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Subsurface Injection of Radioactive Tracers

Field Experiment for Model Validation Testing

Prepared by
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Pacific Northwest Laboratory
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Abstract

Accurate predictions of the movement of radioactive contaminants from disposal facilities are required to evaluate effects, optimize data collection, design remediation strategies, and predict the longterm results of such strategies. A field experiment was undertaken in 1980 and 1981 to provide data to test the limits of model predictions. The purpose of this report is to provide a complete record of data generated during that field experiment for use as a model validation test case. The report combines the information in Sisson and Lu (1984) with unpublished laboratory and field data on the hydraulic properties of the sediments and core data collected at the end of the experiment. The unique features of this experiment were the documented control of the inputs, the three-dimensional nature of the experiment, the measurement of radioactive tracers in situ, and the use of multiple injections. The in situ monitoring methods were neutron moderation for water content and gamma energy analysis for tracer concentration. The data are provided on 3.5-in. diskettes. The data include observation and injection well construction details, injection solution concentrations, radioactive tracer and water content distributions in space and time, neutron probe calibration information, and sediment properties determined in both the laboratory and field.

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Executive Summary

As of 1980, approximately 200 subsurface low-level liquid waste disposal facilities had been constructed at the Hanford Site since its inception in 1944. Accurate model forecasts of the subsequent redistribution of radioactive contamination from these facilities are required to (1) evaluate the effect of waste management practices and alternatives, (2) optimize the collection of site characterization data, (3) provide input to the design of remediation strategies, and (4) predict the performance of the remediation and the long-term results. A field experiment was undertaken to establish the limits of model forecasting and to quantify the various sources of uncertainty with model forecasts. The unique features of this experiment were the documented control of the inputs, the three-dimensional nature of the experiment, the measurement of radioactive tracers in situ, and the use of multiple injections. The primary purpose of this report is to provide a complete record of data generated during the field injection experiment for use as a model validation test case. The report combines the information in Sisson and Lu (1984) with unpublished laboratory and field data on the hydraulic properties of the sediments and core data collected at the end of the experiment.

The field experiment was designed to generate data under closely controlled conditions that were directly comparable to model output. A site with relatively uniform lithology was chosen in the 200 East Area of the Hanford Site. The field design consisted of an injection well connected to a 5700-L tank surrounded by eight concentric rings of observation wells. Soil properties were determined in the laboratory on selected samples collected during placement of the observation wells. In situ conductivities were determined at most depths in wells adjacent to the experimental site.

Initial water contents were estimated using neutron probes in the observation wells. A total of eleven 3790-L injections were made: eight with short-lived radioactive tracers (Cs-134 and Sr-85), three without the tracers. The injections occurred over the period from September 1980 to February 1981. During the injection phase, water contents were measured with neutron probes at selected depths and times. In situ gamma energy analysis data were collected to determine the distribution of radioactive tracers.

Five months after the last injection, water contents and gamma emissions from the tracers were monitored. Three wells were drilled to obtain core samples for analyses of Cl^-, NO_3^-, and water content. Three months later (in October 1981), water contents were measured for the final time.

The original field note[illegible] found. Although more information might [illegible] out of as yet undiscovered records, it is doubtful that much more can be established regarding data integrity or measurement error. Certainly a benefit of the experiment was learning how to conduct the next one. The largest area for improvement is documentation: what was done, when, how, why, with what, and by whom.

An important aspect of the experiment is whether some geostatistical picture of the subsurface can be assembled. Certainly, such a picture could not be put together from the limited soil samples reported in Section 4. More promising for establishing a statistical description are the initial water contents, the natural gamma and gamma-gamma data, and the conductivities determined in situ.

Whether the experiment serves a useful purpose for testing of flow and transport models depends on the data user and the purpose of the use. Because precise quantities of water were injected and monitored in three-dimensions, the experiment offers an opportunity to see how well the design allowed for the measurement of the volume of water injected. Demonstrating that such additions of water could be tracked successfully would be important to any study of contaminant transport in the field. The next steps would be to simulate the injection and redistribution of water, then simulate the transport of the tracers. The site still exists and is available for field testing or a post-mortem study.

This report contains a complete summary of the data available from the experiment. The data are provided on 3.5-in. diskettes. The data include observation and injection well construction details, injection solution concentrations, radioactive tracer and water content distributions in space and time, neutron probe calibration information, and sediment properties determined in both the laboratory and field.

Preface

A field experiment was conducted during 1980 and 1981 in which water and tracers were injected to subsurface sediments. Sisson and Lu (1984) described the experiment and presented results, but their report received little distribution. Subsequently, additional data (e.g., soil properties) for the injection site became available.

Given the current interest in data sets for model validation, this experiment appeared to have unique features that made it suitable for validation testing. Therefore, this report was prepared; it includes much of the original report as well as unpublished data.

Acknowledgments

We thank the staff at Westinghouse Hanford Company and Pacific Northwest Laboratory who volunteered their time and comments. We are especially grateful to Glendon Gee and Charley Kincaid for reviewing this document and to Diana Felmy for assembling some of the data files and figures.

1 Introduction

Some human activities generate waste products that pose a health risk and degrade the environment. Both intentional and inadvertent disposal to surface soils (landfills) or subsurface sediments have always occurred. In our changing society, what were once thought to be safe and appropriate disposal practices are now causes for concern and environmental cleanup. This is particularly true at production facilities for special nuclear materials and at the Hanford Site.

At the Hanford Site in southeastern Washington State, nine production reactors operated at various times between the years 1944 and 1987. The plants that processed the special nuclear materials generated large quantities of liquid waste. The more highly concentrated liquid wastes were stored in 149 single-shell and 28 double-shell tanks. Unfortunately, some of those tanks leaked. The less concentrated and higher volume liquid wastes were disposed to ponds, cribs, and ditches. These disposal methods permitted drainage directly into the soil and subsurface sediments. Accurate predictions of water movement and the transport of radioactive and chemical contaminants in the soil and subsurface sediments at these facilities are required to

- evaluate the effects of waste management practices and alternatives
- optimize the collection of site characterization data
- provide input to the design of remediation strategies
- predict the performance of the remediation and the long-term results.

The currently accepted method of predicting water and contaminant distributions is to use a computer to solve water flow and convection-dispersion equations. While considered scientifically valid, this method has not been fully demonstrated as a predictive tool in the vadose zone of an arid climate such as that at Hanford. In 1980 and 1981, an experiment was conducted to provide data on the subsurface movement of water and contaminants at the Hanford Site (Sisson and Lu, 1984). The data were to be used for model calibration; preliminary simulations were conducted using estimated hydraulic parameters. Experiments of a slightly different nature but similarly designed to provide data for model testing for unsaturated flow and transport have since been conducted in New Mexico (Wierenga et al., 1986).

Subsequent to publication of the Sisson and Lu (1984) report, samples of the sediments at the experiment site were obtained. In 1992, the Nuclear Regulatory Commission (NRC) authorized Pacific Northwest Laboratory (PNL)[a] to analyze the available sediment samples for hydraulic properties, determine the availability of other unpublished data from the experiment, and merge the published data with the unpublished data into a complete data report for the experiment. The rationale for republishing the results of the 12-year-old experiment was that such field experiments have become increasing costly to conduct. Before repeating similar experiments, older experiments should be analyzed to extract the maximum value possible.

The primary purpose of this document is to provide a complete record of data generated during the field injection experiment for use as a model validation test case. The unique features of this experiment were the documented control of the inputs, the three-dimensional nature of the experiment, the measurement of radioactive tracers in situ, and the use of multiple injections.

This report contains six sections and an appendix. In Section 2, the design of the experiment is described. In Section 3, the solution compositions, method of mixing, and injection method are reported. Section 4 explains the methods used to monitor the movement of water and tracers. Properties of the sediments are described in Section 5. The modeling results of Sisson and Lu (1984) are briefly summarized in Section 6. The references are listed in Section 7. The appendix contains a listing of the data files included on 3.5-in. diskette (rather than as actual text in the report). These files

[a]PNL is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

include observation and injection well construction details, solution injection rates, radioactive tracer concentrations in space and time, neutron probe calibration data, neutron probe counts in space and time for calculating water contents, and sediment properties determined in both the laboratory and the field.

2 Design of Experiment

2.1 Experiment Site

The Hanford Site is located in southeastern Washington State. Figure 2.1 shows the location of the 200 East Area (within which the experiment was conducted) relative to the Hanford Site. Cushing (1991) described the climate, soils, vegetation, and geology of the 200 East Area.

2.1.1 Climate

The climate of the Hanford Site is considered semiarid. Hourly weather data have been collected at the Hanford Meteorology Station since 1945; summaries through 1980 are available in Stone et al. (1983). Annual precipitation averages 160 mm/yr. Nearly half the precipitation arrives in the months of November through February. Of that amount, 38% occurs as snowfall. The average monthly temperature ranges from -1.5 C in January to 24.7 C in July. The average monthly humidity ranges from 75% in winter to 35% in summer.

2.1.2 Soils and Vegetation

The surface soil is a coarse sand, locally known as Quincy sand. The vegetation at the site was a mix of sagebrush and cheatgrass. The shrubs were "grubbed" from the site around March 1980 and the site has remained free of shrubs ever since. Vegetation such as cheatgrass, tumbleweed, tumble mustard, and other annuals still remain.

2.1.3 Geology

The 200 East Area rests on an elevated portion of the Hanford Site referred to as the 200-Area Plateau. The upper portion of the plateau was formed during Catastrophic glacial flooding. Flood sediments were deposited when ice dams in western Montana and northern Idaho were breached and massive volumnes of water spilled across eastern and central Washington. A thick sequence of sediments was deposited by several episodes of Pleistocene flooding, the last major flood sequence dating about 13,000 years before present. The sediments deposited are known as the Hanford formation.

Based on data reported in Tallman et al. (1979), a site with relatively uniform lithology and few lithologic units was selected in the 200 East Area (Figure 2.1). The Hanford formation is about 60 -m deep at the experiment site; the depth to groundwater is more than 90 m. The entire experiment was conducted between the 0- and 20-m depths, well within the Hanford formation and well above the water table. The rationale for selecting a site with simple lithology was that such a choice reduced the number of distinct parameters required by a model.

2.2 Well Location and Orientation

Figure 2.2 shows that the well system consisted of an injection well surrounded by thirty-two observation wells. A storage tank that contained the various injection solutions was positioned outside the zone with wells. A pump delivered each solution from the storage tank to the injection well, which was the only source of water and tracers to the sediments. Data were obtained by lowering sensors to the desired depths in the observation wells. The sensors used included neutron probes, Geiger-Muller (GM) probes, gamma energy analysis probes, and gamma-gamma probes.

2.3 Observation Well Construction

Observation wells provided access to various depths and allowed for nondestructive sensing of water contents and the concentrations of the radioactive tracers. Destructive sampling by drilling was used only once (at the end of the experiment) to minimize the disturbance to the experimental site. Rather than metric, British units are reported for the construction details below.

Each observation well was constructed from three 20-ft sections and one 5-ft section of 6-in.-diameter schedule 40 steel casing. The sections were welded to form watertight joints reinforced with four steel straps welded symmetrically around the casing. During installation, the 5-ft section of casing, without a drive shoe, was driven into the soil; then a 20-ft section was welded on, and the driving continued until the top of the casing was

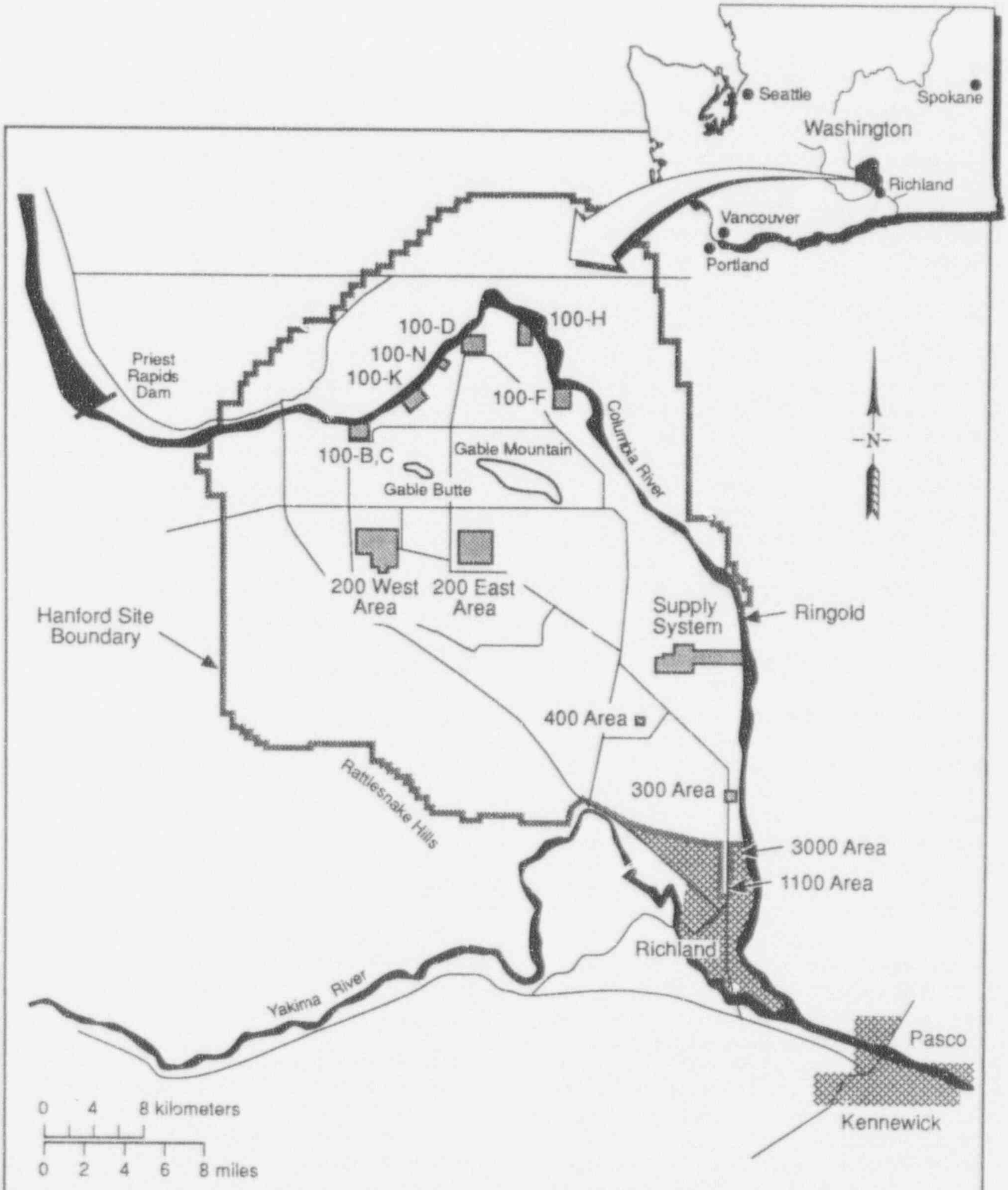


Figure 2.1 Location of injection experiment in 200 East Area of the Hanford Site

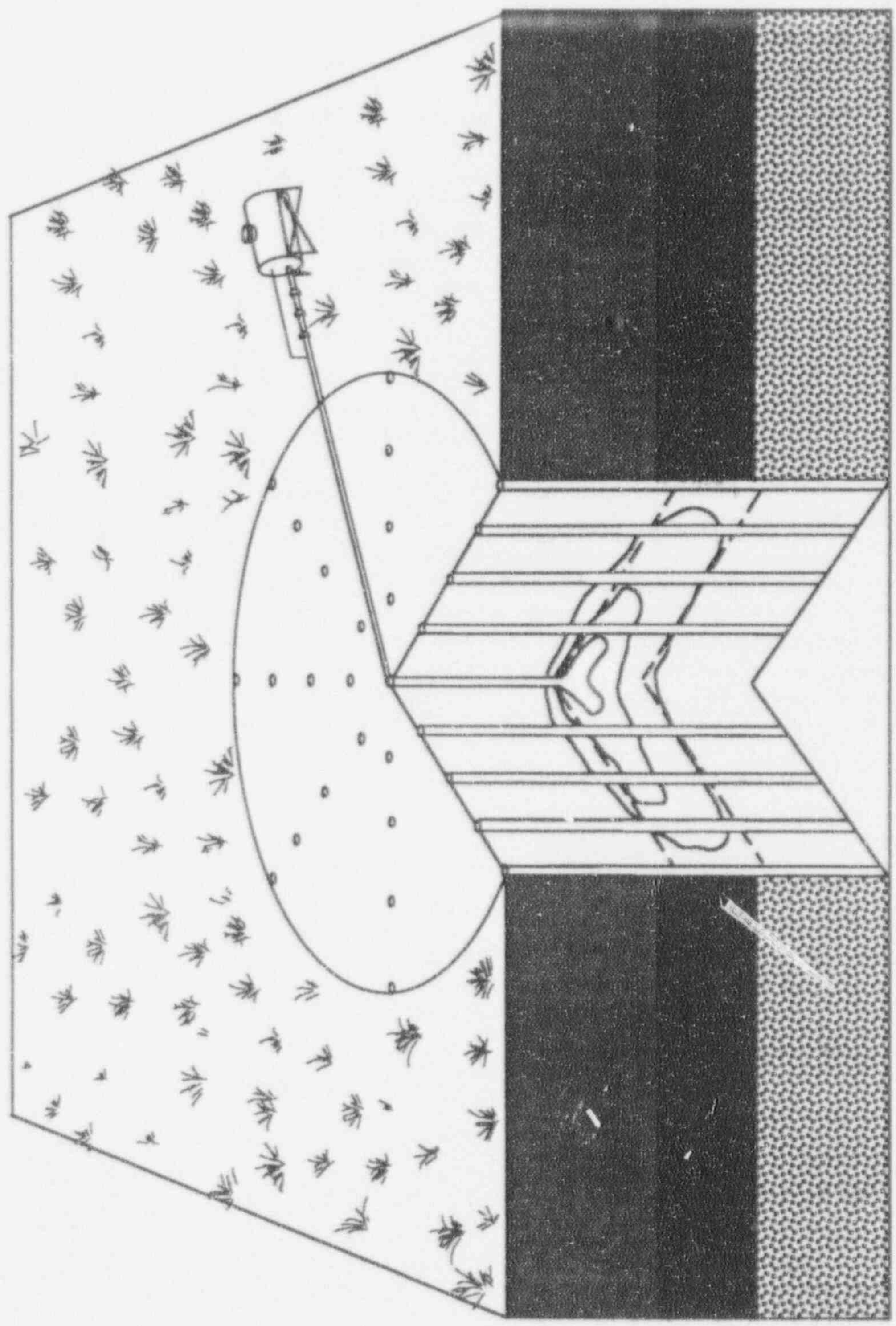


Figure 2.2 Cutaway view of experimental site showing well layout

beyond the reach of the drive hammer. Soils within the casing (drill cuttings) were then removed by advancing 20 ft with a rotary bit using air as a drilling fluid. Cuttings were blown into the atmosphere and fell close to the point of drilling. Figure 2.3 shows the well numbering scheme.

The relatively smooth gamma-gamma logs obtained from the wells constructed by this technique indicated uniform contact between the well casings and sediments. Uniform contact was necessary to minimize preferential flow along any of the wells. The gamma-gamma logs and natural gamma logs from all of the wells were digitized; the results can be found in the appendix. Figure 2.4 shows the average and range of relative densities around the wells. Figure 2.5 shows the average and range of natural gamma emissions from the sediments.

2.4 Injection Well Construction

All water and tracers entered the system through the injection well. The well had to be sufficiently strong to prevent movement of the well should locally high pressures develop during injection, and to minimize possible movement due to settling should erosion occur at the injection point. Rather than metric, British units are reported for the construction details below.

The injection point consisted of a 1-in. galvanized steel pipe protruding approximately 1/8 in. through a 1/8-in. steel plate. The steel plate was welded flush to the end of a 3 5/8-in.-diameter section of NX flush joint drive casing. Thus, 15 ft of 1-in. pipe was inside 15 ft of NX casing, and these were welded together at the lower end. This inner assembly was then placed inside a 15–ft–deep, 6-in.-diameter schedule 40 steel well and cemented.

The cement mix was 94 lb of Type 1 cement in 5.6 gal of water. Before to cementing the annulus formed by the NX and 6-in. casing, 1 ft of sand was placed in the annulus. The sand prevented cement from plugging the 1-in. pipe, and the cementing operation ensured that the well point would not move if high pressures were encountered during the injection. Figure 2.6 shows the injection well construction and a plan view of its position in the well field.

Several days before tracers were added to the tank, the injection well was tested. The test consisted of pumping 60 gal of water into the well and observing the pressure rise. Pressures in excess of 100 psi were encountered initially. A metal rod was then lowered down the center of the injection well and driven 6 in. beyond the well point and into the sediments. The injection well was retested. The gauge pressure was less than 5 psi at the pump, indicating that adequate flow capacity was available for the injection experiment to begin.

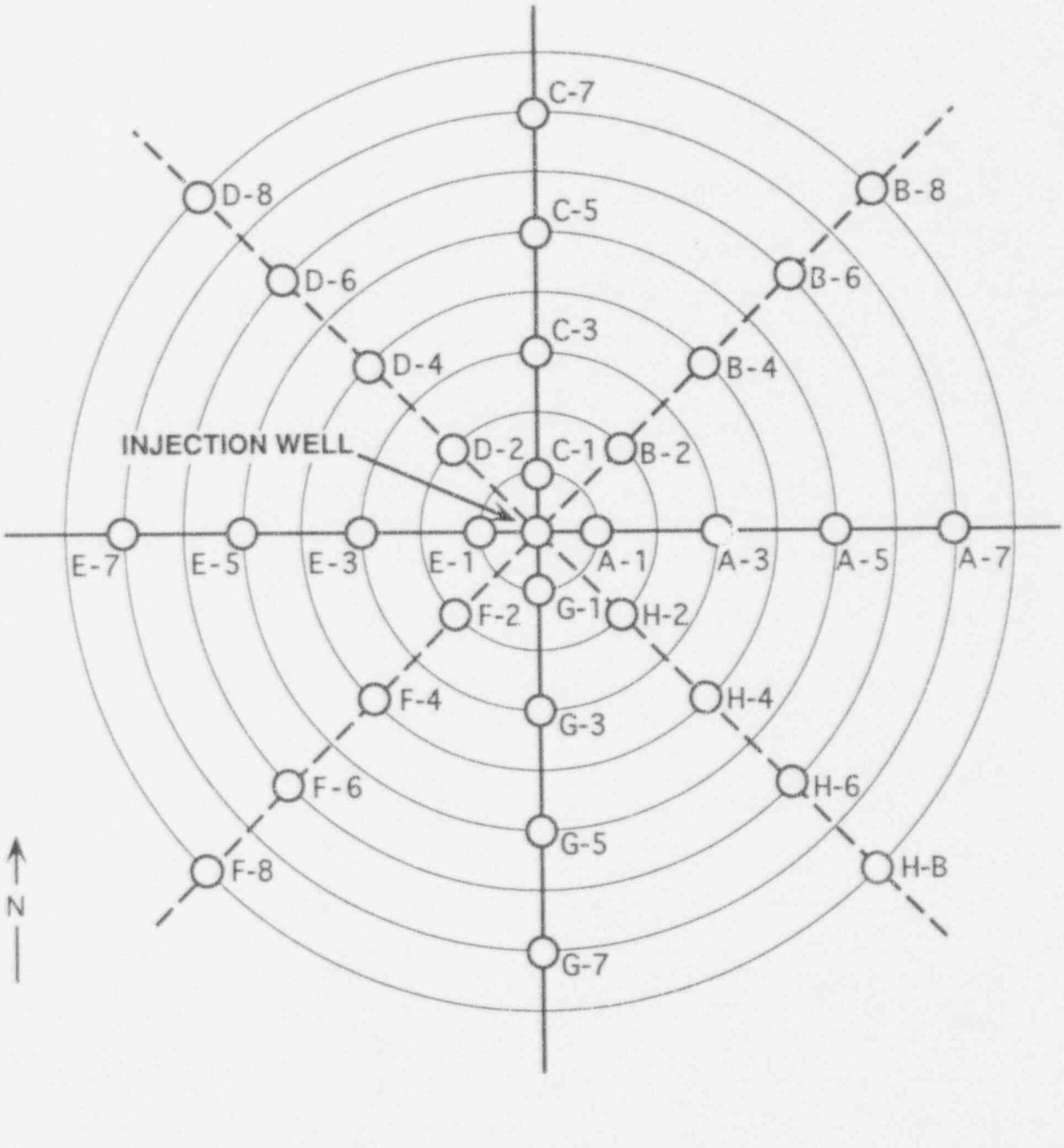


Figure 2.3 Well numbering scheme

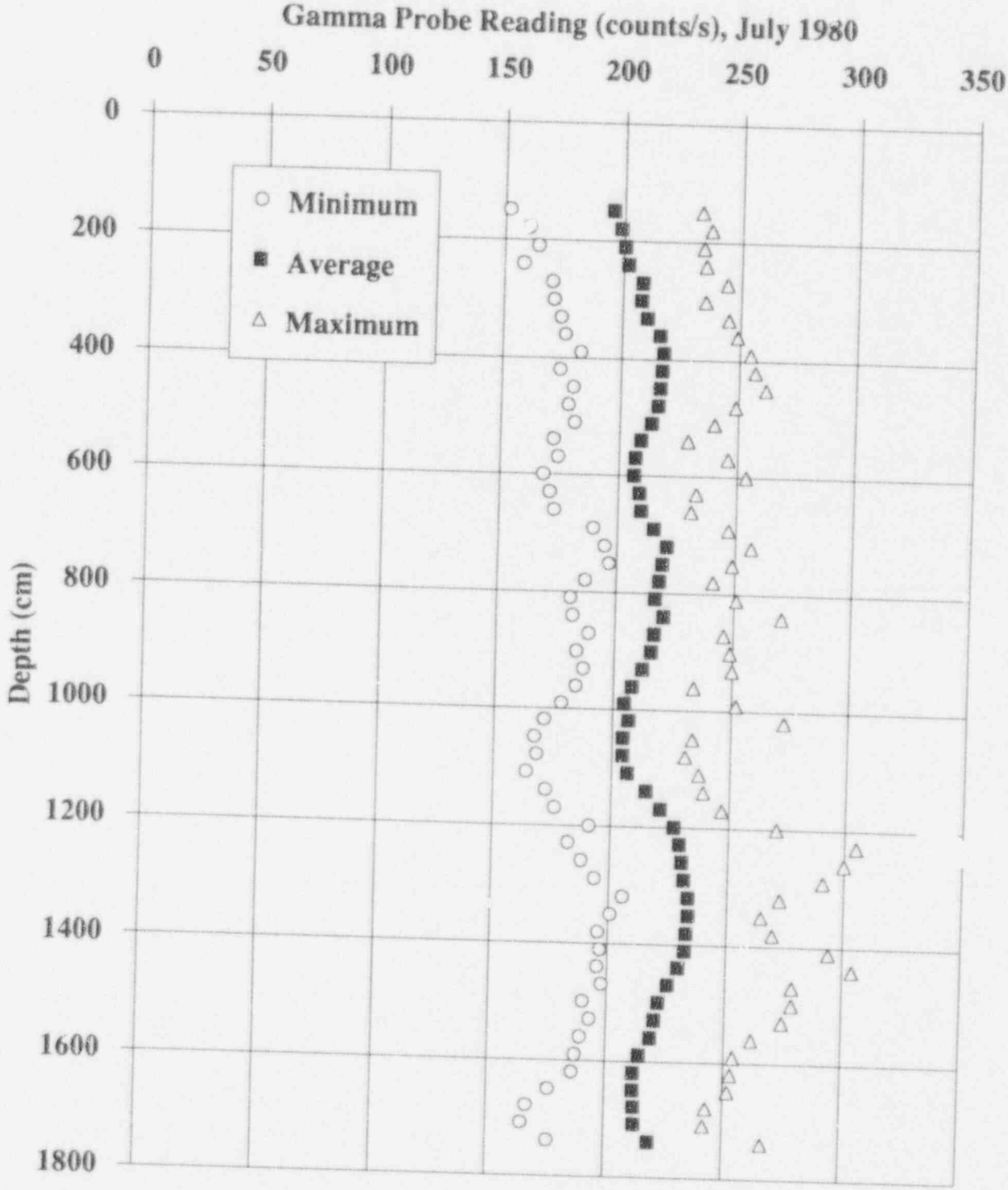


Figure 2.4 Relative density around the wells

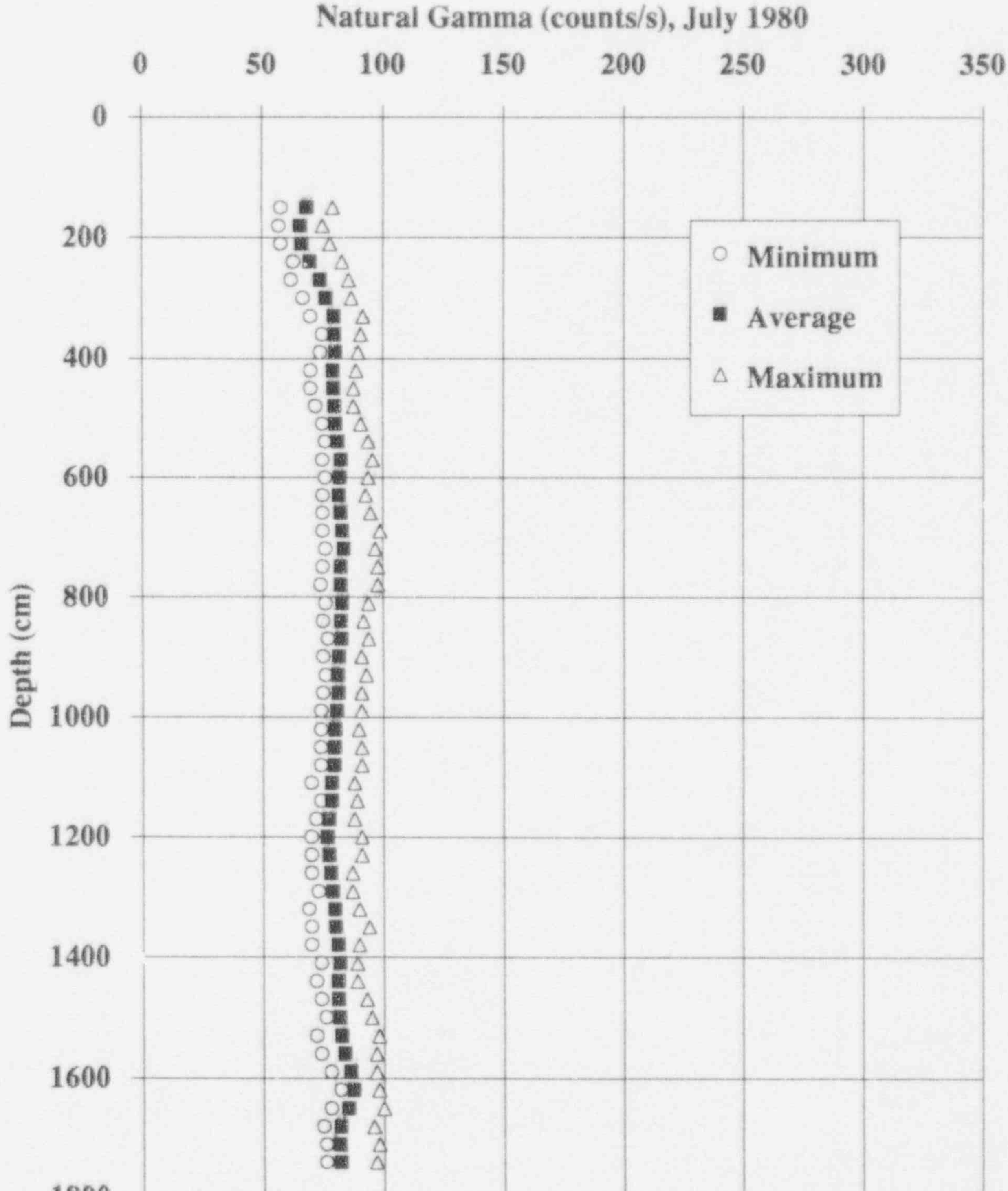


Figure 2.5 Natural gamma emissions from the sediments around the wells

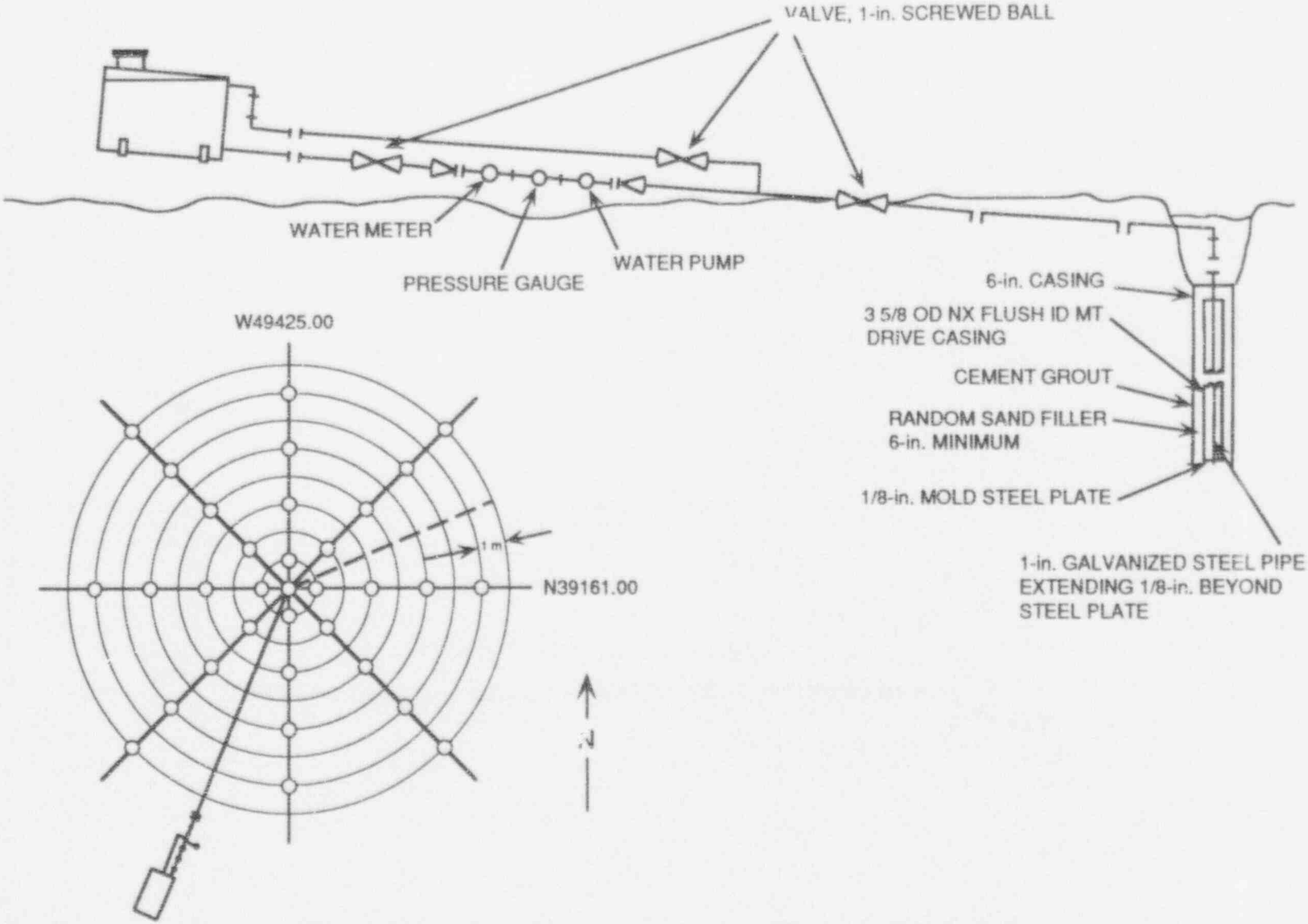


Figure 2.6 Plan view of wells and construction details

3 Injection

3.1 Solution Description

Uniform solutions of calcium chloride, calcium nitrate, barium chloride, rubidium nitrate, and two radioactive ions were delivered to the injection well at weekly intervals. The tracers included sorbing and nonsorbing ions (Table 3.1). Calcium was added at a concentration of 0.01N as 0.005N calcium nitrate plus 0.005N calcium chloride to reduce permeability changes of the sediments during injection, and to provide the nonsorbing ions nitrate and chloride. Cesium-134 was chosen because it is a gamma emitter and undergoes strong sorption by the sediments. Strontium-85 was chosen because it is a gamma emitter but is moderately sorbed by sediments. Table 3.1 summarizes the tracer properties.

The use of multiple and competing tracers complicates the analysis of transport. No sorption measurements were conducted using the injection solutions and sediments from the experiment site. Independent of the injection experiment, some of the ions were studied for their sorption characteristics relative to nearby sediments. Serne and Wood (1990) reviewed the available data and reported a distribution ratio, R_d, which related the solution concentration to the amount of ion sorbed to the sediment. The R_d value, while a simplificatio.. of sorption, allows for easy incorporation in flow and transport models. Serne and Wood chose to report sorption using the R_d rather than K_d symbol because the laboratory experiments did not demonstrate reversibility nor did they show that solution-sorption distribution (i.e., K_d) was independent on the concentration in solution.

Serne and Wood (1990) summarized the range of R_d values for each ion and suggested an average R_d value for those solutions with low salt and organic content and with neutral to basic pH. Although the pH, was never measured, the injection solutions were likely basic in pH, given their components. The relevant R_d values from Serne and Wood (1990) are shown in Table 3.1.

The actual composition of each injection solution was determined by sampling the tank just before or during each injection. Table 3.2 shows the resulting concentrations. The last three injections did not receive the radioactive tracers.

Table 3.1. Tracer Information

Tracer	Atomic Weight	Valence	Half Life	R_d Range (mL/g)	Average R_d (mL/g)
Ba	137.3	+2	-	unknown	50
Ca	40.1	+2	-	variable	10
Cl	35.5	-1	-	0 to <1	0
134 Cs	132.9	+1	2.05 yr	6 to >1000	50
NO_3	62.0	-1	-	0 to <1	0
Rb	85.5	+1	-	unknown	unknown
85 Sr	87.6	+2	64 d	5 to 100	10

Table 3.2 Concentrations of Tracers.

Injection Number	^{85}Sr (µCi/L)	^{134}Cs (µCi/L)	Ca (M)	Rb (M)	Ba (M)	NO_3 (ppm)	Cl (ppm)
1	28	3.4	4.4×10^{-3}	1.6×10^{-5}	2.4×10^{-5}	320	156
2	27	3.1	6.3×10^{-3}	1.9×10^{-5}	4.6×10^{-5}	316	155
3	24	2.4	6.5×10^{-3}	1.0×10^{-5}	$<2 \times 10^{-5}$	293	164
4	23	2.5	5.4×10^{-3}	1.2×10^{-5}	8.0×10^{-5}	305	170
5	24	2.8	4.2×10^{-3}	8.7×10^{-6}	3.2×10^{-5}	272	170
6	23	2.7	7.0×10^{-3}	1.1×10^{-5}	$<1 \times 10^{-5}$	275	169
7	22	2.9	3.2×10^{-3}	8.4×10^{-6}	2.3×10^{-5}	403	186
8	22	2.8	7.4×10^{-3}	5.4×10^{-6}	4.4×10^{-6}	360	160
9	ND[a]	ND	6.9×10^{-3}	4.2×10^{-6}	3.4×10^{-7}	355	159
10	ND	ND	8.3×10^{-3}	$<1.7 \times 10^{-5}$	7.9×10^{-6}	384	160
11	ND	ND	5.5×10^{-3}	NA[b]	$10. \times 10^{-6}$	250	152

[a]Not detectable

[b]Not available

3.2 Mixing Methods

In general, each injection consisted of filling the holding tank, adding the tracers, mixing the water and tracers, and then injecting the solution. Water for each of the injections was transported to the site from a nearby safety shower in 1900-L (500 gal) vinyl bags. From the bags, 3800 L (1000 gal) of water was metered into a 5700-L (1500-gal) tank. Calcium salts and additional sorbing tracers, barium and rubidium, were dissolved in two 50-L (13-gal) carboys at the injection site. Resulting concentrations are shown in Table 3.2. The carboys were rinsed and the rinsing solutions added to the tank.

The radiological tracers ^{85}Sr and ^{134}Cs were delivered for each weekly injection as a 20-ml solution. The glass vial containing the tracers arrived at the site in a lead container called a pig. The pig was placed in the tank on a rack before opening and removing the vial. The vial was handled with modified tongs. The cap was unscrewed from the vial, the vial contents were poured into the calcium solution in the tank, and the vial and cap were rinsed using a polyethylene wash bottle. Washing continued until less than 300 count/s were observable with a hand-held GM probe in contact with the vial and cap.

For the first three injections, the tank contents were circulated until the solution was uniform, as evidenced by constant gamma activity at all points on the tank exterior. Although a uniform count rate was obtainable within 5 min after starting circulation, mixing was continued for 2 h. For the remaining injections, the tracer and calcium solutions were added after 1900 L (500 gal) of water was metered into the tank. Adding the final 1900 L (500 gal) induced enough mixing to obtain a uniform count rate at the tank surface. Both the circulation and partial filling method appeared to provide adequate mixing.

3.3 Injection Method

A stainless steel gear pump was used to deliver each solution from the storage tank to the injection well point. The pump controlled the delivery rate. The first pump developed a leak (on the scale of drips), terminating the first injection; the pump was replaced before the next injection.

The volume of solution delivered during each injection was measured using a positive-displacement water meter. Figure 3.1 shows the injection rate history for the eleven injections (the appendix contains the pump data). Injection 3 was stopped around 1100 h because of a bad plug on the generator. The pump was restarted, turned off briefly to allow sampling of the tank solution, then turned on again. All other injections were delivered at uniform rates (Figure 3.1).

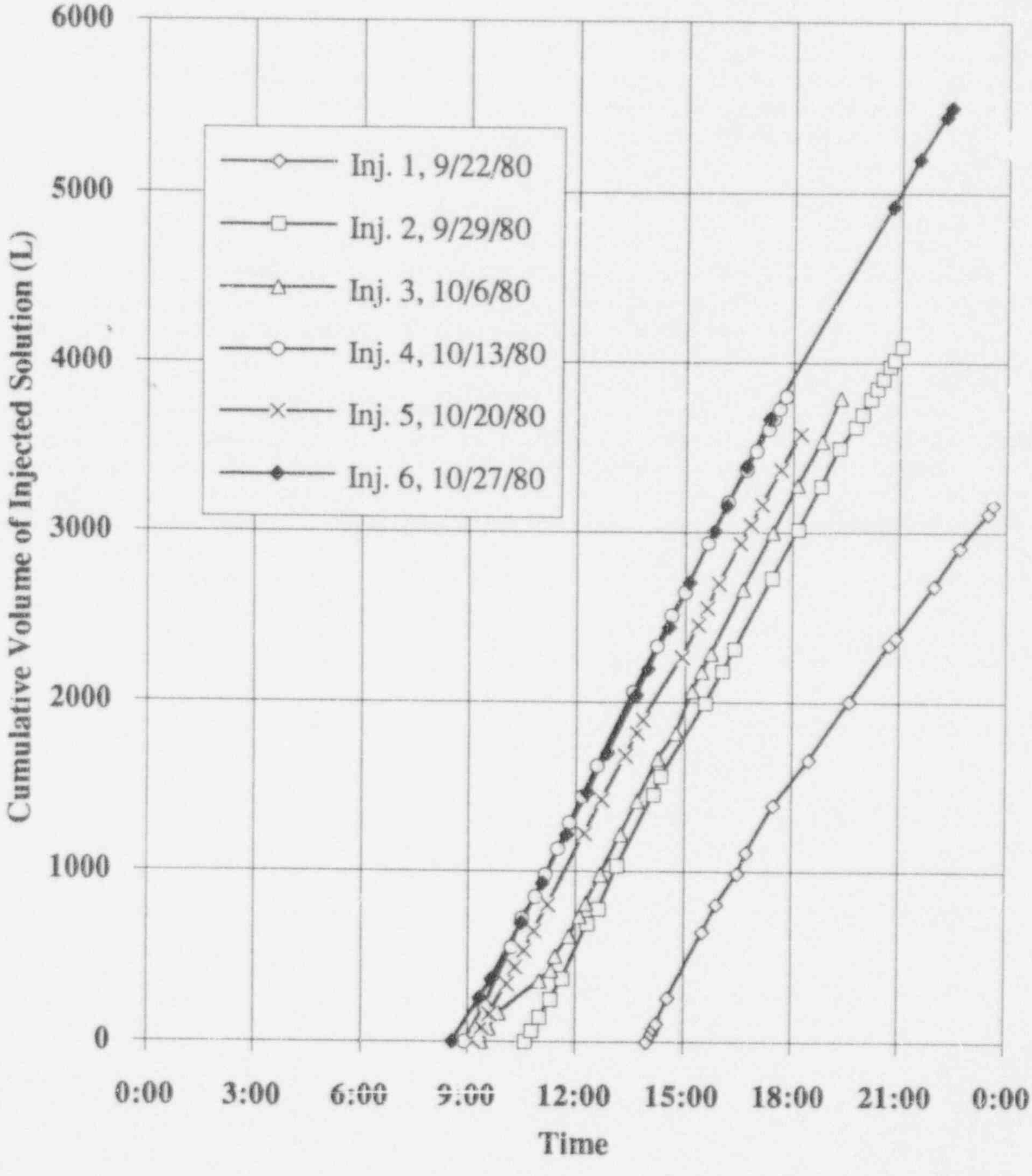


Figure 3.1a Shows the cumulative injection volumes for injections 1 to 6

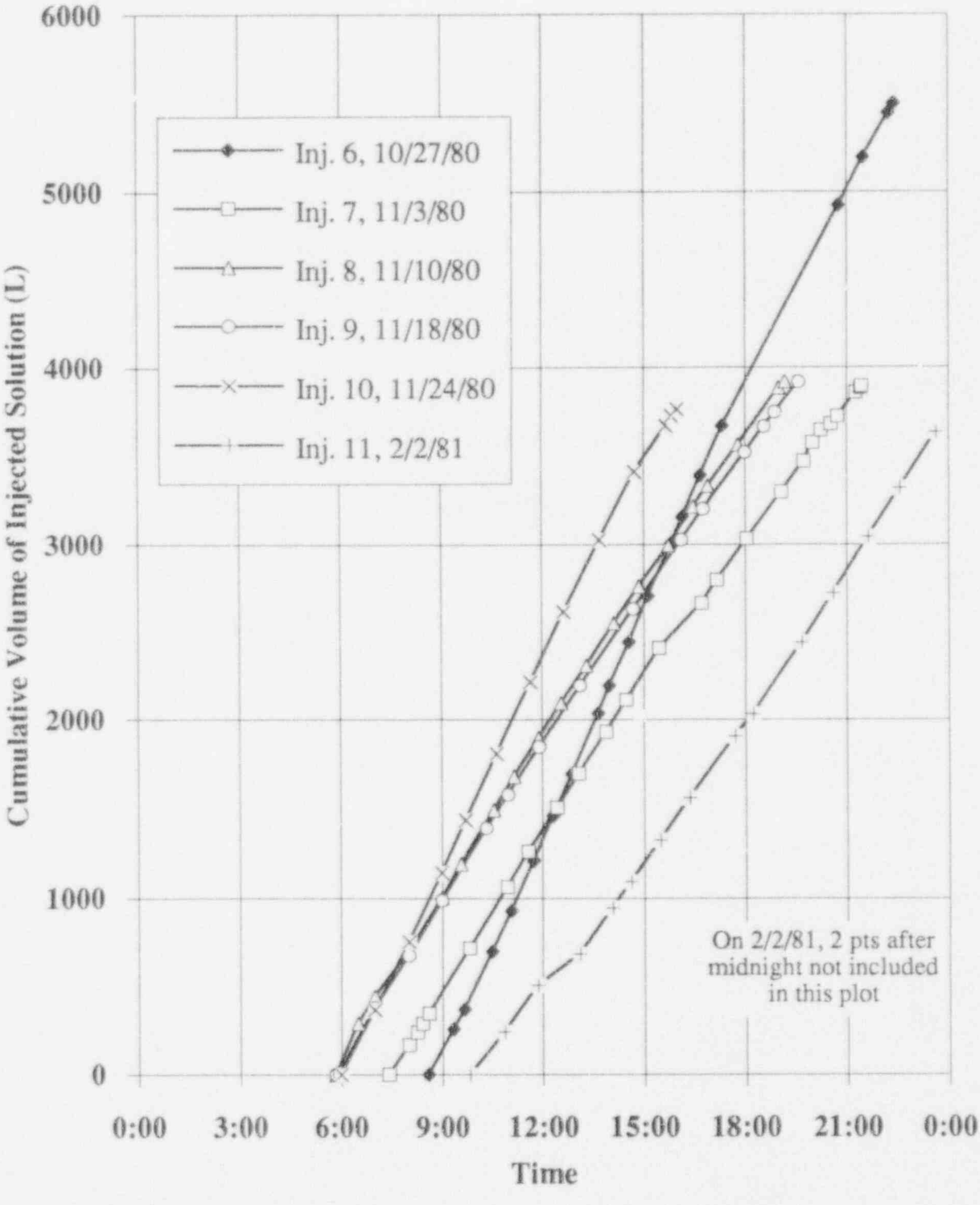


Figure 3.1b Shows the same for Injection 6 to 11

4 Monitoring Methods and Frequency

4.1 Variables

Variables monitored during the experiment were water content (using the neutron probe) and radioactive tracer concentration (using the gamma energy analysis probe). Concentrations of the non-radioactive tracers Cl^- and NO_3^- as well as water content were determined at the end of the experiment by coring at three distances from the injection well. Figure 4.1 shows the monitoring schedule.

4.2 Neutron Probe

Three Campbell-Pacific Nuclear (CPN) neutron probes were used (Table 4.1). The diameter of the probes was slightly less than 2 in., much smaller than the internal diameter of the 6-in. well casing. No attempt was made to center the probes.

Table 4.1 Neutron Probe Information

Probe No.	Serial No.	CPN Model No.	Probe Type
1	H38092510	503	Moisture
2	D79102971	501	Moisture-Density
3	H36011607	503	Moisture

To determine water contents with a neutron probe, a calibration equation is needed that is specific to the sediment and well casing dimensions and material. Sisson and Lu (1984) generated a single calibration equation for the three probes from data obtained from two sets of calibration standards.

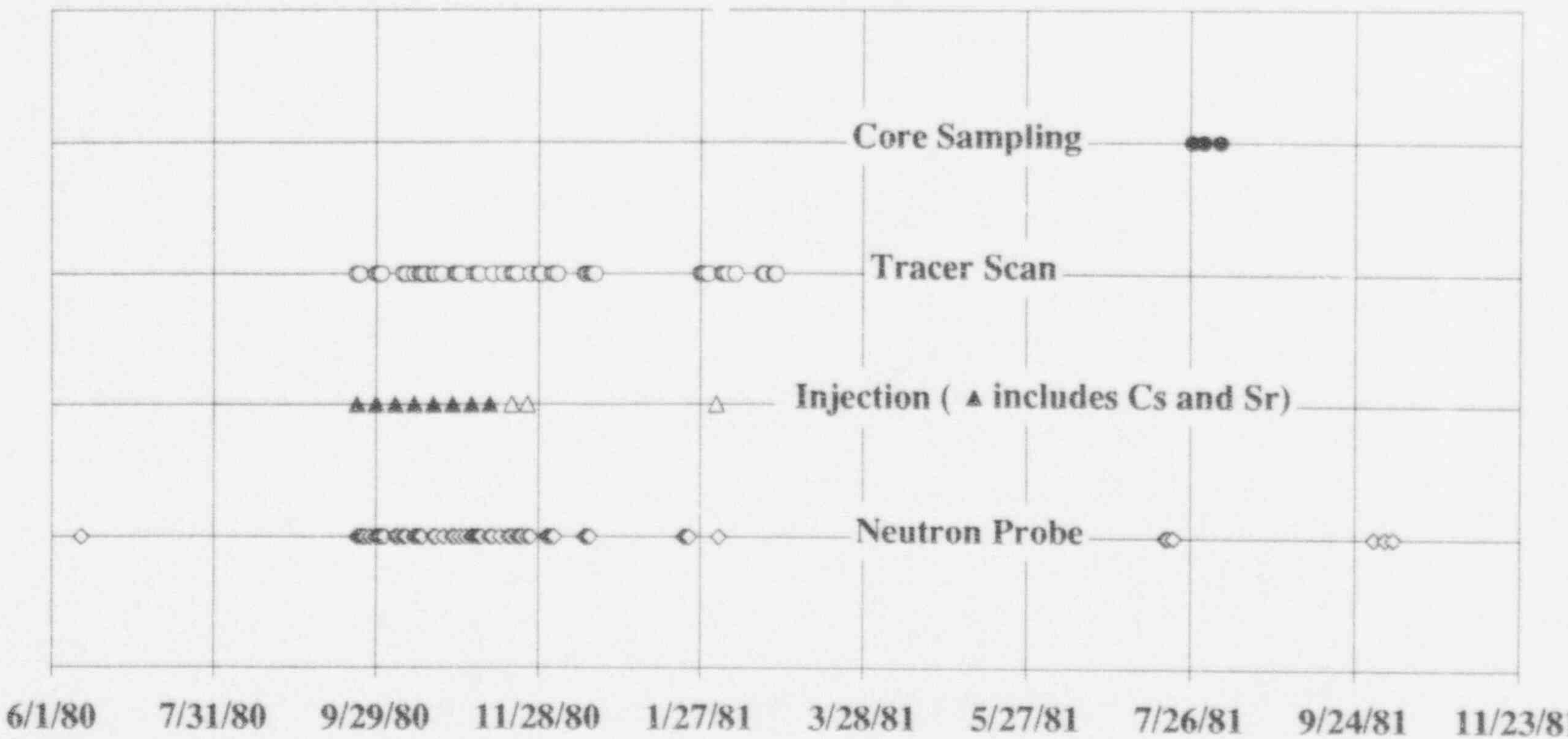
One set of standards was located in a nearby calibration facility. Each calibration standard was constructed under ground by placing a 6-in. well casing into a 90-cm (3 ft) diameter galvanized steel cylinder. The annulus was packed with alum-sand mixtures to represent water contents of 0, 5, 10, and 15%.

The second set of standards consisted of 6-in. well casing in two 55-gal drums packed with oven-dried drill cuttings obtained at the experiment site. One drum was maintained at oven dryness. The sand in the remaining drum was saturated to a value reported to be $0.255\ cm^3/cm^3$. The water was weighed and hauled to the site in carboys. Water remaining after saturating the sand was measured with a 1000-ml graduated cylinder.

The usual calibration method requires computing the ratio of counts in soil to counts in a standard plastic shield. The count ratio method resulted in distinct calibration curves for all three probes. It was found that a single calibration curve could be used for all three probes, when the probes were calibrated as water content versus counts per 15 s. The calibration data can be found in the appendix. Figure 4.2 shows the calibration curve obtained by least-squares regression.

During the preparation of this report, several features of the probe calibration process became suspect. First, the calibration facility was constructed years before the experiment; the only record appears to be an engineering drawing of the construction specifications. That drawing indicates that the various water content standards were obtained by mixing Ottawa sand and alum. Calculated bulk densities ranged from $1.25\ g/cm^3$ for the 15 vol% water content to $1.6\ g/cm^3$ for the 0.0 vol% water content for the pure sand; no record was available of the actual construction densities and water contents achieved. Second, Sisson and Lu averaged all of the field barrel readings from three depths (30, 45, and 60 cm). On many dates, the readings at these depths are different (see appendix), indicating possible probe problems or insufficient barrel dimensions (i.e., smaller than the zone of probe measurement). Finally, notes were discovered that show how much soil and water was placed in the field barrels. According to these notes, the bulk density values were 1.51 and $1.60\ g/cm^3$ for the dry and saturated barrels, respectively. Given that 50 kg of water were added to the barrel and that more than 99% infiltrated, the water content of the saturated barrel was calculated to be about $0.29\ cm^3/cm^3$ rather than the value of 0.255 reported by Sisson and Lu (1984).

Neutron probes were operated by lowering the probe into an observation well to the depth desired. Counts were accumulated for 15 s and then the probe was moved to the next depth. Field notes were maintained so that the data from each point in the system could be observed



4.1 Monitoring dates

over time in the field. This allowed readings to be repeated immediately to verify sudden changes in water content.

The initial water contents were obtained at 30-cm increments over the 30- to 1800-cm depths in all 32 observation wells. The initial readings are in the appendix; the initial water contents can be estimated from these data using the calibration curve given in Figure 4.2.

The depths and radii of neutron probe readings were determined ad hoc. Data within the wetted volume were obtained approximately every 2 h. Efforts were also made to frequently monitor at depths and radii immediately outside the wetted volume. This ad hoc technique resulted in relatively few positions per well being monitored early in the experiment, and a large number of positions per well being monitored later in the experiment. Overall, the inner wells were monitored frequently and the outer wells infrequently. The probe data are in the appendix; water contents can be estimated from these data using the calibration curve given in Figure 4.2. Figure 4.3 shows how water contents in Well A-1 changed during the first injection.

4.3 Gamma Energy Analysis Probes

Concentrations of the radionuclide tracers were inferred from intrinsic germanium and germanium-lithium Ge(Li) probes operated in the observation wells. These probes and the counting equipment were part of an in-field measurement system known as Dev Van II.

The Dev Van II consisted of the gamma radiation detectors, pulse preamplifier, and self-contained battery-operated power supply for the detectors and preamplifier. The nuclear events that occurred in the detectors created electrical pulses. The pulses were fed through a 150-m (500-ft) cable on a motor-driven drum to a multichannel analyzer and its associated electronics in the van. The multichannel analyzer stored the nuclear pulse information in 4096 channels according to pulse height. The height, or amplitude, of the pulse was proportional to the energy deposited in the detectors by the radiation that caused the event. In this way, a spectrum or frequency distribution by energy was acquired in the multichannel analyzer. This spectrum could be displayed on a cathode ray tube (CRT) screen and processed by hand or stored on a tape cassette for later analyses by a computer-based laboratory analytical system. A more detailed description of calibration and field methods can be found in Routson et al. (1979).

Data obtained by Dev Van II are in the appendix. Figure 4.4 shows the variation of Sr-85 for well H-2.

4.4 Coring

Between July 28 and August 6, 1981, three wells were drilled within the observation well perimeter and samples (some of them intact cores) were removed for analyses of Cl^-, NO_3^-, and water content (samples dried to 60°C rather than 105°C). The data for these analyses are in the appendix. Wells 121, 122, and 123 are located at radii of 140, 373, and 232 cm, respectively, relative to the injection well. Figures 4.5, 4.6, and 4.7 show the observed profiles. These data were not reported by Sisson and Lu (1984).

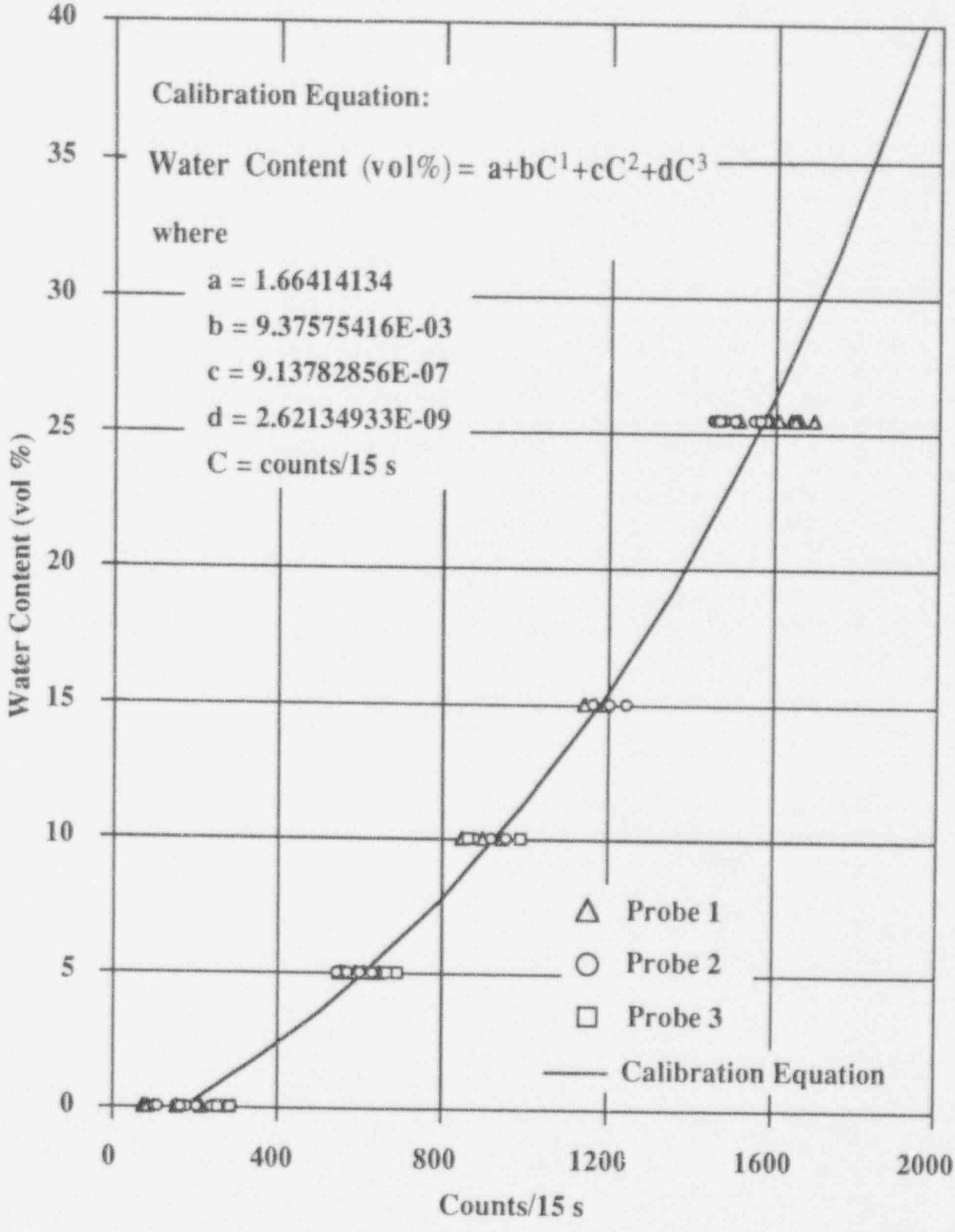


Figure 4.2 Original neutron probe calibration

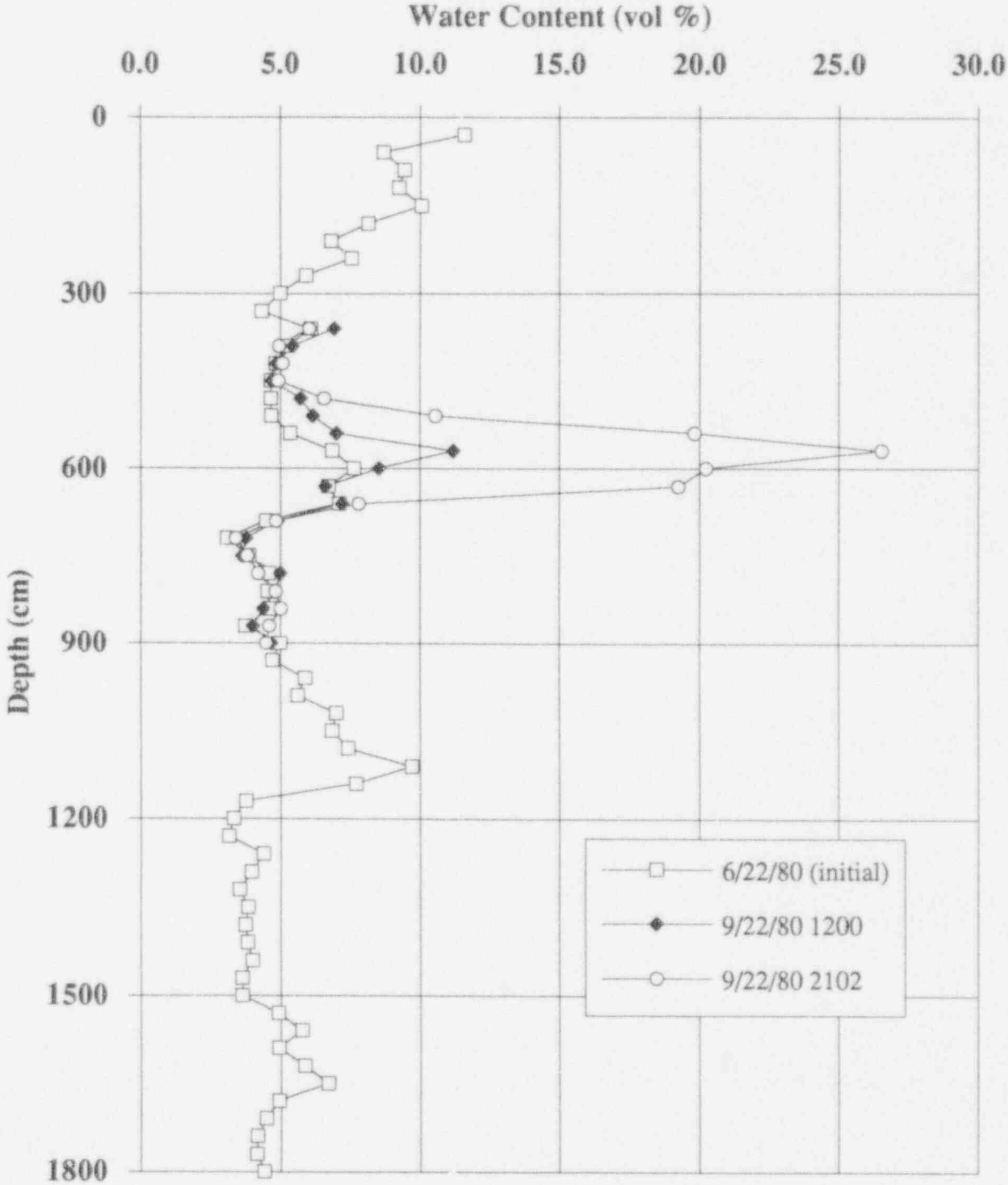


Figure 4.3 Water content changes in well A-1

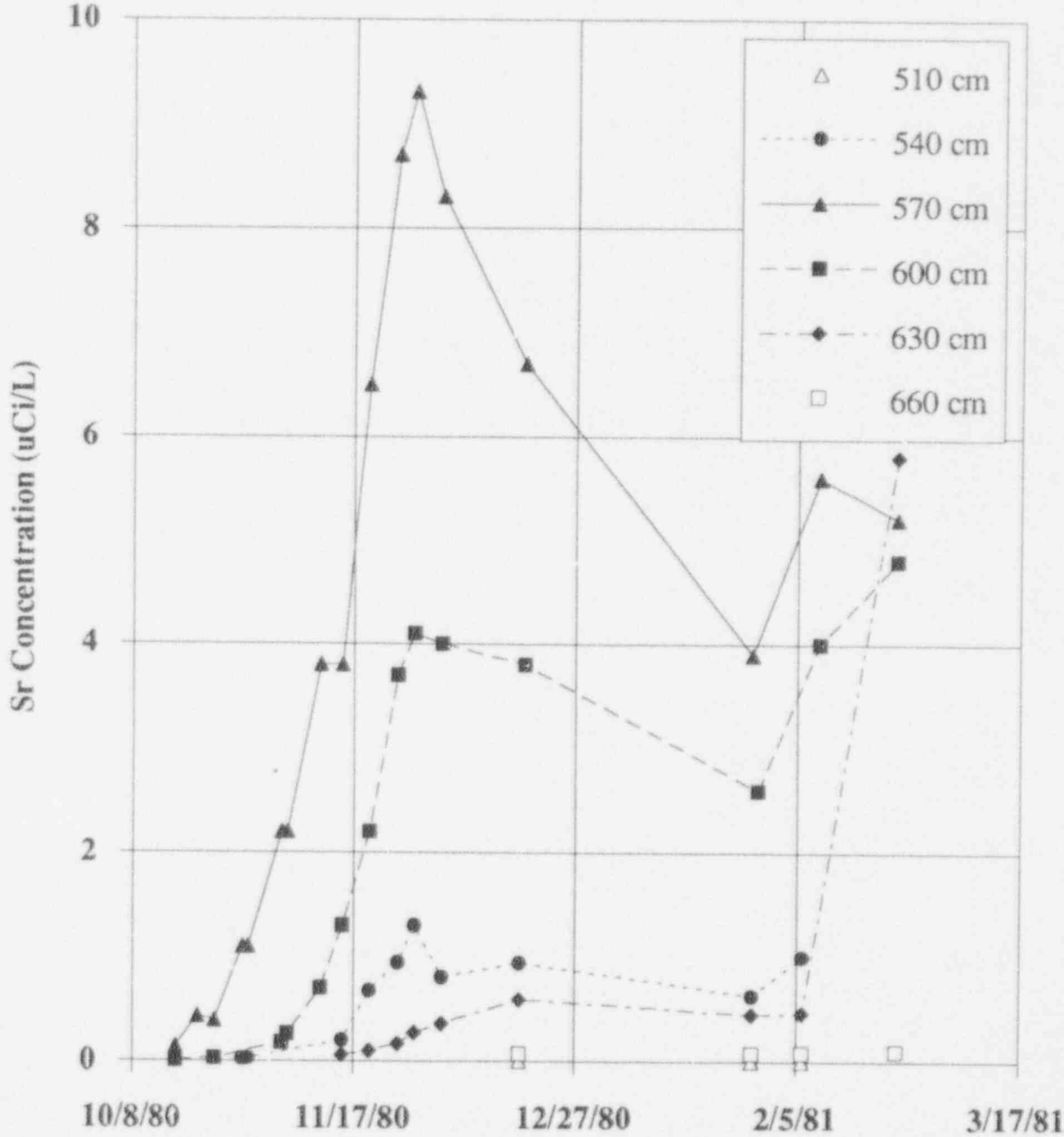


Figure 4.4 Sr-85 changes in well H-2

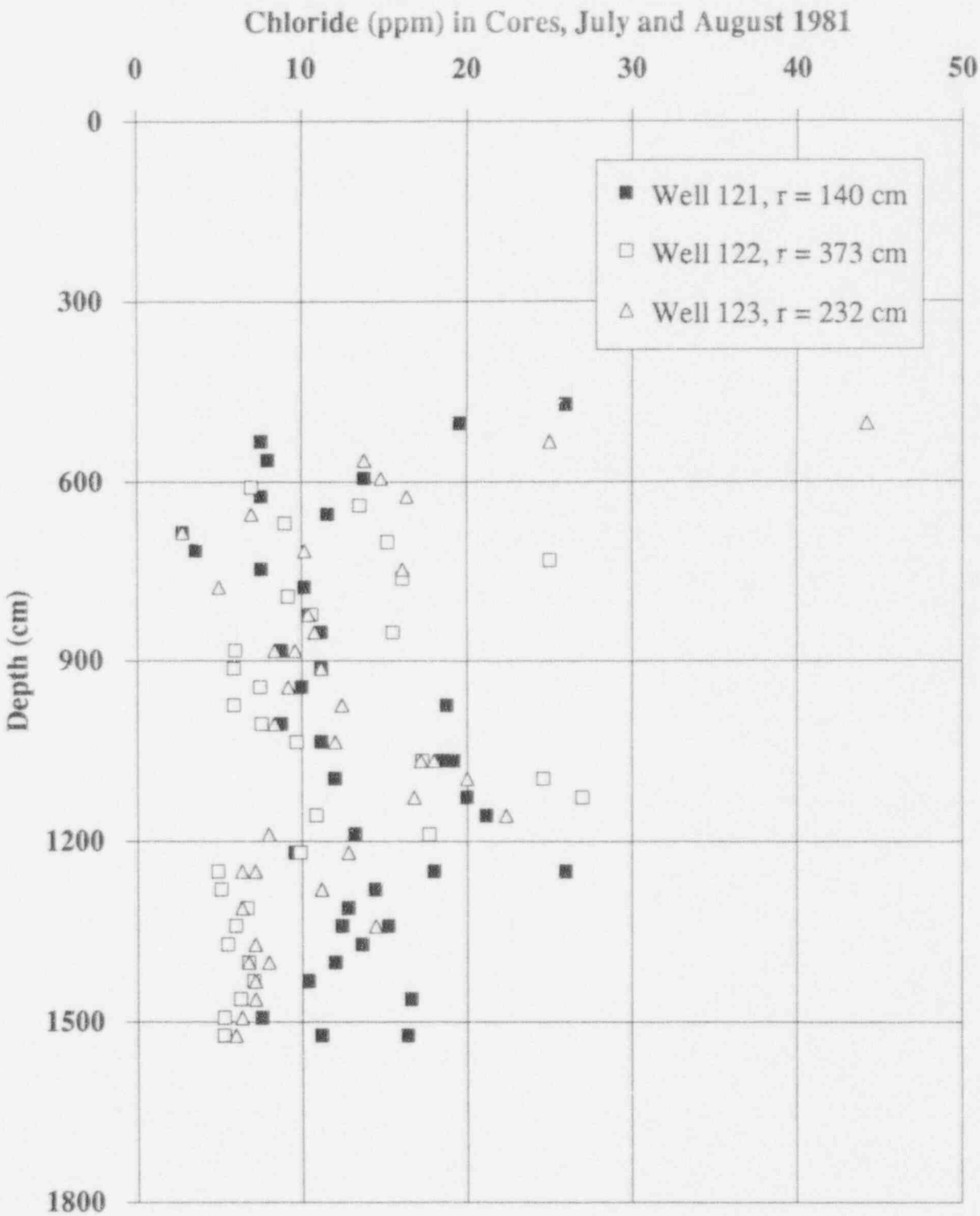


Figure 4.5 Chart chloride

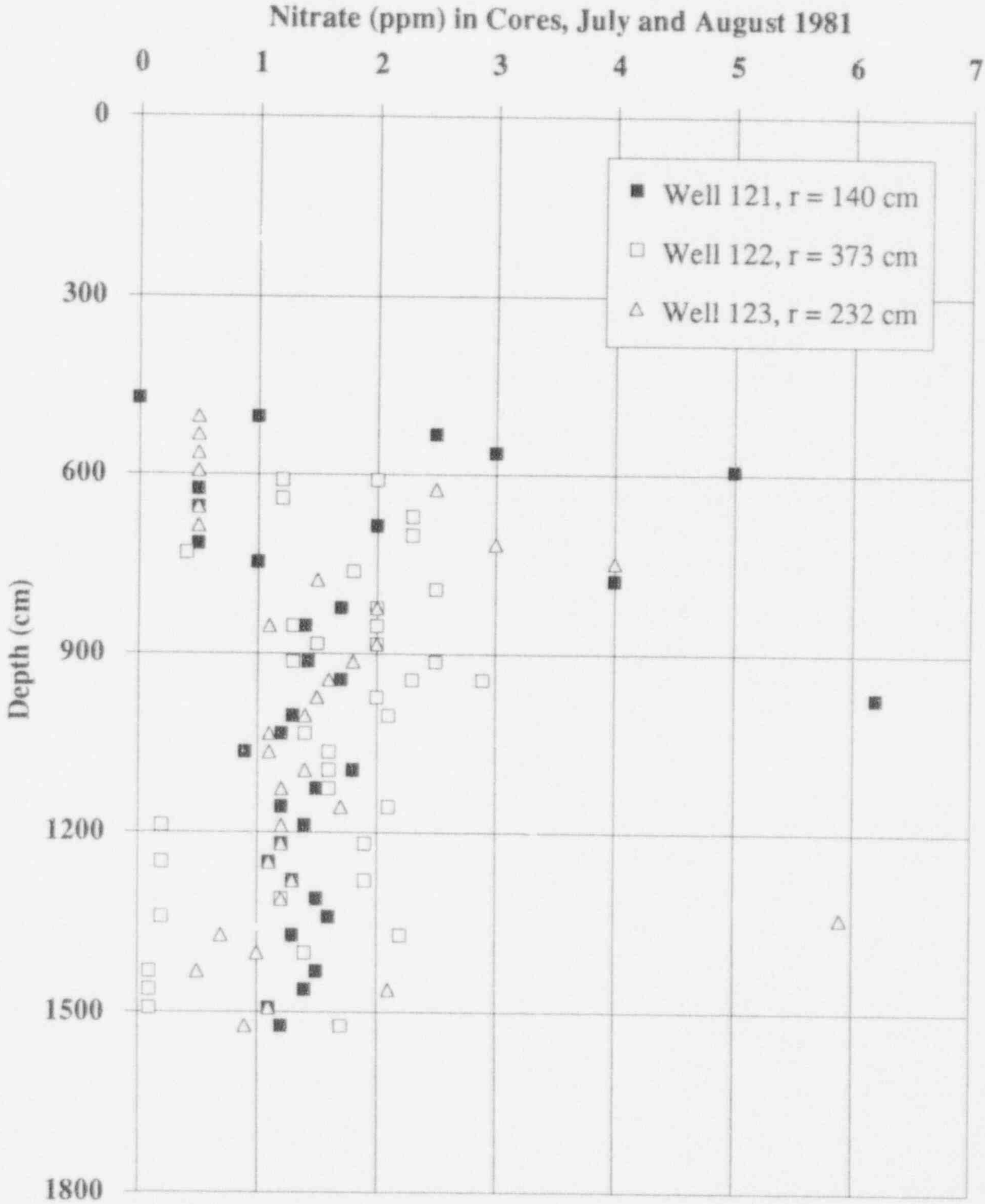


Figure 4.6 Nitrate concentrations in cores collected after the experiment

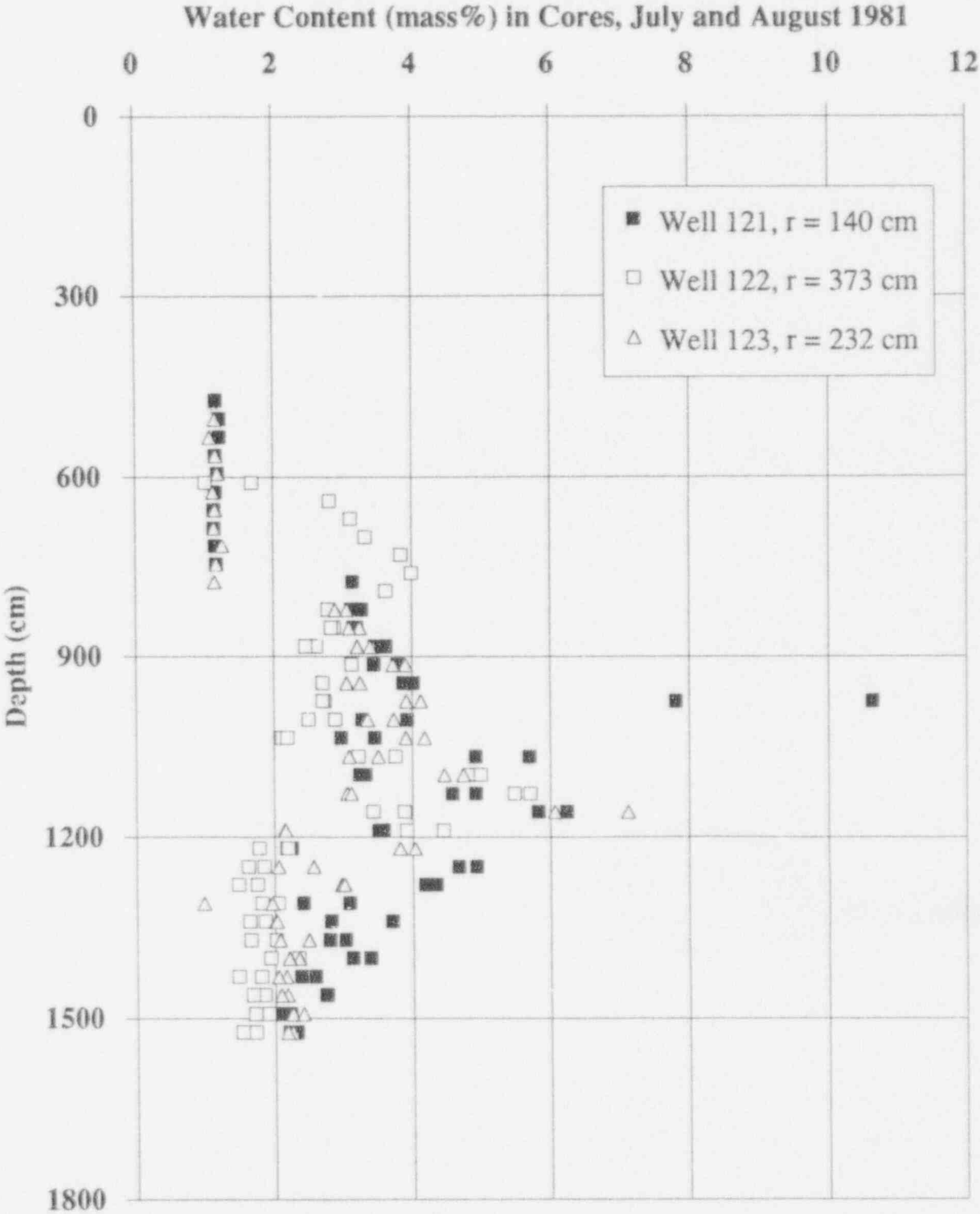


Figure 4.7 Water contents in cores collected after the experiment

5 Sediment Properties

5.1 Laboratory Measurements

During installation of the observation wells, most of the drilled sediments were deposited on the ground. From selected depths in three wells, however, the sediments were collected in plastic bags as they were blown out of the wells. One sample was collected from Well B-8, seven samples were collected from Well E-1, and eleven samples were collected from Well E-7. Sometime after the experiment, the samples were transferred to plastic jars. Each jar contained approximately 10 to 12 kg of dry sediment. About 1 kg was removed from each jar using a riffle splitter. Laboratory analyses were conducted on these 1-kg subsamples. These data were not available at the time of the report by Sisson and Lu (1984).

5.1.1 Particle Density

The density of the sediment particles was determined in triplicate for each sample by the pycnometer method (Blake and Hartge, 1986). The average density of each sample ranged from 2.65 to 2.76 g/cm^3, with an overall average of 2.69 g/cm^3.

5.1.2 Particle Size Distribution

From 350 to 900 g of each sample was dry sieved to determine the distribution of particle sizes in the sand fraction. All but three samples had sand contents greater than 90%, classifying them as sands. The three samples that had less than 90% sand were further analyzed (in duplicate) using the hydrometer method (Gee and Bauder, 1986). Two of these samples classified as loamy sand, the other as sandy loam. Figure 5.1 shows the average and range of the particle size distribution of all samples.

5.1.3 Saturated Hydraulic Conductivity

The saturated hydraulic conductivity was determined using the constant head method on all except samples 1-1417 and 1-1428, which were sufficiently fine in texture to use the falling head method (Klute and Dirksen, 1986). In all cases, samples were packed air dry in a cylinder with a diameter of 8.83 cm and height of 8.9 cm, yielding a sample volume of 545 cm^3. The method of packing was to pour 3-cm-thick lifts of sediment and lightly tamp each lift.

5.1.4 Water Retention

Water retention was determined using three methods: hanging water column on eight samples (0 to 100 cm potential range), pressure plate extraction on all samples (100 to 3000 cm potential range), and vapor adsorption on all samples (>3000 cm potential range) (Klute, 1986; Gee et al., 1992). The hanging water column tests were conducted in duplicate and the pressure plate tests in triplicate. The vapor adsorption tests were conducted on four subsamples of each sample, with each subsample at a slightly different water content. Figure 5.2 shows the average and range of water retention values at each matric potential for all sample.

5.2 Field Measurements

Saturated hydraulic conductivity was determined in the field using the slug test method (Hvorslev, 1951). Three wells were drilled for testing, one hand drilled with a tripod rig using NX casing (3 5/8-in. OD) and the other two with cable tool using 6-in. casing. The tests were conducted during July through September 1980, just before the start of the injection experiment. The test data were analyzed using Formula G (well point filter in uniform soil, variable head; yields horizontal conductivity) on p. 44 of Hvorslev (1951). Figure 5.3 shows the variation in horizontal conductivity with depth. These data were not reported by Sisson and Lu (1984).

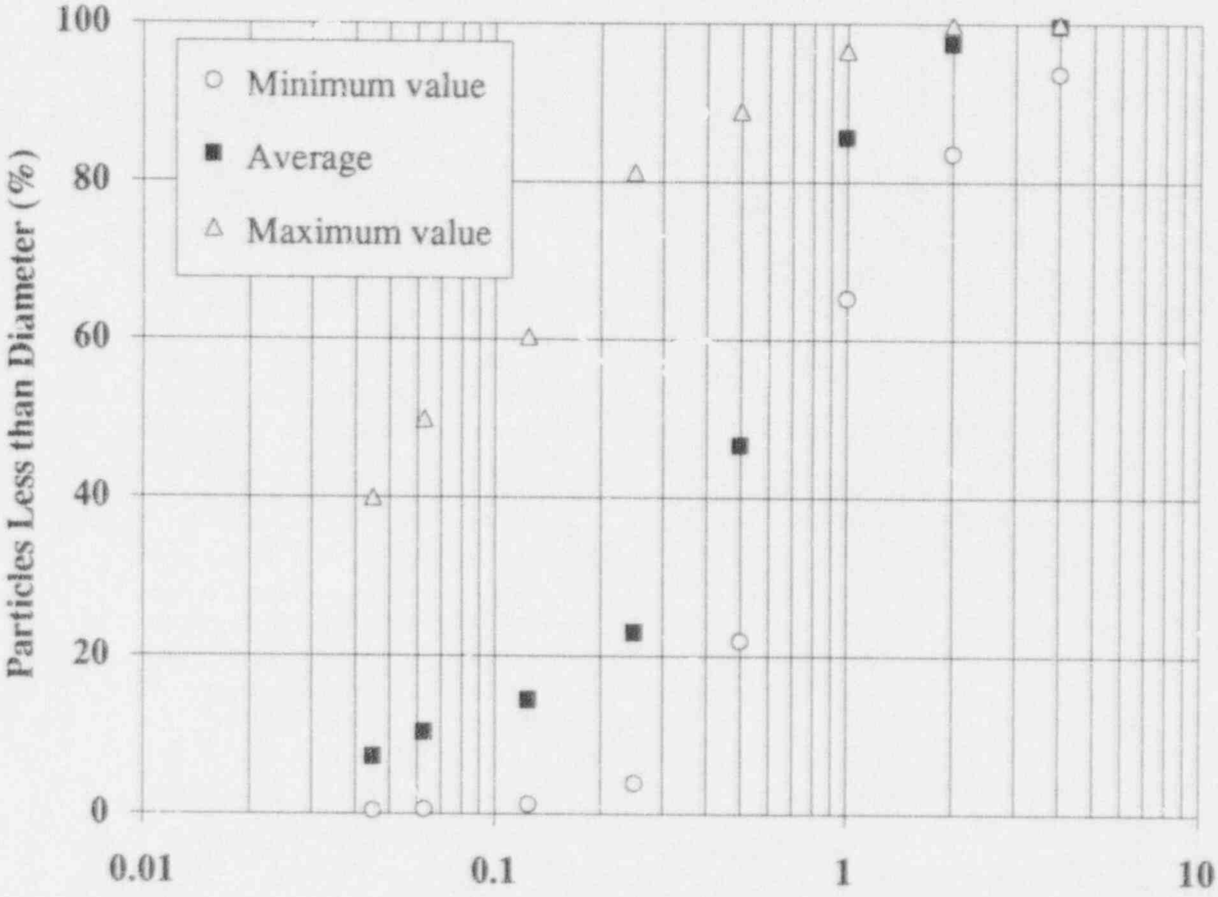


Figure 5.1 Particle size distribution of sediment samples

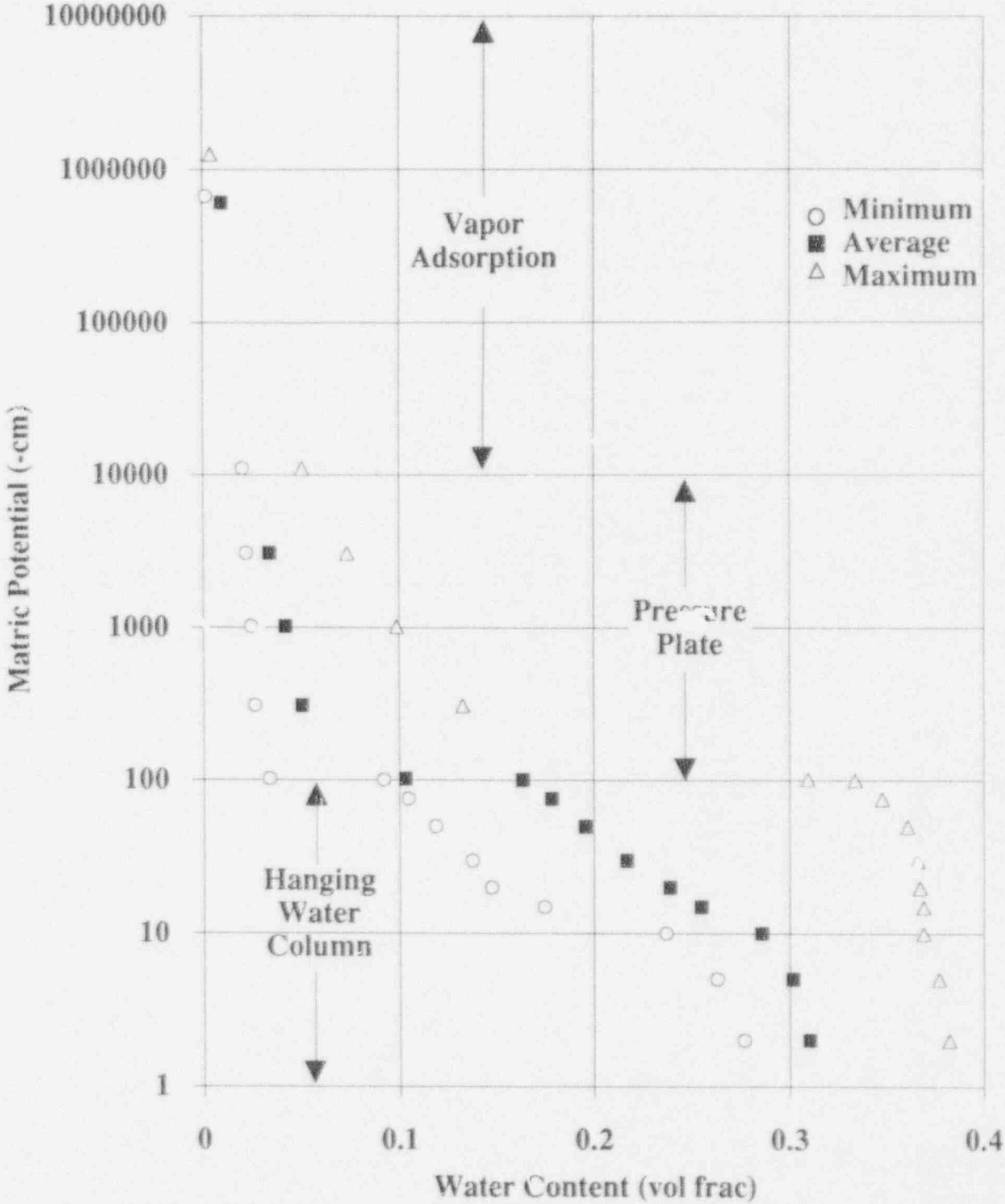


Figure 5.2 Water retention of sediment samples

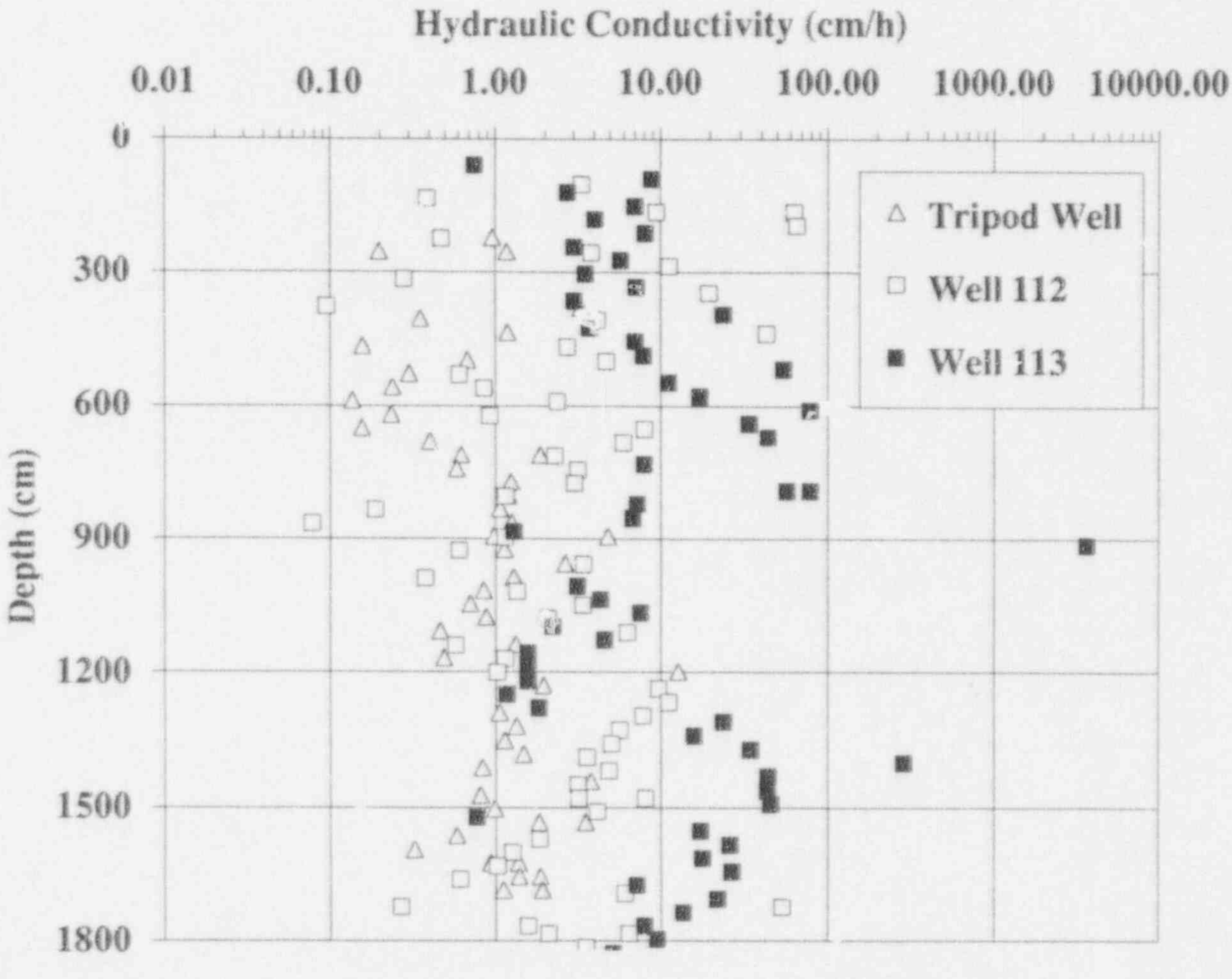


Figure 5.3 Variation in field conductivity values

6 Discussion

6.1 Simulations in Original Report

Sisson and Lu (1984) simulated the injection experiment using a finite element model. At some depths and radii, the field values were nearly symmetrically distributed above and below model forecasts, indicating good agreement. At other depths and radii, the field observations were consistently greater than the predictions, indicating a bias. According to the authors, the model bias could be reduced by simply using different soil types at the depths and radii of concern.

Sisson and Lu also discussed two-dimensional simulation results showing the horizontal spreading that occurred during injection. The horizontal wetting patterns dominated the experiment and were not anticipated fully. For example, assuming a uniform isotropic media for the simulation resulted in predictions of water moving past the 1,800-cm depth. This deep movement did not take place.

As a result of their simulations, Sisson and Lu stated that the "natural" water content (i.e., the initial water content) of the sediments appeared to be the most important single variable for predicting the actual behavior of water injected below the surface of a site.

6.2 Data Assessment

The data contained in this report were derived from the original report (Sisson and Lu, 1984) or from available summary sheets, or were recently obtained in the laboratory (i.e., soil hydraulic properties). The original field notes have never been found. Although more information might be teased out of as yet undiscovered records, we doubt that much more can be established regarding data integrity or measurement error. Certainly a benefit of the experiment was learning how to conduct the next one. The largest area for improvement is documentation: what was done, when, how, why, with what, and by whom.

An important aspect of the experiment is whether some geostatistical picture of the subsurface can be assembled. Certainly, such a picture could not be put together from the limited soil samples reported in Section 4. More promising for establishing a statistical description are the initial water contents, the natural gamma and gamma-gamma data, and the conductivities determined in situ.

Whether the experiment serves a useful purpose for testing of flow and transport models depends on the data user and the purpose of the use. Because precise quantities of water were injected and monitored in three dimensions, the experiment offers an opportunity to see how well the design allowed for the measurement of the volume of water injected. Demonstrating that such additions of water could be measured successfully with neutron probes would be important to any study of contaminant transport in the field. The next step is to verify that computer models can simulate the injection and redistribution of water. This step will likely involve calibration of the sediment hydraulic properties. Once calibrated, the model should be used to simulate the transport of the tracers. Comparisons of the results against the gamma energy and in situ core data should provide feedback on the adequacy of the sorption modeling. The site still exists and is available for field testing or a postmortem study.

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APPENDIX

List of Data Files

The data files are located on a DOS-formatted diskette that can be obtained from the senior author.

General Files

FILELIST.DAT	This listing
WELL.DAT	Information on well installation (e.g., coordinates, drilling method)
MEASDATE.DAT	Dates on which monitoring activities occurred

Concentrations of Radiological Tracers Using Gamma Detection

WELLA1CO.DAT	Concentrations of Cs and Sr in well A-1 as determined by gamma scans
WELLB1CO.DAT	same in Well B-1
WELLC1CO.DAT	same in Well C-1
WELLD1CO.DAT	same in Well D-1
WELLE1CO.DAT	same in Well E-1
WELLF1CO.DAT	same in Well F-1
WELLG1CO.DAT	same in Well G-1
WELLH1CO.DAT	same in Well H-1

Concentrations of Tracers in Soil Cores

CORECONC.DAT	Gravimetric water contents and chloride and nitrate concentrations at multiple depths in three wells in July and August 1981 (after the experiment)

Gamma Data

GAMMGAMM.DAT	Relative density scan with gamma probe conducted in July 1980, before the experiment.
NATGAMMA.DAT	Natural gamma emissions observed in July 1980, before the experiment.

Injection Data

INJECT.DAT	Injection rate data

Neutron Probe Calibration Data

NPCALIB.DAT	Calibration data in Sission and Lu (1984) used to generate their neutron probe calibration.
RAWPROBE.DAT	Neutron probe data found in field notes. Some of these data were not used in the original calibration, but most were averaged to yield the values in NPCALIB.DAT.

Neutron Probe Data

WELLA1NP.DAT	Neutron probe counts for well A-1
•	
•	Similar files for all wells A-3 through H-6
•	
WELLH8NP.DAT	Neutron probe counts for well H-8

Sediment Properties

SEDISAMP.DAT	Sample identification numbers, well numbers, and depths.
HANGWAT.DAT	Hanging water column data for eight samples.
LAB_COND.DAT	Laboratory-determined saturated hydraulic conductivity of all nineteen sediment samples.
PARTICLE.DAT	Particle density and size distribution of all nineteen sediment samples.
PRESPLAT.DAT	Pressure plate data for all nineteen sediment samples.
SLUG_K.DAT	Field saturated conductivity values determined in three wells from July to September 1980, just prior to the start of the experiment.
VAPORADS.DAT	Vapor adsorption data for all nineteen sediment samples.

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11. ABSTRACT (200 words or less)

Accurate predictions of the movement of radioactive contaminants from disposal facilities are required to evaluate effects, optimize data collection, design remediation strategies, and predict the longterm results of such strategies. A field experiment was undertaken in 1980 and 1981 to provide data to test the limits of model predictions. The purpose of this report is to provide a complete record of data generated during that field experiment for use as a model validation test case. The report combines the information in Sisson and Lu (1984) with unpublished laboratory and field data on the hydraulic properties of the sediments and core data collected at the end of the experiment. The unique features of this experiment were the documented control of the inputs, the three-dimensional nature of the experiment, the measurement of radioactive tracers in situ, and the use of multiple injections. The in situ monitoring methods were neutron moderation for water content and gamma energy analysis for tracer concentration. The data are provided on 3.5-in. diskettes. The data include observation and injection well construction details, injection solution concentrations, radioactive tracer and water content distributions in space and time, neutron probe calibration information, and sediment properties determined in both the laboratory and field.

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