CONSTRUCTION AND TESTING
OF
DISPOSAL WELLS 1R, 2, AND 3
REGIONAL POLLUTION CONTROL FACILITY
CITY OF WEST PALM BEACH, FLORIDA

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INTRODUCTION

During January 1976, construction began on three permanent effluent disposal wells at the new regional pollution control facility owned and operated by the City of West Palm Beach, Florida. Completion of the wells was accomplished during October 1977, when the last injection test was performed. Well design and the construction methods used were based on data developed from the 1974-75 test-injection well program, with allowances for modifications dictated by site-specific conditions. In December 1977, effluent disposal operations commenced.

During the construction and testing of the permanent disposal wells, Geraghty & Miller, Inc., provided resident inspection services to assure the wells were constructed in accordance with the specifications and to collect the data necessary to determine final details of the wells' construction. The firm also provided overall project support in the form of project management for the disposal wells, interpretation of the geologic and geophysical data, and overall consulting services on the subsurface aspects of the construction and testing of the disposal wells. These services were provided to Robert and Company Associates, Engineers and Consultants to the City of West Palm Beach for the design and construction of the facility.

As part of the agreement for consulting services with Robert and Company Associates, Geraghty & Miller has prepared this report covering pertinent aspects of the wells' construction and testing. The report is divided into three sections: (1) construction details, (2) pump and injection testing, and (3) subsurface geologic conditions. The geophysical and geologic logs for each of the wells are contained in separate appendices to the report.

SUMMARY

Geologic conditions found to be present at the site of the test well and discussed in the Geraghty & Miller report of June 27, 1975, were found to be present at the sites of each of Disposal Wells 1R, 2, and 3. Correlation of the induction and lateral logs in each of the wells shows that the same rock units having similar properties are present at each well site, and attests to the regional nature of the various beds. Sequences of competent limestones were found to overlie the injection horizon (boulder zone). These serve as the confining beds in the intervals below a depth of approximately 2400 feet. They are composed of a soft, massive, chalky limestone and a limestone known as a "packstone" which is a fine-grained rock with considerable micrite (cementing material). Core data from the test well show this material has an extremely low vertical permeability which would be comparable to that of a clay. Also included in this section are some beds of dolomite ranging in nature from a dense, solid rock to porous material. Minor amounts of chert also are present. Videotapes of the bore hole show the chert occurring as nodules, some of which are rather large.

Additional data on the confining nature of this sequence were obtained from a pressure test performed at Well 1. This well was not completed and was plugged and abandoned by the contractor. The pressure test was the one which was supposed to have been performed on the 24-inch casing and 22-inch liner. After the test had been run, it was discovered that it had been performed on an open hole. In effect, the test was performed on the confining bed sequence and not the casing and liner. A test pressure of 150 psi (pounds per square inch) was used for a 30-minute period as called for in provisos of the DER construction permit for the well. A pressure drop of about six percent was observed, which is well within the ten percent allowable maximum called for in the pressure test for the 24-inch casing in the permit provisos. These results confirm the findings of the core analysis and the interpretation of the various logs and geophysical data.

Owing to the southwesterly dip of the limestone-dolomite sequence, the boulder zone was found at progressively greater depths going in a westerly direction. Correlation of the various logs made it possible to predict the depths to the top of the boulder zone and take this into account in completing each well. The top of the boulder zone was found at approximately 3260 feet at Well 1R, and 3350 feet at Wells 2 and 3. In order to achieve the most effective installation, disposal wells were completed with 350 feet of penetration into the boulder zone. The one exception to this was Disposal Well 3, which was completed at a depth of slightly less than 3400 feet. It could not be drilled any deeper because of caving conditions in the bore hole. This does not affect the well's capability to handle fluids, as the portion of the boulder zone penetrated by the well contains numerous large cavities.

Aside from problems during the construction of Well 1 which necessitated its plugging and abandonment, only two other problems were encountered during the program. At Disposal Well 2, the 36-inch casing collapsed sometime after it was cemented and before pilot-hole drilling began in the limestone. The collapsed portion was successfully milled out and re-cemented. This poses no threat to the well or its operation, as the collapse occurred where relatively impermeable clay of the Hawthorn formation is present. Also, a void was left in the annular space outside of the 48-inch casing during cementing at Disposal Well 2. This problem was easily rectified by the contractor. Other minor problems of a routine nature were encountered by the contractors during the drilling, but these in no way prevented the wells from being successfully completed.

The 24-inch-diameter casing was set to the required depth in all wells. These settings, which proved to be deeper than were originally anticipated, were used to take into account the westward dip of the rock in order to take advantage of their confining properties.

All of the 24-inch casings (and the others) were successfully and completely cemented in place from bottom to top. Each 24-inch casing was pressure tested after cementing. All tests were successful and test results were submitted. Bond logs for the 24-inch casings show no evidence of channelling of cement and indicate successful bonding between the formation and the cement. The cement used was an API Class B material which was used to provide sulfate resistance. Other additives were employed to prevent lost circulation, shrinkage and premature setting. Also, a maximum of four percent gel was used to prevent a loss of strength and bonding capabilities.

The drilling contractor elected to cement the monitor tubes entirely in place and directionally perforate them in the monitor zone. These operations were successfully completed and, after perforating, each tube was developed by injecting into it small quantities of hydrochloric acid. After acidizing, the tubes were cleaned out by pumping to insure they were capable of producing water of a quality representative of the monitor zone.

After completion, pumping and injection tests were performed. Disposal Well 2 was pump tested and injection tests were run in Wells 1R and 3. A rate of 10,000 gpm (gallons per minute) was used for each test, which was run for 72 hours. Data were collected on pumping water levels, injection pressures, and pumping/injection rates. Water levels in the monitor tubes and the test well were measured with automatic recording devices. Injection pressures were measured with a mercury manometer which could read either pressure or vacuum. The U. S. Geological Survey (USGS) participated during the test and collected a number of different geophysical logs. Of particular importance were the temperature logs run in the monitor tubes.

During the injection tests at Wells 1R and 3, manometer measurements at the well heads showed a vacuum; no pressure was observed. These tests were performed using cold, salty water from the boulder zone, which was pumped from one well and injected into the other. Thus, no pressure was needed to overcome a density differential such as is necessary when fresh water is injected into a zone containing salty water. Because cold, salty water was used for testing, temperature changes in the bore hole influenced water level behavior in the monitor tubes. Of particular importance is the change observed in the monitor tube at the wells which were injection tested. Prior to testing, water in both injection well and monitor tube was warm. As the injection test progressed, cold water from the boulder zone lowered the temperature in the bore hole and the monitor tube. This increased water density and caused the column of water in the monitor tube to shorten, giving the appearance of a water-level drawdown. A drawdown occurred quite rapidly. It began within a few minutes after the start of the injection testing.

It should be emphasized that this "drawdown" was observed in the monitor tube at the injection well. If a hydraulic connection existed between the monitor zone and the injection horizon because of either a poor cement job or across the confining bed, no drawdown would have been observed. Instead, a rise in water level would have occurred. The observed behavior of the water level in the monitor tube is interpreted as being indicative of the competency of the confining beds and the adequacy of the cement seal in the annular space outside of the 24-inch casing.

During injection testing of Disposal Well 3, the USGS ran a number of temperature logs in the monitor tube. These clearly show a reduction in temperatures caused by the introduction of comparatively cold water into an area which is normally warmer. This behavior also was noted during the test well program in 1975 and is explained in some detail in the Geraghty & Miller report.

The start of every 10,000 gpm test could be noted on the charts from the recorder at the test well, which is located approximately 1,000 feet from Well 1R. Characteristically, the start of pumping was recorded with a sudden change in the water level of approximately 0.1 foot. For about 15 minutes or so thereafter, the water level would oscillate up and down rapidly with the magnitude of the oscillations gradually diminishing to zero. Thereafter, the only observed water-level changes would be those resulting from the normal tidal variations. Thus, the effect of pumping and injection would be a small magnitude oscillation in the water level which diminished to nothing shortly after the start of pumping. These changes were so small and occurred so rapidly that they could not be used to determine water-transmitting characteristics of the boulder zone. Nevertheless, they do indicate that it is extremely large.

Because of the zone's extremely high transmissivity, bottom hole injection pressures will be extremely low, and furthermore, with long-term injection their rate of increase can be expected to be extremely small.

WELL CONSTRUCTION

During the 1974-75 test program, the so-called "boulder zone," a cavernous dolomite, was found to be at least 350 feet thick. Each of the disposal wells was designed and constructed to tap this zone. To take advantage of the full potential of the boulder zone to accept treated effluent, the full thickness (350 feet) was penetrated by the wells, with the exception of Well 3. The reasons for this will be explained subsequently.

During the course of construction, detailed records and daily logs were maintained to assure that specifications were followed, to permit disputes to be resolved, and to facilitate verification of requests for payment. To take advantage of site-specific conditions, geologic and geophysical data were collected from each well.

The wells were constructed with four strings of casing; each was necessary in order to achieve proper construction and environmental protection. Each well was equipped with an annular monitoring pipe perforated opposite a salt-water-bearing zone occurring above the confining bed sequence overlying the boulder zone. All casings were completely cemented in place. Various mixtures of cement were used; the choice of blend was dependent on hole conditions. In all cases, API Class B (ASTM Type II) cement was used to provide resistance to sulfate deterioration. Neat cement was used to seal the bottom sections of the 24- and 36-inch-diameter casings. The remaining portions were sealed with mixtures of cement, gel, and inert lost-circulation additives.

The inner casing of each well was pressure tested before the cement plug at the bottom was drilled out. Following completion of drilling and clean out, controlled pumping and injection tests were performed. Details of the testing are discussed in another section of this report.

A record of the construction details of Disposal Wells 1R, 2, and 3 is shown on Figure 1. Descriptions of the types of material, quantities used, depths, and casing settings are provided to serve as a permanent record. A brief description of the history of construction is given for each of the three disposal wells, as well as details of construction, events, and plugging of Well 1. The locations for each well, based on the treatment plant coordinates, are

Well	Coordinates
1	S11+50, E2+50
1R	S11+50, E3+00
2	S15+90, W00+50
3	S11+50, W2+50

Disposal Well 1R

Well 1R was drilled as the replacement for Well 1, which was abandoned when the subcontractor could not complete the well in accordance with the specifications. Well 1R is located at a site 50 feet due east of Well 1. The drilling of this well commenced on April 21, 1977, and was completed at the final depth of 3628 feet on September 24, 1977, for a total construction time of 156 days. No unusual problems were encountered during the drilling.

The geologic and geophsyical logs of the well and the record of pressure testing are contained in Appendix A of the report. Site-specific information on geologic conditions is contained in the general section on subsurface conditions based on evaluation of the data from all of the wells.

The 24-inch casing is set at a depth of 3025 feet (pad datum) in a fairly dense, resistive bed of limestone. Hard, crystalline dolomite marking the top of the boulder zone occurs at a depth of 3240 feet (pad datum). The interval between this depth and the bottom of the casing is composed of a fairly massive, white, moderately hard limestone with some dolomitic streaks. Its overall porosity is poor. Examination of the videotapes from this portion of the bore hole reveals its massive nature. The material correlates with that cored in the test well, which laboratory analysis showed to have a low vertical permeability, indicating the confining nature of this unit.

The boulder zone at this location is apparently most permeable below a depth of 3400 feet. Examination of the caliper, induction, and 3-D velocity logs shows the presence of a number of permeable zones and/or cavities, with major ones occurring at depths of 3420, 3450, 3480, 3500, 3550, and 3630 feet. Above 3420 feet to the top of the crystalline dolomite, the rock has a more massive, uniform character; while fracture zones and solution features are present, its permeability probably is not as great as the section below 3400 feet.

Disposal Well 1R is constructed in accordance with the specifications. All strings of casing were set to the prescribed depths and cemented entirely in place. The monitor tube was set to the required depth and directionally perforated opposite permeable salt-water-bearing zones. The high-capacity injection test, which is described in detail in another section of the report, was successful in that it demonstrated (1) the capability of the boulder zone to accept large quantities of injected fluids at high rates, and (2) the integrity of the casing, cementing, and monitor-tube system of Well 1R.

Disposal Well 2

Drilling commenced on February 23, 1976, and the well was completed (except for testing) on April 23, 1977, for a total of 424 days. Such a lengthy time was required because of controversy between the drilling contractor and a subcontractor and two problems associated with the well's construction.

The first problem occurred during the cementing of the 48-inch casing, when a tremie pipe parted and a void was left in the cement. The problem was resolved and the cementing accomplished by drilling a series of small-diameter holes through the cement into the void and pumping it full of cement, filling the annular space between the 48- and 60-inch-diameter casings. These efforts were successful and, aside from the delays it caused, the problem in no way affects or will interfere with the operation of the well.

The second problem occurred when the 36-inch casing collapsed. During this portion of the drilling program, all wells were under construction and it was usual procedure for a particular work task to be completed on a well with no additional work being done until such time as the equipment was available. Also during this time, the drilling contractor and his subcontractor were involved in a dispute over the drilling of one of the other wells. Because of these delays, several months elapsed after the cementing operations before the well was re-entered and the casing found to be collapsed.

This problem with Well 2 was unusual because of the long delay involved before work was resumed. The material present in the collapsed section is a plastic clay. Examination of the records for this portion of the hole indicates a history of squeezing during drilling. The pressure exerted by a plastic clay can be considerable. Since the collapse strength of 36-inch casing is quite low, such pressure, maintained over a long period of time, could have easily caused the casing to collapse. Thus, it is believed collapse occurred because the Hawthorn Formation squeezed in around the casing before it was completely cemented.

The problem was resolved by milling out the collapsed portion of the pipe. This was done in the interval between 488 and 504 feet below the drilling pad. In addition, the milled out section and washed out portion of the bore hole were cement grouted by the contractor to prevent a recurrence of the problem. These efforts were successful.

The 24-inch casing is set and cemented at a depth of 3025 feet (pad datum) in a cherty limestone. The top of the boulder zone, which is characterized by the presence of the dense, brown dolomite, occurs at approximately 3350 feet (pad datum). Total drilled depth of the well is 3680 feet. Permeable zones, which are marked by the overgauge sections on the caliper log, appear to occur scattered throughout the entire section of the bore hole. The largest cavities (or cavity zones) occur between 3490 and 3500 feet and 3680 and 3694 feet. These depths are referenced to those shown on the caliper log.

Disposal Well 2 complies with the specifications and approved changes in construction. The 24-inch casing passed the pressure test, the monitor tube functions, and the pumping test indicates the capability of the boulder zone to accept large quantities of injected fluids at high pumping rates. The geological and geophysical logs for Disposal Well 2 are contained in

Appendix B of the report.

Disposal Well 3

Drilling operations began on February 6, 1976 and were completed on May 22, 1977. Work on this well was not continuous because several rigs were used for the drilling and there were rather lengthy periods of time when no work was done. In addition, because of the dispute between the drilling contractor and a subcontractor, additional delays resulted.

No problems were encountered during the drilling which would affect the integrity of the casings, cement, and monitor tubes. Approximately one week's time was spent in recovering a twisted-off drill pipe and waiting for a new string of pipe.

The boulder zone was encountered at approximately 3350 feet. The pilot hole was completed at a depth of 3650 feet. In order to reach this point, the driller had to deal with severe caving problems in the upper portion of the boulder zone. Because of the caving problem, the contractor could not keep the pilot hole open and it could only be logged to a depth of 3428 feet. These logs are contained in Appendix C, along with the geologists' log and the results of the pressure test on the 24-inch casing.

During the reaming of the pilot hole to 22 inches in diameter, the contractor experienced the same difficulty with caving, which necessitated considerable dredging. Approximately five weeks' time were required to ream the hole to 3650 feet. This was the greatest depth reached, and for about one month after reaching this point, no footage was made. This period of time was spent "dredging" caved material. More hole was lost and eventually it could be kept open only to 3390 feet.

The boulder zone occurs at approximately 3350 feet. Drilling records show the top of the zone contains numerous cavities and fractured rock. This was verified by the caliper log and the video tapes made in the well after its completion. Because of the inordinate amount of time required to dredge the hole and the lack of progress, the contractor applied for relief, stating the well in its condition would be capable of use. This request was granted with the provision that the subsequent testing prove the well capable of accepting injected fluid at a reasonable pressure and without collapsing. The well was tested twice by injecting into it at the 10,000 gpm rate for 72 hours each time. No pump-out tests were performed for fear of causing collapse. The results of testing are described in a subsequent section of the report.

The well has been constructed in accordance with the specifications and approved changes. The results of the injection tests indicate it can be operated without caving. However, there is no guarantee that caving will not occur in the future, and therefore its operation and performance will have to be watched in the future.

Disposal Well 1

Because the drilling subcontractor could not complete the well in accordance with the specifications, it was plugged and abandoned. Evaluation of the pilot-hole data showed the point at which the 24-inch casing was to be set was at approximately 3000 feet. While the 24-inch casing was being set in the hole, the upper portion of the drilling rig mast collapsed. About one week's time was required to repair the mast. When operations were resumed, the casing was found to be stuck in the hole. The bottom of the casing was at 2450 feet, 550 feet short of the designated casing point.

Efforts to free the casing were unsuccessful. The subcontractor then requested permission to deviate from the specifications by setting an epoxy-lined 22-inch O.D. liner to the 3000-foot depth with approximately 100 feet of overlap inside of the 24-inch casing. Permission was granted after approval by the engineers and the regulatory agencies. However, the subcontractor was advised that the casing and liner had to pass the required pressure test and be set to the required depths.

After the 24-inch casing was successfully cemented to 2450 feet, the liner was set. Two attempts were made before it could be installed to the specified depth. The subcontractor then proceeded to cement the liner and in doing so he cemented in about 600 feet of the string of drill pipe and part of a two-inch-diameter work pipe which had been installed to aid in circulating out any surplus cement. These incidents necessitated washover and milling operations.

Eventually, through a combination of washover, milling, and drilling, the liner was cleaned out. A pressure test was performed and the data indicated a satisfactory seal had been obtained.

The pilot hole was then completed to 3628 feet. During subsequent operations associated with the well's completion, a length of the upper portion of the liner was retrieved from the well. It consisted of the cement collar forming the top of the 22-inch liner, and a length of the liner itself. A portion of the liner had been milled away lengthwise.

After this discovery was made, the subcontractor had a number of six-arm caliper logs performed over the length of the liner. According to the subcontractor, the logs showed the liner to be intact (except for the upper portion) and, therefore, the well was in acceptable condition. Despite these claims, it was felt the logs did not demonstrate the integrity of the liner and a television survey was made of the lower portion of the well, including part of the 24-inch casing and much of the liner. The television survey clearly showed that the top of the liner had sustained considerable damage during the washover and milling operations. Remarkably, the damage was such that the drill bit and/or milling tools passed the liner and the well was completed by drilling a "new" hole outside of the liner.

Because of the damage to the liner, and the questionable condition of the 24-inch casing where the milling and washover operations had taken place, Well 1 was declared unacceptable and the contractor was instructed to abandon the well and install a replacement well as stipulated in the specifications and contract documents.

Plugging and abandonment of Well 1 were achieved with mixtures of cement, crushed limestone, and drilling mud placed in stages. Initially, a non-drillable plug made from old drill pipe with two cement baskets was set on a string of drill pipe at a depth of 3244 feet, or just a few feet above the boulder zone. A small amount of broken cement block and dolomite cuttings from the well were set on top of the cement baskets to bridge any openings around the baskets. Neat cement was placed in a series of stages to form a base on which to set the cement plug. Neat cement was used to fill the hole up to 3044 feet. From this depth up to 2164 feet, or 286 feet above the bottom of the 24-inch casing, Class B cement with 4 percent gel, 10 pounds of gilsonite per sack of cement, and flocele was pumped.

From a depth of 2164 feet, the 24-inch casing was filled with limestone gravel and zeogel (drilling mud which does not floculate in the presence of salt water) in stages. To insure the gravel was saturated with zeogel, 750 gallons of the mud was pumped into the well through a pipe followed by 11 yards of gravel. This procedure was repeated until the well was filled to within 50 feet of the drilling pad. The remainder of the well was filled with neat cement. This operation successfully plugged the well without incident.

It should be noted that the pressure test performed on the liner was, in reality, conducted on the <u>open hole</u> from a point just below the bottom of the 24-inch casing at 2450 feet to a few feet above the bottom of the liner at 3000 feet. The test was successful; the observed pressure drop was well <u>within</u> the standard called for in the specifications. However, instead of demonstrating the adequacy of the casing and liner and the cementing, it showed the "tight," relatively impermeable nature of the confining beds overlying the boulder zone.

PUMPING - INJECTION TESTS

Procedures

After the wells were completed and the drilling fluids and cuttings cleaned out, a series of pumping-injection tests was performed. These were accomplished by installing a 10,000-gpm-capacity turbine pump in one of the wells (Disposal Well 2 for all tests), and installing a pipeline, valves, and other fittings to connect with one of the other wells so water could be pumped from one well and injected into another. These tests are considered primarily to be acceptance tests and were conducted to demonstrate the capability of the wells to accept and produce large volumes of fluids at high rates, the competency of the confining beds, the effectiveness of the monitoring tubes, and the influence of temperature changes on the data. This method had to be utilized as there was no place to dispose of the large volumes of saline water that would be produced during a pump-out test and there is no source for the large volumes of uncontaminated water needed for an injection test. Thus, while hydraulic characteristics (i.e. numerical values for transmissivity and storage) of the boulder zone could not be calculated from the test data, they showed that the zone is capable of accepting large volumes of fluids at high injection rates.

A total of three pumping-injection tests were performed. Tests 1 and 2 were run using Disposal Well 3 for injection and Disposal Well 2 for pumping; Test 3 was run using Disposal Well 1R for injection and Disposal Well 2 for the supply well. No pumping test was run on Disposal Well 3 for fear of collapse, and the two injection tests were performed on the well to attempt to determine if repeated injection of fluids into the well would cause collapse and plugging.

For the testing, the pipeline was set up so that the injection rate could be controlled by means of the valve at the head of the injection well. An in-line flow meter capable of reading instantaneous flow rate and total quantity pumped was installed. Water-level measurements were taken in the pumping well, the monitor tubes in both pumping and injection wells, and in the test well constructed during the 1974-75 program. Both manual and automatic devices were used to collect these data. Injection pressures were measured by means of a gauge and a mercury manometer installed at the well head. The manometer was installed after the flow-regulating valve, whereas the pressure gauge was installed ahead of it. Water temperatures were taken during the test by means of the manometer used in conjunction with a "blow-off," which was used for water sampling and to determine if solids were being pumped from the well. The U. S. Geological Survey provided equipment and manpower during the tests, and collected a number of temperature and flowmeter logs, which were of great use in interpreting the various data. USGS personnel also conducted a dye test during the first injection test to determine the rate of travel between two wells.

Test 1 Results - Pumping Well

Test 1 was performed for 72 hours, beginning on May 29, 1977 at 3:10 PM and ending on June 1. Because two diesel engines were needed to operate the pump through a double right-angle drive and the engines had to be synchronized, the pump had to be started at a low rate and gradually increased to the desired value. This procedure also was necessary to minimize the possibility of caving in the boulder zone due to the sudden surge which would be created by starting the pump at 10,000 gpm.

At the time the pump was turned on, the static water level in Disposal Well 2 (the pumping well) was 15.92 feet below the top of the well casing flange. At the initial rate of 2000 gpm, the water level declined to a depth of 26 feet, to about 30 feet at 4000 gpm, 45 feet at 8800 gpm, and 56 feet at 10,000 gpm. The desired test rate was achieved after 320 minutes of pumping. During each step increase of the pumping rate, water samples were collected from the blow-off to estimate the amount of sand and turbid water being pumped. Each time the rate was increased, there was an accompanying increase in sand and turbidity, but this dissipated within a short time. Occasionally during the 10,000-gpm portion of the test, a fragment of gravel could be heard moving along the pipeline. Otherwise the water remained clear, giving evidence that the well was reasonably well developed.

After the desired test rate was reached, it was maintained at that level with the exception of two periods. After approximately 1878 minutes' time, the pump output was reduced to about 8500 gpm because one of the engines stopped running. This required about four hours to repair, after which normal operations were resumed. The second reduction in pumping rate lasted for 7.5 hours. During this period, the USGS performed flowmeter logging in Well 3 to determine where injected water was leaving the bore hole. This necessitated the use of a reduced pumping rate; otherwise the logging equipment would not function properly because of turbulence caused by a high pumping rate and fluid velocity. These changes in pumping rate did not in any way affect the test results; in fact, they proved useful in the interpretation of the data.

The test was terminated after 72 hours pumping. The discharge rate was 10,800 gpm. The pumping water level was at 59.3 feet. When the pump was turned off, the water in the well surged up and down so violently that it was impossible to obtain a reliable water-level measurement for 13 minutes after shutdown. At that time the water level was at a depth of 23.65 feet. Measurements for approximately the next 40 minutes showed that the rate of fluctuation had subsided considerably, and the water level was varying between 24.1 and 24.6 feet. Records of water-level fluctuations taken after the test with an automatic device showed that after the initial period of violent fluctuations, the water level rose slowly; after ten hours of recovery it had risen to 23.1 feet. By the start of Test 2 on June 3, 1977, it had recovered to a depth of 21 feet.

Comparison of the pre- and post-test water levels shows a considerable difference in the non-pumping level (16 feet versus 23 feet). This is attributed to temperature differences. Prior to the test, the well was not pumped for some period of time and the water standing in the bore hole achieved the ambient temperature of the surrounding rock. The water level recorded prior to the test reflects the average density of the bore hole fluid as influenced by ambient temperatures. During the test, when Well 2 was pumped, cooler, denser water from the boulder zone filled the bore hole. When the test ended, the average density of the bore hole fluid was greater than it was prior to the test. Thus, a "shorter" column of fluid was required to balance the bottom-hole pressure. This pressure would be the same before and after the test. Thus, the post-test static level would be lower than the pre-test value because of temperature-induced density changes. During the test, the water temperature was found to be 16°C (60.8°F). This temperature was taken 1008 minutes after the start of pumping.

Evidence of temperature change is given from the temperature logs performed by the USGS. Prior to the start of the test, the USGS set a temperature probe in the monitor tube at Well 2 at a depth of 1100 feet. A pre-test temperature of 21.09°C (69.96°F) was recorded. After 29 hours' pumping, a temperature of 17.35°C (63.23°F) was recorded at the same depth, for a temperature change of 3.74°C (6.73°F).

Arithmetic plots of the water levels in the pumping well (Disposal Well 2) and the monitor tubes in Disposal Wells 2 and 3 versus time are given on Figure 2. Pumping rate variations also are shown. The difference between pre- and post-test static water levels is clearly indicated.

Some idea of the capability of the boulder zone to produce water (and accept injected fluids) can be gained from a determination of the specific capacity of Disposal Well 2. Specific capacity is defined as the rate of discharge of water from a well divided by the water level drawdown, and is a measure of the capability of an aquifer (in this case, the boulder zone) to produce (or accept) water.

In the typical well, the casing is comparatively short and friction losses can be neglected. However, in deep disposal wells, friction loss in the well casing can be significant, and is often the greatest component of the observed drawdown. This is especially so at high pumping rates such as used during the pumping test, and must be compensated for in order to develop an estimate of the specific capacity.

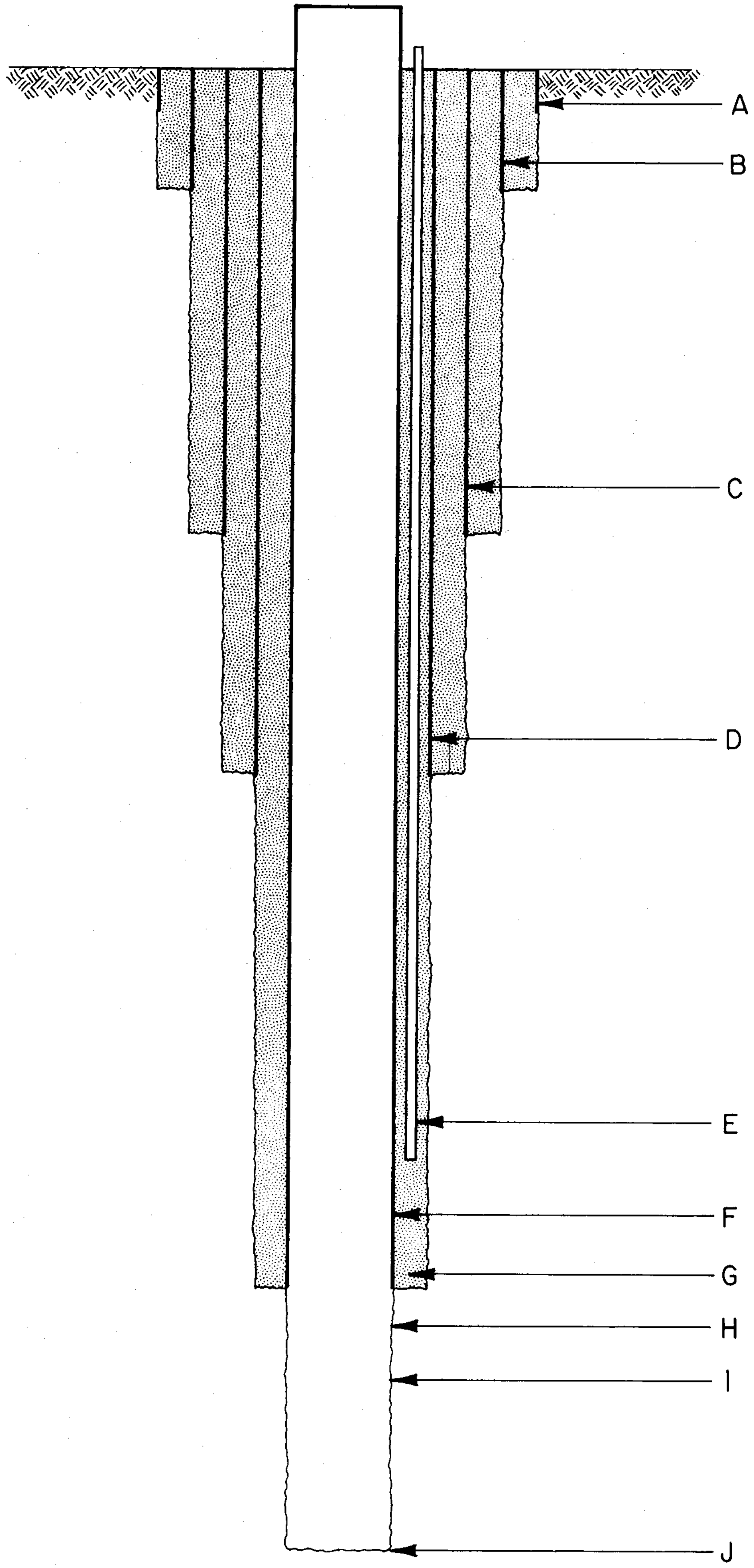
The estimated head loss (drawdown) caused by pumping was computed from a nomograph based on the Hazen and Williams formula using coefficients of 120 and 140. For these coefficients, the lead loss is estimated to be 6 and 8 feet of head (drawdown) for each thousand feet of pipe, respectively. Since the casing in the well is set to slightly more than 3000 feet and the pump intake was set at 150 feet, the total length of pipe through which water flowed during the test was 2850 feet. Therefore, the total head loss due to friction in the pipe was 17 to 23 feet out of a total drawdown of 33 feet. Additional head loss also occurred in the open hole portion of the bore hole, extending from the bottom of the casing to the top of the injection zone at 3350 feet. This portion of the well has a rough surface and varies in diameter. Thus, friction losses cannot be calculated, but are estimated to be significant owing to the nature of the bore hole. As an example, assuming the open portion of the bore hole has a diameter of 22 inches and a roughness coefficient of 100 (similar to concrete pipe), the head loss in that portion of the hole could easily be an additional seven feet. The total drawdown due to friction loss could range between 24 and 30 feet. Thus, the total drawdown in the boulder zone was between 3 and 9 feet. While these estimates cannot be used for quantitative analysis, they clearly demonstrate the capability of the boulder zone to produce and accept water.

Test 1 Results - Injection Well

Injection pressures at the well head in Disposal Well 3 were monitored by means of a pressure gauge installed ahead of the valve and a mercury manometer placed after the valve. The manometer was set up so both pressure and vacuum were monitored. The well took fluid at a vacuum at all injection rates throughout the test; no pressures were noted. The presence of a vacuum at the well head indicates there was little pressure build-up as a result of injection. The static water level in the well stands some 15 feet below the top of the 24-inch casing. During injection, there was some pressure build-up; there had to be because of friction losses and some bottom-hole driving pressure build-up. However, it was not enough to raise the water level in the well to a point where a pressure would be created at the manometer.

The fact that the temperature of the water being injected decreased further complicates matters. As the temperature of the bore hole fluid decreases, water density increases and the length of the column of fluid shortens. This results in an apparent drawdown of the water level. While this is occurring during the initial part of the test, the bottom-hole driving pressure is building up, causing a rise in the water level. The two counteract each other to some degree.

During the initial period of injection, the vacuum varied considerably owing to changes in pumping rate. After the rate was set at 10,000 gpm, and reasonably well stabilized, a vacuum equivalent to 8.93 feet of water (356 minutes of injection) was recorded. The mercury manometer readings were converted to feet of water. Each time the manometer was read, the temperature was noted, and the density of mercury at that temperature was used in converting to equivalent feet of water. Throughout the test there was an apparent decline in the vacuum. This is to be expected because as the pressure builds up, the vacuum will decrease. At no time during the test did the pressure build up to a point where it would have been observed as pressure at the well head.



EXPLANATION		WELL 1 R	WELL 2	WELL 3
A	72-inch casing	10 feet	10 feet	10 feet
B	60-inch casing 0.375-inch wall thickness 238.5 lbs/ft	114 feet	115 feet	114 feet
C	48-inch casing 0.375-inch wall thickness 190.7 lbs/ft	404 feet	396 feet	397 feet
D	36-inch casing 0.375-inch wall thickness 142.7 lbs/ft	1018 feet	1030 feet	1037 feet
E	2-inch I.D. monitor tube	2258 feet	2310 feet	2321 feet
	Perforated zones	2194 – 2208 ft 2154 – 2166 ft	2270–2277 ft 2228–2238 ft	2226–2236 ft 2283–2293 ft
F	24-inch casing 0.375-inch wall thickness 94.6 lbs/ft	3026 feet	3026 feet	3034 feet
G	Cement – CLASS B	25,977 feet^3	20,402 feet^3	22,948 feet^3
H	22-inch open hole	611 feet	654 feet	381 feet
I	Top of Boulder Zone	±3260 feet	±3350 feet	±3350 feet
J	Total depth of well	3637 feet	3680 feet	3415 feet

NOTES

1. All measurements referenced to drilling pad elevation +19 feet msl, except 24-inch casing, which is 1.25 ft above drilling pad.
2. Drawing not to scale

FIGURE 1

CONSTRUCTION DETAILS OF DISPOSAL WELLS 1R, 2 AND 3

REGIONAL POLLUTION CONTROL FACILITY
CITY OF WEST PALM BEACH, FLORIDA

GERAGHTY & MILLER, INC., WEST PALM BEACH, FL 8-78

Values of the manometer readings at Disposal Well 3 during the injection test are listed on Table 1. No data are shown for the early part of the test when the rate was being varied. An effort was made to graphically analyze these data, but was unsuccessful owing to the wide scatter of the plotted data, which is attributed to variations in pumping rate. Nevertheless, the data do show that a reduction in the vacuum occurred as the test progressed, indicating a gradual build-up in pressure. This was to be expected, but, of course, the rate of build-up was low owing to the extremely high transmissivity of the boulder zone.

When the test was terminated, water level measurements were taken in Disposal Well 3 through the fitting on the well head which was used for logging. These showed that for approximately 2.5 hours after shutdown, the water level declined, as would be expected in an injection well. Thereafter, the water level varied somewhat in response to tidal fluctuations, but, in general, there was an overall rising trend in the water level caused by a warming of the water in the bore hole.

The warming trend began the instant injection stopped, but its effect was masked by the declining water-level trend result because of "recovery" due to injection. Approximately one hour

TABLE 1

Mercury Manometer Readings
at
Disposal Well 3 during Test #1
May 29 - June 1, 1977

Time (minutes since start of test)	Vacuum (feet of water)
327	8.393
356	8.934
508	8.936
715	8.125
803	8.125
920	8.126
1013	7.293
1128	8.650
1260	8.647
1310	8.648
1800	8.658
2275	6.769
2451	7.035
3235	7.035
3354	7.038
3537	7.309
3660	7.309
3778	7.040

after shutdown, the water level was at a depth of 23.4 feet below the top of the well casing. This corresponds quite closely to the water level in the pumping well at the same time. This is to be expected because, by the time the test ended, the fluid in both bore holes had been cooled to approximately the same temperature, and therefore possessed the same density. The wells tap the same zone. Since they are only 500 feet apart, the heads or water levels would be essentially the same.

The fact that the pressure build-up resulting from injection was so low it resulted in a vacuum reading at the well head attests to the high transmissivity of the boulder zone. The levels of the pressure build-up caused by injection was primarily the result of friction loss in the bore hole, previously estimated at between 17 and 23 feet (from the Disposal Well 2 data). It would have been approximately the same in Well 3 because the two wells have approximately the same lengths of 24-inch casing installed and the open portions of the bore holes between the casing and the injection zone are about the same length.

Temperature-Induced Density Changes

During the 1974-75 testing program, it was shown that temperature-induced density changes caused water levels to fluctuate and were the sole reason why the levels in the monitor tubes changed. Because of this, particular attention was paid to temperature changes during and after the testing because of their influence on fluid density and water levels.

In contrast to shallow ground water, which can have a temperature of $\pm 26^{\circ}C$ ($78.8^{\circ}F$), water contained in the boulder zone is much colder than normal ($\pm 16^{\circ}C/60.8^{\circ}F$). At the West Palm Beach site, and elsewhere throughout southeastern Florida, the normal earth temperature gradient is not present: Temperatures do not increase gradually with respect to depth. Instead, there is some increase with respect to depth, but as the boulder zone is approached, the gradients reverse and temperatures become colder.

When water is extracted from the boulder zone through a well, the temperature of the water standing in the well will be reduced. This will cause an apparent water-level drawdown in the well. Similarly, the displacement of warm water with cold water in an injection well will result in an apparent drawdown because of the increased density accompanying a reduction in temperature. For example, salt water (35,000 mg/l of total dissolved solids) at a temperature of $25^{\circ}C$ has a density of 1.023362, whereas at 16°C the density of the same water will be 1.025766. Both densities are referenced to distilled water at 4°C.

Whenever cold water is pumped from or injected into a well, heat energy will be transferred from the warmer materials surrounding the well to the water in the bore hole. Heat flow in this situation is analogous to pumping water from a well. With colder water present constantly in the bore hole, the surrounding materials also will be cooled. In the case of a water-filled monitor tube, the fluid in the tube will become colder and more dense as time progresses, and the water level (really the length of the column of fluid) will decline. This will occur in the monitor tubes in both the pumping and injection wells. This can be seen by examination of Figure 2, where the water-level fluctuations from the monitor tubes for the wells are shown.

The rate of water-level decline/rise in the monitor tubes at the beginning and at shutdown of Test 1 (covered in another section of this report) can be explained by an examination of Fourier's Law for heat transfer by conduction. This is stated mathematically by the following:

$$dQ/d\theta = -kA\ dt/dx$$

where

$dQ/d\theta$ = heat flow

k = thermal conductivity

$-dt/dx$ = rate of change in temperature with distance in direction of heat flow (temperature gradient)

A = area at right angles to heat flow

For the monitor tube encased in cement and the well casing through which heat flows, the terms k and A are constants. When cold water in the bore hole reaches a certain point in the bore hole and replaces the warmer water, the temperature gradient, dt/dx, is some maximum value and the rate of heat flow is a maximum. Therefore, the temperature, density, and water-level changes are at some maximum values and occur rather rapidly with respect to time. Since the colder bore hole fluid is moving and carrying heat away at a rate faster than it is being transferred to the bore hole through the cement and casing, cooling occurs. By the end of the test, the temperature of the monitor tube and the bore hole fluids are nearly equal. Thus, at the end of the test, the gradient, dt/dx, is smaller than it was at the beginning. When the pump was stopped and fluid motion stopped, a low (comparatively speaking) temperature gradient existed. Consequently, the rate of heat flow was low, and the warming trend, which began because the bore hole fluid no longer functioned as a heat sink, had to proceed at a slower rate than the cooling trend at the beginning of the test. Thus, temperature-associated density changes and the accompanying rise in water levels were slower in contrast to the behavior noted at the start of the test.

This is important to note and is an entirely different type of behavior than would occur if the monitor zone and injection horizon were hydraulically connected. With hydraulic connection, the rate of water-level change at the start and end of the test would be the same, not different. Furthermore, the water levels in the injection well monitor tube would rise rapidly, not decline, at the end of the test.

More detailed information on the influence of temperature changes on densities and water levels may be found in the 1975 Geraghty & Miller report on the test program.

Test 1 Results - Monitor Tubes

During Test #1, water-level fluctuations in the monitor tubes in Wells 2 and 3 were measured. Also, the USGS collected a number of temperature logs prior to and during the test. These were taken in the Well 3 monitor tube; the tube at Well 2 could not be entered with the logging tool. A temperature log of the entire length of the monitor tube was performed prior to the start of injection, and several temperature logs were made at different times during the injection test. In addition, records of temperature changes with respect to time were taken. This was done by setting the temperature probe in the bore hole at a fixed depth, permitting the chart-drive mechanism on the logger to run at a constant speed during the logging period.

Examination of the data for Monitor Tube 3 shows a rise in water level occurring for a short while after the start of injection, followed by a decline from a high of slightly less than 15 feet below the top of the tube to a low of slightly more than 16 feet. Thereafter, the water level rose throughout the test and showed some fluctuations or departures from the rising trend; these were caused by the logging activities. At the end of the test, the water level was at the 14-foot level and still rising. The end of the test was not reflected or shown by any change in the rising trend.

Before the test started, the well was flowing. In order to suppress the flow so the logging tool could be installed, salt was added as weight material. This lowered the water level, stopped the flow, and prevented a spill from occurring during the test. A stripper head could not be installed on the well to prevent the flow. After the salt was added, it mixed with the fluid in the well bore, and there was a gradual rising trend as the water level attempted to re-establish its normal equilibrium position. The rising trend resulting from the addition of the salt can be noted in the pre-test data. In contrast, there was no such trend in the water level in Monitor Tube 2.

The rise in water level in Monitor Tube 3 accompanying the start of pumping was caused by temperature changes because (1) very warm water contained in the pipeline to the well was introduced in the well, and (2) normally warm water in the upper portion of the bore hole was driven into deeper portions of the well where the water is colder. The time-temperature data from the probe set at a depth of 1100 feet prior to and maintained at that level for approximately 1.5 hours after the start of pumping shows an unchanging temperature of 21.09°C (69.9°F) for the first ten minutes. Then the temperature rose, reaching a peak of 22.97°C (73.3°F) 33 minutes after the start of pumping. Thereafter, the temperature declined. Shortly before the end of the test it had declined to 17.64°C (63.75°F).

The temperature log for the monitor tube taken prior to the start of pumping shows the temperature of the water was warmer above the 1100-foot level and became colder with depth. Also, water standing in the pipeline was warm. When pumping started, the warmer water entered Well 3, replacing the colder water and warming the water in the monitor tube. As the density decreased, the water level rose somewhat.

This trend was short-lived. As the test progressed, colder water drawn from the boulder zone through Well 2 was injected into Well 3. This is shown by the cooling of the water beginning 33 minutes after the start of pumping and continuing throughout the test.

The total temperature change at the 1100-foot level was 3.84°C (6.9°F), based on temperature logs taken prior to pumping and shortly before the pump was turned off. Over the entire length of the bore hole, the average temperature change was much greater, 7.34°C (13.2°F), with the greatest change occurring at the top of the monitor tube where the initial or pre-test temperature was the warmest and the least occurring at the bottom of the monitor tube where the pre-test temperature was the coolest.

When the test was terminated, the water level in Monitor Tube 3 continued to rise, but at a slightly greater rate than it was prior to shutdown. The change in the rate of water-level (rise) was a reflection of a warming trend which began at the time the flow of cold water stopped. At that time the bore hole fluid no longer functioned as a sink conducting heat away from the monitor tube (and the surrounding area). Also, since the bore hole fluid was colder than the surrounding area, heat continued to flow towards it, but since the water was no longer in motion, it began to warm up.

The behavior of the water-level in Monitor Tube 2 is an excellent example of temperature-induced water-level fluctuations and the contrasting behavior which will occur at the beginning of pumping and after shutdown. Prior to the test, the water level in the tube was essentially stable and was cyclically fluctuating only about 0.1 foot in response to variations in tidal loading. Within a few minutes after the start of pumping, the water level began a rather rapid decline, as cold water from the boulder zone replaced the normally warmer water in the well casing. As the temperature was lowered rapidly, the increased density of the monitor-tube water caused a rather rapid water-level decline; 12 hours after the start of pumping, the water level had declined from a static position of 5.97 feet (below the top of the tube) to 9.52 feet. At the end of the test, it was at 10.02 feet and fluctuating only from tidal influences. Total observed drawdown (uncorrected for the 0.1-foot tidal fluctuations) was 4.05 feet.

Actually, the maximum drawdown occurred after approximately 2600 minutes of pumping. For the remainder of the test, the water level remained at the ±10 feet level.

When the test was ended, the water level in the monitor tube began to rise immediately, but at a relatively slow rate in contrast to the water-level behavior observed during the initial part of the test. This was due to the differences in the rate of heat flow described previously and is proof of the effect of temperature-induced density changes. The contrasting behavior is interpreted as indicative of a lack of hydraulic connection between the confining beds and monitor zone and the adequacy of the cement seal around the 24-inch casing.

Test 1 - Conclusions

The test results clearly show the capability of the boulder zone at the sites of Wells 2 and 3 to accept large volumes of fluids at high rates, with low injection pressures. It must be remembered that salt water was used during the testing. Also, water was recirculated between the wells. In an actual operating situation, fresh water will be injected and additional pressure will be required to overcome the density differential between the fresh water and saline fluid in the injection zone. This will require an additional head capacity estimated at 30 to 35 psi (pounds per square inch).

Test 2 Results

A second test was performed using Well 2 for pumping and Well 3 for injection. This test was run to aid in determining if the previous test had caused any collapse and plugging of Well 3. As noted previously, this well could not be completed at the planned depth because of severe caving. The test was a duplicate of the first and was run for 72 hours during the period July 3 - 6, 1977. The test results were essentially the same as observed during the first test, indicating that plugging of Well 3 had not occurred. Hydrographs of the water levels in the pumping well and monitor tubes are shown on Figure 3, along with a record of the pumping-injection rates. No temperature logs were taken during this test.

Examination of Figure 3 shows a number of observations worthy of noting, particularly with regard to water-level behavior in the monitor tubes. First, the degree of drawdown in the tubes during this test was much less than observed during Test 1. However, the static water levels in the tubes prior to the start of Test 2 were at different positions than they were for Test 1.

In Well 3, for example, the water level was at 12.74 feet, or higher than it was prior to the start of Test 1, when it was at approximately 15 feet. Throughout both tests the water level in this tube was on a rising trend. As shown on Figure 3, this trend was disturbed during the initial 1000 minutes of the test when water temperatures in the tube were lowered. However, the rising trend soon overcame this, and for the remainder of the test and afterwards, the water level continued to rise with little or no deviation from the trend.

Temperature-induced drawdowns in Monitor Tube 3 were less during Test 2 than they were during Test 1. This is because temperatures in the monitor tube had not risen or recovered back to the levels they were at prior to the start of Test 1. Thus, there was less temperature differential between the monitor tube and bore hole fluid at the start of Test 2, and, therefore, only smaller temperature, density, and water-level changes could occur. This can be seen by comparing the initial water-level changes shown on Figures 2 and 3, which clearly show a smaller change occurred during the first portion of Test 2.

The difference in monitor tube water-level behavior during the two tests is best illustrated by examining the curves from

Monitor Tube 2 shown on Figures 2 and 3. At the start of Test 1, the level in Monitor Tube 2 was at a depth of approximately 6 feet. The level declined to approximately 10 feet during the test, for a total drawdown of 4 feet. After shutdown, the water level rose slowly and by the time the second test started it had recovered to approximately 8.5 feet. It should be noted that during Test 2 the level again declined to approximately 10 feet, the same level observed during Test 1, for a total drawdown of 1.5 feet, which is less than that observed during Test 1.

The difference in behavior was again due to the same reasons noted previously for Monitor Tube 3. It is interesting to note that the maximum or greatest depth to water in Monitor Tube 2 was the same level during both tests. This can be explained quite easily. The temperature of the fluid in the 24-inch well casing was the same for both tests. The tests were identical and therefore the temperature and density of fluid (and the water level) in the monitor tube would be the same for both tests.

The pumping water level in Disposal Well 2 was at basically the same elevation during both tests. Similarly, the vacuum noted in Disposal Well 3 was essentially the same during both tests, indicating no plugging occurred. The behavior of water levels in the monitor tubes during Test 2 reinforces conclusions regarding the confining bed and adequacy of the cement seal reached on the basis of the evaluation of the data from Test 1.

Test 3 Results

Test 3 was performed using Disposal Well 1R for injection and Disposal Well 2 for pumping. The same test set-up and procedures were used as in the previous tests. The USGS performed a series of temperature logs in the Well 3 monitor tube, which were used in the analysis to verify the effects of temperature changes. The behavior of water level was essentially the same as was observed in the other tests. Results of the 72-hour test are described below. The reasons for the observed water-level fluctuations are the same which have been described previously. There is one exception--the water-level behavior in the pumping well.

Measurements taken in this well throughout the test showed the water level to be at a depth of approximately 47 feet. These are shown on Figure 4. During the previous tests at the same rate, water levels of 56 and 57 feet were recorded. The same reference datum was used in all tests. Measurements during Test 3 were taken with an "M" Scope (electric tape) as well as a chalked tape. All measurements agreed within 0.1 foot. The most plausible explanation for the difference in water levels between the tests is that development of the well occurred as a result of the pumping, although this should have been noted as a rising water level (for a constant pumping rate) during one or all of the tests. Apparently, the well's specific capacity was improved so that during Test 3 it produced more efficiently. The same would apply to its performance as an injection well. In any event, the test results bear out the fact that the injection zone tapped by Disposal Well 2 is highly transmissive.

The injection pressures in Well 1R were low; the mercury manometer registered a vacuum at the well head throughout the test. During the first 10 minutes of injection, the well head vacuum registered between 5.0 and 5.7 inches of mercury as the rate was being adjusted. As the test progressed, the vacuum dropped, but at an extremely low rate. After 24 hours, it was 4.64 inches; it was the same after 48 hours and at the end of the test. The extremely low rate of change is an indication of the extremely high transmissivity of the boulder zone.

Water levels in Monitor Tube 1R declined in response to the reduction in temperature and water density. At the start of injection, the level was at a depth of 0.69 feet below the top of the pipe, and five minutes afterwards the level began to decline. After one hour it had declined to 2.48 feet, to 3.8 feet after four hours, and 4.40 feet after ten hours of injection. It reached a level of 4.88 feet after 21.5 hours (1290 minutes). Thereafter, it fluctuated due to tidal loading, but stayed at essentially the same depth. Total observed drawdown was 4.19 feet.

The drawdown of water level observed in the injection well monitor tube was due solely to temperature-induced density changes. As an example, the USGS set their probe at a depth of 1100 feet and collected data on temperature variations for about one day, beginning shortly before the start of injection. The pretest temperature was 27.10°C (80.8°F), and after 23 hours of injection it was 17.8°C (64.0°F), for a total decline of 9.3°C (16.7°F). Similarly, temperature logs taken over the entire length of the monitor tube prior to the test and shortly before shutdown show an overall reduction in temperature. Before the test, the average temperature was 25.8°C (78.4°F); prior to shutdown the average temperature was 17.5°C (63.5°F) or a total change of 8.3°C (14.9°F).

Examination of the hydrograph for Monitor Tube 2, given in Figure 4, shows the characteristic rapid decline of water level accompanying the equally rapid change in monitor tube temperature.

Conversely, at the end of the test, the water level rose, but at a very low rate, illustrating the difference in heat flow explained previously and indicating the effectiveness of the confining bed(s) sequence separating the injection horizon from the monitor zone.

The water level in Monitor Tube 2 behaved in the same way observed in the previous tests--an initial, rather rapid water-level decline, trending toward stabilization as temperatures in the monitor tube and bore hole equalized. At the end of the test, the water level rose slowly in contrast to the initial behavior.

Test 3 - Conclusions

Results of the injection test on Well 1R show the high transmissivity of the injection zone tapped by this well, and signify the capability of that zone to accept large quantities of fluids at high injection rates. The test also demonstrates the capability of Disposal Well 2 to function as an injection well and the satisfactory operation of the monitoring tubes.

SUBSURFACE CONDITIONS

Subsurface geologic conditions at each of the disposal wells are essentially the same as those encountered at the test well located approximately 1000 feet to the east. Lithologic characteristics were found to be the same; structural characteristics were found which influenced the construction of the various wells. These will be discussed subsequently.

The determination of subsurface conditions is based on analysis of the cuttings from each of the wells and the various geophysical logs. Formation samples were collected at intervals of ten feet; after analysis by Geraghty & Miller personnel and the wells' completion they were forwarded to the Florida Bureau of Geology by the drilling contractor. A variety of geophsyical logs were taken in each hole. Copies of these, as well as the geologic logs, are contained in Appendices A, B, and C. Of particular value are the induction, caliper, and 3-D velocity logs. When used in conjunction with the sample analyses, they enable one to develop a good description of the properties and relationships of the various rock units.

Neutron porosity and density logs (source tools) were taken in some of the wells. However, these proved to be somewhat unreliable because the compensating mechanisms in the tools were not sufficient to override the influence of the variations in hole diameter to produce representative values on the logs. No source tools were run in the boulder zone.

The induction logs were extremely useful in correlating marker beds between the wells. Numerous readily-identifiable units were found and traced between wells (as well as the test well). Thus, rocks having the same properties (i.e. ability to transmit or confine fluids) could be traced. Since the various geologic formations underlying southeastern Florida can be correlated for considerable distances, it is logical to assume that beds having similar physical properties also are areally extensive.

The following description of subsurface conditions is based on the data from Disposal Well 1R. Conditions were found to be basically the same at the other wells. The choice of using data from Disposal Well 1R is arbitrary; information from the other wells would have served equally as well.

The shallow deposits consist of sand and shells. These occur to approximately 50 feet, where the first bed of limestone is encountered. From that depth to approximately 260 feet, a sequence of limestone and shells is present. These materials are quite permeable and constitute the so-called "Turnpike Aquifer," a significant source of potable ground water in the area. The basal portion of this sequence also contains beds of sand.

At 260 feet, the first marl or clay is encountered (Hawthorn Formation?). This sequence is present to 890 feet, and consists of clay with traces of shells and sand. Shells are quite abundant in the lower 60 feet of this section. For all practical purposes, this sequence is impermeable and forms the confining bed which protects the fresh ground-water contained in the Turnpike Aquifer from the upward migration of brackish ground-water contained (under pressure) in the deeper Floridan Aquifer.

The limestone encountered at 890 feet marks the beginning of the thick sequence of carbonate rocks underlying peninsular Florida. The first 100 to 150 feet of this section also contains beds of shells and marl. As a consequence, the 36-inch casing is seated well into the upper portion of the limestone to provide protection during future drilling operations. The depths for the settings of this casing are noted on Figure 1 and range between 1018 and 1037 feet.

Aside from minor layers and nodules of chert, all of the wells penetrate limestone and dolomite. A variety of limestone "types" are present in the bore holes, ranging from fairly dense, crystalline rock to porous material composed of fossil fragments with little cementing material. Similarly, the dolomite found in the deeper portions of the wells ranges from dense, crystalline rock to porous material; fractures may or may not be present.

In Well 1R, for example, the limestone occurring between 990 and 1550 feet is medium to soft in nature and generally porous. Examination of the caliper log for the well shows this section to contain numerous intervals that are considerably overgauge. In fact, the smallest diameter shown is 39 inches (the bit size was 34 inches), and much of the hole here has a diameter in excess of 45 inches--the maximum capability of the logging tool.

This portion of the hole forms the upper portion of the Floridan Aquifer. In this case, the Floridan Aquifer is defined as those permeable zones producing brackish water; the base of the Floridan is at the contact between brackish and salty water (Personal communication, Garald G. Parker). On the whole, this section is quite porous and permeable. Much of the permeability is secondary owing to the effects of solution activity on the limestone. Some comparatively "tight" zones are present; their presence is indicated by the "gauge" sections of the hole shown on the caliper log.

At 1550 feet, the nature of the rocks changes somewhat. Extending from that depth to approximately 2520 feet, the rock is more competent. Both tight and porous zones are present according to the caliper and geologic logs. The hole is closer to gauge size. Dolomite first occurs at 1600 feet in the interval between 1550 and 1670 feet. Its presence is revealed by the resistive beds shown on the induction log and the higher velocity sections shown on the 3-D velocity log. On the whole, this section appears to be quite tight. Samples of the cuttings show much crystalline material, and considerable micrite (carbonate mud) and biomicrite. Some porous zones are present.

Between 1670 and 1890 feet, beds of limestone, dolomitic limestone, and dolomite are present. Numerous washed out, overgauge sections occur in this interval, according to the caliper log. Presumably, this section will yield water. At 1590 feet, the nature of the rock changes somewhat. A fairly competent dolomitic limestone and limestone sequence is present to 1960 feet. This section appears to be tight, as examination of the cuttings shows it has a generally low porosity. At 1960 feet and extending to 1980 feet, a poorly cemented, porous limestone occurs, as evidenced by the pronounced overgauge hole shown on the caliper log.

From 1980 to 2520 feet, an alternating sequence of limestone and dolomite beds are present. The dolomite beds are easily identified on the induction log, and they form distinctive marker beds. The bulk of this section appears to be more uniform in nature than the overlying beds; porosity ranges from low to moderate, judging by the sample descriptions. There are five distinctive washed out, porous, and presumably permeable zones in this section. These occur between 2280 and 2425 feet.

Beginning at 2425 feet, there is a marked change in the character of the carbonate rocks. They become more massive and uniform. This can be seen by examination of both the caliper and 3-D velocity logs. The top of this section is marked by a 10-foot-thick dolomite bed, which lies directly under a washed out section of the hole formed by a poorly cemented, porous limestone. From this point to 2520 feet a fairly massive limestone is present. From 2520 to 2780 feet, an off-white to cream colored limestone which is soft to moderately hard and has a poor to fair porosity is present, along with minor amounts of brown dolomite.

At 2780 feet, cherty, cream-colored limestone and dolomite were encountered. This association of rocks persisted to 3040 feet. The chert was fractured quite easily by the bit and it appears on the caliper log as forming a jagged, uneven hole.

From 3040 feet to the top of the dolomite marking the boulder zone at 3250 feet, white, soft limestone, dolomitic in part, and limey dolomite are present, along with some soft, marly lime. These rocks are characterized on the caliper log as a washed out overgauge section due to the presence of the marly material. Their overall porosity, because of the marl, is rather low.

Dolomite marking the top of the boulder zone was encountered at 3250 feet. This material exhibits a wide variety of characteristics. It is generally very hard and drills with some difficulty. It can be massive and dense, or vuggy. Fracturing is quite common, as evidenced by the large, irregular, angular fragments dredged from the hole by the reverse-air drilling process, and cavities are present. Their distribution is irregular throughout the section. On the caliper log the dolomite shows the characteristic gauge hole, somewhat jagged in appearance, marked by numerous overgauged sections indicating the presence of cavities. These were also reported by the driller as well as fracturing, which necessitated "dredging" to remove the material that collapsed during the drilling process.

The lithology of the carbonate rock section penetrated by the disposal wells is typical of the rocks described by Puri and Winston in their study of the geologic framework of the transmissive zones underlying south Florida. The upper portions of the section appear to be coarser-grained and porous (grainstone). It has been affected by solution activity and can have a high secondary permeability. These, of course, form water-bearing zones. Relatively tight zones are also present. In the interval between 890 feet and 2420 feet, porous and tight zones alternate.

Permeable zones within this section produce brackish water. With increasing depth, salinity of the water increases; eventually it reaches that of sea water. This appears to occur in the interval between 1900 and 2100 feet.

From 2420 feet to the top of the boulder zone, the rocks are, in general, finer-grained, exhibit more chalky, micritic interstitial material, and are comparatively impermeable. This section corresponds to the one cored in the test well in 1975; laboratory analysis of the cores give vertical permeability values of 10^{-6} cm/sec (centimeters per second). This section forms the confining bed sequence overlying the boulder zone. Its confining properties are well demonstrated by the fact that this is the open-hole section which was pressure tested when Well 1 was under construction. Results of that pressure test are given in Appendix A. Visual examples of the tight nature of the rocks are seen in the videotapes of the borehole which were made after Well 1R was completed.

After the geophysical logs had been taken from Well 1, correlation with that data and the logs from the test well about 1000 feet to the east indicated that the beds were dipping to the west. The dip angle appeared to be quite steep, at least for this portion of southern Florida. Subsequently, it was predicted that the boulder zone at the site of Well 1 would occur about 100 feet or so deeper than it was found at the test well. This prediction proved to be true, and formed the basis for subsequent "picks" for the boulder zone at the other well sites. These also proved to be correct.

Examination of the induction logs for the three disposal wells shows they can be easily correlated, and they clearly indicate that the beds are dipping to the west--approximately southwest, to be more precise. More importantly, the dip or inclination of these beds ranges from 8 to 10 degrees.

To establish these values, nine distinct horizons or marker beds were correlated between the three disposal wells. These are formed by dolomite beds below 1600 feet and limestone beds above this depth. These are referred to by letter designation, beginning with A for the deepest bed to I for the shallowest. The induction logs for the pilot holes contained in the various appendices have been marked to show these horizons.

Depths to these horizons for the various beds are given in the following table, along with calculated values for dip and strike.

Marker Bed	Depth(1) (Ft.)				
	Well 1R	Well 2	Well 3	Dip (°)	Strike
A	2798	2878	2882	10.6	N22°W
B	2670	2747	2748	10.1	N23°W
C	2559	2635	2637	10.0	N23°W
D	2243	2301	2312	8.6	N17°W
E	1726	1783	1794	8.5	N16°W
F	1658	1734	1720	9.4	N14°W
G	1621	1672	1683	7.9	N15°W
H	1257	1275	1287	4.4	N 5°W
I	1142	1151	1174	4.7	N13°E

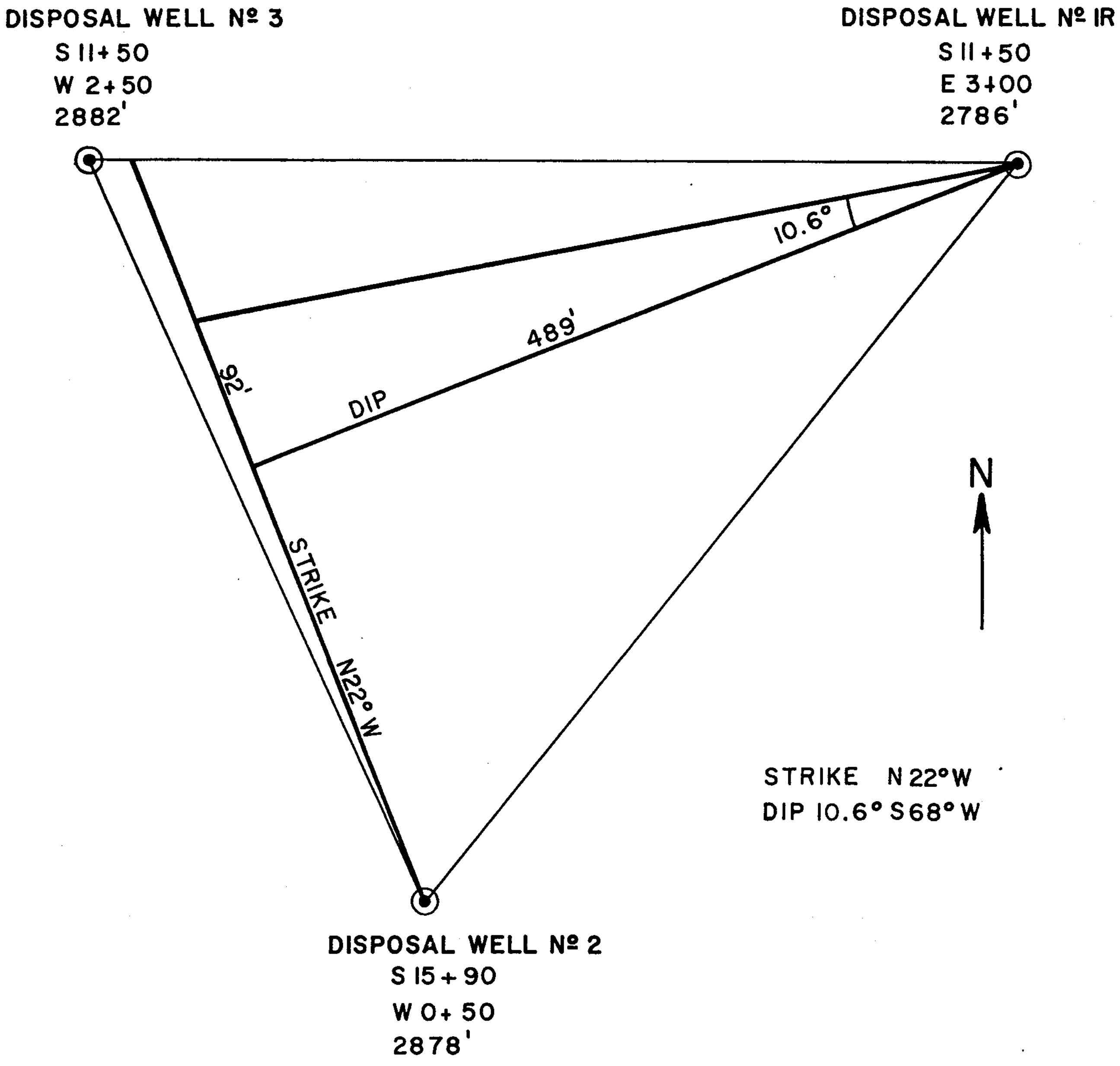
NOTE: (1) Depths are referenced to the drilling pad at elevation +19 feet MSL, except for Well 1R, which are referenced to the kelly bushing 12 feet above the pad. Dip calculations are based on all measurements referenced to the drilling pad datum.

Figure 5 shows a map giving the locations of the three disposal wells referenced to the plant coordinate system, and the various values for the depth to marker A at each well, along with a graphic presentation of the strike and dip of that horizon. Correlations also have been made with the test well; these show that basically the same relationship exists.

It is interesting to note that all horizons are dipping in the same general direction, and that the dip angle increases with depth. There also appears to be a thickening of the section in the same direction; the difference in depth (thickness) between the A and I horizons at Well 1R is less than it is at Wells 2 and 3--1656 feet at Well 1R compared to 1727 and 1708 feet at Wells 2 and 3, respectively.

The waste-water treatment plant is located on the northeast side of the South Florida basin, and beds would be expected to dip to the southwest. Since the basin also has subsided during its geologic history, the various beds can be expected to be thicker toward the southwest and the dip angles greater in the older, deeper beds than in the shallower beds.

The upper two marker beds show much lower dip angles than the deeper beds. This suggests a disconformable contact exists somewhere between marker beds G and H. At some time in the past,



EXPLANATION

S15+90 W0+50	PLANT COORDINATES
2882'	DEPTH TO MARKER BED A, DATUM DRILLING PAD AT ELEV + 19.00 MSL

Scale: 1" = 100'

FIGURE 5

STRIKE & DIP OF MARKER BED A

REGIONAL POLLUTION CONTROL FACILITY
CITY OF WEST PALM BEACH, FLORIDA

GERAGHTY & MILLER, INC., WEST PALM BEACH, FL. 8-78 the beds below Marker G were exposed to erosion; subsequently they were buried as the younger deposits containing beds H and I were deposited on the ancient erosion surface above bed G. Such contacts between the various geologic beds in Florida are common and give rise to the geologic setting found today.

The rather severe dips of the various beds shown to exist between the wells is believed to be a local phenomenon. Data from more widely scattered oil wells show much less severe dip angles to exist. Of course, these relationships will be of considerable interest to the geologist. To the City of West Palm Beach they will be significant: Future wells, located to the west of the first three wells, will have to be deeper to tap the boulder zone and will require more casing to take maximum advantage of the confining bed sequence. Conversely, shallower wells and less casing will be required at sites located to the east. Also, because of the lesser density of the injected effluent, it will tend to migrate up-dip in an easterly direction.

CONCLUSIONS

(1) Disposal Wells 1R, 2, and 3 have been successfully completed and have been constructed in accordance with the specifications and contract documents.

(2) Disposal Well 1, which was abandoned because it did not meet specifications, has been successfully plugged with cement, drilling mud, and crushed limestone.

(3) The disposal wells tap an injection zone which has an extremely high transmissivity; each well is capable of accepting the desired quantity of treated effluent at the anticipated low injection rates.

(4) The test data demonstrate the competency of the confining bed sequence overlying the boulder zone.

(5) There was no indication of plugging or caving in the wells during the pumping-injection tests. However, the potential for caving exists at Well 3, and the well should be carefully operated in the future to aid in avoiding problems.

Respectfully submitted,
GERAGHTY & MILLER, INC.

Vincent P. Amy

Vincent P. Amy
Senior Scientist

Date:
September 25, 1978

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OCT 4 . 1978

ROBERT AND CO. ASSOC.
W. PALM BEACH, FLA.

3 October 1978

Mr. William F. Glass
Robert and Company Associates
2250 Palm Beach Lakes Boulevard
West Palm Beach, Florida 33409

Dear Bill,

In the report entitled "Construction and Testing of Disposal Wells 1R, 2, and 3, Regional Pollution Control Facility, City of West Palm Beach, Florida," there are two errors in the table given on page 60. The compass directions given for the strike of the various marker beds are the bearing, or direction, of the dip. Also, the depth to Marker Bed A at Well 1R should be 2798 feet. A corrected copy of page 60 is attached to be placed in the report.

Please excuse the error.

Sincerely,
GERAGHTY & MILLER, INC.

Vince

Vincent P. Amy

VPA/k
Enclosure (7 cys)