GM-1 Pilot Study Report

Prepared for

North Carolina LLRW Management Authority
116 Jones Street
Raleigh, NC 27603-8003

HLA Project No. 36595.301

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October 27, 1997

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February 27, 1998

Edward R. Burt, Ph.D.
Chief, LLRW Section
Division of Radiation Protection
Dept. of Environment, Health and Natural Resources
3825 Barrett Drive
Raleigh, NC 27609-7221

Re: February 1998 Revision Package for the GM-1 Pilot Study Report
NC Low-Level Radioactive Waste Disposal Facility Project

Dear Dr. Burt:

Enclosed are 15 copies of the above-referenced information, prepared in response to the 12 and 13 November 1997 Topical Meeting on DP-1 and the 20 November 1997 LWP-SC meeting. The package consists of additions and revisions to the 27 October 1997 document in the form of errata sheets or new inserts. The following items are provided, with instructions regarding their incorporation in the report.

- Replacement Table of Contents, reflecting revisions
- Insert Plates D1 through D4 providing a comparison of Wellbore images, graphic core logs, and core photographs of four mapping units in W205CH1. These color oversized plates are provided as a roll and we have included sleeves in the event the report recipients wish to fold and store these plates in a 3-ring binder format.
- Replacement page 5-6 with updated text on faults and introducing new section 5.1.1.4
- Insert text pages 5-6a through 5-6c, which include a new section 5.1.1.4 - Comparison of Wellbore Logging Techniques
- Replacement Figures 5-1 through 5-4 along with copies of old figures marked "superseded"
- Insert plates 5-1A and 5-1B consisting of cross sections GMA-A' and GMB-B', respectively
- Insert figure 5-9a consisting of the location map for the geologic cross sections
- Insert text pages 5-18a and 5-18b which discuss correlation along strike and cross sections GMA-A' and GMB-B'.
- Replacement text page 6-3 with updated text
- Replacement Figures A-2-4, A-2-5, A-2-6, A-2-8, and A-2-9.

Replacement pages supersede existing sheets, the latter of which should be discarded. Insert pages and graphics are designed to fit into the existing numbering or pagination schemes without disruption.

The revisions and additions contained herein along with the "Revised Summary Report for Decision Point 1" comprise our agreement to complete revisions to the documentation of the DP-1 submittals. We understand that you will distribute both the attached documents and the Revised Summary Report (provided under separate cover) to the appropriate persons including representatives of both Wake and Chatham counties.

If you have any questions or need additional information, please give the undersigned or Mr. Eric Lappala a call at 919.481.1660.

Sincerely,

HARDING LAWSON ASSOCIATES

Vernon E Keys

Vernon E. Keys
Project Manager

Enclosure
15 copies

2c w/encl:	Walter Sturgeon, NCLLRWMA
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1c w/o encl:	Kathryn Haynes, SE Compact Commission

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APPENDICES

1.0 INTRODUCTION

This GM-1 Report documents the field activities, the data analysis, and the data integration completed along the GM-1 Pilot Study Investigation Area (Study Area) by Harding Lawson Associates (HLA) and their subcontractors. The report describes the scope of the field activities, explains the data synthesis and integration process, and develops the hydrogeologic conceptual model along the GM-1 Trench. The report outlines the detailed steps taken to arrive at the definition of mapping units and the correlation of these units along the GM-1 cross section. It explains the rationale for the recommended set of hydrogeologic investigative tools, and the conceptual strategy and current thinking of HLA regarding the Supplemental Investigation Program (SIP).

This report one of several DP-1 Work Product Deliverables that have been developed to accomplish the objectives set forth for DP-1 in the Licensing Work Plan. This report refers to documents and deliverables previously provided to the Division of Radiation Protection (DRP) of the Department of Environment, Health, and Natural Resources (DEHNR) under separate cover, and which contained additional detail of the technical aspects discussed in this report. All technical issues pertinent to the GM-1 Pilot Study are addressed in this document; however, the reader may find additional detail in some of the previous work product deliverables associated with the individual technical topics. All pertinent data associated with the GM-1 Pilot Study Program have been included in the Project Database or have been transmitted in paper form to the DRP review team.

1.1 Background

Prior to the implementation of field activities, considerable effort and technical planning were applied to develop the appropriate plans and procedures needed to guide the implementation of the many field investigation techniques, to insure reproducibility, and to allow for the Quality Control and Quality Assurance of the technical information compiled. Draft technical procedures were produced and distributed to the DRP review team. After DRP review, a telephone conference was held among the principal author(s) of each technical procedure, an HLA project management team member, and the principal DRP reviewers, to discuss their comments and to resolve any major differences regarding the implementation of each field technique. The final technical procedure for each investigation technique was published after addressing all review comments. A total of 23 technical procedures and a Lexicon of Geologic Terms (the Lexicon) have been finalized and published.

The work plan for the GM-1 Pilot Study (HLA, 1997) provided the framework for the implementation of this proposed investigation. This work plan was designed using the following guidance: 1) the guidance letter provided by the DRP dated November 21,1996 and its associated attachment; 2) the guidance review meeting held with DRP on January 27, 1997; 3) technical discussions and comments from the DRP and its consultants during the GM-1 Planning Meeting held on February 18 and 19, 1997; 4) the Licensing Work Plan (LWP) dated May 31, 1996 and, 5) comments received from

DRP at a meeting held on March 12, 1997. At the GM-1 Planning Meeting, the preliminary geologic cross section along the existing GM-1 trench was shown and discussed with respect to various hypotheses related to hydrogeologic characterization of this area. These joint discussions led to the selection of the locations and depths for the proposed boreholes planned as part of the GM-1 study. The GM-1 Pilot Study work plan was delivered in draft form to the DRP on March 7, 1997, and technical comments from the DRP were incorporated into the final work plan issued on March 27, 1997. This final work plan represented agreement on both the scope of the activities to be performed, and the location and depth of the pilot study borings. The field activities conducted at the Site started on April 1, 1997 and most of the logging and packer testing activities were completed by the end of May, 1997. Surface geophysical surveying, trench mapping, and some additional borehole logging activities were completed in June, 1997.

During the process of data analysis and integration, the GM-1 project team conducted briefings and meetings with the DRP review team on the status of work and on specific technical topics as called for in the LWP. Table 1-1 summarizes the topical meetings held related to the GM-1 activities. Two meetings were held to discuss the substitution of various borehole imaging techniques for rock core obtained from conventional drilling techniques for the purpose of geological information compilation. Other technical meetings were conducted to give status reports on the sub-discipline topics such as vadose zone characterization and site groundwater geochemistry. A large amount of geologic information was integrated during the GM-1 Pilot Study regarding the lithologic character of the rocks encountered along the GM-1 cross section area. Geological integration meetings were conducted to review the core re-qualification process, trench mapping, GM-1 Pilot Study cross section correlations, and definition of mapping units.

1.2 Purpose of the GM-1 Pilot Study

As presented in the LWP, the primary objectives of the GM-1 Pilot Study are to:

- Evaluate the suitability of the investigative techniques and their protocols;
- Develop the methodologies and strategies for a comprehensive approach to the SIP;
- Delineate the mapping scale and correlation detail needed for site wide studies;
- Update hypotheses regarding the important hydrogeologic, geochemical, and engineering components of the site conceptual model; and
- Evaluate the convergence of integrated lines of evidence regarding site conditions.

1.3 GM-1 Pilot Study Program Overview

The GM-1 Pilot Study consisted of a program of surface and subsurface exploration activities. The surface program included trench mapping and a pilot seismic reflection survey. The subsurface program involved core and air rotary drilling, hydrophysical logging, borehole image analysis, borehole geophysical logging, hydraulic testing, geochemical sampling, core logging, and vertical seismic profiling. An overview of the program is given in this section. In general, the sequence of the subsurface testing and logging activities was completed as follows:

- Vadose zone sampling and casing installation;
- Bedrock coring and field core logging;
- Air rotary drilling at a 6.75-inch nominal diameter;
- Borehole imaging,
- Borehole geophysical logging;
- Hydrophysical logging; and
- Packer testing and geochemical sampling.

1.3.1 Trenching Program

The trenching program extended the previously mapped GM-1 trench west, to the western limits of the buffer zone, and east, to the borrow pits as shown in Figure 1-1. The trench provided near-surface exposures for evaluating the presence of faults, stratigraphic description, and fracture characterization. These features were measured, mapped, photographed, surveyed, and incorporated into a graphics package in order to produce a trench map at a scale of 1 inch = 5 feet. The trench map was employed extensively during the definition and correlation of mapping units along the GM-1 Pilot Study Area.

1.3.2 Drilling and Coring Program

The GM-1 drilling program consisted of nine boreholes, including seven 6.75-inch air rotary boreholes with depths varying from 115 to 465 feet (including the "rat" hole for logging tools), and two coreholes which were cored to 562 (W205CH1) and 515-feet (W208CH1) deep. After coring was complete, these two coreholes were reamed by air rotary methods to 6.75-inch diameter prior to logging and packer testing. W205CH1 was reamed to a total depth of 715 feet. The shallow, weathered portions of the holes were sampled continuously using a standard penetration test split barrel sampler and a split-tube coring method to provide geologic data through the cased portion of each hole.

The hole locations were selected, and agreed upon with the DRP review team, to provide overlapping stratigraphic coverage and to provide geologic control on the orientation of the W8 fault.

1.3.3 Geophysical Logging, Core Logging, and Borehole Imaging

A comprehensive program of borehole imaging and geophysical logging was performed for eight of the boreholes installed along the GM-1 Pilot Study. All geophysical logs were acquired in combination with a gamma ray (GR) measurement to confirm the accuracy of depth measurement through comparison with the gamma ray signature as it varies with depth. The following is a list of the geophysical tools/tool arrays run in the boreholes:

- Array Induction Tool (AIT),
- Borehole Image Processing (BIPS),
- Combinable Magnetic Resonance (CMR),
- Dipole Shear Imager (DSI),
- Elemental Capture Sonde (ECS),
- Formation Micro Imager (FMI),
- Natural Gamma Spectrometry (NGT),
- Platform Express (PEX), and
- Three-Arm Caliper (3-CPR).

Table 1-2 summarizes the distribution of the logging runs for each of the geophysical and imaging tools in each of the eight boreholes along the GM-1 Pilot Study Area. BIPS and caliper were run in one additional borehole (W201AR1B) which was drilled to demonstrate an alternative drilling technique.

One primary goal of the GM-1 program was to evaluate the ability of downhole imaging and geophysical logging to replicate, replace, or provide more information than rock core. Comparison of the geologic logs of the two coreholes with the geophysical logs and imaging data form the primary basis for this assessment of the adequacy of the downhole tools. In addition to the hydrophysical logging techniques, the GM-1 program results indicate that a combination of six logs best identify the hydrogeologic and lithologic characteristics of the subsurface units at the site. The six logs proposed for use as the standard suite during the supplemental investigation program include:

1. Spectral Gamma (Schlumberger's NGT, or equivalent tool from another contractor).

2. Three-Arm Caliper.

3. Neutron and Density (Schlumberger's PEX, or equivalent tool from another contractor).

4. Resisitivity (Schlumberger's PEX, or equivalent tool from another contractor).

5. High Resolution, Electrical Imaging (Schlumberger's FMI, or equivalent tool from another contractor).

6. Full Wave Form, Acoustic (Schlumberger's DSI, or equivalent tool from another contractor).

Additional tools and or techniques maybe utilized during the supplemental investigation program if conditions are encountered in the boreholes requiring further investigation. These tools and/or techniques may include BIPS, other standard borehole TV camera, Acoustic Televiewer, and/or the actual recovery of rock core within selected stratigraphic intervals.

1.3.4 Hydrophysical Logging Program

Upon reaching total depth in each borehole, water levels in the open borehole were monitored to estimate groundwater inflow rates. All boreholes with inflow rates exceeding 0.01 gpm, were hydrophysically logged to locate the depth of the inflow interval(s). If the filling rate did not exceed 0.01 gpm (or about 2 feet in eight hours), the hole was considered dry and no hydraulic testing of any type (hydrophysical or packer) was conducted at that location. This rate criterion was selected because it approximates the anticipated level of resolution for the hydrophysical logging. Only W208CH1 was found to be essentially dry.

Hydrophysical logging techniques were completed in eight boreholes along the GM-1 Pilot Study Area. The results of hydrophysical logging provided the project team with a definitive analysis of groundwater movement within the geologic strata encountered within the bores. A total of 27 yielding intervals were identified within the eight boreholes tested. The inflow rates for these yielding intervals ranged from 0.001 to 1.06 gallons per minute (gpm). The yielding intervals observed were concentrated in the upper 150 feet of the boreholes; however the depth of holes was not uniform. Of the 27 yielding intervals identified only five were below a depth of 150 feet. Most of those five intervals were in the hanging wall of the W8 Fault. No borehole inflow intervals were found below approximately 300 feet in depthThis suggests that the frequency of occurrence of borehole inflow decreases with depth, as determined by the hydrophysical logging. Nonetheless, the highest inflow rate was observed in W205CH1 at a depth of 158.1 feet with a cumulative flow rate of 1.1 gpm.

1.3.5 Packer Testing and Groundwater Sampling Program

Packer testing intervals were selected based upon the hydrophysical logging results. Consequently, all of the conductive features in all the boreholes were identified prior to the start of the packer testing. Packer testing was focused primarily on those features which exhibited the highest hydraulic conductivity, because these features are most important for characterizing the hydrogeology of the site. The packer testing results quantify the hydraulic properties and the hydraulic geometries of the inflow features delineated by the hydrophysical logging. A total of sixteen intervals were hydraulically tested using a packer to isolate specific intervals of the boreholes. The data obtained during the testing program provides important information for further refinement of the conceptual model for the site. The highlights from the packer testing program can be summarized as follows:

1) The relative ratings from the hydrophysical logging shows good consistency with the transmissivities derived in the transient analyses of the packer test data,

2) The transmissivities derived in the analyses range between 2.13E-09 and 7.14E-05 m^2/s,

3) From the five tests encompassing the highest rated conductive features, three show a restriction in flow after a homogeneous formation model that was matched with three no flow boundaries. The two other production tests were matched with a dual porosity formation model. The responses may also be equally well matched with a composite fractional dimension model showing a reduction in flow dimension away from the borehole. Additional geological and geophysical data is needed to discern which flow model is most appropriate,

4) The static formation heads show a decrease with depth based on the information from the three boreholes with more than one test, and

5) Boreholes near the pumping well were monitored by dataloggers to observe the interference responses to pumping. Only one observation well from the seven examined showed a response during any of the pumping periods.

To minimize geochemical disturbance, a complete log of all water additions and withdrawals from the boreholes was maintained during the drilling and coring activities. With some exceptions, all drilling fluids were recovered from the boreholes. Groundwater samples were taken in 19 intervals in seven of the boreholes during the packer testing activities. Time series groundwater samples were taken in eleven of these packer tested intervals. The groundwater samples were analyzed for major ions, pH, specific conductance, and selected isotopes. To the extent possible, the water levels in boreholes were maintained at their natural head values or lower to minimize injection of foreign water to the conductive zones.

1.3.6 Seismic Reflection Program

A seismic reflection program was completed and consisted of approximately 1000 feet along the GM-1 trench line and approximately 500 feet along a north-south line. The program was conducted to determine whether seismic reflection profiling can resolve stratigraphic and structural variations in sufficient detail, and to evaluate which combinations of energy sources and geophone spacings provide the best resolution. Seismic reflections could not be identified in the upper 0-50 milliseconds (ms) of two-way travel time at the GM-1 Pilot Study Site in spite of a tight survey designed to delineate the presence of shallow targets. Coherent noise and signal attenuation,were the primary impediments since the earth itself prohibited sufficient energy to be returned at high frequencies to resolve the near-surface reflectors.

1.3.7 Vertical Seismic Program

Vertical seismic profiling (VSP) was conducted in the upper 300 ft of W205CH1 hole, which was optimally located to integrate results of the VSP and the seismic reflection surveys. Processed VSP data yielded few reflections in areas of overlap with the seismic reflection sections.

1.3.8 Integration of GM-1 Program Results and DP-1 Assessments

The results of GM-1 Pilot Study Program have been integrated to address some critical technical questions including:

- Refinement of the hydrogeologic conceptual model along the GM-1 trench;
- Identification of a minimum set of site investigation tools for use in the supplemental investigation program;
- Delineation of the groundwater-conducting features and or hydrogeologic units
- Development of the geological controls on the nature and occurrence of groundwater
- Determination of the value of each hydraulic testing and geophysical tool for locating and extrapolating conductive zones.

The integration of the GM-1 Pilot study information indicates that groundwater occurs and moves within three related types of hydrogeologic features or units including the weathering zone (generally 40 to 80 feet bgs), along concentrated fractures which are sub-parallel to bedding, and within the fracture system of the hanging wall of the W8 fault. The hydrogeologic features controlling groundwater are summarized in the following:

1. The base of the weathered zone contains the greatest number of producing intervals, except in W205CH1 which is located in the hanging wall of the W8 fault. A producing zone is generally present at or just above the base of the weathered zone.

2. Fluid flow is dominated by the presence of open fractures. At shallow depths, the fractures tend to be sub-parallel to bedding (strata-concordant). In deeper boreholes, where data are available, the importance of bedding parallel fractures may decrease with depth due to the lithostatic load increase. In some cases especially in W205CH1 (W8 fault hanging wall), open high angle fractures appear to be the water conductors especially where the intersection of sub-horizontal and steeply dipping fracture sets occur. At greater depth, the more steeply dipping fractures may assume a more important hydraulic role.

3. In many cases, the permeable strata-concordant fractures occur at the contact between an upper, more permeable unit (usually sandstone) and a lower impermeable unit (usually mudstone or siltstone). These sandstones are relatively clean, well-sorted, coarse sandstones, that are often conglomeratic.

4. Strata-concordant features are difficult to isolate from permeable stratigraphic units such as sands. These strata-concordant features may be faults which accommodated differential slip during folding. Strata-concordant faults are mechanically more likely to occur along fold limbs and where large contrasts in rock mechanical properties occur across a contact.

5. Faults such as the W8 fault are clearly visible in image data and appear to be fluid flow conduits; their properties are likely to vary with orientation and position at the site. The flow conduits are likely to be associated with a several foot thick zone of more intense or more open fracturing adjacent to the fault.

6. Fractures inclined to bedding may also play an important role if they connect other features. These fractures are likely to be confined to individual units and to be truncated at bedding contacts. They may form in response to mechanical stresses associated with basin formation, with folding and/or with uplift. Several generations of these features are likely within this basin.

1.4 Report Organization

This document, the GM-1 Pilot Study Report, is an outgrowth of the implementation of the GM-1 Work Plan, subsequent meetings and correspondence with the DRP and their consultants, and internal technical discussions of the Project Integration Team (PIT). The opinions and interpretations provided in this report represent the integrated analyses of the entire project team, not those of a select few. Technical personnel from many firms contributed to the data collection and acquisition, and the technical analysis and interpretations detailed in this report. The team included Harding Lawson Associates, GeoMechanics International, Geological Resources, Applied Geosciences Inc., Golder Associates, LBG-Guyton Inc., University of South Carolina-Earth Sciences Research Center, Dr. Paul Thayer, University of North Carolina-Wilmington, Earth Data Inc., Colog Inc., Schlumberger Well Services, and McCall Bros.Drilling.

This document is divided into seven major sections and numerous subsections. Following this Introduction and Background, Section 2 summarizes the technical questions answered and the hypotheses tested, by the GM-1 Pilot Study activities. Section 3 reports the activities that were completed and describes the technical steps and procedures employed in data acquisition. Section 4 reports the data analysis and interpretation process with respect to the various techniques including: drilling hydraulic responses, the geophysical logging and borehole image data, hydrophysical and packer testing of the yielding intervals, groundwater geochemistry, and seismic data analysis. Section 5 describes the integration of hydrogeologic data for refinement of the GM-1 Pilot Study cross section. Section 6 presents a summary of the hydrogeologic conceptual model along the GM-1 Pilot Study, and Section 7 provides a list of references.

The report also contains a series of appendices that provide additional detail concerning the data compiled during the investigation. Many deliverables have been provided to the DRP review team during the data integration and analysis in the form of graphic logs, panel diagrams and montages, BIPS images, trench maps, and draft reports on the packer and hydrophysical logging test activities. The report contains a series of tables, figures, and illustrative plates that summarize interpretations regarding the hydrogeologic conditions along the GM-1 Pilot Study Area.

2.0 TECHNICAL QUESTIONS ADDRESSED BY THE GM-1 PILOT STUDY

As a part of the preparation for the GM-1 Pilot Study, an initial preliminary cross section was constructed along the existing GM-1 trench. This cross section was developed using the available data. The initial cross section was presented to the DRP review team at the GM-1 Planning Meeting. During the correlation and construction of this cross section, various technical issues and hypotheses were identified and were outlined in the GM-1 Work Plan. These critical technical issues, hypotheses, and questions were considered during the analysis and integration of the GM-1 Pilot Study results. Most of these issues and hypotheses are related to the refinement of the site conceptual model and to the applicability of the various investigative techniques for use in the SIP. The purpose of this section is to summarize the progress made in addressing these site specific hypotheses and technical questions. Note that the preliminary cross section described above was revised based on data collected during the GM-1 Pilot Study. A detailed discussion of the development of this cross section is presented in Section 5.0.

2.1 Hypothesis Refinement

The hypotheses identified in the GM-1 Work Plan and the current thinking of the Project Team are summarized in the following:

1. **There exists a set of geologic, geophysical, hydrologic and geochemical techniques which in combination allow characterization of the GM-1 area.**

The analysis and the integration of the geophysical logging and image data indicate that six logging techniques can provide sufficient hydrogeologic, lithologic, and fracture information to characterize the site conditions. These techniques include:

- Three-arm caliper,
- Full wave form acoustic,
- High resolution electrical imaging
- Density/neutron,
- Spectral gamma, and
- Resistivity.

This series of six geophysical and imaging techniques has been recommended as a part of the standard logging suite for the SIP. These techniques, in combination with both hydrophysical and hydraulic packer testing of the identified inflow zones, will compile a sufficient data set to allow the appropriate hydrogeologic characterization of the site. Surface geophysical surveying did not definitively delineate reflectors in the GM-1 Study area at shallow depths. Therefore, the widespread use of this technique in the SIP, is not justified.

2. **Integrated data from these techniques identify a set of mappable geologic units and their scale.**

Each map unit is characterized by a distinctive lithofacies assemblage and vertical profile. Five map units are recognized based on data derived from core logging, trench mapping, and geophysical logging:

- (U_f) upward fining sequences, generally consisting of conglomerate and sandstone at the base with mudstone at the top;
- (M_s) massive mudstone with minor sandstone;
- (S_m) massive sandstone with minor mudstone;
- (S_{wb}) well-bedded sandstone with minor mudstone; and
- (M_{wb}) well-bedded mudstone with subordinate sandstone.

While the definitions of the map units are primarily based on lithofacies associations, they also incorporate geophysical response criteria. A detailed description and discussion of development of the map units is presented in Section 5 1 1. Based on evalutions conducted during the GM-1 Pilot Study, the scale required for the identification of map units varies depending on the data source being used. Lithologic logging of core or trench exposures at a scale of 1 inch equals 5 feet provides sufficient detail for recognition of all map units. However, map units can best be recognized from geophysical logs at a scale of 1 inch = 10 feet.

3. **The integrated data set along the GM-1 Pilot Study area determines the correlation scale of mappable geologic units.**

Two approaches were used for stratigraphic correlation: 1) using geophysical logs and the trench cross section, and 2) using graphic core logs and the trench stratigraphic column. These two approaches were used to assess the reliability of using geophysical logs for correlation during the sitewide investigation. A detailed discussion of the correlation process is presented in Section 5.4.1.

Using the first approach correlations, were made by matching patterns on the gamma-ray and resistivity (primarily useful east of the W8 fault) logs between boreholes, followed by matching major (thicker) rock units between trenches and nearby boreholes. Rock unit matching was constrained by bedding orientation data collected from the trenches and the FMI logs. Following the correlation of lithologic units, these were grouped to define larger-scale map units that are associated with distinctive gamma-ray log patterns. Once map units were defined, it was found that they could be correlated more reliably than individual rock units.

Using the second approach correlations were made using the graphic logs for W205CH1, W208CH1, and the requalified logs in conjunction with the trench graphic log. Correlations were made by pattern matching of various rock units in conjunction with their lithofacies designations. Using this approach, only minor revisions in correlations and map unit definitions made using the geophysical logs were required. Therefore, graphic core logs are not considered necessary for correlation of mapping units. Although lithofacies were initially helpful in defining mapping units, the addition of lithofacies is also not considered necessary for future defining of map units and correlating stratigraphy.

In addition to lithofacies, diagenetic and biogenic features were also added onto the cross section to assess whether these features are important for correlating or whether they are diagnostic of water-producing intervals. Based on results of the GM Pilot Study (described in detail in Section 5.0), diagenetic and biogenic features do not appear to be a valuable aid in making correlations nor can they be used to predict the location of producing intervals.

Success in defining lithologic groups by means of borehole imaging and geophysical logs suggests that, during the sitewide investigation, stratigraphic interpretations and correlations can be made using only borehole imaging and geophysical logs if boreholes are spaced closely enough. In comparing the various scales of data, it was found that lithologic correlations are best made at a scale of 1 inch = 10 feet using both approaches described above.

4. **The integrated data set will allow the identification of significant hydrologic features and the determination of their hydrologic properties.**

Hydrophysical logging is the one of the better techniques available to determine the inflow rates and intervals in extremely low transmissive hydrogeologic systems. Discrete inflow intervals separated by as little as one foot were detected using this technique along the GM-1 Pilot Study area. Hydrophysical logging also provided inflow rate estimates that give the relative contribution of each permeable interval to the overall borehole inflow.

Results of the hydrophysical logging exhibited 27 inflow intervals with inflow rates ranging from .0001 gpm to 1.06 gpm. The distribution of conductive features shows that they are concentrated in three primary areas; within the weathered zone as defined by geophysics, along strata-concordant fractures, and within the hanging wall and adjacent to major faults. Most of the conductive features were observed to occur within and at the base of the weathered zone.

The increased number of conductive features in the weathered zone is interpreted to be a result of enhanced secondary porosity/permeability due to chemical weathering, or to enhanced fracturing as a result of isostatic unloading.

A conductive features was identified at or near the base of the weathered zone in every borehole except W206AR1, indicating that this contact may be a preferential pathway for groundwater flow.

Below the weathered zone, conductive intervals identified during hydrophysical logging occur primarily along strata-concordant fractures or high-angle fractures in sandstones, except in W205CH1. In W205CH1, conductive features were also identified to occur within some of the finer grained units. Hydraulically significant strata-concordant fractures (i.e., greater than .1 gpm) below the weathered zone generally occur at the contact between coarse-grained to conglomeratic sandstones and underlying siltstones or claystones. These strata-concordant fractures are most likely a result of slip along these surfaces to accommodate stress associated with faulting. Based on the hydrophysical logging, there are examples of significant strata-concordant fractures that did not produce flow during the hydrophysical logging. An example is at 90 to 100 feet in W204AR1. Although this sandstone is characterized by a strata-concordant fracture at its base, it did not produce measurable inflow. This sandstone in W204AR1 has a higher clay content than the correlated sandstone in W205CH1 based on the geophysical log response; and probably as a result, did not produce measurable yield from that interval.

The fault zones are also interpreted to be zones of higher connectivity. W205CH1, located on the hanging wall of the W8 fault, had the greatest number of producing features and higher porosity zones in the GM-1 Pilot Study area. Although several conductive features were identified in the weathered zone in W205CH1, several conductive features were identified along both strata-concordant fractures and as high-angle fractures within sandstones and claystones below the weathering zone. As indicated from the BIPS, FMI, and Stoneley waveforms, this borehole exhibits extensive fracturing throughout the vertical section, with an extremely high density of fractures approaching the W8 fault and for some depth beneath it. The high density of fractures is interpreted to be a result of fracturing associated with the hanging wall of the W8 fault.

Packer testing was conducted for intervals where hydrophysical logging identified a conductive feature. The packer testing results indicate that the transmissivity (T) within the weathered zone ranges from 10E-6 to 10E-8 meters squared per second (m^2/s) with the higher values being measured in weathered bedrock sands. The highest T values below the weathered zone (10E-5 m^2/s) were measured in the two strata-concordant fractures which produced in W205CH1 (i.e., 129 and 159 feet bgs) and in the high-angle fracture which produced in the same borehole at 270 feet bgs. The second highest yielding fracture (0.69 gpm at 159 feet in W207AR1) also had a T value of 10E-5 m^2/s. The sandstones above the strata-concordant fractures have estimated effective porosities of up to 8 percent based on the CMR and ELAN logs. Thus, the higher T values in these zones may be a result of both fracture porosity and secondary porosity in the sands. T values elsewhere in the unweathered zone ranged from 10E-5 to 10E-9 m^2/s.

2.2 Technical Questions Related to the GM-1 Pilot Study Activities

Many of aspects of these hypotheses can be framed as technical questions. Two categories of technical questions were outlined in the GM-1 Work Plan: 1) those related to investigative techniques and 2) those related to the conceptual model along the GM-1 Pilot Study. Many of these technical questions are discussed in greater detail within the data analysis (Section 4.0) and data integration and interpretation sections of this document (Section 5.0). Some of the more pertinent questions are briefly summarized below.

2.2.1 Technical Questions Related to Investigative Techniques

1. **Is there a single investigative technique or combination of multiple techniques that provides information sufficient to replicate, replace or improve upon information previously obtained through collection of rock core?**

In additional to the hydrophysical logging and packer testing techniques, a combination of six standard logs best identify the hydrogeologic and lithologic characteristics of the subsurface units at the site. The six techniques proposed for use as the standard logging suite during the SIP include:

- Spectral Gamma
- High Resolution Three-Arm Caliper
- Neutron and Density
- Resisitivity
- High Resolution, Electrical Imaging
- Full Wave Form, Acoustic

Additional tools or techniques may be necessary, such as BIPS, during the SIP if conditions are encountered in the boreholes requiring further investigation. These techniques will be integrated along with standard field and trench mapping techniques, core logging of the cased interval, requalification of selected core, limited core drilling (as called for in the LWP) as necessary to calibrate the geophysical logging, and imaging in the western portion of the SIP focus area. Baseline water level monitoring, and groundwater and surface water sampling and analysis will also be conducted during the SIP.

2. **Are the logistical requirements for proposed investigation techniques compatible with each other and the planned scope of the site-wide characterization studies?**

Site access to drill sites, trench weather protection, and the delivery of water for core drilling were the largest logisitical problems encountered during the GM-1 Pilot Study. For the SIP, the trench mapping and subsequent review will have to be more timely and better coordinated with the DRP review teams. The use of a physically closer "water source" for the drilling and coring may need to be considered. The geochemical impacts of the water source will need to be reviewed with the project geochemists. The sequence of well testing and well construction implemented in the GM-1 Pilot Study worked well. The sequence of logging in each borehole will be more simplified because of the elimination in most boreholes of the BIPS technique. The general proposed sequence for well installation and testing is anticipated as follows:

- Construct required drill site access
- Conduct continuous split spoon sampling and/coring to set casing
- Conduct air rotary percussion drilling with the addition of site groundwater during drilling
- Allow a borehole water level recovery period or if needed, addition of site groundwater for geophysical logging
- Conduct geophysical logging and imaging surveys
- Conduct hydrophysical logging
- Conduct packer testing and groundwater sampling
- Perform monitoring well construction and monitoring

3. **Are the data processing, display, analysis, and integration requirements for each investigative technique compatible with the scope, schedule, and data management plans for the site-wide characterization effort?**

The data management and processing steps implemented during the GM-1 Pilot Study need improvement to provide a more real-time exchange of preliminary data. HLA and the project team are evaluating more efficient methods of data transfer from the field to the data analysis teams and are minimizing the number of ditigal format changes required for entry to the database and/or other analysis software packages.

2.2.2 Technical Questions Related to Understanding of the Site

1. **Does the combination of hydrophysical testing and interval packer testing adequately profile transmissivity and allow the identification and characterization of zones of higher hydraulic conductivity?**

Hydrophysical logging in combination with specific interval packer testing provides the detailed analysis of the flow characteristics of individual boreholes. Integrating the data from a combination of water level response monitoring during drilling, hydraulic testing, and hydrogeologic analysis of the mapping units from the geophysical logging and imaging tools, the transmissivity and connectivity profile can be extrapolated between holes for a detailed site characterization. In addition, further study of the transmissivity and connectivity profile will be done in the SIP through tracer and interference testing.

2. **Does the hydraulic information collected (in concert with geochemical, water level and/or other data) provide additional insights into the possible geometry and/or interconnection of these significant hydrogeologic features?**

During drilling of W205CH1, water level response to both water additions and water withdrawal were observed at significant distances (510ft) along strike at the W8MC12 location. This interference response occurred when the boring had penetrated the clean sandstone located at a depth of approximately 157 ft bgs. These strata-concordant zones appear to be well connected, at least on the order of 500 feet along the dip direction and a comparable distance along the strike of the beds.

3. **Can more definitive correlations be made in the GM-1 area between hydraulic characteristics, such as permeability or water loss intervals and geologic characteristics such as lithology, weathering, degree of fracturing or proximity to fault zones? Also, are the significant hydraulic features identified correlatable to specific geologic characteristics identified in the core logging and/or borehole logging techniques?**

The weathered zone contains the greatest number of producing intervals, except in W205CH1 which is located on the hanging wall of the W8 fault. A producing zone is generally present at or just above the base of the weathered zone. The depth of hydraulically significant weathering can be assessed by identifying a change in rock matrix based on the porosity logs, the density log, the sonic log, and the caliper log. The log analysis indicates this zone to be higher in porosity, lower in acoustic velocity, and comprised of lower density geologic materials.

Analysis of both the geophysical and image tool results in combination with the hydrophysical logging indicate that fluid flow appears to be dominated by open strata-concordant fractures, particularly at shallow depth. Based on data from W205CH1, there is evidence that the hydraulic importance of the bedding parallel fractures decreases with depth as the lithostatic load increases. At greater depth the more steeply dipping fracture set associated with high-angle faults may assume a more important hydraulic role.

In general, the hydraulically significant strata-concordant fractures occur at the contact between an upper, more permeable unit (usually sandstone) and a lower impermeable unit (usually mudstone or siltstone). These sandstones are relatively well-sorted, coarse sandstones, that are often conglomeratic. It is difficult to determine whether inflow at a given location is more dependent on strata-concordant fractures or on a lithologic unit that is relatively more permeable or more porous than the surrounding lithologies.

Near the W8 fault a fractured rock zone associated with the hanging wall of the fault acts as a fluid flow conduit. Fractures inclined to bedding may also play an important role if they connect one bedding-plane fracture to another.

4. **Can the data from some or all of the various investigations be integrated into converging lines of evidence to support one or more hydrologic conceptual models of the GM-1 area, and, by analogy, other parts of the Site?**

Integration of the data from the drilling, hydrophysical logging, geochemical analysis, water-level monitoring, geophysical logging and image analysis demonstrate the presence of three important types of hydrogeologic features or units: 1) the weathering zone unit 2) sub-parallel to bedding conductors, and 3) the fractured zone associated with the hanging wall of the W8 fault. Results of the GM-1 Pilot Study and correlation along the GM Trenches have identified the presence of five mapping units which have a characteristic geophysical signature.

5. **Are the stratigraphic correlations presented on the preliminary GM-1 cross section enhanced by information collected during the GM-1 work ?**

A comparison of the the preliminay and the final cross section produced with this report indicate substantially more detail to the correlations; however the initial correlation across the GM-1 Pilot Study Area did not significantly change.

6. **Are the most identifiable, extensive "mappable units" at the site the thick sections of fine grained siltstones, mudstones and claystones? Do the concepts of "stratigraphic sequences" or "packages" aid in the stratigraphic correlation?**

Considerable detail has been added to the GM-1 cross section since its preliminary construction. The cross section has integrated both stratigraphy, lithofacies associations (i.e., mapping units), and structural data along with hydrogeologic yield and inflow information from the packer and hydrophysical testing data. Five mapping units were delineated based upon the trench map, geophysical logs and images, and the core from W205CH1 and W208CH1. Each map unit is characterized by a distinctive lithofacies assemblage and vertical profile. The five units include: 1) upward fining sequences (U_f), generally consisting of conglomerate and sandstone at the base with mudstone at the top; 2) massive mudstone with minor sandstone (M_s); 3) massive sandstone with minor mudstone (S_m); 4) well-bedded sandstone (S_{wb}) with minor mudstone; and 5) well-bedded mudstone (M_{wb}) with subordinate sandstone. The thick sections of finer-grained rocks make up approximately 50 percent of the strata in the GM study area. It is likely that these units will carry greater distances away from the GM cross section than the coarser-grained materials. The development of stratigraphic "packages" did aid in conducting stratigraphic correlations and will allow for more reliable correlations on a sitewide basis.

7. How can such "mappable units" be projected laterally away from the trench (along strike) to other known observations in boreholes or trenches?

A geologic map has been revised along the GM-1 Pilot Study area using the delineated mapping units and the trench map. Successful projections along strike on the order of 500 feet to the W8 cluster were correlated using the trench map and the mapping units.

8. Are the topographic variations in the vicinity of the GM-1 trench related to lithology or geologic structure as exposed in the trench or in borings? If so, can a geomorphologic analysis adequately refine geologic mapping in areas lacking in extensive exposure or subsurface investigations?

The location of certain drainages across the site was hypothesized to be controlled by the presence of major faulting. Comparison of the revised geologic map and the trench maps along the GM-1 Pilot Study Area and the apparent absence of faults in the topographic lows indicate that the topography is more likely controlled by stratigraphy rather than by structure. A correlation does exist between topographic saddles and strike-parallel drainages in the GM Pilot Study area which are underlain by fine-grained units such as mudstones. Similarly, topographic highs and ridge-lines tend to correlate with thicker sandstone units mapped in the trenches and on the geologic map.

9. Can the shallow seismic reflection technique resolve "mappable units", individual key reflectors and/or important structural features between boreholes? Is the additional information gained considered substantive and cost-effective?

During the source tests and walkaways, very low signal-to-noise ratios were observed. Attempts to increase these ratios, including stacking and filtering, made only small improvements. When such low ratios are inherent in seismic data, subsequent use of the data is limited. The major limitation, namely the inability to interpret laterally continuous beds, is due to the loss of coherency. Loss of coherency occurs due to near-surface inconsistencies or discontinuous geology. As the source energy passes through the earth, its strength is reduced. The more reduced or attenuated the signal strength becomes the less coherent the recorded signal.

Due to the low signal-to-noise ratio and narrow bandwidth of the data, enhanced processing was deemed necessary. The raw data were sent to Sterling Seismic Services, Ltd. (Sterling) for processing. Careful muting of the near-surface "noise" signals was a necessary step in the processing. Since these signals are of a much higher amplitude than other desired signals down the record, allowing them to remain in the data is counterproductive. Since the overall quality of the seismic sections is fair at best, further processing in terms of migration to depth was deemed inappropriate due to the time and expense without expectation of gaining significant additional information.

The limits of resolution of the seismic data are subject to interpretation. The horizontal resolution was estimated to be around 80 feet to 150 feet. The vertical resolution is somewhat more difficult to calculate. Given the insensitivity of the data to changes in frequency and velocity, the errors in vertical resolution increase greatly with depth. From 0 to 200 feet the vertical resolution may be approximately 15 to 25 feet, but from 200 to 400 feet below ground surface the resolution is on the order of 70 to 80 feet. Since the useable data is largely below 125 feet, the vertical resolution is approximately 70 feet at best.

Interpretation of the seismic data was performed by identifying packages of reflections on the seismic section. Due to the need to reduce near-surface signals (muting) to eliminate unwanted returns such as refractions, ground roll and wide-angle reflections, the first interpretable reflections begin at approximately 40 milliseconds (msec) or approximately 125 feet below ground surface. Rigorous and exact correlation of seismic reflections with known geologic units was difficult, mainly due to lack of coherency (caused by the non-uniform near-surface) and also due to the truncation of reflections at the 40 msec level (caused by the removal or muting of much of the data from 0 to 40 msec or so to remove unwanted noise). The focus was placed then on identifying groups or packages of reflections that would indicate the overall dip of the beds, larger scale faulting, and other structural features such as folds. A total of six packages of reflections have been interpreted from this data set. The seismic data interpretations are limited in corroborating the geologic interpretations and provided help only in delineating larger-scale structural features such as the syncline/anticline and the possible fault zones. Since the data lack coherency and therefore continuity and confidence, even detailed work with synthetics would be limited in application to the area immediately adjacent to the borehole. For the objectives of the seismic survey, namely to bridge the data gap between the trench and the boreholes above 150 feet, continued seismic surveying is not indicated.

10. Does the VSP survey add substantially to the quality of the existing deep seismic reflection data set and its interpretation?

The processing and results are discussed in the Blackhawk report (Appendix 4.6.A.). In summary, the use of the vibratory source severely limited the first arrival identification in the VSP data. This limitation affected subsequent calculation of engineering parameters along with velocity and time data for processing the entire VSP data set.

Processed VSP data yields few reflections; there are two that are notable - one at approximately 55 msec and one at 25 msec. Both of these reflections are above the zone of interpretable data on the CDP sections.

11. Does the collection of continuous core in the soil and weathered rock section above the depth to base of the casing provide substantive, cost effective information for the geologic and/or hydrologic characterization of the Site or engineering design evaluations?

The continuous sampling performed in the cased intervals of the eight borings installed for the GM-1 Pilot Study provided excellent lithologic information of the shallow vadose zone. No engineering tests were planned or conducted on GM-1 Pilot Study samples; however, the sampling and coring techniques employed do enable samples to be submitted for standard geotechnical laboratory testing.

3.0 SUMMARY OF GM-1 PILOT STUDY ACTIVITIES

This section provides an overview of activities performed during the GM-1 Pilot Study and details the technical steps and procedures employed in data acquisition. This activity summary consists of nine subsections addressing the following elements: Trenching, Drilling and Coring, Borehole Imaging and Geophysical Logging, Hydraulic Testing, Geochemical Sampling, Seismic, and Data Management and Quality Control

3.1 GM-1 Trenching Program

The objective of the Geologic Trench Mapping (GM) program is to establish a continuous stratigraphic description over approximately 4000 feet along an east-west line bisecting the original footprint and buffer zone (Figure 1-1). Along this interval, the beds generally dip from 15° to 20° east, thus the trenches provide a near-surface reference for rock units and structural elements encountered at depths up to several hundred feet in boreholes. The trench mapping was conducted under the supervision of Dr. Jerry Bartholomew of the University of South Carolina - Earth Sciences Research Center, a subcontractor to HLA.

Subsequent to the start of the GM-1 Pilot Study, the configuration of the facility layout was changed. This was the result of the findings in Decision Point 2. (See Section 5 of the Summary Report for Decision Point 1.) Throughout the text and illustrations in this report, references are made to the original site layout and buffer zone since it was the basis for location of the pilot study activities. Subsequent to this report, the new area of focus and/or facility layout will be referenced.

3.1.1 Trench Location

GM trenches were mapped to provide continuous stratigraphic sections at specific locations across the site. The new trenches mapped during the GM-1 Pilot Study (GM-2 through GM-4) extend from the east and west ends of the original, 2000-foot-long, GM-1 trench which was mapped during a previous study. Therefore, the four trenches provide a continuous stratigraphic section from the west end of GM-3 to the east end of GM-4, with the exception of Site Road 4, near Borehole W206AR1. Beginning at 440 feet E (east) in GM-4, that trench deviates from the east-west trend and bears approximately S 60° E to the end of GM-4 at 663 feet.

3.1.2 Trenching and Mapping Methods

Trenching and mapping were conducted in accordance with Technical Procedures (TP) TP-4 (Surveying), TP-6 (Trench Excavation), and TP-9 (Trench Mapping and Documentation). Trenches were opened with a backhoe equipped with a 4-foot-wide bucket. The bottom of the opened trench was one bucket width. Field personnel coordinated with the backhoe operator, and suspended digging approximately every 15-20 feet to ensure that an appropriate depth was maintained such that less-weathered, recognizable bedrock was observable in the bottom of the trench. If unique features such as faults or folds were encountered, the Trench Project Field Geologist made local adjustments to depth to ensure adequate examination of such features. At any specific time, the portion of the trench length which was being actively mapped was kept covered by a tent to provide adequate cover/protection from rainfall.

Once the required length was opened, with benching and/or bracing provided where needed and access areas provided approximately every 25 feet, the south wall of each trench was scraped to remove all bucket marks and smeared material. Five-foot intervals were then located along each south trench-wall using a 6-foot level. These locations were numbered sequentially from west to east (0 foot E, 5 feet E, 10 feet E, 15 feet E, etc.) and were marked with 3 x 5 inch cards and a piece of pink tape, both imprinted with the trench number and the 5-foot interval number. The 3 x 5 inch cards and the pink tape were secured into the wall using 8 inch (or longer) spikes.

Trench mapping was conducted by the Trench Project Field Geologist (TPFG) and the Assistant Field Geologists under the direct supervision of the TPFG. Each individual mapped a specific type of feature (lithologic contact; fracture, etc) along that portion of the trench; and all mapped features were checked by the TPFG. The mapping began with the identification and marking of the contacts between the completely weathered rock, the lower limit of very severely weathered rock, and the individual lithic units. The boundary between completely weathered rock and very severely weathered rock was marked by a series of nails ornamented with green tape (yellow tape was also used for this boundary in the first 200 feet of GM-2 and the first 100 feet of GM-3). This boundary was placed at the base of brown or brownish gray soil which was lacking a relic rock fabric. The boundary between very severely weathered rock, which exhibits some lithic fabric but may have significant clay and degraded characteristics, and severely weathered rock was delineated using white tape and nails. This boundary was placed at the base of abundant subhorizontal clay surfaces within recognizable rock fabric.

The boundary between individual lithic units was defined using nails ornamented with orange tape. A larger nail, ornamented with a wider (2 inch) orange tape bearing the number and trench designation of the unit was placed within each unit at the location chosen to be described as representative of that unit. A separate larger nail, also ornamented with a wider (2 inch) orange tape bearing the unit number with the letters "SW" and the trench designation, was also placed within the very severely weathered portion of each lithic unit (any part of the unit above the boundary marked by the white-taped nails). This location was chosen to be described as representative of the soil characteristics of the very severely weathered portion of that lithic unit.

Fractures (e.g., joints, faults, clastic dikes) were delineated using blue tape on at least two nails at the top and bottom of each fracture. A larger nail with blue tape marked with the fracture number was placed near the middle of each fracture which was described. In the eastern end of GM-4, different fracture sets were delineated using variously striped tapes.

Once all features within a specific portion of a trench (generally 100-200 feet) were marked by tapes/nails, then photographs were made of each five-foot interval. The photographs were developed the same day or the next day and two sets of prints were made. The photographs were labeled on the back to show the trench number, interval or feature photographed, the date, and the name of the photographer. One set of photographs was then set aside, unmarked, so that the photographic record preserves the trench in pristine condition in case of weather-induced changes. The other set of photographs was used to mark all contacts, fractures and other features which were mapped, delineated by decorated nails, and/or labeled. This set of photographs provided a record of the actual features mapped and surveyed, and served as a verification tool for the preparation of the computer-generated trench-maps.

After delineating the units and features, the lithic units were described. Description terminology for soils, lithic units and fractures was in accordance with the project Lexicon. Strike and dip measurements (plus pitch if appropriate) were measured for each fracture. All data for units and fractures were recorded in an electronic spreadsheet format. Spatial location of all trench elements, nail by nail was accomplished by use of laser surveying equipment (a 'total station'). The survey data were downloaded into a programmable Hewlett-Packard calculator, and subsequently imported into a spreadsheet.

The survey data for each surveyed location contained the following elements:

- Survey station number,
- Northing,
- Easting,
- Elevation, and
- Text description, indicating station type (unit contact or description, fracture or description, five-foot markers, soil contact, [severely] weathered contact or lithic inclusion in soil.)

These elements are imported into an Excel Workbook (spreadsheet) and sorted by type (unit contact, soil, fracture, etc).. Each type was imported separately, as individual points, into a Intergraph Microstation software to form an in-situ template for drawing the trench section. Because the orientation of the trench was nearly east-west along most of its length, Northing values were set to zero, Easting values were considered as "X" coordinates and elevation as "Y" coordinates. In the far eastern end of trench GM-4, which diverged at an angle of approximately 30° from the original orientation in order to avoid a power line, the hypotenuse projection onto the east-west line was plotted as the "X" coordinate. To construct the cross section, points of each separate type were connected, using different colors generally corresponding to those used in the trench mapping. The trench photographs were used as a quality control both to verify that contact and fracture lines were accurately constructed and to determine appropriate labels for units and fractures.

The Excel Workbook data for GM2, GM3 and GM4 are located in Appendix A-1. Each Workbook contains the following information: lithologic description abbreviations, lithology, soil abbreviations, soil descriptions, fracture abbreviations, fracture descriptions, photography log, and bed orientation.

3.1.3 Trench Mapping QA/QC

Quality Assurance and Quality Control (QA/QC) was accomplished during the mapping by Dr. Bartholemew and by HLA. Initial QA/QC was done while unit boundaries and fractures were being identified and marked on the trench walls with marking tape and nails. The TPFG checked the work of the assistant geologists in the field and examined all contacts and fractures delineated by them.

The photographs of the mapped trenches were taken either by the TPFG or one Assistant Field Geologist designated for photographing, labeling and mapping on the photographs. The TPFG checked the contacts and features shown on the photographs with those same features in the trench for accuracy and consistency. These photographs provide a permanent visual record of the excavations and the features mapped.

After the computer-generated trench maps and Excel spreadsheets were produced, a team of three assistant geologists then compared the spreadsheets with the trench maps in the field and made modifications as appropriate.

Subsequent to the receipt of the draft trench maps and data spreadsheets, HLA conducted a QC review of the data including a check of the consistency of data within the spreadsheets and between the trench map and the spreadsheet. Additionally, an independent field check of 18 locations in the trench was conducted by HLA to confirm the data.

3.2 Drilling and Coring Program

The GM-1 Pilot Study drilling and coring activities began on April 1, 1997 and were completed on April 22, 1997. A total of nine boreholes were drilled and sampled during this time period. The borings were located along the pre-existing GM-1 trench, or the new extensions of that trench (GM-2 through GM-4), which are oriented east to west across the Site (Figure 1-1). All drilling and coring activities were conducted in accordance with TP-1 (Drilling), TP-4 (Surveying), TP-8 (Geologic Logging of Core Samples), TP-11 (Core Transfer), TP-23 (Data Management and Preservation), and TP-29 (Core Logging Procedures).

The previous Site well numbering system was adopted with minor modifications for use during this pilot study. Each well name begins with a "W" indicating the boring is located at the Wake County Site, followed by a sequential number designating the location of the borehole on the Site, followed by a two letter designator indicating the drilling or sampling method used ("AR" for air rotary or "CH" for core hole), followed by another sequential number indicating the number of this particular type of borehole that is present at that Site location. Additionally, an "A" or "B" was used to differentiate between identical borings drilled within 10 feet of each other at the W201 location. The Borings were sequentially numbered with borings W201AR1A and W201AR1B located on the west end of the extended trench line, and boring W208CH1 located on the east end (Figure 1-1). The drilling was conducted by McCall Bros. Drilling Co. and their subcontractor Graham & Currie Well Drilling Co., Inc.

3.2.1 Sampling and Drilling

Drilling work included the sampling of the unconsolidated soil and non-competent bedrock, surface casing installation, and competent bedrock sampling and drilling. Prior to the commencement of drilling activities the location of each borehole was established by a State of North Carolina licensed surveyor.

3.2.1.1 Unconsolidated and Non-Competent Deposits

The methods used to drill and sample the unconsolidated soil and non-competent bedrock were the same at each borehole location. This included initial sampling of the surface soil and the weathered non-competent bedrock, reaming of the borehole drilled during sampling, and installation of a surface casing.

Unconsolidated Soil

At each borehole location initial drilling was conducted using a truck-mounted auger drill rig (CME-85), equipped with 6-inch outer-diameter hollow-stem augers. Continuous sampling of surface soil was conducted through the hollow stem of the auger by driving a two foot long, 1.5- or 2.5-inch outer-diameter split-spoon sampler ahead of the augers with a 140 pound hammer (using an approximate 30 inch drop). The split-spoons were lined with clear polybutyrate tubes. Upon retrieval, each split-spoon was taken apart and the liner was capped on both ends with plastic caps. Split-spoon sampling was conducted until spoon refusal occurred, approximately 4.9 to 12.4 feet below ground surface (bgs) (see Table 3-1). Sample recovery from this zone averaged 69 percent.

Non-Competent Bedrock

Upon spilt-spoon refusal, the auger drill rig was set up for coring. This included the use of a two inch inner-diameter (NQ core) double-tube core barrel. Initially a ten-foot-long, solid core barrel was utilized for the non-competent bedrock coring work. However, to improve recovery, a five-foot-long, spilt-barrel sampler was used instead, which increased recovery and improved sample quality. Overall, sample recovery from this zone averaged 92 percent.

The use of drilling fluids during coring activities was necessary to lubricate the core bit and to flush cuttings from the borehole. Therefore, during coring a mud tank was set-up to recirculate drilling fluids, which consisted of water obtained from the Site's production well. Coring of the non-competent bedrock continued at each location until bedrock suitable for anchoring the base of a surface casing was encountered. The total depth of this coring ranged from 22.5 to 36 feet bgs (Table 3-1).

Reaming / Surface Casing Installation

Upon completion of the unconsolidated soil and non-competent bedrock sampling work, each borehole was reamed out to approximately 12 inches in diameter. The reaming work was conducted utilizing air rotary drilling methods by an Ingersoll Rand T3W drill rig, equipped with a percussion bit (button bit). Water was not introduced into the air stream during the surface casing reaming work. Each borehole was reamed to the approximate depth drilled during the non-competent bedrock sampling work, ranging from approximately 24 to 36 feet bgs (Table 3-1).

After reaming was complete, an 8-inch inside-diameter, Schedule 40, polyvinyl chloride (PVC) surface casing was lowered to the base of the boring. A rigid tremie pipe was lowered to a point near the base of the boring and was used to pump grout into the annular space between the casing and the borehole wall. Pumping of grout continued until the consistency of the grout returned to the top of the borehole was similar to the grout pumped into the borehole, and was later topped off if settling occurred. The grout consisted of a cement-bentonite mix with a density equal to or greater than 8.64 pounds per gallon. It was allowed to set at least 16 hours (typically several days were allowed) prior to conducting the additional drilling work discussed in Section 3.2.1.2 (Competent Bedrock Sampling and Drilling). Upon completion of sampling and drilling work, a locking well cap was installed at each borehole and the elevation of the top of the surface casing was surveyed relative to Mean Sea Level by a State of North Carolina licensed surveyor (Table 3-1).

3.2.1.2 Competent Bedrock

After the surface casings had been installed, as discussed in Section 3.2.1.1 (Unconsolidated and Non-Competent Deposits), drilling and sampling of the competent bedrock was conducted. All GM-1 Pilot Study boreholes except W205CH1 and W208CH1 were advanced using air rotary drilling techniques without any additional coring. At W205CH1 and W208CH1 the boreholes were advanced through the competent bedrock by coring to a specified depth and then reamed or advanced further using the air rotary drilling techniques described below.

Air Rotary Drilling

Similar to the reaming work described in Section 3.2.1.1 (Unconsolidated and Non-Competent Deposits), air rotary drilling through competent bedrock was conducted by an Ingersoll Rand T3W drill rig. However for this work two different drill bits were used, either a button bit or tri-cone bit (Table 3-1). The different drill bits were used to evaluate the bit's effect on borehole wall surface roughness and any corresponding effect on the quality of the borehole imaging discussed in Section 3.4 (BIPS and Wireline Logging). During the air rotary drilling of sections of bedrock that had not been cored, samples of the rock cuttings were collected at 5 foot intervals for the purpose of developing the Field Borehole Record as described in Section 3.2.1.3 (Logging Procedures). Also, except for at boreholes W201AR1A and W201AR1B, limited quantities of water from the Site's production well was introduced into the air stream during air rotary drilling. This change was implemented because a moist air stream produced a cleaner borehole wall that was better suited for the borehole imaging.

All boreholes were drilled 15 feet deeper than the proposed target depth, to provide a "rat hole" required for the wireline logging tools, as discussed in Section 3.4 (Borehole Imaging and Geophysical Logging Program). The total depth of the boreholes that were not cored below the surface casing, but were advanced using air rotary drilling (all GM-1 Pilot Study boreholes except W205CH1 and W208CH1), ranges from 115 to 465 feet bgs (Table 3-1).

Rock Coring

Rock coring of the competent bedrock (bedrock below the surface casing) was conducted at boreholes W205CH1 and W208CH1. The same coring methods described in Section 3.2.1.1 (Unconsolidated and Non-Competent Deposits) were used to core the competent bedrock, except that a temporary, 4-inch-diameter, flush-threaded, steel core casing was also used. This casing was installed through the 8-inch-diameter surface casing and fit snugly into the 4-inch-diameter hole created by the coring. Three centralizers were used to insure that the core casing was installed in the center of the larger diameter surface casing. The temporary core casing was installed to a depth of 140 and 30 feet in boreholes W205CH1 and W208CH1, respectively. With minor exceptions, a 10-foot-long, solid core barrel was used during the coring of the competent bedrock, because use of the solid core barrel (as compared to the split-barrel) did not reduce sample recovery or degrade sample quality when coring the competent bedrock. Upon completion of coring, the temporary core casing was removed.

In general, the drilling fluid used when coring the competent bedrock consisted of water obtained from the Site's Production Well. The only exceptions to this occurred at W205CH1. On April 6, 1997, when a water loss zone was encountered and fluid circulation was lost at a depth of approximately 157 feet bgs, a drilling polymer (ADP Poly 50) was added to the drilling fluid to regain circulation. Additional small amounts of polymer (1 to 5 gallons) were added daily, as needed, on April 9 through 11, 1997 and again on April 14, 1997.

Coring was conducted to a maximum depth of 562 feet at boring W205CH1, and a depth of 500.1 feet at borehole W208CH1. Coring was discontinued at W205CH1 because of the drilling problems discussed below; coring was stopped at W208CH1 because the desired target depth was achieved. With a few notable exceptions the recovery was good in the cored intervals, although it was better at W208CH1. When coring the competent bedrock, an average recovery of 94 percent was achieved at W205CH1, whereas, an average recovery of greater than 99 percent was achieved at W208CH1.

Difficulties with core recovery were experienced at Borehole W205CH1 beginning at a depth of 331 feet bgs. This depth corresponds with a zone of highly fractured and breciated bedrock. Apparently, at approximately 331 feet bgs, loose fragments of bedrock became lodged inside the core bit. This prohibited the collection of core, but still allowed the advancement of the bit through the strata. Typically, a blockage of this sort will not allow advancement of the bit. Because of this, several core runs were attempted while the bit was blocked, with little or no core recovery. After several attempts the drill string was removed from the borehole and the blockage was cleared. The resultant core loss zone extends from 331 to 366 feet bgs.

Coring difficulties also occurred at W205CH1 that were related to the temporary, 4-inch-diameter core casing. Typically, only short lengths (30 feet) of the temporary casing are required. However, the circulation of drilling fluids in borehole W205CH1 caused erosion (wash-out) of the bedrock at the base of the temporary casing, causing it to slip downhole and requiring additional lengths to be added to the casing string. Eventually, after the borehole had been cored to a depth of 556 feet bgs, the temporary casing string became prohibitively long (approximately 140 feet) and could no longer be lengthened. Therefore, the temporary casing was removed and the borehole was reamed to 6.75-inches in diameter using a button-bit reaming tool as described below. A temporary casing, consisting of a 4-inch-diameter steel pipe, was then installed in the borehole to a depth of approximately 556 feet bgs. To minimize scoring of the borehole wall, and to insure that the casing could be removed at a later date, centralizers were not installed with this casing. Multiple core runs through this casing produced some core recovery in the interval from 556 to 562 feet bgs. However, attempts to core the bedrock through this casing were generally unsuccessful and resulted in unacceptable scoring to the drill string and downhole loss of a core bit. Because of this, and because evaluation of data indicated that approximately 169 feet of bedrock below the W8 fault had been cored at this location, coring was discontinued and the temporary casing was removed.

Final Corehole Reaming

Upon completion of coring work at W208CH1 and after W205CH1 had been cored to a depth of 556 feet bgs, the coreholes were reamed to a diameter of approximately 6.75 inches. Two different reaming bits were used, both tools utilized a guide bit and a guide tube to maintain a vertical, non-deviated orientation. At W205CH1 the reaming tool was a button-bit; at W208CH1 a tri-cone reaming tool was used. Limited quantities of water from the Site's production well were introduced into the air stream during reaming. This was done because it was observed that a moist air stream produced a clean borehole wall that was well suited for borehole imaging. After reaming was completed to a depth of 556 feet at W205CH1 and 500 feet at W208CH1, the air rotary drilling methods described above were utilized to complete the boreholes to their final depths of 715 and 515 feet bgs, respectively (Table 3-1).

3.2.1.3 Logging Procedures

Several records were maintained of the drilling activities. In the field this consisted of a Logbook and a Field Borehole Record. These records were used to help produce the Final Borehole Record discussed in Section 3.3 (Core Logging Program).

Logbook

The Logbook was maintained by each Project Rig Geologist and was used to document daily activities. Included in each logbook were the:

Name and title of the author, date and time of entry, and physical/environmental conditions during field activity

- Detailed description of the field activity,
- Name(s) and title(s) of field crew,
- Name(s) and title(s) of Site visitors,
- Sample collection or measurement method,
- Description of measuring reference point(s),
- Unique boring or sample identification number(s),
- Documentation of field equipment used,
- Field observations and comments,
- Disposition of all field generated wastes,
- Records of problems encountered and the resolution of those problems,
- Records of water usage and water production from the boreholes during field activities, and
- Hand measurements of water level in the boreholes during field activities.
- Field Borehole Record

The Field Borehole Record was used by the Project Rig Geologist to document sampling methods and intervals, sample recovery, rock quality designation, driller's observations, and to develop a preliminary geologic log of the soil and bedrock samples collected. Geologic terminology used for this record was in accordance with the project Geologic Lexicon of Terms.

3.2.1.4 Sample Handling Procedures

Three types of samples were collected during drilling and coring activities. These include split-spoon samples of the unconsolidated soil, core samples of the non-competent and the competent bedrock, and bedrock cuttings collected during air rotary drilling.

Unconsolidated Samples

Split-spoon soil samples were retained in the clear, polybutyrate tube used to line the split-spoon during collection. Upon retrieval, the liner was trimmed to size, capped with plastic end caps, and labeled in accordance with TP-1 (Drilling) to indicate the depth interval and the top and bottom of the sample. The sample was then placed in a protective wood core box as described below.

Core Samples

Upon extrusion of the rock core from the core barrel, the top and bottom of the core, and the end of the core run were labeled in accordance with TP-1 (Drilling). After labeling was complete the core was logged and then broken into lengths that would fit into the protective core box. Wood spacers, painted red, were placed in the core box to mark identified core loss zones. Plastic bubble wrap was used to line the core box to minimize damage to the core during transport. At the end of each day the core boxes were taken to the onsite Temporary Core Storage Facility (a trailer located adjacent to the HLA field office trailer) and checked into storage by the Field Activities Manager or his designee. The next day of drilling only the last, partially filled, core box was taken out of storage and transported back to the drill site, as necessary.

Air Rotary Cuttings

Samples of bedrock cuttings produced during air rotary drilling were collected from the discharged air stream with a strainer. Approximately 1 to 2 cubic inches of cuttings were collected at each 5-foot interval. The cuttings were placed in a clear plastic compartmentalized box and set in the sun to dry. Each compartment was labeled in accordance with TP-1 (Drilling). Upon completion of sampling, the box was sealed with duct tape. Similar to the core boxes, at the end of each day the plastic sample boxes were taken to the onsite Temporary Core Storage Facility and checked into storage by the Field Activities Manager or his designee. On the next day of drilling, only the last, partially filled, plastic sample box was taken out of storage and transported back to the drill site, as necessary.

Temporary Core Storage Facility

At the Temporary Core Storage Facility, the Field Activities Manager reviewed the Field Borehole Records to confirm usage of terminology consistent with the Geologic Lexicon of Terms. The Field Borehole Records were then compared to the collected samples to verify sample labeling and the depth of collection. Any discrepancies noted were corrected, and the corrections initialed, dated, and reviewed with the Project Rig Geologist that was responsible for collection of the samples. Each core box was then photographed prior to transfer to the Interim Core Storage Facility (Morrisville, North Carolina).

3.2.2 Hydraulic Monitoring

Two types of hydraulic monitoring were conducted during drilling and sampling activities. This included monitoring the amount of water used or produced during drilling activities, and periodic monitoring of the water levels in nearby wells and boreholes.

3.2.2.1 Water Usage and Production

Records of the volume of water introduced into, or produced from the boreholes during field activities were kept by the Project Rig Geologist. During drilling and sampling, the amount of water introduced into a borehole was monitored by recording the volume of water transferred from the supply tank into the recirculating mud tank during coring activities, or introduced into the air stream during air rotary drilling. Each drilling location was set-up, such that, any excess water produced from the borehole would flow into a plastic-lined mud pit that had been dug near the borehole location. When the mud pits were emptied the volume of water pumped from the pit was recorded. The net loss or production of water from the boreholes was then calculated from these records.

The presence of water loss zones was also noted when possible. These zones were identified by the occurrence of sudden increases in water usage or production from distinct depths in the boreholes. Details of water loss and production during field activities is discussed in Section 4.1 (Analysis of Hydraulic Response during Drilling and Testing).

3.2.2.2 Water Level Monitoring

For the purpose of evaluating hydraulic responses to field activities, water levels were measured periodically in the newly drilled boreholes and in some of the existing wells located in the vicinity of the GM-1 trench. During drilling, the depth to groundwater in the newly drilled boreholes was measured by hand to the nearest 0.1 foot using an electric water level meter. Later during packer testing this data was collected in these wells at two minute intervals, to the nearest 0.01 foot, using pressure transducers and data loggers. Pressure transducers and data loggers were also used during the entire GM-1 Pilot Study to collect depth to water measurements at two minute intervals, to the nearest 0.01 foot, in nearby existing long term monitoring wells and in Well W8MC11. The analysis of this data is presented in Section 4.1 (Analysis of Hydraulic Response during Drilling and Testing).

3.3 Core Logging Program

During the GM-1 Pilot Study, soil and bedrock core samples were collected at eight boreholes, as discussed in Section-3.2 (Drilling and Coring Program). At each of these locations, soil and bedrock core was collected in the shallow portions (generally less than 36 feet bgs) of the boreholes, because this shallow interval cannot be logged by most geophysical techniques. At Boreholes W205CH1and W208CH1 bedrock core samples were also collected from deeper depths. Table 3-2 lists all the boreholes and depth intervals logged by traditional core logging methods during the GM-1 Pilot Study. The core logging conducted was based on direct observations and measurements of the soil and rock samples. The logging methods used were in accordance with TP-8 (Field Logging of Core) and TP-29 (Core Logging), and are described below.

3.3.1 Pre-Logging Activities

To ensure that all significant information obtainable from rock core would be recorded completely and consistently, three documents were generated prior to logging; including: 1) a Graphic Core Log paper form (form) containing spaces to record (log) all the significant geologic data at the depths at which they occurred, 2) a Lexicon (Lexicon) to be used by all investigators so that uniform descriptions and terminology would be applied to the rocks and their properties, and 3) TP-29 that describes a detailed procedure for core logging.

The form used for logging core is the same one developed by AGI for the core requalification work. The form was developed during March and April, 1997, with review and comment by the North Carolina Geological Survey at a meeting on April 29, 1997. The form provide spaces for recording data that makes possible the classification of rocks and an interpretation of their origins, as well as their weathering, diagenetic and structural histories. The logging form is designed so that all significant features of rocks that are present can be recorded. If some features are not present, the form requires that this information is also recorded in a comments section.

The form is printed on legal size paper (8.5 x 14 inch) and has space to record data for 10 feet of core. The form has two pages: one page for recording rock classification and relative proportions of gravel, sand and mud (silt/clay) and lithologic characteristics, and a companion page for the same depth interval used for recording fracture information. Copies of the completed form for Boreholes W201AR1 through W208CH1 have been submitted under separate cover.

The Lexicon was developed jointly by those performing core requalification, core logging, and trench mapping. It also was reviewed and commented on by the North Carolina Geological Survey. The Geologic Lexicon of Terms requires that rocks be classified using the Folk (1974) Classification System. It also provides definitions for rock characteristics and structures. Adoption of the Geologic Lexicon of Terms made possible consistency in use of descriptive terminology by various investigative teams. Abbreviations for geologic terms and rock properties were written and used for placing descriptive information on core logging forms, and for entering information into electronic spreadsheets.

TP-29 was designed to guide core logging activities and preparation of the Final Borehole Record. The document requires use of the adopted core logging forms, specifies approved terminology and descriptors defined in the Lexicon, and dictates core logging methods.

3.3.2 Core Cleaning and Depth Measurements

Prior to logging, all bedrock core was gently cleaned by sponging with water and allowed to dry. Even though core had been photographed after placing in core boxes in the field, it was rephotographed at the Interim Core Storage Facility after it had been cleaned and allowed to dry.

Core depths, as recorded on box lids, were verified against end-of-run and end-of-recovery information recorded on tabs in the core boxes and on the Field Borehole Record. In the event of discrepancies in depth measurements recorded at different places, efforts were made to reconcile differences. After this depth verification was complete, the beginning depths were recorded at the left hand end of each row of core in boxes. For core runs in which the missing interval could not be determined at the drill rig, TP-29 calls for core to be placed in the middle of the core run with spacers at each end.

A core loss interval totaling 26.2 feet occurred in borehole W205CH1 between depths 331 and 366 feet below ground surface. The loss appears to have been due to fractured and broken rock wedged in the core barrel as drilling passed through the W8 Fault Zone. Some core fragments, most with abraded ends, were recovered in each 10-foot core run interval in the 30 feet below the Fault. Following procedures in TP-29, these core fragments were placed in the center of run depths with spacers on each side to complete the ten-foot interval in the core boxes. If core fragments had abraded ends, they were logged as individual pieces and indicated as such on the core logging forms by showing each piece bounded at the top and bottom by a horizontal line. A very small space was left between each piece in the log. If the pieces could be fitted together or appear to have been separated by a fracture, these were logged as continuous core but containing a natural or induced fracture.

At the end of the core run to 366 feet, the entire drill string was raised to the surface and inspected. At this time core that was wedged in the core bit but not recovered during the three previous runs was removed. Since the depth from which the core originated was not known with certainty, it was logged as recovered from the depth interval 331-366 feet on a separate form labeled Page 37X.

3.3.3 Natural Fractures and Induced Fractures

Natural fractures and possible natural fractures in core were plotted on fracture forms to the nearest 0.1 foot depth intervals and described in accordance with TP-29. Fractures induced during drilling and handling at the drill rig are marked on the core with double lines in accordance with TP-8. Other fractures, induced later during core logging or naturally by desiccation, are not marked on the core nor were they logged.

3.3.4 Core Logging

During core logging, TP-29, the Geologic Lexicon of Terms, a list of abbreviations for geologic terms and rock properties, and the Field Borehole Record were kept within reach for reference, as needed. Items listed in Technical Procedure 29, Section 2.3.3, Tools, Materials and Equipment, were available for use during logging. Considerable use was made of the binocular microscope during logging of very fine sandy and silty lithologies to determine sorting and grain size distributions and to identify clast components.

Three persons were involved in core logging. Principal logging was performed by Dr. Paul A. Thayer, Professor of Geology at the University of North Carolina at Wilmington. He was assisted by Dr. Henry S. Brown, Professor Emeritus of Geology at North Carolina State University at Raleigh. Mr. Lewis Land, Ph.D. candidate at the University of North Carolina at Chapel Hill, was responsible for core cleaning and assisted with core measurements and data recording.

Each logging form (Appendix B) has space for logging ten feet of core at a scale of one inch = one foot. Locations of features were measured and recorded to an accuracy of 0.05 foot. Measurements were accomplished by placing a measuring tape, with each foot divided into 100 units (0.01 foot), alongside the core to be logged and measuring from the depth recorded at the beginning end (left end) of each core row. Logging usually followed the following sequence:

1. Marking and recording depths of lithologic contacts.

2. Defining lithologies between contacts based on the Folk Classification System (1974) and estimating gravel, sand and mud relative proportions within the lithologies.

3. Lithologic and relative abundance curves were drawn on core logging data forms according to instructions provided in TP-29.

4. Contacts were classified according to types defined in the Lexicon and contact dip angles were recorded where appropriate.

5. Lithologic characteristics and depth measurements were recorded in appropriate columns on the core logging forms, using abbreviations representing terms and attributes based on the Geologic Lexicon of Terms. If an attribute was not present (e.g., biogenic features burrowing and/or rooting) the space in the appropriate column for that attribute was marked "N" meaning not present. No spaces within named columns were left blank.

6. Fractures and their attributes were recorded (to the nearest 0.05 foot depth) at a scale of one inch = one foot on an accompanying page for each 10-foot interval.

7. In cases where a feature required additional information or had no designated column on the core logging data forms, it was noted at its correct depth position in the Comments Column and explained in the space at the bottom of the data sheet.

Data forms were numbered in sequence. For example, page 1 contains information from the 0 to 10 foot depth. Its companion fracture data form would be numbered 1A. Page 2 would contain information from the 10 to 20 foot depth and its companion form would be numbered 2A, and so on. Both Dr. Thayer and Dr. Brown initialed and dated each core logging data form as it was completed. Data sheets generated each day were photocopied at the end of the day. Original logs were placed into a filing cabinet at the Interim Core Logging Facility office and the photocopies were transferred to HLA's office in Morrisville, North Carolina.

At intervals during core logging, all data recorded on core logging forms were rechecked by Dr. Thayer and verified against the core samples. After they had gone through this quality assurance check and any errors on the original data forms corrected, Dr. Thayer signed and dated each page of the form.

3.3.5 Data Management

Upon completion of core logging for a borehole, copies of completed and signed core logging data sheets were entered into an Excel Workbook (spreadsheet). A quality assurance check of data entry was performed by placing each original core logging data sheet on a light table and overlaying it with the same form printed from the workbook. Upon completion of the overlay process and when the Excel workbook accurately represented the original work sheets, the data in the finalized workbook were expanded to the Apple Core graphic log package to produce a set of graphic core logs. Graphic core logs for W205 and W208 are presented in Appendix B-1 at a scale of 1-inch = 10-feet. The graphic corelog for the shallow portion of W201 through W208 is included in the panel diagrams located in Appendix D-3.

3.4 Borehole Imaging and Geophysical Logging Program

A comprehensive program of borehole imaging and geophysical logging was developed for the eight boreholes drilled and sampled as part of the GM-1 Pilot Study. One of the goals of the Study was to identify a subset of these tools that would to provide sufficient information for the hydrogeologic characterization of the Site.

3.4.1 Quality Assurance Program

Technical procedures were developed for borehole imaging and geophysical logging before the logging contractors were selected. These procedures included TP-13 (Geophysical Logging - General Procedure), TP-14 (Borehole Image

Processing System [BIPS]), TP-15 (Caliper Logging), and TP-27 (Technical Procedure for Schlumberger Borehole Logging). Each of these procedures were reviewed by the Authority and the DRP prior to the start of field work. All borehole imaging and geophysical logging work was conducted in accordance with these procedures.

3.4.2 Data Formats and Deliverables

Deliverables from geophysical logs include both data and data displays. A very large number of curves, images, and related data are recorded during logging. Not all of these data can be displayed or discussed here.

The curves listed below were provided in LAS (Log ASCII Standard) format on IBM-format diskettes by Schlumberger at the conclusion of logging. Paper copies of these curves were also provided at 1 inch = 10 feet scale. The curves which are not included here, and additional data including sonic full waveforms and FMI image data, are provided in DLIS (Digital Log Information Standard) format, as there is too much data to be stored as LAS files. FMI Images were also provided at 1 inch = 1 foot scale. Copies of the field logs have been provided to DPR under separate cover.

The BIPS data from Colog are provided on CD in a proprietary format, which was subsequently converted to the GMI-Imager™ format for analysis. The Imager format data were provided on ZIP disks, along with 1 inch = 10 feet paper logs which are included as an Appendix to this report. Colog provided 3-Arm Caliper data as LAS format data on IBM-format diskettes. The BIPS images are presented in Appendix C.

3.4.2.1 Mnemonics and Measurement Physics

Because of the large number of measurements and tool combinations used in this study, mnemonics are applied to shorten the discussion. This section of the report defines tool and delivered curve mnemonics (acronyms) and also provides a brief description of the physics behind each measurement. The borehole imaging and geophysical mnemonics used are listed in Table 3-3.

All of the geophysical logs were acquired in combination with a gamma ray (GR) measurement, which allows post-logging depth shifts to be made to correct for small errors in the depth measurement system. BIPS and the associated 3-arm caliper log were run without a GR measurement, and depth shifted based on anomalies which were common to all of the logs.

3.4.2.2 Array Induction Tool (AIT)

The Array Induction Tool (AIT) is Schlumberger's induction resistivity measurement which employs a number of detectors to calculate the vertical distribution of resistivity. The resistivity at a given depth is calculated from measurements obtained from depths which extend as much as 85 feet above that point; therefore the data does not extend all the way to the surface. The AIT does not require fluid in the borehole. It investigates formation properties from 10 to 90 inches from the borehole wall (this range depends somewhat on the electrical properties of the rock and formation). The vertical resolution for each measurement is 1 foot. In addition the tool measures the resistivity of the fluid in the borehole, which is called the mud resistivity. Run separately in W201AR1A, this tool was combined with the Natural Gamma Spectrometry Tool (NGT) in the other boreholes. Primary data derived from the AIT are:

- AIT-H Two Foot Resistivity A10 (AHT10),
- AIT-H Two Foot Resistivity A20 (AHT20),
- AIT-H Two Foot Resistivity A30 (AHT30),
- AIT-H Two Foot Resistivity A60 (AHT60),
- AIT-H Two Foot Resistivity A90 (AHT90), and
- AIT-H Input Borehole Mud Resistivity to AIT Processing (AHIMR).

3.4.2.3 Borehole Image Processing System (BIPS)

The Borehole Image Processing System (BIPS) tool is a video logging system operated by Colog Inc. under licensed from RaAX. The tool records a 360° image of the well bore using a video camera and lighting system. Work conducted during the GM-1 Pilot Study determined that the best images are obtained from a borehole filled with optically clear liquid (without suspended particles). Wet borehole wall surface irregularities in an air-filled borehole create glare on the BIPS image and makes interpretation more difficult.

3.4.2.4 Combinable Magnetic Resonance (CMR)

The Combinable Magnetic Resonance (CMR) tool is Schlumberger's magnetic resonance device which investigates a "cigar-shaped" volume about 1 inch in diameter and 6 inches long, centered approximately 1 inch away from the outer surface of a pad pressed against the borehole wall. Permanent magnets in the CMR skid set up a powerful magnetic force that aligns the hydrogen protons in the formation. A pulse is transmitted from the antenna, causing the protons to tip 90° and precess. This precessional motion creates a signal that the antenna detects between pulses. The time constant of the energy decay rate of these signals is called the transverse relaxation time (T_2) and is a function of the pore size distribution in the formation. The total energy (integrated over all T_2) is a direct measure of porosity. Short T_2 times indicate small pores and low permeability, while longer times indicate larger pores with generally higher permeabilities. The total energy (integrated over all T_2) is a direct measure of the volume of the pores with T_2 values within the range detected by the CMR. By selecting an appropriate time constant (here 33 millisecond [msec]), free porosity can be differentiated from porosity associated with bound water. Permeability from CMR is calculated from porosity, mean T_2, and the empirical calibration of a standard equation.

Because of the extremely shallow depth of investigation of 1 inch, CMR measurements are very sensitive to borehole enlargements. CMR measurements include:

- CMR Free Fluid (CMFF),
- CMR Porosity (CMRP), and
- Permeability from CMR (KCMR).

3.4.2.5 Dipole Shear Imager (DSI)

The Dipole Shear Imager (DSI) is Schlumberger's acoustic logging tool which records the full waveform of signals from monopole and dipole sources. These signals are processed to determine P-wave and S-wave velocities along the borehole. Used in low-frequency Stoneley mode, waveforms can be obtained which are propagated along the borehole wall. Sonic logs such as DSI require a fluid-filled borehole. At shallow depths above approximately 100 to 200 feet, dipole waveforms are degraded due to the low ambient pressure. The DSI investigates properties within approximately one acoustic wavelength of the borehole wall, which for P- and S- waves is approximately 1 to 5 feet. DSI measurments include:

- Compress. wave inverse velocity (1/Vp) (DTCO),
- Shear wave inverse velocity (1/Vs) (DTSM), and
- Stoneley wave inverse velocity (DTST).

3.4.2.6 Elemental Capture Sonde (ECS)

The Elemental Capture Sonde (ECS) is Schlumberger's geochemical logging tool that uses a chemical neutron source to identify and quantify the amount of silicon (Si), iron (Fe), calcium (Ca), titanium (Ti), sulfur (S), gadolinium (Gd), and hydrogen (H) in the formation. The measurements are based on neutron capture where thermal neutrons are captured by nuclei that emit gamma rays of specific energies dependent on the capture nucleus. The number of gamma rays within these energy windows is a measure of the number of atoms within the volume investigated by the tool. This tool was tested in W201AR1A before use in W205CH1 and W208CH1. ECS tool measurements include:

- ECS Capture Iron Relative Yield (CFE),
- ECS Capture Titanium Relative Yield (CTI),
- ECS Capture Gadolinium Relative Yield (CGD),
- ECS Capture Calcium Relative Yield (CCA),
- ECS Capture Silicon Relative Yield (CSI), and
- ECS Capture Sulphur Relative Yield (CSUL).

3.4.2.7 Formation Micro Imager (FMI)

The Formation Micro Imager (FMI) is Schlumberger's imaging device that measures relative conductivity of the rock. The FMI uses four pads pressed against the borehole wall, each containing an array of detectors (buttons). Each detector measures the relative conductivity of a small (approximately 1-inch-deep) rock volume. The spacing of the buttons is approximately 0.25 inch. In a 7-inch-diameter borehole virtually the entire surface is mapped. The resistivity image can be calibrated using the high resolution invaded zone resistivity (RXO8) from Platform Express (PEX), or data measured using the AIT. Analysis of the calibrated resisitivity image can provide specific data on the electrical conductance of individual fractures or beds.

3.4.2.8 Natural Gamma Spectrometry Tool (NGT)

The Schlumberger Natural Gamma Spectrometry Tool (NGT) is a natural gamma ray detection system which measures the energies and intensities of naturally occurring gamma rays and divides the signal into the activity of three radionuclide families (potassium-40, thorium, and uranium). The vertical resolution of this system of about 1 foot is slightly better than the GR used for depth correlation. This tool was run separately in W201AR1A, and was run in combination with AIT in the remaining boreholes. NGT measurements include:

- Total Gamma Ray (SGR),
- Computed Gamma Ray (Total minus URAN) (CGR),
- Thorium (THOR),
- Potassium (POTA), and
- Uranium (URAN).

3.4.2.9 Platform Express (PEX)

The Platform Express (PEX) is Schlumberger's combination tool consisting of the following devices:

- **Neutron** -The neutron porosity logging system measures the hydrogen index of the formation, regardless of whether it is water in a pore space or an hydroxyl ion in a clay mineral lattice.

- **Density** - The bulk density is calculated through the measurement of the Compton scattering of gamma rays by the formation. The tool has a collimated gamma ray source (Cs-137) and two detectors that measure the number of gamma rays that traverse the formation. The ratio of counts is proportional to the density of electrons within the formation. A density correction term is provided which if below 0.05 generally indicates a valid measurement.

- **Photoelectric Factor** - The photoelectric factor (Pe) measurement is also provided by the density tool. Gamma rays interact with matter through pair production, Compton scattering, and photoelectric absorption. Photoelectric absorption becomes much more prevalent at low gamma ray energies where it becomes primarily dependent upon the formation atomic number, Z. The more low-energy gamma rays, the lower the formation Pe because fewer of the gamma rays have been photoelectrically absorbed.

- **Micro-resistivity** - The above measurements are all obtained from detectors mounted on a skid pressed against the wall of the borehole. Micro-resistivity (MCFL) is also measured using electrodes mounted on the same skid.

- **Caliper** - a measure of the extension of the backing arm used to press the detector skid against the borehole wall. Equivalent to a 2-arm caliper, this measures the large diameter of the borehole and has less vertical resolution than the 3-arm caliper.

The following measurements are provided by the PEX:

- HRCC Cal. caliper SC (HCAL),
- Thermal Neutron Porosity (TNPH),
- Thermal Neutron Porosity (Ratio Method) (NPHI),
- Enhanced Thermal Neutron Porosity (NPOR),
- HiRes Enhanced Thermal Neutron Porosity (HNPO),

- HRDD Formation Photoelectric Factor (PEFZ),
- HRDD HiRes Formation PEF (PEF8),
- HRDD Formation Density (RHOZ),
- HRDD HiRes Formation Density (RHO8),
- HRDD Density Correction (HDRA),
- HRDD Density Porosity (DPHZ),
- HRDD HiRes Density Porosity (DPH8),
- MCFL Invaded Zone Resistivity (RXOZ), and
- MCFL HiRes Invaded Zone Resistivity (RXO8).

3.4.3 Field Activities

Borehole imaging and geophysical logging was conducted over four separate time periods. Two contractors were selected to carry out the measurements, Colog (Golden, Colorado) and Schlumberger Well Services (Englewood, Colorado).

3.4.3.1 Colog

Colog, Inc. (Colog) is the sole source provider of BIPS video images under license to RaAX, the manufacturer of the BIPS imaging system. Three-arm caliper logs were also obtained from Colog to provide borehole size information necessary to compute fracture dip from the images. Colog conducted logging work during two different time periods:

- During April 7 through April 13, 1997, Colog acquired BIPS video images and 3-arm caliper logs in a subset of wells. The results of analysis of this data allowed selection of the optimal drilling and preparation method to achieve the best image quality and resolution. In addition, some changes to the field procedures were dictated and a modification of the tool and calibration system was performed to optimize the accurate rendition of color from the video images. These modifications were identified at Colog's Golden, Colorado office over the period from April 15 to April 18 and implemented by Colog prior to returning to the Site to acquire the final set of logs.

- A complete set of BIPS image and caliper logs were acquired in the GM-1 boreholes over the period April 24 to May 8, 1997. Prior to commencement of logging, Quality Assurance training was completed for the Colog field operators and HLA oversight personnel.

3.4.3.2 Schlumberger

Schlumberger Well Services (Schlumberger) is the provider of the remainder of the geophysical log measurements. Schlumberger also conducted logging activities during two different time periods, including:

- Schlumberger carried out their first logging phase from April 29 through May 3. Prior to commencement of logging, Quality Assurance training was completed for the field operators and oversight personnel. All wells with the exception of W201AR1B were logged with the FMI, AIT, NGT, PEX, and DSI tools. W201AR1A was logged with ECS (as a test). CMR data was also acquired in W201AR1A. The core boreholes W208CH1 and W205CH1 were logged with ECS.

- Schlumberger returned on August 2 and 3, 1997 to complete CMR logging. All boreholes were logged with the CMR tool at this time except Boreholes W201AR1A, W201AR1B, and W208CH1. Borehole W208AR1 was not logged with the CMR because it was "dry" (suggesting extremely low formation permeability), and because the logging truck could not access this location (by this time the GM-4 Trench had been excavated across the access road). Borehole W201AR1A was logged during the previous trip, and W201AR1B was not logged using the CMR because it was within 10 feet of W201AR1A. A number of station measurements were made to provide information about specific depth intervals and to evaluate the parameters used to acquire the data while logging.

Detailed borehole imaging and geophysical logging field activity chronology is listed on Table 3-4.

3.5 Hydraulic Testing Program

The hydraulic testing program conducted during the GM-1 Pilot Study included hydrophysical and packer testing. The hydrophysical logging was conducted by Colog and the packer testing was conducted by Earth Data, Inc. under the direction of Golder Associates (Golder).

3.5.1 Hydrophysical Logging

The hydrophysical testing technique identifies water producing zones in the borehole. To conduct hydrophysical testing the borehole is filled with low-electrical conductivity water (deionized [DI] water) and the hydraulic head in the borehole is lowered. Resistivity profiling of the borehole is then conducted as higher conductivity formation water flows back into the borehole. This testing method can identify the location of hydraulically conductive intervals to a resolution of one borehole diameter, and quantify the interval-specific flow rate to a resolution of 0.01 gpm.

This method was utilized in all GM-1 Pilot Study boreholes except W208CH1, which was below the minimum inflow rate criteria for testing. The higher conductive zones identified during hydrophysical testing were then targeted for packer testing.

3.5.1.1 Test Method

Hydrophysical testing was conducted in accordance with TP-17 (Technical Procedures and Work Instructions for FEC Logging) and TP-19 (Hydrophysical Logging for Aquifer Characterization). The following steps were employed during each test.

- A field calibration of the fluid electrical conductivity (FEC) and temperature logging tool was conducted. This calibration employed National Institute of Standards Testing (NIST) traceable standard solutions in three different temperature baths.

- Prior to the installation of any pumping equipment, the fluid column was logged for ambient FEC and temperature profiles with a 1.5-inch-diameter sonde.

- Pumping equipment was installed in the borehole and an initial evaluation of well production was performed by removing a slug of borehole fluids (sufficient to produce 1- to 2-feet of head drop in the borehole), and monitoring water level recovery. An analysis of the recovery data was then conducted to determine which testing protocol (either slug testing or low rate pumping) would be used after DI water emplacement.

- Borehole fluids were then replaced with DI water prior to conducting a second slug or low rate pumping test. This was accomplished by inserting a tremie pipe to the base of the borehole and injecting DI water through the tremie pipe while pumping fluids out of the top of the borehole. Care was exercised during this procedure so as to minimize the volume of DI lost to the formation.

- After DI water emplacement, a baseline FEC log was conducted. Immediately following the baseline log, slug testing or low flow rate pumping was begun. For each slug test, a slug of borehole fluids was removed. During the recovery period, water level elevations were recorded with respect to time and periodic FEC logs were obtained. For each low rate pumping test, low flow rate pumping of the borehole fluids and continuos FEC logging was conducted. During the low rate pumping, water level elevations, instantaneous flow rate and total gallons pumped were recorded with respect to time. The resulting FEC logs and the water level recovery data were evaluated to identify the inflow locations and interval specific flow rate during recovery

3.5.2 Packer Testing

The design of the packer testing, the development of the protocol and the analysis of the data were carried out by Golder within the project team. The test equipment and the data acquisition were run by Earth Data Inc. (St. Michael's, Maryland).

3.5.2.1 Test Method

The following sections describe how intervals were selected for packer testing, the type of equipment which was deployed and the various test methods which were used. Packer testing was conducted at all GM-1 Pilot Study boreholes except W208CH1. All packer testing work was conducted in accordance with TP-5 (Packer Testing).

Selection of Test Intervals

The preliminary evaluation of the hydrophysical logs was used to identify potential test zones. The preliminary evaluation of the hydrophysical logging had categorized all inflow points as shown in Table 3-5.

The packer testing aimed to test all features categorized as low flow rate or higher. Some of the inflow features were separated by only short intervals. In these cases the inflow features are likely to be parts of the same feature or to be connected some short distance from the borehole. It is difficult to reliably isolate features which are close together and therefore in these cases a test interval was selected which straddled both inflow features. Having identified the interval which was to be measured, the caliper logs were examined to identify sections of the borehole as close to the intervals as possible which were relatively smooth and could therefore be expected to provide good packer seats. This evaluation also resulted in some inflow zones being combined into a single test interval. The final details of test interval was partly governed by the length of spacers available to set specific packer straddles, a desire to limit the number of times the packer straddle interval was changed during the testing of a single borehole, and any problems encountered during the test to obtain a good seal. The intervals actually tested during this test program are listed in Table 3-6.

3.5.2.2 Test Equipment

Protocols were established to assure satisfactory operation of mechanical equipment and traceability for measuring devices to calibration records. Prior to mobilization to the site the downhole gauges and flowmeters were calibrated by the manufacturer. In addition, the downhole equipment was tested in a borehole to assure the performance upon arrival on site. At the start of each test the fluid level above the gauge was compared to the transducer reading, assuming freshwater density, as a function check for accuracy of readings. Also the readings between depths were checked to assure the gauges were recording the correct change in pressure.

The flowmeters were function checked against a calibrated container during each production test and documented in the testing logbook.

Surface Equipment

The main components of the surface equipment are the flowmeters, data acquisition system, gauges to monitor packer pressure and controls for the operation of the shut-in tool.

The data acquisition was performed with a laptop computer in conjunction with a Metrosonics dl-714 Data Logger. The data logger was capable of monitoring voltage, current and temperature data. Pressure and flow rate data were obtained by inputting the manufacturer's calibration coefficients. The fastest data acquisition rate was 1 second.

The upper and lower packers were inflated through individual lines with nitrogen. At completion of inflation, the line to the nitrogen bottles was shut off and the packer inflation pressure was monitored for leaks with 0 to 1000 psi Weksler gauges. No leaks were detected during the investigation.

The downhole shut-in tool was opened and closed through a sliding sleeve mechanism that requires positive pressure of about 200 psi for both operations. The source of the pressure was a nitrogen bottle on site and the operation pressure was monitored with a 0 to 1000 psi Noshock gauge.

Downhole Equipment

The main components of the downhole equipment include the pressure transducers, packers, the shut-in tool, pump shroud and various pumps.

Three downhole pressure transducers were used to monitor the annulus pressure (P1), test zone pressure (P2) and the bottom hole conditions (P3). All the gauges were initially positioned above the top packer. At the first test location (W207AR1) the function checks indicated that the readings from P2 and P3 were erroneous due to air trapped in the ¼ inch nylon tubing leading from the gauge to the interval of interest. This was corrected for the test zone transducer by placing the gauge in the interval, thus eliminating the need for the tubing. It was not possible to reposition the P3 gauge and therefore the readings need to be corrected for the air in the tubing. No correction was applied as the measurements were used only to confirm the integrity of the packer seal and not used for analysis purposes. Electrical lines transferred the signal to the data acquisition system

The packers were of the sliding end type manufactured by Baski, Inc. These medium duty packers have an unconfined pressure rating of 500 psi. The uninflated diameter is 5.4 inches with a maximum recommended hole size of 10.5 inches. The seal length is approximately 50 inches. Each packer contained a separate 0.25 inch nylon inflation line with a 2500 psi burst rating. No packer problems were encountered during testing. Both double and single packer arrangements were used.

A downhole Baski shut-in tool was placed in the test section. The main purpose of this tool was to isolate the test section from the tubing to reduce borehole storage effects. The tool contains two actuating lines; one to close the valve and one to open the valve. No equipment problems were encountered.

The majority of the production phases were performed with a 2 inch Grundfos pump. This pump was lowered into the test string manually to the desired depth for each production phase. The pump was also used to create drawdowns for pulse and slug phases. With the shut-in tool closed, the pump was lowered into the tubing and a volume of water was removed. Upon opening the shut-in tool an instantaneous drawdown was created.

A pump shroud was only used during tests 1 and 2 in Borehole W205CH1. The pump shroud allows a 4 inch pump to be installed within the test string. The larger output from this pump was not needed in the majority of the boreholes. Therefore the shroud was eliminated to simplify the set-up. There was indication that the pump shroud was leaking during the two tests it was used resulting in a portion of the pumped fluid coming from the annulus. Because there was no significant conductive features within the annulus, this impact was considered minimal.

3.5.2.3 Test Design

The initial test design was based on test objectives, anticipated influence of pressure history, expected relative hydraulic conditions, and time constraints. The goal of the test design was to use different test types in combination to reduce uncertainty. Real time analysis was used to redefine the original design based on the measured formation response.

The tests were carried out with a combination of the following test types:

- Constant Rate Tests - Applicable for high to medium transmissivity environments. In low transmissivity environments, target rates are below the lower limit of most pumping equipment and formation response is dominated by borehole storage and skin effects. The recovery period is often emphasized in the analysis due to a well defined inner boundary condition; i.e., flowrate is equal to zero.

- Slug Tests - These tests are usually best fitted to moderate transmissivity environments. In high transmissivity environments, the recovery is very rapid resulting in a small radius of investigation. For low transmissivity environments, the recovery is too small as the pressure change may be in the same range as the gauge resolution. The interval may be shut-in prior to reaching full recovery. The recovery phase may be analyzed with constant rate solution if the slug phase is discretised into approximately constant rate events.

- Pulse Tests - These tests are typically best suited for low transmissivity environments. Similar to pulse tests, the derived transmissivity in a pulse test is directly dependent on the borehole storage coefficient (C). For slug tests, the C value is well constrained and computed from the tubing radius and density of fluid. For pulse tests, C value is not as well constrained and dependent on compressibility of fluid in the wellbore, borehole walls and packer equipment. The test is performed by applying an instantaneous pressure change and then shutting-in the interval. The shut-in condition results in a higher rate of recovery compared to a slug phase. The analysis assumes that there was no flow from the formation prior to isolating the interval. In high to medium transmissivity environments, this requirement is not met.

At the start of each test the interval was shut-in by closing the downhole shut-in tool to partially dissipate pressure history effects. The period typically lasted less then 1 hour and depended on the rate of pressure change. When the interval pressure was relatively stable, the next phase was initiated. The next phase depended on the expected relative transmissivity conditions based on the hydrophysical logging results. For expected relatively low transmissivity conditions, a pulse test was carried out. A constant rate production test was performed in high transmissivity conditions. For moderate transmissivity condition, a slug test was carried out. In many cases, the intervals were relatively shallow limiting the head available for pumping and therefore a slug test was the only option. If the slug test did not reach full recovery in a reasonable time period (i.e., 1 to 2 hours), the shut-in tool was closed. Analysis of the recovery phase allows for extrapolation to the static formation conditions and application of constant rate solution to compare to results of the slug test.

The testing scheme was designed to optimize the information obtained from the higher conductive features. Hence, the production part of these tests were started in the afternoon so that the recovery could be monitored overnight.

In some tests there was a drawdown response in the annulus or zone below the bottom packer that could be correlated to the start of a production or slug phase in the test zone. These tests were ended and the packer seat was adjusted a few feet to see if an improved seal could be obtained while still encompassing the feature of interest. In all cases, the packer bypass was attributed to a diffuse hydraulic connection through the formation as there was no suggestion for packer leakage. The second packer seat also showed bypass indicating a relatively well connected fracture system in this section of the borehole. If the bypass was attributed primarily to the lower packer and the target conductor was the highest rated feature below the upper packer, a single packer test was performed. Otherwise, a double packer test was performed and the bypass was noted in the test summary.

3.6 Geochemical Sampling Program

Groundwater samples were collected for geochemical analysis as part of the packer testing program conducted during the GM-1 Pilot Study. The geochemical sampling included the collection of samples for the measurement of field parameters (pH, temperature, specific conductance, dissolved oxygen), and laboratory analysis of major ions (Ca, Mg, Sr, Na, K, SO_4, HCO_3, Cl, Br), stable isotope ratios (ΔD and $\Delta^{18}O$), and radon-222 (^{222}Rn). The objective of the geochemical sampling program was to identify changes in groundwater chemistry as a result of:

1) mixing of groundwater with drilling fluids (primarily production well water as described in Section 3.2 [Drilling and Coring Program]);

2) lithologic and structural variations and;

3) communication or mixing of water types along relatively permeable zones over the duration of the pump tests.

3.6.1 Previous Sampling Work

In the previous field programs, samples of groundwater were collected from wells in accordance with procedures established for site characterization. These procedures, however, did not include provisions for the collection of samples from discrete zones. Hence, it has been inquired whether the length of a screened interval might affect the chemical signature of a sample by allowing groundwater of different compositions to mix within the borehole. The packer tests provided an opportunity to collect discrete samples of groundwater from more productive intervals to ascertain whether discernible changes in geochemical composition can be identified and then characterized at the Wake Site.

3.6.2 Sampling Program Implementation and Design

The packer test sampling program was conducted from May 11, 1997 through May 21, 1997. All sampling work was conducted in accordance with TP-22 (Sampling for Geochemistry of Groundwater). Intervals were selected for the packer tests based on the results of a hydrophysical logging program to identify conductive zones within the boreholes. For the purpose of collecting geochemical samples, water was diverted through a flow cell to monitor temperature, pH, and specific conductance. The flow cell could only be used when the zone being tested had sufficient inflow to support a pumping test and a low flow rate of less than 2 gallons per minute (gpm). At discharge rates greater than about 2.5 gpm, the flow cell was disconnected and field parameters measured at the end of the discharge hose. In such cases, the first geochemical sample was collected from the first water to flow from the discharge hose. If an interval did not yield enough to support a pumping test, a sample from the column of water within the production string was collected. In such cases, a peristaltic pump was used to draw a sample of water from the drill stem.

Samples were collected in certified clean containers provided by the contract laboratory, and were shipped overnight under chain-of-custody to approved laboratories. Savannah Laboratories (Savannah, Georgia) performed the major-ions analyses. The University of Arizona Laboratory of Isotope Geochemistry performed the stable-isotope ratio analyses (ΔD and $\Delta^{18}O$), and Teledyne Brown Engineering of (Westwood, New Jersey) performed the ^{222}Rn analyses.

3.7 Seismic Program

The seismic program was comprised of two major elements: a shallow seismic reflection/refraction Test Survey, and a vertical seismic profiling (VSP) Survey. The seismic reflection/refraction Test Survey had three objectives: 1) to evaluate the ability of a shallow-focused seismic reflection survey to provide correlation between boreholes, 2) to delineate faults and stratigraphic reflectors in the upper 150 feet, and 3) to determine the thickness of weathered bedrock. The objective of the VSP Survey was to help optimize the processing of the seismic reflection data, and to facilitate the correlation of the seismic reflection data to geologic features. In addition, the VSP survey was to provide P- and S-wave velocity data for an engineering analysis of the subsurface materials at the site.

The seismic reflection/refraction Test Survey was performed along two perpendicular lines centered on borehole W205CH1. The VSP survey was performed using borehole W205CH1. Field work was performed from May 13 through May 27, 1997 by Blackhawk Geometrics (Blackhawk) of Golden, Colorado. Data processing and analysis was performed during the months of June and July, 1997, and Blackhawk Geometrics produced a report (Blackhawk, 1997). Prior to performing work, the Seismograph Operator and the Test Supervisor reviewed appropriate technical procedure documents. Of particular importance were documents TP-7 (Seismic Reflection Pilot Study), and TP-31 (Vertical Seismic Profile [VSP] Survey. In addition to reviewing the technical procedure documents, which detail the duties and responsibilities of the Seismograph Operator (Blackhawk) and the Test Supervisor (HLA), the Operator and Supervisor also received a QA orientation from HLA's NCLLRWDF QA Manager, in accordance with the requirements of this project.

3.7.1 Shallow Seismic Reflection/ Refraction Test Survey

The shallow seismic reflection/refraction test survey was conducted in three phases: 1) Walkaway Test, 2) Walkaway data evaluation and Test Survey design, and 3) Test Survey data acquisition. Equipment calibration and functional checks were performed in accordance with TP-7; the checks included factory validations of the seismographs and geophones before and after the survey, and functional and calibration checks of the seismographs at the beginning and end of each field day.

3.7.1.1 Walkaway Test and Noise Survey

Walkaway tests and noise surveys were performed in two areas to see if data quality varied across the site (Figure 3-1). In addition, the walkaway test arrays were orientated perpendicular to each other so that the amount of seismic anisotropy, and its possible relation to geologic structure, could be determined. Walkaway Test 1 was performed in an east-west (dip) direction along the north edge of the east-west gravel road, near borehole W204AR1. Walkaway Test 2 was performed in a roughly north-south (strike) direction, along the eastern edge of the site access road, near borehole

W206AR1. Supplemental shotpoints for Walkaway Test 2 were positioned on either side of the backfilled GM-1 trench to see if the trench reduced coherent noise (i.e., ground roll) in the reflection data.

A number of equipment failures impeded the progress of the Walkaway Test. Failures included a bad seismograph power supply, a programming error in the seismograph data display parameters, and short-circuits and component failures in the vibratory seismic energy source.

Walkaway Test Configuration and Data Recording System

The geophone spreads for the Walkaway Tests were 120 feet long, and consisted of 120 groups of three Mark Products 40-Hz geophones. The geophone groups were spaced 1-foot apart (Figure 3-2). Seismic data were recorded by two Geometrics Stratiview Model R-60 60-channel seismographs electronically linked to produce a 120-channel seismic recording system. For Walkaway Test 1, seismic energy source points (shotpoints) were positioned off the east end of the geophone spread at 60-foot intervals to a distance of 240 feet from the closest geophone group. For Walkaway Test 2, shotpoints were moved northward at 120-foot intervals to a distance of 240 feet.

Walkaway Test Seismic Energy Sources

Four different types of seismic energy sources were tested: impact, high-frequency projectile, explosive, and vibratory. The specific sources tested are as follows:

- Impact: Hammer and plate using 12 oz., 3 lb, and 12 lb hammers
- Projectile: Betsy Seisgun firing 3 oz. lead projectile
- Explosive: Downhole firing rod ("Buffalo Gun") with 150 and 500 grains of black powder
- Vibratory: iVi Minibuggy with the following frequency sweeps:
  - 80-240 Hz
  - 100-300 Hz
  - 100-400 Hz
  - 100-550 Hz
- A side-by-side comparison of the vibratory source on native soil and the gravel road was also performed

Figure 3-2 shows a schematic of the Walkaway Test layout and illustrates the energy sources tested.

3.7.1.2 Walkaway Test Data Processing and Data Evaluation Procedures

Sesimograms were printed after each shot as the Walkaway Test progressed. The seismograms were inspected in the field to assess noise levels and to look for indications of reflection events. The seismograms were also reviewed carefully to insure that data clipping did not occur. Data for each shot were also saved using the seismograph's computer memory. The computer datafile name, together with the corresponding field information, such as energy source type and shotpoint location, were recorded on Seismic Observers Logs by the Seismograph Operator. At the end of each day, the Observers Logs were submitted to the Test Supervisor, who photocopied them and placed the originals in a fireproof file cabinet at the HLA field office. The seismograph instruments were transported to Blackhawk's hotel room, where the Walkaway data were downloaded to a computer workstation for processing, and written in SEG-2 format to 4mm DAT tape for backup. The backup DAT tapes were placed in the fireproof file cabinet upon returning to the HLA field office the next morning.

Walkaway Test Data Processing

In general, the Walkaway Test data were processed at night and hardcopy displays of the processing results were reviewed the next morning. The processing results included raw Walkaway data panels, filter panels, absolute average amplitude displays to show the relative strengths of the different seismic phase energies, and spectral analysis displays to show the frequency content of the recorded energy. The processed Walkaway data are presented in Blackhawk's report (Blackhawk, 1997).

Walkaway Test Data Evaluation

The Walkaway data display panels were reviewed at a meeting on May 17, 1997. The meeting was held at HLA's Morrisville, North Carolina, office and included the Seismograph Operator (Blackhawk), the Test Supervisor (HLA), and a representative of the North Carolina Department of Environment, Health, and Natural Resources. Also participating via telephone were a QA geophysicist representing DRP, and a QA geophysicist from the HLA's Novato, California, office. The two QA geophysicists had received copies of data display panels prior to the meeting. After a review of the raw and processed Walkaway data, the following conclusions were drawn:

- No reflection events were apparent on any of the display panels; therefore, expectations that the subsequent Test Survey will produce reflections should be lowered accordingly.
- Most of the recorded energy is seen in the refracted arrival and the air wave phases.
- Panels show strong "ringing" from the refracted arrival.

- Most of the recorded energy is clustered in a narrow frequency band centered around 120 Hz; site conditions do not seem to allow for the desired broad-band frequency spectrum in recorded data.
- Vibratory source shows the most promise; other sources show significantly lower frequencies, which were considered too low to produce useable reflections in the very near surface.
- Stacking 3 vibrator sweeps seems to improve the signal to noise ratio.
- Changes in data quality from soil vs. gravel road not significant, although shooting across the GM-1 trench seems to reduce ground roll slightly.
- No significant seismic anisotropy between the two Walkaway tests was observed.
- For Test Survey, low end of vibrator sweep should start above 80 Hz, as sweeping at 80 Hz seems to excite ground roll.
- For the Test Survey, the high end of the vibrator sweep should be set at 400 Hz. Even though little energy, and no apparent signal, was recorded at that frequency, the Test Survey parameters should not preclude recording higher frequency data should it be available.
- For the Test Survey, geophones should be buried to mitigate the air wave; the air wave can probably be filtered/muted through additional processing.
- For the Test Survey, the receiver array should be "pushed" in front of the source to minimize the possibility that Minibuggy vibrations will loosen ground coupling of the near geophones.

Test Survey Parameters

On the basis of the walkaway test results and ensuing discussions, the following seismic reflection/refraction Test Survey parameters were established:

Seismic Reflection Test Survey

- Energy Source: iVi Minbuggy vibrator
  - sweep parameters: 100-400 Hz over 2.5 seconds
  - stack: 3
  - shotpoint interval: 2 feet

- Receiver Array:
  - geophone group: three 40-Hz geophones in a tight group
  - group interval: 2 feet
  - number of groups: 120
  - total array length: 240 feet
- Recording System:
  - 120 channels (96 minimum)
- Record Length:
  - 3072 milliseconds uncorrelated
  - 512 milliseconds correlated
- Recording Interval:
  - 0.25 milliseconds
- Spread Configuration:
  - type: end-on, pushed
  - source minimum offset: 6 feet
  - source lateral offset: 5 feet

Seismic Refraction Survey

- Energy source: Betsy Seisgun, 3 oz. Projectile
- Receiver array: 240 feet long with 120 geophone groups spaced 2 feet apart (i.e., the seismic reflection arrays already in place)
- Recording System: 120 channels
- Shotpoint locations: One on each end of the receiver array, one in the middle of the array, and one 120 feet off each end of the array. Five shotpoints- total spread length, including shotpoints - 480 feet

3.7.1.3 Test Survey Data Acquisition

Data acquisition for the Test Survey was scheduled to begin on May 18 but was delayed for two days due to the failure of the Minibuggy computer, which programs the vibration sweeps. After contacting the manufacturer, it was determined that the computer could not be repaired in the field. The Test Survey began on May 20, when a replacement computer arrived. In addition, a radio transmitter unit, which coordinates Minibuggy vibrator with the seismic recording system, failed on May 21. A replacement unit arrived on May 22. Later, an unrelated data recording error affected all reflection data obtained after May 22. The nature of this recording error is discussed in the Blackhawk's report (Blackhawk, 1997).

Test Line Layout

The seismic reflection/refraction Test Survey was performed along two mutually perpendicular test lines centered near borehole W205CH1 (Figure 3-1). Test Line 1 was 1,000 feet long and was positioned along the north edge of the east-west gravel road. North-south Test Line 2 was 500 feet long and centered on Test Line 1. The lines were positioned by the Test Supervisor, who used a fiberglass tape measure to mark each line at 20-foot intervals with pin flags labeled with the corresponding shotpoint number. The Test Supervisor also measured the relative elevation change between the flagged locations using a field-calibrated hand level. The test lines were also marked at selected locations with wooden stakes, and the staked locations were surveyed by a land surveyor who measured their position and elevation. The land survey data were combined with the hand-level data to produce detailed topographic profiles along the two test lines.

Seismic Reflection Survey Procedures

The Test Survey along Line 1 proceeded from east to west, and the survey along Line 2 proceeded from south to north. In general, Test Survey procedures were as follows: First, all available (200) geophone groups were buried at two-foot intervals along the test line. The geophone groups were then connected via geophone cables to a roll switch, which selects the appropriate 120 geophone groups (e.g., groups 1 to 120) and feeds their signals into the seismic recording system. Next, shotpoint locations were marked on the ground with spray paint. Finally, the Minibuggy was driven to the first shotpoint location (SP-1), where the vibrator plate was lowered to the ground and a series of three vibration sweeps was initiated.

When the sweeps at SP-1 were completed, the Minibuggy advanced to SP-2. Using the roll switch, the Operator then advanced the receiver array one station (by de-selecting geophone group 1 and selecting group 121), and the next set of sweeps was initiated. Because of the precise positioning required by the two-foot shotpoint spacing, a worker stood along the test line to help position the Minibuggy vehicle. As the Minibuggy advanced down the test line, de-selected geophones were disconnected from the cables, leap-frogged to the far end of the array, and reconnected. This procedure was repeated until the end the test line was reached. Figure 3-3 shows a schematic of the seismic reflection survey procedure.

In accordance with TP-7, functional tests and calibration checks were performed on both seismographs before data acquisition began; these tests were performed again at the end of each field day. Hardcopy records documenting the results of these tests were produced and submitted to the Test Supervisor. In addition, line checks were performed on the geophone arrays, and the performance of individual geophone groups was checked at random. Records documenting the results of these checks were also submitted to the Test Supervisor, who placed them in the fireproof file cabinet at the HLA field office at the end of each field day.

Seismic Reflection Data Processing and Data Handling

For each shotpoint, data from the three vibration sweeps were stacked and saved as a single uncorrelated record. Next, the stacked data were correlated using the seismograph manufacturer's installed software, and the resulting correlated record was also saved. The purpose of saving the uncorrelated data was to allow for additional data (re)processing, possibly using advanced techniques and software that are as yet undeveloped.

The Seismograph Operator previewed each correlated record on the seismograph display screen prior to saving to insure that the data were of acceptable quality. In addition, selected correlated records, generally for every 20th shotpoint, were printed out to provide hardcopy records to document data quality. The large volume of data obtained for this survey precluded printing every shotpoint record.

As with the Walkaway Test, the reflection data were saved into the seismograph's computer memory, and the pertinent information (e.g., filename and shotpoint location) recorded on Seismic Observers Logs. The Observers Logs were submitted to the Test Supervisor who photocopied them each evening. The seismographs were transported to Blackhawk's hotel room each evening, and the Test Survey data were dumped from seismograph memory to 4mm DAT tape. No further processing was performed in the field. A backup copy of each tape was made and given to the Test Supervisor, who placed it in the fireproof safe the next morning. Upon completion of the field work, DAT tapes with the seismic reflection data, along with copies of the Observers Logs, were hand-carried to Blackhawk's office for processing and analysis. Data processing details and the results of the seismic reflection survey are presented in the Blackhawk Geometrics report (Blackhawk, 1997).

Seismic Refraction Survey Procedures

The seismic refraction survey was performed concurrently with the reflection survey. Although the same receiver arrays and recording equipment was used for both surveys, the Betsy Seisgun was used for the seismic refraction energy source. In general, the seismic refraction survey proceeded as follows: first, the Minibuggy was shut down and the

Betsy Seisgun was mobilized. Next, the appropriate receiver array (i.e., geophone groups 1 to 120) was selected with roll switch, and the Betsy Seisgun fired a 3 ounce lead projectile at five shotpoint locations spaced 120 feet apart and centered on the receiver array. One shotpoint was positioned in the center of the array, one shotpoint was positioned on either end of the array, and one shotpoint was placed 120 feet off each end of the array (Figure 3-3). Counting all five shotpoint locations, the length of each refraction spread was 480 feet.

The seismic reflection survey was then resumed. When enough geophone groups were in place for the next refraction receiver array (i.e., geophone groups 121 to 240), the Seisgun was again mobilized and fired at five shotpoints centered on the second receiver array. This process was repeated, as the reflection survey progressed, until the end of each test line was reached. In this manner, seismic refraction data coverage was obtained along the entire length of each test line.

The seismic refraction data were handled in the same manner as the reflection data, i.e., seismograms for selected shotpoints were printed, data were digitally recorded and downloaded to DAT tape, and Seismic Observers Logs were kept. DAT tapes with the refraction data were hand-carried to Blackhawk's office for processing and analysis. Data processing details and the results of the seismic refraction survey are presented in Blackhawk's report (Blackhawk, 1997).

3.7.2 Vertical Seismic (VSP) Survey

The VSP survey comprised three elements: 1) VSP Survey preparation, 2) a VSP test survey, and 3) a VSP production survey. VSP Survey procedures are detailed in TP-31. In the same manner as with the seismic reflection/refraction Test Survey, seismograph calibration was performed twice daily, VSP data were dumped onto DAT tape daily, and backup tapes were made. Hard copy printouts (seismograms) of the VSP data were output in the field and reviewed for data quality. VSP data were returned to Blackhawk's office in Golden, Colorado, for processing and interpretation. The results of the VSP survey are presented in Blackhawk's report (Blackhawk, 1997).

3.7.2.1 VSP Survey Preparation

Borehole W205CH1 was used for the VSP survey, and was prepared expressly for that purpose. As specified in TP-31, the Test Supervisor and the Seismograph Operator inspected the caliper log, deviation survey data, and viewed the high-resolution borehole video (BIPS) for W205CH1 prior the VSP survey. Although the caliper log showed a few breakout zones within the borehole, the deviation survey showed that the borehole was within 10 degrees of vertical, as required by TP-31. Overall, the caliper and BIPS data showed smooth borehole walls, indicating the potential for good geophone coupling to the borehole wall. It was noted, however, that the BIPS video tape showed borehole conditions to only 230 feet bgs, and not for the entire 712-foot borehole depth shown by the caliper log and borehole deviation survey.

Parameters for the VSP test survey are set forth in TP-31. In general, TP-31 required that VSP test data be obtained from multiple surface locations to see if data quality varies with respect to source point location. In particular, the nature of the tube wave noise with respect to source point offset distance was to be studied, as was seismic anisotropy related to offset direction. TP-31 also specified that P-wave data were to be generated using the same source and recording parameters that were used for the seismic reflection Test Survey. TP-31 further specified that an S-wave VSP survey be performed to aid in the engineering analysis of subsurface materials near the borehole.

3.7.2.2 VSP Test Survey

The VSP test survey was performed on May 25, 1997 using five surface source locations (Figure 3-4). The source locations were distributed along two perpendicular alignments roughly corresponding to the strike and dip directions of the bedding at the site. The sources were spaced 10, 30, and 100 feet from the borehole along strike, and 10 and 100 feet from the borehole in the updip direction. Downhole measurements for the VSP test survey were made at 50-foot intervals to a depth of approximately 300 feet bgs. During the test survey it was discovered that the borehole was blocked at 330 below ground surface (bgs). An unsuccessful effort was made to bump the tool through the blockage.

VSP Data Acquisition System

The data acquisition system comprised a Geostuff Model BHG-2 14-Hz tri-axial downhole geophone, and a single Geometrics Stratiview R-60 seismograph. In addition, a set of three orthogonal 28-Hz geophones was placed on the ground surface approximately 50 feet from the borehole to monitor any changes in source characteristics as the VSP survey progressed. VSP data were recorded on six channels - three for the downhole geophone, and three for the surface geophones. The seismograph channel numbers corresponding to the axes orientation of each geophone were recorded on the Seismic Observers Logs.

VSP Test Survey Procedure

In general, the VSP survey procedure entailed lowering the geophone to the desired depth and then wall-locking it with a motor-driven steel strip, which bowed out from the geophone housing. The motor was turned off and the geophone cable was gently tugged to insure that the geophone was adequately coupled to the borehole wall. Seismic energy was then generated at the surface, and VSP data were recorded; the steel strip was retracted and the geophone moved to the next measurement depth, where the process was repeated. P-wave VSP test data were obtained at all five source location. S-wave VSP test data were obtained at the two 10-foot offset locations after the Minibuggy was shut down.

As with the seismic reflection Test Survey, P-wave energy was generated by stacking three 100- to 400-Hz vibrator sweeps. The S-wave energy was produced by striking the opposite sides of an S-wave anvil (a heavy metal box coupled to the ground by 4-inch spikes) with a 12-lb sledgehammer. Striking one side of the anvil produces a horizontally polarized S-wave; striking the opposite side of the anvil produces an S-wave that is polarized in the opposite (reversed) direction (Figure 3-5). For QC purposes, S-waves were identified in the field by noting phase reversals (transposition of peaks and troughs) between data printouts from forward and revised hammer blows. S-waves were also identified by stacking forward shots then subtracting reverse shots directly on the seismograph; the resulting waveforms were then viewed on the seismograph display screen.

Downhole depth measurements were made using the 5-foot marks on the geophone cable, and also by using a fiberglass tape measure fastened to the geophone cable. The tape measure served to verify the geophone cable depth marks, and provided depth measurements for intervals smaller than five feet.

3.7.2.3 VSP Test Results

Seismograms from the VSP test survey were reviewed by the Test Supervisor, the Seismograph Operator, and the DRP QA geophysicist. The following conclusions were drawn:

- P-wave arrivals from the Minibuggy were pickable; tube waves could also be identified and were generally distinguishable from P-wave arrivals.
- S-wave arrivals were easily visible to 300 feet bgs.
- Primary reflections were not seen; a possible tube wave reflected from a fault intersecting the borehole was noted.
- No significant horizontal anisotropy was observed.
- Changing the offset distance of the source point from borehole does not appear to affect P-wave character.
- Blackhawk expressed confidence that the tube wave can be filtered to help make P-waves more readily identified.
- With absence of reflection events in both the reflection and VSP test data, the VSP production survey should use near-offset source points to obtain better velocity and engineering information
- A check-shot survey using the Betsy Seisgun should be performed to help identify and time P-wave arrivals from the Minibuggy vibratory source.

3.7.2.4 VSP Production Survey

On the basis of the VSP test survey results, a three-phase VSP production survey was performed. The VSP production survey consisted of: 1) a near-offset P-wave survey , 2) an S-wave survey and, 3) a limited far-offset VSP survey. In addition, a check-shot survey using the Betsy Seisgun was also performed

Near-offset P-wave VSP Survey

The near-offset P-wave VSP production survey used two source points: one point 10 feet from the borehole in the strike direction, and one 10 feet from the borehole in the updip direction (Figure 3-4). Downhole measurements were made at 2-foot intervals in the upper 100 feet, and 5-foot intervals below 100 feet (Figure 3-5). The survey was performed to a depth of 330 feet bgs, where the borehole was blocked. After conferring with the project managers at HLA's Morrisville, North Carolina office, it was decided that the field crew should complete the VSP production survey to 330 feet, not standby for the borehole to be cleared. VSP data below 330 feet was deemed less critical because the depth of investigation for the associated shallow seismic reflection Test Survey was only 150 feet; additional VSP data below 330 feet could be obtained later, if required.

The two-foot measurement interval in the upper 100 feet was designed to provide the resolution necessary to delineate a thin, shallow weathered zone that is believed to transition sharply to less-weathered bedrock. The two-foot spacing was also designed to provide sufficient data density for a detailed engineering analysis of the shallow subsurface. VSP data from the second near-offset source location was obtained to check repeatability, and for redundancy in the event that P-wave arrivals were difficult to pick on the first data set.

S-wave VSP Survey

The S-wave production VSP survey was performed using the same source point locations as the near-offset P-wave VSP survey. Downhole measurements were made at 4-foot intervals in the upper 100 feet, and 10-foot intervals from 100 to 330 feet bgs. The 4- and 10-foot measurement intervals provided S-wave data at the same depths as the P-wave data to facilitate the calculation of elastic properties for the engineering analysis of subsurface materials adjacent to the borehole.

As with the VSP test survey, S-wave energy was generated using the S-wave anvil. In general, energy from five successive hammer blows was combined (stacked) to produce one data record. At each measurement depth, separate data records were made for forward and reversed shots. Seismograms from selected pairs of forward and reversed shot records were output in the field and superimposed to verify phase reversal and insure that adequate S-wave energy was being produced.

Limited Far-Offset VSP Survey

A limited far-offset VSP survey was performed using two source points positioned 100 feet from the borehole in the strike and updip directions (Figure 3-4). Downhole measurements were made at 10-foot intervals from 200 to 330 bgs. The purpose of the far-offset VSP survey was to further evaluate horizontal anisotropy related to geologic structure, and to aid in the analysis of tube wave noise.

Check Shot Survey

A check-shot survey using the Betsy Seisgun as a P-wave source was also performed. Downhole measurements were made every 50 feet to a depth of 300 feet bgs. The purpose of the check shot survey was provide preliminary P-wave velocity information in the field, and to help identify P-wave arrivals on the VSP seismograms during subsequent data processing and analysis.

3.8 Data Management

Data management tasks were conducted, in accordance with the Technical Procedures appropriate for the field task, and in accordance with TP-23 (Electronic Data Management and Preservation) and the Data Management Plan.

3.8.1 Field Data Management

Oversight of field data management was the responsibility of the Field Activities Manager and the Field Operations Manager. At the end of each work day all field logbooks, field forms, diskettes, video tapes or other field data were placed in a locked, fire-resistant safe located in an onsite, access-controlled area by the HLA personnel responsible for those data. Each morning only the items necessary to conduct that day's work (e.g., field logbooks, relevant field forms) were taken out to the work site by HLA personnel.

Upon the completion of the field work and compilation of the Data Deliverables, the Technical Investigator submitted all field data deliverables to the Project Manager for inclusion into the Project Files or Project Database, as appropriate.

3.8.2 Electronic Data Management

Procedures for the management and preservation of electronic data are described in TP-23 (Electronic Data Management and Preservation) and the Data Management Plan. In summary, these documents, finalized during the GM-1 Pilot Study field activities, describe how a Technical Investigator compiles a Data Deliverable containing field data, office data, and other information, and transfers that Data Deliverable to the Project Manager for inclusion in the Project Database and/or the Project Files.

Because HLA is still in the process of identifying the Data Deliverable format and content for each field activity, much of the data generated during the GM-1 Pilot Study field activities are not yet loaded into the Project Database. The process of writing descriptions of Data Deliverable format and content is expected to be completed by mid-November, 1997, and will result in detailed descriptions that can be incorporated into each Technical Procedure. As the Data Deliverable descriptions are completed, the remaining data generated during the GM-1 Pilot Study field activities will be compiled into a Data Deliverable, transferred to the Project Manager, and uploaded into the Project Database and/or Project Files.

3.9 Quality Assurance

The GM-1 pilot study was conducted under the controls of the Project quality assurance program. The objective of the quality assurance program for all phases of the Project is to provide assurance that technical requirements, and ultimately the operational Facility's performance objectives will be met. Project quality assurance focused on data gathering, data processing and data analysis as the primary quality affecting activities for the pilot study. To support this, surveillances were performed to verify compliance with procedural requirements for various field activities.

The following surveillances of field activities were conducted as oversight of a representative sample of the quality affecting work under the GM-1 Pilot study. Opportunities for improvement identified during these surveillances were presented as either a Recommendation, a Concern, or a Nonconformance(NCR). Recommendations are for consideration only and therefore do not require a written response from the recipient. Recommendations are, however, tracked by Quality Assurance to support trend analysis. Concerns identify a condition requiring a written response and positive corrective action from the recipient to correct or avoid a work activity deficiency, and NCRs identify procedural violations that must be formally addressed with documented, planned and implemented corrective action. Any strengths identified during the surveillance are also documented to record noteworthy aspects of an activity's performance.

Summary of surveillances:

- Observed the setup and start of the drilling activities at the Site. Adequacy of procedural controls, as well as actual drilling practices were observed and evaluated. This work was performed under HLA procedures TP-1 (Drilling Procedures), TP-8 (Field Logging of Core), and TP-11 (Core Transfer). This surveillance reported the following:

  Recommendation #1

  A Work Instruction was incompletely filled out in that some spaces on the form were left blank. On any document that will become a record of Project activities, all appropriate spaces on the form should be either filled in, or N/A marked in that space to provide for completeness or closure of that document. If the space in question is determined to be unnecessary, then consideration should be given to modifying the form.

Recommendation #2

TP-11 Appendix A form 1 refers to "Technical Program Director". This title is no longer applicable and should be corrected at the next procedure revision.

Strength

The field logbook entries made were thorough, neat and legible and documented in accordance with section 6.1 of TP-1. The entries provided a clear chronology of work performed, environmental conditions and other potentially useful information not directly related to the technical aspects of the work, such as a notation of visitors to the drill site.

Concern #1

Section 6.1 of TP-1 requires that the Field Activities Manager (FAM) be responsible for checking the thoroughness of field documentation and correct any noted deficiencies. While discussion with the FAM revealed that this requirement reflected actual practice, TP-1 does not currently provide direction for the mechanism for documentation of this review, or the required periodicity of this review. Since this procedural step describes a discrete quality control check for the drilling activity, it is important to establish a systematic approach to its implementation. This Concern is applicable to both the review of the Field logs as well as the Borehole Record forms. TP-1 should be revised to provide this requirement. To address this Concern, the FAM should provide a memo to Quality Assurance documenting the action that will be taken and it's associated completion date.

Resolution:

TP-1 was revised on 5/5/97 to provide clearer guidance for these checks

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The individual signing as Reviewer of TP-8 was not on record as having completed the required training to perform this function as required by section 4.5.2 of QAP-5, Preparation of Quality Assurance Procedures and Work Instructions. The Quality Assurance Manager is responsible for ensuring that Project personnel are trained to understand their roles in support of the Project's QA program, and the Project Manager (or his designee) as procedure Approval authority for HLA procedures, is responsible for ensuring that those signing as preparers or reviewers have been appropriately trained for that function. Therefore, resolution of this Nonconformance should be coordinated by both the Quality Assurance Manager and the Project Manager.

Resolution:

The NCR was responded to on 6/1/97, with the immediate training of the technical reviewer involved, as well as a commitment from Project management to maintain a stronger awareness of the training needs for new Project team arrivals. The NCR was closed on 6/1/97.

- Observed Site trench excavation and mapping activities; reviewed and evaluated adequacy of procedural controls versus actual practice. This work was performed under HLA procedures TP-6 (Trench Excavation) and TP-9 (Trench Mapping and Documentation). This surveillance observed trench excavation activities only, and no discrepancies were noted during the surveillance.

- Observed Site trench mapping activities; reviewed and evaluated adequacy of procedural controls versus actual practice. This work was performed under HLA procedure TP-9 (Trench Mapping and Documentation). This surveillance reported the following:

Recommendation #1

The records of the training provided to personnel performing trench mapping work should be generated by TPFG and maintained as Project records. The Geosciences Discipline Lead is responsible for ensuring that documented training takes place on this and other site geoscience studies prior to the start of that activity.

Recommendation # 2

TP-9 should be revised at the earliest opportunity to restructure it to follow more closely with the Project's standard procedure template. This action will help clarify actual implementing steps for both the users and reviewers of the procedure.

Recommendation # 3

TP-9 should be revised at the earliest opportunity to clarify this step's intent.

Concern # 1

TP-9 does not currently provide clear direction for the mechanism for documentation or periodicity of the QC reviews called out in section 6.2. Since this procedural step describes a discrete quality control check for the trench mapping activity, it is important to establish a systematic approach to its implementation.

Resolution:

TP-9 is being revised for publication prior to the start of site-wide characterization.

- Observed BIPS activities and related activity controls. This work was performed under HLA procedures TP-13 (Geophysical Logging) and TP-14 (Borehole Image Processing System [BIPS]). This surveillance reported the following:

  Recommendation #1

  Any records that represent instrument or device calibration/comparison check traceability to known standards, and could be considered important records for the validation of activity deliverables should be identified and included as part of that deliverable.

  Recommendation #2

  The individual in charge of an activity at the site should coordinate with the office document distribution staff to have an appropriate number of controlled copies of necessary documents in place in the field prior to start of work.

  Strength

  A designated HLA staff member actually at the work site with direct supervision over, and responsibility for subcontractor work in progress represents a solid activity controls approach.

- Observed the startup of geophysical logging work performed by Schlumberger and evaluated related activity controls. This work was performed under HLA procedures TP-13 (Geophysical Logging - General Procedure) and TP-27 (Schlumberger Borehole Logging). No deficiencies were noted during this surveillance.

- Observed hydrophysical logging performed by COLOG and evaluated related activity controls. This work was performed under HLA procedure TP-19 (Hydrophysical Logging for Aquifer Characterization). This surveillance reported the following:

  Recommendation #1

  Discussion should take place between HLA and the COLOG OLS to identify and correct any conflicts between procedural work sequencing requirements and actual needed field practices to avoid the potential for procedural nonconformance.

4.0 DATA ANALYSIS

This section describes the data analysis and interpretation process conducted by the HLA project team with respect to the techniques described previously in Section 3.0. The description of analytical work is included in the following six subsections:

- Analysis of Hydraulic Response During Drilling and Testing
- Analysis of BIPS/FMI Image Data
- Analysis of Borehole Geophysical Logs
- Hydraulic Testing Analysis
- Geochemical analytical results
- Seismic Reflection

Based on our evaluation of the results of the Pilot Study and the various tools used, a discussion of our recommended set of tools is presented at the end of section 4.0. The analytical results are then integrated in Section 5.0 where an interpretation is also provided.

4.1 Analysis of Hydraulic Response During Drilling And Testing

As discussed in Section 3.2.2 (Hydraulic Monitoring), the presence of distinct water loss zones, and the volume of water lost or produced at each borehole was noted during field work. These field observations, such as field activity chronology, cumulative water usage or production at each borehole, April and May, 1997 meteorological data, and hydraulic responses to field activities are assembled on Plate 4-1 and discussed below.

4.1.1 Water Loss Zones

Observations of the rate of water usage or production during drilling were utilized to identify water loss zones. Use of drilling fluids, although beneficial for coring and for producing a clean borehole suitable for wireline logging, tended to mask minor water use fluctuations and made it difficult to identify the lower yield water loss or production zones during drilling. Additional information, including the monitoring well hydraulic responses discussed below, were also used to identify significant zones of water loss.

Based on these field observations, two distinct water loss zones were identified at Boring W205CH1. The zones are present at approximately 157 and 321 feet bgs. During coring work at Boring W205CH1, circulation was suddenly lost at the 157 foot depth, which generally corresponds with a bedding-plane fracture present at the base of a sandstone unit, and with hydraulic responses at Monitoring Well W8MC12, first noted when this zone was encountered. The water loss zone at 321 feet bgs was characterized by a slow increase in water usage during coring or an increase in water production during reaming, once this depth was encountered. This zone appears to correspond to an interval of highly brecciated bedrock, and possibly another bedding plane fracture, that are present directly above the W8 fault at this location.

The only other obvious water loss or production zone observed during drilling GM-1 Pilot Study boreholes is present at Boring W201AR1A. Borings W201AR1A and W201AR1B were the only boreholes drilled dry, without the addition of water into the compressed air stream during air rotary drilling of the competent bedrock. Therefore, it was easier to identify lower yielding water production zones in these borings, than in the other borings, where small quantities of water were added to the compressed air to produce a moist air stream during drilling. However, because of evaporative losses into the air stream, very low yield water-bearing intervals could still not be identified. At W201AR1A a small production of water was noted when air rotary drilling at approximately 88 feet bgs. Geophysical logging and hydrophysical logging discussed in Sections 4.3 and 4.4 respectively did not support the existence of a water yielding zone at this depth in Borehole W201AR1A, but did indicate low-yielding, water-bearing intervals at depths of 45.2 and 48.8 feet bgs.

4.1.2 Water Usage and Production

Records of water usage during field activities allowed correlation of water usage and production to specific field activities. In general, bedrock coring activities (where drilling fluids were circulated during coring) would generally result in a net loss of drilling fluids to the formation. Whereas, air rotary drilling or reaming (where large quantities of air was injected into the borehole) generally resulted in a net production of water from the formation (Plate 4-1).

At all drilling locations except Borehole W206AR1, field activities generally resulted in a net production of water from the borehole, or in one case, a minor loss to the formation (109 gallons were loss to the formation at Borehole W204AR1). Field records indicated that field activities at Borehole W206AR1 resulted in a net loss of 1,449 gallons of water to the formation. The most significant exchange of water occurred at Borehole W205CH1. At this location approximately 14,235 gallons of drilling fluids were lost during coring activities, whereas approximately 34,098 gallons of formation water was later produced during air rotary reaming, air rotary drilling, and packer testing, resulting in a net production of 19,863 gallons of water from W205CH1.

4.1.3 Hydraulic Response Analysis

The production and loss of water in the boreholes produced measurable hydraulic responses (changes in head) in some of the wells monitored during field activities. Table 4-1 and Plate 4-1 present the hydraulic response data collected during the GM-1 Pilot Study. For the purpose of analysis and discussion, the observed responses were numbered from 0 to 25, as indicated on Table 4-1 and Plate 4-1.

The majority of the noted hydraulic responses represent natural groundwater recovery in the borehole after drilling (Responses 0, 4, 8, 10, 13, and 15), packer testing (Responses 6, 11a, 16, 21a, 22, 24, and 25), or geochemical sampling (Response 23) at those locations. Two of the noted responses represent a lowering of groundwater head in Borehole W205CH1 after air rotary drilling (Response 9) or reaming (Response 7) at that location. The remainder of the hydraulic responses were interpreted to represent hydrogeologic interconnection between boreholes, and are discussed below.

Hydraulic responses interpreted to be related to Borehole W205CH1 field activities were observed at Boreholes W203AR1, W206AR1, W109VS3, and W8MC12 (Table 4-2). The most complete data set showing hydraulic responses to W205CH1 field activities is the hydrograph for Well W8MC12 (Responses 17 through 20), which is located approximately 500 feet north (along formation strike) of W205CH1. Daily rises in head related to coring activities as well as falling head responses related to air rotary reaming and drilling are apparent in the W8MC12 hydrograph. Initial hydraulic responses to coring activities occurred on April 7, 1997, at the same time that a bedding plane fracture was encountered at a depth of approximately 157 feet bgs in Borehole W205CH1 (observed to be present at 161 feet bgs in core samples). These responses correlate well to the daily coring activities with an averaged increase in head of 0.2 feet a day. The air rotary reaming event (April 14 through April 16, 1997) at W205CH1 produced a 3.2 foot drop in water level at W8MC12, whereas the air rotary drilling event (April 21 through April 22, 1997) produced a 2.5 foot drop in water level.

Well W109VS3, located approximately 110 feet west (up dip) of W205CH1, also exhibited hydraulic responses (Response 11b). The observed changes in head occurred during packer testing of W205CH1. During this period (April 16 through 19, 1997), several drops in head (up to 21.7 feet) and related recovery responses were measured. Water levels were not monitored in W109VS3 during W205CH1 drilling activities.

W206AR1, located 350 feet east of W205CH1 (down dip and across the W8 fault), exhibited hydraulic responses to drilling activities at W205CH1 (Responses 12 and 14), but did not have observable changes in hydraulic head during packer testing of W205CH1. The observed responses occured during air rotary drilling activities (April 21 and 22, 1997), in which a total of 14,500 gallons of water was produced from the formation at W205CH1. Decreases in head of at least 9.4 feet were observed at W206AR1 at this time. It is likely that no responses were observed during packer testing because considerably less water was produced from the formation at W205CH1 during this activity.

At Borehole W203AR1, located approximately 530 feet west (up dip) of W205CH1, hydraulic responses to both drilling activities (Responses 1 through 3, and 5) and packer testing (Response 11c) were observed. Drops in head of up to 22.2 feet were measured during air rotary drilling or reaming activities, whereas increases in head of up to 9.7 feet were measured during coring activities. Smaller responses were measured during packer testing. A drop in head of approximately 4.7 feet was observed at W203AR1 at this time.

The only other hydraulic response interpreted to represent a hydrogeologic connection between boreholes occurred at W201AR1B. This response (Response Number 21b), appears to be related to packer testing conducted at Borehole W201AR1A, located approximately 10 feet west of W201AR1B. The response is characterized by an initial rise in head of approximately 0.6 feet, probably due to the installation of the packer in Borehole W201AR1A, followed by a drop in head of approximately 1.2 feet, caused by the withdrawal of water from W201AR1A during the packer test. This is followed by a slow recovery of the water level after the packer test was completed.

4.2 Analysis Of BIPS/FMI Image Data

Image data were recorded in boreholes drilled during the GM-1 Pilot Study (Schlumberger and COLOG) to evaluate the stratigraphic, structural, diagenetic, weathering, textural, and mineralogical features detectable in the borehole wall. It was used to locate and orient fractures and bedding planes to aid in the analysis and interpretation of in-situ physical and hydrologic properties. Further, this data was used to perform direct comparison of wellbore images to recovered core from the same corehole and may be used to orient recovered core. The results of the assessment of the imaging tools as a technique for the sitewide investigation is presented in Section 4-7 and summarized in Table 4-10.

The BIPS image data analysis was performed by GeoMechanics International (GMI) using an image analysis software package GMI•Imager with associated convert routines for BIPS and FMI data which run on a MacOS CPU. However, the FMI data collected to date by Schlumberger has not been released in a format that can be analyzed using the GMI• Imager.

4.2.1 BIPS Data Calibration

Analysis of the BIPS data requires an independent diameter (caliper) determination. This caliper data was recorded by COLOG directly after BIPS logging was completed for each borehole. The caliper and BIPS data were offset by 4.25 feet from most data sets. This offset is the result of the difference in the geometry of the BIPS and caliper probes. In some boreholes, however, the caliper was offset by more than 4.25 feet and the source of this offset is unknown. All data files were aligned with the bottom of casing to assure accurate calibration for borehole diameter. This resulted in an acceptable level of depth matching throughout the logged interval in all wells.The beginning and ending depths of the digital image data files were verified against caliper (casing ties, fractures) to ensure proper depths of digital data. The orientation of the digital BIPS data was calibrated against the measurement obtained during the instrument calibration in the field calibration tank before and after logging to check color accuracy and lighting intensity. Figure 4-1 shows the calibration image recorded before and after the W208CH1 logging run. These images provide verification that the tool was functioning properly during the entire logging run. The BIPS image was also checked over the same relogged wellbore interval for consistency.

The wellbore image data was corrected for magnetic declination directly after conversion from raw data format to the format of GMI•Imager. The BIPS image data required brightness enhancement prior to analysis to improve feature visibility.

4.2.2 BIPS / Geophysical Log Integration

As previously stated, the FMI data were not analyzed using the GMI Imager software. Rather, the data were provided in hard copy format which was used, in conjunction with the BIPS data, for the stratigraphic analysis. A full analysis of the FMI data was performed by Schlumberger and provided to GMI, allowing for a comparison of the two data sets. In comparing the two data sets, the only problem which affects data integration is an approximately one foot difference between depths measured by COLOG and those measured by Schlumberger. This caused registration mismatch between BIPS and FMI images, and between 3-arm caliper (which was used as a washout indicator) and the Schlumberger logs. Correction required depth tie checks among the BIPS, FMI and log data using features such as casing and clearly identified fractures.

4.2.3 Stratigraphic Analysis

To analyze the stratigraphic units, an interactive software routine is used which allows the user to fit a sinusoidal trace to both the bed dip and interval height. Once the unit is selected, the software records the contact depth, bedding orientation and thickness corrected for apparent dip. Lithologic contacts and stratigraphy were classified according to the project Geological Lexicon of Terms using the digital BIPS and analog plots of the FMI data. In addition, the spectral gamma logs were used to help identify lithologies. Strata were classified according to rock type (sandstone, mudstone, etc.,), modifiers (sandy, silty, etc.), color, bedding features (laminated, graded), contact type (sharp, gradational) and associated features (burrows, bleached zones, etc).

It was generally possible to discriminate changes in lithology in a straightforward way using both the BIPS and the FMI data sets. Because most of the lithologies at this site have a similar color range, the distinction between siltstone and very-fine sandstone and between the various sandstone classifications (fine- to medium-grained) was difficult based on the BIPS data alone. Stratigraphic interpretation required the use of the FMI data to distinguish relative grain size changes as this tool is a sensitive indicator of lithologic composition change. As discussed in the GM-1 Pilot Study Work Plan, the FMI tool operates using AGC and data must be normalized for interpretation. Because of this normalization, it is not possible to use the FMI data to determine grain size in an absolute sense. However, relative grain size does map to a consistent false-color range for a given logging run.

Using the BIPS image data, accessory features such as burrows, color mottling, etc., could be resolved which is not possible with the FMI data. It is possible to directly measure clast size and estimate clast percent from the BIPS images which is not possible using FMI data. The resolution of the BIPS is, of course, less than the resolution available through direct inspection of the core and it was difficult in many cases to distinguish burrowing from root casts or from areas that are stained or color mottled.

The gamma ray log can help delineate contacts and constrain FMI/BIPS interpretations. However, it is possible to miss-identify "shales" unless the source of the gamma signature can be clearly identified.

For the purpose of this report, the FMI/BIPS/gamma ray interpretation data were exported to the Apple Core graphic log package to produce a set of graphic logs. These "interpretive graphic logs" based on the FMI/BIPS/gamma ray analysis are presented at a scale of 1-inch = 10-feet in Appendix B-2.

4.2.4 Comparison of Graphic Logs

Lithologic graphic logs were generated for all boreholes drilled in the GM-1 Pilot Study. Graphic core logs were produced from W205CH1 and W208CH1 cores and from requalified cores (HLA, 1997). Interpretive graphic logs were produced by analyses of geophysical and borehole imaging data for all W200 series boreholes drilled during the GM-1 Pilot Study. Both types of graphic logs were printed using the Apple Core graphics program. Methods of producing graphic logs are discussed in section 3.3.1.5 and 4.2.3. Graphic logs are included in this report (Appendix B).

Reviews of graphic logs generated by the Apple Core graphics package indicate the following required adjustments:

- Graphic Core Log grain size curves do not always accurately portray lithologic types. This is especially noted in the case of conglomerates.

- Interpretive graphic logs need explanations of rock colors and abbreviations.

The following observations suggest adjustments may be required:

- Interpretive graphic logs subdivide the siltstone/mudstone lithologies into four units with two siltstones colored tuscan red and two mudstones colored purple. This two-color approach creates confusion when comparing interpretive graphic logs with graphic core logs on which siltstones and mudstones are lumped together and colored tuscan red.

- Both graphic core logs and interpretive graphic logs subdivide sandstones with medium- to very coarse-grain sizes colored yellow and fine- to very fine-grain sizes colored orange. This yellow-orange boundary at the medium- to fine- grain size break is not compatible with the yellow-orange boundary in the trench map where it occurs at the medium- to coarse- grain size break.

A comparison of interpretive graphic logs with graphic core logs for W205CH1 and W208CH1 indicates that information provided is not equivalent. Interpretive graphic logs report more fine-grained sandy lithologies than graphic core logs indicating that the sand content of mudstone tends to be underestimated during core logging. In general, compared to graphic core logs, interpretive graphic logs provide better resolution of the very fine-grained lithogies, ie: rocks in the range of very fine sandstone to claystone. On the other hand, biogenic, epigenic and diagnostic features are best observed during core logging.

4.2.5 BIPS/FMI Fracture Analysis

Structural features observed in the FMI/BIPS images were analyzed using an interactive software routine which allows the user to fit a sinusoidal trace to the feature. Once the feature is selected the software records the depth, orientation and apparent aperture of the feature. The term apparent aperture is used because the apertureof a fracture can be mechanically enlarged at its intersection with the drillhole by the drilling process. For this reason, apparent aperture as measured by the BIPS is not necessrily related to and should not be used to provide a measure of hydraulic aperture. It should also be noted that variations in mechanical properties of different rock types may allow for contacts to be preferentially eroded during the drilling process and, thus, these zones may mistakenly be interpreted as bedding-plane fractures.

Fractures and faults imaged with the BIPS system have been measured and classified according to the project Lexicon. During the BIPS analysis, the depth, dip, dip direction, aperture (if measurable), fracture type (i.e., normal, shear, bedding) and fracture description (i.e., open, closed, mineral filled) were determined for each planar feature. To qualify as an "open" feature the fracture or fault had to satisfy two criteria: 1) the feature had to exhibit a sharp, well-defined break, without evidence of sealing or induration and, 2) the feature had to maintain a continuous trace for over 80 percent of the borehole circumference. Stereonet plots of the fracture data are presented in Appendix E. The FMI analyses presented in these plots were obtained by Schlumberger with their proprietary software system.

In addition to assessing the properties of individual fractures, fractures were also analyzed with respect to their occurrence in a particular lithology. Based on an evaluation of the tadpole plots shown on the montages and panel diagrams and their associated graphic log, there does not appear to be a direct correlation between fracture density or fracture orientation and lithology.

A comparative analysis between BIPS fractures and the FMI fracture data provided by Schlumberger was performed for boreholes W201AR1 through W208CH1. In general, using the BIPS image data, it is possible to clearly distinguish bedding parallel fractures from the actual bedding contacts, whereas the FMI analysis picks boundaries between beds as bed boundaries and does not discriminate bedding parallel fractures. For this reason, the number of fractures measured from the BIPS image data are significantly greater than that measured using the FMI image data (i.e., BIPS data set includes both high-angle and bedding parallel fractures). However, the population of bedding parallel fractures detected in the optical image data is represented by the population of the bedding fabric and bed contacts measured in the electrical image data. In comparing the two data sets, it is apparent that the overall structural trends of the fractures and strata are quite similar for both imaging methods.Many of the differences between the methods are due to differences in the display and analysis tools used to interpret the data. Differences in the classification of planar features may also be the result of different interpretations of these features by the analysts. A detailed discussion of the fracture analysis comparison is presented in Appendix E.

The BIPS tool provides geometrically accurate data and it is therefore possible to directly measure apparent fracture aperture. FMI data requires substantial processing to determine fracture aperture but these measurements will be available to compare to the direct aperture measurements made using the BIPS data. The BIPS data do not provide fracture hydraulic aperture.

When interpreting the FMI hydraulic fracture aperture data it is important to consider that FMI fracture aperture is calculated from electrical conductivity anomalies. Since clays are very conductive relative to the pore fluid, a clay filled (sealed) fracture may appear to be electrically conductive and hence to have a high hydraulic conductance. However, the fracture may not be hydraulically conductive, but just sealed by the clays. The importance of this effect depends on the specific conductance of the clay relative to that of the pore fluid. Although mineralogy of the fracture filling cannot be distinguished using the image techniques, it may be possible to assess the presence of a conductive clay using the gamma log.

A separate analysis of the full waveform Stoneley data can help discriminate which fractures detected in FMI data are fluid filled. Reflected Stoneley waves (see Section 4.3.1) emanate from fluid-filled fractures or from borehole washouts. Thus, Stoneley data may be extremely useful when used in conjunction with the FMI image data to detect the hydraulically important fractures. An important caveat in utilizing Stoneley reflections to assess fracture permeability is that Stoneley reflection will occur at borehole washouts, even if the associated fracture is not a fluid source. The caliper data can also be used to help assess which fractures may be hydraulically important if the assumption is made that washouts correspond to fluid-filled fractures.

4.3 Analysis of Borehole Geophysical Logs Data

This section presents a discussion of the analysis of the borehole geophysical data collected during the GM-1 Pilot Study. It is broken into a discussion of log handling and post-logging processing, the presentation for the logs, the type of data obtained from the logs, results of the log analysis, and significant observations about the GM-1 Pilot Study area based on log interpretations.

4.3.1 Log Handling and Post-logging Data Processing

The format and handling of the field data has been described in Section 3.4 of this report. In most cases, the field results were used for analysis without modification. In other cases, post-log reprocessing was necessary to enhance the usefulness of the final data. Post-log processing was required to obtain some results because the computations cannot be performed in the field. Interpretations of image data to provide fracture orientations and stratigraphic details are described in Section 4.2 and in Appendices D-1 and D-2).

The following logs were reprocessed prior to use:

- DSI: DTCO, DTSM, and DTST were recomputed from the monopole waveforms and from the Stoneley-wave logging mode data. The reprocessed values appear to have been smoothed more than the field derived data and therefore have less vertical resolution. In places where the data resolution is good, the results are similar to those provided in the field.

The following log curves were computed by Schlumberger at their computing center:

- Stoneley-wave reflectivity: This is computed using the waveform data obtained from the low-frequency "Stoneley-wave" DSI logging mode. Processing of the Stoneley-wave data allows extraction of the amplitude of the direct arrival and of energy reflected from impedance contrasts along the borehole. Stoneley-wave reflectivity is the ratio of reflected to incident amplitude. Because reflections are generated at the intersection of permeable fractures with the borehole, it is tempting to use this analysis to characterize fracture permeability. However, when doing this it is important to realize that hole size changes associated with mechanically weak fractures (that is, those which may in fact be permeable) also cause large impedance contrasts and make it difficult to use this method to quantify fracture permeability. Because the same fractures can be detected in 3-arm caliper logs, the information from this analysis is largely redundant.

- CMR Permeability: CMR permeability is computed from CMR porosity and the spectrum of T_2 times, as described in Appendix D-1. The equation is generally calibrated using laboratory data. In this study, default values were appropriate, as revealed by direct comparisons of log-derived permeability and gas permeabilities measured in mini-cores.

- FMI fracture apparent aperture or apparent transmissivity: FMI images provide relative values of electrical resistivity using an array of electrodes spaced approximately 1 cm apart. The data are usually displayed as a false-color image. Fracture apparent electrical aperture can be computed using FMI images which have been calibrated to provide absolute measures of resistivity. The RXO8 curve can be used for this purpose. Once the image is calibrated, the apparent fracture aperture can be computed by integrating the electrical conductivity along the fracture, dividing by its length, and scaling by an assumed value of the conductance of the material within the fracture. A parallel plate model for fluid flow can then be used to compute hydraulic transmissivity from the apparent aperture. Unfortunately, if clays are electrically conductive and fill a fracture, it will appear to have a large hydraulic aperture when in fact it does not. It is possible using gamma or other logs to identify fractures where this occurs.

- Seismic correlations were prepared by GMI using the reprocessed DTCO data and the RHOZ field data.

- Time-to-depth: Time-to-depth curves used to correlate reflections in seismic data to lithologic features identified using logs are obtained by integration of DTCO. Because no data are obtained above the water table, an arbitrary offset is applied to obtain a tie point to the seismic data. Using density and DTCO together, a synthetic seismic trace can be computed to make it easier to correlate the log data to the seismic image. An accurate source-time function convolved with the reflection coefficient time series is necessary to optimize this process.

4.3.2 Presentation of Geophysical Logging Results

Due to the nature and design of the GM-1 Pilot Study, geophysical logging results are and have been available in a vareity of forms as described below:

Montage Plots. Montage plots were prepared by Schlumberger Wireline Services for W205CH1 and W208CH1. The montages have been transmitted under separate cover. A description of the data displayed in each track of the montage plots has been included in Appendix D-1 to this report. Many of the tracks displayed in these plots are identical to those displayed in the panel diagrams described below. In addition, however, the montages display quality control information and raw data from which some of the results displayed in the panel diagrams were obtained.

ELAN and FMI Logs. ELAN and FMI logs were prepared by Schlumberger for boreholes W201 through W208. The results of the ELAN and FMI interpretation for W205 and W208 are presented on the Montages (Appendix D-1) mentioned above. Separate ELAN strip logs for boreholes W201 through W204 and W206 and W207 have been transmitted under separate cover at a scale of 1-inch = 10-feet. Separate FMI strip logs for W201 through W208 have also been transmitted under separate cover at scales of both 1-inch = 10-feet and 1-inch = 1-foot. A full description of the FMI image data interpretation process is included in Appendix D-2.

Panel Diagrams. Panel diagrams were prepared for each well by GMI which include relevant individual log curves and interpretations based on the geophysical data, in addition to the results of image and core analyses and hydrologic and hydrophysical measurements. The geophysical logs which are presented in these panels are those which provided the best data for the purposes of site characterization.

Data from approximately the lowermost ten feet of logged depth in a borehole is often corrupted by bad nuclear data. This is particularly apparent in the NGT curves. These intervals have been edited out on the panel diagrams. The panel diagrams are presented as Appendix D-3 along with a detailed description of each track shown on the diagrams (for convenience, the panel diagrams accompany this report in a map tube).

Field Strip Logs. Copies of the strip logs for W201AR1A through W208CH1 that were originally delivered in the field from Schlumberger have been transmitted under separate cover. The scale of these logs is 1-inch = 10-feet.

Sonic Waveform Analysis. Separate Sonic Waveform Analysis strip logs including Stoneley refectivity for boreholes W201AR1 through W204AR1 and W206AR1 and W207AR1 have been transmitted under separate cover. The scale of these logs is 1-inch = 10-feet.

4.3.3 Data Obtained from Geophysical Logs

Data obtained from the geophysical logs include physical properties, lithologic and mineralogic data, and structural data as described below.

4.3.3.1 Physical Properties

Physical properties derived directly from individual logs recorded during the GM-1 Pilot Study include:

1. Elastic-wave velocities, which are measured by the DSI tool and provided as DTCO (compressional-wave inverse velocity), DTSM (shear-wave inverse velocity), and DTST (Stoneley-wave inverse velocity). In this study, excellent compressional-wave and Stoneley-wave velocities were obtained throughout. However, shear-wave velocities were poorly determined above approximately 200 feet and adjacent to fractures associated with hole enlargements. Velocities provided an extremely sensitive indication of the depth of the "weathered zone".

2. Density, which is measured by the PEX combination suite and is provided as RHOZ and RHO8.

3. Porosity, which is measured directly by the CMR tool and is provided as CMRP. Porosity was also computed with sufficient accuracy for the purposes of this study from density using an average grain density of 2.71 gm/cm^3, as determined from core measurements and from log analysis. On the other hand, neutron logs, which provide a measure of the volume concentration of hydrogen in the formation and are sometimes referred

to as porosity logs, are dominated at this site by the large amount of hydrogen in and closely bound to the surfaces of clay minerals and phyllosilicates. The CMR was useful during the GM-1 study because it revealed that porosity in the mudstones and claystones is extremely low. But because porosity is so low, it was not possible to calculate permeability or grain size distribution using the CMR tool. There was too little signal energy. One additional concern when using the CMR at this site, is that fractures and the associated hole enlargements generally caused anomalously large CMR porosity readings because the volume sampled by the tool is too close to the pad surface. Because of these issues, and because density porosity appears to be adequate for site characterization purposes, CMR is not considered to be necessary for further site characterization work.

4. Resistivity, which is provided by the AIT and on the PEX tool string as RXOZ and RXO8. Resistivity provides a measure of the volume of pore fluids (porosity) using Archie's law, and of conductive particles (primarily clays and very fine sands, along whose surfaces current can be conducted). The AIT is inappropriate for use at this site because it requires data from at least 85 feet above a given measurement point. RXOZ is sufficient because of the relatively small invasion and formation damage and because resistivity is primarily used for lithologic description rather than quantitative data.

5. Permeability, which is calculated from CMR porosity and the T_2 relaxation time spectrum. CMR-derived permeability in higher porosity sandstones was comparable to gas permeabilities measured in cores, but in low-porosity intervals which comprised the majority of the study volume permeabilities were lower than the measurement threshold of the log. Because hydrologically important intervals are tested using packers, this log is not critical to site activities. Rather, it is sufficient to identify higher-porosity sands from the other porosity logs and to test these intervals during hydrophysical logging or packer testing.

4.3.3.2 Lithologic and Mineralogic Data

Lithologic and mineralogic data obtained from the analysis of individual logs recorded during the GM Pilot Study include the following:

1. Spectral gamma, which could be used to determine the relative volume of minerals containing radioactive elements. This log indicated that illite is the primary clay component at the site. Gamma logs were also used to perform well-to-well correlations, as described in Section 5.4.

2. PEF from the PEX tool, which is a rough measure of average atomic number and is lower in quartz-rich intervals and higher where larger amounts of clay, mica and mafic minerals are present. U, which is the product of PEF and density, is a sensitive measure of the relative volume of quartz because quartz has a lower density and mean atomic number than most rock-forming minerals.

3. ECS elemental yields, specifically Si, Fe, and Ca, which were used in ELAN calculations to quantify feldspar and muscovite content. Although ELAN results (Section 4.3.4.3) which included the ECS were similar to core-derived mineralogical analyses where these were obtained, in general the results appear to yield values of muscovite content which are too high in most of the logged interval. For this and for reasons discussed further below the ECS is not considered to be necessary for further site characterization work.

4.3.3.3 Structural Data

Structural data were obtained from the FMI and BIPS image data and, indirectly, from the caliper log, as follows:

1. FMI and BIPS - Fractures can be identified and orientations obtained using image data. These logs and their analyses have been described in detail in Section 4.2. The FMI has been selected as the imaging tool for the sitewide characterization because the requirements for optimum data collection are difficult to obtain with the BIPS, the data processing and integration for BIPS requires excessive time and cost, and because the FMI provides the same (and more) information considered important to the project as the BIPS.

2. Caliper - Helped to identify washouts associated with fractures which affect CMR-derived data and the short-detection PEX curves (RHO8, etc…).

4.3.4 Results of Log Analysis

Logs can be interpreted either singly or in combination. Interpretations can be made using the actual measurements or with values calculated from the measurements using certain assumptions which may or may not be valid in all cases. Furthermore, conditions in the hole (for example, hole enlargements associated with fractures) may affect log response. These issues are addressed below in specific cases where they affect the interpretations. Analysis of the individual logs were used to provide data on the lithology, rock properties, and structure of the GM-1 Pilot Study area. In addition, the ELAN multi-log analysis was performed to provide addtional data on various rock properties, including mineralogy.

4.3.4.1 Lithologies and Associated Rock Properties

Geophysical logs can be used to identify boundaries between rock units with different properties, but because most of these logs have volumes of investigation with radii greater than one foot,it is not possible to characterize fine-scale stratigraphy within a single well. The FMI/BIPS image log, a discussion of which is presented in Section 4.2, sufficed to identify and characterize sub-foot-scale bedding stratigraphy and fine structure. In combination, the logs and images were sufficient to identify and characterize the properties of the important lithostratigraphic intervals at the site.

It is sufficient for site characterization to discriminate between "log-sands" (that is, intervals with relatively small amounts of clay minerals and sub-sand-size particles) and "log-shales" (that is, more clay-rich and finer-grained intervals). Log-shales are characterized by density greater than 2.6 gm/cm^3, U above 7.5, high gamma, and high neutron porosity relative to the porosity derived from the density log. Log-sands have lower density, gamma and U, and more similar neutron and density porosities. Log-shales are generally less resistive than log-sands.

Variations with depth of the relative volumes of "log-sands" and "log-shales" provide character to the logs. Correlations between boreholes are improved by using the vertical variation of individual log response. For example, clay-rich intervals, massive sands, fining-upward sequences, and intervals of mixed "sand" and "shale" can be identified and correlated between boreholes, even where the response within individual units changes.

In combination, density, neutron, resistivity, sonic and gamma logs can be used to improve lithologic and physical properties determined from analysis of individual logs. Simple inversions of the PEX logging suite allow approximate determination of the volume of "log-sand", "log-shale", and porosity. The majority of the logged section at this site is classified as a "log-shale". Porosity is less than 2 percent, and permeability is less than 0.1 milliDarcy (often several orders of magnitude lower). Although log-sands generally were easy to differentiate from log-shales, using either the gamma curve, U, or PEF, their properties appeared to be more variable. Particularly, the porosity and apparent (CMR) permeability differed significantly for different log-sand units, and in some cases even within a single unit identified at more than one borehole. Porosities in log-sands generally range from 5 percent to 10 percent and rare log-sands have porosities approaching 15 percent. Velocities in high-porosity sands were lower than in adjacent shales. The ratio of Vp to Vs, which can often be used to constrain quartz volume because quartz has a very low Vp/Vs in comparison to other minerals, was not by itself a useful parameter at this site.

4.3.4.2. Structure (fractures)

Fractures can be identified and oriented using image data, as discussed in Section 4-2. In addition, fractures affect logs in a variety of ways. For example, Figures 4-3 and 4-4 illustrate the obvious association of hole enlargements with a variety of geophysically-derived indicators of elevated permeability. In Figure 4-4, all of the conductive features identified by hydrophysical logging are also shown. The HpL™ -derived conductivity of most of these features is roughly proportional to the hole size increase and Stoneley-wave reflectivity.

Figure 4-3 illustrates the reasons for some of the most important effects of fractures on log response. Hydrologically important fractures are likely to be mechanically weaker than those which are not. Those fractures tend to be associated with hole enlargements which can be observed on 3-arm caliper logs; the largest of these will also be seen on 2-arm calipers such as HCAL. Washouts will generate Stoneley-wave reflections. Pad tools will lose contact with the hole wall resulting in higher neutron, lower density, higher CMR porosity and permeability, and lower resistivity, all of which can be misinterpreted to infer a highly permeable and porous interval. Also, if the hole is sufficiently enlarged the FMI pad will lose contact and the image will have less resolution. However, if a fracture is permeable it will generate

Stoneley wave reflections and may be associated with lower density and higher porosity rocks. In addition, the zone surrounding the fracture may be affected by fluids which flow through it, and thus may have lower seismic velocity, higher (or lower) porosity, and elevated (or depressed) gamma ray activity. In general, elevated gamma is associated with deposition of uranium in a reducing environment, and thus the uranium curve is useful in this regard.

Permeable fractures which contain fluids will be more electrically conductive, as will fractures which contain clay minerals or metallic sulfides. The gamma response surrounding a fracture can help to differentiate between clay-filled and open fractures.. PEF or U can help if sulfides are responsible for the excess conductivity. Thus fracture apertures determined using calibrated FMI data should be evaluated in combination with these logs.

4.3.4.3 ELAN Multi-Log Analysis

Combined analysis of a group of logs can provide information which cannot be obtained through analysis of the individual logs in isolation. Schlumberger offers an analysis technique called "ELAN" which was used in this study to invert the log data for mineralogy. ELAN logs for W205 and W208 are presented on the previously transmitted Montages for these coreholes. ELAN logs at the scale of 1-inch = 10-feet for , W206AR1, and W207AR1 have been previously submitted under separate cover. The ELAN logs have also been included in the panel diagrams presented in Appendix D-3. When examining the panel diagrams it should be kept in mind that the ELAN with ECS in W205 used the CMR porosity curve, whereas because CMR was not run in W208, a different curve replaced it. In W208 the porosity with ECS is larger than without; in W205CH1 it is smaller, consistent with the general observation that CMR porosity is generally a lower bound in these rocks. Exceptions include intervals where CMR porosity reads anomalously high due to the presence of large washouts (for example, at 330 feet in W205CH1).

Several important results were found using ELAN. First, there are definite differences between the volumes of clay minerals and grain minerals determined using the different inputs. Figure 4-5 compares the total volume of quartz hematite and albite from the ELAN data derived without ECS inputs to the total volume of quartz calcite hematite and albite from the process with the ECS inputs. The result with ECS is consistently smaller than that without the ECS. The addition of muscovite to the ECS volume is also illustrated in this figure; it does not improve the correlation to the sum without ECS. It is not clear which inversion is "better". Both reveal intervals of high and low "sand" fraction; these intervals correlate quite well. Examination of the Montages (Appendix D.1) reveals that the inversion with ECS provides a "sand" volume which is more consistent with the direct result of ECS analysis alone (the "quartz/feldspar/mica", or QFM). This is not surprising as the inversion was carried out with the goal of matching this value where possible.

A second concern with the ELAN inversion is that the volume of muscovite derived using ECS is quite high in many places. Core analyses have revealed finite intervals of lithic sandstones with large amounts of phyllitic schist. These may have muscovite content approaching 25 percent. However, they are less common than the ELAN results would suggest.

It is important to adequately clean the input data prior to the ELAN analysis, in particular to eliminate effects due to fractures. A correlation which appears in the data is that higher volumes of montmorillonite are predicted in intervals with higher porosity (for example, in W207AR1), especially those adjacent to fractures. This may be a real phenomenon as the rock surrounding fractures often differs in important ways from the adjacent intervals.

One additional feature of the ELAN data is that the uppermost interval immediately below casing is sometimes characterized by much higher montmorillonite volume than elsewhere. It is possible that this is due to the presence of the grout used to place the casing. In W201AR1A it is associated with elevated FEC.

An ELAN-style analysis is valuable to quantify the log analysis. However, the above observations suggest that it cannot provide quantitatively accurate mineral volumes throughout the site. This is because although mineralogy is restricted to relatively few species, variations in the properties and chemistry of some of the major species make it impossible to associate a unique and invariant log response to each mineral. In spite of the fact that the precision possible with the ELAN technique is misleading, appropriate use of similar inversion schemes would facilitate rapid log analysis and interpretation in a site-wide study. Better vertical resolution in the outputs could be obtained using as inputs logs with the highest possible vertical resolution.

4.3.5 Significant Observations Based on Geophysical Log Analysis

4.3.5.1 Variation in Mineralogy Across the Site

By plotting histograms of various log-derived measures it was possible to identify a distinct difference between the rocks on the east and west side of the W8 fault. That is, logs recorded in W201AR1, W202AR1, W203AR1, and W204AR1 differed from similar logs recorded in W206AR1, W207AR1, and W208AR1. These differences were first identified using ELAN quartz and clay-bound water content (Figure 4-6). In the holes west of the fault quartz content ranges from 30 percent to more than 60 percent, whereas on the east side of the fault the range of values is smaller and clusters around a mean slightly above 50 percent. Clay-bound water contents higher than 10 percent are more common on the west than the east side of the fault. Based on these data, the material on the east side of the fault appears to be less clay rich and more silica rich and to have a smaller range of clay contents, such that there are fewer extremely clay-rich intervals on the east compared to the west side of the fault.

Differences highlighted by the histograms shown in Figure 4-7 can be seen in a number of the logs displayed in the panels, but is easiest to detect using gamma (CGR). For example, in W202AR1 a thick log-sand at 92 to 96 feet has CGR less than 60 API units, but a log-shale immediately below that interval at 110 to 114 feet has CGR above 120 API.

In contrast, CGR in W206AR1 and W207AR1 only rarely approaches 120 API; it is generally less than 100. Although there are some intervals with large differences in CGR below a depth of 330 feet in W205AR1, the interval above that depth is more similar to the data to the west side of W8, and the interval below that depth is more similar to the data from boreholes on the east side of W8.

4.3.5.2 Shallow Zone of Relatively Higher Porosity

A number of logs revealed the presence of a near-surface interval extending to approximately 50 to 80 feet, with properties distinct from those of materials below this depth. In this shallow interval, density is lower and porosity is somewhat higher. The data which best delineated this interval were the sonic DTCO and DTST curves; DTCO was generally greater than 80 µs/ft and DTST was greater than 250 µs/ft in this zone. In general, the base of this zone coincides with a fracture / hole enlargement and associated zone of high DTCO (low velocity). Examination of the panel diagrams reveals that this zone sometimes coincides with the base of a "log-sand" (for example, in W203AR1). In other cases it does not (for example, in W201AR1). In most cases, the base of this zone coincides with producing intervals based on hydrophysical logging. In this upper, shallow zone, CMR porosity is slightly less than density porosity (using a grain density of 2.71 gm/cm^3), which suggests that the process that created the zone decreased the mean grain density slightly. This shallow zone recognized from geophysical logs has been interpreted to represent the weathered zone. A detailed discussion of the weathered zone is presented in Section 5.1.3.

4.4 Hydraulic Testing Analysis

As discussed in section 3.5, the hydraulic testing program conducted during the GM-1 Pilot Study included hydrophysical and packer testing. This section is divided into two parts to present the analysis and results of the hydrophysical and packer testing program.

4.4.1 Hydrophysical Logging

Documentation and results of the hydrophysical logging program conducted by COLOG during May 1997 were included in their 2 June 1997 report which was transmitted under separate cover (COLOG, 1997). The sections below with reference to Appendix F of this report provide a summary of data and results. The reader is referred to the full report for further details.

4.4.1.1 Analysis Method

A general description of the steps for processing the HpL ™ data follows:

1. The digital data was downloaded to a processing work station.

2. The hydraulic response data was plotted and reviewed.

3. The HpL ™ data was processed. This processing involved the application of COLOG's proprietary version of the U.S. Department of Energy's (DOE's) code BORE (Hale and Esang, 1989). The results of this processing were both tabular and graphical presentations of the depth of the hydraulically conductive intervals and the associated interval specific inflow rate. In addition, the field FEC logs were compared with the synthetic FEC logs generated by code BORE.

4.4.1.2 Results

Table 4-3 and plots of FEC with time and depth from each borehole are provided in Appendix F and summarize the results of the hydrophysical logging study. Two types of well testing were performed for the GM-1 Pilot Study during hydrophysical logging: Slug withdrawal and constant discharge tests. Slug tests were performed at six wellbores (W201AR1A, W201AR1B, W202AR1, W203AR1, W204AR1, and W206AR1) and constant discharge pumping tests were performed at two wellbores (W205CH1 and W207AR1). The maximum drawdown ranged from 2.8 to 8.5 feet for slug tests and 5.6 to 10.8 feet for pumping tests. Total inflow rates observed during the slug tests of wellbores W201AR1A, W201AR1B, W202AR1, W203AR1, W204AR1, and W206AR1 ranged from 0.014 to 0.160 gpm (Table 4-3). Total inflow rates observed during the pumping tests were 1.391 gpm for wellbore W205CH1 and 0.570 gpm for wellbore W207AR1. The total inflow rates estimated by model simulation match closely with the observed total inflow rates (Table 4-3).

As seen in Table 4-3, hydraulically conductive intervals were identified in all eight wellbores. Wellbores W201AR1A, W201AR1B, W202AR1, W203AR1, W204AR1, and W206AR1 contained hydraulically conductive intervals with very low to low inflow rates (< 0.05 gpm). Well bores W205CH1 and W207AR1 contained hydraulically conductive intervals with widely varying flow rates ranging from very low to high. The hydraulically conductive zones identified during the hydrophysical logging were used as the basis for packer test interval selection.

4.4.2 Packer Testing

A total of 21 packer tests were performed in the seven boreholes along the GM-1 Pilot Study. These packer tests were conducted with packer intervals ranging from 13.4 to over 413.9 feet Of the 21 tests performed, 18 of the tests were conducted with the packer interval less than or equal to 21 feet. Three types of tests were employed during the packer testing program: Slug, Pulse, or Constant Rate. A total of 10 slug tests, 9 constant rate tests, and 2 pulse test were conducted in the seven boreholes. Documentation and results of the packer testing program conducted during May 1997 were included in Golder's June 1997 draft report which was transmitted under separate cover (Golder, 1997). The sections below with reference to Appendix G of this report provide a summary of data and results. The reader is referred to the full report for further details.

4.4.2.1 Analysis Method

The pressure-time data was analyzed using two analysis software tools, FLOWDIM and INT2. FLOWDIM is a software package designed to analyze for change in flow dimension and or change in the hydraulic properties away from the borehole. INT2 applies a specific geologic model to the test data. A detailed description of the test methodology and the steps of test analysis are provided in the following sections.

Software

The main software package used for analysis was Golder's in house program FLOWDIM. This program was used to analyze slug/pulse test data and on-site analysis of constant rate tests. FLOWDIM is a modular well test interpretation program which can be used to analyze constant rate, constant pressure and slug/pulse tests in both source and observation zones. This software incorporates the generalized radial flow model of John Barker (1988). It can handle several flow models for any flow geometry between linear (dimension = 1) and spherical (dimension = 3). In addition, the program contains a composite model which can be used to match test data with either a change in flow dimension or a change in hydraulic properties away from the borehole. Other features include two-step superposition of constant rate events (i.e., flow period followed by a build-up) and automatic curve fitting using a non-linear regression algorithm.

The detailed analysis of constant rate periods was performed with INTERPRET/2 (INT2) OF SCIENTIFIC SOFTWARE INTERCOMP, Windows version 1.6. INT2 is an interactive program that uses a constant rate solution to provide optimized hydraulic parameters for a wide range of potential reservoir models. Some of the features of INT2 include extensive superposition of constant rate events, non-linear regression and multi-event validation plots. Additionally, it can accommodate changing wellbore storage and skin between the test periods. Another useful feature is the calculation of equivalent drawdown responses to reduce some of the ambiguity in identification of the flow model.

It is important to emphasize the difference between the two packages. FLOWDIM examines the data in a general sense while INT2 uses a specific geologic model to match the test data. For example, take the case for a restriction in flow away from the borehole after a homogeneous formation response. In using FLOWDIM the test data would be matched with composite flow model with an inner flow dimension of 2 and an outer flow dimension of less then 2. The model does not distinguish between a restriction in flow from a less well connected fracture system away from the borehole, or a restriction due to the intersection of the pressure transient with a relatively impermeable rock or structure such as a fault. This distinction can only be made by examining supporting data.

Both programs incorporate the pressure derivative for enhanced recognition of the flow model. On the log-log plot, the change in pressure (Theis type curve) is accompanied by the derivative of the dimensionless pressure with respect to the logarithm of dimensionless time as proposed by Boudet et al., 1984. The advantage of the derivative plot is that it is able to display many separate flow regimes that would otherwise require different plots and uses transitional data to optimize parameter reliability. The stable slopes of the derivative data is used to diagnose the formation response. A synthetic data set was simulated to illustrate the derivative plot (Figure 4-8). A unit slope of the pressure and pressure derivative data in early time is diagnostic of pure wellbore storage effects. After wellbore storage effects cease, the derivative curve becomes flat indicating a radially infinite-acting flow regime with respect to the geometry of the wellbore. Boundaries have various influences on the pressure derivative depending on the number and type and whether it is a production or recovery phase.

In general, the formation response may be divided into "early," "middle" and "late" time data. The early time data is flow regimes associated with the wellbore or features connected to the wellbore. After the near wellbore response, the test response is dominated by the undisturbed formation response in "mid time data." In "late time" the test response may be influenced by boundaries depending on duration of test and distance to the boundaries. The case illustrated (Figure 4-8) is idealized and often all three relative time regimes may not be seen due to insufficient test duration or masking of the formation response by near wellbore and outer boundary effects.

Well Test Analysis Approach

The analysis of the individual phases was started with determination of the best estimate for input parameters. In the analysis of constant rate events, the next step was to discretise the test into a series of constant rate events. Each of the relevant test phases is subsequently analyzed using the following steps:

- Identification of the flow model by evaluation of the derivative on the log-log diagnostic plot. Initial estimates of the model parameters are obtained by conventional straight line analysis.

- Superposition type curve matching in log-log coordinates. A non-linear regression algorithm is used to provide optimized model parameters.

- Non-linear regression in semi-log coordinates (superposition HORNER plot). In this stage of the analysis, the static formation pressure is selected for regression.

- Simulation of the entire test sequence in Cartesian coordinates using the optimized parameter set obtained from the analysis of the individual phase. This final step is used to check the consistency of the model to the entire data set.

The steps are repeated until a consistent characterization of the test event has been achieved.

For slug and pulse tests the analysis progresses as follows:

- Identification of the flow model by evaluation of the derivative data on the log-log de-convolution log-log plot.
- Match the data to the appropriate type curves.
- Examine the match on RAMEY A, B, and C plots (Ramey et al., 1975) with each plot emphasizing different parts of the data set.
- Iterate between the plots until the quality of fit is optimized.

The analysis would normally be completed with sensitivity analyses to examine both the influence of uncertain input parameters on test results, and alternative flow models that may be used to match the data set. A best estimate of parameters is typically derived from the phase that is considered to contain the most reliability and sufficient duration to identify the flow model. Confidence limits are derived based on results of analyses of individual phases and sensitivity analyses.

Input Parameters

The physical parameters used in the analysis of the tests is shown in Table 4-4. These input parameters were measured and estimated using available data, or calculated using PVT correlations.

Representative Analyses

The following subsections will illustrate the analysis of the test types in a step by step format. The pulse and slug phases will be first examined which are typically performed in low to moderate borehole transmissivity with a radius of influence on the order of few feet. Finally, the constant rate analysis of the production tests will be examined with radius of influences on the order of tens to hundreds of feet. The analyses of all the production tests will be described here as these tests were performed in the higher transmissivity zones. The identification and characterization of the higher conductivity zones is a primary objective of this investigation.

Pulse Phase

A pulse phase was performed in test 7 in borehole W205CH1 (Appendix G Figure3-2A) based on the preliminary relative flow rating of "very low" for the conductive feature 203.0 to 207.0 feet BGS. The test was started with a

0.6 hour shut-in phase to allow the test section pressure to partially equilibrate. A pulse phase was started with an instantaneous drawdown of approximately 94 feet and lasted 0.8 hours with a final recovery over 98 percent.

The first step in the analysis of pulse phase was to calculate an equivalent radius that is based on the borehole compressibility as the recovery takes place under shut-in conditions. This value may be measured by taking fluid measurements before and after the shut-in tool is opened and closed. The difference in fluid level is due to the compressibility of the test interval if there is no flow from the formation. Alternatively, the equivalent radius may be computed from so called casing tests or a default value may be chosen. In this case the borehole compressibility was assumed to be equivalent to the compressibility of water, 5.5E-10 1/Pa, multiplied by the interval volume.

The next step is to examine the formation response in the log-log deconvolution plot (Appendix G, Figure 3-2B) to identify the flow model. The following flow model was used to analyze the test response:

Inner boundary: skin

Formation model: composite with increase in transmissivity away from the borehole

Outer boundary: infinite in lateral extent

In this model, the leveling off of the derivative data in mid time data is assumed to be the radial flow stabilization for the inner zone. The downward trend in the derivative data in late time indicates a transition to an outer zone with higher permeability. The derived parameters for this case are considered highly uncertain due to the non-uniqueness of the flow model. The early time data could also be matched with a flow dimension of 1.5 which would result in a higher transmissivity.

The next step is to look at the match to Ramey A, B, and C type curves (Appendix G, Figures 3-2C-E) with the parameters derived on the deconvolution plot. The Ramey B and C type curves are sensitive to the late and early time data, respectively. The Ramey A curve is equivalent to Cooper type curves.

The results for the composite model show an inner zone transmissivity of 2.31E-09 m^2/s and an outer transmissivity of 3.85E-09 m^2/s at a discontinuity radius of approximately 1 foot.

Slug Phase

Test 4 in borehole W207CH1 (Appendix G, Figure 3-3A-C) was selected to illustrate analysis of a slug test in a moderate transmissivity test section. The packer depth was selected to encompass the water conductive feature, 46.0 to 47.0 feet bgs, identified in the hydrophysical logging. The preliminary relative flow rating is "low."

The test was started with a 0.9 hour shut-in phase to allow the test section pressure to partially equilibrate. A slug phase was started with a instantaneous drawdown of approximately 17 feet. Upon reaching 64 percent of the total drawdown, the downhole shut-in tool was closed. The subsequent shut-in lasted 1.0 hour and recovered to within 0.5 feet of the conditions prior to the initiation of the slug. There was no suggestion of packer bypass during the test.

The analysis was started with examination of the data on the deconvolution plot (Appendix G, Figure 3-3B) to identify the flow model. The early time data shows a leveling off of the pressure derivative data that was assumed to represent infinite-acting radial flow stabilization. In late time, the pressure derivative data shows an increasing slope which indicates a restriction in flow away from the borehole. This part of the data set was not matched. The results show a near wellbore transmissivity of 5.58E-07 m^2/s with a restriction in flow away from the borehole.

As a confirmation for the parameters derived in the slug period the shut-in phase was analyzed with constant rate solution. The first step was to discretise the test into a series of constant rate periods as shown in Appendix G (Figure 3-4A). The next step was to examine the formation response on the log-log plot to identify the flow model. The following flow model was chosen to analyze the data set:

Inner boundary:	wellbore storage and skin
Formation model:	homogeneous
Outer boundary:	channel boundaries (no flow)

The formation response on the deconvoluted slug data and constant rate analysis of recovery phase show similar character with two exceptions: 1) the near wellbore radial flow stabilization is masked by wellbore storage effects in the recovery phase and 2) the late time restriction in flow in the recovery period shows a longer period of response due to longer duration of the phase. Hence, the near wellbore properties should be taken from the analysis of the slug phase due to lack of wellbore storage effects and the outer zone parameters should be derived from the analysis of the recovery phase due to its longer duration. The results of the recovery phase show a near wellbore transmissivity of 4.89E-07 m^2/s with a restriction in flow away from the borehole that was matched with channel boundaries of the no flow type.

Constant Rate Analysis

This sections reports the detailed analysis for the packer tests using pumping as the hydraulic stress. These pumping tests contain a production phase of up to 4 hours in duration and recovery data that was measured overnight. The initial two tests will be discussed in detail to illustrate the analysis methodology of representative formation responses. The discussion on the latter three tests will be restricted to a discussion of the formation response on the log-log plot.

Test 4 in Borehole W205CH1 is shown in Appendix G, Figure3-4A-C. The packer depth was selected to encompass the water conducting feature, 313.0 to 334.0 feet bgs, identified in the hydrophysical logging. The preliminary relative flow rating is "moderate."

The test was initiated with a 0.8 hour shut-in phase to allow the test section pressure to partially equilibrate. A production phase was subsequently started but was soon terminated due to electrical interference between pump and downhole gauges. It was decided to shut-in the test section and repair the problem. The main production period lasted 2.0 hours at a flowrate of approximately 5 gallons per minute (gpm) with a total drawdown of 25 feet at the end of the phase. The subsequent shut-in period was 9.8 hours in duration and recovered to within 1 foot of the initial shut-in. The test was terminated with a slug phase. The annulus pressure mimicked the test zone pressure during the production phase but showed a lower magnitude of change. This suggests a possible diffusive hydraulic communication through the formation between the test section and the annulus.

The analysis of the test was started with diagnosis of the formation response on the log-log plot (Appendix G, Figure 3-4B). The following model was used to analyze the test data:

Inner boundary:	wellbore storage and skin
Formation model:	dual porosity
Outer boundary:	infinite in lateral extent

The next step was to regress on the Horner plot by selecting only the static formation pressure (Appendix G, Figure 3-4C). The model and parameters derived from analysis of the recovery phase were then compared to the entire simulation plot (Appendix G,Figure 3-4D). The match is reasonable confirming the selection of both the flow model and the parameters. A poor match to the initial production phase is attributed to erroneous pressure measurements due to electrical interference problems that was subsequently corrected.

The data can also be matched with a flow dimension approach. Appendix G, Figure 3-4E shows a good match to the data set using a composite fractional dimension model. The inner zone flow dimension is 2.8 and the outer flow dimension is 1.7 with a distance to the discontinuity of 2 feet. The derived transmissivity is 2.94E-06 m^2/s and compares to 2.34E-06 m^2/s derived with the dual porosity model.

Test 6 in Borehole W205CH1 shows a formation response with a restriction in flow away from the borehole (Appendix G, Figure 3-5A). The diagnosis of the recovery phase formation response on the log-log plot results in the following model:

Inner boundary: wellbore storage and skin

Formation model: homogeneous

Outer boundary: open ended rectangle with three no flow boundaries

The response shows a log cycle of a flat derivative data in early time which will result in reliable derivation of the near wellbore transmissivity. In mid and late time, the derivative data shows an increasing trend that suggests a restriction in flow away from the borehole. In this case three no flow boundaries at various distances were used to match the test response. The relative distances to boundaries are highly correlated and therefore non-unique. The absolute distance to boundaries is computed based on an assumed storativity.

A method to increase reliability in derived parameters is to show consistency of formation responses between various phases in the test. This can be achieved with a multi-phase diagnostic plot. Appendix G, Figure 3-5C shows both the production period and recovery phase on a single log-log plot. As can be seen, the formation response are reasonably consistent except the production data is nosier due to small fluctuations in the rate. This illustrates the reason for emphasizing the analysis results from the recovery period. In addition, the production period shows a longer period of wellbore storage effects.

Appendix F, Figures 3-7, 3-8, and 3-8 show log-log analyses for the recovery phases for the remaining production tests. Test 2 in Borehole W207AR1was matched with a dual porosity formation model. A composite model was also shown to match the data set with an increase in transmissivity away from the borehole. Test 3 in Borehole W207AR1 and Test 2 in Borehole 205CH1 were both matched using a homogeneous formation model with open ended bounded system in late. The boundaries are all of the no flow type. Test 3 shows a skin effect in early time, followed by a log cycle of radial flow with a restriction in flow in late time. The boundaries are closer to the borehole in test 2 which nearly completely mask the formation response.

4.4.2.2 Results

The summary of packer test results are summarized in Table 4-5. In addition, numerous observation boreholes were monitored in the area with pressure transducers and recorded electronically at 2-minute intervals during the testing program. For this report, observation boreholes W201AR1A through W207AR1 were examined and are described in this section.

Source Zone

Packer Test Flow Model Interpretation and Analysis

The conceptual models used to interpret packer tests should be examined with respect to scale. The slug and pulses are considered to have a relatively small radius of influence due to their relatively short duration compared to production tests and are typically performed in lower transmissivity units. The interpretation may be summarized as follows:

1. Early time data which may be matched with either type curves with a flow dimension less than 2 and/or may be attributed to wellbore effects. In this study, the early time data was in most cases matched as wellbore effects. The early time data in some tests is partially masked by inertia effects.

2. The middle data shows a leveling off of the derivative data which indicates a radial flow response.

3. The late time data shows either an increasing or decreasing trend in the derivative data which may be transitional data to the next flow regime or a change in flow dimension away from the borehole. The data in this study was matched with a conceptual composite flow model characterized by either 1) an increase in transmissivity away from the borehole for the case of decreasing trend in the derivative data or, 2) a reduction in transmissivity for the case of an increasing derivative trend. The parameters derived for the outer zone are less certain compared to the near wellbore properties due to lack of an outer zone radial flow stabilization to confirm both the model and the parameters. In the some cases, there is an increase in the transmissivity away from the borehole. These results should be viewed with caution as this may be due to end effect from nearly complete recovery in the slug test.

A total of 5 production tests were performed, all in boreholes W205CH1 and W207AR1. These tests encompassed the "moderate to high" conductive features identified in the hydrophysical logging. A production test was also conducted in borehole W202AR1 but was examined as a slug in the analysis. The derivative plot showed pure wellbore storage during the pumping phase indicating the borehole was being emptied with no flow from the formation.

The radius of influence (d) in a production test is directly dependent on the duration of the period and diffusivity (T/D) as shown below:

$$d = A\sqrt{\frac{T}{S}t,} \quad \text{STRELTSOVA (1988)}$$

It can be seen that for single well tests the radius of influence is a function of the elapsed time when the response occurs (t_s), of the matched formation permeability and of the assumed storativity. This equation is also used to compute distances to boundaries. The coefficient 'A' is a constant dependent on the definition for the radius of investigation. The 'A' constant used in the INT2 analyses is 1.89, corresponding to a dimensionless drawdown of approximately 0.3.

The computed radius of influence for pumping tests varies between 213 and 6792 feet. As stated above, these values are dependent on the assumed storativity which is typically not known within an order of magnitude without observation well data. In addition, many tests showed no flow boundaries during the test. Accordingly, the radius of influence will not be symmetrical away from the borehole.

The test response from the 5 production tests can be classified into two groups. Group 1 shows a homogeneous formation model with a restriction in flow away from the borehole that was matched in INT2 with 3 no flow boundaries in the shape of an open rectangle. An analysis in FLOWDIM show a composite model with a near wellbore flow dimension of 2 and an outer zone flow dimension of less than 2.

The Group 2 was matched with a dual porosity formation model, infinite in lateral extent. It was shown that the data may also be equally well matched with a composite fractional dimension model. Additional geological and geophysical data is needed to constrain the number of viable flow models due to the inherent non-uniqueness in well test analysis

Transmissivity

The transmissivities derived in the analyses range between 2.13E-09 and 7.14E-05 m^2/s. There is a good correlation between the relative flow rating derived from the hydrophysical logging and transmissivities derived in the transient analysis of packer tests (Table 4-6 and Figure 4-9). The only exception are high transmissivity values derived relative to the flow rating for test 6 in Borehole W205CH1 and test 1 in Borehole W203AR1. The flow model for both tests shows a restriction in flow relatively close to the borehole. The derived transmissivity for both of these tests represents a relatively small radius of influence while the hydrophysical logging averages the properties within the radius of its influence to derive the relative rating. Hence, the difference may be attributed to difference in the radius of influence.

Pressure Head

The static heads were typically computed from the average of the final pressures measured at the end of the initial shut-in and from the final pressure measured at the end of the main test phase. The pressure in the first shut-in was typically stable or falling relatively slowly at the end of the phase and provides an upper limit for the static formation pressure. The pressure was increasing to equilibration at the end of the main test phase and therefore provides a lower limit for the static formation pressure. The static formation is normally derived from the extrapolation of the shut-in data on a Horner plot. However, the final pressures measured at the end of the shut-in phases typically showed over 90 percent recovery to provide reasonable approximations for the static formation pressure. In addition, complex pressure transients are not expected due to the relatively high transmissivities encountered.

For boreholes with more than one test, the head data was plotted against the midpoint of the interval to access vertical gradients (Appendix G, Figures 4-2 thru 4-4). The plots show a decrease in head with depth although there is scatter in the data. No head was computed for test in Borehole 202AR1 as the test was performed over the entire open interval and the static head may be an average of several conducting features at various depths.

Observation Zones

The observation zones were monitored with a pressure transducer that recorded water level changes in the open borehole at 2 minute increments. Hence, although specific conductive features were tested in the borehole, the observation zones were monitoring all the conductive features in the entire open interval in adjacent borings. This set-up may mask responses in observation boreholes with vertical gradient due to "cross flow" effects.

No observation zone responses were expected for slug or pulse phases due to the relatively small radius of influence. The only exception was in Borehole W201AR1B due to its proximity to the source Borehole W201AR1A, 9.4 feet to the east.

A response in the observation zone is defined as:

1. A drawdown above background noise

2. The first appearance of the drawdown after the start of pumping in the test interval

3. The first appearance of recovery after the start of the recovery phase in the test interval

Two pressure responses were observed in the observation boreholes during the entire testing campaign. Both responses were not analyzed as the first response was attributed to events prior to the start of a test and the second response could not be correlated to a single production event.

Prior to the start of the slug test in borehole W201AR1A there was a relatively rapid 0.6 feet increase in the water level in Borehole W201AR1B, located 9.4 feet to the west. This may be attributed to displacement of fluid in the source borehole while running the tools to test depth. Both boreholes contain conductive features at approximately 45 feet bgs.

The only borehole which showed a response during all the production phases was observation borehole W203AR1 during testing in Borehole W205CH1. The start of the drawdown appeared to be consistent with the initiation of pumping for test 2 in W205CH1. The drawdown continued for some 50 hours at different rates that were not correlated to specific production events in the test interval. The drawdown continued some 10 hours after the final production period in Borehole W205CH1. Accordingly, there may have been another source affecting the test response outside of the hydraulic tests.

Lack of response in the other observation zones may be attributed to:

1. No flow boundaries

2. Observation zone outside of the radius of influence

3. Lack of connection between feature in the source zone and observation zone

4.4.2.3 Conclusions

The objective of the program was to demonstrate that the proposed packer testing methodology was viable and could be employed to determine the hydraulic properties and geometry of the identified higher conductivity features. The program can be viewed in terms of equipment performance, test design and analysis techniques.

The equipment were able to provide relatively "clean" data with minimal influence from tool operation. The shut-in tool was essential in reducing wellbore storage effects for improved diagnosis of the flow model. The data acquisition system was able to record at a rate of 1 second intervals at the start of phases to reduce ambiguity in the analysis. In addition, the data system was able to record data overnight to maximize the efficiency of the testing program. The use of relatively high accuracy flowmeters and pressure transducers with electronic output provided a good basis for all the analyses. Packer bypass problems were experienced during some of the tests. This was attributed to a diffuse hydraulic connection through the formation between the test interval and adjacent zone, rather than to leakage of the packer systems.

The test design was shown to be appropriate for the relative range of transmissivity encountered during the testing program. The overall design was to optimize the radius of influence for the tests that encompassed the higher conductive features to see the formation flow model and boundary effects. On a test basis, the design included an initial shut-in phase to partially dissipate any pressure history effects. A pulse phase was used for relatively low transmissivity conditions that enhances the recovery compared to slug tests by changing the wellbore storage from open tubing to borehole compressibility. For moderate range transmissivity conditions a slug and shut-in phase was carried out. This design provides two phases for analysis with different inner boundary conditions that may be analyzed and reliability can be established by showing consistency in results. For higher transmissivity conditions, a single rate was selected to provide sufficient drawdown at the end of the phase that was above background noise to reduce ambiguity in model recognition. The maximum drawdown was limited to approximately 150 feet to minimize any potential stress effects. The duration of the recovery period was optimized within the constraints of the program to identify boundary effects. On-site analysis was important in determining the duration of individual test phases.

The analysis techniques were shown to optimize both test design and derivation of hydraulic parameters. The slug/pulse deconvolution application was shown to reduce ambiguity in derived parameters through improved diagnosis of the formation response and with a longer duration of formation response in comparison to constant rate tests due to lack of wellbore storage effects. The detailed constant rate analysis methodology provided a good tool to recognize the flow model, derive reliable hydraulic parameters and to qualitatively examine the inherent ambiguity in well test analysis.

Two complimentary software packages were used during the program. INT2 provided a variety of flow models and full superposition to analyze the data set. In this approach the flow area is assumed to be infinite acting radial flow and changes in geometry are matched with single or intersection of boundaries of the no flow or constant pressure type. Contrary to this approach, FLOWDIM derives a flow dimension in the analysis which is a parameter that describes the flow through area with distance from the borehole. This is a more general techniques that does not use specific geologic model(s) to describe the data set.

The data obtained during testing program provides important information for further refinement of the conceptual model for the sight and provides input for regional modeling. The highlights from the packer testing program can be summarized as follows:

1. The relative rating from the hydrophysical logging shows good consistency with the transmissivity derived in the transient analysis of the packer test data.

2. The transmissivities derived in the analyses range between 2.13E-09 and 7.14E-05 m^2/s.

3. From the five tests encompassing the highest rated conductive features, three show a restriction in flow after a homogeneous formation model that was matched with three no flow boundaries. The two other production tests were matched with a dual porosity formation model. The responses may also be equally well matched with composite fractional dimension model showing a reduction in flow dimension away from the borehole. Additional geological and geophysical data is needed to discern which flow model is most appropriate.

4. The static formation heads show a decrease with depth based on the information from the three boreholes with more than one test.

Only one observation well from the seven examined showed a response during all the pumping periods.

4.5 Geochemical Analytical Results

As described in Section 3.6, groundwater samples were collected for geochemical analysis as part of the packer testing program described elsewhere in this report. Samples were shipped under chain-of-custody to three separate labs for major-ion, isotope, and radon analyses. Table 4-7 presents an inventory of sample designations, dates and times of collection, and geochemical results obtained in support of the packer testing program. Analytical results are presented and discussed below.

4.5.1 Discussion of GM-1 Packer-Test Field Parameter Major Ion Results

Figure 4-10 is a Piper diagram (Piper, 1944) illustrating the range of chemical compositions of the packer test samples, along with two samples from the production well used to supply water for all drilling at the Wake Site. The production well is located more than one mile south of the proposed footprint of the disposal area, and procedures from geologic materials that are not found within the area under investigation during the GM-1 Pilot Study. The production well is completed within a diabase dike that cuts discordantly through beds of siliciclastic sediments. Analytical results from the production and site wells are plotted using different symbols, so that the diagram provides not only a graphic representation of the chemical signatures at a given well, but also a basis of comparison between the production and site wells.

The distribution of points within the trilinear cation field (TCF) indicates that sodium is the dominant cation among the packer test samples, accounting for between 55 and 95 percent of the equivalent weight among the major cations. Potassium, which is plotted along with sodium, is a relatively minor constituent, at less than 1 percent of equivalent weight in 41 samples. Calcium ranges from less than 5 to approximately 30 percent, and magnesium from less than 1 to approximately 20 percent.

Within the trilinear anion field (TAF), the dominant ion is chloride, followed by bicarbonate and sulfate, respectively. Among 47 of the 49 samples, chloride as a percentage of equivalent weight among the major anions ranges from approximately 45 to 90 percent. The lowest values for chloride are around 13 percent in two samples from W204AR1. Bicarbonate ranges from less than 10 to about 85 percent, with most between 30 and 50 percent. Sulfate ranges from zero to 10 percent in all but a few samples, and the highest values are around 13 percent in samples from W205AR1.

For the two samples of water from the production well, calcium is the predominant cation at approximately 47 percent, followed by sodium and magnesium at about 27 and 26 percent, respectively. As the principal anion, bicarbonate accounts for around 84 percent of the equivalent weight. Chloride averages about 11 percent, and sulfate about 5 percent.

The locations of the points within the diamond-shaped field (DSF) of the Piper diagram indicate that chemical compositions vary among the wells, but are relatively uniform for intervals from which multiple samples were collected. Table 4-8 lists the chemical compositions of the sampled intervals from each well. The nomenclature is adapted from Back (1960 and 1961). Cations are listed first, according to decreasing percentages of equivalent weight. Anions follow the same pattern. Only those ions with equivalent weights exceeding 10 percent of the total for each major group are included in the classification. For intervals from which two or more samples were collected, the classification is based on the average percentage of each ion.

The Piper diagram (Figure 4-10), and the classifications reported in Table 4-8 reveal distinct differences in the chemical compositions of samples collected during the packer testing program and water used as drilling fluid. Of the 19 intervals sampled during the program, 11 yielded water classified as Na-Cl-HCO_3, six produced water dominated by sodium, calcium, chloride, and bicarbonate, with minor percentages of magnesium; one yielded water of Na-Ca-Mg-Cl composition; and another produced water with a Na-Ca-Mg-HCO_3-Cl signature. Points representative of most of the packer test samples are located near the lower right leg of the DSF, reflecting the strong influence of sodium, chloride and bicarbonate. Points influenced by higher percentages of chloride along with calcium and/or magnesium lie closer to the right corner of the DSF and roughly subparallel to the upper right leg of the DSF. The points indicating groundwater of Na-Ca-Mg-HCO_3-Cl composition are located along the lower left leg of the DSF. The two points representative of drilling fluid water, which is of Ca-Na-Mg-HCO_3-Cl composition, are located near the left corner of the DSF.

The distribution of the points on the Piper diagram indicate not only marked differences in the chemical makeup of drilling water and Wake Site groundwater, but also suggest that the samples collected as part of the packer testing program (1) do not reflect the composition of dike water, and (2) are suitably representative of local groundwater geochemical signatures to warrant their use in support of the development of a site conceptual model. To help better describe changes in the chemistry of water withdrawn during the packer test, time-series plots of pH, temperature, and specific conductance were constructed from intervals that produced sufficient volumes of water to support pumping tests.

4.5.1.1 Time-Series Plots

Time-series plots using the results of repeated sampling during packer tests were constructed for six intervals at W205AR1 and for two intervals at W207AR1 (Appendix H). The fractured zones of interest at the other five wells evaluated were neither porous nor permeable enough to support pumping tests. The plots trace changes in specific conductance, pH, temperature, and the volume of water pumped from each interval during a packer test. The plots are discussed below in the order in which the pumping tests were conducted.

W207AR1/67.5 - 77.5

A packer test was conducted over the interval from 67.5 to 77.5 feet at Well W207AR1 on 5/11/97. Initial field parameter measurements were made from a sample of water drawn from the interval prior to the commencement of pumping at 12:50. After the sample was collected, the well was shut in, and a pumping test was initiated at 14:34, at a flow rate of 1.07 gpm. The well stopped flowing at 14:48, and the well was shut in once again. The test resumed at 15:08 at a flow rate of 0.45 gpm.

The plots show differences between the initial and subsequent measurements of specific conductance, pH, and temperature during the test. Specific conductance increased from 1,845 microsiemens (mS) to 2,580 microsiemens (μS), and then steadily decreased to 1,845 mS by the end of the test. The change in specific conductance was accompanied by a slight increase in pH (Appendix H) at the beginning of the test, and then again during the test from 7.62 to 7.93. Temperature measurements dropped from 19.8 °C in the first sample of water to 16.9 °C at the beginning of the pumping test, and then settled at between 17.8 and 18 °C. The total volume of water pumped during the test was estimated to be 69 gallons, based on flowmeter readings.

Samples of water for analysis of major ions were collected at 12:50, 16:05, 16:20, 16:45, and 17:00. The major ion chemical composition of the well water from this interval collected during the pump test are shown in Appendix H in the form of Stiff diagrams. These Stiff diagrams show a relatively consistent pattern. Table 4-8 lists the representative composition for this interval as Na-Ca-Cl-HCO_3.

W207AR1/153

Time-series plots of specific conductance, pH, temperature and the volume of water pumped for the interval 153 to 465 feet total depth collected on 5/12/97 are shown in Appendix H. This test was originally set up to evaluate the interval 156.14 to 166.54 feet at a flow rate of 2.04 gpm. However, leakage around the lower packer forced abandonment of the test after about 5 gallons had been discharged. Golder's representative decided to deflate the lower packer and to conduct the test over the interval 156 to 465 feet total depth. The second test, however, was abandoned after less than 10 minutes, because the pump became clogged. By this time, approximately 15 gallons of water had been discharged. The upper packer was reset at 153 feet, and a third test was initiated at 16:55 at a flow rate of 3 gpm.

Specific conductance was relatively stable throughout this pumping test. Specific conductance started at 1,573 μS, decreased to 1,454 μS after 10 minutes, and then steadily increased to 1,545 μS by the end of the test. The initial pH measurement was 8.02, and subsequent measurements stabilized at approximately 8.3. Temperature varied between 16.6 and 16.8°C. Including water discharged during the aborted pumping tests, the total volume of water pumped was estimated to be 170 gallons. Specific conductance and temperature measurements appeared to be lower for this zone than for the shallower test interval, but pH was higher.

Samples of water for analysis of major ions were collected at 17:20, 17:35, and 17:45. A sample was also collected at the beginning of the first aborted test at 15:25. The major ion chemical compositions are shown in Appendix H in the form of Stiff diagrams. The patterns for these four samples are similar to those from the first pumping test, but the average composition is Na-Cl-HCO_3, as shown in Table 4-8.

W205AR1/145.18 - 166

Time-series plots of specific conductance, pH, temperature and the volume of water pumped for the interval 145.18 to 166 feet in Well W205AR1 and collected on 5/12/97 are shown in Appendix H. This test was terminated after 90 minutes because of leakage around the upper packer. Specific conductance started at 261 μS, and then jumped to 804 μS seven minutes later. Specific conductance then decreased to 754 μS by the time the test was aborted at 17:15 The initial measurement of pH was 8.81, and subsequent measurements varied from between 8.25 and 8.32. The first temperature measurement was 17.6 °C, and all other measurements were either 16.9 or 17 °C. An estimated 288 gallons of water were discharged at a pumping rate of approximately 3.2 gpm.

Samples for analysis of major ions were collected at 15:47, 16:01, 16:31, and 17:00. The chemical compositions are represented by Stiff diagrams (Appendix H). The diagram for the first sample is significantly different from subsequent diagrams presumably due to the gradual introduction of formation water. The composition shifts from a relatively dilute Na-Cl water to a dominantly Na-Cl-HCO_3 signature. The larger Stiff diagrams representing the second through the fourth samples are consistent with the increase in specific conductance discussed above.

W205AR1/148.2 - 169.2

Packers were reset for a second pumping test over the interval from 148.2 to 169.2 feet, overlapping most of the interval from the previous test. This test was initiated at 18:30 on 5/16/97 and ran for 3 hours and 2 minutes, ending at 21:32. Time-series plots of specific conductance, pH, temperature, and the volume of water discharged are shown in Appendix H.

Specific conductance decreased from an initial measurement of 757 μS to approximately 730 μS after about one hour, and pH fluctuated between 8.29 and 8.16. Temperature from between 16.9 and 17.6 °C in the first two measurements, and then stabilized at between 16.3 and 16 °C after about 90 minutes. The volume of water discharged during the test was estimated to be 1,443 gallons, at a flow rate of 7.9 gpm.

Samples of water were collected at 18:30, 19:09, 19:41, 20:13, 20:50, and 21:32. The chemical signatures of the six samples as shown by Stiff diagrams (Appendix H) are similar to the previous group of samples for the interval 145.18 to 166 feet but the composition is Na-HCO_3-Cl (Table 4-8).

Specific conductance was slightly lower in this interval, with the measurements leveling out within an hour after the first readings. During this test, pH values are slightly lower by 0.05 to 0.10 standard units. The greatest difference, however, is in the lower temperatures recorded during the test. The temperature of groundwater was consistently around 17 °C near the end of the first test, but dropped approximately 1 °C by the end of the second test.

W205AR1/313 - 334

The next pumping test at W205AR1 was conducted with the packers set over the interval 313 to 334 feet. The test was initiated at 14:59 on 5/17/97, and was terminated after 22 minutes because of leakage around the lower packer. Time-series plots of specific conductance, pH, temperature, and the volume of water discharged during the test are provided in Appendix H. The plots reveal marked changes in specific conductance and pH, and relatively stable temperature measurements. Specific conductance started out at 882 µS, and dropped to 585 µS within 14 minutes. Subsequent readings remained stable to the end of the test at 15:21. Measurements of pH fluctuated between 8.56 and 9.24 during the first 14 minutes of the test, and then settled at around 8.7 when specific conductance reached 585 µS. Temperature displayed relatively little variability, ranging from 17.1 to 17.4 °C. The volume of water discharged during this test was 44 gallons, at an average flow rate of 2 gpm.

Samples of water were collected at 15:01 and 15:21. The chemical composition of these samples is represented by Stiff diagrams (Appendix H). These Stiff patterns are representative of Na-Cl-HCO_3 water (Table 4-8), and are similar to the patterns observed for samples collected during earlier pumping tests over the shallower fractured zones. The Stiff diagram representing the second sample, however, indicates a trend toward lower total dissolved solids, and lower concentrations of sodium and chloride in particular. This is consistent with the decreasing trend of specific conductance measurements made over the first 14 minutes of the test.

W205AR1/301 - 715

After the previous test was aborted, the upper packer was reset at a depth of 301 feet, and the lower packer was left open. The interval covered by this test was from 301 to 715 feet, the total depth of the well. Measurements of field parameter were made between 17:55 and 20:36 on 5/17/97.

Time-series plots of specific conductance, pH, temperature, and the volume of water discharged during the test are shown in Appendix H. Specific conductance, pH and temperature fluctuated sharply within the first 30 minutes. Specific conductance jumped from approximately 570 to 700 µS and then dropped to 582 µS. These measurements increased to 698 µS by the end of the test at 20:36. Measurements of pH increased from 8.12 to 8.84 within the first 30 minutes, dropped to 7.98, and rose again to 9.23 by the end of the test. These were among the highest pH readings for any of the pumping tests. Temperature dropped from 19.1 to 17.9 °C, then ranged between 17.6 to 17.2 °C over the remainder of the test. The volume of water discharged was estimated to be 677 gallons.

Samples of water were collected at 18:42, 18:49, 19:13, 19:45, 20:16, and 20:36. The chemical compositions are represented by Stiff diagrams (Appendix H). These Stiff patterns indicate signatures that are indistinguishable from those of the previous test (Na-Cl-HCO_3), indicating no appreciable change in the composition of the groundwater.

The figures in Appendix H indicate marked differences in the trends of all three field parameters between the first and second tests conducted over this same basic interval. The most apparent changes appear to be related to specific conductance and pH. The sharpest change in specific conductance occurred during the first test, with a decrease of more than 300 µS in approximately 20 minutes. The trend over the second test is less irregular, as specific conductance increased, but at a decreasing rate. The change in pH was irregular throughout the first test, and at the beginning of the second. However, pH increased in a more regular pattern over the last two hours of the second test. Temperatures were generally higher at the beginning of the second test, and gradually decreased to measurements similar to those of the first test.

W205AR1/262.88 - 283.89

The packers were reset over the interval 262.88 to 283.89 feet for a packer test conducted between 9:33 and 9:57 on 5/18/97. The test, however, was aborted after 24 minutes because of leakage around one of the packers. Changes in specific conductance, pH, temperature, and the volume of water discharged during the test are shown in Appendix H. Specific conductance decreased from 867 to 650 µS within 7 minutes after the first measurement, and then increased to 804 at the time the test was terminated. The trend for pH was toward lower values, as the readings decreased moderately from 8.97 to 8.72 within the first 12 minutes, and then to 8.10 at the end of the test. The temperature of groundwater decreased from 19.1 to 17.4 °C by the end of the test, and the volume of water discharged was 42 gallons, at an average flow rate of 1.75 gpm. Samples of water were collected at 9:33 and 9:57. Stiff diagrams provided in Appendix H show these samples to be Na-Cl-HCO_3 in composition.

W205AR1/266.88 - 287.88

The final pumping test at W205AR1 covered the interval 266.88 to 287.88 feet. The test was conducted between 11:03 and 13:50 on 7/18/97. The interval overlapped the zone from the previously aborted pumping test. Specific conductance varied moderately during the test, increasing from 794 to 822 µS in the first 10 minutes, and decreasing to 762 µS at the end of the test. The pH increased from 8.10 to 8.36. Temperature decreased from 18.9 to 17.5°C, and the volume of water discharged was 298 gallons at an average rate of 1.78 gpm.

Samples of water were collected at 11:03, 11:13, 11:47, 12:15, 12:45, 13:15, and 13:20. The Stiff diagrams (Appendix H) show these samples to be Na-Cl-HCO_3 in composition. This is consistent with the chemical signatures of water from the aborted pumping test over the interval 262.88 to 283.89.

Specific conductance exhibited changes of as much as 200 µS during the first test, with relatively little fluctuation during the second. The trend shown for the second test was downward, but at a decreasing and apparently regular rate. The sharpest change in pH was observed during the first test, as pH decreased from approximately 9 to 8.1. The trend shown for the second test is toward slowly increasing pH. Finally, the highest temperatures were recorded at the beginning of each test, at approximately 19 °C.

4.5.1.2 General Observations

Intervals from only two wells (W205AR1 and W207AR1) were sufficiently porous and permeable to support sustained withdrawal of water, and, at this time, it is not possible to extrapolate any of the results from specific intervals in these wells to the site as a whole. The distribution of points on a Piper diagram, however, indicates relatively uniform chemistry in each well, with moderate to significant differences observed between wells. None of the samples has a signature that appears to have been influenced by water from the production well, and it is possible that some of the chemical variability for samples collected during pumping tests may be attributable to minor differences in the concentrations of major ions as functions of local rock-water interaction, residence time, and possibly mixing of groundwater along flowpaths. However, it is not currently possible to speculate on the utility of these analyses for delineating flowpaths or degrees of hydraulic interconnectivity between different fractured intervals.

The chemical signatures of these samples are not dissimilar to those of wells sampled during the 1993 and 1995 field programs. We will compare these analyses with those of the earlier field programs to ascertain whether and to what extent differences or similarities can be documented based on depth and location of wells, along with the mix of lithologies penetrated by the wellbores.

Further work will also involve the development of quantitative geochemical models to evaluate the influence of mixing of water of different compositions, along with efforts to account for specific ranges of rock-water interaction on chemical compositions.

4.5.2 Oxygen Deuterium Results

Samples were collected during the packer testing program for oxygen and deuterium when sufficient water was available. Results were then plotted against groundwater, surface water, and rain water, across the site to identify whether results gave an indication of communication between waters with differing isotopic signatures within the aquifer system. Appendix H includes a plot and table of results used to make this comparison. Results for the water collected during the packer tests range from -5.3 to -6.3 for ΔO and between -26 and -35 for ΔD. These values plot slightly above the local meteoric line and in the vicinity of other groundwater samples from the site. Like most other groundwater samples from the site these values are slightly below those values reported for surface and rain water. Equipment blank and trip blank values range from -7.5 to -7.7 and between -43 and -46 ΔO and ΔD, respectively. These sample results plot low on the local meteoric line away from site groundwater presumably because they represent distilled waters from an outside source.

Results for oxygen and deuterium are consistent with the overall site conceptual model and suggest that mixing of surface and rain water with groundwater did not occur during the pump tests.

4.5.3 Radon Results

Radon analyses were collected during the packer tests to evaluate the change in radon concentrations with depth to evaluate the use of radon as an indicator of groundwater and surface-water system interactions. Appendix H includes a plot showing the change in radon concentrations with depth. As expected, radon concentrations appear to increase with depth. Values reported range from 70 to 1,400 pCi/l. These values are consistent with results reported elsewhere on the site for groundwater; however, insufficient control is currently available to confirm that this observation holds across the entire site. Results are consistently above the detection limit in the groundwater sampled. This suggests that groundwater from the packer tests has not come from the surface. Because of the relatively low concentration of radon in the shallower intervals, radon is considered to be a poor indicator of the mixing between groundwater and surface water.

4.5.4 Qualification and Validation of Analytical Results

Analyses were qualified for use based on (1) evaluation of electroneutrality by charge balance for major ions, (2) an assessment of the degree to which charge imbalances likely affected the utility of these results, and (3) validation of the raw data in accordance with method and project QA requirements.

Electroneutrality, a fundamental concept in water chemistry, requires that the sum of the cations be equal to the sum of the anions (expresses in milliequivalents). Large deviations from electroneutrality are interpreted to signify either (1) analytical errors or (2) ionic species at significant concentrations that were not included in the analysis. The degree of deviation from electroneutrality is given by the charge-balance equation, which is described in several widely used sources on the evaluation of water chemistry and water quality (Freeze and Cherry, 1979; Hem, 1985; Tchobanoglous and Schroeder, 1987; Mazor, 1991). The ionic species listed at the beginning of this document typically account for the majority of dissolved ionic species in groundwater. For this reason, charge-balance analyses do not usually include trace elements, rare earth elements, or transition metals. Solubility controls and the relatively low crustal abundance generally renders the impact of these elements on charge balance negligible.

Procedures used to validate data and methodologies used to analyze the data include, but are not limited to, an evaluation of the following:

- Conformance with procedures
- Comparability with duplicate analyses

- Review raw data to evaluate technical defensibility of the reported results

Sample collection, handling, identification, and shipping procedures were performed in accordance with the QA Program as described in Procedure S70-QA-001, *Quality Assurance Program*, formally the SECD NQA-1 QA Plan, NUREG-1383 (NRC, 1989), and applicable EPA protocols to assure that the information, data, and resulting decisions compiled under a specific activity are technically sound and properly documented. In addition, the sampling procedures for the more innovative technologies (e.g., stable and radioisotope analytical procedures) are based on the best scientific practices as cited in relevant literature and as adopted as standards by the organizations performing the analyses as approved by the HLA NQA-1 QA Plan. The QA/quality control (QC) procedures implemented during this and future studies will consist of the following:

- Training of sampling personnel on specific documented procedures, tools and equipment necessary for performance of the work, calibration of field instrumentation, and records requirements

- Field sampling procedures, including collection and analysis of field blanks, rinsate blanks, and duplicate samples

- Maintenance of proper field documentation and sample chain of custody

- Field record validation

- Data validation

Field sampling documentation has and will consist of completing (1) daily logs for all activities, (2) Field Sampling Report forms for groundwater major ions analysis, and (3) Onsite Geochemical Data Log and Sample Collection Records for stable isotope and radioisotope analyses, which were maintained in the field upon sample collection. These logs were completed to record events, procedures, and data and to provide a permanent record of all activities. Original completed logs are maintained in HLA project files, and copies of all completed logs are included with the data packages.

Complete chain-of-custody documentation has and will be maintained from sample collection to analysis to provide full traceability of the possession of the samples. Chain-of-custody documentation has and will be maintained in accordance with Tables 2.6–13 through 2.6–15 of CNSI Procedure S70-PR-001 and Procedure A92-QA-017. Chain-of-custody documentation was reviewed by HLA personnel upon receipt of the analytical results to verify full traceability. No breach of chain of custody was identified. Chain-of-custody documentation is contained in the support data packages.

4.5.4.1 Field Record Validation

Following completion of field activities, field data forms and activities logs are reviewed by HLA personnel independent from the field teams to assure that the records reflect conformance with procedures.

4.5.4.2 Analytical Data Validation

Water samples for non-radiological parameters were analyzed under strict QA/QC protocol at Savannah Laboratories and Environmental Services (Savannah). All sample handling and analyses were performed in accordance with Savannah's QC SL Level 3, which is equivalent to EPA Level IV Contract Laboratory Program (EPA CLP) protocol. In addition, analytical data received from the subcontract laboratories were evaluated by HLA to compare sample analysis with specific EPA analytical method protocols.

4.5.4.3 Acceptable Range of Analytical Error for Major Ion Analyses

Analytical method results for major ions are accepted as having an accuracy of ± 2 to ±10 percent, under normal operating conditions (Hem, 1985, p. 163). This means that the difference between the reported result is within 2 and 10 percent above or below the concentration in a sample. Analytical accuracy is typically better than ± 5 percent for samples with concentrations greater than 100 mg/l for any one target ion, and the limits of precision are similar. Accuracy and precision decrease as the concentration of a dissolved species decreases.

Based on industry accepted guidelines (Mazor, 1991, p. 65) and the data quality objectives established by HLA for the project, analyses with charge imbalances of between ± 5 percent are considered acceptable. Errors between ± 5 to ± 10 percent are also acceptable, but will be flagged in the database as estimated based on charge balance errors (CBE). Errors within this range may limit the use of these analyses to qualitative types of evaluations. Errors greater than ± 10 percent will be considered unacceptable for most uses except those involving purely descriptive analyses (CBR). For example, precipitation, surface water, and dilute water of Zone Zero (see Summary Report for Decision Point 2 - Facility Layout Assessment, June 16, 1997) will have the greatest likelihood of falling outside of the ± 10 percent range. Analyses of this water are integral to the site conceptual model, and properties such as specific conductance, temperature, and pH will provide useful points of comparison with these analyses regardless of whether they meet quantitative criteria for inclusion into the final project database.

4.5.4.4 Data Validation and Qualification Results

The project team is currently implementing the previously described data validation program to assure the technical defensibility of the data collected in support of site activities. Several levels of review have and will continue to be conducted to assure the reliability of data used to make project decisions at the Wake County site. Several important changes to the program from that conducted during previous events will include:

- Check of 100 percent of the raw data and packages for completeness and achievement of the method and project required QC performance criteria

- Detailed review of between 10 and 20 percent of the raw analytical data and reported results for completeness and accuracy to assure the legal defensibility of the results and identification of systemic errors

- Preparation of validation reports for each sample delivery groups (SDGs) analyzed

These elements are critical to assuring the long-term defensibility of the conclusions made in support of project activities and are consistent with HLA's longstanding QA/QC policy.

Data being collected and data collected by previous parties that are of value to advancing the project will be treated as follows:

- Validation results presented for data included in the 1994 Chem-Nuclear License Application will be reviewed and qualifiers in the database confirmed for consistency with standard EPA and HLA project requirements. Available validation and nonconformance reports will be compiled and filed in a fashion consistent with those for data collected as part of the 1995, 1997, and future analytical programs.

- Raw data will be obtained from the analytical laboratories for the results collected during the 1995 programs and reviewed and data quality verified in a manner consistent with the prior mentioned program and documentation requirements.

- Major ion data from the 1997 program have been validated and qualifiers applied to the project database and is undergoing secondary review and requests for resubmittals as necessary prior to inclusion into the executive record for the facility.

- Radon and oxygen/deuterium raw data have been received and are under review and will be qualified as soon as possible when resubmittals are received and the data archived along with the validation summaries in the executive record as soon as possible.

- Charge balance calculations have been performed for the major ion data for all available results and a summary of the results and qualifiers applied to the project database are provided in Appendix H.

Based on this status summary the following details the findings for the validation efforts that are currently available. As additional data becomes available HLA will update the project files and submit the results of the ongoing validation efforts to DRP.

4.5.4.5 Summary of Data Validation Results Presented in the 1994 License Application

Non-radiological data were reviewed and validated in support of the 1994 license application by SECD. HLA is attempting to locate raw radiological isotope data collected in support of this effort so it can be validated and incorporated into the project database. At this time the data are considered to be preliminary. The following summarizes the results of the SECD validation effort and the data qualifiers being verified by HLA for incorporation into the project database.

Analytical data received from the subcontract laboratories were evaluated by SECD to compare actual sample holding times before analysis with specific EPA analytical method holding times.

Subsequent to initial submittal of analytical data, the subcontract laboratory identified several labeling and reporting errors that resulted in the submittal of inaccurate data. Specifically, the chloride values for Samples W2DC4 and W12DC4 were reversed, a sampling labeling problem resulted in a misreported sodium value for Sample W4MC3, and the sodium value (12.0 mg/L) for Sample W10MC13 was reported as 120 mg/L. A nonconformance report (NCR-93-01-005) for these data was filed in accordance with SECD NQA-1 QA Plan. The nonconformance report was closed upon the receipt of revised data reports from the subcontract laboratory.

Subsequent to receiving analytical data from the subcontract laboratories, data were evaluated by SECD relative to prescribed handling procedures. Specifically, actual sample holding times before extraction or analysis were compared to specific EPA analytical method holding times. Holding times were exceeded for orthophosphyate and nitrate analyses of groundwater from Well W2DC5, total organic carbon analysis of groundwater from Wells W4MC and W160B4, semivolatile organic analysis of groundwater from Well W9MC32, and QA/QC sample of groundwater from Well W160B4F. A nonconformance report (NCR-93-01-003) for these data was filed in accordance with SECD NQA-1 QA Plan. Every effort was made to validate these data to achieve maximum data utility.

The wells for which holding times were exceeded for orthophosphate, nitrate, and total organic carbon analysis were resampled and reanalyzed. Orthophosphate, nitrate, and total organic carbon concentrations in these samples were comparable to the original reported results. The well for which the holding time was exceeded for semivolatile organic compounds was not resampled because no analyzed compounds were present above the laboratory quantitation limits, analyses for this parameter from other wells were below quantitation limits, and this analysis was performed to determine qualitatively the presence or absence of naturally occurring petroleum hydrocarbons. The semivolatile organic data were flagged as "estimated" and, consistent with EPA protocol, designated in the data set with a "J" suffix.

4.5.4.6 Metals and Major Ion Data Validation Results for 1997 Packer Tests

During data validation, HLA reviewed data packages for completeness and accuracy and listed method non-conformities on method-specific data validation reports. The reports, developed by HLA, were designed to conform to EPA guidelines. HLA evaluated method non-conformities to assess their impact on the usability of the data relative to their intended use. To accomplish this, HLA examined analytical data packages to verify that the required deliverables were included, that quality control (QC) requirements were met, and that data use restrictions were clearly defined. The data validation and data quality assessment were conducted according to EPA, HLA, and laboratory guidelines for the EPA's Contract Laboratory Program (CLP) *National Functional Guidelines for Inorganic Data Review* (EPA, 1994) for major ion and metals data. HLA applied standard EPA qualifiers to the data as necessary to document the usability of the data and identify use restrictions.

HLA validated analytical results of groundwater from Savanah Laboratories to fulfill the 20 percent validation goal established by the project team. At least one full suite of analytical results was and will be validated for a minimum of one case for each environmental sampling medium and sampling event for the 1997 event and other sampling events.

This data validation summary includes a review of results for laboratory method blanks, laboratory duplicate samples, and matrix spike/matrix spike duplicate (MS/MSD) samples. Method blanks are QC samples collected and analyzed internally as part of the laboratory quality assurance (QA) program. Laboratory method blanks identify sample contamination during laboratory preparation before analyzing. Duplicate samples are collected for sample-specific parameter(s) to provide information regarding intralaboratory precision. Included in this data validation summary is an assessment of instrument calibration method requirements, holding times, and reporting requirements.

The data selected for review are consistent with CLP data package deliverable requirements. HLA considers the following list representative of data package contents required to technically defend the reported results:

- Case narrative
- Sample data package
  - Sample holding times
  - Analytical data sheets
  - Raw data
  - Compound identification

  - Analyte quantitation

- QC summary package
  - Surrogate recoveries
  - MS/MSD and tracer recoveries
  - Analytical sequence
- Standard data package
  - Initial calibration
  - Continuing calibration
  - Internal standard peak areas
  - Raw data
  - Quantitation
- Raw QC data
- Overall data assessment

Information impacting the quality of the reported results is detailed in the following method-specific data validation section.

The following summarizes the overall quality and data use restrictions for data packages with samples analyzed for metals and major anions in support of the 1997 packer test program.

4.5.4.7 Metals and General Chemistry (Major Ion) Analysis

HLA validated five cases of metals and general chemistry sample data in support of the packer testing program. The laboratory performed the metals analyses using EPA SW-846 Method 6010. General chemistry analyses for anions were performed using EPA SW-846 9000 series methods and bicarbonate was analyzed using EPA SW-846 Method 310.1. Water samples were analyzed for total metals and anion content. Metals analyses using inductively coupled plasma (ICP). Wet chemical and ion chromatography were used for general chemistry analyses.

Case Narrative

Case narratives were provided by the laboratory and no major problems were noted during the analyses.

Sample Data Package

The laboratory prepared and analyzed samples within the required holding times. The analysis data sheets, bench sheets, and analysis run logs were included in the data packages.

QC Summary Package

The laboratories provided required QC summary packages for the cases reviewed and included results from analyses of interference check samples, MS, matrix duplicates, LCS, method blank samples as required by the method. The results for the LCS met the acceptance criteria. Preparation and calibration check blank sample results contained artifacts of calcium, sodium, magnesium, potassium, strontium, and silica. These artifacts resulted in the need to elevate reporting limits in some dilute QC samples (Appendix H).

Standard Data Package

The initial calibration results met the method-required QC acceptance criteria for target analytes and data were not qualified due to initial calibration problems. Percent recoveries for continuing calibration verification (CCV) samples met the method-required criteria.

Raw QC Data

Laboratory artifacts were flagged by the laboratory prior to submittal of the data and data qualified by HLA as shown in Appendix H.

Overall Data Assessment

The metals and general chemistry results are acceptable as qualified.

4.5.4.8 Charge Balance Results

Charge-balance errors were calculated for samples collected during the 1993, 1995, and 1997 field programs. The calculations were made and checked against output of the geochemical modeling program NETPATH (Plummer, et al., 1991). In Appendix H charge balance errors are plotted against the concentration of chloride. Lines marking the ± 5 percent and ± 10 percent ranges are shown on each figure.

Nine of the 52 analyses from the winter 1993 and summer 1995 programs have charge imbalances between ±5 and ±10 percent, and five greater than ±10 percent. These sample analyses have been flagged in the project database as "CBE" or estimated and "CBR" valid only for qualitative analysis as a result of charge balance considerations. All others are within ±5 percent of electro-neutrality. These are based on samples from wells outside of the Wake Site drainages. Of the 43 analyses from the 1995 drainage study, 15 are between ±5 and ±10 percent, and nine are greater than ±10 percent. Thus, 19 are within ± 5 percent of electro-neutrality. Thirty-two samples make up the 1997 ground-water/drainage study. Nine of these samples have charge balance errors between ±5 and ±10 percent, and another 11 are greater than ±10 percent. Twelve are within ±5 percent of electro-neutrality. The largest sample group of ground-water samples is made up of 46 analyses from the packer tests. This group has the smallest number of charge balance errors outside of the ± 5 percent range. Four are witin ±5 and ±10 percent, and two are beyond the ±10 percent cutoff. Surface-water samples make up the largest group, and largest number of errors that require some type of qualification. Of the 52 samples that make up this group, 13 have charge balance errors of ±5 and ±10 percent, and 30 are beyond the ±10 percent range. The large number of errors for this group is not unexpected, because most of the surface-water samples very dilute, and the concentrations of the major ions are close the limits of detection. Tables provided in Appendix H summarize the results of the analyses, and includes the the associated data flags.

Based on the qualification standards proposed for this investigation, it is inferred that most charge-balance errors (65 percent) for groundwater analyses lie within an acceptable range (±5 percent) of electro-neutrality to warrant the application of these analyses in the development of a conceptual groundwater flow model, and for inclusion in quantitative geochemical models to be developed later. A smaller number of errors (21 percent) lie within the ±5 to ±10 percent range. This does not preclude analyses with these errors from being used to support the development of a conceptual model, but does require that HLA (1) flag the analyses and (2) notify representatives of DRP and the North Carolina Geological Survey of the manner in which the analyses are employed. Fourteen percent of the groundwater analyses have charge-balance errors that lie outside of the ±10 percent range, and will therefore be used with extreme caution; the use of selected field and laboratory parameters will be considered only to support non-quantitative interpretations.

The charge-balance errors calculated for analyses of surface water are largely outside of the error range deemed to be acceptable to support the development of the site conceptual model. This distribution is not unexpected, however, because of the low total-dissolved-solids concentrations in most samples of surface water. The protocol for the use of these samples will be adhered to as described in previous sections of this report.