# MARCO LAKES AQUIFER STORAGE AND RECOVERY PILOT PROJECT FINAL REPORT

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## 1.0 EXECUTIVE SUMMARY

This submission provides the complete and final report for the Big Cypress Basin Board of the South Florida Water Management District and Florida Water Services, Inc. joint ASR pilot study located at Florida Water Services' Marco Lakes Facility (Figure 1-1). This report describes the results of a multi-phase aquifer storage and recovery (ASR) pilot project conducted for Florida Water Services at the site of their raw water source. Water from Marco Lakes supplies the lime softening treatment plant for Marco Island. The project was conducted through a cooperative funding agreement between the Big Cypress Basin Board of the South Florida Water Management District and Florida Water Services.

The overall purpose of this project was to determine if ASR technology could be implemented at the Marco Lakes facility to generate additional freshwater for Marco Island. Some of the important findings and recommendations of this investigation include:

1. Testing and analysis results indicate that aquifer storage and recovery can be successfully performed at the Marco Lakes raw water source site by utilizing the Lower Hawthorn/Upper Suwannee Formation.

2. ASR recovery efficiency improved during cyclical testing from an initial value of 30 percent during the first cycle to 75 percent for the third cycle. Recovery efficiency was based on a cutoff concentration of 350 mg/l dissolved chloride.

3. Both field testing and computer model results indicate that the ultimate recovery efficiency per 150 million gallons of injected water could reach 60 to 70% within 3 cycles.

4. During recovery of the stored water, it is appropriate to recover water up to a maximum dissolved chloride concentration of 350 mg/l. This will allow blending of the recovered water with the raw surface water and still maintain an acceptable final water quality. The chloride concentration of the lake water should be monitored in order to achieve a desired blend ratio. ASR well recovery rates can be adjusted to optimize production rate and water quality of the blended water. This blend should also consider present and future treatment options.

5. Filtration of the raw water can be accomplished to an acceptable level using pressure sand filters. The filters used for this project were automatically cleaned by backwashing once a day and when the differential pressure across the filter bed reaches 16 psi.

6. Cyclical test data indicate that significant plugging of the formation occurs even if the surface water is highly filtered and contains low levels of suspended solids. This plugging is most likely due to chemical precipitation on the walls of the receiving formation at the borehole. It was found that this plugging can be avoided by lowering the pH of the injected water. The pH of the injected water should be maintained within the range of 7.5 to 7.8 in order to prevent the plugging problem.

7. An acceptable method of adjusting pH is the use of hydrochloric acid. However, for the wellfield expansion, other alternatives are being evaluated for this purpose.

8. Data from the ASR interval monitor well indicate that color and THM concentration are attenuated within the formation. These compounds were not shown to be present or were present at highly reduced concentration levels within the ASR zone at a distance of 375 feet. These results are

consistent with previous studies.

9. A design for an expanded ASR wellfield was developed in order to provide recoverable storage of more than 800 million gallons of water using a recovery efficiency of 65 percent. This wellfield would require 9 wells and uses a spacing of 400 feet. The wellfield would provide 7 million gallons per day (MGD) of additional freshwater for a period of 120 days.

10. For the first phase expansion a wellfield of 3 wells is recommend. This wellfield should provide about 2.4 mgd for a period of 120 days after 3 ASR cycles.

## 2.0 INTRODUCTION

### 2.1 Background Information

As the demand for potable water increases in Southwest Florida, utility companies and the South Florida Water Management District (SFWMD) are pursuing innovative methods for maximizing water resource availability. One method utilized by the SFWMD to encourage the development of alternative water supplies has been to provide funding for projects which demonstrate potential to meet the objective of increasing water supplies. This project received such support and was jointly funded by the Big Cypress Basin Board of the SFWMD and Florida Water Services, Inc. (Florida Water Services) under the alternative water supply grants program. The project was undertaken to evaluate the viability of Aquifer Storage and Recovery (ASR) technology using excess surface water which is available in large volumes during only a portion of a typical year.

This pilot project was undertaken by Florida Water Services to supply the Marco Island potable water system with an increased amount of freshwater during the winter and spring months which constitute the dry season in south Florida. Marco Island is a rapidly developing resort community which currently has a permanent resident population of about 14,000 residents. However during the winter and spring tourist season, the population expands to approximately 40,000 residents. The combined impact of a lack of rainfall during the winter and spring months and the seasonal increase in population results in an increased seasonal demand for potable and irrigation water.

### 2.2 The Marco Island Water Supply System

There is no freshwater resource on Marco Island. Potable water is provided to the community from two sources. One source provides raw water from an abandoned limestone quarry (Marco Lakes) located adjacent to Henderson Creek Canal. This water is treated by conventional lime softening. A second source of water is a desalination plant (reverse osmosis) which is located on the island, and which treats brackish groundwater developed from deep wells.

The cost of producing and treating the freshwater source from Marco Lakes is much less than the cost of desalination. In addition, costs of desalination are expected to rise due to the continuously increasing salinity of the deep brackish water supply. In order to keep water production costs at the lowest level, it is desired to maximize the production of freshwater from the mainland.

### 2.3 The Advantages of Aquifer Storage and Recovery

This project was undertaken to increase the raw, freshwater supply to the island using Aquifer Storage and Recovery (ASR) technology. At this site, excess recharge water is pumped from the Marco Lakes and stored in a subsurface aquifer located 750 feet below land surface (bls). The stored water is later recovered for use during the dry season when the raw freshwater supply is low and when demands are high.

The Marco Lakes project is considered an excellent ASR candidate because:

1) In the wet season, excessive amounts of freshwater discharge into the Rookery Bay estuary down Henderson Creek Canal. The loss of the excess water can be reduced somewhat by an ASR project in this area.

2) Additional freshwater can be pumped to Marco Island using the existing pipeline and pumping system. The expanded use of existing pumping and transmission facilities maximizes use of the facility and minimizes costs associated with developing new supplies.

3) ASR would provide an emergency water supply in the event of a storm surge which might contaminate the freshwater source.

4) The ASR storage facilities can be constructed in an unobtrusive manner on the small amount of existing property.

### 2.4 Project Scope of Services

The work scope for this project is presented in the following phases:

**Phase I, Exploratory Drilling and Testing**. The purpose of Phase I was to identify the specific hydrogeology of the site and to select the best subsurface interval for storing the water. Geological and flow test data, collected during the construction of the exploratory well, were used to select the ASR storage interval and to choose the geological markers required to identify the target interval. Phase I concluded with the completion of the exploration well as a dual zone monitor well.

**Phase II, ASR Well Construction, Well Testing, and Construction of Surface Facilities**. The work provided under this phase included the construction of the ASR well and the performance of certain tests and analyses. In addition, the surface facilities for pretreatment of the water were designed and constructed during this phase.

**Phase III, Cyclic Testing**. ASR cyclic testing involves pumping water into storage and then recovering the water while monitoring system performance to evaluate the operational efficiency. Phase III was initially proposed to cover one 100 million gallon cycle of injection storage and recovery. However, a smaller volume initial cycle and two additional cycles were performed to collect additional information concerning system performance.

**Phase IV, Wellfield Design.** Wellfield design criteria are provided in Section 8 of this document. The design criteria developed in this document are based on solute transport modeling, pressure buildup, and field test data.

# 3.0 HYDROGEOLOGY

## 3.1 Geology

This description of the geology and groundwater hydrology of the project site is based on analysis of drill cuttings, geophysical logs (Appendix 3.1), and hydraulic tests conducted for the pilot ASR project. Lithologic logs for the pilot ASR well (CO-2428) and dual zone monitor well (CO-2427) are provided in Appendix 3.2. The deepest depth penetrated on-site was 817 feet below pad level (bpl) in the borehole of the exploration well (well CO-2427). A schematic hydrostratigraphic column for well CO-2427 is provided in Figure 3-1.

The geologic formations identified range in age from Holocene to Oligocene. They consist of undifferentiated Quaternary deposits, the Tamiami Formation, the Peace River and Arcadia formations of the Hawthorn Group, and the Suwannee Limestone Formation. Lithologic characteristics of these units are described below. The ASR storage zone, which extends from 740 to 790 feet bpl, occurs within carbonate rocks in the basal portion of the Arcadia Formation and the uppermost strata of the Suwannee Limestone.

### Undifferentiated Quaternary Deposits

Undifferentiated sediments of Pleistocene to Holocene age, averaging less than 10 feet thick, form the uppermost strata at the site. These surficial deposits consist mainly of quartz sand, but may also include shell beds, marl, and sandy limestone.

### Tamiami Formation

The Pliocene age Tamiami Formation unconformably underlies the undifferentiated surficial sediments. The Tamiami can be subdivided into upper and lower limestone units (Pinecrest and Ochopee members), which are separated by a gray to green marl or marly limestone (Bonita Springs member). The combined thickness of the Tamiami Formation is over 100 feet. The limestones generally exhibit good to excellent moldic porosity, and become more quartz sandy with depth. The Bonita Springs marl is typically less than 20 feet thick in the area and thickens from south to north.

### Peace River Formation (Hawthorn Group)

The predominantly Miocene-age Hawthorn Group in south Florida is divided into an upper unit of mainly siliciclastic sediments, referred to as the Peace River Formation; and a lower unit consisting predominantly of carbonate rocks, termed the Arcadia Formation (Scott, 1988). The Peace River Formation extends from about 140 to 290 feet bpl at the project site. The upper sediments of the formation consist mainly of unconsolidated quartz sand, variably indurated sandstone, and sandy limestone. The sands are underlain by finer-grained sediments that include dolosilt, lime mud, and sandy clay. Phosphatic sand and gravel are common throughout the Peace River Formation.

### Arcadia Formation (Hawthorn Group)

The top of the Arcadia Formation is marked by the occurrence of light gray to white, phosphatic limestone at a depth of 293 feet in the exploration well. The base of the formation is picked at 755 feet. Limestones below this depth are assigned to the Suwannee Limestone, because they are non-phosphatic, calcarenites and biomicrites that exhibit low natural gamma radioactivity (refer to Figure 3-1).

The Arcadia Formation consists of an interbedded sequence of phosphatic carbonate rocks and lime mud. Porosity of the limestones is variable, tending to be best developed where fossil shell has dissolved to form molds. The lower portion of the Arcadia Formation contains thick sequences of marl and marly limestone that form the confining beds above the ASR storage zone.

Suwannee Limestone Formation

The Suwannee Limestone Formation is early to middle Oligocene in age. About 62 feet of the formation was penetrated in the exploration well. The upper 45 feet of strata consist of pale orange, calcarenite or biomicritic limestones with good to excellent moldic porosity and low gamma activity. The underlying sediments penetrated consist mainly of marl and marly limestones with low apparent permeability.

## 3.2 Aquifer Designations

The aquifers and confining units identified at the site are illustrated on Figure 3-1. The major aquifer systems present include the surficial aquifer system, consisting of the water table and lower Tamiami aquifers; the intermediate aquifer system, which includes a series of aquifers and confining units within the Hawthorn Group; and the upper Florida aquifer, which occurs within a thick sequence of Oligocene to Eocene age carbonate rocks.

Two principal aquifers are generally recognized in the Arcadia Formation; the mid-Hawthorn and lower Hawthorn aquifers. Both of these broad hydrostratigraphic units can be further subdivided into more discrete water-yielding zones. The basal 15 feet of the Arcadia Formation at the project site is included in the upper Floridan aquifer, because these sediments are in direct hydraulic communication with permeable carbonate rocks in the upper portion of Suwannee Limestone.

Fresh water resources in the site area are generally limited to the water table aquifer and the upper portion of the lower Tamiami aquifer. Groundwater in deeper aquifers is brackish or saline, and requires desalination for potable and most other uses.

### 3.3 Storage Interval Description

The ASR storage interval occurs within permeable limestones present in the lower 15 feet of the Arcadia Formation and the upper 50 feet of the Suwannee Limestone (740 to 790 feet bls). Flow log data indicate that the limestones are most productive near the top of the storage zone, and somewhat less permeable with depth. Native groundwater in the storage interval and overlying aquifers is most appropriately classified as G-II (Section 3.5).

The confining beds overlying the storage zone consist of about 120 feet of low permeability lime mud and marly limestones that are mixed with interbeds of more permeable carbonates in the lower portion of the Arcadia Formation. Natural gamma activity is generally high within this interval (Figure 3-1).

Some lime mud and a decrease in porosity is reported for the drill cuttings from 797 to 811 feet bpl in the exploration well (CO-2427). The flow log and video survey of the well show the presence of confinement below the storage zone more clearly than the cuttings, apparently due to wash-out of the clay-sized fraction during drilling. The video survey indicates that clayey sediments actually extend from 790 to 814 feet bpl. No measurable flow was recorded by the flow log below 785 feet, with the exception of a minor flow zone at about 802 feet. A peak in gamma activity between 800 and 808 feet is another good indicator of clayey sediments and the presence of basal confinement.

### 3.4 Structural Geology

A subsurface structure contour map depicting the top of the Suwannee Limestone in southwestern Collier County was included in the supporting document for the pilot

ASR well construction permit application (ViroGroup, 1995a). The presence of a structural high feature resembling an anticline in shape, with an axis that trends northwest/southeast roughly parallel to US 41, is indicated from this work. The top of the Suwannee Limestone at the Marco Lakes based on regional data is shown to occur at approximately 735 feet below sea level (bsl). The actual pick for the top of the formation is 755 feet bpl, or approximately 745 feet bsl.

No known, suspected, or mapped faults have been reported in the Marco Lakes area.

### 3.5 Native Water Quality

The base of the underground source of drinking water (USDW), defined in applicable state and federal regulations as 10,000 mg/l total dissolved solids, was not penetrated at the project site. The USDW was picked at a depth of 1,095 feet in well CO-2080, located about 2 miles south of the Marco Lakes, and at 885 feet in well RO-15 on Marco Island (ViroGroup, 1996b).

As discussed in Section 5, flow tests were performed on the mid-Hawthorn Zone I, the lower Hawthorn Zone I, and the ASR storage interval during the construction of the exploration/monitor well. A flow test was also performed on the ASR well after drilling was completed.

Table 3-1 provides a comparison of measured water quality values for aquifers that exist below 300 feet at this site. These data show that there is only a minor change in salinity over the subsurface interval between 300 and 800 feet bpl where chloride concentrations ranged between 2520 ASR interval and 3750 mg/l. An evaluation of how the native formation water within the storage interval compared with U.S. EPA drinking water standards is provided in Appendix 3.3. The analyzed data show that the native water does not contain constituents at sufficient concentrations to preclude the use of the recovered water. The brackish nature of the water in the storage interval was anticipated. Additional data concerning recovered water quality are provided in Section 7 which addresses the cyclic testing.

# 4.0 WELL CONSTRUCTION PROGRAM

Topics covered in this section include site preparation, construction of drill pads and pad monitor wells the exploration/monitor wells, construction of the ASR well, and the construction of a shallow well identified as the Tamiami well. This well is installed as a condition of the FDEP permitting process.

## 4.1 Site Preparation

### 4.1.1 Produced Water Discharge

Prior to beginning construction of the exploratory well, a trench (Figure 4-1), lined with heavy duty landscape fabric and reinforced visqueen, was constructed to act as a storage and settling area for water produced from the well during reverse-air drilling and aquifer testing. An 8-inch diameter SDR 26 PVC pipeline was installed to convey the produced water from the trench to a point downstream of the Henderson Creek weir located at the intersection of the Henderson Creek Canal and U.S. 41 (Figure 4-1). A letter notifying the FDEP of the intended discharge was submitted on November 7, 1995 along with results of the water sample analysis. An additional sample analysis was submitted to the FDEP within the allotted 30 day time period. All tests showed that the produced water was within the regulatory limits for discharge. Based on the above information, discharge below the weir at Henderson Creek was permitted under the State of Florida's Generic NPDES permit for the discharge of produced water from a non-contaminated site activity. A high capacity discharge pump was used to pump the produced water from the retention trench to the Henderson Creek Weir through the 8-inch pipeline.

#### 4.1.2 Drill Pad Construction

A drilling pad with a one foot high containment wall was constructed at each well site as indicated in Figure 4-2 to contain water at the wellhead and around the drilling rig. Two pad monitor wells were installed at each drilling pad to monitor for excess spills and leakage of salt water from the pad. The containment was removed once construction of the wells was completed. Figure 4-3 provides a schematic of the pad monitor wells.

### 4.2 Exploratory/Monitor Well Construction

Actual well construction began on September 27, 1995. Weekly summary reports were prepared throughout well construction and are included in Appendix 4.1. Well construction began with the installation of the 16-inch diameter steel pit casing into a 22-inch nominal wellbore drilled to 15 feet. The 16-inch diameter casing was set at a depth of 13.5 feet below pad level (bpl) and grouted in place using neat portland cement.

#### 4.2.1 Surface Casing Installation

After the installation of the pit casing, a nominal 16-inch diameter bit was used to drill to a depth 300 feet bpl. After the completion of the nominal 16 inch borehole, an electrical resistivity log was run. At this point the well began to flow. A cement plug was then placed in the bottom of the hole to stop the flow. The hole was reopened to a depth of 297 feet bpl and 10-inch diameter, schedule 80 PVC casing was run to a setting depth of 293 feet bpl. The annulus was grouted with neat portland cement grout in three stages. A total of 161 sacks of cement grout were placed in the annulus.

### 4.2.2 Deep Zone Monitor Casing Installation

Drilling from the base of the 10-inch casing started on November 7, 1996 with a 9 7/8-inch bit using the reverse-air method. At 313 feet bpl, a large flow zone was encountered which exceeded the capacity of the reverse-air discharge system to convey the flow to the trench. The drill rods were removed from the hole and the well was shut-in to control the flow. A stripper head assembly was obtained to control the flow from the wellhead during emergency flow conditions. Actual wellhead flow was controlled as necessary by the addition of salt to the well during drilling.

Drilling continued to 399 feet bpl when a flow test was conducted. After the completion of the first flow test (Section 5.1), the borehole was advanced to 622 feet bpl. The second flow test was conducted in the well with a packer set at 550 feet bpl. At the completion of the flow test, drilling resumed to 679 feet bpl when coring was attempted with a 3-inch diameter core barrel (2 1/2-inch core diameter). The core recovery was only 15% of the 10 foot interval cored. Coring resumed at 689 feet bpl to 699 feet bpl. This 10 foot interval yielded a core recovery of 85%. The borehole was advanced to 699 feet bpl where drilling resumed to 720 feet when another core was attempted. No sample was recovered from the 10 foot cored interval. The drilling continued from 730 feet to 744 feet when another core was attempted. No sample was recovered. Based on previous success in obtaining a second core in a previously cored hole, a fifth coring attempt was made between 754 and 764 feet. Approximately 1.2 feet (12%) of the core was recovered. Drilling resumed from 764 feet to the total depth of the well at 817 feet bpl.

Caliper and gamma survey logs (Appendix 3.1) were run in the borehole to determine the characteristics of the subsurface sediments and aid in determining the casing setting depth. The depth selected for setting the final casing string, based on analyses of the geophysical logs and drill cuttings, was 745 feet. The original proposed well completion called for a string of 4-inch diameter casing set and cemented in place to land surface. However, because 6-inch diameter casing was available from the flow test of the upper zone and since additional testing and sampling of the permeable interval at approximately 300 feet was warranted, the well design was modified. The design modification, which was approved by FDEP, called for 6-inch black iron casing to be set at 745 feet bpl with the annulus grouted from the base of the casing to approximately 350 feet bpl. This design resulted in a dual-zone monitor well completion designed to monitor the mid-Hawthorn Zone I and the ASR storage zone. Specifications for the casing strings provided for the monitor well appear in Appendix 4.2. Figure 4-4 provides a diagram of the exploratory well, and Figure 4-5 provides a schematic of the wellhead for the monitor well. Tables 4-1 and 4-2 provides the casing summaries for the surface and longstring casing respectfully.

The 6-inch casing was set in the well with a cement basket placed at 745 feet bpl. The cement basket was set 1.7 feet above the bottom of the casing. After setting the casing a small stage of neat portland cement was pumped through a tremmie on top of the basket. The following day a tremmie line was run in the annulus to continue cementing. However, no fill was measured above the cement basket. A gamma log was run inside the 6-inch pipe to tag the bottom and to compare the log with previous logs. The log and bottom tag indicated that the cement had gone past the basket and filled 4 feet of the open-hole. It was decided to place coarse sand to fill in the open-hole before resuming cementing. The annulus was grouted in 6 stages with neat portland cement up to 352 feet (146 sacks). The sand in the open-hole was removed by reverse air circulation and the wellhead was installed.

## 4.3 ASR Test Well Construction

Actual well construction for the ASR test well began on May 24, 1996. Weekly summary reports were prepared throughout well construction and are included in Appendix 4.1. Construction began with the installation of the 24-inch diameter surface casing.

### 4.3.1 Surface Casing Installation

A nominal 30-inch diameter bit was used to drill to a depth of 44 feet bpl. After the completion of the nominal 30-inch borehole, 42 feet of steel casing was run to a setting depth of 40 feet bpl. The annulus was grouted with neat portland cement grout in one stage. A total of 40 sacks of neat portland cement was used to pressure grout the casing in place.

### 4.3.2 Production Casing Installation

After the completion of the surface casing installation, the top of the 24-inch casing was cut-off flush with the pad and a stripper-head assembly was installed on the well. Drilling of the 24-inch pilot hole began by the mud rotary method on May 29, 1996 with a nominal 12-inch bit from the base of the 24-inch casing. The borehole was advanced to a depth of 752 feet bpl. Inclination surveys were performed every 90 feet (Table 4-3).

Electrical resistivity and a gamma survey (Appendix 3.1), were run in the borehole to determine the characteristics of the penetrated sediments and to aid in determining the casing setting depth. The depth selected for setting the final casing string, based on analyses of the geophysical logs and drill cuttings, was 745 feet.

A 23 1/2-inch stepped bit was used to ream the pilot hole. The pilot hole was reamed to a depth of 750 feet bpl (752 feet bpl from the end of the lead bit).

The casing string which consisted of 593 feet of 12-inch schedule 80 PVC at the bottom of the string and 152 feet 16-inch schedule 80 PVC at the top was set in the well at 745 feet bpl. Table 4-4 provides a tally of the casing installed in the borehole. Specifications for the casing string provided for the ASR well are provided in Appendix 4.3. The first stage was pressure grouted with 160 sacks of neat portland cement. The remaining annulus up to land surface was cemented in 4 additional stages with 262 sacks of portland cement with 12% bentonite. Temperature logs were run after stages 2 to 5 and are provided (Appendix 3.1).

### 4.3.3 Open-hole Construction

After cementing the production casing in place, the drilling of the open-hole was initiated. The open-hole was drilled with a 10 3/4-inch bit to a depth of 790 feet bpl. The top of the lower confining unit was encountered at a depth of 787 feet bpl and was determined by the examination of drill cuttings. The borehole was advanced three additional feet to verify the presence of the lower confining unit. A well construction diagram is provided as Figure 4-6.

### 4.3.4 Well Development

Reverse air circulation was used through the drill string to remove the drilling mud from the well until the well began to flow. All water produced during development was discharged to the settling trench and then pumped down the 8-inch discharge line to a point downstream of weir on Henderson Creek.

Air development of the well began through drill pipe set to 100 feet bpl. The well was air developed with periodic surging for 5 hours and then allowed to flow for an additional 8 hours. A water sample was taken at the completion of development and analyzed for chlorides and conductivity. The measured chlorides were 2,520 mg/l and the conductivity was 6,000 umhos/cm.

### 4.3.5 Pump Installation and Wellhead Completion

At the completion of the well, a 16-inch tee with reducer was placed on the 24-inch flange on the top of the surface casing. On August 21, 1996 a vertical shaft turbine pump was installed in the well. During pump installation the well was allowed to flow through piping installed from the side of the tee to the settling trench. The water from the trench was conveyed through the discharge pipeline to a point downstream of the weir.

A three stage pump was installed with the intake set to a depth of 145 feet bpl on 10-inch diameter steel drop pipe. The electric pump motor is 75 horsepower and the pump system is rated at 1800 gpm. A wellhead diagram is provided as Figure 4-7.

## 4.4 Tamiami Monitor Well

As part of the permitting process Florida Water Services was required to install a shallow well located at an approved site south of Marco Lakes. In order to meet these requirements, a 50 foot well (Figure 4-8) was drilled on the old road grade near the intersection of U.S. 41 and Henderson Creek downstream from the weir (Figure 4-9). The purpose of this well is to monitor for movement of more saline water into this zone.

## 5.0 FLOW TESTS AND ANALYSES

### 5.1 Mid-Hawthorn Zone I

The first flow and recovery test was conducted in the exploratory/monitor well in the mid-Hawthorn Zone I between the depths of 296 feet to 399 feet. Initially, a step rate test was performed to establish the approximate specific capacity of this interval. Table 5-1 summarizes the data obtained during this test. As indicated in Table 5-1, specific capacity values measured in this interval were 220 gpm/ft at 220 gpm, 201 gpm/ft at 401 gpm, and 171 gpm/ft at 600 gpm. When the specific capacity data are plotted against flow rate and the best fit straight line is extrapolated to zero flow rate (Figure 5-1), the estimated transmissivity can be calculated using the relationship of Walton (1970), provided by Driscoll (1986, p.558). This method utilizes the relationship between specific capacity (at zero flow rate) and formation transmissivity. The estimated transmissivity of the mid-Hawthorn Zone I at the Marco Lakes site using this relationship is approximately 500,000 gpd/ft.

A short term flow test was also performed to establish an approximate transmissivity for this interval. In this test, the well was allowed to flow at a constant rate of 600 gpm for a total of 180 minutes. At the completion of the flow test, the recovery data were collected for 180 minutes after the well was shut-in. The data from the recovery test was plotted semi-logarithmically as the difference in head from static conditions versus the total time since beginning of the flow test divided by the time since recovery was initiated. A graph of the data plot is included as Figure 5-2. A regression line from the plot of the data was chosen based on the final 2 hours of recovery. The slope of the line was estimated to be approximately 0.5 ft/cycle. Based on a slope of 0.5 ft/cycle, $\Delta s$, and a production rate, Q, of 600 gpm, the Hawthorn Zone I transmissivity, T, is calculated to be 317,000 gpd/ft.

### 5.2 Mid-Hawthorn Zone II

The mid-Hawthorn Zone II was not tested since this is the interval currently utilized by Collier County Utilities for their treated potable water ASR project. In order to avoid concerns of potential impact, this zone and was not considered as a storage interval for this project.

### 5.3 Lower Hawthorn Zone I

The second flow and recovery test in the exploratory/monitor well was conducted over the subsurface interval between 550 and 622 feet bpl. This interval was also considered to be a potential target ASR interval. However, once the zone was isolated, the well was found to be capable of only flowing at a constant rate of 5 gpm. Therefore, a constant rate flow test was conducted over this interval at a flow rate of 5 gpm for 4 hours. Recovery data were collected at the completion of the test. The data from the recovery test were plotted semi-logarithmically as the difference in head from static conditions versus the total time since beginning of the flow test divided by the time since recovery was initiated. A graph of the data plot is included as Figure 5-3. A regression line from the plot of the data was chosen based on the later portion of the recovery. The slope of the line was estimated to be was approximately 3.8 ft/cycle. Based on a slope of 3.8 ft/cycle and a production rate of 5 gpm, the Lower Hawthorn Zone I transmissivity is calculated to be 350 gpd/ft.

The estimated transmissivity of this zone was too low to consider use of this zone as an ASR interval.

### 5.4 ASR Storage Interval - Exploratory/Monitor Well

The flow and recovery test performed on the ASR storage interval was conducted from the open-hole portion of the well (745 feet to 811 feet bpl) after setting the 6-inch steel casing at 745 ft bpl. This aquifer performance test was conducted at a flow rate of 187 gpm for a period of 4 hours and 35 minutes. Recovery flow data were collected at the completion of the flow portion of the test. The data from the shut-in recovery test were plotted semi-logarithmically as the difference in head from static conditions versus the log of the total time since beginning of the flow test divided by the time since recovery was initiated. A graph of the data plot is included as Figure 5-4. A regression line from the plot of the data was chosen based on the later portion of the recovery. The slope of the line was approximately 0.81 ft/cycle. Given a slope of 0.81 ft/cycle and a production rate of 187 gpm, the ASR storage interval transmissivity was calculated to be 61,000 gpd/ft.

### 5.5 ASR Storage Interval - ASR Well

A flow and recovery test was performed on the ASR storage interval in the open-hole portion of the ASR well (745 feet to 790 feet bpl) after setting the 12-inch/16-inch production casing at 745 ft bpl. The aquifer performance test for this unit was conducted at a flow rate of 463 gpm for a period of 8 hours and 20 minutes. Data were collected in the ASR well and exploratory/monitor well using pressure transducers and data loggers. Recovery (shut-in) data were also collected in both wells at the completion of the flow portion of the test.

The time versus drawdown data collected from the flow test were plotted on log-log graphs for the ASR well data (Figure 5-5) and the monitor well data (Figure 5-6). The plot of the data from the monitor well was compared to type-curves to determine a match-point for use in the analysis of aquifer parameters. A suitable match-point was determined from the monitor well data and an analyses of aquifer parameters was undertaken. A transmissivity of 68,000 gpd/ft was calculated for this interval.

A leakance value of 0.005 gpd/ft$^3$ was calculated from the value of the transmissivity determined in the previous equation and the relationship developed by Hantush and Jacob (1954). Aquifer storage was calculated to be 6.5 x $10^{-5}$.

The data from the recovery test were plotted semi-logarithmically for each well as the difference in head from static conditions versus the log of total time since beginning of the flow test divided by the time since recovery was initiated. A graph of the data plot from the ASR well is included as Figure 5-7. A regression line from the plot of the data was chosen based on the later portion of the recovery. The slope of the line was approximately 1.0 ft/cycle. Based on a slope of 1.0 ft/cycle, $\Delta s$, and a production rate, Q, of 463 gpm, the ASR storage interval transmissivity, T, is calculated to be 122,000 gpd/ft.

A semi-logarithmic graph of the recovery data plot from the monitor well is included as Figure 5-8. A regression line from the plot of the data was chosen based on the later portion of the recovery. The slope of the line was estimated to be was approximately 1.33 ft/cycle. Based on a slope of 1.33 ft/cycle, $\Delta s$, and a production rate, Q, of 463 gpm, the ASR storage interval transmissivity, T, was calculated to be 91,900 gpd/ft.

The data provided in Table 5-2 provides the final values chosen to describe the various aquifers at this site. These values are taken directly from the field data and form the basis for the flow and transport modeling.

## 6.0 SURFACE TREATMENT FACILITY DESIGN AND PERFORMANCE

The surface equipment installed at this site for this project were designed to treat the injected water with 3 to 5 mg/l sodium hypochlorite to eliminate or reduce coliform activity to 4 colonies/100 ml or less. The equipment was also designed to control the injection pressure and to filter suspended solids from the injected water. Equipment details are provided in Appendix 6.1. A diagram identifying the location of the various units is provided in Figure 6-1.

### Chlorination System

The chlorination system consists of a 1000 gallon storage tank containing 11 to 12% sodium hypochlorite rented from Allied Chemicals and a metering pump that discharges the concentrated hypochlorite solution directly into the filtered injection stream. Chlorination was performed downstream of the filters to reduce the volume of chlorine required to treat filterable, organic material that may be present in the water.

### Pressure Control

Pressure control was required to limit the pressure on the filters and at the ASR wellhead. Therefore, a pressure control valve was utilized to reduce the line pressure provided from a maximum of 150 psi to less than 100 psi.

Automatic control of the pressure reducing valve was provided by a 1/4-inch bypass line, a pilot valve, and an in-line orifice. The valve design required that a small fraction of water flow around the control valve and through the 1/4-inch bypass line.

Since the automatic control valve was required to control the maximum pressure on the filters, it was located upstream of the filters. Thus, suspended solids within the unfiltered raw water would periodically plug the 1/4-inch bypass line. As the flow in the bypass tubing was reduced, the control valve would open further. The opening of the control valve would allow pressures higher than the downstream set pressure to be reached at the filters. The pressure control problem was resolved by the installation of low flow rate cartridge filters in the 1/4-inch bypass line upstream of the orifice and pilot control valve. The installed filters on the bypass line were routinely changed on a weekly basis. Good pressure control was maintained over Cycles 2 and 3.

### Filtration

Filtration of the full injection stream was provided by a pressure sand filter system (Appendix 6.1) capable of filtering water at rates up to 1750 gpm. The filters were set to automatically backwash once a day or when differential pressure across the filters reached 16 psi. The once a day backwash setting was sufficient for tests performed for this project.

### Injected Water Quality

Table 6-1 provides a summary of the measured water quality obtained during injection. From a regulatory perspective, the three major water quality parameters for this site are coliform presence, THM concentration, and color. From an operational perspective, the presence of suspended solids and chemical precipitation during injection were considered critical.

### THM Concentrations

The data provided in Table 6-1 show that THM values averaged 75 ug/l with a median value of 52.1 ug/l. The highest value measured during this period was 409 and was taken at the end of the injection cycle immediately prior to shut-in. The chlorine level was increased at this time in preparation for well clearance activities that were required when the well was cycled for recovery.

### Coliform Activity

Cyclic test results indicate that the proposed disinfectant dosage rate is sufficient to reduce total coliform levels to applicable injection standards. Some interpretation of the test data is required due to variations in the analytical methods used. Coliform activity was not detected in the injected water when the analyses were performed by the membrane filter (MF) method. This method is used to quantify the number of bacteria colonies. When the non-quantitative "MMO-MUG" method was used, one laboratory generally reported coliform present, while another laboratory consistently reported them absent.

Experience at other sites indicates that the MMO-MUG method is subject to false positive responses, which may explain the detection of coliforms reported by one laboratory only. It is not possible by the MMO-MUG method to determine whether coliform concentrations, if present, exceed the 4 col/100 ml standard. Therefore, the MF filter method is more appropriate, and should be used in future monitoring of the ASR system. No fecal coliform bacteria were detected in any of the injected water samples.

### Color

Color values of the injected water range from 17 to 30 c.u., with an average value of 21 c.u.. As indicated in Table 6-1, a progressive color increase occurred during cycle 2 injection. This may represent a seasonal trend related to declining rainfall and lake recharge rates. Actual color levels are much lower than the approved limit of 100 c.u.'s used in solute transport modeling performed to predict color impacts during the cyclic tests (ViroGroup, 1995a). The data provided in Table 7-4 show that no significant change in color was observed at the monitor well although the water contained a high fraction of injected water. Based on the chloride concentration, the color of the recovered water at the monitor well should have reached a value of 8 c.u. or higher. This suggests that the movement of these natural color units is retarded in this aquifer.

Suspended Solids

In the initial stages of Cycle 1, injectivity dropped dramatically. The rapid drop in injectivity generated concerns over the appropriate selection of filters for the selected ASR storage interval. However, as indicated in Appendix 6.2, the total suspended solids concentration in the filtered water was less than 2 mg/l. This level of suspended solids is not sufficient to cause the observed problem.

Two attempts were made to redevelop the ASR well for injection by back flowing and surging the ASR well. Although back flowing the wells increased injectivity, the well injectivity rapidly decreased with injection. At this point, the project team determined that the best option for reducing the plugging was to acidize the well. However, due to a number of complications, a standard acid treatment was not proposed for this well. Instead, it was determined that the pH of the water should be lowered so that minor dissolution of the formation would occur and the precipitation of metal compounds such as calcium carbonate might be retarded. This process was implemented successfully. As indicated in Figure 7-1, the injection of water with a reduced pH was able to increase injectivity and eliminate well plugging.

Additional discussion of the impact of adjusting the pH of water from 8.3 to 7.9 are presented in Section 7.

## 7.0 CYCLICAL TESTING

The Aquifer Storage and Recovery (ASR) cyclical testing at Florida Water Service's Marco Island Raw Water Supply Lakes (Marco Lakes) site has been accomplished using three injection/recovery cycles to evaluate the suitability of the selected aquifer as an ASR storage unit.

Cycle 1 was begun on June 26, and completed on August 19, 1997. A total of 19.7 million gallons (MG) were injected and 6.0 MG were recovered during the first cycle. The recovery efficiency of the first cycle was 22% at a cut-off concentration of 250 mg/l dissolved chloride, and 30% at 350 mg/l.

The volume of water injected during the second cyclic test was 86.6 MG. The second cycle was initiated immediately after the completion of the first cycle. After injection was concluded, the ASR well was shut-in from November 17, 1997 to January 16, 1998. The second recovery cycle was completed on February 25, 1998 after 30.2 MG were recovered. The recovery efficiency of the second cycle was 5% at 250 mg/l dissolved chloride and approximately 30% at 350 mg/l.

Since the results from Cycle 2 were not anticipated, a third cyclic test was undertaken to evaluate the recovery efficiency of a non-plugging well and the change in efficiency after multiple cycles using a volume comparable to the first cycle. A total of 21.0 MG were injected and 17.2 MG were recovered. The recovery efficiency of the third cycle was 39% at a cut-off concentration of 250 mg/l and 75% at a cut-off concentration of 350 mg/l. Table 7-1 provides data on the injection/recovery cycles beginning and ending dates, total volumes, and a monthly summary of rates and volumes.

## 7.1 ASR and Dual Zone Monitor Well Water Quality and Data

Native Water Quality

Base water quality values for the primary and secondary drinking water standards for the ASR storage interval and the upper monitor interval are provided in Table 7-2. The data provided in this table shows that all drinking water standards appear to be met by the native water with the exception of sodium (1650 mg/l), chloride (2600 mg/l), sulfate (718 mg/l), TDS (5620 mg/l), and radioactivity (24.5 picocuries/liter). The magnitude of these values, as addressed in the next section, will have little impact upon the water recovered which contain less than 400 mg/l chlorides.

Water Quality - ASR Well

The data collected at the ASR well for injection and recovery are provided in Table 7-3. These data show that the recovered chloride concentration remained below 400 mg/l, the THM concentration remained on the order of 1 ug/l, and the color of the recovered water remained less than the average of 23 c.u. for the injected water and decreased from the maximum value as the recovered volume increased. A review of the radionuclide results indicate that the background level in the native formation water is approximately 24 piC/l and less than 8 piC/l in the injected water. The radioactivity in the recovered water was less than 15 piC/l except for the water sample collected at the end of Cycle 2 (22 piC/l).

Deep Monitor Zone Water Quality Data

Table 7-4 presents the analytical data for the water samples collected from the deep monitor well. These data show that chemical constituent concentration vary in an manner consistent with injection and recovery cycles. It is relevant to note that the color of the water recovered at this well remained less than 6 c.u. and is similar in color to the water recovered from the shallow monitor well. The injected water average of 23 c.u.. It would appear that there is significant retardation of the movement of color within the ASR storage interval based on these data.

THM concentration levels at the deep monitor well remained less than 25% of the MCL value of 100 ug/l. These values fall well within the drinking water standards.

The radioactivity of the water recovered from the deep monitor well decreased as the injected volume increased. These data indicate that little to no radioactive materials are being solubilized while the injected water is being stored. Thus, gross alpha levels are anticipated to remain below the regulatory level of 15 PCi/l. However, the operational need to provide a 50/50 mixture of the ASR water with the surface water assures that the radioactivity standard of 15 PCi/l will not be exceeded.

### Shallow Monitor Interval - Mid-Hawthorn Zone I

Table 7-5 provides the water quality data from the shallow monitor zone. The data collected from this interval is extremely important since there is little probability that this interval could be contaminated by injection into the ASR storage interval except through the existing casing. Thus, measured concentrations from this well should reflect more on the analytical techniques rather than the quality of water.

A review of the Table 7-5 data shows that coliforms were present at the end of cycle 1 injection and at the start of Cycle 1 recovery. Similar observations were made for the deep monitor well and the ASR well. However, no other coliform activity was noted before or after this time. The lack of coliform activity after this period clearly indicates that these were false positive readings since coliform activity would be expected to increase with time.

The maximum THM concentration level measure in this well was 39.9 ug/l. However, the median value was <0.5 ug/l and 16 of the 22 measured concentration levels were recorded to be 0.5 ug/l or less. No pattern was observed for the measured THM levels that was consistent with the cyclic activities conducted at the ASR well. Thus, the reported concentrations, which fall below the MCL value of 100 ug/l, are high and do not reflect actual aquifer THM concentrations.

The current data sets indicate that water color and THM do not migrate into the shallow monitor interval.

**TAMIAMI WELL**

No change in water quality has been observed at the Tamiami well (Appendix 7.1).

## 7.2 Cyclic Testing

### 7.2.1 Cycle 1

Cycle 1 Injection

Cycle 1 injection commenced on June 26, 1997. Table 7-6 and Figure 7-1 provides a summary of injection pressures, rates, and specific injectivity reported during Cycle 1 injection. The initial injection rate was approximately 1100 gpm at and injection pressure of 69 psi (specific injectivity = 8.1 gpm/ft). However, soon after injection started, the injection rate fell to 520 gpm (specific injectivity = 3.7 gpm/ft). The injection rate continued to decline to 185 gpm (specific injectivity = 1.4 gpm/ft) over the next five days. At the end of this five day period, 3.18 MG of water had been injected in the well. At this point, the well was back flowed and surged at rates in excess of 1300 gpm to increase injectivity. After the backwash operation, injection was re-initiated. The injection rate returned to 520 gpm at an injection pressure of

69 psi (specific injectivity = 3.82 gpm/ft). Injection then continued until July 10, 1997 when the injection rate had gradually been reduced to 395 gpm at 66 psi due to plugging. On July 10, the system was shut down for repair. During the shut-down period, a stimulation treatment using hydrochloric acid (HCl) was planned and implemented.

On July 21, 1997, injection into the well was re-initiated along with the injection of 10 Molar HCl at a rate of 500 ml/600 gals of water. The pH of the injected water ranged between 6.4 and 6.8. As can be seen in Figure 7-1, the injectivity increased almost immediately after injection of the acid started. The flow rate after the first few hours of injection increased to 900 gpm at 58 psi which correlates to a two-fold increase in injectivity. Based on these results, a decision was made to continue to inject the acid at the current rate rather than to lower the pH of the injected water further. On July 24, the acid injection rate was reduced to 250 ml/900 gal with a commensurate increase in the pH of the injected water to 7.4. On July 28, 1997, the injection rate of the acid was reduced to 62.5 ml/900 gal. The pH increased to approximately 7.8. As can be noted in Figure 7-1, the injectivity continued to increase during the entire period when acid was being added to the injection stream. The final injectivity exceeded 9 gpm/ft in the last stages of this injection cycle.

<u>Cycle 1 Recovery</u>

The recovery began immediately following completion of injection on August 4, 1997. However, upon start-up it was determined that the discharge line from the wellhead required repair. The re-start of recovery cycle was delayed until August 7 to repair the discharge line. Table 7-7 presents a summary of the water quality data and flow data obtained during this cycle. As indicated in Table 7-7 and Figure 7-2, recovery of water proceeded at a fairly steady rate. Recovery efficiency is defined as the volume of water recovered divided by the volume of water injected during that cycle.

The recovery efficiency of the first cycle was determined to be 22% (4.4 MG) at a cut-off concentration of 250 mg/l. The recovery efficiency at a cut-off concentration of 350 mg/l was 30% (6 MG).

### 7.2.2 Cycle 2

Cycle 2 Injection

The Cycle 2 injection cycle began on August 21, 1997, two days following the completion of the first recovery cycle. Table 7-8 summarizes the injection pressures, rates, and specific injectivity measured during the second injection cycle. Figure 7-3 graphical provides a representation of these data.

The Cycle 2 injection was conducted without acid injection to assess the effects of filtered raw water injection on specific injectivity over a full cycle. The initial flow rate at the beginning of injection was 1300 gpm at an injection pressure of 57 psi. The initial specific injectivity was 12 gpm/ft and reflects the injectivity reached near the end of Cycle 1. Injection continued until November 17, 1997 when the injection was stopped because of water demands on Marco Island. During the injection phase, specific injectivity, based on instantaneous readings, slowly declined from a high of approximately 12 gpm/ft to a low of 5.44 gpm/ft at the end of the cycle. Injection rates were variable throughout the cycle due to plugging and subsequent cleaning by back-washing of the well. Loss of productivity was considered to be caused by plugging at the face of the formation. Average flow rates declined each month of operation during Cycle 2. Injection decreased from 863 gpm in August to 505 gpm in November due to plugging (refer to Figure 7-3).

## Cycle 2 Recovery

Following the injection phase of Cycle 2, the well was shut in for two months until the recovery phase was initiated. A small volume of water was withdrawn on January 16, 1998 to test the pump and discharge system before full-scale recovery was initiated on January 19. Table 7-9 presents a summary of the water quality data and flow data obtained during this cycle. The initial recovery rate was set at approximately 1000 gpm (actual rates ranged between 820 and 1050 gpm). Chloride concentrations began to rise from 140 mg/l to 252 mg/l within three days. On January 22, the pump was shut down and the well was allowed to flow under artesian pressure. The recovery rate was reduced to 400 gpm. The rate was reduced to assess if the rise in chloride concentration was due to the higher pumping rate.

The recovery was continued at 400 gpm until February 10, when the chloride concentrations approached the 350 mg/l cut off. The rate of increase in chloride concentration had slowed from the rate of increase noted during the initial pumping (Figure 7-4). The rate was further reduced to 235 gpm to see if a further lowering of recovery rate would effect the change in chloride concentrations. The low rate injection was continued with an increase in chloride concentration noted until February 17 when the pump was restarted. A pumping rate of 920 gpm was initiated. A drop in the chloride concentration of almost 100 mg/l was noted within four hours. The chloride concentration began to increase over the next six days when the pumping rate was increased to the maximum rate of 1600 gpm. A lowering of the chloride concentration by about 40 mg/l was noted for two hours at this increased rate, however, the chloride concentration began again to rise at approximately the previous rate. Chloride concentrations fluctuated around the 350 mg/l level for 11 days. As determined by the total volume recovered at the time the chloride concentration exceeded the 350 mg/l level, the recovery efficiency is approximately 30%. The sensitivity of salinity to flow rate suggested that at least two permeable intervals were contained in the storage interval.

The low recovery efficiency during Cycle 2 was not expected based on the results obtained during Cycle 1. However, the poor results associated with Cycle 2 recovery were reasonably associated with the known plugging that occurred. A review of the data and computer modeling suggested that the most likely problem was that more than one separate permeable interval was open to injection and recovery. Preferential plugging of one interval during injection could account for the observed behavior. This conclusion was supported by the sensitivity of the water salinity to flow rate. Therefore, a third injection cycle was conducted to test this hypothesis. For the next injection cycle, the pH of the injected water was to be lowered using HCl to prevent plugging.

### 7.2.3 Cycle 3

Cycle 3 Injection

Injection began for Cycle 3 on March 5, 1998. Table 7-10 summarizes the injection pressures, rates, and specific injectivity measured during the third injection cycle. Figure 7-5 provides a graphical presentation at the Cycle 3 injection data. The change in water quality related to the pumping rates during the second cycle recovery phase and modeling conducted during that phase indicated that the injection interval contained at least two zones separated by minor confinement. The data also indicated that at least one of the zones was differentially plugged during injection. To reduce the possibility of differential zone plugging and to reduce the noted decline in specific injectivity, as indicated above, acid was added to the ASR injection stream during the third cycle. The acid concentration was used to lower the pH of the injected water by 0.3 to 0.8 pH units. The pH of the injected water was maintained between 7.5 and 7.8. Injection continued at an average rate of 560 gpm until March 31, when a total of 21.054 MG had been injected. The reduced injection rate during this cycle was based on water demand on Marco Island and not pressure limitations. Only slight plugging was apparent over this cycle.

Cycle 3 Recovery

Recovery of injected water for Cycle 3 began on April 2, 1998. Table 7-11 and Figure 7-6 presents a summary of water quality data for the recovered water and the flow data. A recovery rate of 440 gpm was continued throughout the cycle. A slight decrease in chloride concentration was noted initially, however, concentrations increased steadily during the cycle. The recovery was completed on April 29. A total of 17.2 MG were recovered. The recovery efficiency at the 250 mg/l cut off is determined to be 39% and 75% at the 350 mg/l cut off.

The greatly improved recovery efficiency obtained during Cycle 3 supports the conclusions from preliminary work that ASR can be successfully accomplished using the current storage interval. It also strongly indicates that plugging must be avoided during injection if sufficient recovery efficiency is to be maintained. The results of the testing indicate that adjusting the pH of the injected water to within the range of 7.5 to 7.8 should prevent the precipitation of compounds which caused the plugging problems on the test well. The use of HCl for adjusting pH is acceptable from an operational point of view. However, in the design process for the expansion of the system, other alternatives will be evaluated for preventing wellbore plugging.

## 8.0 DESIGN OF WELLFIELD EXPANSION

This section of the report addresses the final wellfield design and the modeling that was performed based on field data. The items addressed in Section 8 include:

- ASR Cyclical Test Performance
- Operational Considerations
- Model Selection
- Model Calibration
- Predictive Model Simulations and Results
- Recommended Design for the Expanded System

### 8.1 Cyclic Testing and ASR Performance

Three ASR cycle tests were performed on the ASR 1 well during this investigation. Each ASR cycle involved the injection, storage, and recovery of water while monitoring water quality. The first test included the injection of 19.76 million gallons (MG) and the recovery of 6.05 MG. The second test included injection of 86.7 MG and recovery of 30.2 MG. The third cyclic test consisted of injecting 21.05 MG and recovering 17.23 MG. The cyclic volumes injected and recovered, and the recovery efficiency for each cycle is reported in Table 8-1.

Cyclic recovery efficiency is defined as:

$$\frac{\text{Volume of water recovered at or below the cut-off limit}}{\text{Volume injected during that cycle}} \times 100\%$$

Figures 7-2, 7-4, and 7-6 provide a graphical representation of the variation in chloride concentration with the volume of recovered water during each cycle. These figures can be used to estimate the chloride concentration at any recovered volume.

These data can also be used to calculate the recovery efficiency based on any specified cut-off chloride concentration for the recovered water.

## 8.2 Design Considerations

The following operational issues were considered during this modeling effort:

| | |
|---|---|
| Recharge (Injection) Rate: | Based on the performance of ASR-1, the maximum recharge rate was set at 1.7 MGD per well and the average recharge rate was set at 1.5 MGD per well. |
| Recovery Rate : | For modeling purposes, the recovery rate was set at 1.5 MGD per well. |
| Period of Recharge: | The recharge period for these calculations was assumed to be 100 days. This time period represents the availability of water during the rainy season and will likely be extended or contracted depending on rainfall. |
| Cyclic Storage Volume: | The cyclic well storage volume was set at 150 MG per well. This volume was selected because it represents the volume of water that could be injected into each ASR well at 1.5 MGD for a period of 100 days. |
| Recovered Water Quality Limits: | In order to estimate recovery efficiency, two chloride concentrations, 250 mg/l and 350 mg/l, were defined as cut-off concentrations. The first value, 250 mg/l, represents the primary drinking water standard and |

the water that can be recovered without blending. The second value, 350 mg/l, represents the chloride concentration that, when mixed at a 1:1 ratio with lake water, yields a chloride concentration slightly less than 250 mg/l.

### 8.3 Model Selection

The primary computer code used for analyses, decision making, and development of the wellfield design was the Sandia Waste Isolation-Flow and Transport (SWIFT) code (Ward, 1993). This code was developed for use by the U.S. Geological Society and by the Nuclear Regulatory Commission over a sixteen year period. The SWIFT model provides both solute transport and hydraulic simulation of subsurface water movement based on the basic aquifer parameters such as layer thickness, horizontal and vertical hydraulic conductivity, porosity, water density differences, and mixing (dispersivity).

The SWIFT code has been extensively reviewed and tested to verify its applicability to a variety of problems (Reeves et al, 1984; Reeves et al, 1986b). The current SWIFT code was obtained from GeoTrans, Inc. who revised the main frame computer code so that it could be operated using a personal computer.

Although the SWIFT code can be used to calculate impacts of pumpage, a standard analytical code (Walton, 1970) was used to evaluate pressure build-up calculations for various wellfield geometries. Both codes were ultimately used to establish the well spacing required to maximize recovery efficiency while minimizing interference between wells.

### 8.4 Model Calibration

Initially, a seven layer, radial model was used to model the three ASR cycles. This model was capable of providing values similar to those currently estimated for Cycles 1 and 3, but the reduced recovery efficiency associated with Cycle 2 could not be simulated. The model was than expanded to nine layers as listed below: Layers modeled in the nine layer system include:

mid-Hawthorn Zone II
Confining Unit 1
mid-Hawthorn Zone III
Confining Unit 2
ASR Storage Interval 1
Confining Unit 3
ASR Storage Interval 2
Confining Unit 4
Upper Suwannee

In the 9-layer system, the ASR storage unit was divided into three intervals, two permeable units and a semi-confining unit separating the two permeable units. Injection into this system was altered so that the observed plugging (Section 7.2.2) preferentially diverted a portion of the injected water from the upper ASR interval to the lower ASR interval. The flow of water from the two permeable ASR intervals during recovery were set equal, since there was no evidence of plugging during recovery. The application of preferential plugging allowed all three cycles to the simulated.

Once the nine layer radial model was calibrated, a five layer Cartesian coordinate model was developed so that the impact of additional wells could be represented. The five layer, Cartesian coordinate model included the mid-Hawthorn Zone III, confining unit 2, a single ASR storage unit, confining unit 4, and the upper Suwannee. The use of a single ASR storage unit was based on the assumption that continuous stabilization of the injected water is possible and that a permanent method of stabilization would be implemented.

Table 8-2 provides an overview of the comparison between the radial model results and the actual recovery efficiency of the three test cycles. The aquifer parameters derived from field tests were used as input parameters to the model. Dispersion was varied to optimize the fit of the modeled value with the actual value.

### 8.4.1 Aquifer System Parameters

The basic model input parameters for all 5 layers of Cartesian model are provided in Table 8-3. These aquifer parameters were developed during the testing of the ASR 1 well and the dual zone monitoring well. The analyses performed for this project were previously reported and discussed in Section 5. Ultimately, during the calibration, the leakance was lowered to one tenth of the measured value. The reduced leakance allowed the best match with the current data. However, as shown in Table 8-2, the modeling under estimated the volume of water that is recovered at a cut-off of 350 mg/l chlorides.

### 8.4.2 Calibration Results

Once the final modeling parameters were set, the three cycle tests were simulated using the solute transport modeling. As can be seen by the comparison of the actual and radial model results (Table 8-2), the radial model provides a good representation of aquifer performance. Therefore, the radial model parameters were used to generate a model based on Cartesian coordinates so that additional wells could be included in the model.

Table 8-4 provides a comparison between the radial and Cartesian coordinate models. The purpose of this comparison was to demonstrate that the Cartesian model provided comparable values with the radial model in the absence of plugging and the elimination of four layers. The data provided in Tables 8-2 and 8-4 demonstrate that the Cartesian model provides results similar to the radial model and therefore provides satisfactory estimates of future recovery efficiency.

## 8.5 Predictive Model Simulation and Results

The basic theory of ASR developed by Merritt (1985) indicates that recovery efficiency should increase with injected volume for a fixed dispersivity. The previous statement implies that, when possible, a single well should be used for all injection. However, as occurs in most cases, the required injection rate will typically exceed the capacity of the well. Therefore, a multi-well system must be designed. The concept of a single well leads to the conclusion that the next best well arrangement would be to place the additional wells as close together as possible based on injection rate and pressure limitations. In order to inject 13.5 MG at this site at 1.5 MGD per well, 9 wells are required. The final well configuration and well spacing was based on pressure build up and the use of a square well spacing pattern (Figure 8-1). Model runs indicate that a minimum well spacing of 400 feet can be used without causing aquifer pressure near the wellbore to exceed formation fracture pressure (Figure 8-2).

### 8.5.1 Pressure Buildup

Design surface piping requirements provide the primary limitations affecting individual well flow and wellhead pressure. An upper limit of 100 psi has been set for the maximum operating pressure at the pumping station for a 13.5 MGD recharge rate. As will be demonstrated, this pressure is sufficient for the operation of the proposed wellfield and remains less than the pressure required to extend a fracture within the formation.

**Estimated Wellhead Injection Pressure**

The actual calculated wellhead injection pressure, $P_{max}$ is:

$$P_{max} = \Delta P_{aq} + P_{stat} + \Delta P_{wellbore} \qquad \text{Equation 8.1}$$

where:

$P_{max}$ = Maximum Wellhead Injection Pressure

$\Delta P_{aq}$ = Change in aquifer pressure

$P_{stat}$ = Static wellhead pressure under no flow conditions

$\Delta P_{wellbore}$ = Pressure loss in the wellbore and/or the near wellbore region due to well inefficiency and gradual plugging during injection.

The following values have been used to estimate the maximum wellhead injection pressure at the Marco Lakes location:

$\Delta P_{aq}$ = 65 psi at an individual well based on 9 wells, 400 ft spacing, and 1.5 MGD per well.

$\Delta P_{stat}$ = 10 psi based on static pressure at ASR-1.

$\Delta P_{wellbore}$ = 30 psi estimated well inefficiency in wellbore due to injection (Estimated).

The sum of these values provides an estimated maximum injection pressure of:

$P_{max}$ = 105 psi at the surface.

**Fracture Formation Potential**

Since the proposed maximum injection pressure is higher than tested, it was necessary to address concerns that the maximum injection pressure will not result in the extension of a fracture within the formation.

The fracture gradient (FG) required to extend a fracture within a subsurface formation is, according to Hubbert and Willis (1957) and Eaton (1969):

$$FG = \alpha*(S/D) + (1-2\alpha)*P/D$$

where:

$\alpha$ = Poisson's Ratio
S = Overburden
D = Depth to fracture zone
P = Pore pressure at depth (psi)

A fracture gradient of 0.6 psi/ft is considered to be at the lower limits of the fracture gradient in Florida (U.S.G.S. Circular 631). The base of the casing is located at approximately 745 feet for the wells completed within the ASR storage zone. If the weakest point in the formation is assumed to be at 745 feet, and if the fracture gradient is assumed to be 0.6 psi/ft, then the maximum allowable injection pressure build-up at the face of the formation is 124 psi.

Since the maximum available injection pressure build-up is limited to less than 100 psi at the wellhead by design, and since the 100 psi limit is less than the 124 psi required to extend a fracture, under a worst case scenario, there is no potential to extend a fracture at this site. It should be noted that an additional safety factor is also built into this analysis since no effort was made to exclude wellbore loses (estimated to be 30 psi) or include formation breakdown pressure (tensile strength of the rock). The inclusion of well loss decreases the maximum pressure at the formation to 70 psi which is 54 psi less than required to extend a fracture.

**Drawdown in the Storage Zone**

The change in aquifer pressure for drawdown is theoretically the negative of the change due to pressure build-up, but corrected for the static head. Thus the net drawdown, $P_{dd}$, at the wellhead will be:

$$\begin{aligned} P_{dd}\ (\text{psi}) &= -\Delta P_{aq} + \Delta P_{stat} - \Delta P_{wellbore} \\ &= -65\ \text{psi} + 10\ \text{psi} - 30\ \text{psi} \\ &= -85\ \text{psi (196 feet) below land surface} \end{aligned}$$

Since the current expansion only relies on 3 wells, the pump bowls will be set at 230 feet below land surface.

### 8.5.2 Solute Transport

The following parameters were unchanged for each of the following modeling parameters:

- o Aquifer parameters as specified in Table 8-3.
- o Cycle volume per well was set at 150 MG
- o Grid Size and Spacing
- o 400 Feet Well Spacing

The basic model was then utilized to investigate five separate scenarios.

1) Injection into a single well was utilized to evaluate recovery efficiency for a single 150 MG cycle. The purpose of this calculation was to establish the minimum recovery efficiency anticipated for the wellfield.

2) Injection of 1350 MG into a single well was utilized to establish the maximum wellfield recovery efficiency.

3) Injection of 450 MG total into 3 wells arranged in a line was utilized to estimate the recovery efficiency for an approximate 5 MGD wellfield.

4) Injection of 1350 MG into 9 symmetrically placed wells at 13.5 MGD was performed to compare recovery efficiencies of the wellfield with that for a single well.

5) Injection of 1350 MG into 9 symmetrically placed wells to estimate how the recovery efficiency will increase with two additional cycles of 1300 MG was performed.

A basic assumption in the different scenarios is that one cycle will be accomplished each year. All model input and output data are provided in Appendix 8-1.

An extended storage period was not tested during the pilot tests and therefore the affects could not be calibrated with respect to actual data. The affect of long-term storage should be evaluated after sufficient operating data has been obtained.

#### 8.5.2.1 Modeling Results

Table 8-5 provides the recovery efficiencies estimated for the different modeled scenarios. These data indicate, that as anticipated, that injection of a larger volume of water into a single well will improve recovery efficiency for a fixed dispersivity. Therefore, closer spacing between wells is anticipated to improve recovery efficiency. The modeling results indicate that some minor adjustment in well spacing could be accommodated if necessary for engineering purposes. However, the symmetrical placement of the wells remains crucial.

The data provided in Table 8-5 also indicate that the current expansion of the wellfield to three wells will provide approximately 200 MG of quality water on the first recovery cycle (150 MG/Well). Higher efficiency for this configuration can be expected using multiple cycles.

The modeled cyclical performance, based on two additional cycles for the nine well system (scenarios 5), suggests that recovery efficiencies for injected water could reach or exceed 60 to 70% at a cut-off concentration of 350 mg/l. This level of recovery from a brackish aquifer containing 2800 mg/l dissolved chloride is good.

A basic assumption associated with the system design is that the wellfield will be operated as a single unit. This means that water should be added or withdrawn in a symmetrical fashion to minimize plume movement due to an asymmetric pumping of the wellfield.

### 8.6 Design Recommendations

The following design recommendations are provided based on information provided in Section 8:

1. The wellfield configuration should be based on a nine well system organized in a square pattern with 400 feet spacing between the wells.

2. The worst case pumping level is calculated to lie 176-196 feet below land surface. Therefore, the setting depth of the pump bowls should be approximately 230 feet below land surface.

3. Injection and recovery should be performed in a symmetrical manner so that the injected water remains centered within the wellfield. This is most easily accomplished by operating all wells simultaneously and adjusting the flow rate as needed on all wells simultaneously.

4. The current evaluation is based on yearly cycles, and approximately 100 day storage cycles. If substantially longer storage periods are required then additional testing should be performed and the model should be recalibrated.

5. A permanent method for preventing wellbore plugging should be implemented at this site.

## 9.0 REFERENCES


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TABLE 5-2

## MARCO LAKES ASR
## AQUIFER TEST ANALYSIS SUMMARY

| Aquifer | Test Description | Transmissivity (gpd/ft) | Storage Coefficient Dimensionless | Leakance Coefficient (gpd/ft$^3$) |
|---|---|---|---|---|
| Mid-Hawthorn Zone I | Step-Drawdown Test Exploratory Well | 500,000 | ND | ND |
| Mid-Hawthorn Zone I | Constant Pumping/Recovery Test, Exploratory Well (Recovery Data Analysis) | 317,000 | ND | ND |
| Lower Hawthorn Zone I | Constant Pumping/Recovery Test, Exploratory Well (Recovery Data Analysis) | 350 | ND | ND |
| ASR Storage Zone | Constant Pumping/Recovery Test, Exploratory Well (Recovery Data Analysis) | 61,000 | ND | ND |
| ASR Storage Zone | Constant Rate Pumping Pilot ASR Well, Hantush Analysis Of Drawdown Data From Offset Monitor Well | 68,000 | $6.5 \times 10^{-5}$ | $5 \times 10^{-3}$ |
| ASR Storage Zone | Analysis Production Well Recovery Data From Above Test | 122,000 | ND | ND |
| ASR Storage Zone | Analysis Monitor Well Recovery Data From Above Test | 91,900 | ND | ND |

ND - Not Determined

# FLORIDA GEOPHYSICAL LOGGING, INC.

## FLUID CONDUCTIVITY TEMPERATURE LOG

Company WATER RESOURCE SOL.
Well ASR #2
Field MARCO LAKES ASR EXPAN
Country COLLIER
State/Prv FLORIDA

Company WATER RESOURCE SOLUTIONS
Well ASR #2
Field MARCO LAKES ASR EXPANSION
Country COLLIER State/Prv FLORIDA
Location
Other Services SEE REMARKS

| | | | |
|---|---|---|---|
| Permanent Datum | PAD | Elevation 8' | Elevation K.B. |
| Log Measured From | PAD | | D.F. |
| Drilling Measured From | PAD | | G.L. |

| | |
|---|---|
| Date | 8/27/99 |
| Run Number | THREE |
| Depth Driller | 780' |
| Depth Logger | 780' |
| Bottom Logged Interval | 780' |
| Top Log Interval | SURFACE |
| Open Hole Size | 12.25" |
| Type Fluid | WATER |
| Density / Viscosity | N/A |
| Max. Recorded Temp. | N/A |
| Estimated Cement Top | N/A |
| Time Well Ready | ON ARRIVAL |
| Time Logger on Bottom | 1030 |
| Equipment Number | 103 |
| Location | FT. MYERS |
| Recorded By | FERGUSON |
| Witnessed By | N. KUGER DENISON |

| Borehole Record | | | | Tubing Record | | | |
|---|---|---|---|---|---|---|---|
| Run Number | Bit | From | To | Size | Weight | From | To |
| ONE | 12.25 | SURFACE | 750 | | | | |
| TWO | 12.25 | CASING | 780 | | | | |

| Casing Record | Size | Wgt/Ft | Top | Bottom |
|---|---|---|---|---|
| Surface String | 26" | 375 W.T | SURFACE | 27' |
| Prot. String | 16" | 1" PVC | SURFACE | 736' |
| Production String | | | | |
| Liner | | | | |

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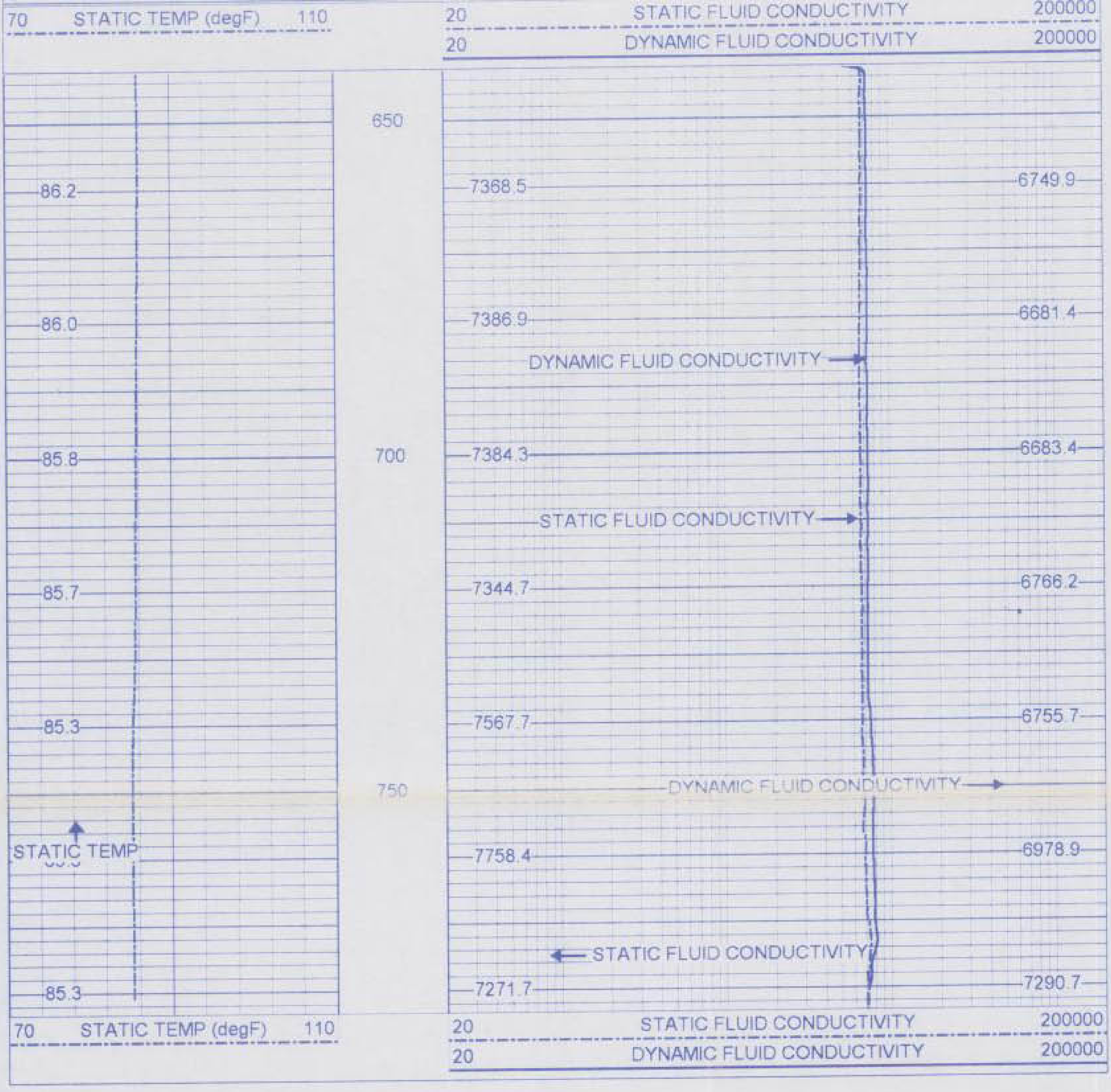
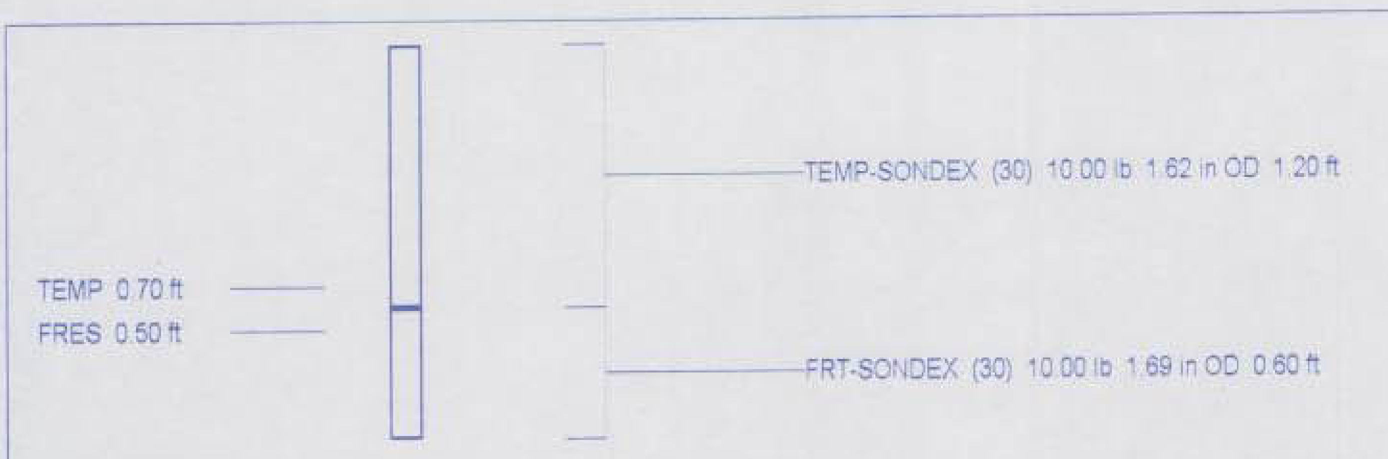
### Comments

X-Y CALIPER
DUAL INDUCTION LL3/SP
BOREHOLE COMPENSATED SONIC
FLOWMETER
VIDEO

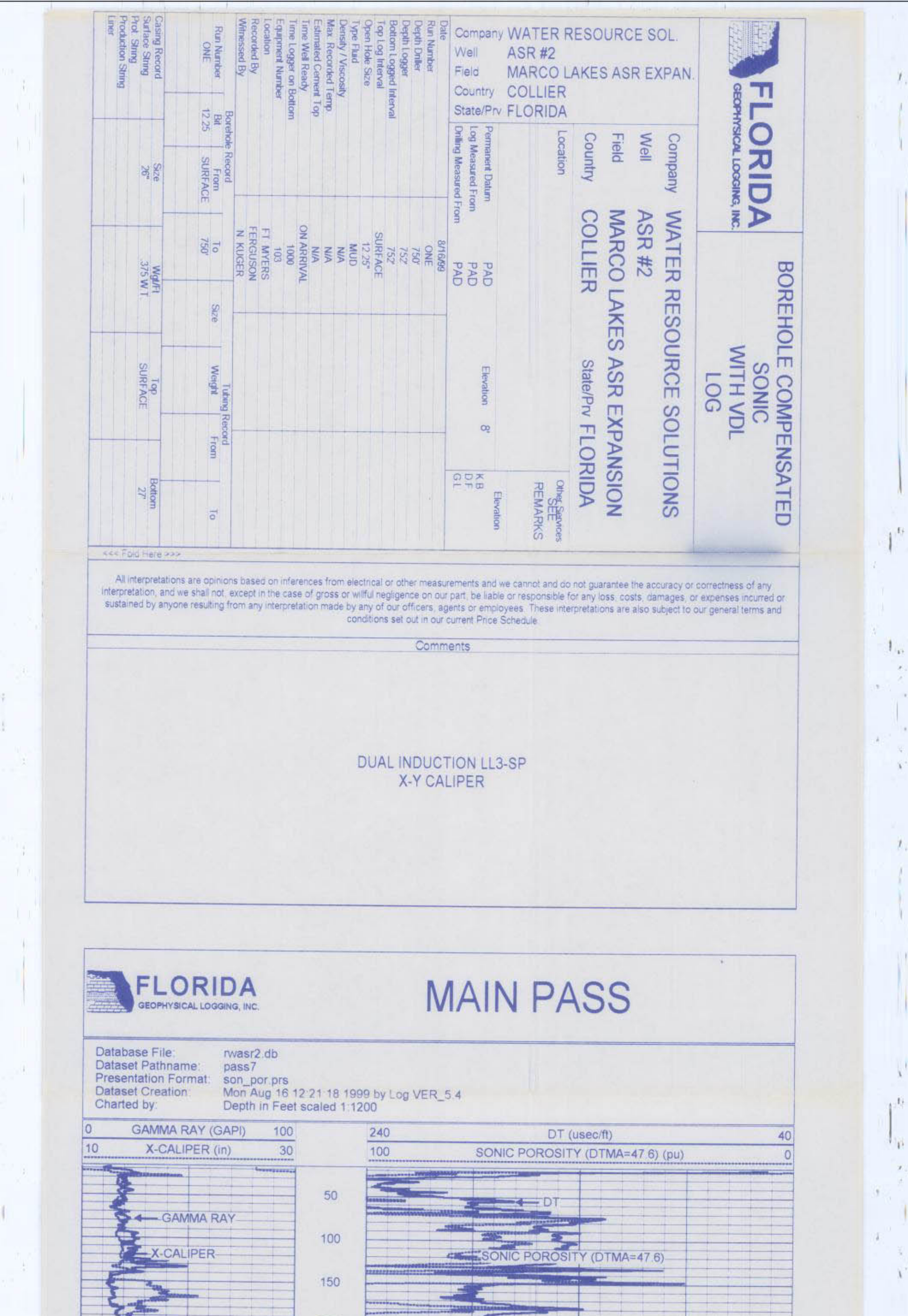
# FLORIDA GEOPHYSICAL LOGGING, INC. MRGD FLUID CONDUCTIVITY

Database File: rwasr2.db
Dataset Pathname: run3/pass16
Presentation Format: frttmpmg.prs
Dataset Creation: Fri Aug 27 16:19:38 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240



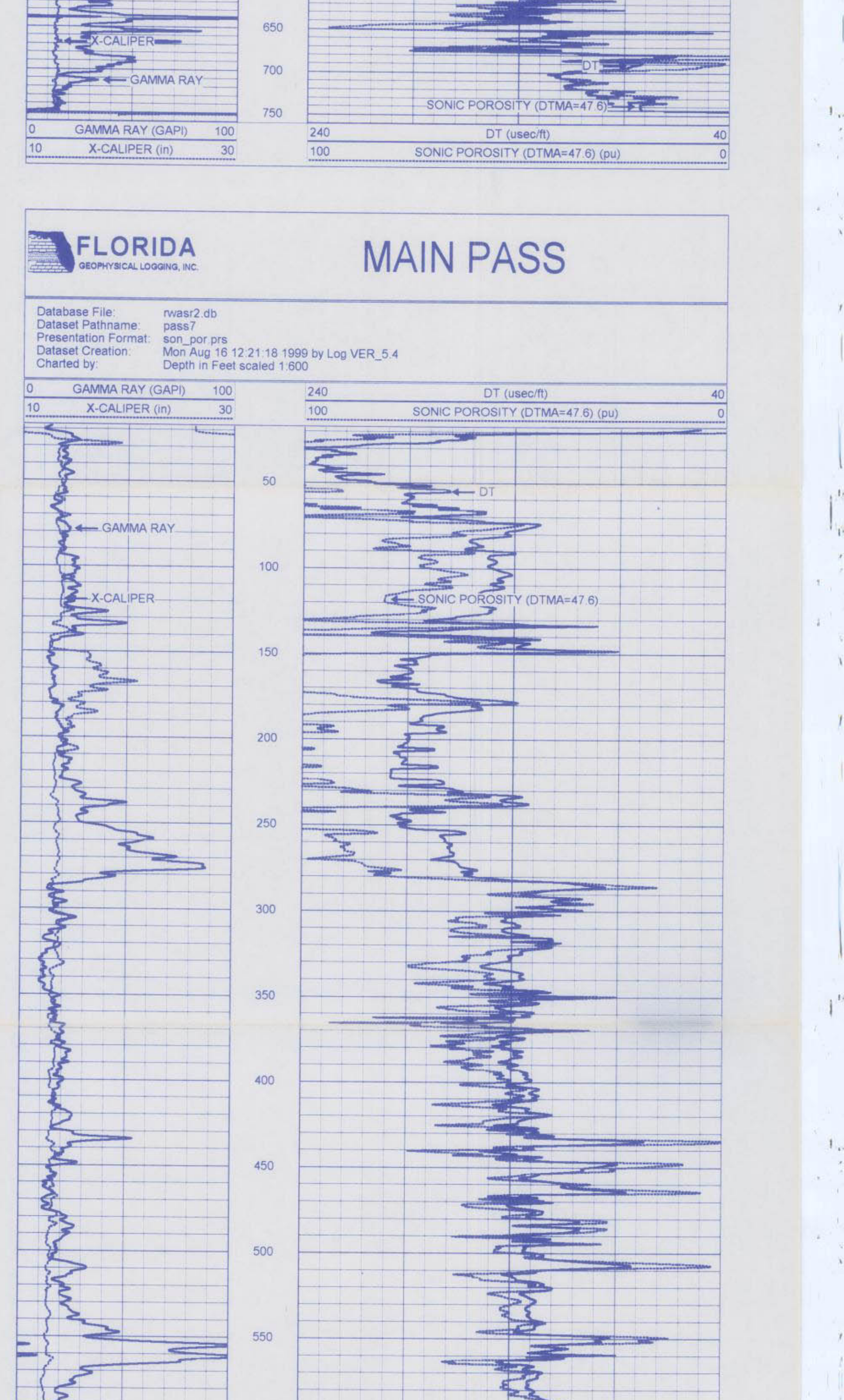




Dataset: run3/pass16
Total Length: 1.80 ft
Total Weight: 20.00 lb
O.D.: 1.69 in



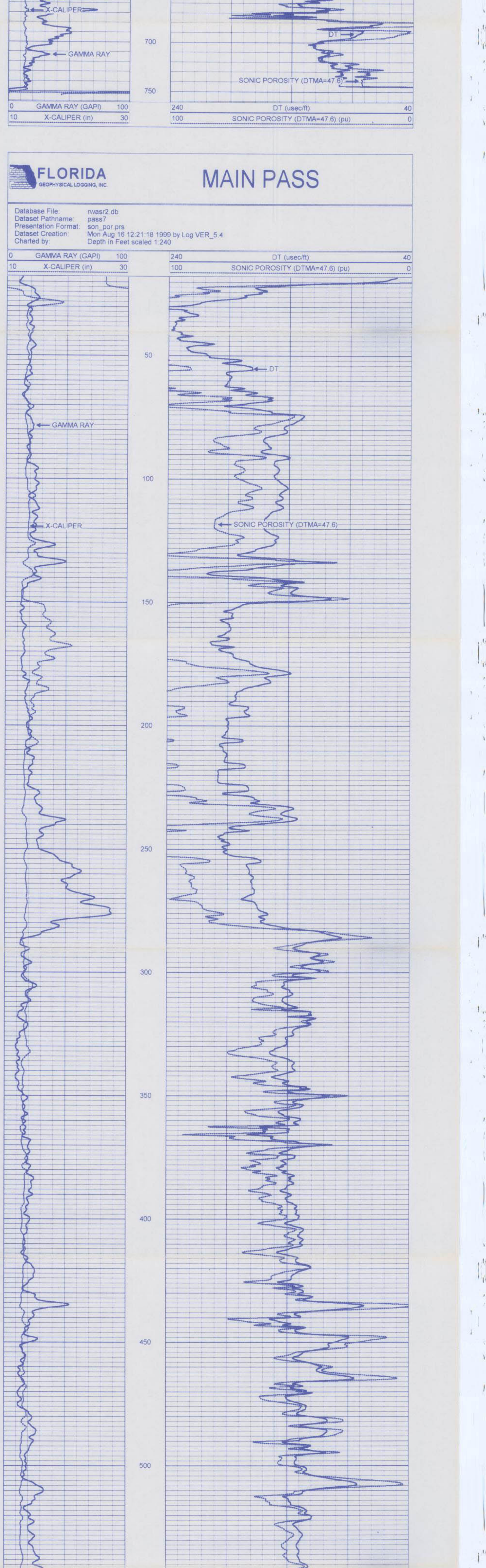
## MAIN PASS

FLORIDA GEOPHYSICAL LOGGING, INC.



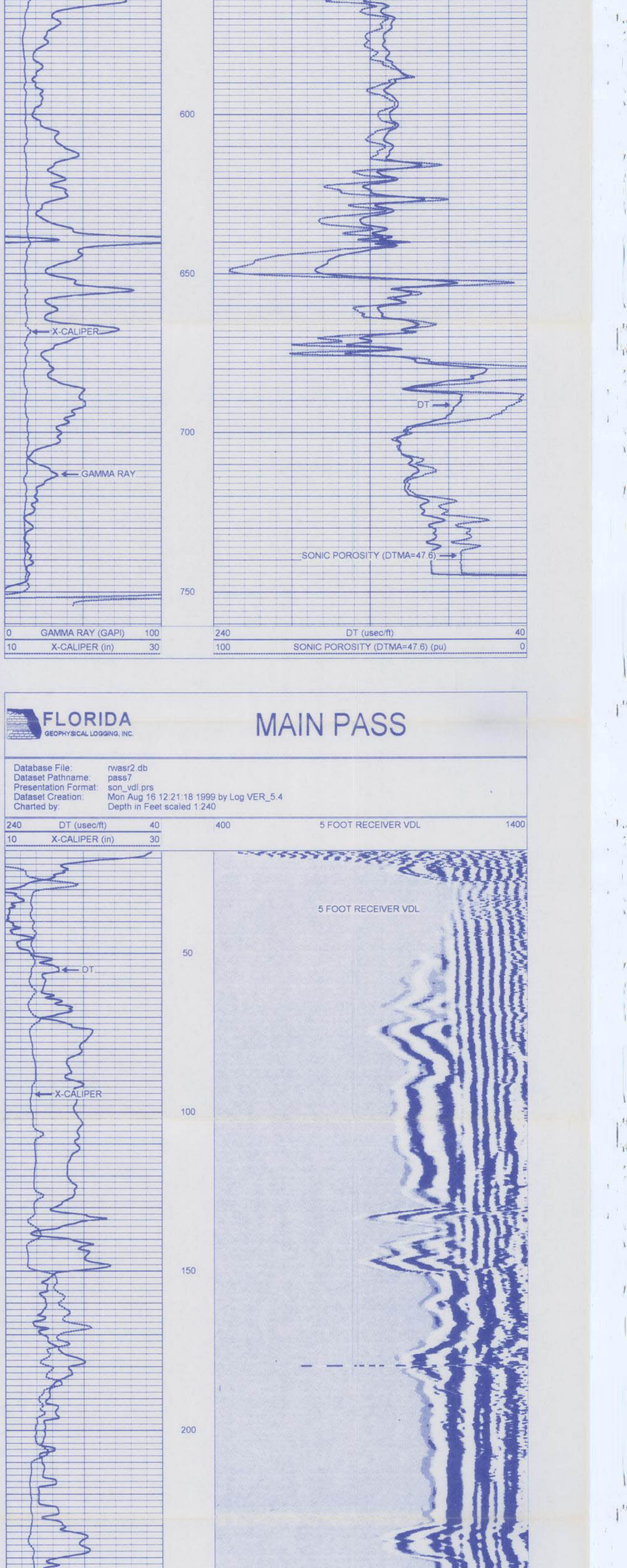
## MAIN PASS

FLORIDA GEOPHYSICAL LOGGING, INC.



## MAIN PASS

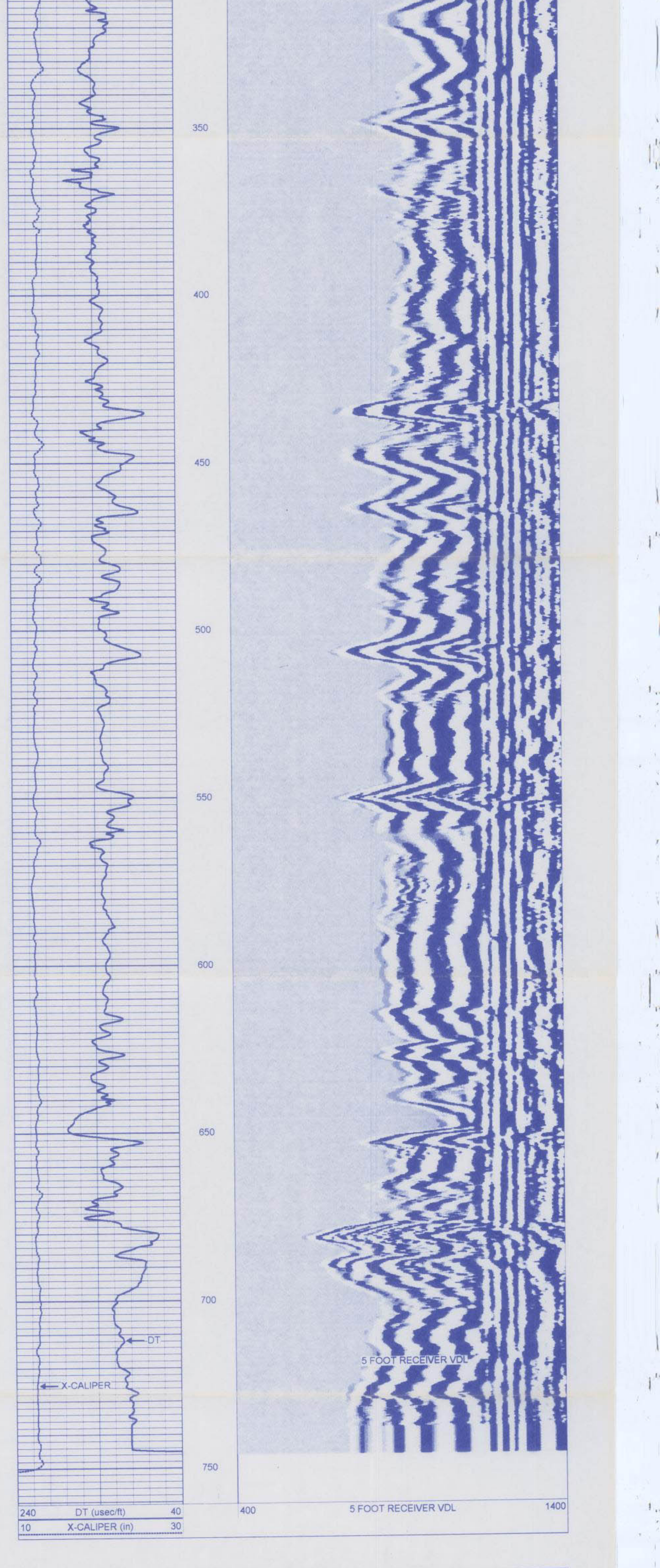
FLORIDA GEOPHYSICAL LOGGING, INC.




## MAIN PASS

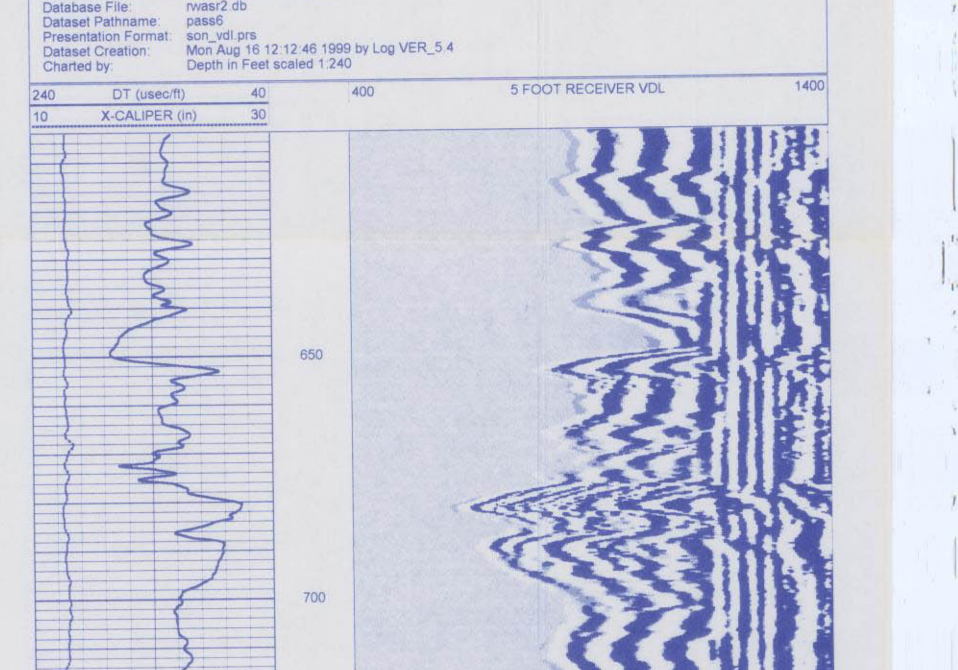
FLORIDA GEOPHYSICAL LOGGING, INC.

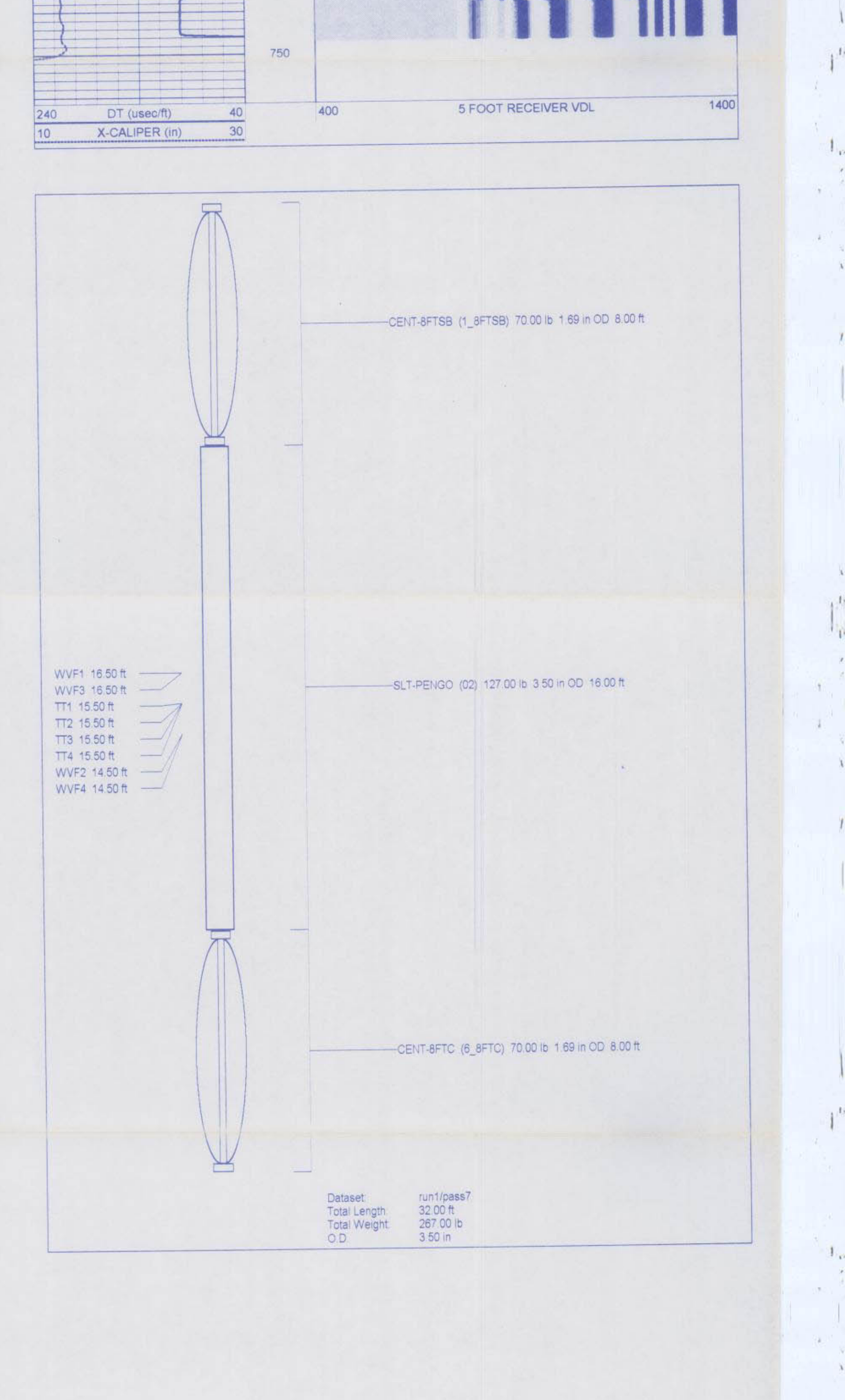
Database File: rwasr2.db
Dataset Pathname: pass7
Presentation Format: son_vdl.prs
Dataset Creation: Mon Aug 16 12:21:18 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240



## REPEAT PASS

FLORIDA GEOPHYSICAL LOGGING, INC.





# FLORIDA
GEOPHYSICAL LOGGING, INC.

## DUAL INDUCTION
## LL3 - SP
## LOG

| | |
|---|---|
| Company | WATER RESOURCE SOL. |
| Well | ASR #2 |
| Field | MARCO LAKES ASR EXPAN. |
| Country | COLLIER |
| State/Prv | FLORIDA |

| | |
|---|---|
| Company | WATER RESOURCE SOLUTIONS |
| Well | ASR #2 |
| Field | MARCO LAKES ASR EXPANSION |
| Country | COLLIER |
| State/Prv | FLORIDA |
| Location | |
| Other Services | SEE REMARKS |

| | | Elevation | |
|---|---|---|---|
| Permanent Datum | PAD | 8' | K.B. |
| Log Measured From | PAD | | D.F. |
| Drilling Measured From | PAD | | G.L. |

| | |
|---|---|
| Date | 8/16/99 |
| Run Number | ONE |
| Depth Driller | 750' |
| Depth Logger | 752' |
| Bottom Logged Interval | 752' |
| Top Log Interval | SURFACE |
| Open Hole Size | 12.25" |
| Type Fluid | MUD |
| Density / Viscosity | N/A |
| Max. Recorded Temp. | N/A |
| Estimated Cement Top | N/A |
| Time Well Ready | ON ARRIVAL |
| Time Logger on Bottom | 1000 |
| Equipment Number | 103 |
| Location | FT. MYERS |
| Recorded By | FERGUSON |
| Witnessed By | N. KUGER |

| Borehole Record | | | | Tubing Record | | | |
|---|---|---|---|---|---|---|---|
| Run Number | Bit | From | To | Size | Weight | From | To |
| ONE | 12.25 | SURFACE | 750' | | | | |

| Casing Record | Size | Wgt/Ft | Top | Bottom |
|---|---|---|---|---|
| Surface String | 26" | .375 W.T. | SURFACE | 27' |
| Prot. String | | | | |
| Production String | | | | |
| Liner | | | | |

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Comments

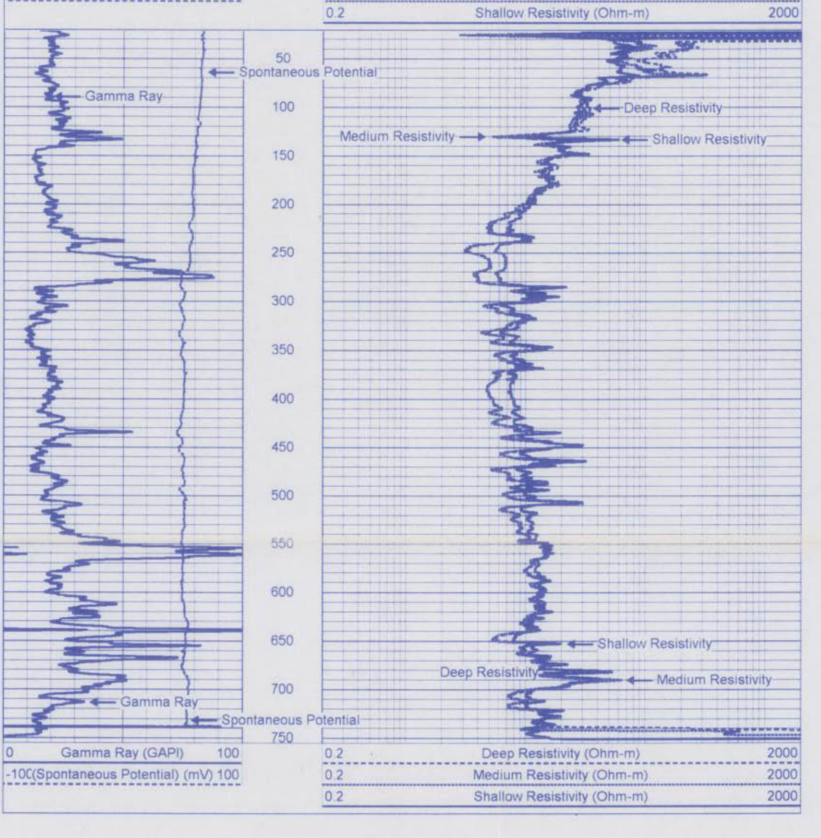
X-Y CALIPER
BOREHOLE COMPENSATED SONIC WITH VDL

FLORIDA GEOPHYSICAL LOGGING, INC.

## MAIN PASS

Database File: rwasr2.db
Dataset Pathname: pass5
Presentation Format: dil.prs
Dataset Creation: Mon Aug 16 11:23:33 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:1200

| | | | | |
|---|---|---|---|---|
| 0 Gamma Ray (GAPI) 100 | 0.2 | Deep Resistivity (Ohm-m) | 2000 |
| -100 (Spontaneous Potential) (mV) 100 | 0.2 | Medium Resistivity (Ohm-m) | 2000 |
| | 0.2 | Shallow Resistivity (Ohm-m) | 2000 |



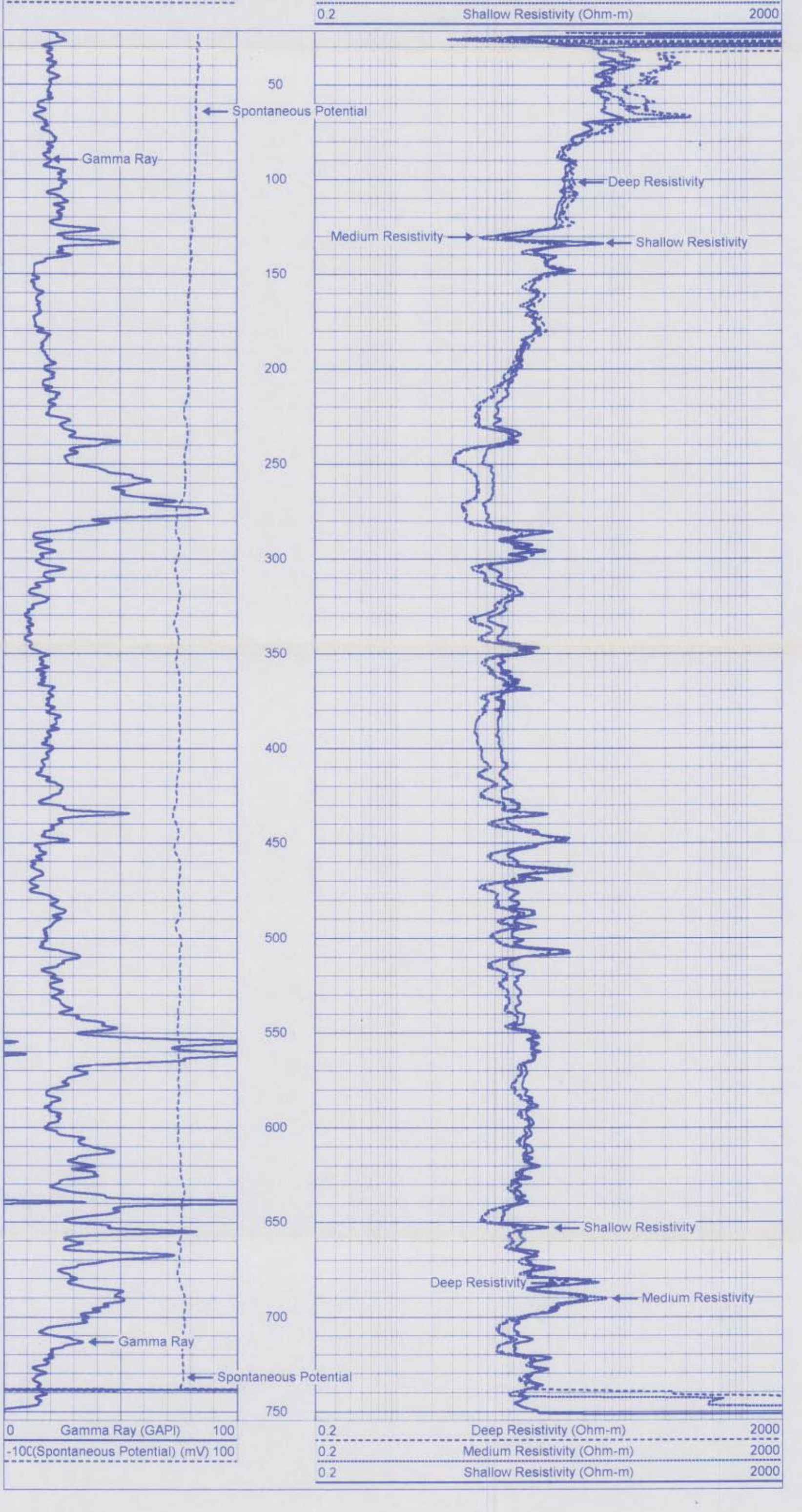

| | | | |
|---|---|---|---|
| 0 Gamma Ray (GAPI) 100 | 0.2 | Deep Resistivity (Ohm-m) | 2000 |
| -100 (Spontaneous Potential) (mV) 100 | 0.2 | Medium Resistivity (Ohm-m) | 2000 |
| | 0.2 | Shallow Resistivity (Ohm-m) | 2000 |

FLORIDA GEOPHYSICAL LOGGING, INC.

## MAIN PASS

Database File: rwasr2.db
Dataset Pathname: pass5
Presentation Format: dil.prs
Dataset Creation: Mon Aug 16 11:23:33 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:600

| | | | |
|---|---|---|---|
| 0 Gamma Ray (GAPI) 100 | 0.2 | Deep Resistivity (Ohm-m) | 2000 |
| -100 (Spontaneous Potential) (mV) 100 | 0.2 | Medium Resistivity (Ohm-m) | 2000 |
| | 0.2 | Shallow Resistivity (Ohm-m) | 2000 |



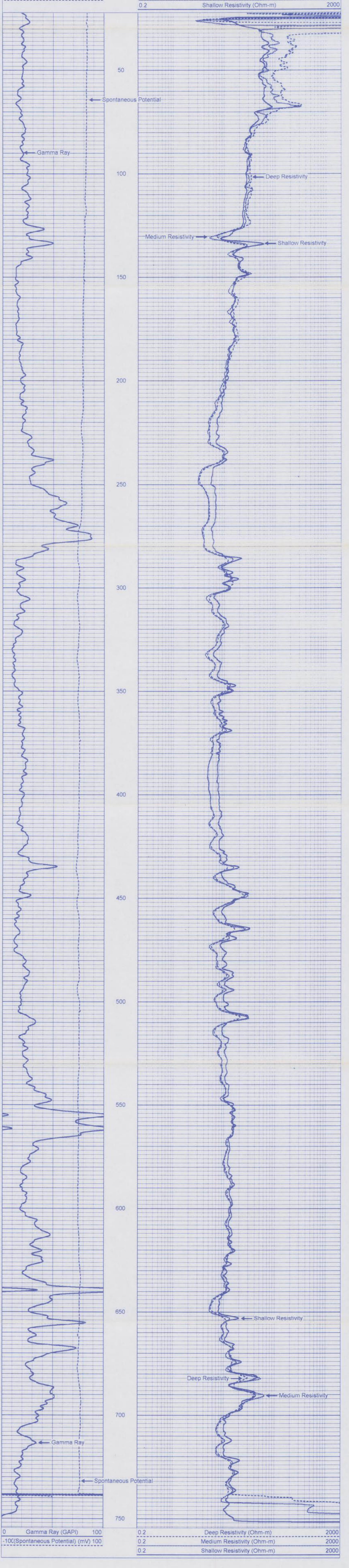

| | | | |
|---|---|---|---|
| 0 Gamma Ray (GAPI) 100 | 0.2 | Deep Resistivity (Ohm-m) | 2000 |
| -100 (Spontaneous Potential) (mV) 100 | 0.2 | Medium Resistivity (Ohm-m) | 2000 |
| | 0.2 | Shallow Resistivity (Ohm-m) | 2000 |

FLORIDA GEOPHYSICAL LOGGING, INC.

## MAIN PASS

Database File: rwasr2.db
Dataset Pathname: pass5
Presentation Format: dil.prs
Dataset Creation: Mon Aug 16 11:23:33 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240

| | | | |
|---|---|---|---|
| 0 Gamma Ray (GAPI) 100 | 0.2 | Deep Resistivity (Ohm-m) | 2000 |
| -100 (Spontaneous Potential) (mV) 100 | 0.2 | Medium Resistivity (Ohm-m) | 2000 |
| | 0.2 | Shallow Resistivity (Ohm-m) | 2000 |



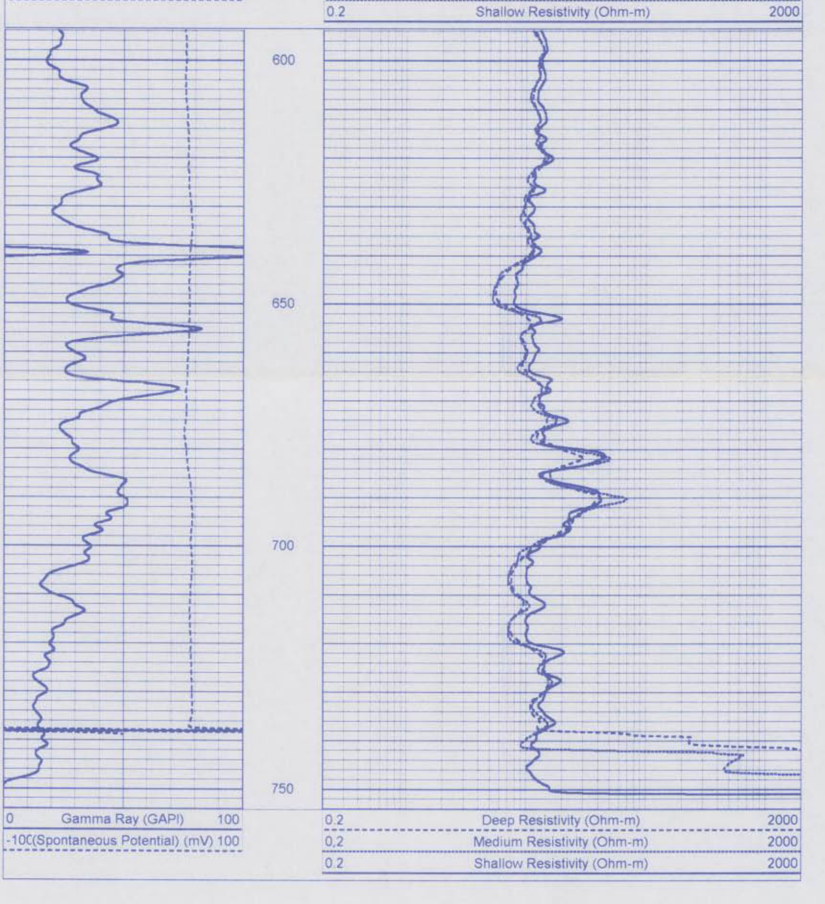

| | | | |
|---|---|---|---|
| 0 Gamma Ray (GAPI) 100 | 0.2 | Deep Resistivity (Ohm-m) | 2000 |
| -100 (Spontaneous Potential) (mV) 100 | 0.2 | Medium Resistivity (Ohm-m) | 2000 |
| | 0.2 | Shallow Resistivity (Ohm-m) | 2000 |

FLORIDA GEOPHYSICAL LOGGING, INC.

## REPEAT PASS

Database File: rwasr2.db
Dataset Pathname: pass4
Presentation Format: dil.prs
Dataset Creation: Mon Aug 16 11:17:27 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240

| | | | |
|---|---|---|---|
| 0 Gamma Ray (GAPI) 100 | 0.2 | Deep Resistivity (Ohm-m) | 2000 |
| -100 (Spontaneous Potential) (mV) 100 | 0.2 | Medium Resistivity (Ohm-m) | 2000 |
| | 0.2 | Shallow Resistivity (Ohm-m) | 2000 |




| | | | |
|---|---|---|---|
| 0 Gamma Ray (GAPI) 100 | 0.2 | Deep Resistivity (Ohm-m) | 2000 |
| -100 (Spontaneous Potential) (mV) 100 | 0.2 | Medium Resistivity (Ohm-m) | 2000 |
| | 0.2 | Shallow Resistivity (Ohm-m) | 2000 |

### Dual Induction Calibration Report

Serial-Model: 1510-C
Surface Cal Performed: Thu Apr 29 16:47:18 1999
Downhole Cal Performed: Mon Aug 16 11:06:29 1999
After Survey Verification Performed: Mon Aug 16 11:22:09 1999

**Surface Calibration**

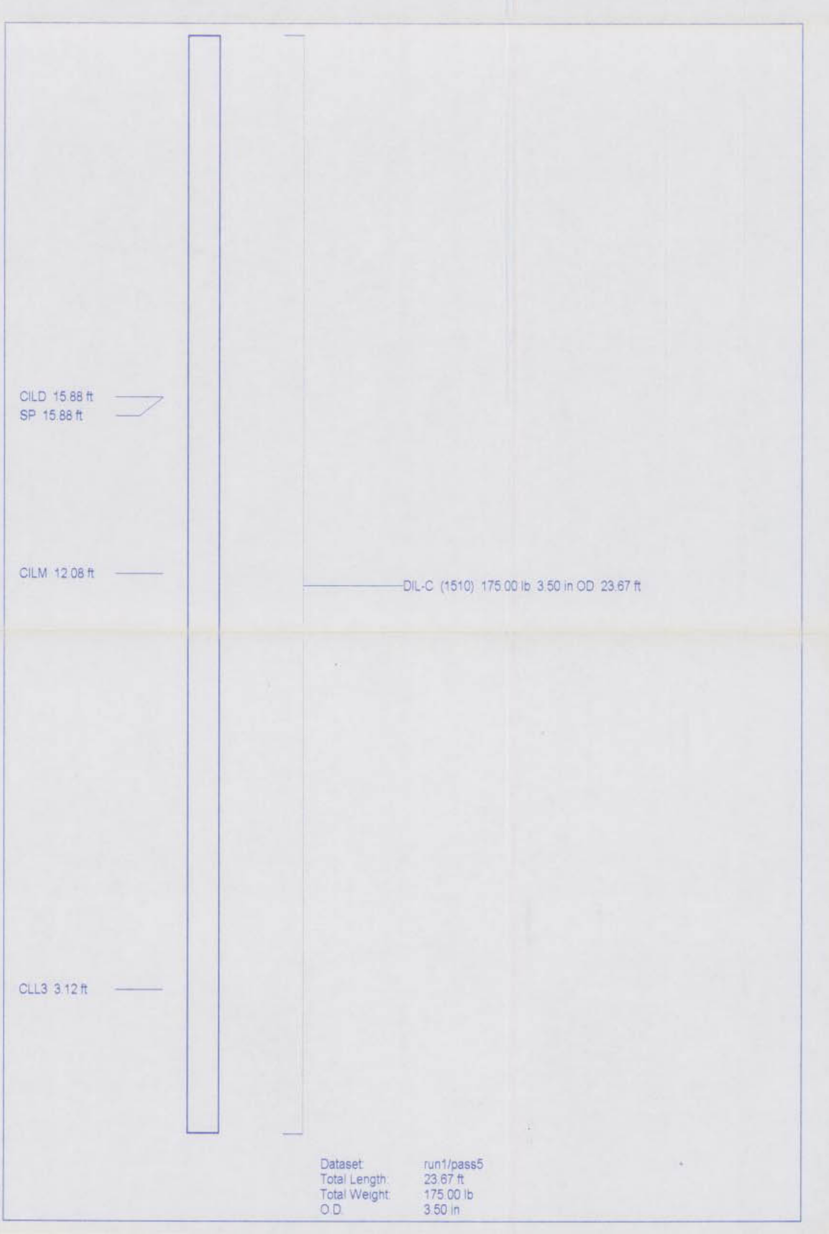
| | Readings | | | References | | | Results | |
|---|---|---|---|---|---|---|---|---|
| Loop: | Air | Loop | | Air | Loop | | m | b |
| Deep | -0.014 | 0.631 | V | 0.000 | 400.000 | mmho-m | 620.172 | 8.975 |
| Medium | -0.001 | 0.703 | V | 0.000 | 464.000 | mmho-m | 659.905 | 0.362 |
| Internal: | Zero | Cal | | Zero | Cal | | m | b |
| Deep | 0.012 | 0.641 | V | 17.680 | 407.650 | mmho-m | 620.191 | 10.098 |
| Medium | 0.009 | 0.728 | V | 6.060 | 482.670 | mmho-m | 662.558 | 0.111 |

**Downhole Calibration**

| | Readings | | | References | | | Results | |
|---|---|---|---|---|---|---|---|---|
| Internal: | Zero | Cal | | Zero | Cal | | m | b |
| Deep | 17.034 | 417.314 | mmho-m | 16.557 | 406.514 | mmho-m | 0.974 | -0.038 |
| Medium | 5.901 | 492.863 | mmho-m | 6.287 | 480.989 | mmho-m | 0.975 | 0.535 |
| Shallow | 0.035 | 0.425 | | 3.000 | 88.900 | mmho-m | 220.276 | -4.659 |

**After Survey Verification**

| | Readings | | | Targets | | | Results | |
|---|---|---|---|---|---|---|---|---|
| Internal: | Zero | Cal | | Zero | Cal | | m' | b' |
| Deep | 17.189 | 408.964 | mmho-m | 17.034 | 417.314 | mmho-m | 0.974 | -0.038 |
| Medium | 5.788 | 482.805 | mmho-m | 5.901 | 492.863 | mmho-m | 0.975 | 0.535 |
| Shallow | 3.648 | 89.310 | mmho-m | 3.000 | 88.900 | mmho-m | 1.003 | -0.658 |




Dataset: run1/pass5
Total Length: 23.67 ft
Total Weight: 175.00 lb
O.D. 3.50 in

021 - 135

# FLORIDA GEOPHYSICAL LOGGING, INC.

# X-Y CALIPER GAMMA RAY LOG

Company: WATER RESOURCE SOL.
Well: ASR #2
Field: MARCO LAKES ASR EXPAN.
Country: COLLIER
State/Prv: FLORIDA

Company: WATER RESOURCE SOLUTIONS
Well: ASR #2
Field: MARCO LAKES ASR EXPANSION
Country: COLLIER
State/Prv: FLORIDA
Location: Lat 26 04 01 Long 81 41 34
34-505-26E
Other Services: SEE REMARKS

| | | | |
|---|---|---|---|
| Permanent Datum | PAD | Elevation 8' | Elevation |
| Log Measured From | PAD | | K.B. |
| Drilling Measured From | PAD | | D.F. |
| | | | G.L. |

| | |
|---|---|
| Date | 8/16/99 |
| Run Number | ONE |
| Depth Driller | 750' |
| Depth Logger | 752' |
| Bottom Logged Interval | 752' |
| Top Log Interval | SURFACE |
| Open Hole Size | 12.25" |
| Type Fluid | MUD |
| Density / Viscosity | N/A |
| Max. Recorded Temp. | N/A |
| Estimated Cement Top | N/A |
| Time Well Ready | ON ARRIVAL |
| Time Logger on Bottom | 1000 |
| Equipment Number | 103 |
| Location | FT MYERS |
| Recorded By | FERGUSON |
| Witnessed By | N KUGER |

| Borehole Record | | | | Tubing Record | | | |
|---|---|---|---|---|---|---|---|
| Run Number | Bit | From | To | Size | Weight | From | To |
| ONE | 12.25 | SURFACE | 750' | | | | |

| Casing Record | Size | Wgt/Ft | Top | Bottom |
|---|---|---|---|---|
| Surface String | 26" | 375 W.T. | SURFACE | 27' |
| Prot. String | | | | |
| Production String | | | | |
| Liner | | | | |

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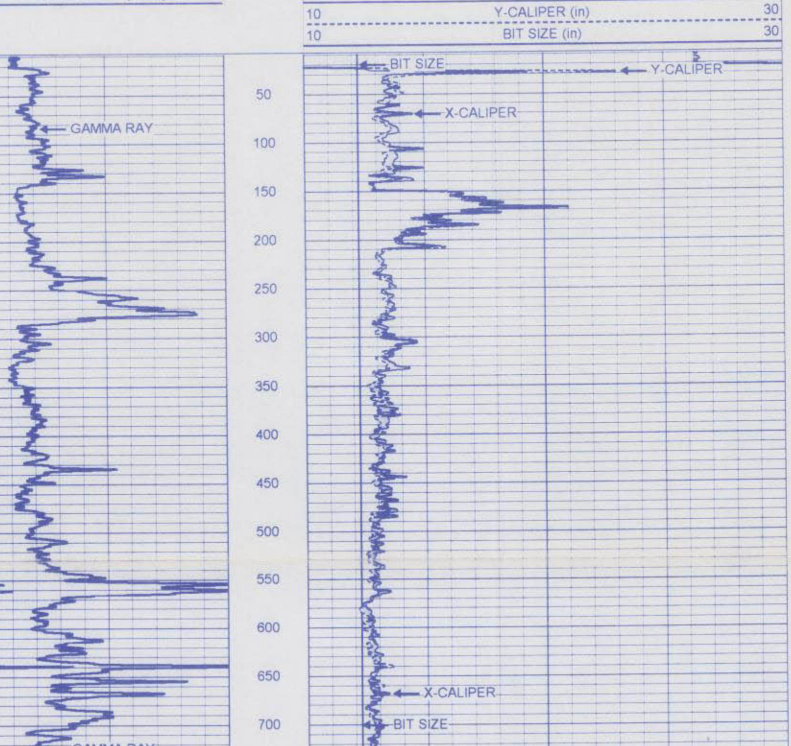
Comments

DUAL INDUCTION LL3/SP
BOREHOLE COMPENSATED SONIC WITH VDL

FLORIDA GEOPHYSICAL LOGGING, INC.

## MAIN PASS

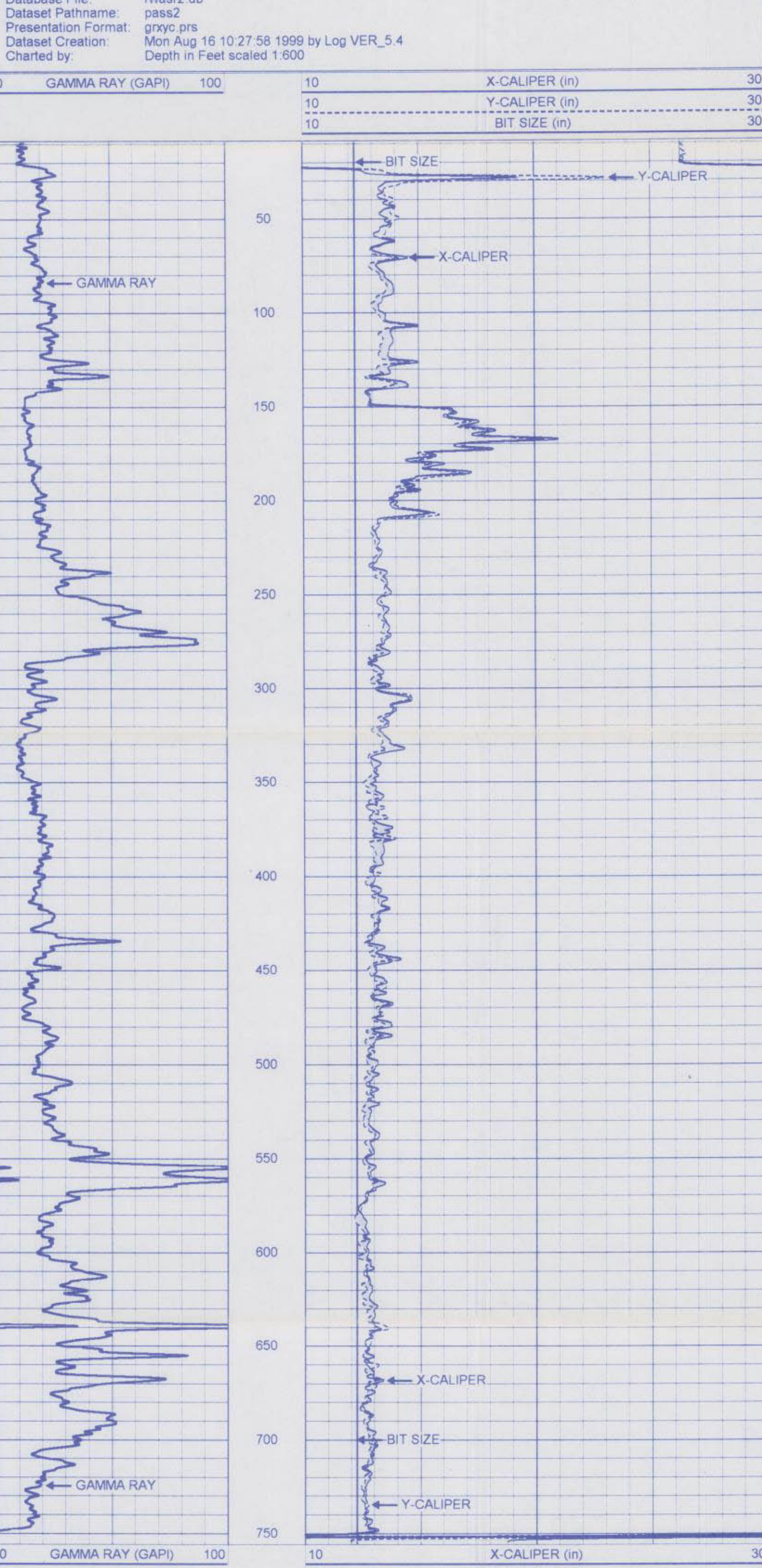
Database File: rwasr2.db
Dataset Pathname: pass2
Presentation Format: grxyc.prs
Dataset Creation: Mon Aug 16 10:27:58 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:1200




FLORIDA GEOPHYSICAL LOGGING, INC.

## MAIN PASS

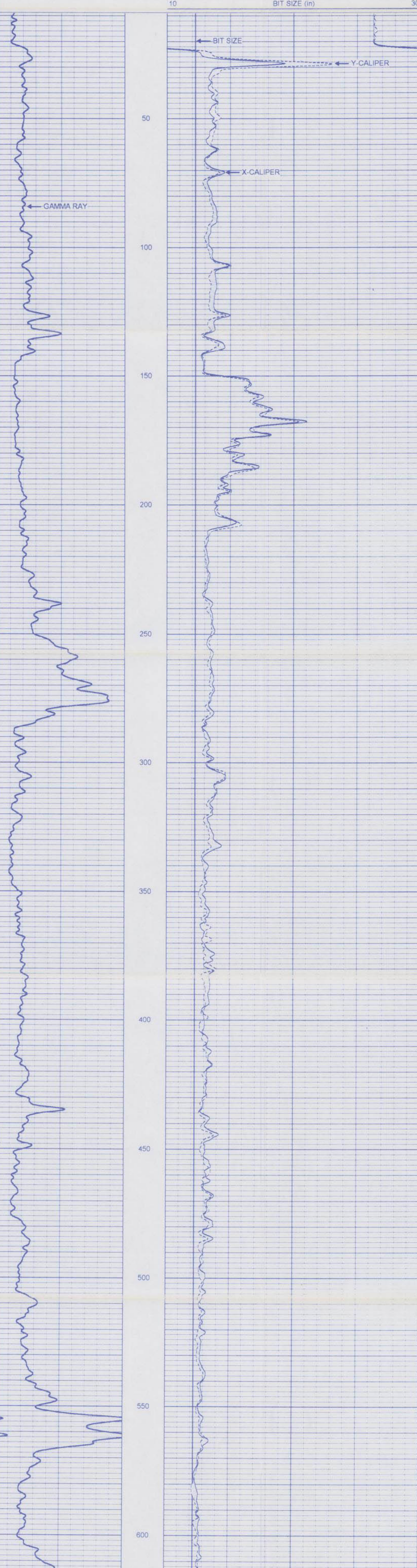
Database File: rwasr2.db
Dataset Pathname: pass2
Presentation Format: grxyc.prs
Dataset Creation: Mon Aug 16 10:27:58 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:600




FLORIDA GEOPHYSICAL LOGGING, INC.

## MAIN PASS

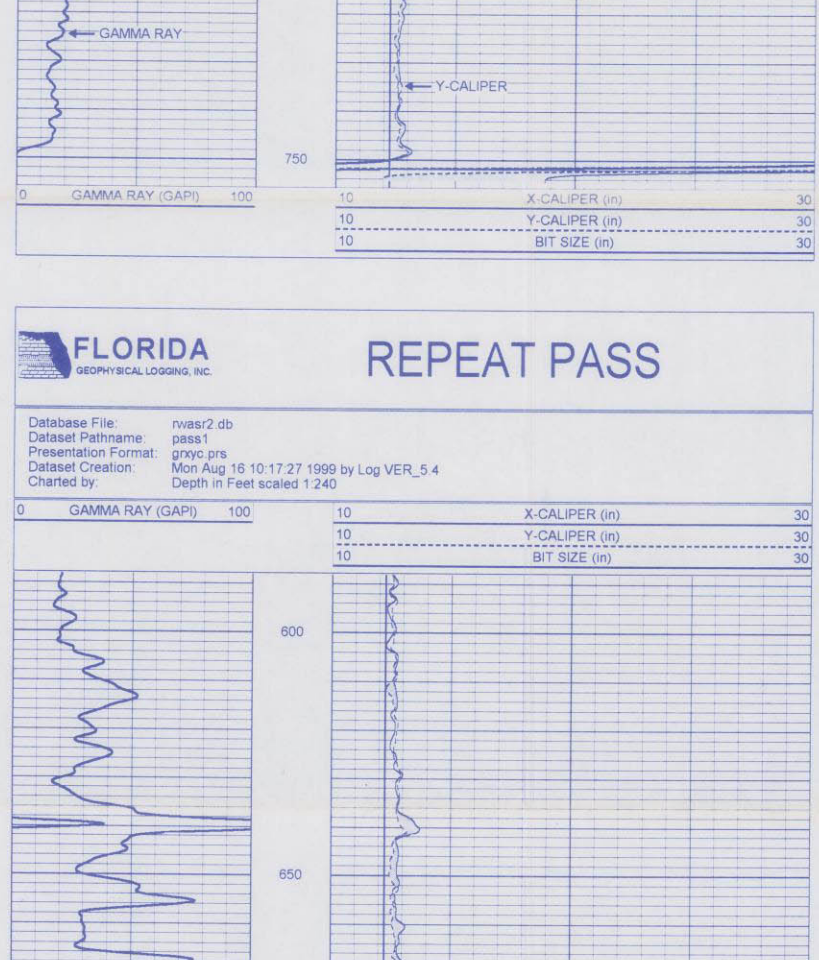
Database File: rwasr2.db
Dataset Pathname: pass2
Presentation Format: grxyc.prs
Dataset Creation: Mon Aug 16 10:27:58 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240




FLORIDA GEOPHYSICAL LOGGING, INC.

## REPEAT PASS

Database File: rwasr2.db
Dataset Pathname: pass1
Presentation Format: grxyc.prs
Dataset Creation: Mon Aug 16 10:17:27 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240



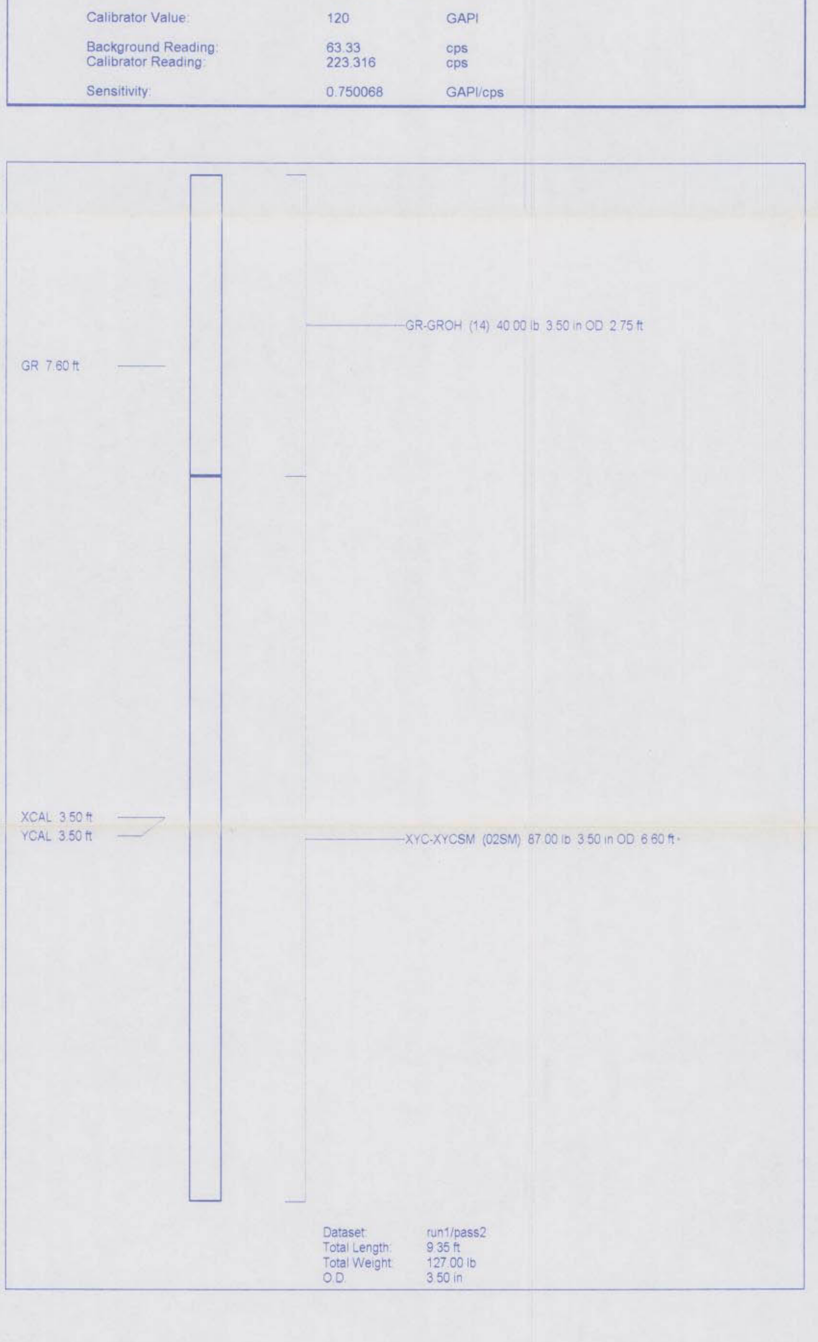

### XY Caliper Calibration Report

Serial Number/Model: 02SM-XYCSM
Performed: Mon Aug 16 10:04:28 1999

| Ring | | | X Caliper | | Y Caliper | |
|---|---|---|---|---|---|---|
| 1: | 5.81 | in | 716.517 | cps | 789.189 | cps |
| 2: | 13.4 | in | 917.265 | cps | 966.168 | cps |
| 3: | 28 | in | 1403.8 | cps | 1388.29 | cps |
| 4: | | in | | cps | | cps |
| 5: | | in | | cps | | cps |
| 6: | | in | | cps | | cps |

### Gamma Ray Calibration Report

| | | |
|---|---|---|
| Serial Number: | 14 | |
| Tool Model: | GROH | |
| Performed: | Tue Jun 29 09:15:26 1999 | |
| Calibrator Value: | 120 | GAPI |
| Background Reading: | 63.33 | cps |
| Calibrator Reading: | 223.316 | cps |
| Sensitivity: | 0.750068 | GAPI/cps |




Dataset: run1/pass2
Total Length: 9.35 ft
Total Weight: 127.00 lb
O.D.: 3.50 in

FLORIDA
GEOPHYSICAL LOGGING, INC.

# BOREHOLE COMPENSATED SONIC WITH VDL LOG

| | |
|---|---|
| Company | WATER RESOURCE SOL. |
| Well | ASR #2 |
| Field | MARCO LAKES ASR EXPAN. |
| Country | COLLIER |
| State/Prv | FLORIDA |

| | |
|---|---|
| Company | WATER RESOURCE SOLUTIONS |
| Well | ASR #2 |
| Field | MARCO LAKES ASR EXPANSION |
| Country | COLLIER |
| State/Prv | FLORIDA |
| Location | |
| Other Services | SEE REMARKS |

| | | | |
|---|---|---|---|
| Permanent Datum | PAD | Elevation | 8' |
| Log Measured From | PAD | | |
| Drilling Measured From | PAD | | |
| Elevation | K.B. | D.F. | G.L. |

| | |
|---|---|
| Date | 8/27/99 |
| Run Number | THREE |
| Depth Driller | 780' |
| Depth Logger | 780' |
| Bottom Logged Interval | 780' |
| Top Log Interval | SURFACE |
| Open Hole Size | 12.25" |
| Type Fluid | WATER |
| Density / Viscosity | N/A |
| Max. Recorded Temp. | N/A |
| Estimated Cement Top | N/A |
| Time Well Ready | ON ARRIVAL |
| Time Logger on Bottom | 1030 |
| Equipment Number | 103 |
| Location | FT. MYERS |
| Recorded By | FERGUSON |
| Witnessed By | N. KUGER / DENISON |

| Borehole Record | | | | Tubing Record | | | |
|---|---|---|---|---|---|---|---|
| Run Number | Bit | From | To | Size | Weight | From | To |
| ONE | 12.25 | SURFACE | 750' | | | | |
| TWO | 12.25 | CASING | 780' | | | | |

| Casing Record | Size | Wgt/Ft | Top | Bottom |
|---|---|---|---|---|
| Surface String | 26" | .375 W.T. | SURFACE | 27' |
| Prot. String | 16" | 1" PVC | SURFACE | 736' |
| Production String | | | | |
| Liner | | | | |

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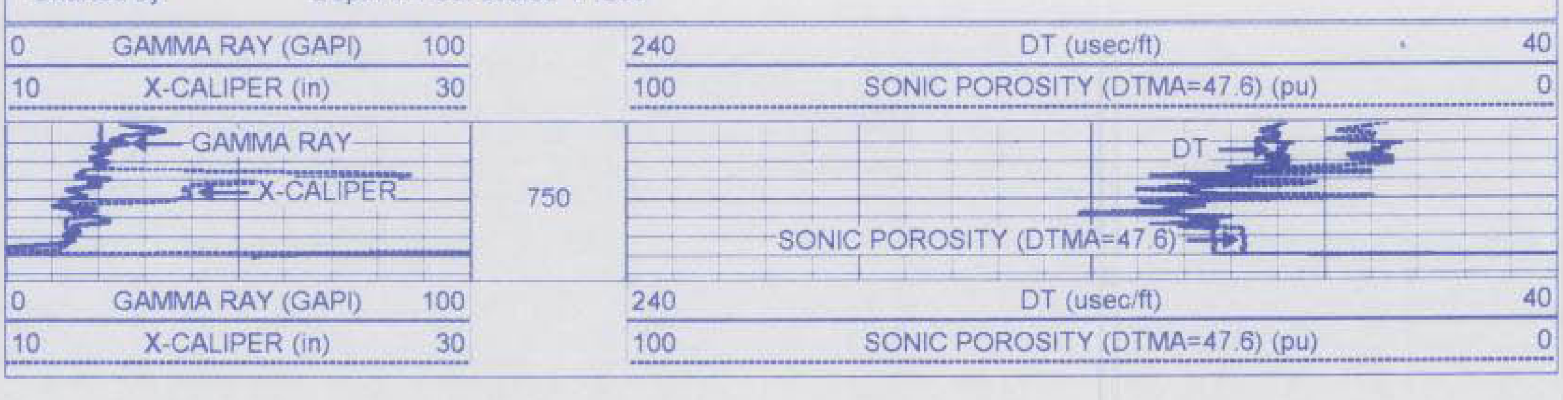
Comments

X-Y CALIPER
DUAL INDUCTION LL3/SP
FLOWMETER
FLUID CONDUCTIVITY
VIDEO

FLORIDA
GEOPHYSICAL LOGGING, INC.

## MAIN PASS

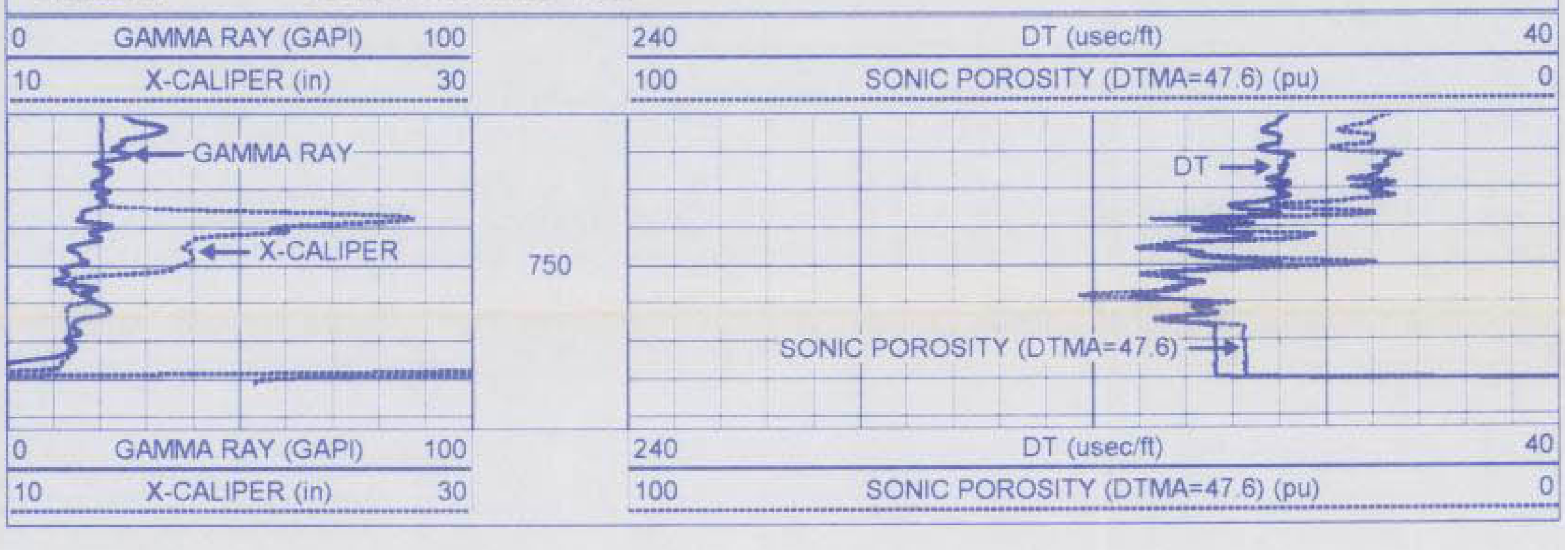
Database File: rwasr2.db
Dataset Pathname: run3/pass9
Presentation Format: son_por.prs
Dataset Creation: Fri Aug 27 12:50:28 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:1200




FLORIDA
GEOPHYSICAL LOGGING, INC.

## MAIN PASS

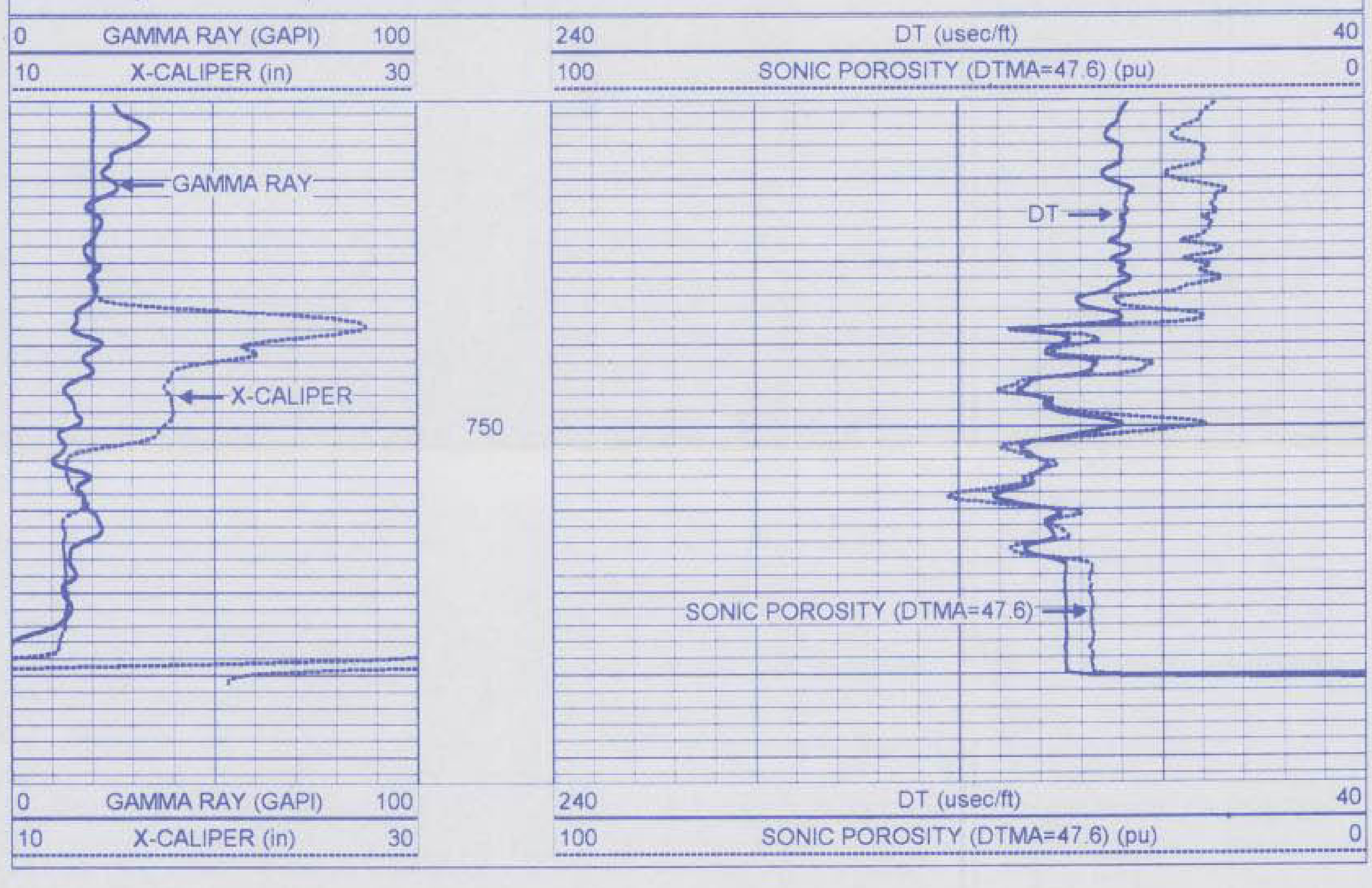
Database File: rwasr2.db
Dataset Pathname: run3/pass9
Presentation Format: son_por.prs
Dataset Creation: Fri Aug 27 12:50:28 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:600




FLORIDA
GEOPHYSICAL LOGGING, INC.

## MAIN PASS

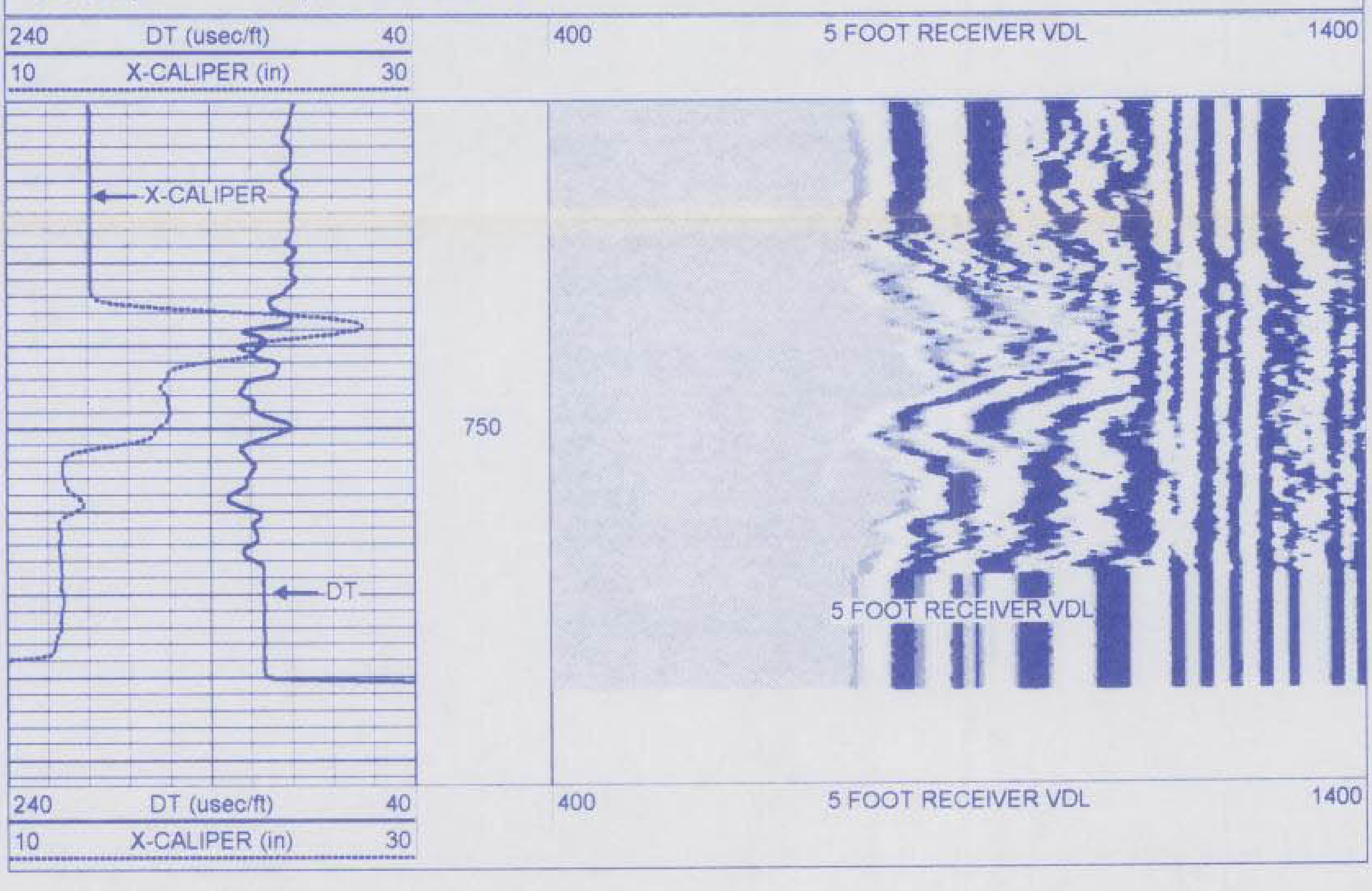
Database File: rwasr2.db
Dataset Pathname: run3/pass9
Presentation Format: son_por.prs
Dataset Creation: Fri Aug 27 12:50:28 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240




FLORIDA
GEOPHYSICAL LOGGING, INC.

## MAIN PASS

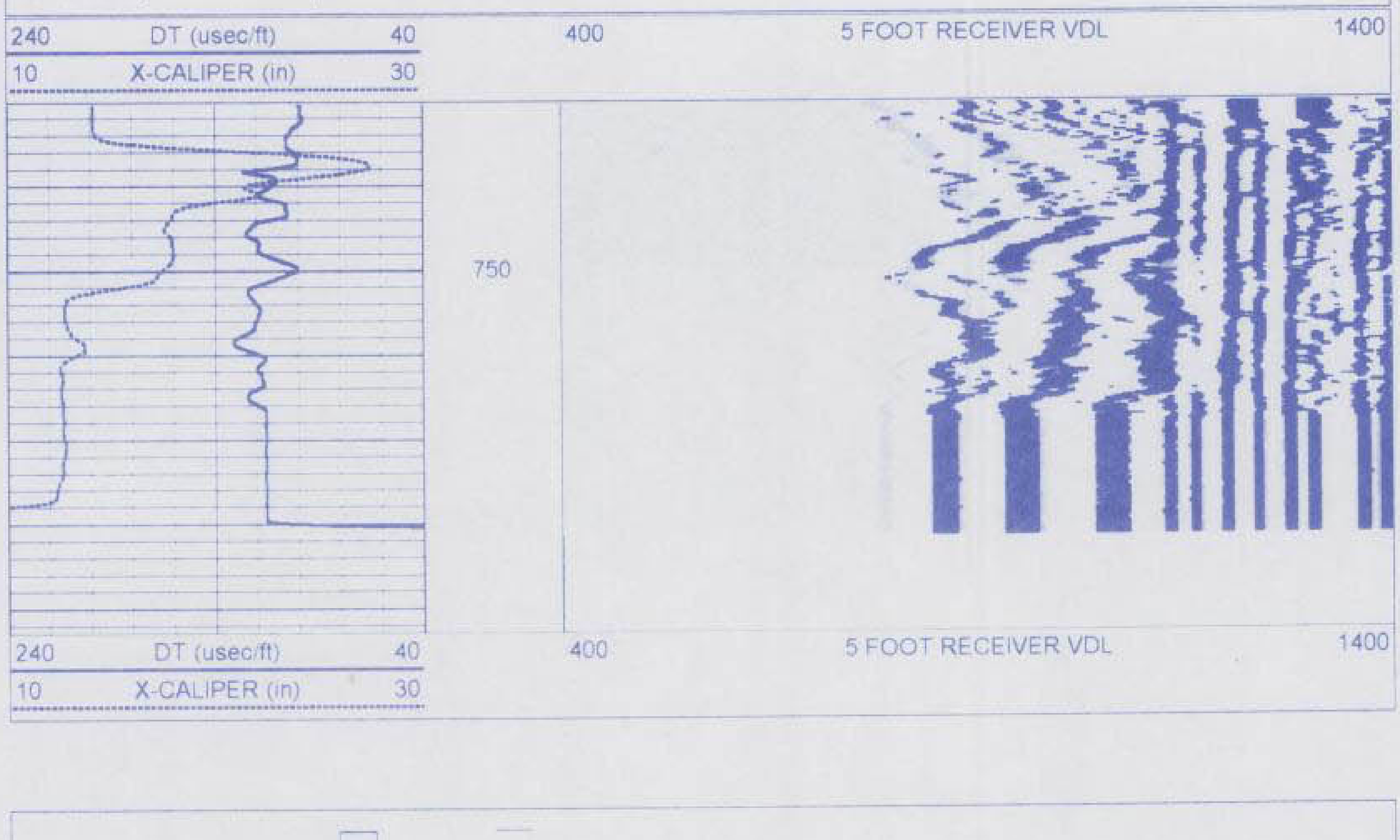
Database File: rwasr2.db
Dataset Pathname: run3/pass9
Presentation Format: son_vdl.prs
Dataset Creation: Fri Aug 27 12:50:28 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240

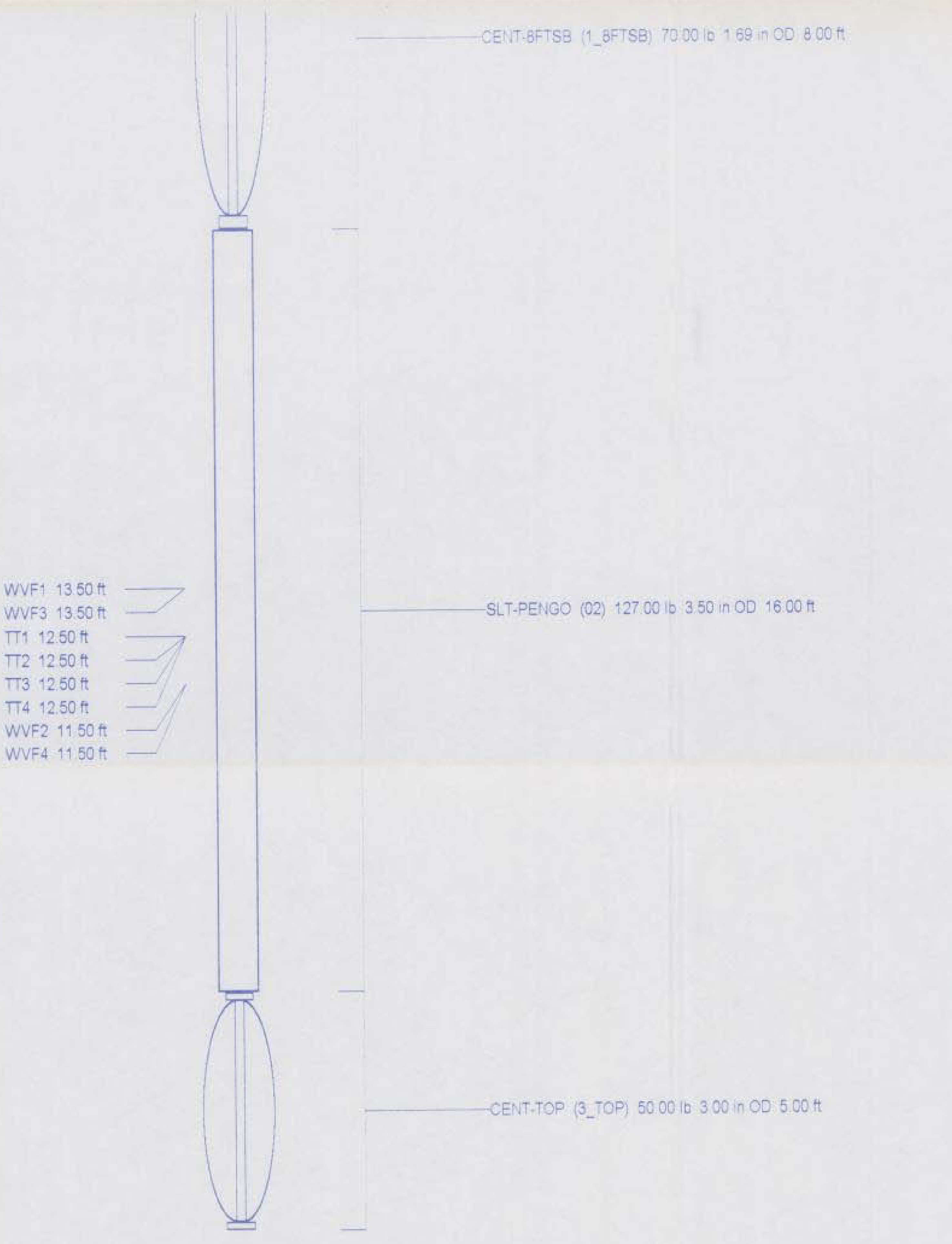



FLORIDA
GEOPHYSICAL LOGGING, INC.

## REPEAT PASS

Database File: rwasr2.db
Dataset Pathname: run3/pass8
Presentation Format: son_vdl.prs
Dataset Creation: Fri Aug 27 12:46:39 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240




Dataset: run3/pass9
Total Length: 29.00 ft
Total Weight: 247.00 lb
O.D.: 3.50 in

# FLORIDA GEOPHYSICAL LOGGING, INC.

# FLOWMETER LOG

| | |
|---|---|
| Company | WATER RESOURCE SOLUTIONS |
| Well | ASR #2 |
| Field | MARCO LAKES ASR EXPANSION |
| Country | COLLIER |
| State/Prv | FLORIDA |
| Location | |
| Other Services | SEE REMARKS |
| Permanent Datum | PAD |
| Elevation | 8' |
| Log Measured From | PAD |
| Drilling Measured From | PAD |
| Elevation | K.B. / D.F. / G.L. |

Well ASR #2
Field MARCO LAKES ASR EXPAN.
Country COLLIER
State/Prv FLORIDA

| | |
|---|---|
| Number | THREE |
| Depth Driller | 780' |
| Depth Logger | 780' |
| Bottom Logged Interval | 780' |
| Top Log Interval | SURFACE |
| Open Hole Size | 12.25" |
| Type Fluid | WATER |
| Density / Viscosity | N/A |
| Max. Recorded Temp | N/A |
| Estimated Cement Top | N/A |
| Time Well Ready | ON ARRIVAL |
| Time Logger on Bottom | 1030 |
| Equipment Number | 103 |
| Location | FT. MYERS |
| Recorded By | FERGUSON |
| Witnessed By | N. KUGER / DENISON |

Borehole Record

| Run Number | Bit | From | To |
|---|---|---|---|
| ONE | 12.25 | SURFACE | 750' |
| TWO | 12.25 | CASING | 780' |

Tubing Record

| Size | Weight | From | To |
|---|---|---|---|
| | | | |

Casing Record

| | Size | Wgt/Ft | Top | Bottom |
|---|---|---|---|---|
| Surface String | 26" | 375 W.T. | SURFACE | 27' |
| String | 16" | 1" PVC | SURFACE | 736' |
| Production String | | | | |

<<< Fold Here >>>



Comments

X-Y CALIPER
DUAL INDUCTION LL3/SP
BOREHOLE COMPENSATED SONIC
FLUID CONDUCTIVITY
VIDEO

## FLORIDA GEOPHYSICAL LOGGING, INC. — FLOW CAL DOWN

Database File: rwasr2.db
Dataset Pathname: run3/pass10
Presentation Format: flowcals.prs
Dataset Creation: Fri Aug 27 15:27:48 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240

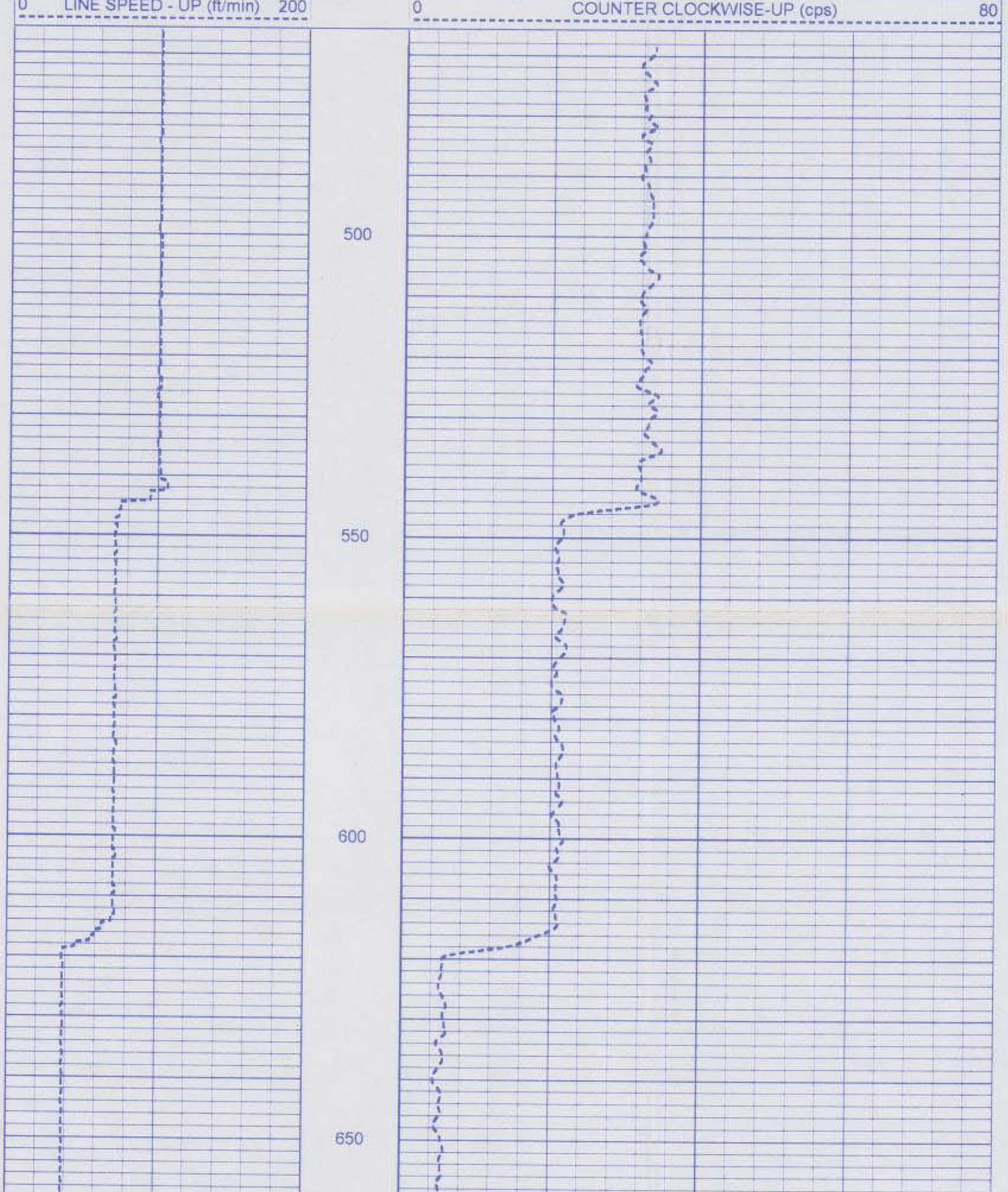
0 LINE SPEED-DOWN (ft/min)-200 | 0 CLOCKWISE-DOWN (cps) 80
0 LINE SPEED - UP (ft/min) 200 | 0 COUNTER CLOCKWISE-UP (cps) 80


0 LINE SPEED-DOWN (ft/min)-200 | 0 CLOCKWISE-DOWN (cps) 80
0 LINE SPEED - UP (ft/min) 200 | 0 COUNTER CLOCKWISE-UP (cps) 80

## FLORIDA GEOPHYSICAL LOGGING, INC. — FLOW CAL UP

Database File: rwasr2.db
Dataset Pathname: run3/pass11
Presentation Format: flowcals.prs
Dataset Creation: Fri Aug 27 15:31:07 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240

0 LINE SPEED-DOWN (ft/min)-200 | 0 CLOCKWISE-DOWN (cps) 80
0 LINE SPEED - UP (ft/min) 200 | 0 COUNTER CLOCKWISE-UP (cps) 80

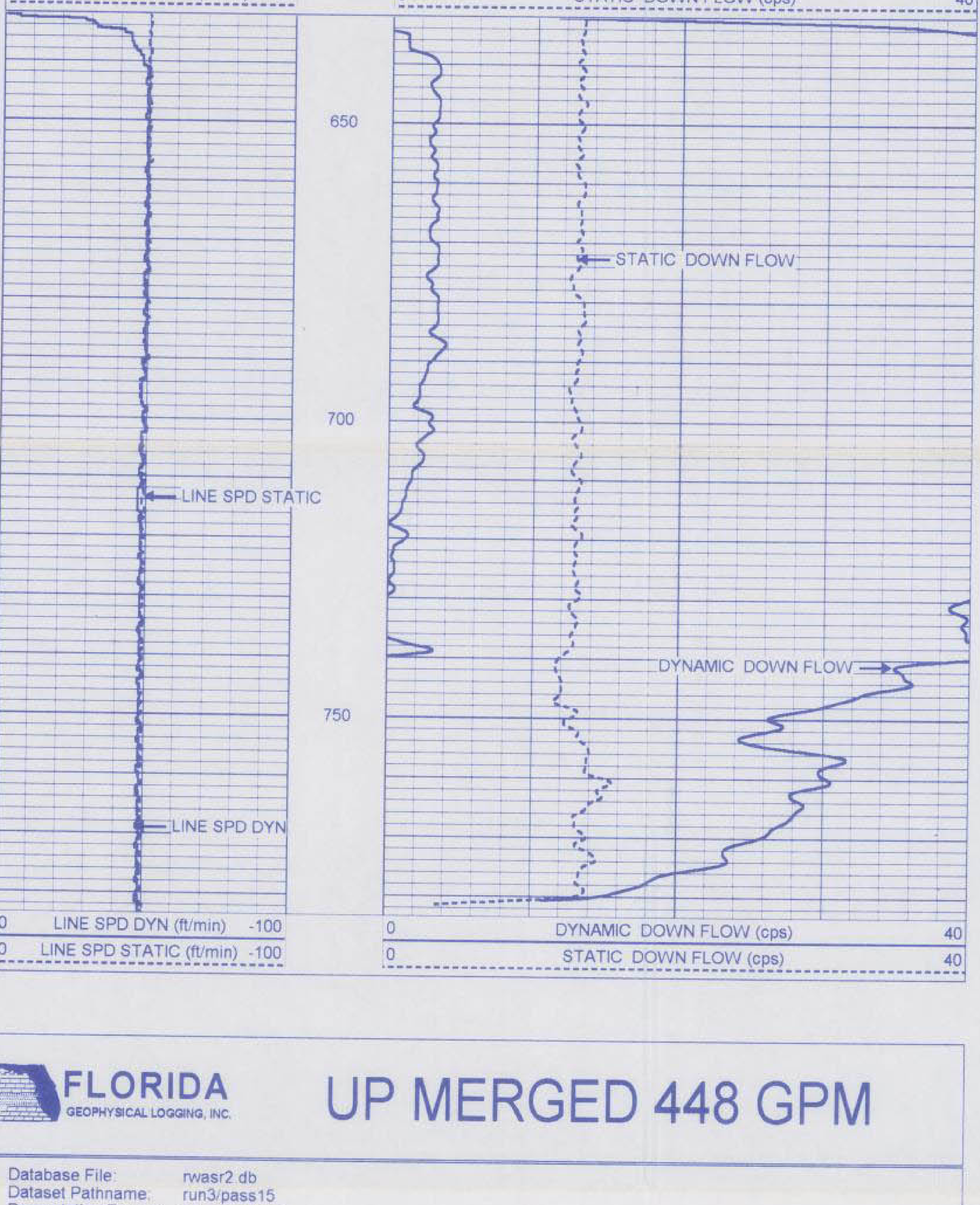



0 LINE SPEED-DOWN (ft/min)-200 | 0 CLOCKWISE-DOWN (cps) 80
0 LINE SPEED - UP (ft/min) 200 | 0 COUNTER CLOCKWISE-UP (cps) 80

## FLORIDA GEOPHYSICAL LOGGING, INC. — DOWN MERGED 448 GPM

Database File: rwasr2.db
Dataset Pathname: run3/pass14
Presentation Format: fm_dnmg.prs
Dataset Creation: Fri Aug 27 15:46:24 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240

0 LINE SPD DYN (ft/min) -100 | 0 DYNAMIC DOWN FLOW (cps) 40
0 LINE SPD STATIC (ft/min) -100 | 0 STATIC DOWN FLOW (cps) 40

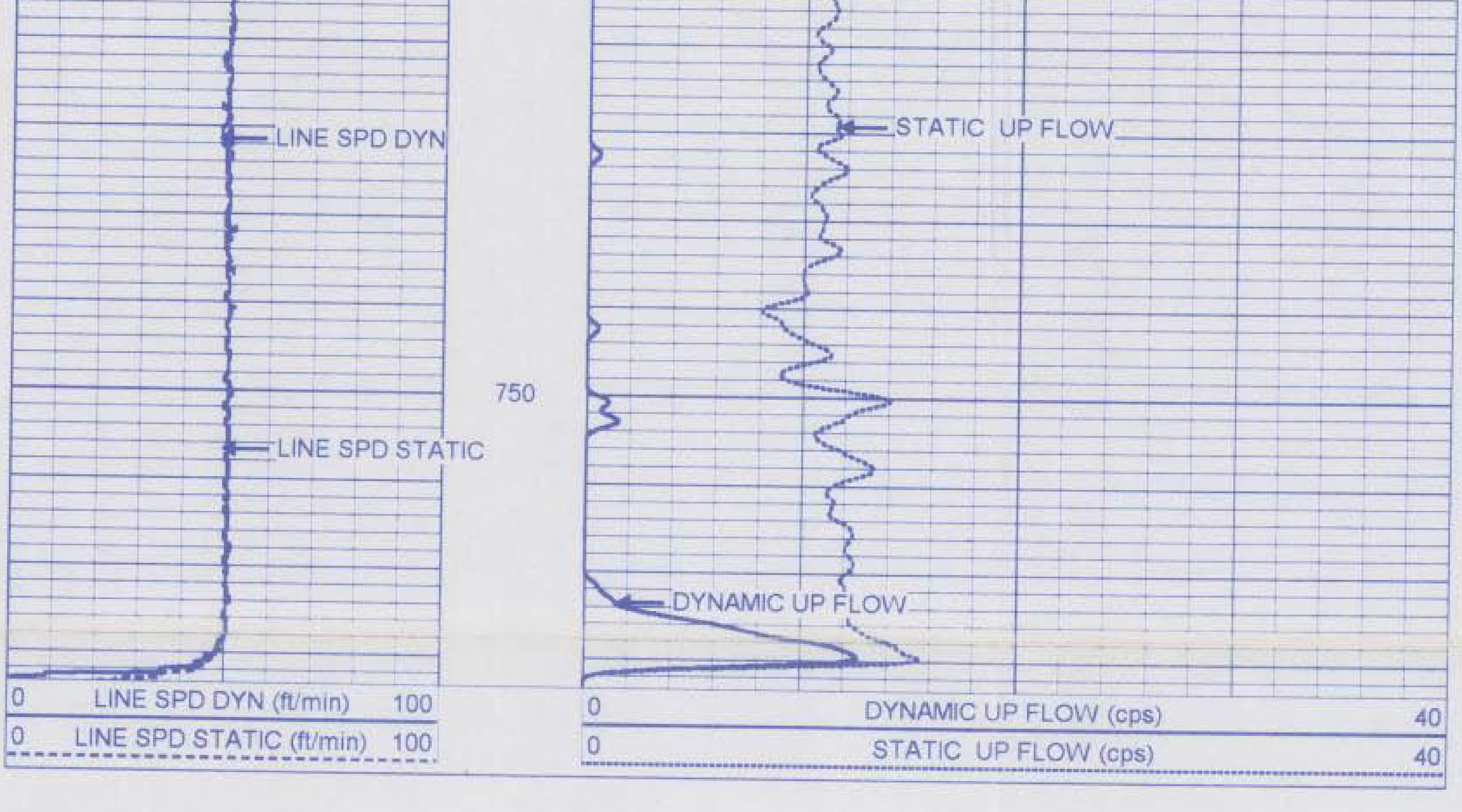



0 LINE SPD DYN (ft/min) -100 | 0 DYNAMIC DOWN FLOW (cps) 40
0 LINE SPD STATIC (ft/min) -100 | 0 STATIC DOWN FLOW (cps) 40

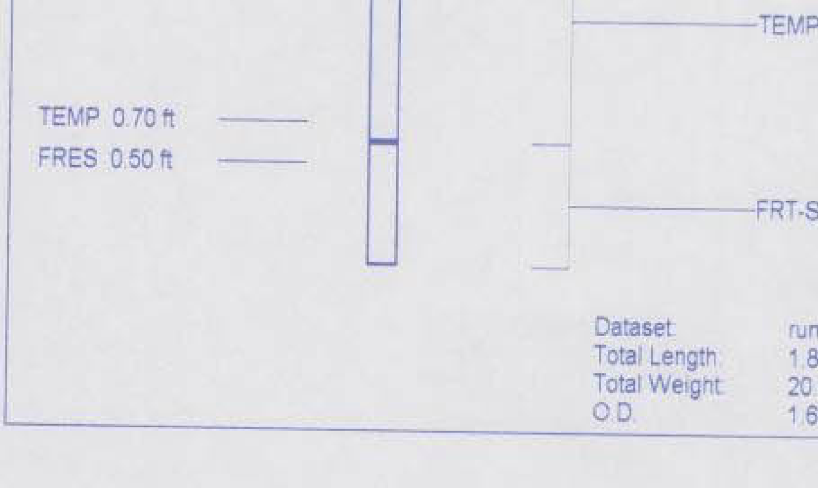
## FLORIDA GEOPHYSICAL LOGGING, INC. — UP MERGED 448 GPM

Database File: rwasr2.db
Dataset Pathname: run3/pass15
Presentation Format: fm_upmg.prs
Dataset Creation: Fri Aug 27 15:50:01 1999 by Log VER_5.4
Charted by: Depth in Feet scaled 1:240

0 LINE SPD DYN (ft/min) 100 | 0 DYNAMIC UP FLOW (cps) 40
0 LINE SPD STATIC (ft/min) 100 | 0 STATIC UP FLOW (cps) 40




0 LINE SPD DYN (ft/min) 100 | 0 DYNAMIC UP FLOW (cps) 40
0 LINE SPD STATIC (ft/min) 100 | 0 STATIC UP FLOW (cps) 40




Dataset: run3/pass16
Total Length: 1.80 ft
Total Weight: 20.00 lb
O.D. 1.69 in