000 ppm) with total dissolved solids probably three or four times greater than the Waste Gate formation waters . On the other hand, the concentrations of magnesium and iodine are actually greater in sea water than in the Waste Gate aquifers sampled in the DOE Crisfield Airport well.

It seems unlikely that the Waste Gate Formation will become a competitive source of commercial brines. Although the brines may have specialized industrial applications, particularly if developed as a by-product of geothermal production (Saleem and Mott, 1980, p. xx-5), the economic feasibility of such projects would have to be carefully considered.

Geothermal Applications: Beneath the Maryland portion of the Delmarva Peninsula reservoir temperatures for the Waste Gate aquifers probably range from a low of 120° F to perhaps as high as 175° to 190° F (fig. 4). These temperatures are considered low for geothermal utilization, but can be used for space heating and for various agricultural and horticultural purposes.

For direct geothermal applications, two resource factors determine whether the energy requirements of the potential user can or cannot be met. The factors to be considered are the flow rate and temperature drop of the hot water through the heat exchange area, expressed approximately as:

$$E = 500\ Q \Delta T \text{ (EG \& G Idaho, 1979)}$$

where E = Energy, Btu/hr.
ΔT = Temperature drop, °F
500 = Constant, $\frac{\text{Btu/hr.}}{\text{gpm/°F}}$
Q = Flow rate, gpm

As a rule of thumb, EG & G Idaho (1979) suggests that ΔT can be related to the useable resource temperature (Tr) by the approximate relationship, $\Delta T = 0.6Tr - 70$ expressed in °F. As a conservative estimate the Tr of the Waste Gate Formation probably ranges be-

tween 125° and 175° F (fig. 4), yielding potential ΔT's between 5° and 35° F. Estimated flow rates required to provide a range of energy requirements are summarized below:

Maximum Energy Requirement (Btu/hr)	Tr (°F)	ΔT (°F)	Approximate Flow Rate (gpm)
1×10^6	133°	10°	200 gpm
(e.g., small school building)	175°	35°	55 gpm
5×10^6	142°	15°	665 gpm
(e.g., large school building)	175°	35°	285 gpm
15×10^6	158°	25°	1200 gpm
(e.g., small college campus)	175°	75°	855 gpm

As can be seen the well production requirements sharply increase as reservoir temperature (and ΔT) decreases. For this reason many geothermal space heating projects are designed so that either heat pumps or fossil fuel burners can be used to supplement direct heat transfer during intervals when the outside temperature falls below a design value. The technical and economic feasibility of using low-temperature geothermal energy to heat specific installations has been addressed by Ryback (1979); Meyer, Coe, and Dick (1981); and Leffel (1981).

Because relatively large flow rates are required to offset small ΔT's in low temperature geothermal applications, the productive capacity of the reservoir rocks is a critical constraining factor. Although permeabilities of the Waste Gate Formation are relatively low for a Coastal Plain aquifer, the unit is hundreds of feet thick with sand beds accounting for 50 to 75 percent of the section (fig. 2). Because the transmissive properties of an aquifer are a function of both permeability and thickness, the possibility remains that a reasonably productive hot water well could be developed if the total cumulative sand thickness was opened for production. The Theis non-equilibrium formula (Ferris and others, 1962, p. 92) which relates drawdown to discharge can be used to test the productivity of the Waste Gate under a set of given conditions. Hansen (1982, p. 38) estimated that individual well yields in the 135 gpm to 385 gpm range might be expected if total cumulative sand thickness was utilized:

Well	Cumulative Sand Thickness (ft)	Hypothetical Yield (gpm)
DOE Crisfield Airport	160	135
Ohio Hammond	435	355
Socony-Mobil Bethards	690	290
Esso Maryland	925	385

Given the assumptions of Hansen's analysis it seems apparent that geothermal wells yielding several hundred gallons per minute can be completed in the Waste Gate Formation in most areas. To compensate for its relatively low permeability, however, the operator should be prepared to open for production as many of the interbedded sands as economically feasible. This will entail perforating hundreds of feet of casing, or, alternatively, installing long sections of interspersed blank and slotted casing or well screen.

Deep Well Disposal of Liquid Wastes: The U.S. Environmental Protection Agency has defined an underground source of drinking water as "an aquifer or its portion which either currently provides water for human consumption or is capable of yielding water containing fewer than 10,000 mg/l of total dissolved solids" (U.S. Environmental Protection Agency, 1980, p. 42,480). By this definition water from the Waste Gate Formation is nonpotable because it is salty with NaCl salinities ranging between about 50,000 and 100,000 mg/l. In addition, the Waste Gate Formation is separated from the fresh-water flow system by overlapping units of the Potomac Group, which also contain salty water. Because the Waste Gate contains nonpotable water and is isolated from the fresh-water flow system it may be therefore considered a potential reservoir for subsurface disposal of liquid wastes.

The fluvial-deltaic Waste Gate Formation is not ideal for well injection because of its complex sand stratigraphy. Individual aquifers and confining beds are only locally correlative. The geometry of each sand body is complex. With sparse well control, it is impossible to predict unequivocally whether a potential reservoir is laterally connected with an adjacent sand or whether it wedges out within a clayey confining bed. As a consequence, the isolation of an individual sand can never be assured. In practical terms the waste disposal reservoir should be viewed as including not only the injection zone, but one or two of the adjacent sands as well. Because the Waste Gate Formation is hydrologically isolated from the shallow fresh-water flow system, this contingency should not preclude waste injection unless local conjunctive use of the Waste Gate is anticipated.

By restricting injecting pressures to 0.64 psi/ft, the minimum pressure gradient at which hydraulic fracturing theoretically occurs (Hubbert and Willis, 1972, p. 251), Hansen (1982) has estimated that a 75-foot thick Waste Gate sand could be expected to accept a waste stream of 30 to 115 gpm for fluids ranging in viscosity between 1 to 2.2 centipoises. Pretreatment of the waste prior to injection may be required to prevent the deterioration of formation permeability due to precipitate reactions between the waste water and the formation water and matrix. For example, certain types of acidic wastes may react with the feldspathic aquifer material:

$$\text{Feldspar(s)} + H^+ \text{ (aqueous)} \rightleftharpoons \text{Clay(s)} + \text{Cations (aqueous)},$$

producing clays that might reduce aquifer permeability near the disposal well. At the very least entrained gasses and suspended solids must be removed from the waste water prior to injection.

SUMMARY AND CONCLUSIONS

The name Waste Gate Formation is proposed for an overlapped, subsurface sequence of interbedded sandstones (sands), and shales (clays) occurring near the base of the Early Cretaceous Potomac Group beneath the eastern Delmarva Peninsula. The unit is dated Berriasian to Hauterivian (?) because it contains pre-Palynozone I (Brenner, 1963) palynomorphs apparently older than the mid-Barremian to early Albian assemblages characteristic of the overlapping Patuxent Formation. The Waste Gate Formation ranges in thickness from an up-dip feather's edge to about 1,500 feet at the Coast. Cumulative sand percentages are in the 50 to 70 percent range. The arenaceous beds are unconsolidated to moderately lithified and consist largely of light gray to whitish, arkosic to feldspathic sandstones. The sandstones often exhibit a pervasive, clayey (kaolinitic) matrix. The more indurated sandstones are calcareously cemented. Sandstone porosities estimated from geophysical logs are largely in the 19 to 27 percent range. These characteristics suggest that the Waste Gate sandstones typically have relatively low permeabilities, perhaps an order-of-magnitude of 15 to 150 millidarcies.

The Waste Gate aquifers yield salty water of the sodium-calcium chloride type, with total dissolved solids in the 50,000 to 100,000 mg/l range. Below 3,000 feet fluid pressures approach a hydrostatic condition, exhibiting a gradient of about 0.44 to 0.46 psi/ft. Below about 1,000 feet, a normal geothermal gradient (1.3° to 1.7° F/100 ft.) seems to characterize the area. Formation temperatures may be as high as 190° F (at the Coast), but are more likely in the 124° F (at 3,500 feet) to 172° F (at 7,180 feet) range.

Potential utilization of the Waste Gate aquifers include:

1. *Extraction of chemical commodities:* This possibility is least likely because the Waste Gate is not competitive with commercial brines produced elsewhere (e.g., Michigan) that have salinities close to saturation (>300,000 ppm).

2. *Extraction of geothermal heat:* A combination of modest formation temperatures (124° F to 172° F) and relatively low permeabilities (15 to 150 millidarcies) combine to diminish the geothermal potential of the Waste Gate aquifers. Production of 300 gallons per minute of 170° F water may be feasible from one well, but it would require

opening for production hundreds of feet of section (e.g., 370 cumulative feet of 85 millidarcy sand) at well depths of about 6,200 to 7,200 feet.

3. *Disposal of liquid wastes:* The Waste Gate Formation is isolated from the shallow fresh-water flow system by overlapping saline to brackish units of the Potomac Group. Its hydrogeologic setting is suitable for liquid waste disposal. The transmissive and storage properties of the Waste Gate aquifers may be sufficiently large to accept economical volumes of wastewater within prescribed injection pressures. It is estimated that a 30 to 115 gallon per minute waste stream could be injected into a typical Waste Gate sandstone without fracturing the aquifer and its confining beds. Larger volumes could be injected by increasing the number of sandstones receiving the waste.

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