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# Field Assessment of Monitoring and Water Supply Well Seals

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## ABSTRACT

Monitoring and water supply wells are sealed with low hydraulic conductivity grout placed in the annulus between the casing and the drillhole. The well seal protects groundwater from pollution by restricting fluid flow through the annulus. A defective well seal compromises public health. Field assessment of well seals, failed and intact, will improve the methods and materials used for well seal construction.

Well seal performance was evaluated using a downhole, ultrasonic device developed at the University of Wisconsin-Madison in the Department of Civil and Environmental Engineering. Sixteen monitoring and water supply wells were field tested. Factors influencing seal integrity, including type of sealant, seal placement method, and influence of geology and hydrogeology, were considered.

Results from the study demonstrate the effectiveness of the ultrasonic probe for use in well seal inspection. All wells showed seal degradation near the ground surface where desiccation cracking and frost action is the greatest. Monitoring well seals constructed with bentonite slurries performed the best overall when the water table was shallow. Bentonite slurry based seals performed poorest for wells with deep water tables (>10 m). This was especially apparent for the water wells logged in this study. Poor water well seal performance is attributed to dilution of the drilling mud, settling and infiltration into the adjacent coarse grained formation, and bridging of cuttings shoveled into the annulus.

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# INTRODUCTION

The focus of this project is ultrasonic evaluation of annular well seals in groundwater supply and monitoring wells. An open annulus is created between the well casing and the borehole wall during well construction. The annulus is sealed with grout to prohibit flow and commingling of surface water and groundwater. If the seal is ineffective, the aquifer may become contaminated. Thus, it is essential that wells be properly sealed and that the integrity of seals be examined after construction.

Well seal inspection is challenging because the seal is situated below the ground surface and behind the casing. An ultrasonic probe was developed in the Department of Civil and Environmental Engineering at the University of Wisconsin-Madison for *in situ*, down-hole evaluation of well seals. The Wisconsin probe is conceptually similar to other ultrasonic devices that have been used to log the condition of cement seals surrounding large-diameter oil well casings (Suman and Ellis, 1977) or the condition of backfill surrounding natural gas pipes buried in the ground (Sancar and Sawyer, 1986). However, unlike previous technology, the Wisconsin probe can be deployed in well strings having small diameter (51 mm minimum) and can be used to assess cement and bentonite-based grouts.

The objective of this study was to evaluate various well sealing methods by conducting a survey of monitoring and water supply wells with the down-hole ultrasonic probe. Wells were selected based on several considerations, including: (1) type of sealant (high solids-content grouts, bentonite chips, bentonite slurry/cuttings, neat cement, etc.); (2) type of formation (clay, sand, coarse sand and gravel); (3) hydrogeology (deep or high water table); (4) method of seal placement (mud circulation, tremie pumping, dropping); (5) hydrochemistry (presence of aggressive pollutants that may potentially impact seal quality); (6) age of the seal (existing or new construction); and (7) wells known to have suspected problems. The study of water supply and monitoring wells provides an interesting comparison since well sealing practice for the water wells investigated are different from those used in monitoring well installation.

Evaluation of well seals using the downhole ultrasonic logging tool provides a unique opportunity to collect information for improving well sealing techniques. To understand the complexities in constructing an intact seal, background information describing the annular well seal, sealing practices, and potential problems associated with sealing practices is provided. Examples from the literature illustrate the occurrence and seriousness of failed well seals. Methods for evaluating well seals are briefly discussed and demonstrate the need for well seal assessment technology.

## ANNULAR WELL SEAL

The proper composition and placement of annular seal materials is important to the successful performance of water supply and monitoring wells. In addition to providing protection against cross-contamination from vertical migration of polluted surface water or groundwater, the seal functions to hydraulically and chemically seal off discrete sampling zones, preserve the representativeness of water samples and hydraulic characteristics of the aquifer, and protect the casing from chemical degradation (Aller et al., 1989). A defective well seal compromises public health and well performance.

The annular seal is one of the basic components of a well, including the borehole, casing, screen, filter pack, and protective wellhead (Figure 1). The seal material, often referred to as grout or sealant, occupies the annulus between the casing and borehole wall. Well grouting is sometimes conducted in three distinct stages using three different grouts. The first stage involves placement of a high solids content sealant above the filter pack sand (e.g., 9.5 mm bentonite chips). This filter pack seal functions to prevent additional annular seal material from seeping into the filter pack sand and clogging the well screen. The second stage involves filling the majority of the annulus from the filter pack seal to near the ground surface. This material can be a continuation of the filter pack sealant or a new annular seal material (e.g., a bentonite slurry pumped on top of bentonite pellets). The final borehole sealing stage involves constructing the surface seal. The surface seal functions to keep surface water from entering the annulus. Some surface seals are constructed with cement such as for flush mount well heads that must resist wear from vehicle traffic.

## SEALING PRACTICES

Well seals are placed in the annulus using a variety of techniques. The common methods include pouring the material down the annulus (free-fall), pouring the material down a tremie pipe, mixing a slurry and pumping it down a tremie pipe, or by pumping the grout down through the center of the casing and forcing it to return to the surface while displacing drilling fluid and cuttings out the annulus. In addition to having the necessary low hydraulic conductivity, a good seal material will also have characteristics that make it easy to place in the annulus.

Potential seal defects are illustrated in Figure 2. Gravity placement methods rely on the ability of the material to settle uniformly at depth after traveling through the annulus. Bridging of sealant is a common occurrence. Collapsing of the formation also contributes to bridging or incomplete seal placement by blocking the pathway for the sealant. The collapsed formation may also act as a high hydraulic conductivity window within the seal (Nielsen and Schalla, 1991).

Finally, the type of seal material has an important bearing on the success of the well sealing job. The hydraulic conductivity of the sealant should ideally be less than the hydraulic conductivity of the adjacent formation. Monitoring well construction requires the use of such sealants. However, in Wisconsin, sealing practices for water wells are not as stringent. The seal material in water wells consists of drilling mud and cuttings. Study of this type of seal indicates that even when high mud weight slurries are used (e.g., 1.32 $g/cm^3$), the annulus may not be adequately sealed (Edil et al., 1992).

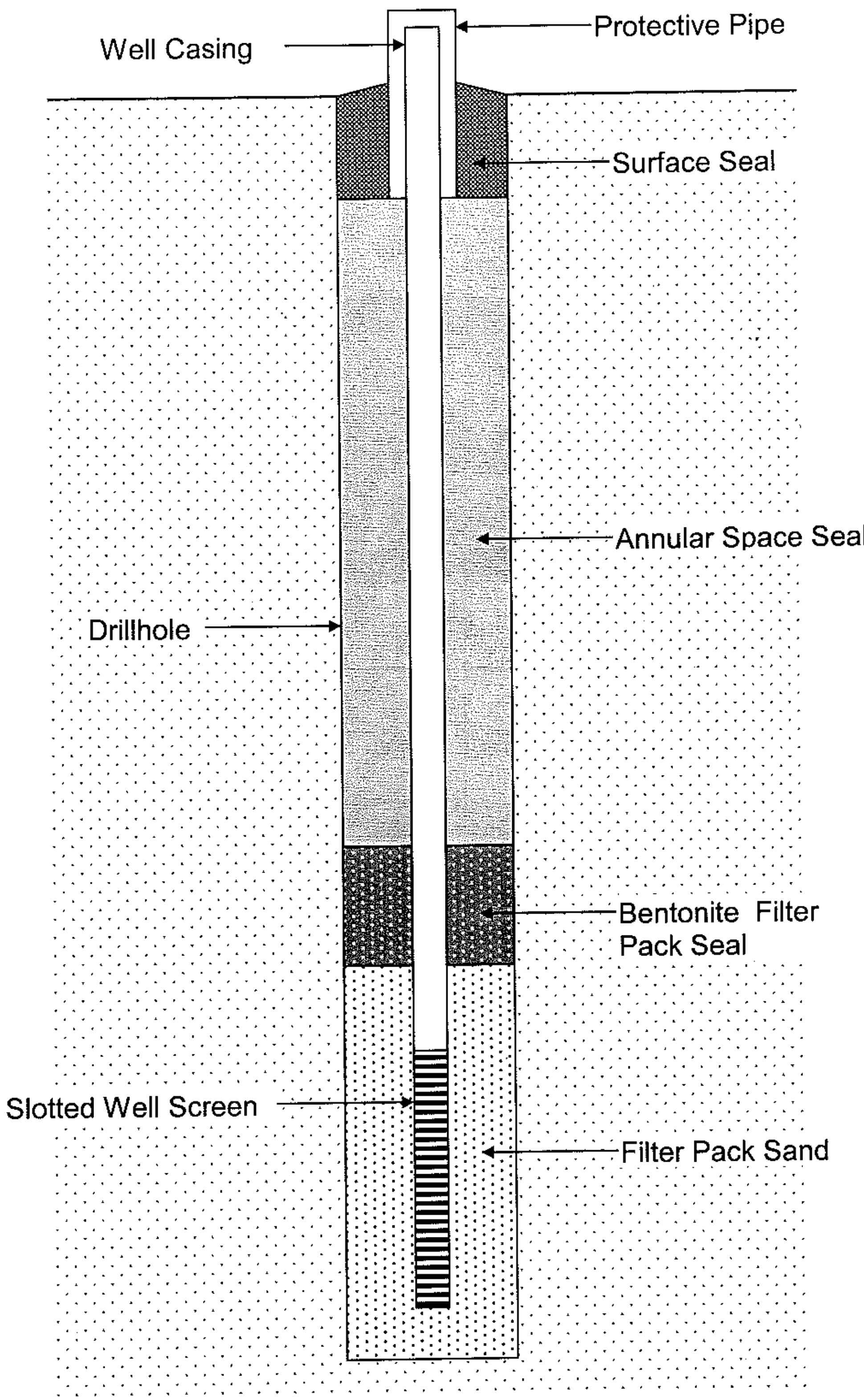


Figure 1. Components of basic well contruction.

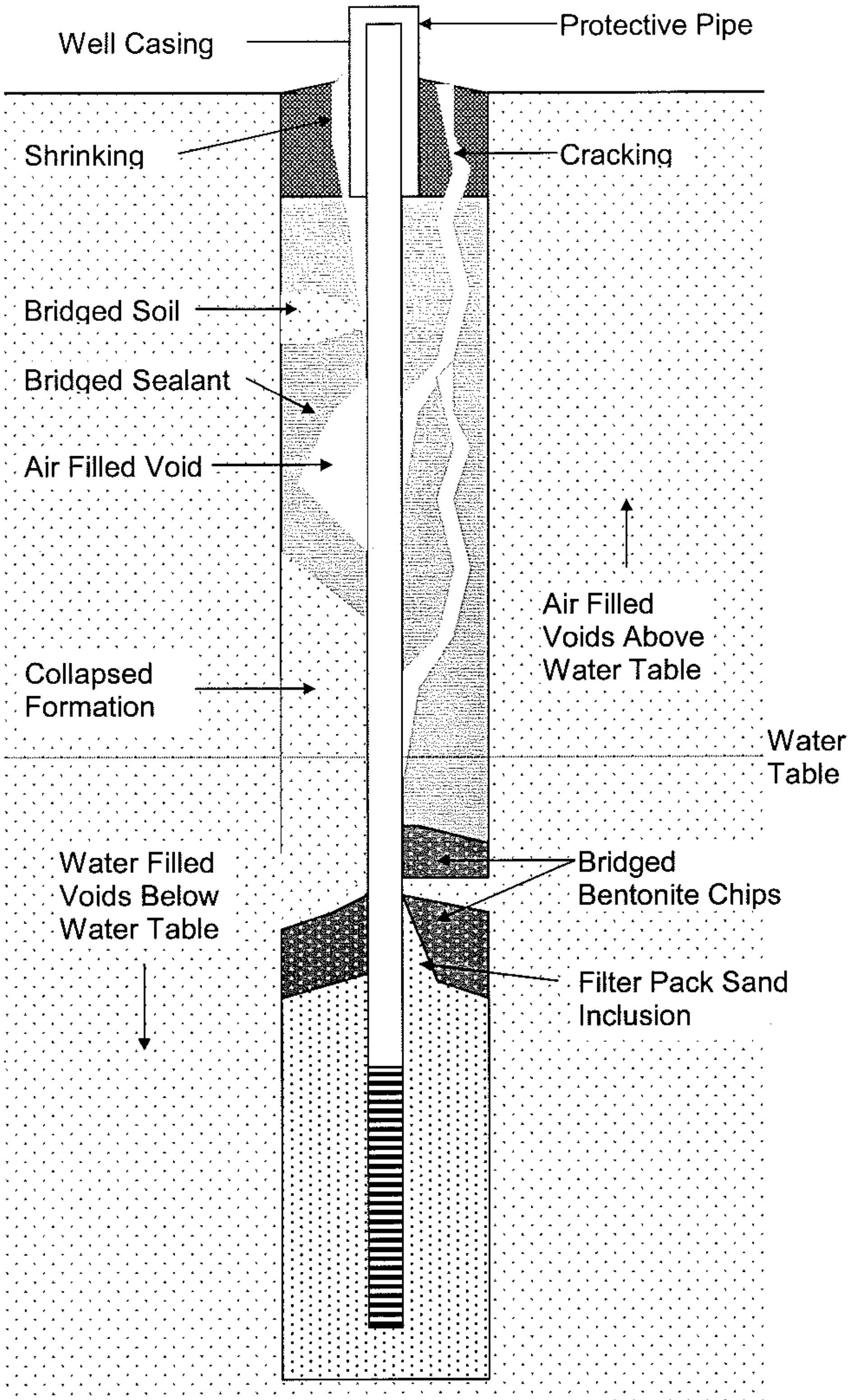


Figure 2. Potential well seal defects.

## WELL SEAL FAILURE

There are numerous articles citing evidence of failed well seals or concern about seal integrity. Case histories of cross contamination through leaky annular seals are presented by Maguire (1988), Meiri (1989), Landry (1992), and Calhoun (1988). Defective well seals are investigated as a possible explanation for groundwater sample anomalies in studies by Keely and Boateng (1987), Martin and Lee (1989), and Lesage et al. (1991). In one study by Jacobs Engineering Group (1993), the integrity of well seals had come under such scrutiny that at least 50 of 168 monitoring wells in a hazardous waste study are being analyzed for seal defects and potential replacement. McQueen (1990) reported more than 50% of the regulated sites in northern Louisiana have wells with grout integrity problems. An investigation of the long term durability of monitoring wells at the Love Canal site in New York revealed that 41 of the 327 monitoring wells had concrete collars or annuli that were no longer intact (Welling and Foster, 1994). Other research efforts involved pilot well seal tests or well seal assessment programs to minimize potential well seal problems in future wells where the risk of cross-contamination is high (McNeal and Mill, 1986; Smith et al., 1991). Analytical models (Avci, 1992, 1994) and numerical models (Lacombe et al., 1995; Pekarun, 1994) of contaminant transport through leaky boreholes illustrate that failed well seals may contribute significantly to inter-aquifer contaminant spreading.

Well seals fail for a variety of reasons. A failed seal may allow fluid to flow through channels developed in the seal, through voids in the seal, or through the seal material itself. Channels may develop through the seal if the material is improperly formulated or installed, leading to cracking, shrinking, or deterioration (Nielsen and Schalla, 1991). Leakage may occur between the casing and the grout material because of temperature changes during grout curing, swelling and shrinking of the grout, or poor bonding between the grout and the casing (Kurt and Johnson, 1982). Frost heave can severely crack and damage cement annular seals (Gates, 1989). Voids may develop in the seal material due to bridging of the seal material during placement or bridging of soil that sloughs off the borehole walls, blocking placement of the grout. Fluid flow may occur through the seal material if it does not have an adequate, stable hydraulic conductivity (Edil et al., 1992; Lutenegger and DeGroot, 1994; Riewe, 1996).

There are numerous guidelines for the selection and emplacement of well seal material that are designed to minimize potential seal defect problems. Acceptable or approved methods of well seal installation are described in testing procedures like ASTM 5092 (American Society for Testing and Materials, 1995a) or state codes like Wisconsin NR-141 (monitoring wells) and NR-812 (water supply wells) (Wisconsin Department of Natural Resources, 1995, 1996) or the Michigan Water Well and Pump Installation Construction Code (Michigan Department of Public Health, 1994). Research efforts have been directed towards well construction procedures, seal placement techniques, and seal materials for improving annular seal reliability. In order to assess whether these methods and materials result in functional well seals, the well seal must be investigated and evaluated in the field.

## SEAL INTEGRITY AND PERFORMANCE EVALUATION

Investigation of failed and intact well seals can lead to improved seal placement and formulation methods. Unfortunately, direct inspection of the seal is only possible at the ground surface around the well. By digging away the soil around the well, more of the seal can be exposed for visual inspection. Digging can disturb the seal and make observations difficult. Such direct observations are also limited in depth. For deeper exploration, down-hole seal evaluation methods have to be used.

Well seal evaluation is not a new concept. Several methods exist for testing well seal integrity. They include hydraulic conductivity testing, well hydraulics, and traditional geophysical well logging. Yesiller (1995) described the advantages and disadvantages of the various *in-situ* seal evaluation methods (Table 1). Density logging has been successfully used to distinguish between seal materials and detect voids in monitoring and water wells (Yearsley et al., 1991; Hall, 1993). While the method shows significant promise, it remains costly. The limitations of these methods indicate the need for a non-destructive, ultrasonic testing method that it is sensitive enough to evaluate a wide range of casings and sealants and allows for repetitive testing to monitor the performance of the seal with time.

The value of a non-destructive, well seal evaluation tool includes, but is not limited to, assessment of well construction techniques, well seal emplacement techniques, well seal materials, casing-seal adhesion, and the role of soil/rock in seal effectiveness. By pinpointing failed seals in the field, these issues can be addressed. The ultrasonic, non-destructive, well seal evaluation tool developed at the Department of Civil and Environmental Engineering, University of Wisconsin-Madison provides a means to assess water supply and groundwater monitoring well seal problems.

Table 1. Advantages and disadvantages of *in situ* seal evaluation methods (modified from Yesiller, 1995).

| Method | Advantages | Disadvantages |
|---|---|---|
| Level Monitoring (water level inside casing monitored) | • Simple<br>• Can be conducted repeatedly after seal placement | • Crude<br>• Location of defects cannot be identified |
| Pressure Testing (Casing pressurized against seal) | • Can be conducted repeatedly after seal placement | • Only cement seals in rock formations can be tested<br>• Location of defects cannot be identified |
| Cement Logging (Condition of seal evaluated from inside a casing by sending and receiving sonic waves) | • Both casing-seal and seal-formation bonds can be evaluated<br>• Exact location of defects can be identified.<br>• Can be conducted repeatedly after seal placement | • High cost<br>• Services provided by a limited number of companies using specialty equipment<br>• Only cement seals around steel casings are tested |
| Temperature Logging (Curing temperature of cement monitored to determine amount of seal | • Simple | • Only cement seals can be tested<br>• Must be conducted within 12 to 24 hours after seal placement<br>• Location of defects cannot be identified |
| Radioactive Logging (Radio-active tracer mixed into seal prior to placement monitored) | • Location of defects can be identified<br>• Can be conducted repeatedly after seal placement | • High cost<br>• Special procedures required for handling of radioactive material |
| Density Logging (Backscattered gamma rays roughly proportional to bulk density) | • Location of defects can be identified<br>• Can discriminate between water and bentonite seals<br>• Both casing-seal and seal-<br>• formation bonds can be evaluated | • High cost<br>• Services provided by a limited number of companies using specialty equipment |

## MATERIALS AND METHODS

Ultrasonic inspection is used extensively for nondestructive testing to detect material or structural flaws (e.g., cracks, inclusions, weld skips) and to determine material properties (e.g., density, thickness) (Cartz, 1995). The well seal assessment tool utilizes ultrasonic waves to inspect the condition of the contact between the casing and annular sealant. Defects in the seal are indicated by regions of poor casing-seal contact. The ultrasonic well seal evaluation method detailed in Yesiller (1994) and summarized as follows.

### EQUIPMENT AND DATA ACQUISITION

The tool consists of a 13-mm diameter pulse-echo transducer that transmits and receives ultrasonic energy via an active piezoelectric element (Panametrics, 1995). The transducer is housed in a plastic cylindrical casing 82 mm high and 49 mm in diameter. The plastic housing is lowered into the well on a series of rigid, 1.8-m long aluminum rods. The tool can be rotated horizontally inside the casing to acquire data at different azimuths. A back piston, activated by pressurized air controlled at the ground surface, seats the housing against the interior casing wall to stabilize the tool during measurements and to maintain a fixed distance between the transducer and casing (Figure 3). The transducer is triggered by a pulser-receiver, which is connected to a waveform analyzer for digitization of data. Reflections generated as the waves pass into the casing and seal are analyzed to investigate the integrity of the seal (Yesiller, 1997).

### DATA ACQUISITION AND ANALYSIS

Ultrasonic well seal evaluation is based on the analysis of the reflected wave energy from the casing-seal interface. Reflections occur at interfaces between materials with different acoustic properties. The amount of energy reflected from the casing-seal interface is used to characterize the material in the annulus.

The reflected wave energy (ENG) is determined by calculating the area under the amplitude-time plot over the interval encompassing the casing-seal reflections (Yesiller, 1994). A seal that is in full contact with the casing is an intact seal, whereas defects consisting of water or air around the casing correspond to a defective seal. A low value of ENG is indicative of an intact seal, whereas a high value for ENG indicates a defective seal (Yesiller, 1997).

The measured ultrasonic response is compared to air and water reference ENG values. The reference values represent the average ultrasonic response when air or water is backing the casing. Defective seals will consist of air (typically above the water table) or water (typically below the water table), while an intact seal should be in good contact with the casing and have an ENG less than the water reference line, whether it is situated above or below the water table. These ENG values are used to quantitatively discriminate between defective and intact seals (Yesiller, 1997). The measured profile of ENG is compared statistically to the profile expected

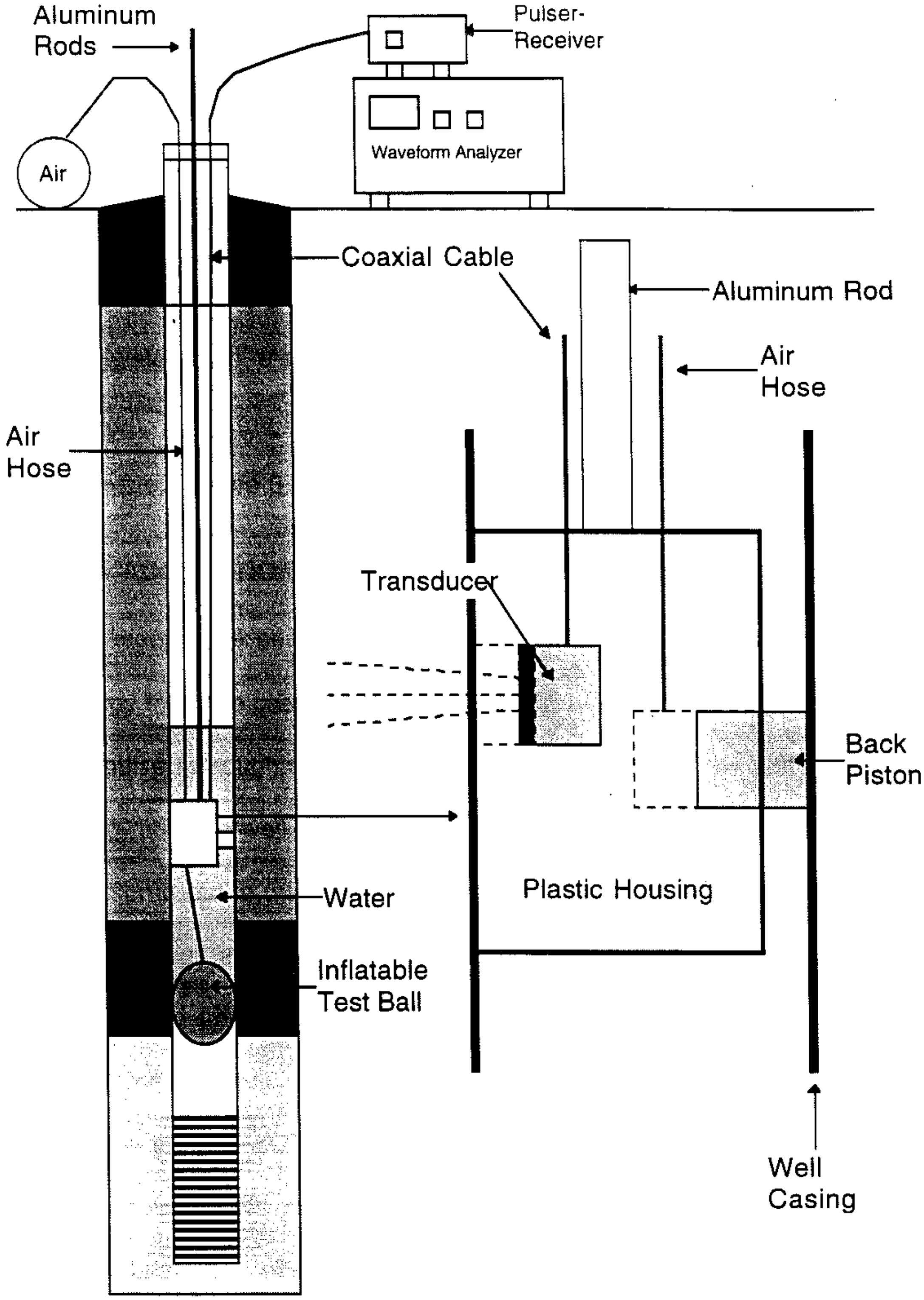


Figure 3. Well seal assessment tool equipment schematic.

for a defective seal using a t-statistic (Yesiller, 1994). Tables including the t-statistic analysis are in Klima (1996).

**WELLS TESTED**

Sixteen wells from nine different sites were tested with the ultrasonic probe. Table 2. summarizes key well construction components, including casing, seal material, and seal placement method. A qualitative indication of the number of anomalies detected in a particular well is also provided.

All of the sites are located in Wisconsin. Site names and well numbers were kept anonymous for this project. Results for well A-1 (test well) and wells B-1 and E-1 (two shallow water table wells) are in Klima (1996).

Table 2. Field test well summary.

| Test Site | Well Number | Casing and Interior Diameter | Primary Seal Material | Seal Placement Method | Anomalies |
|---|---|---|---|---|---|
| A | A-1 Test Well | Steel Sch 40 50 mm (2.0 inch) | Bentonite, Neat-cement | Gravity | Test Well-Anomalies Detected |
| B | B-1 Monitoring Well | PVC Sch 40 62 mm (2.45 inch) | Granular Bentonite | Gravity | Not conclusive |
| | B-2 Monitoring Well | PVC Sch 80? 58 mm (2.3 inch) | Bentonite Slurry 84.3 g/cm$^3$ ( 1.21 lb/gal) | Tremie Pumped | Few |
| | B-3 Monitoring Well | PVC Sch 40 51 mm (2 inch) | Cement-Bentonite Grout | Unknown (prb. Tremie Pumped) | Moderate |
| C | C-1 Monitoring Well | PVC Sch 40 52 mm (2.05 inch) | Bentonite-sand slurry | Tremie Pumped | Moderate |
| | C-2 Monitoring Well | PVC Sch 40 52 mm (2.05 inch) | Granular Bentonite | Gravity | None |
| D | D-1 Monitoring Well | PVC Sch 40 51 mm (2.01 inch) | Cement-Bentonite (5%) Grout | Tremie Pumped | Moderate |
| E | E-1 Monitoring Well | PVC Sch 40 62 mm (2.44 inch) | Granular Bentonite | Gravity | Not Conclusive |
| | E-2 Monitoring Well | PVC Sch 40 62 mm (2.44 inch) | Bentonite Slurry 82.7 g/cm$^3$ (1.19 lb/gal) | Tremie Pumped | Few |
| | E-3 Monitoring Well | PVC Sch 40 62 mm (2.44 inch) | Bentonite Slurry 82.7 g/cm$^3$ (1.19 lb/gal) | Tremie Pumped | None |
| F | F-1 Monitoring Well | PVC Sch 40 52 mm (2.04 inch) | 9.5 mm Bentonite Chips | Tremie Dropped | Few |
| | F-2 Monitoring Well | PVC Sch 40 52 mm (2.04 inch) | Bentonite Slurry 83.5 g/cm$^3$ (1.20 lb/gal) | Tremie Pumped | Few |
| | F-3 Monitoring Well | PVC Sch 40 52 mm (2.04 inch) | Bentonite Slurry 83.5 g/cm$^3$ (1.20 lb/gal) | Tremie Pumped | Few |
| G | G-1 Monitoring Well | PVC Sch 40 51 mm (2 inch) | Bentonite Slurry | Tremie Pumped | Numerous |
| H | H-1 Water Well | PVC Sch 40 127 mm (5 inch) | Drilling Mud and Cuttings | Pumped and Gravity | Numerous |
| I | I-1 Water Well | PVC Sch40 127 mm (5 in) | Drilling Mud and Cuttings | Pumped and Gravity | Numerous |

## WATER WELL INVESTIGATION

The ultrasonic well seal assessment tool was used to evaluate annular seal integrity in water supply wells. Factors affecting well seal performance include type of sealant, method of seal placement, hydrogeology, and type of formation, were investigated. The site location and well names were kept anonymous for this study.

Water well installation is generally guided by less stringent regulations than monitoring well installation, particularly in annular seal emplacement. Private well owners depend on the water well construction to protect them from contamination at the source of their clean water supply. In Wisconsin, water well construction guidelines are provided in NR-812 (Wisconsin Department of Natural Resources, 1996). The code specifies that if neat-cement or concrete grout are not required, the annulus can be sealed with sodium bentonite drilling mud slurry and cuttings if the mud weight is greater than 1.32 g/cm$^3$ (11 lb/gal). The mud-based seal is known to be susceptible to settlement (Riewe, 1996) and may not produce an adequately low hydraulic conductivity (Edil et al., 1992). A failed seal may lead to direct contamination of the drinking water supply. The ultrasonic well seal assessment tool was used to evaluate the integrity of mud slurry annular seals in two water wells.

## WELL CONSTRUCTION AND COMPLETION METHOD

The water supply wells tested during this study were constructed with 127-mm (5-inch) Sch. 40 PVC casing. The wells were drilled with a mud rotary system. In a mud rotary system, drilling mud is circulated through the well to enhance drill bit performance, carry soil and rock cuttings to the surface, and provide hydrostatic head to maintain an open borehole. The drilling mud consists of 200-mesh powdered bentonite and water. It is mixed with a Venturi hopper mud mixer into a portable mud pit to achieve a mud weight of about 1.08 g/cm$^3$ (9 lb/gal) at the surface. It is pumped from the mud pit by a mud pump into and through the hollow drill stem to the bottom of the drillhole. Fluid in the annulus is displaced by the drilling mud that is pumped through a tri-cone bit (Figure 4). The mud that returns to the surface is recirculated from the mud pit into the well until drilling operations are completed.

The type of soil and rock encountered while drilling is determined by the cuttings that are transported to the surface in the drilling mud. The cuttings are examined by washing the mud returns in a sieve. The sample depth is estimated from the depth of the drill bit and the time required to circulate mud to the surface. The cuttings are described and recorded by a member of the drilling crew. (The geologic information is plotted to the left of the ultrasonic profiles in the figures showing the ultrasonic response of the wells (Figures 5, 7-18).

At the completion of drilling the drill stem is removed, leaving the drill filled with drilling mud and cuttings. The well screen is attached to the end of the casing. Both wells used in this study had 1.2-m (4-foot ) long stainless steel, wound-wire well screens. The casing is lowered into the 229-mm (9-inch) diameter mud-filled hole as each segment is solvent-welded

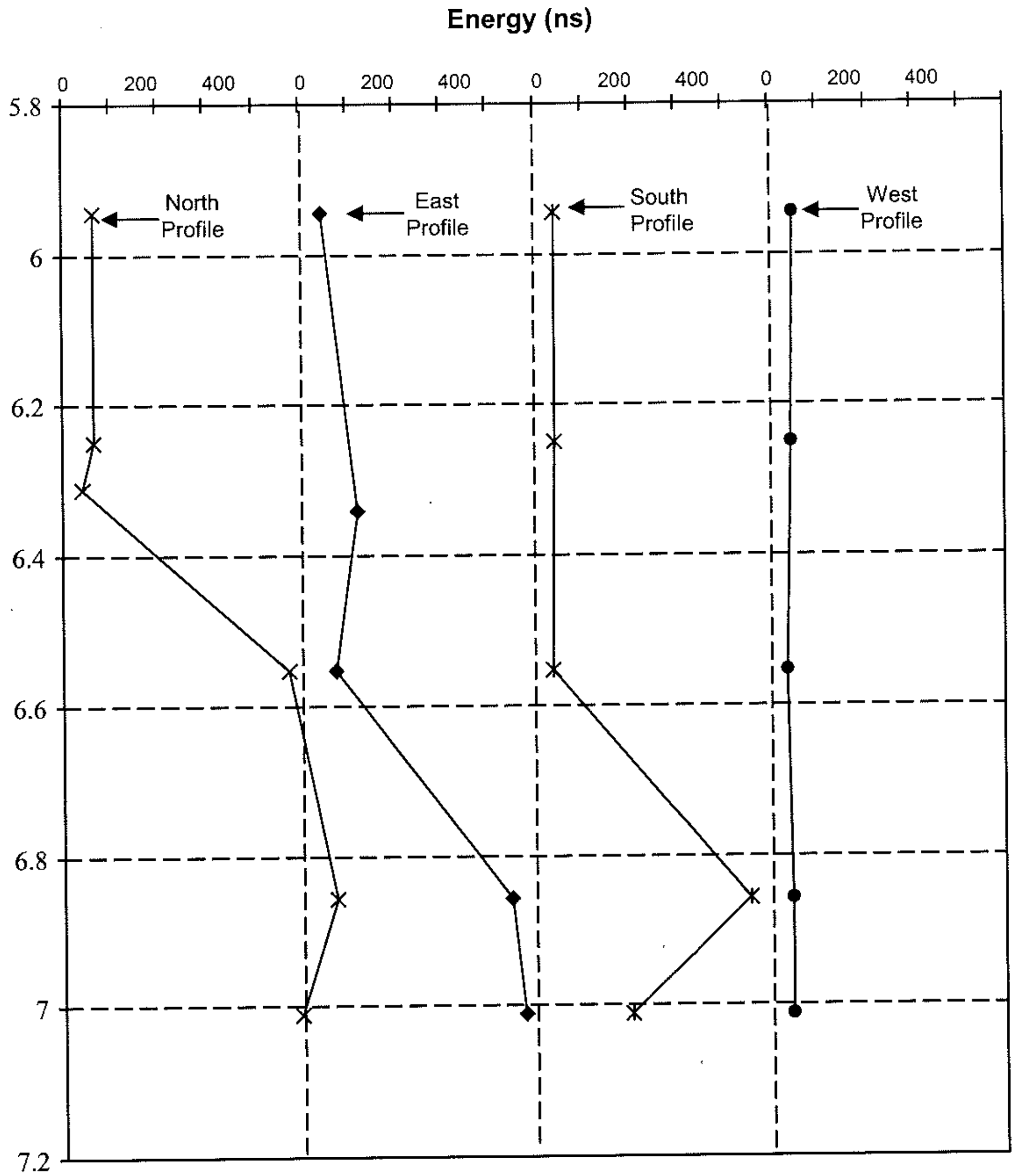


Figure 6. Three-dimensional inspection of seal defect.

had an energy response between 85 and 150 ns (average 131 ns). These readings were much lower than expected for the air backing. The mud-covered casing is apparently dampening the ultrasonic energy response. Fortunately, the measured intact well seal segments had a much lower ultrasonic response of about 40 ns, providing a clear distinction.

## SITE I, TWIN LAKES, WISCONSIN

Site I is located in southeastern Wisconsin in the town of Twin Lakes. Water supply well I-1 was drilled to a total depth of 60.7 m (190 feet). The well was completed and developed approximately 24 hours prior to the ultrasonic evaluation. The transducer was oriented along the east side of the casing. The ultrasonic response for the well is shown in Figure 7. The average ENG for the air reference line was 830 ns. The water response was determined in the laboratory to be 120 ns.

Two relatively continuous air-filled defects were detected in the annulus. One large void is situated from the surface to about 2.5 m (8 feet) depth. The upper portion of the void, a large hole extending about 1.2 m (4 feet) deep, was visible at the surface. A soil bridge partially filled the annulus at 1.2 m (4 feet), but a small hole in the bridge made it possible to see annular material was missing along a portion of the well at greater depth than 1.2 m (4 feet). The low ENG at about 1.3 m (4 feet) could be due to the small soil bridge contacting the well casing. From about 1.4 to 2.5 m (4.6 to 8 feet), a large air-filled void is present in the annulus.

The second large defect is from approximately 6.6 to 8.8 m (22 to 29 feet) (Figure 7). The ENG is greater than the air reference line, indicating air backing. Since the defect is situated above the water table, the void is expected to be filled with air. The defect is probably caused by the bridging that occurs when cuttings are shoveled into the annulus. The base of the air void correlates well with the top of the sandy soil layer. The ENG at the top of the sand layer [8.8 to 9.7 m (29 to 32 feet)] is slightly higher than the water reference line. The response could be due to water-filled sand that collapsed against the casing. Since the water table is 25.9 m (85 feet) below the ground surface, the water in the sand would have to be perched or slowly draining. Drilling fluids from the previous day and rain from the previous evening may have been sufficient to temporarily saturate the sand.

There are several smaller ENG spikes that are greater than the water reference line from 3.7 to 6.4 m (12 to 21 feet) indicating that seal contact is generally poor along this segment of casing. Again, bridging of the shoveled cuttings is suspected as the primary cause for the poor seal.

## SUMMARY OF FINDINGS – WATER SUPPLY WELLS

The following is a list of key findings from the water well investigation:

- Diluted drilling fluid settles down the annulus and into coarse-grained formations leaving an open annulus at the surface.

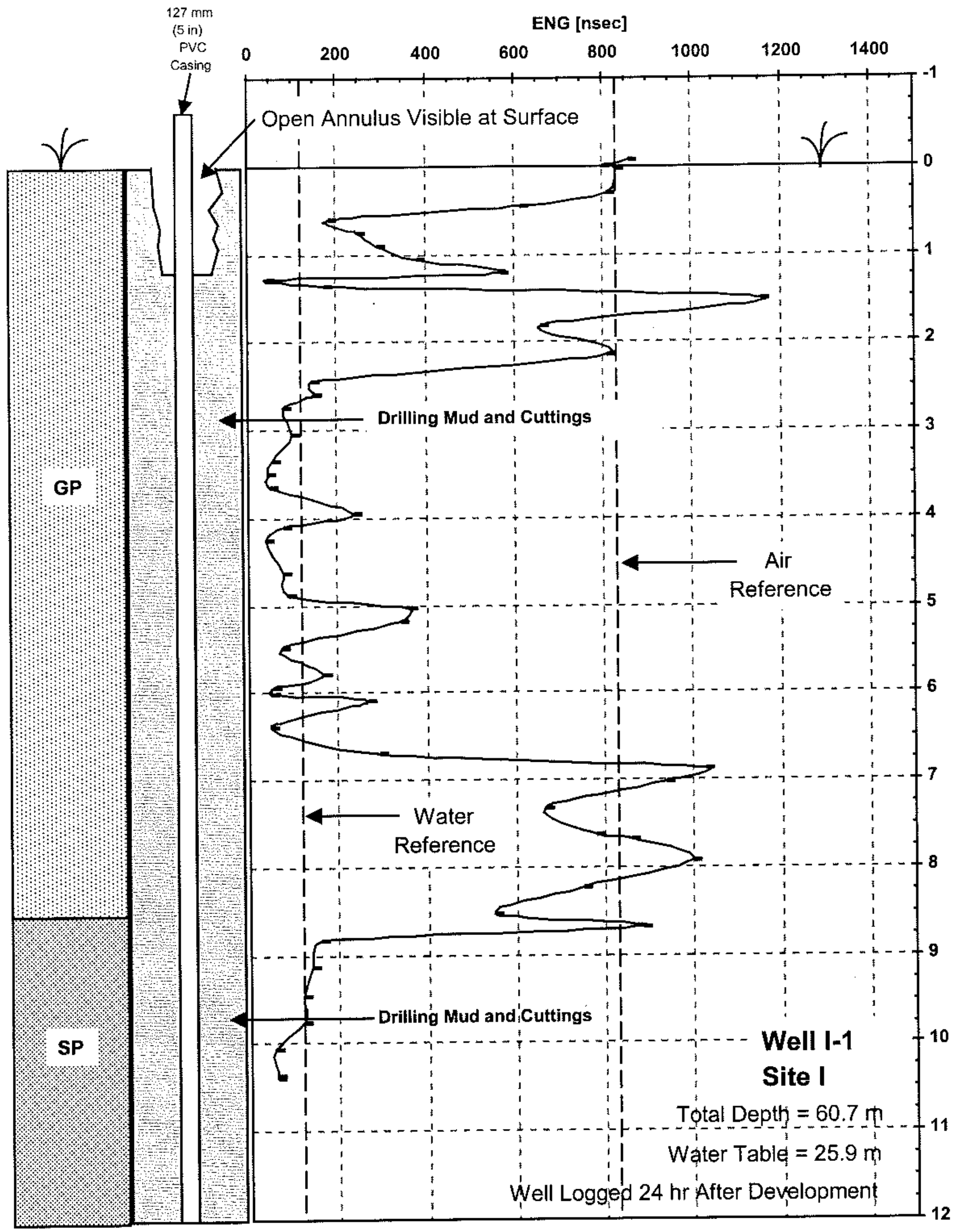


Figure 7. Ultrasonic response of water supply well I-1, Site I.

- Seals appear to perform more pooly in coarse-grained soils, as evidenced by the numerous anomalies detected adjacent to gravel layers.
- Slurry seals appear to perform more poorly above the water table.
- Drill cuttings and mud shoveled into the annulus cause bridges to form in the annulus.
- Soil collapsed against the casing does not form a good seal if it has a high hydraulic conductivity (e.g., collapsed sand).
- Drilling mud slurry used as the annular well seal performs best adjacent to low hydraulic conductivity soils.

# MONITORING WELL INVESTIGATION

Monitoring wells are used to monitor chemical constituents of groundwater and hydraulic properties of the aquifer. They are designed to obtain specific groundwater data. Faulty well seals can contribute to misleading data and result in inaccurate chemical or hydraulic interpretations. Monitoring wells are commonly installed in aquifers with known contamination, therefore, the threat of cross-contamination through a defective well seal is significant.

Several monitoring wells were investigated using the ultrasonic probe. The objectives of the investigations were to evaluate the integrity of the annular seal. Monitoring wells were selected based on the following characteristics: (1) type of seal material; (2) method of seal placement; (3) type of native soil and/or rock; and (4) potential seal problems.

The monitoring well tests were conducted at six anonymous sites for 14 wells. To facilitate comparison between monitoring wells, wells with similar characteristics are grouped together. The groups include granular bentonite and bentonite slurry wells, cement-bentonite wells, wells completed in bedrock, shallow water table wells, and wells with suspected problems.

## WELL CONSTRUCTION AND COMPLETION

The construction of monitoring wells is specified in NR-141 (Wisconsin Department of Natural Resources, 1995). The guideline is designed to protect public health by ensuring proper well construction. Seal materials and placement methods are detailed for the filter pack seal, annular space seal, and the surface seal.

A variety of methods can be used to drill monitoring wells. Most of the monitoring wells surveyed during this study were drilled with a hollow stem auger. At Site E, a rotary drilling system was used to drill the final portion of the wells where bedrock was encountered. The rotary drilling system is used to drill through hard rock formations. The borehole diameters vary from site to site.

The type of soil and rock encountered while drilling is determined by the cuttings that are transported up the auger flights and from split spoon samples (American Society for Testing and Materials, 1995b). The split spoon sampler is driven in advance of the bit through the center of the hollow stem augers. The sampler can recover approximately 30 cm of sample. The sample geology is described by on-site personnel.

The ultrasonic response for each well is presented as ENG versus depth. The ground surface is taken as the origin. A schematic column showing the geologic section and annular seal materials for the monitoring well is included left of the ultrasonic response profile. The well construction forms and boring logs for all the monitoring wells are included in Klima (1996).

## AIR AND WATER REFERENCE ENG

Air and water reference ENG values were measured in the field when possible to verify the reference values for the specific well casing. The average value of the readings is plotted on the log showing the ultrasonic response profile for the particular well. If the reference value could not be measured in the field, a laboratory measured value was used. For example, the laboratory measured average ENG for 51 mm (2 inches) Sch. 40 PVC casing with water backing is 220 ns. The average laboratory measured air value is 1000 ns.

## WELLS WITH BENTONITE SEALS

The following group of wells were constructed according to NR-141 guidelines (Wisconsin Department of Natural Resources, 1995) with bentonite slurry, granules, or chips in the annulus. In general, the ultrasonic response of these wells indicates good casing-seal contact, which suggests that the seals are intact.

### Well F-1

Three monitoring wells were tested with the ultrasonic well seal assessment tool at Site F located east of Madison, Wisconsin. All three wells were made with 52 mm (2.04 inches) interior diameter Sch. 40 PVC casing. The wells were installed in 193-mm (7.6-inches) diameter boreholes drilled with hollow stem augers.

Well F-1 was drilled to about 12 m (39 feet) below the ground surface. The annular space was filled from the filter pack sand to the ground surface with 9.5-mm (0.4-inches) bentonite chips. The chips were delivered to the annulus by gravity through a tremie pipe.

The ultrasonic response of the well is shown in Figure 8. At about 1 and 2.5 m (3.3 and 8 feet), the energy approaches the water reference line, indicating a defective seal. Perhaps the position of the water table with seasonal fluctuations affects the integrity of the bentonite seal. Bentonite seals situated in the unsaturated zone may tend to dry and crack. The higher ENG readings at 1 and 2.5 m (3.3 and 8 feet) could be caused by water-filled cracks in the bentonite. Temperature fluctuations are also larger at the surface. Freezing and heating may cause the bentonite seal to separate from the casing or cause the bentonite to crack.

Below 3 m (10 feet), the bentonite chip seal has ENG lower than the water reference line, indicating that the seal is in good contact with the casing and that the seal is intact. The high energy spikes at 8.3 and 9.2 m (27 and 30 feet) are due to dispersion of the ultrasonic waves in the slotted portion of the well screen. Reliable ultrasonic measurements cannot be made in the screened interval. Since the annular fill material in the screened interval should consist of filter pack sand, the ultrasonic response in the screened interval would only be useful for measuring the water-filled voids in the sand (i.e., the water backing response for the water ENG reference line). Additionally, sometimes the screen joint or roughness in the screen makes it difficult to

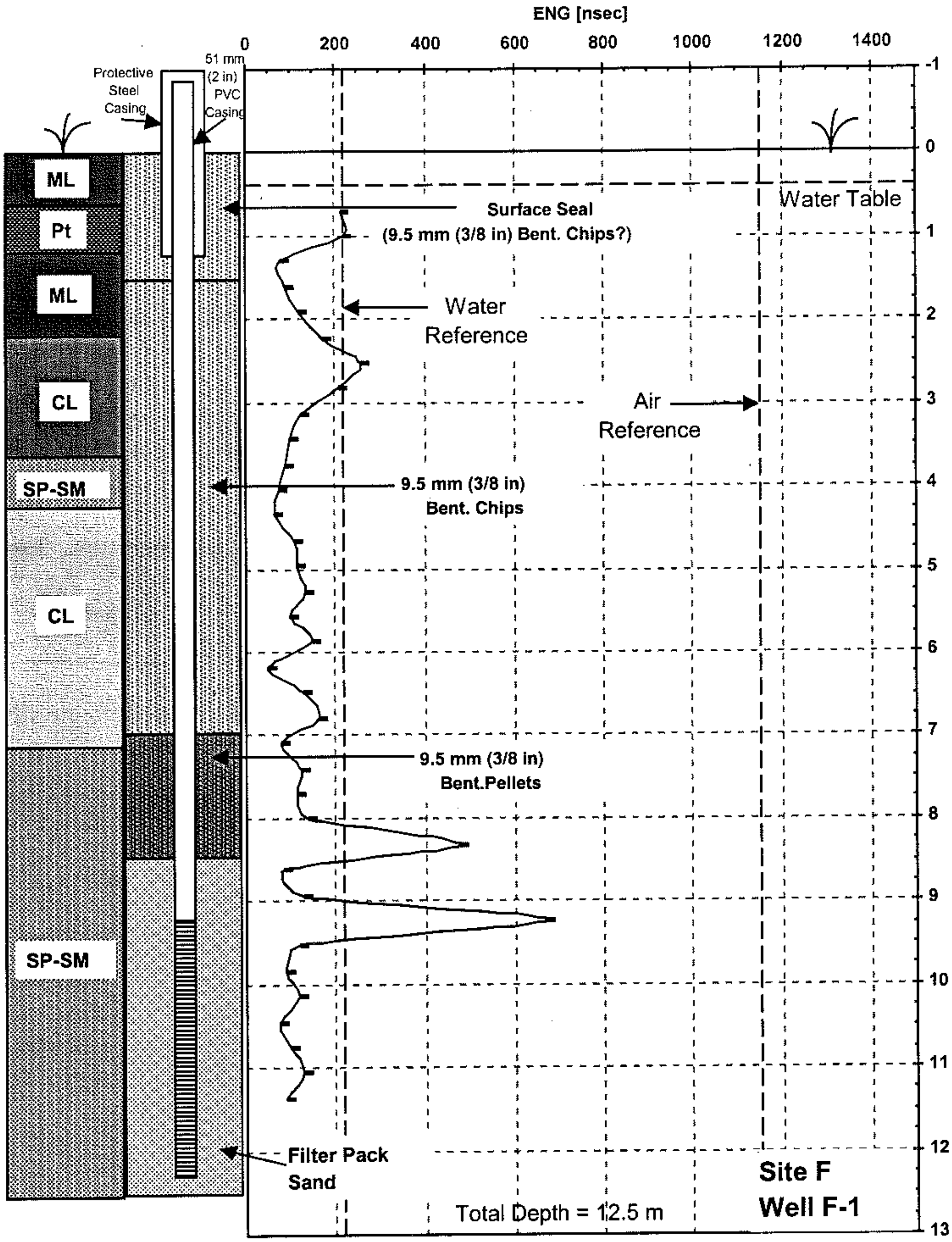


Figure 8. Ultrasonic response of monitoring well F-1, Site F.

retract the probe from the well. Though a significant portion of the screened interval was logged in well F-1, readings are typically not taken in the screened interval.

**Wells F-2 and F-3**

Wells F-2 and F-3 are each about 26 m (85 feet) deep and were similarly constructed. The annular space in this well was filled with tremie-pumped, 1.20 g/cm$^3$ (10.0 lb/gal) bentonite slurry. The ultrasonic response for wells F-2 and F-3 are shown on Figures 9 and 10.

Immediately below the ground surface, ENG is higher than the water reference line to 5 m (16 feet) depth in F-2 and to 2.8 m (9 feet) depth in F-3. This indicates a poor casing-seal contact, possibly due to a defective seal in this portion of the well. Near the ground surface, the water table and temperature fluctuations probably play a role in affecting the integrity of the bentonite seals. The portion of the seal above the water table probably tends to dry out and crack. This portion of the seal is also most susceptible to freeze-thaw action, which could result in seal degradation.

The majority of the seals in wells F-2 and F-3 appears to be in good condition. From about 5 to 17 m (16 to 56 feet), the ENG for both wells is lower than the lowest energy observed in F-1 (bentonite chip seal). Very low energy readings (<100) indicate excellent contact between the seal and casing.

There is an increase in ENG in the lower portion of both wells above the bentonite filter pack seal. The increase occurs from approximately 17 to 23 m (16 to 75 feet) in F-2 and from 21 to 22.5 m (69 to 74 feet) in F-3. The energy response approaches or crosses the water reference line, indicating a potential degradation of seal integrity. Soil or bentonite chip bridging could create void spaces resulting in the elevated ENG response. In well F-2, the sand situated at 19 m (62 feet) could have collapsed against the casing. The water-filled voids would have an ENG higher than an intact bentonite seal.

Overall, the bentonite slurry performed well. The slurry appears to perform slightly better than the annular seal in F-1 which was made entirely of 9.5 mm (0.4 inch) bentonite chips dropped through the tremie pipe. Additionally, the slurry seal performs well over a period of time since the tests were conducted approximately 1.5 years from the time the wells were constructed.

**Well B-2**

Well B-2 is located in Site B on the north side of Madison, Wisconsin. The well is 33.5 m (110 feet) deep. B-2 was constructed with 58-mm (2.30-inch) interior diameter Sch. 80 PVC that was inserted into a 244-mm (9.6-inch) diameter borehole. The 29-m (95-foot) long section of annular space above the bentonite filter pack seal was sealed by tremie pumping 1.21 g/cm$^3$ (10.1 lb/gal) bentonite slurry into the annulus. The bentonite filter pack seal was made with 1.5 m (5-feet) of 9.5-mm (0.4-inch) bentonite pellets. The pellet emplacement method is unknown.

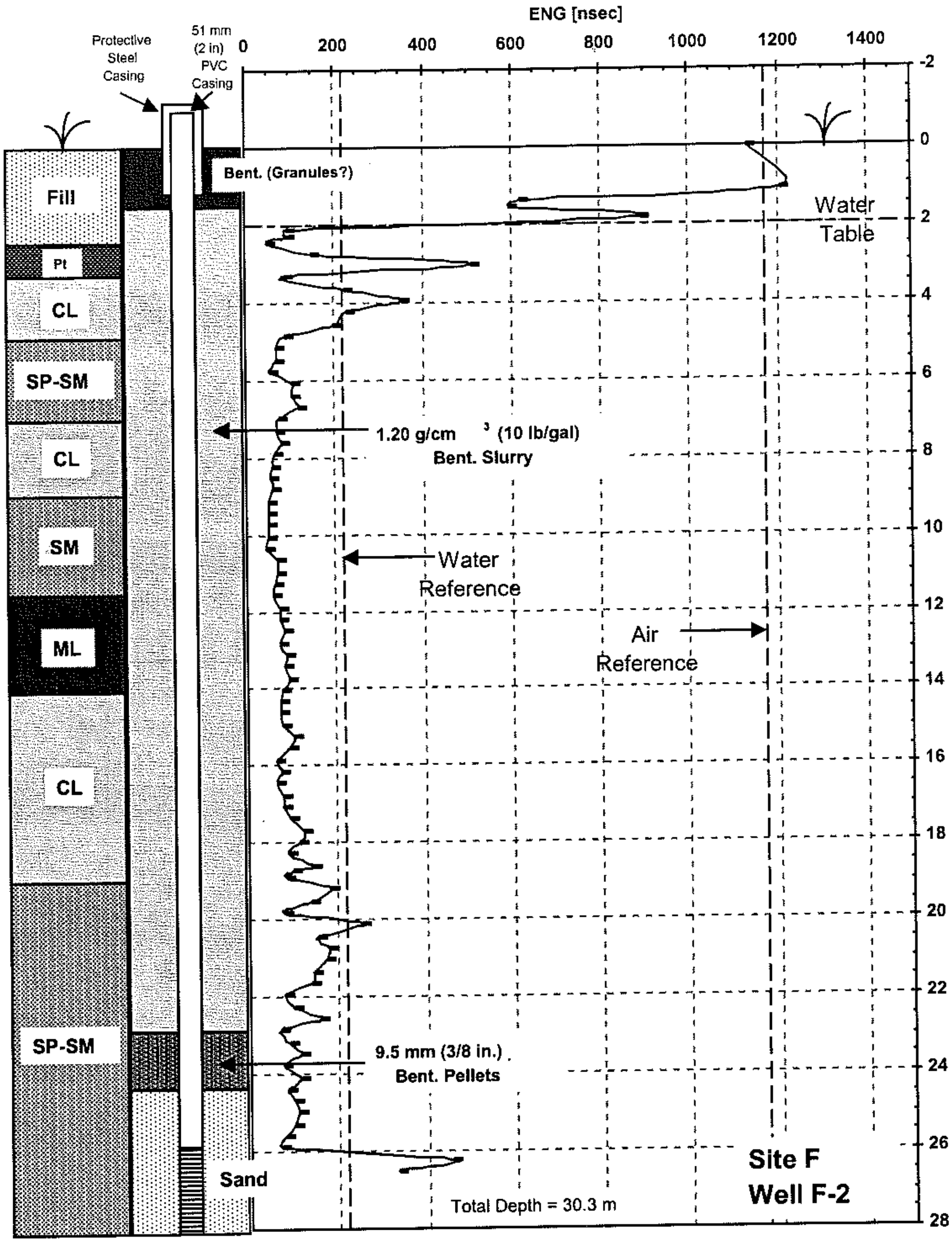


Figure 9. Ultrasonic response of monitoring well F-2, Site F.

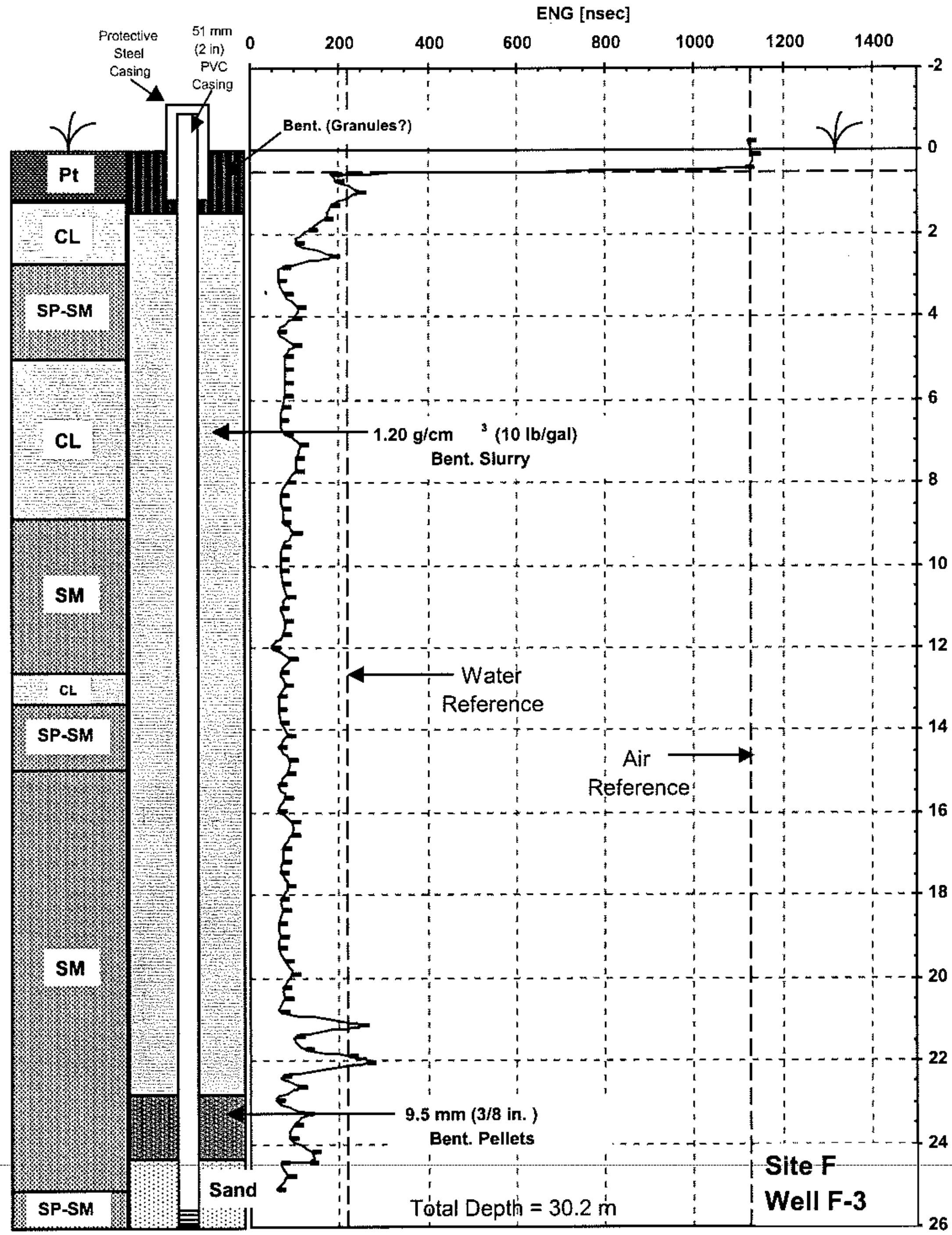


Figure 10. Ultrasonic response of monitoring well F-3, Site F.

The surface seal was made with bentonite. The water table was about 2.4 m (8 feet) below the ground surface. ENG measurements were not made above the water table for this well.

The ultrasonic response of well B-2 is shown in Figure 11. The bentonite slurry seal appears to have performed well overall as evidenced by the low energy readings for most of the well. Only a few ENG spikes approach the water reference line. At approximately 27 m (89 feet) ENG increases, indicating poorer contact between seal and casing. This zone roughly corresponds to the bentonite pellet seal above the filter pack sand. The pellets may have bridged during placement leaving water-filled voids. The higher ENG readings could be due to either irregular pellet placement or inadequate pellet expansion after hydration.

Another explanation for the higher ENG readings is related to the development procedure. Well B-2 was developed with compressed air. The casing was pressurized to clean sediment out of the screen interval and filter pack sand. The seal nearest to the screen may have been disturbed by the high pressure air. The higher ENG reading above the screen from 27 to 29 m (89 to 95 feet) may be indicative of the air pressure development. The air would have disturbed the pellets during or immediately after hydration. The disturbance could include, but is not limited to, inclusion of air, inclusion of water forced out of the casing, or dilution and mixing of the seal material with sediment fines. All these factors could have degraded the contact between the seal and casing.

## WELLS IN BEDROCK

Site E is located on the south side of Madison, Wisconsin. The seals in these wells are bentonite slurries similar to those described previously. The reason the following wells were placed in a separate section is because these wells were drilled partially in bedrock. The wells at Site E were constructed with 62 mm (2.4-inch) interior diameter Sch. 40 PVC that was installed in 244-mm (9.5-inch) diameter boreholes. Bedrock at Site E is relatively shallow, requiring one monitoring well to be set about 10 m (33 feet) into the bedrock. The ultrasonic response from these monitoring wells will be examined for changes in sealing characteristics potentially due to interactions with the soil and bedrock.

### Well E-2

Well E-2 is more than 21 m (69 feet) deep. The ultrasonic response of the well is shown in Figure 12. The well was drilled through clays and silty sands. The bottom 2.5 m (8 feet) of the well was set in bedrock consisting of interbedded sandstone and dolomite. The shallow clay and silty sand portion of the well was drilled with a hollow stem auger and the deeper bedrock portion was drilled with a rotary drill. Water was used as the drilling fluid.

The annular space was sealed with 1.19 g/cm$^3$ (9.9 lb/gal) tremie pumped bentonite slurry. The bentonite seal above the filter pack is 1.5 m (5 feet) long and consists of 9.5 mm (0.4-inch) bentonite pellets. The ultrasonic response of the riser above the ground level had high

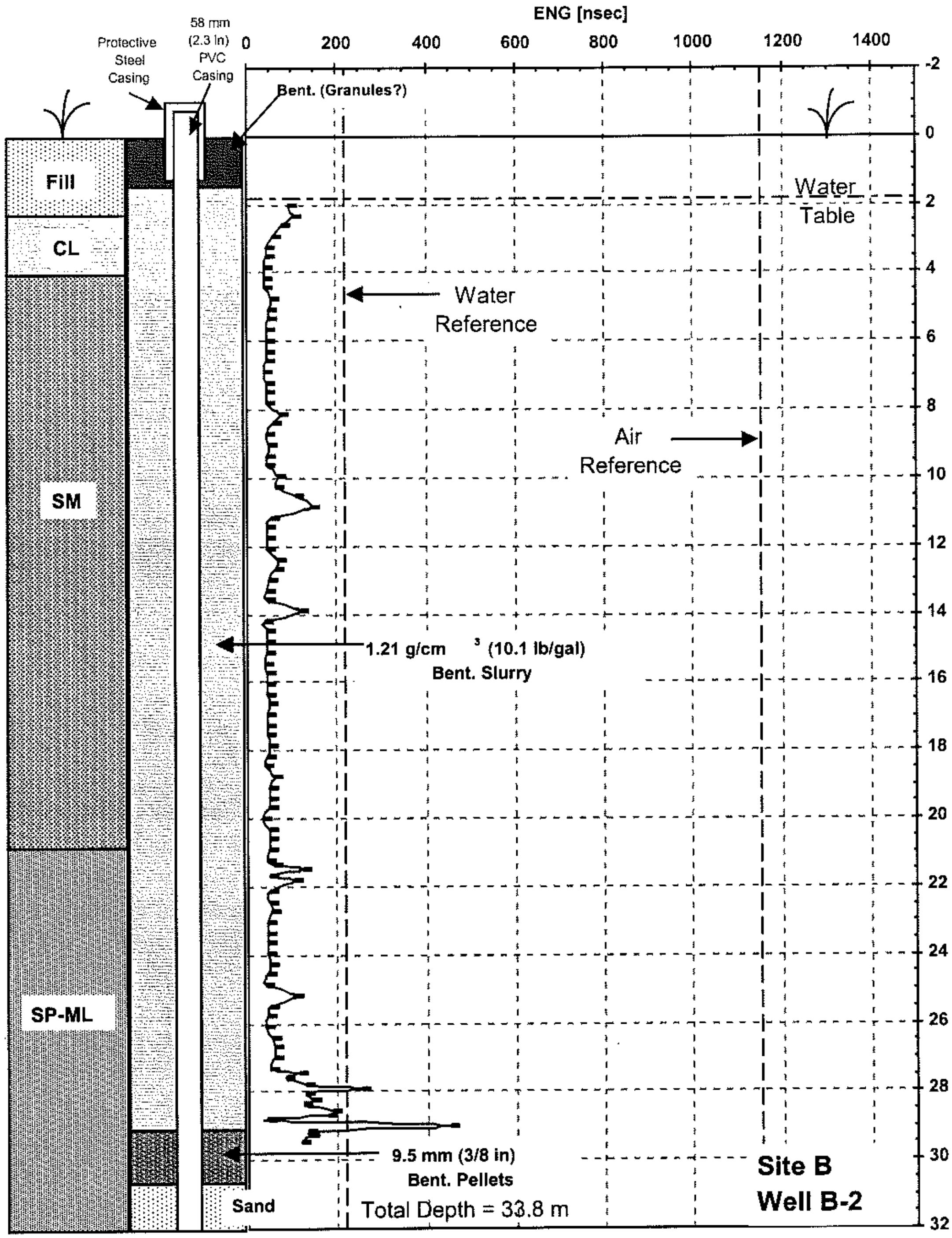


Figure 11. Ultrasonic response of monitoring well B-2, Site B.

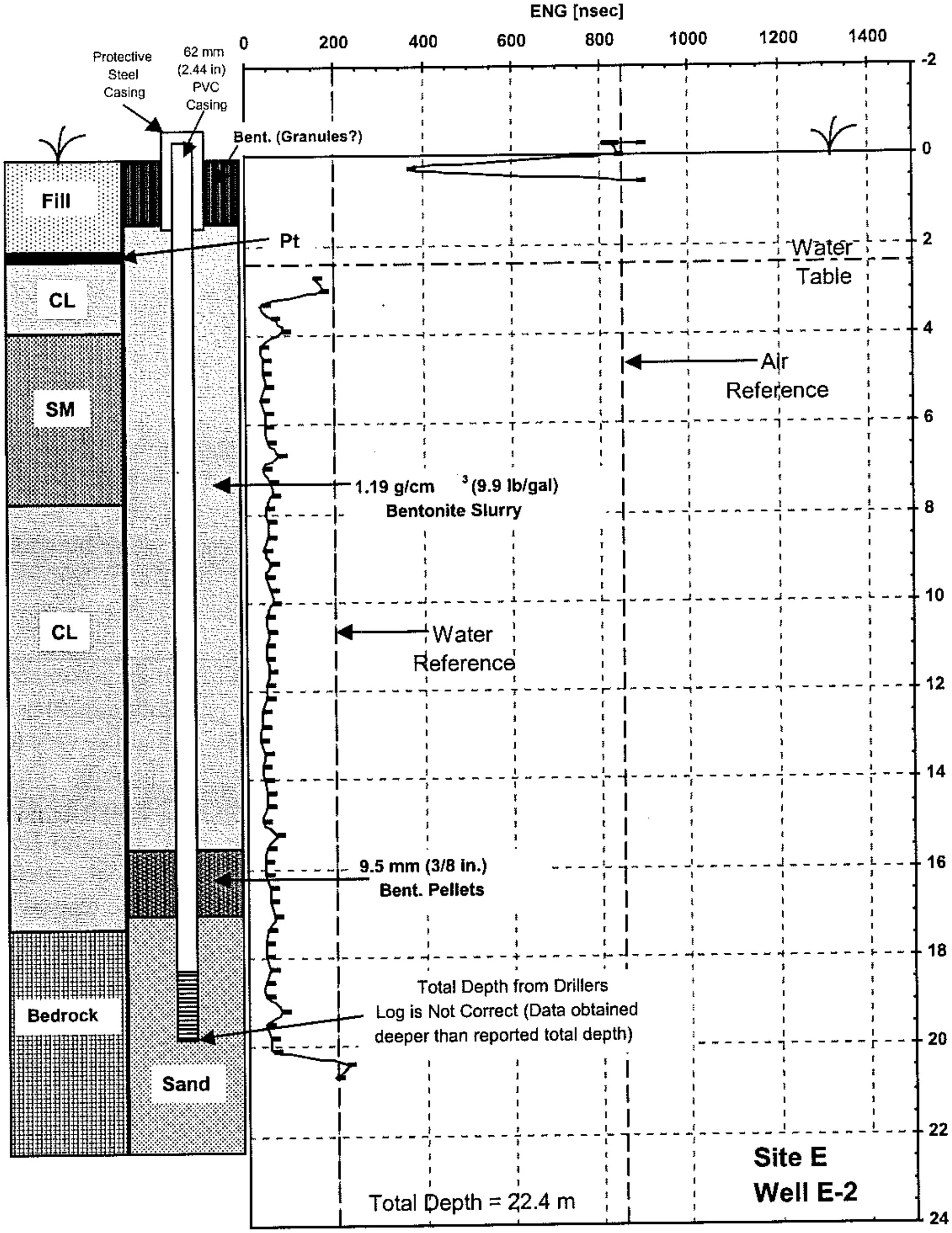


Figure 12. Ultrasonic response of monitoring well E-2, Site E.

energy with air backing, yet the air readings were lower than measured in standard 51 mm (2-inch) interior diameter, Sch. 40 PVC (i.e., 1000 ns). The lower value is probably due to the thicker casing used at Site E. The casing thickness for 62-mm (2.4-inch) interior diameter casing is 7-mm (0.3-inch). The thickness of the 51-mm (2-inch) interior diameter Sch. 40 PVC casing is 3.9-mm (0.2 inch). The thicker casing acts to dampen the energy slightly.

The ultrasonic response from approximately 3 to 20 m (10 to 66 feet) shows little variation (Figure 12). The energy is lower than the water reference line, indicating good contact between the seal and casing, which suggests the seal is intact. The bentonite slurry performs very well below the water table. The total depth reported on the driller's boring log was incorrect. Data was obtained below the reported total depth.

### Well E-3

Well E-3 was constructed similarly to well E-2 (a hollow stem auger to drill the upper portion and a rotary drilling rig to drill the bedrock portion of the well). Approximately 10 m (33 feet) of this well was drilled into the interbedded sandstone and dolomite bedrock. An 1.19 $g/cm^3$ (9.9 lb/gal) bentonite slurry was tremie pumped into the annular space. The bentonite filter pack seal was 1.5-m (5 feet) long and was constructed with 9.5-mm (0.4-inch) bentonite pellets. Bentonite was observed between the protective casing and riser at the surface.

The ultrasonic response of the well is shown in Figure 13. The ENG from approximately 4.5 to 17 m (15 to 56 feet) depth is lower than the water reference line and probably indicates an intact seal with good casing contact. Air backing readings could only be obtained at the very top of the well since bentonite filled the annulus between the protective casing and the riser. From about 1.2 to 4.2 m (4 to 14 feet), the ENG approaches the air reference line. The high ENG at 2.6 m (8.5 feet) is probably due to air trapped in the bentonite. The higher ENG readings from 1.2 to 4.2 m (4 to 14 feet) could indicate poorer contact between the casing and seal material compared to the section from 4.5 to 17 m (15 to 56 feet). The poor contact could be caused by desiccation above the water table or freezing and thawing of the bentonite. Freezing and thawing may cause the bentonite to separate slightly from the casing.

At about 17 m (56 feet), the energy increases above the 9.5-mm (0.4-inch) bentonite pellet seal. This could be due to bridging of the pellets during installation, leaving a water-filled void. As in Well E-2, there is no distinct correlation between the energy measured in the soil portion of the well and the bedrock portion of Well E-3. The bentonite slurry sealing practice appears to work well in the sandstone and dolomite bedrock near Madison, Wisconsin.

## CEMENT-BENTONITE SEALED WELLS

Bentonite is sometimes added to a cement grout to improve the workability of the cement, reduce the slurry weight and density, and produce a lower unit cost sealing material. Bentonite also has adverse effects, including reducing the set strength of the seal, lengthening set time, and

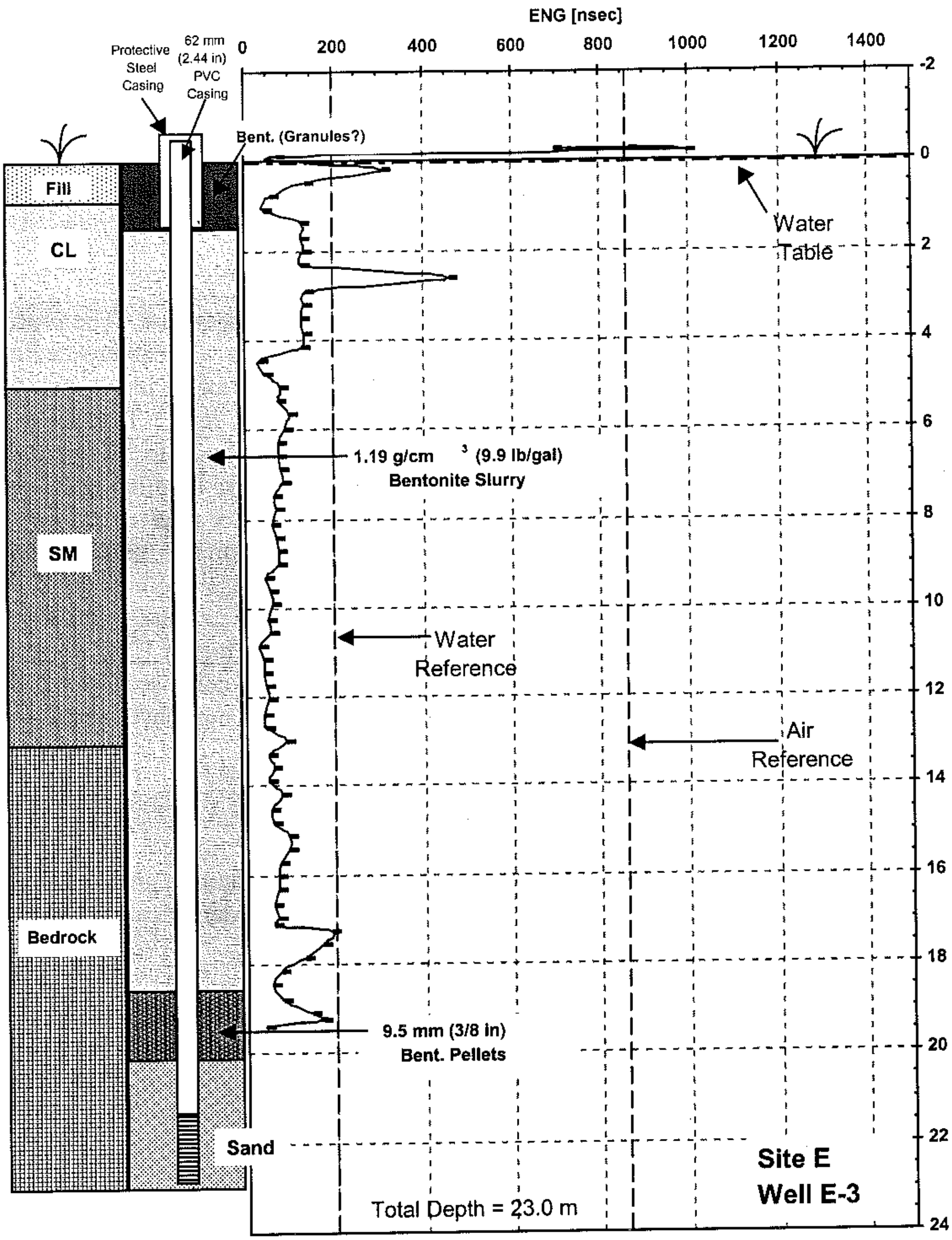


Figure 13. Ultrasonic response of monitoring well E-3, Site E.

may be chemically incompatible with the cement. Cement causes flocculation of bentonite, reducing its ability to swell (Nielsen and Schalla, 1991).

**Well B-3**

Well B-3 was completed in 1987 or 1988 at Site B on the north side of Madison, Wisconsin. Well B-3 is a 32.3-m (106-feet) deep monitoring well made of 51-mm (2-inch) diameter Sch. 40 PVC. The annular seal material consists of a cement-bentonite grout. The percentage of bentonite mixed with the cement is unknown.

The ultrasonic response of the annular seal material is shown in Figure 14. The profile consists of zones with very low ENG alternating with ENG approaching the water reference line. The low ENG zones, indicating good casing-seal contact and the presence of an intact seal, are from approximately 5 to 7 m (16 to 23 feet) and 16 to 23.8 m (52 to 78 feet). The zones of higher ENG are from approximately 1.3 to 5 m (4 to 16 feet), 7.5 to 16 m (25 to 52 feet), and 23.8 to 25.7 m (78 to 84 feet). The deepest high ENG response occurs where the filter pack sand is situated around the casing. The ultrasonic response is similar to the water reference since the filter pack sand voids are filled with water. The zone from the surface to 5 m (16 feet) may have higher ENG due to water table fluctuations or freeze-thaw effects that cause degradation of the cement. The high ENG zone in the middle may be due to cement curing effects and shrink swell. Considering that the well is drilled through a relatively sandy section, the higher ENG response from 7.5 to 16 m (25 to 53 feet) could be due to water-filled sand that collapsed against the casing during construction. The tremie-pumped cement slurry may not have adequately displaced the sand.

**Well D-1**

Site D is located in the City of Madison, Wisconsin. A cement-bentonite grout was used to seal the annular space of well D-1. A high effort, densely spaced soil densification program was carried out in the vicinity of the well.

Well D-1 was constructed of 51-mm (2-inch) diameter Sch. 40 PVC that was installed in a 152-mm (6-inch) diameter borehole. The well was drilled using a mud rotary system and bentonite drilling mud. A 5% bentonite-cement grout was tremie-pumped into the annular space. The cement-bentonite grout was installed on top of the filter pack sand and brought to the surface.

The ultrasonic response of well D-1 is shown in Figure 15. Readings were only made below the water table [5 m (16 feet) and deeper]. The overall energy of the cement-bentonite seal is similar to the water reference line (measured in the laboratory). Two isolated low energy spikes at approximately 8.2 and 11 m (27 to 36 feet) may indicate a good seal contact. For most of the well, however, the cement-bentonite grout appears to have poor contact, which suggests the seal is defective.

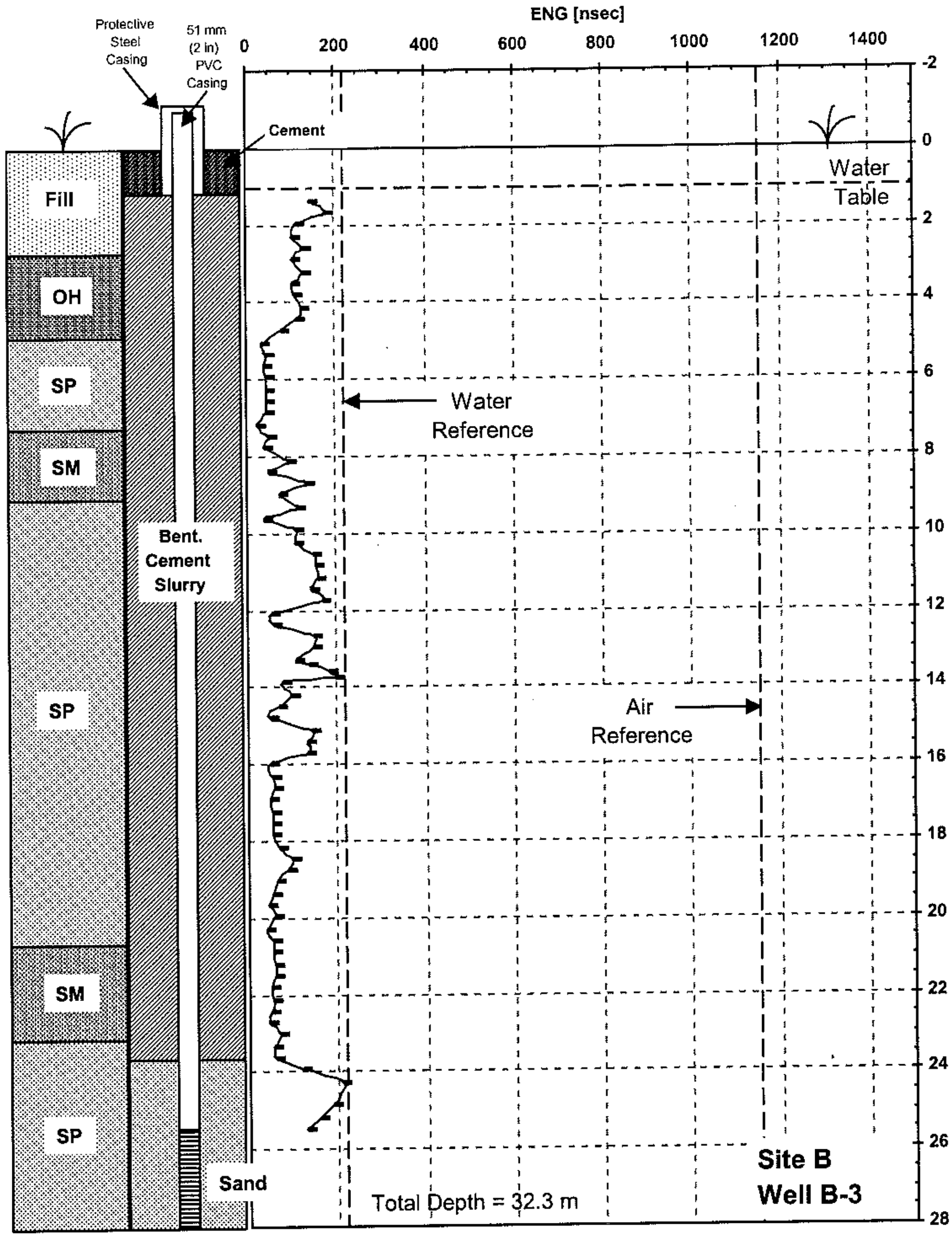


Figure 14. Ultrasonic response of monitoring well B-3, Site B.

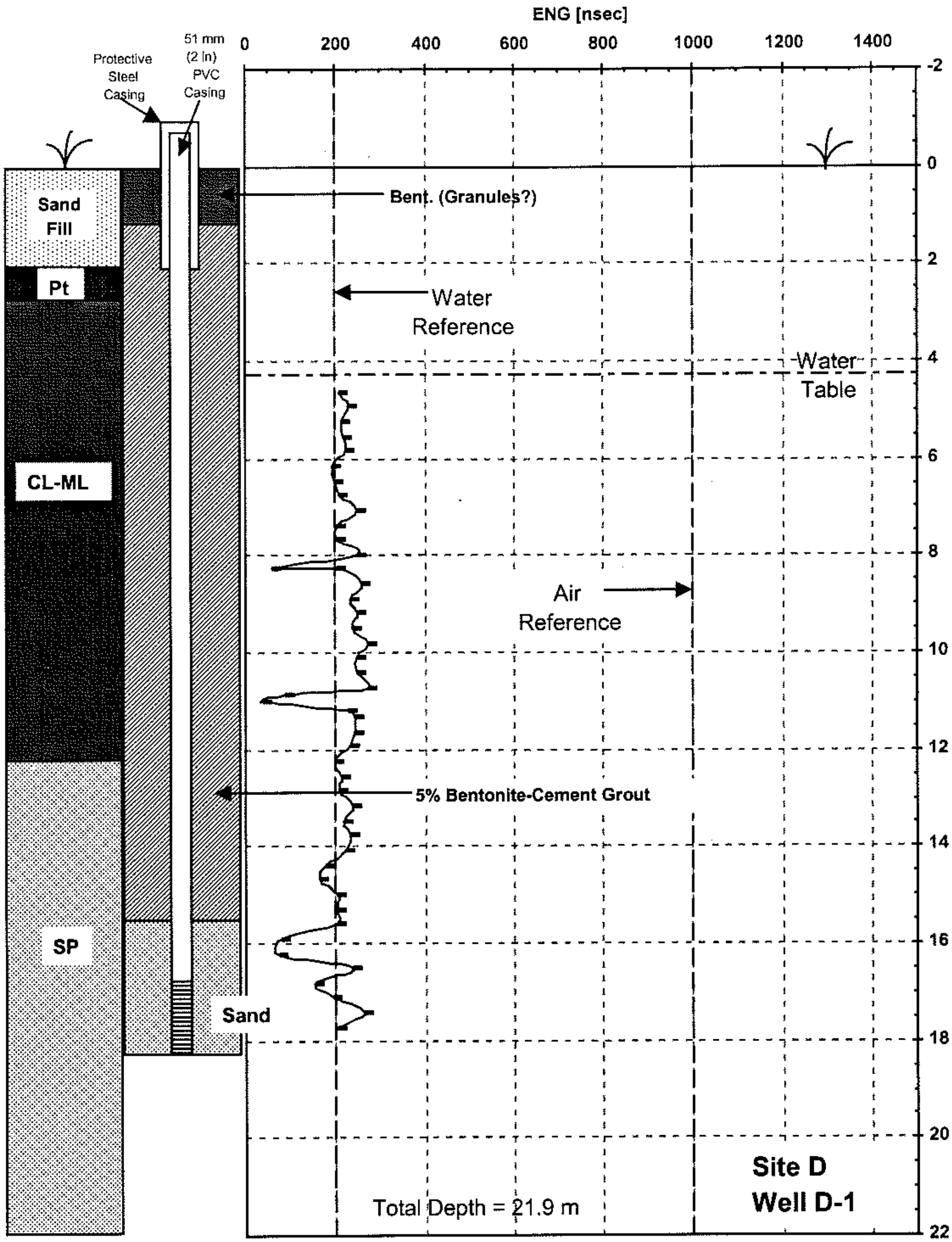


Figure 15. Ultrasonic response of monitoring well D-1, Site D.

The cement-bentonite grout in D-1 has water-like energy response over a longer percentage of the riser compared to cement-bentonite Well B-3. Well B-3 has localized segments of good contact and poor contact between the casing and sealant, while well D-1 appears to have poor contact along its entire length. This could be due to the shrinking potential of the cement and disturbance of the rigid cement-bentonite seal by the nearby soil densification program.

## WELLS WITH SUSPECTED PROBLEMS

The well seal assessment tool was used to evaluate seal integrity in two wells with suspected seal problems. Two monitoring wells were tested near a fly ash disposal facility at Site C. The wells were sealed with different materials. A layer of fly ash exists approximately 1.2 to 2.4 m (4 to 8 feet) below the vegetated cover at Site C. Well C-1 had high levels of sulfate and boron (approximately 500 ppm), two contaminants commonly found in fly ash, whereas well C-2 was minimally impacted (approximately 10 ppm). The contaminants were suspected of infiltrating from the surface through a defective annular seal in well C-1. The ultrasonic seal evaluation tool was used to investigate seal integrity.

Well C-2 is constructed of 51-mm (2-inch) Sch. 40 PVC that was installed in a 152-mm (6-inch) diameter borehole. The well was drilled using a hollow stem auger. The surface seal and annular space seal consist of granular bentonite that was installed by gravity. The bentonite seal above the filter pack sand, also installed by gravity, consists of 9.5-mm (0.4-inch) bentonite pellets.

The ultrasonic response for well C-2 is shown in Figure 16. The segment of the riser within the protective casing has high energy values, indicating an air backing. Once below the protective pipe and into the bentonite seal, the energy is less than the water reference line, indicating good contact between the bentonite and the casing. The granular bentonite seal, from 1 to about 11 m (3 to 36 feet), has similar ENG response compared to the 9.5 mm (0.4-inch) bentonite pellet segment from about 11.8 to 13 m (39 to 43 feet), indicating the granular and pellet-type bentonites performed equally well.

An interesting feature in this well (and also in the well C-1) is that the segment of the casing with saturated sand backing, from 13.3 m (44 feet) to total depth, has an energy response less than the water reference line. Saturated sand should have an energy response similar to water. One explanation could be that bentonite infiltrated into this zone.

Well C-1 was constructed in a similar manner to C-2 except that a different annular space seal material was used. Well C-1 was drilled to a depth of 16.9 m (55 feet). The borehole was drilled with a hollow stem auger. A bentonite-sand slurry was installed in the annular space using a tremie pipe. The bentonite seal above the filter pack consisted of 9.5 mm (0.4-inch) bentonite pellets.

The ultrasonic response of the monitoring well is shown in Figure 17. In addition to the air response obtained at the top of the casing, a field-measured ENG response was obtained for

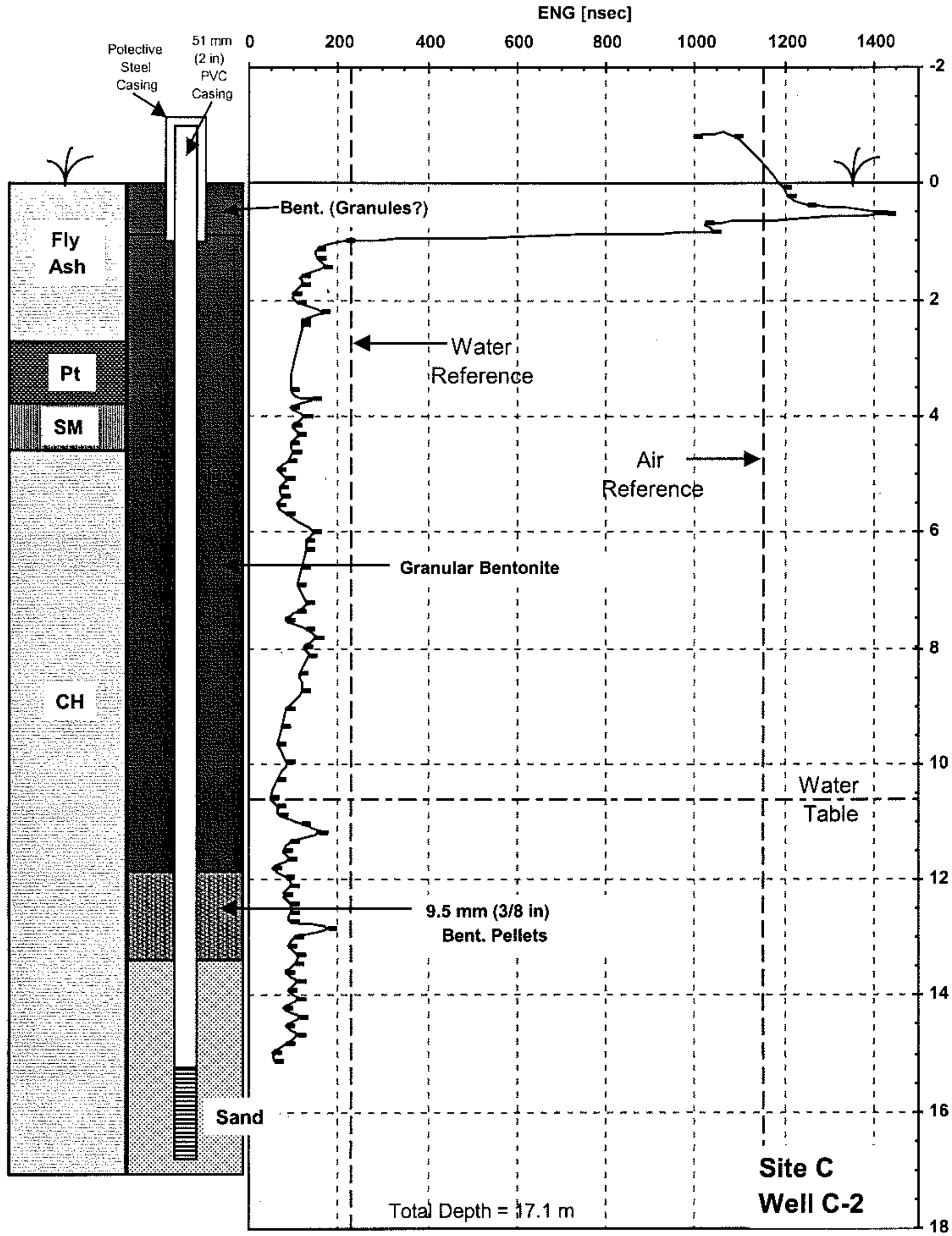


Figure 16. Ultrasonic response of monitoring well C-2, Site C.

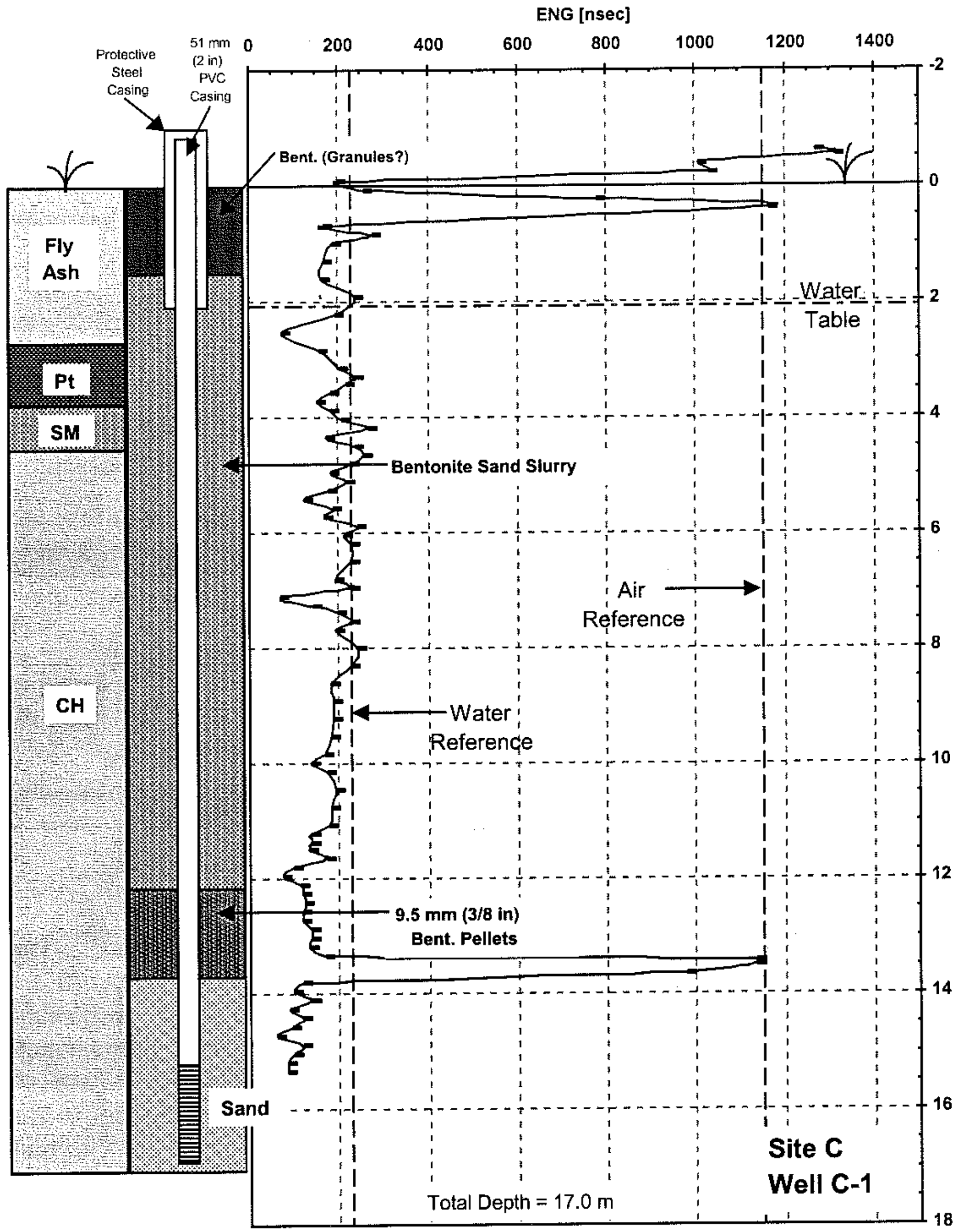


Figure 17. Ultrasonic response of monitoring well C-1, Site C.

the casing with water backing. The space between the pipe is usually filled with air, as measured in well C-2. However, a portion of this space was filled with water. The average water backing response was 230 ns. The water reference line on Figures 16 and 17 is based on the value measured in the field.

The portion of the well sealed with the bentonite-sand slurry has an energy response slightly less than water from ~ 1 to 12 m (3 to 39 feet) depth. The higher ENG compared to the ENG for the granular bentonite seal in C-1 may indicate the bentonite sand seal has poorer contact than the bentonite seal in C-1. It is difficult to determine for certain that the bentonite-sand slurry seal is defective.

The ENG for the bentonite pellet seal [~ 12 to 13.3 m (39 to 44 feet)] is 25% lower than the ENG for the overlying bentonite sand slurry. The bentonite pellets appear to provide better contact than the bentonite-sand seal. Compared to well C-2, the bentonite pellet seal in C-1 has a similarly low ENG.

An energy peak at 13.5 m (44 feet) was observed in the well. The magnitude of the peak indicates an air backing. Perhaps a small air-filled void due to bridging or air in a casing coupling joint caused this anomalous spike.

Since the bentonite pellet seal appears to be intact and providing good casing-seal contact, the well may be adequately protected from surface infiltration even though the bentonite-sand seal provides a poorer seal. The single air spike is a local defect and is not indicative of a failed seal. Contamination of the well with fly ash constituents could have been caused during drilling. The well was drilled though a thin fly ash layer at the surface. The fly ash could have been carried down the annulus or fallen down the annulus during drilling operations.

**Well G-1**

Site G is located in Verona, Wisconsin. Benzene, ethylbenzene, toluene, and xylenes were detected in water samples from well G-1. Well G-1 was constructed with a 51-mm (2-inch) interior diameter Sch. 40 PVC casing and was installed in a 216-mm (8-inch) diameter borehole. The well was drilled with a hollow stem auger to a depth of 22.9 m (75 feet). A tremie-pumped bentonite slurry was used to seal the annular space in the well. The slurry was 1.02 g/cm$^3$ (8.5 lb/gal) mud weight bentonite, and it was placed from the top of the filter pack sand to 0.6 m (2 feet) below ground surface. The water table is approximately ~ 13 m (43 feet) below the ground surface.

Well G-1 is the only monitoring well surveyed during this study that showed significant potential problems in seal integrity. The previously discussed tremie-pumped bentonite slurry wells appear to be performing well. Monitoring well G-1, however, has a different behavior.

The ultrasonic response of well G-1 is shown in Figure 18. From the ground surface to 2.7 m (9 feet) and from 4.7 to 7.7 m (15 to 25 feet), ENG is greater than the water reference

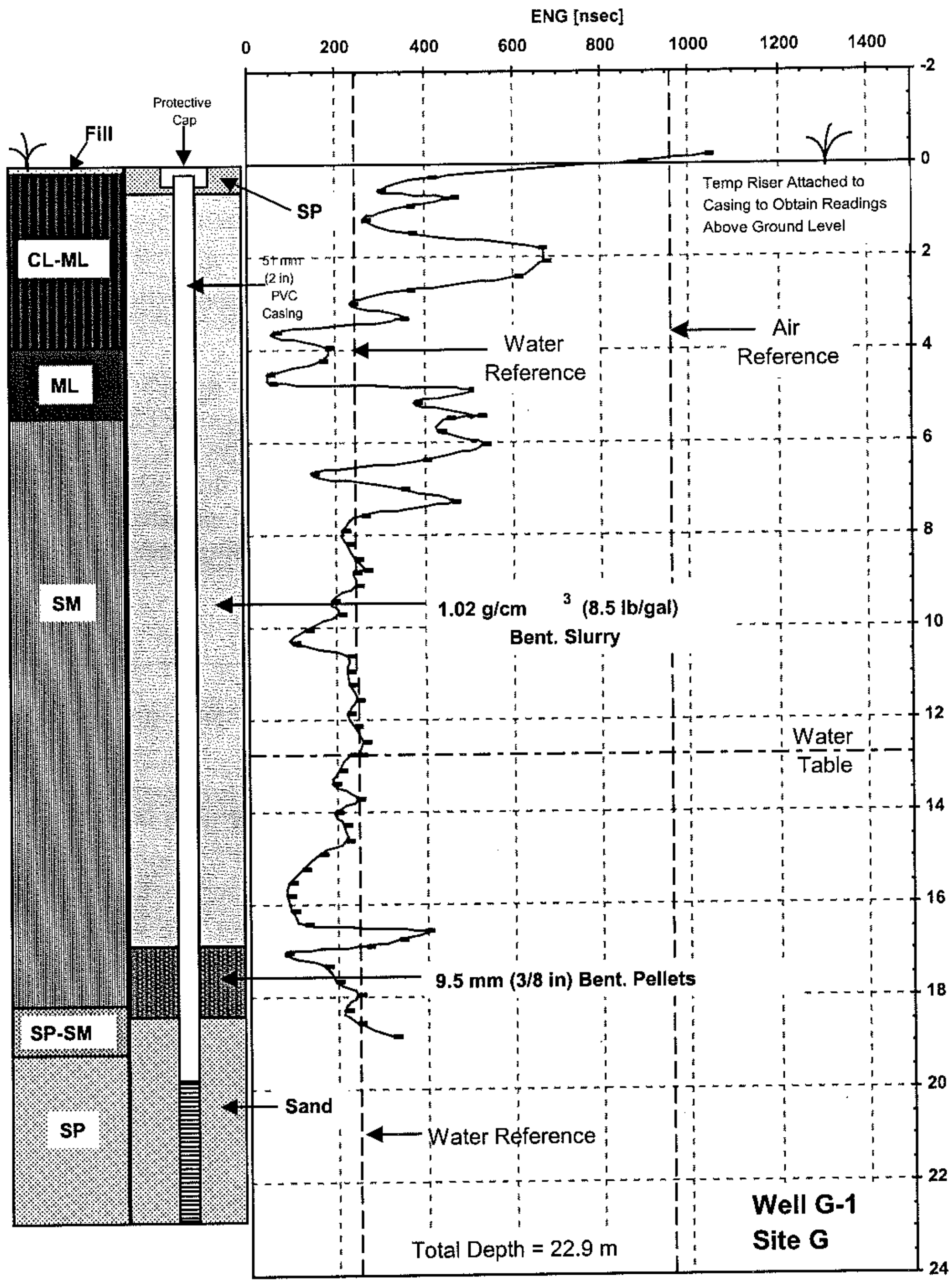


Figure 18. Ultrasonic response of monitoring well G-1, Site G.

value, yet is less than the air reference value. Bentonite seals situated in the unsaturated zone may tend to settle and desiccate. The low ENG from approximately 3.5 to 4.7 m (11 to 15 feet) indicates the seal is in good contact with the casing. The low response is probably due to bentonite slurry perched on a soil bridge or to the collapse of the adjacent silty clay around the casing.

The ultrasonic response approximates the water reference ENG from about 7.7 to 14.7 m (25 to 58 feet). This zone is adjacent to a silty sand soil. Silty sand that collapses against the casing and remains saturated would have a response similar to water backing because the voids are filled with water. Perhaps the sand mixed with the bentonite slurry, resulting in the saturated material above the water table.

The contact between seal material and casing improves from 15.0 to 16.5 m (49 to 54 feet) as evidenced by the low ENG values. This zone is immediately above the bentonite filter pack seal. A high ENG spike correlates with the top of the filter pack seal [16.7 m (55 feet)], and another low ENG spike is found at 17.2 m (56 feet). One explanation for these ENG responses could be that the bentonite pellets were delivered at a shallower depth than indicated on the well construction form. The pellets may have bridged during placement causing poor casing seal-contact at 16.7 m (55 feet)

## SUMMARY OF FINDINGS

The following is a summary of the key findings from the monitoring well seal investigations:

- Bentonite slurry seals have performed well, especially when the water table is shallow and the mud weight is approximately 1.20 g/cm$^3$ (10 lb/gal).
- All seals show degradation of the casing-seal contact from the ground surface extending to a shallow depth (usually the water table for the wells tested in this study).
- Slurry seals performed well in sandstone and dolomite bedrock near Madison, Wisconsin.
- Bentonite slurry was not effective with a deep water table, shallow coarse-grained soils, and relatively low mud weight (e.g., 1.02 g/cm$^3$).
- Cement-bentonite seals have poorer casing-seal contact than slurry seals, which is consistent with findings of a laboratory study by Edil et al. (1992).

# CONCLUSIONS

The downhole, ultrasonic well seal assessment tool was successfully used to evaluate a variety of well seals. Sixteen wells from nine different sites were tested with the ultrasonic probe. Factors influencing seal integrity, including type of sealant, seal placement method, and influence of geology and hydrogeology, were considered.

Results from the field tests illustrate a sharp contrast between the seal integrity of monitoring wells and water wells. The water supply wells tested in this project had significantly more defects compared to the monitoring wells. Water supply wells are typically sealed by circulating a bentonite slurry (drilling mud) through the borehole. The slurry contains drill cuttings and tends to become diluted during well development. Ultrasonic seal tests indicated that significant portions of the water well seals were defective. In one instance, a large air-filled void was visible at the ground surface. The ultrasonic response of this void was similar to that of other anomalies detected deeper in the well, implying that the deeper anomalies also correspond to air-filled voids.

The majority of anomalies in water wells were found within coarse-grained formations above the water table. The diluted sealant escapes into coarse-grained soils leaving an open annulus. Zones of alternating good and poor casing-seal contact are attributed to frequent bridging [bridges less than 15 cm (6 inches) in length]. Drill cuttings and mud shoveled into the annulus may exacerbate the bridging problem. In general, drilling mud sealed best when adjacent to low hydraulic conductivity soils below the water table.

Monitoring well installation guidelines require that a low hydraulic conductivity grout ($<10^{-7}$ cm/sec) be used to seal the annulus. In general, significantly fewer anomalies were detected in the monitoring wells compared to the water supply wells. All monitoring wells showed seal degradation near the ground surface where desiccation cracking and frost action are greatest. Monitoring well seals constructed with tremie-pumped bentonite slurries, where the water table was shallow, generally had an intact seal in good contact with the casing. Granular bentonite and bentonite chips, installed by dropping through the annulus or a tremie pipe, provided an overall intact seal with slightly poorer casing-seal contact than the bentonite slurry. This slight degradation in casing-seal contact is attributed to bridging or incomplete placement of the sealant. Cement-bentonite seals generally had poorer casing seal contact relative to the bentonite-sealed wells. Shrinkage of the cement during curing, or expansion and contraction of the PVC casing due hydration heat from the cement, may cause the casing-seal contact to degrade and form a microannulus. The poorest monitoring well seal tested in this project was made with a relatively low mud weight bentonite slurry (1.02 g/cm$^3$) for a well with a deep water table [>10 m (33 feet)].

The results of this project should form a foundation for future improvements in well seal construction. Considering the variety of sealing practices in use, additional monitoring and water

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