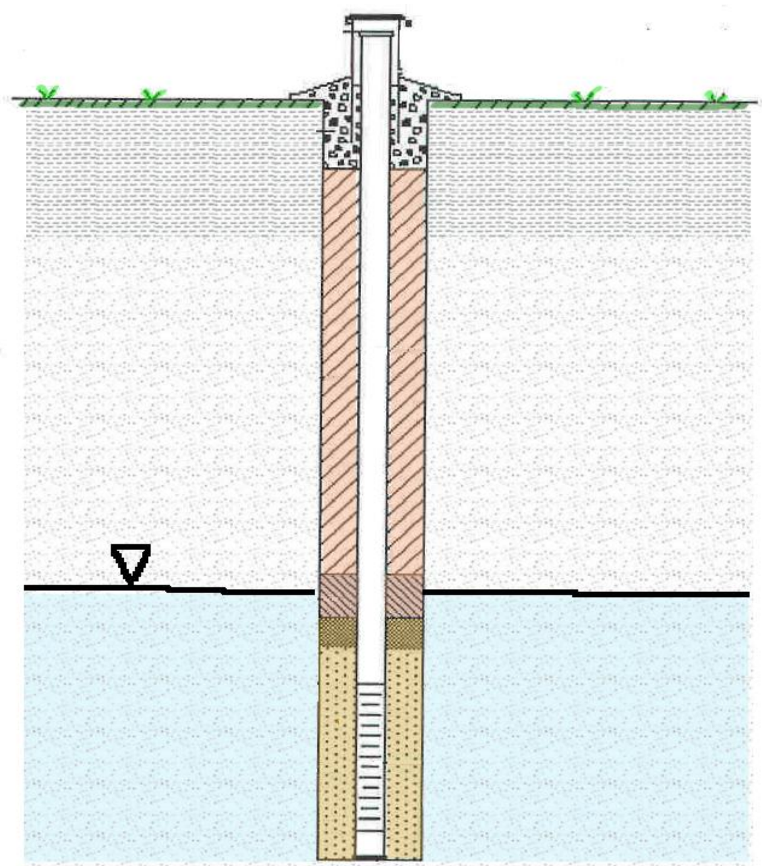
State of Ohio
Environmental Protection Agency

Division of Drinking and Ground Waters

Technical Guidance Manual for Ground Water Investigations

Chapter 7

Monitoring Well Design and Installation



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Director : Chris Korleski

TECHNICAL GUIDANCE
MANUAL FOR
GROUND WATER INVESTIGATIONS

CHAPTER 7

Monitoring Well Design and Installation

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PREFACE

This document is part of a series of chapters incorporated in Ohio EPA's *Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring* (TGM), which was originally published in 1995. DDAGW now maintains this technical guidance as a series of chapters rather than as an individual manual. The chapters can be obtained at http://www.epa.state.oh.us/ddagw/tgmweb.aspx

The TGM identifies technical considerations for performing hydrogeologic investigations and ground water monitoring at potential or known ground water pollution sources. The purpose is to enhance consistency within the Agency and inform the regulated community of the Agency's technical recommendations and the basis for them. In Ohio, the authority over pollution sources is shared among various Ohio EPA divisions, including the Emergency and Remedial Response (DERR), Hazardous Waste Management (DHWM), Solid and Infectious Waste (DSIWM), and Surface Water (DSW), as well as other state and local agencies. DDAGW provides technical support to these divisions.

Ohio EPA utilizes ***guidance*** to aid regulators and the regulated community in meeting laws, rules, regulations and policy. Guidance outlines recommended practices and explains their rationale. The Agency may not require an entity to follow methods recommended by this or any other guidance document. It may, however, require an entity to demonstrate that an alternate method produces data and information that meet the pertinent requirements. The procedures used to meet requirements usually should be tailored to the specific needs and circumstances of the individual site, project, and applicable regulatory program, and should not comprise a rigid step-by-step approach that is utilized in all situations.

MAJOR CHANGES FROM THE FEBRUARY 1995 TGM

The Ohio EPA Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring (TGM) was finalized in 1995. This guidance document represents an update to Chapter 7 (Monitoring Well Design and Installation). Listed below are the major changes from the 1995 version.

1. Deleted language cautioning against the use of multi-level wells. Added information on multi-level well systems.
2. Added text indicating that vertical water profiles can be obtained with passive sampling techniques.
3. Revised text to state that PVC is preferable to PTFE for monitoring well screens when organics are present. Studies have shown that PTFE sorbs organic compounds at a higher rate than does PVC.
4. Added language stating that a filter pack can be much less thick than previously recommended.
5. Added language describing the use of pre-packed screen wells.
6. Changed the recommendation for selecting the screen slot size of a naturally packed well from a slot that retains 30 to 60% of the filter pack to one that retains 70%.
7. Added information on methods for creating high-solids bentonite.
8. Revised text to note potential problems with using a bentonite/cement mixture. However, the guidance does not rule it out as a potential sealant for monitoring wells. Some literature has indicated problems with the use of a bentonite as an additive to neat cement for well sealing. Because of this, the Ohio rules applying to drinking water wells do not allow the use of a bentonite/cement mixture (OAC 3745-09). However, there are also articles that favor its use, and many states still allow (and recommend) it.
9. Added section on procedures for installation of neat cement grout.
10. Added recommendation that, due to its potential to affect ground water chemistry, bentonite sealing material should be placed a minimum of 3 to 5 feet above the top of the well screen.
11. Included references to new documents that have become available since 1995, including:
    - Updated existing references.
    - Added new ASTM reference for installation of pre-packed screens.
    - Added new ASTM reference for maintenance and rehabilitation of ground water monitoring wells.
    - Added reference to the Technical Guidance for Ground Water Investigation Chapter 15 - Use of Direct Push Technologies for Soil and Ground Water Sampling.

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CHAPTER 7

MONITORING WELL DESIGN AND INSTALLATION

To collect representative ground water samples, it is necessary to construct monitoring wells to gain access to the subsurface. This chapter covers installation and construction of single-riser/limited interval wells, which are designed such that only one discrete zone is monitored in a given borehole, and multiple interval wells designed to measure multiple discrete depth intervals at a single location. Whether a single riser or multiple interval well is installed, it is important that efforts focus on intervals less than 10 feet thick and be specific to a single saturated zone.

All monitoring wells should be designed and installed in conformance with site hydrogeology, geochemistry, and contaminant(s). While it is not possible to provide specifications for every situation, it is possible to identify certain design components. Figure 7.1 is a schematic drawing of a single-riser/limited interval well. The ***casing*** provides access to the subsurface. The ***intake*** consists of a filter pack and screen. The ***screen*** allows water to enter the well and, at the same time, minimizes the entrance of filter pack materials. The ***filter pack*** is an envelope of uniform, clean, well-rounded sand or gravel that is placed between the formation and the screen. It helps to prevent sediment from entering the well. Installation of a filter pack and screen may not be necessary for wells completed in competent bedrock. The ***annular seal*** is emplaced between the borehole wall and the casing and is necessary to prevent vertical movement of ground water and infiltration of surface water and contaminants. ***Surface protection***, which includes a surface seal and protective casing, provides an additional safeguard against surface water infiltration and protects the well casing from physical damage.

DESIGN OF MULTIPLE-INTERVAL SYSTEMS

It is often necessary to sample from multiple discrete intervals at a given location if more than one potential pathway exists or a saturated zone is greater than 10 feet thick. Chapter 5 - Monitoring Well Placement discusses the concepts involved in selecting zones to monitor. Multiple-interval monitoring can be accomplished by installing single-riser/limited interval wells in side-by-side boreholes (well clusters) or using systems that allow sampling of more than one interval from the same borehole (multi-level wells, well nests, or single-casing, long-screen wells). Multiple-interval monitoring may be useful to:

- Determine the hydraulic head distribution.
- Measure temporal changes in vertical hydraulic head.
- Determine vertical contaminant distribution.
- Provide long-term multilevel water quality monitoring.

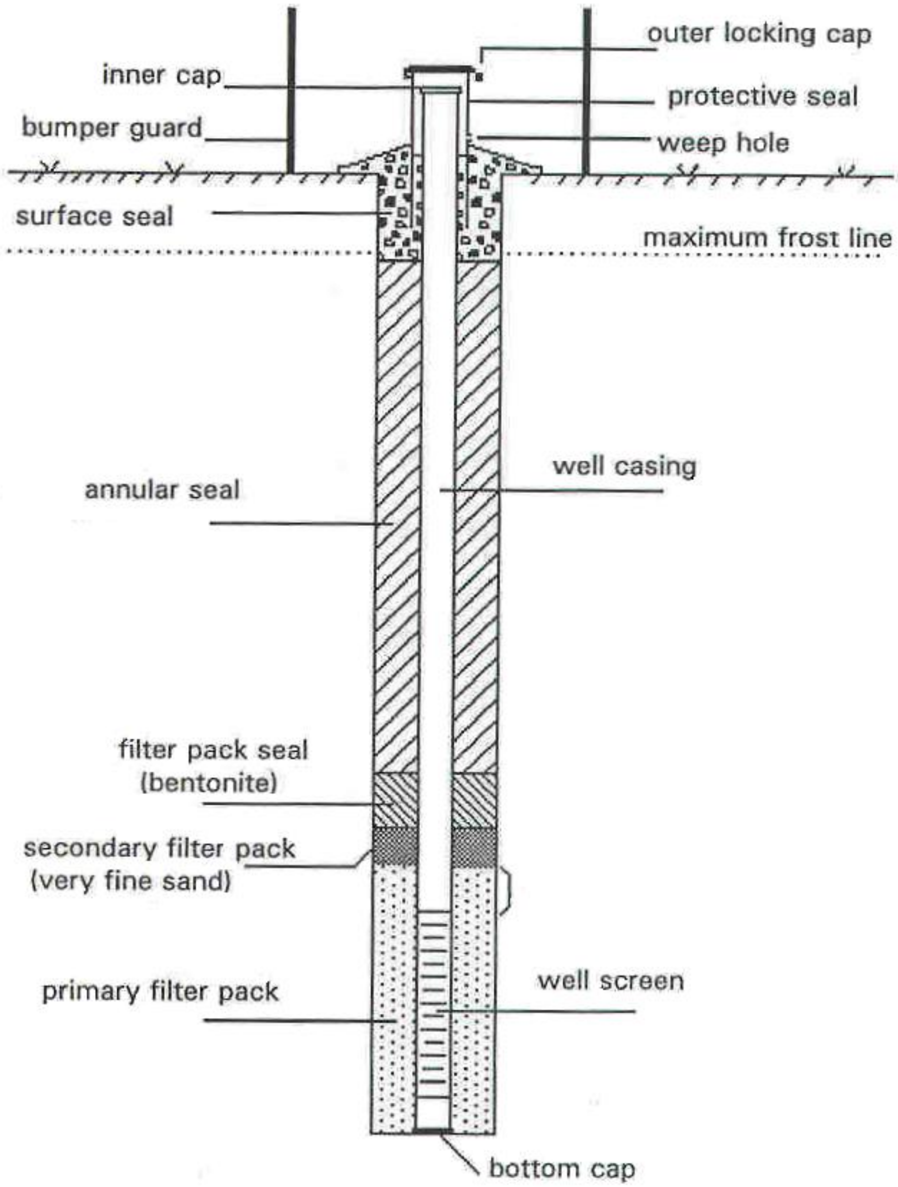

Figure 7.1 Cross-section of a typical single-riser/limited interval monitoring well.

WELL CLUSTERS

When monitoring multiple intervals at one location, single-riser/limited interval wells are often installed in adjacent, separate boreholes. These well clusters can be used to determine vertical gradients when distinct differences in head exist. They may be used to monitor discrete zones or evaluate chemical stratification within a thick zone. If flow direction has been determined prior to installation, the shallow well should be placed hydraulically upgradient of the deeper well to avoid the potential influence on its samples caused by the presence of grout in the annular space of the deeper well.

MULTI-LEVEL WELLS

Multi-level wells allow sampling of more than one interval in a single borehole. These levels are isolated within the well either by packers or grout. Probes, lowered into the casing, can locate, isolate and open a valve into a port coupling to measure the fluid pressure outside the coupling or obtain a sample. Individual tubes run from sampling levels to the surface.

The use of multiple-level monitoring wells in Ohio has been limited due to: 1) cost of installation, 2) difficulty in repairing clogs, and 3) difficulty in preventing and/or evaluating sealant and packer leakage. Detailed workplans (including construction and installation, methods to measure water levels and obtain samples, references to situations where these types of wells have been used successfully, and advantages and disadvantages) should be submitted prior to installing multi-level systems.

Several systems are commercially available for obtaining multi-level monitoring of a single borehole. Most consist of casing or tubing with monitoring ports located at user-selected intervals. In one system, however, a lining containing intermittent sampling ports is placed in the borehole. The systems may be sampled with small diameter pumps and bailers, or using proprietary samplers that go with the monitoring system. See Nielsen and Schalla (2006) for more information on multi-level well systems.

NESTED WELLS

Nested wells involve the completion of a series of single-riser wells in a borehole. Each well is screened to monitor a specific zone, with filter packs and seals employed to isolate the zones. Nested wells are not recommended because they are difficult to install in a manner that ensures that all screens, filter packs, and seals are properly placed and functioning. It is more efficient to install single-riser wells for each interval to ensure that representative samples can be collected. Aller et al. (1991) indicated that individual completions generally are more economical at depths less than 80 feet. According to Nielsen and Schalla (2006), the cost of installing well clusters is comparable to the cost for nested wells. Well clusters can enable savings on sampling and future legal costs that may be necessary to prove the accuracy of nested wells.

SINGLE-CASING, LONG-SCREEN WELLS

Single-casing, long-screen wells are monitoring wells that, in general, are screened across the entire thickness of a water-bearing zone. If purging is performed immediately before sampling, only composite water samples are yielded, which are not adequate for most monitoring studies. If natural, flow-through conditions can be maintained, vertical water quality profiles can be obtained with passive sampling techniques. Vertical profiling may be a cost effective initial assessment to determine the depth of final wells.

Long-screen wells are not appropriate for detection monitoring. Furthermore, these wells can allow cross-contamination between different zones and, therefore, should not be used in contaminated areas.

CASING

The purpose of casing is to provide access to the subsurface for sampling of ground water and measurement of water levels. A variety of casing types have been developed. Items that must be considered during well design include casing type, coupling mechanism, diameter, and installation.

CASING TYPES

Three categories of casing are commonly used for ground water monitoring, including fluoropolymers, metallics, and thermoplastics (Aller et al., 1991). All have distinctive characteristics that determine their appropriateness.

Fluoropolymers

Fluoropolymers are synthetic plastics composed of organic material. They are resistant to chemical and biological attack, oxidation, weathering, and ultraviolet (UV) radiation. They have a broad useful temperature range, a high dielectric constant, a low coefficient of friction, display anti-stick properties, and have a greater coefficient of thermal expansion than most other plastics and materials (Aller et al., 1991). Standard properties of the various materials have been provided by Aller et al. (1991).

The most common fluoropolymer used for monitoring wells is polytetrafluoroethylene (PTFE). It can withstand strong acids and organic solvents and, therefore, it is useful for environments characterized by the presence of these chemicals. It maintains a low tensile strength, which theoretically limits installation of Schedule 40 PTFE to an approximate depth of 250 ft[1]. It is also very flexible, which makes it difficult to install with the retention of straightness that is needed to ensure successful insertion of sampling or measurement devices. Dablow et al. (1988) found that the ductile nature of PTFE can result in the partial closing of screen slots

[1] The maximum depth for PTFE casing depends on site hydrogeology. If the casing largely penetrates unsaturated soils, the depth may be limited to approximately 100 feet. However, if the casing is placed mostly in water-bearing zones, then depth may be as great as 375 feet.

due to the compressive forces of the casing weight. This makes slot size selection very difficult. PTFE is costly, generally ten times more expensive than thermoplastics. Studies by Gillham and O'Hannesin (1990), Parker et al. (1990), and Parker and Raney (1993) (in Nielsen and Schalla, 2006), found that PTFE showed higher sorption rates than PVC of organic compounds. These studies concluded that PVC was a better material to use when organics are present.

Metallics

Metallic materials include low carbon, carbon, galvanized, and stainless steel. Metallics are very strong and rigid and can be used to virtually unlimited depths. Corrosion problems are the major disadvantage for low carbon, carbon, and galvanized casings, as electrochemical and chemical attack alters water sample quality. U.S.EPA (1992) has listed the following as indicators of corrosive conditions (modified from Driscoll, 1986):

- Low pH (< 7.0).
- Dissolved oxygen exceeds 2 ppm.
- Hydrogen sulfide in quantities as low as 1 ppm.
- Total dissolved solids (TDS) greater than 1000 ppm.
- Carbon dioxide exceeds 50 ppm.
- Chloride (Cl^-), bromide (Br^-), and fluoride (F^-) content together exceeds 500 ppm.

According to Barcelona et al. (1983), flushing before sampling does not minimize the bias of low carbon steel due to the inability to predict the effects of disturbed surface coatings and corrosion products accumulated at the bottom of the well. Due to their high corrosion potential, all metallics except stainless steel are unacceptable for monitoring wells.

Stainless steel is manufactured in two common types, 304 and 316. Type 304 is composed of iron with chromium and nickel. Type 316's composition is the same as Type 304's, but includes molybdenum, which provides further resistance to sulfuric acid solutions. Stainless steel is readily available in a wide variety of diameters.

Stainless steel can perform quite well in most corrosive environments. In fact, oxygen contact develops an external layer that enhances corrosion resistance (Driscoll, 1986). However, several studies cite the formation of an iron oxide coating on the surface of stainless steel casing that forms in long-term exposure to ground water that can have unpredictable effects on the adsorption capacity of the casing material (Nielsen and Schalla, 2006). Under very corrosive conditions, stainless steel can corrode and release nickel and chromium into ground water samples (Barcelona et al., 1983). Combinations and/or extremes of the factors indicating corrosive conditions generally are an indication of highly corrosive environments. For example, Parker et al. (1990) found that both 304 and 316 showed rapid rusting (<24 hrs.) when exposed to water containing chloride above 1000 mg/l, and a study by Oakley and Korte (in Nielsen and Schalla, 2006) noted corrosion of stainless steel at even lower chloride levels (600-900 mg/L). Like PTFE, stainless steel is relatively expensive in comparison with thermoplastics. Nielsen and Schalla (2006) and Aller et al. (1991) provided additional information on the properties of stainless steel.

Thermoplastics

Thermoplastics are composed of large, synthetic organic molecules. The most common type used for monitoring wells is polyvinyl chloride (PVC), while a material used less often is acrylonitrile butadiene styrene (ABS). These materials are weaker, less rigid, and more temperature-sensitive than metallics. Thermoplastics are very popular due to their light weight, high strength to weight ratio, low maintenance, ease of joining, and low cost.

Common, acceptable PVC types are Schedule 40 and Schedule 80. The greater wall thickness of Schedule 80 piping enhances durability and strength, provides greater resistance to heat attack from cement, and allows construction of deeper wells. Only rigid PVC should be used for monitoring wells. Flexible PVC is composed of a high percentage of plasticizers (30 - 50%), which tend to degrade and contaminate samples (Jones and Miller, 1988). All PVC casing should meet Standard 14 of NSF International. This standard sets control levels for the amount of chemical additives to minimize leaching of contaminants (NSF International, 1988). Additional specifications have been provided by Nielsen and Schalla (2006) and Aller et al. (1991).

Drawbacks of PVC include brittleness caused by ultraviolet (UV) radiation, low tensile strength, relative buoyancy in water, and susceptibility to chemical attack. It is immune to corrosion and is resistant to most acids, oxidizing agents, salts, alkalies, oils, and fuels (NWWA/PPI, 1981). Additionally, Schmidt (1987) showed that no degradation of PVC occurred after six months immersion in common gasolines. However, studies have shown that high concentrations (parts-per-thousand or percentage concentrations) of tetrahydrafuran, methyl ethyl ketone, methyl isobutyl ketone, and cyclohexane degrade PVC (Nielsen and Schalla, 2006). Barcelona et al. (1983) reported that low molecular weight ketones, aldehydes, amines, and chlorinated alkenes and alkanes may cause degradation. Studies by Ranney and Parker (1995, 1997) and Parker and Ranney (1994b, 1995, 1996), showed that PVC is degraded when exposed to higher concentrations (0.2 and 0.4, or 20% and 40% of the solubility limit of the solvent in water) of aromatic hydrocarbons, aromatic and aliphatic chlorinated solvents, ketones, anilines, aldehydes and nitrogen-containing organic compounds. It is recommended that PVC not be used in situations where the material may be exposed to concentrations of known solvents or swelling agents of PVC greater than 25% of the solubility limit of the solvent or swelling agent (Nielsen and Schalla, 2006).

TYPE SELECTION

Many regulated parties choose PVC casing because of its lower cost; however, well integrity and sample representativeness are more important criteria. The high cost of analysis and the extreme precision of laboratory instruments necessitate the installation of wells that produce representative samples. Above all, the burden of proof is on the regulated party to demonstrate that casing is appropriate. The proper selection can be made by considering casing characteristics in conjunction with site conditions.

Casing characteristics include strength, chemical resistance, and chemical interference potential. The ***strength*** must withstand the extensive tensile, compressive, and collapsing forces involved in maintaining an open borehole. Since the forces exerted are, in large part, related to well depth, strength often is important when planned depth exceeds the maximum range of the weakest acceptable material (100 to 375 ft. - PTFE). In these instances, either stainless steel or PVC should be chosen. Strength can be the overriding factor because the concern for chemical resistance and interference become insignificant if an open borehole cannot be maintained. Nielsen and Schalla (2006) provided specific strength data for commonly used materials.

The casing also must withstand ***electrochemical corrosion and chemical attack*** from natural ground water and any contaminant(s). Chemical resistance is most important in highly corrosive environments, when contaminants are present at extremely high levels, and when wells are intended to be part of a long-term monitoring program. For extended monitoring in corrosive environments, PTFE and PVC are preferred over stainless steel because of the potential for the metallic material to degrade. If high concentrations of organics (parts per thousand) are present, either PTFE or stainless steel should be selected. PVC should not be used if a PVC solvent/softening agent is present or the aqueous concentration of a solvent/softening agent exceeds 25% of its solubility in water. It is suitable in most situations where low (parts per billion to low parts per million) levels of most organic constituents are present (Nielsen and Schalla, 2006).

The casing also should not interfere with sample quality by ***adding* (*leaching*) *or removing contaminants*.** In most cases, the magnitude of this interference is a function of the ground water's contact time with the casing. The longer the contact, the greater the potential for leaching and sorption. Various studies have been conducted [Barcelona and Helfrich (1988), Curran and Tomson (1983), Gillham and O'Hannesin (1990), Jones and Miller (1988), Miller (1982), Parker and Jenkins (1986), Parker et al. (1990), Reynolds and Gillham (1985), Schmidt (1987), Sykes et al. (1986), Tomson et al. (1979), Hewitt (1992, 1994), Parker and Ranney (1994)] to compare the sorbing and leaching characteristics of the three favored materials. No conclusive results have been obtained to indicate that any one is best. Most of these studies involved contact lasting days, weeks, and even months and, therefore, the results cannot be correlated to field conditions where contact is often minimal because sampling is generally conducted soon after purging.

In many cases, concern about sorption or leaching may be exaggerated. Barcelona et al. (1983) and Reynolds and Gillham (1985) both concluded that the potential sorption biases for casing may be discounted due to the short contact after purging. Also, Parker et al. (1990) indicated that sorption of various constituents never exceeded 10 percent in the first 8 hours of their tests. They concluded that, on the basis of overall sorption potential for organic and inorganic compounds, PVC is the best compromise.

In summary, the appropriate casing should be determined on a case-by-case basis. PVC is acceptable when free product is not present and the solubility limits of organic contaminants are not approached (e.g., levels that exceed 0.25 times the solubility). Ohio EPA recognizes the difficulty inherent in establishing a "cut-off" level for when aqueous concentrations of organics cause failure of PVC. To be certain that casing will retain integrity, particularly when monitoring is planned for long periods of time (e.g., 30 years), Ohio EPA may recommend a more resistant casing when aqueous concentrations are relatively high but still below the criteria mentioned above.

HYBRID WELLS

Casing not in contact with the saturated zone generally is not subject to attack. Therefore, it may be possible to install less chemically resistant material above the highest seasonal water level and more inert material where ground water continually contacts the casing. Such a "hybrid well" commonly is installed to reduce costs. For example, when monitoring a zone with high concentrations of organics, stainless steel could be installed opposite the saturated materials, while PVC could be used opposite the unsaturated materials. Thus, resistant, more expensive casing would be present where contact with highly contaminated ground water may occur, while less resistant, inexpensive casing would be present where contact does not occur.

Variations in ground water levels caused by seasonal or pumping effects should be taken into account when planning the casing material configuration (Nielsen and Schalla, 2006). Different varieties of steel never should be installed in the same well. Each type is characterized by its own electro-chemical properties. Installation of different types in contact can increase the potential for corrosion.

COUPLING MECHANISMS

Casing sections should be connected using threaded joints that provide for uniform inner and outer diameters along the entire length of the well. Such "flush" coupling is necessary to accommodate tools and sampling devices without obstruction and to help prevent bridging during the installation of the filter pack and annular seal. It should be noted that thread types vary between manufacturers and matching can be difficult. A union among non-matching joints should never be forced, otherwise structural integrity of the joint and the entire well could be compromised. To alleviate these problems, the American Society of Testing and Materials has developed Standard F 480-90 (1992) to create a uniformly manufactured flush-threaded joint. Most manufacturers now produce the F 480 joint, which is available in both PVC and stainless steel.

Solvent cements should never be used because they are known to leach organics. Metal fasteners such as rivets or screws should not be used to supplement threaded joints. Use of such fasteners can reduce the effective inner well diameter, and may damage pumps or other tools lowered into the well (Nielsen and Schalla, 2006).

It is recommended that either nitrile, ethylene propylene, or Viton O-rings be used between sections to prevent the seal and/or affected water from entering (Nielsen and Schalla, 2006). Nielsen and Schalla (2006) indicated that Teflon tape can be used in place of O-rings, although it does not ensure as good a seal. Although welding stainless steel can produce a flush joint that is of equal or greater strength than the casing itself, this method is not used as commonly as threaded joints due to the extra assembly time, welding difficulty, corrosion enhancement, ignition danger, and the potential to lose materials into the well (Nielsen and Schalla, 2006). Threaded steel casing provides inexpensive, convenient connections. It should be noted that threaded joints reduce the tensile strength of the casing; however, this does not cause a problem for most shallow wells. Also, threaded joints may limit or hinder the use of various sampling devices when thin-walled stainless steel (Schedules 5 and 10) is employed. Thin-walled casing is too thin for threads to be machined, so the factory welds a short, threaded section of Schedule 40 stainless steel pipe to the end of the thin-walled pipe. These joints are made to be flush on the outside, but not the inside.

If hybrid wells are installed, it is essential that the joint threads be matched properly. This can be accomplished by purchasing casing screen that is manufactured to ASTM F480-90 (1992) standard coupling.

DIAMETER

Choice of casing diameter is site-specific. Small wells are considered to be less than 4 inches in diameter. Wells installed using conventional drilling methods are generally 2 or 4 inches in diameter. Wells installed by direct push technologies (see Chapter 15 – Use of Direct Push Technologies for Soil and Ground Water Sampling) have diameters of 2 inches to as small as 0.5 inch. Advantages of small diameter wells are as follows:

- Water levels require less time to recover after purging.
- They produce a smaller volume of purged water that must be disposed.
- Construction costs are lower.
- They are more easily installed by driven, direct push, jetting, or hollow stem augers.

Some disadvantages of small diameter wells include:

- Access may be limited for sampling devices.
- Filter packs and seals are more difficult to install.
- They offer a lower depth capability due to lesser wall thickness.
- Development can be more difficult.
- Less ground water is pumped during a hydraulic test or a remediation extraction.
- The amount of available water may be too small for chemical analyses.
- Slower recovery after water removal.

CASING INSTALLATION

Casing should be cleaned thoroughly before installation. Strong detergents and even steam cleaning may be necessary to remove oils, cleansing solvents, lubricants, waxes, and other substances (Curran and Tomson, 1983; Barcelona et al., 1983). It is strongly recommended that only factory-cleaned materials be used for monitoring wells. Casing can be certified by the supplier and individually wrapped in sections to retain cleanliness. If it has not been factory-cleaned and sealed, it should be washed thoroughly with a non-phosphate, laboratory grade detergent (e.g., Liquinox) and rinsed with clean water or distilled/deionized water as suggested by Curran and Tomson (1983) and Barcelona et al. (1983). The materials should be stored in a clean, protected place to prevent contamination by drilling and site activities.

When installing casing, it is important that it remain centered in the borehole to ensure proper placement and even distribution of the filter pack and annular seal. In addition, centering helps ensure straightness for sampling device access. If a hollow-stem auger is used, no additional measures are necessary because the auger acts as a centralizing device. If casing is installed in an open borehole, centralizers made of stainless steel or PVC can be used. They are adjustable and generally attached just above the screen and at 10 to 20 foot intervals along the riser. If centralizers are used, measures should be taken to prevent them from bridging the filter pack and seal material during their installation.

If the well screen and riser are significantly lighter than the buoyant force of the fluid in the borehole, the casing assembly may require ballast to offset the tendency of the materials to float in the borehole. The riser may be ballasted by filling it with water of a known and acceptable source or with water previously removed from the borehole. Alternatively, hydraulic rams on the drill rig may be used to push the riser into the borehole (ASTM D5092-04).

INTAKES

Although every well is unique, most have a screen and filter pack comprising the well intake. Monitoring wells in cohesive bedrock may incorporate open borehole intakes.

FILTER PACK

Wells monitoring unconsolidated and some poorly consolidated materials typically need to have a screen (discussed later) surrounded by more hydraulically conductive material (filter pack). In essence, the filter pack increases the effective well diameter and prevents fine-grained material from entering.

Types of Filter Packs

Filter packs can be classified by two major categories, natural and artificial. ***Natural packs*** are created by allowing the formation to collapse around the screen. In general, natural packs are recommended for formations that are coarse-grained, permeable, and uniform in grain size. Grain size distribution of the formation should be determined through a sieve analysis of samples from the formation. According to Nielsen and Schalla (2006), natural packs may be suitable when the effective grain size (sieve size that retains 90%, or passes 10%) is greater than 0.010 inch and the uniformity coefficient (the ratio of the sieve size that retains 40% and the size that retains 90%) is greater than 3. Ideally, all fine-grained particles are removed when the well is developed, leaving the natural pack as a filter to the surrounding formation.

Installation of ***artificial packs*** involves the direct placement of coarser-grained material around the screen. The presence of this filter allows the use of a larger slot size than if the screen were in direct contact with the formation. Artificial packs generally are necessary where: 1) the formation is poorly sorted; 2) the intake spans several formations and/or thin, highly stratified materials with diverse grain sizes; 3) the formation is a uniform fine sand, silt or clay; 4) the formation consists of thinly-bedded materials, poorly cemented sandstones, and highly weathered, fractured, and solution-channeled bedrock; 5) shales and coals that provide a constant source of turbidity are monitored; and 6) the borehole diameter is significantly greater than the diameter of the screen (Aller et al., 1991), (Nielsen and Schalla, 2006). Artificial packs generally are used opposite unconsolidated materials when the effective grain size is less than 0.010 inches and when the uniformity coefficient is less than 3.0 (Nielsen and Schalla, 2006). Pre-packed well screens (discussed below) may also be used to install an artificial filter pack. The filter pack for these screens is installed at the surface, ensuring an effective filter pack.

An artificial pack may include two components. The ***primary pack*** extends from the bottom of the borehole to above the top of the screen. In some cases, it may be desirable to place a ***secondary pack*** directly on top of the primary pack. Its purpose is to prevent the infiltration of the annular seal into the primary pack, which can partially or totally seal the screen.

Nature of Artificial Filter Pack Material

The artificial pack material should be well-sorted, well-rounded, clean, chemically inert, of known origin, and free of all fine-grained clays, particles and organic material. Barcelona et al. (1983) recommended clean quartz sand or glass beads. Quartz is the best natural material due to its non-reactive properties and availability. Crushed limestone should never be used because of the irregular particle size and potential chemical effects. Materials should be washed, dried, and packaged at the factory, and typically are available in 100 lb. bags (approximately one cubic foot of material) (Nielsen and Schalla, 2006).

The material should be based on the formation particle size. If chosen grains are too small, it is possible that loss of the pack to the formation can occur (Nielsen and Schalla, 2006), which could lead to the settling of the annular seal into the screened interval. On the other hand, if the grains are too large, the pack will not effectively filter fine-grained material, leading to excessively turbid samples. For these reasons, the universal application of a single well screen/filter pack combination to all formations should be avoided (ASTM D5092-04).
The primary pack generally should range in grain size from a medium sand to a cobbled gravel. Most materials are available in ranges, such as 20- to 40-mesh (0.033 to 0.016 inches, Table 7.1). The grain size of the primary filter pack should be determined by multiplying the 70% retention size of the formation by a factor of 3 to 6 (U.S. EPA, 1975). A factor of 3 is used for fine, uniform formations; a factor of 6 is used for coarse, non-uniform formations. Where the material is less uniform and the uniformity coefficient ranges from 6 to 10, it may be necessary to use the 90% retention (10% passing) size multiplied by 6 (Nielsen and Schalla, 2006). This is to ensure that the bulk of the formation will be retained. The ratio of the particle size to the formation grain size should not exceed 6, otherwise, the pack will become clogged with fine-grained material from the formation (Lehr et al., 1988). If the ratio is less than 4, a smaller screen slot size will be necessary, full development of the well may not be possible, and well yield may be inhibited. When monitoring in very heterogeneous, layered stratigraphy, a type of pack should be chosen that suits the layer with the smallest grain size.

It is preferred that the filter pack be of uniform grain size. Ideally, the uniformity coefficient should be as close to 1.0 as possible and should not exceed 2.5 (Nielsen and Schalla, 2006, ASTM D5092-04, 2005). Uniform material is much easier to install. If non-uniform material is used, differing fall velocities cause the materials to grade from coarse to fine upwards along the screen. This can result in the loss of the upper fine-grained portion to the well during development.

The secondary filter pack material should consist of a 90% retention sieve size (10% passing) that is larger than the voids of the primary pack to prevent the secondary pack from entering the primary pack (Nielsen and Schalla, 2006). In general, the secondary 90% retention size should be one-third to one-fifth of the primary 90% retention size (Nielsen and Schalla, 2006).

Dimension of Artificial Filter Pack

The filter pack should be thick enough to completely surround the well screen. The well annulus should be large enough to preclude bridging of the filter-pack material. Centering of the well screen in the borehole will ensure adequate space for an effective filter pack. Driscoll (1986) states that the mechanical filtration function of the filter pack can be achieved with a filter pack of only 2 to 3 grains in thickness. Filter packs of less than a half inch thick have been successfully used in pre-packed well screens that are installed in direct push boreholes (Nielsen and Schalla, 2006).

The primary pack should extend from the bottom of the screen to at least 3 feet above its top (Nielsen and Schalla, 2006). In deeper wells (i.e., >200 feet), the pack may not compress initially. Compression may occur after installation of the annular seal, which may allow the seal to be in close contact with the screen. Therefore, additional pack material may be needed to account for settling and, at the same time, provides adequate separation of the seal and the screen. However, extension of the pack should not be excessive because it enlarges the zone that contributes ground water to the well, which may cause excess dilution. The length of the secondary pack should be 1 foot or less.

Artificial Filter Pack Installation

Methods that have been used for artificial pack installation include tremie pipe, gravity emplacement, reverse circulation, and backwashing (Nielsen and Schalla, 2006). The material should be placed in a manner that prevents bridging and particle segregation. Bridging can cause large voids and may prevent material from reaching the intended depth. Segregation can cause a well to produce turbid samples. During installation, regular measurements with a weighted tape should be conducted to determine when the desired height has been reached, and also act as a tamping device to reduce bridging. The anticipated volume of filter pack should be calculated.[2] Any discrepancy between the actual and calculated volumes should be explained.

[2] Anticipated filter pack volume can be calculated by determining the difference in volume between the borehole and casing (using outside diameter of the well) from the bottom of the borehole to the appropriate height above the well screen.

Table 7.1 Common filter pack characteristics for typical screen slot sizes (From Nielsen and Schalla, 2006).

Size of Screen Opening [mm (in.)]	Slot No.	Sand Pack Mesh Size	1% Passing Size (D_1) (mm)	Effective Size (D_{10}) (mm)	30% Passing Size (D_{30}) (mm)	Range of Uniformity Coefficient	Roundness (Powers Scale)	Fall Velocities[a] (cm/s)
0.125(0.005)	5	40-140	0.09-0.12	0.14-0.17	0.17-0.21	1.3-2.0	2-5	6-3
0.25 (0/010)	10	20-40	0.25-0.35	0.4-0.5	0.5-0.6	1.1-1.6	3-5	6-6
0.50 (0.020)	20	10-20	0.7-0.9	1.0-1.2	1.2-1.5	1.1-1.6	3-6	14-9
0.75 (0.030)	30	10-20	0.7-0.9	1.0-1.2	1.2-1.5	1.1-1.6	3-6	14-9
1.0 (0.040)	40	8-12	1.2-1.4	1.6-1.8	1.7-2.0	1.1-1.6	4-6	16-13
1.5 (0.060)	60	6-9	1.5-1.8	2.3-2.8	2.5-3.0	1.1-1.7	4-6	18-15
2.0 (0.080)	80	4-8	2.0-2.4	2.4-3.0	2.6-3.1	1.1-1.7	4-6	22-16

[a] Fall velocities in centimeters per second are approximate for the range of sand pack mesh sizes named in this table . If water in the annular space is very turbid, fall velocities may be less than half the values shown here. If a viscous drilling mud remains in the annulus, fine particles may require hours to settle.

The preferred method for artificial pack installation is to use a ***tremie pipe*** to emplace material directly around the screen (Figure 7.2). The pipe is raised periodically to help minimize bridging. The pipe generally should be at least 1 inch ID, but larger diameters may be necessary where coarser-grained packs are being installed. When driven casing or hollow-stem augering is used to penetrate non-cohesive formations, the material should be tremied as the casing and auger is pulled back in one to two foot increments to reduce caving effects and ensure proper placement (Nielsen and Schalla, 2006). When installing wells through cohesive formations, the tremie pipe can be used after removal of the drilling device.

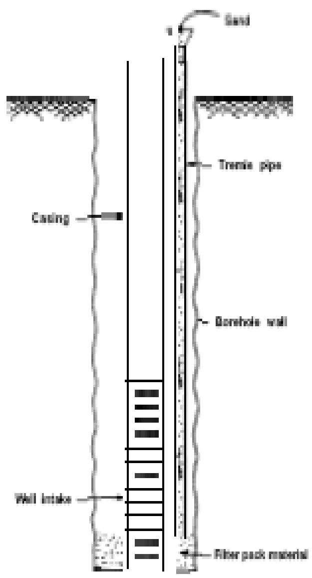

Figure 7.2. Installation of artificial filter pack material with a tremie pipe. (Source: Aller et al., 1991).

Gravity emplacement is accomplished by allowing material to free-fall to the desired position around the screen. Placement by gravity should be restricted to shallow wells with an annular space greater than 2 inches, where the potential for bridging or segregation is minimized (Nielsen and Schalla, 2006). For low-yielding formations, it may be possible to bail the borehole dry to facilitate placement; however, segregation is generally not a problem if the pack has a uniformity coefficient of 2.5 or less. Gravity placement also can cause grading if the material is not uniform. In addition, formation materials are often incorporated during placement, which can contaminate the pack and reduce its effectiveness. For most cases, gravity placement is not recommended.

Reverse circulation involves the insertion of a sand and water mixture through the annulus. Sand is deposited around the screen as the water returns to the surface through the casing. Due to the potential water quality alteration, this method generally is not recommended.

Sand is deposited around the screen as the water returns to the surface through the casing. Due to the potential water quality alteration, this method generally is not recommended.

Backwashing is accomplished by allowing material to free-fall through the annulus while clean water is pumped down the casing. The water returns up the annulus carrying fine-grained material with it. This creates a more uniform pack; however, the method is not commonly used for monitoring well installation and generally is not recommended due to the potential for alteration of ground water quality. Nonetheless, it is sometimes used for placing packs opposite non-cohesive heaving sands and silts.

SCREEN

The screen provides an access point to a specific portion of a ground water zone, as well as providing a barrier to keep unwanted formation particles out of ground water samples.

Screen Types

Recommended screen compositions are stainless steel, PTFE, and PVC. The same discussion and concerns for casing materials apply to screens. Only manufactured screens should be used, since these are available with slots sized precisely for specific grain sizes. Field-cut or punctured screen should never be used, due to the inability to produce the necessary slot size and the potential for the fresh surface to leach or sorb contaminants. A bottom cap or plug should be placed at the base of the screen to prevent sediments from entering and to ensure that all water enters the well through the screen openings.

Slotted and continuous slot, wire-wound screen are the common types used for monitoring wells. In deep wells, slotted screen generally retains structural integrity better than wire-wound; however, continuous slot, wire-wound screens provide almost twice the open area of slotted casing. More open area per unit length enhances well recovery and development. A slot type should be chosen that provides the maximum amount of open area in relation to the effective porosity of the formation. Opinions vary regarding the optimum percentage of open area needed for effective hydraulic performance of well screens. Though it has been suggested that a range of open areas from 8 to 38% do not differ significantly in well performance, Driscoll (1986) recommended that the percentage of open area should be at least equal to the effective porosity of the formation and filter pack. In common situations with 8 to 30 percent effective porosities, continuous slot screens are preferred, although not required. A high percentage of open area is of greater importance when wells are installed in fine-grained formations where smaller slot sizes and fine-grained filter packs are required (Nielsen and Schalla, 2006).

Pre-Packed Screen Wells

A pre-packed screen is an assembly consisting of an inner slotted screen surrounded by a wire mesh sleeve that acts as a support for filter media. The pre-packed screen assemblies can either be shipped with filter media already packed within the mesh sleeve or can be shipped without filter media and packed with filter sand in the field. Refer to ASTM D5092-04 for appropriate sizing of filter pack material. Pre-packed well screens help eliminate problems in the placement of filter pack around the screens of small diameter wells. In fine-grained formations pre-packed screens may be best for ensuring proper filter pack placement.

(ASTM D5092-04). The wells are sealed and grouted using the same procedure described for conventionally completed DPT wells. ASTM D6725-04 provides additional guidance on the use of pre-packed wells.

Slot Size

When selecting a screen slot size for an artificially filter-packed well, a sieve analysis should be conducted on the pack material. The selected size should retain at least 90% of the pack. In many situations it is preferable to retain 99% (Nielsen and Schalla, 2006 and ASTM D 5092-90, 1994). See Table 7.1 for a guide to the selection of slot sizes for various packs.

For naturally-packed wells, the screen should retain at least 70% of the pack (Nielsen and Schalla, 2006, ASTM D5092-04). For additional information on pack and screen selection, see Aller et al. (1991), Nielsen and Schalla, (2006), and ASTM D 5092-90 (1994).

It should be noted that if a PTFE screen is used in a deep well, a slightly larger slot size than predicted should be selected due to the material's lower compressive strength, which allows the openings to compress (Dablow et al., 1988).

Length

Screen length should be tailored to the desired zone and generally should not exceed 10 ft. A 2 to 5 ft. screen is desirable for more accurate sampling and discrete head measurements. Longer screens produce composite samples that may be diluted by uncontaminated water. As a result, concentrations of contaminants may be underestimated. In addition, if vertical flow is present, the well screen may provide a pathway for redistribution of contaminants, and possible cross-contamination of the formation (Nielsen and Schalla, 2006). Furthermore, the screen should not extend through more than one water-bearing zone to avoid cross-contamination. When a thick formation must be monitored, a cluster of individual, closely spaced wells, screened at various depths, can be installed to monitor the entire formation thickness. The length of screens that monitor the water table surface should account for seasonal fluctuation of the water table. For related information on screen length, refer to Chapter 5 – Monitoring Well Placement.

OPEN BOREHOLE INTAKES

When constructing monitoring wells in competent bedrock, an artificial intake is often unnecessary because an open hole can be maintained and sediment movement is limited. Installing a filter pack in these situations may be difficult due to loss of material into the surrounding formation. In some cases, however, intakes are a necessary component of bedrock wells. A screen and filter pack should be installed in highly weathered, poorly cemented, and fractured bedrock (Nielsen and Schalla, 2006). They are usually necessary when monitoring the unconsolidated/consolidated interface in Ohio.

Open hole wells often are completed by casing and grouting the annulus prior to drilling into the monitoring zone. In cases where the zone has been drilled prior to sealing the annulus, a bridge (cement basket or formation packer shoe) must be set in the hole to retain the grout/slurry to the desired depth (Driscoll, 1986).

If an open hole well is installed, the length of open hole generally should not exceed 10 feet to prevent sample dilution. To maintain a discrete monitoring zone in consolidated formations, the casing should be extended and grouted to the appropriate depth to maintain the 10 foot limit. Driven casing may be necessary to avoid loss of the annular seal into the surrounding formation.

ANNULAR SEALS

The open, annular space between the borehole wall and the casing must be sealed properly to: 1) isolate a discrete zone, 2) prevent migration of surface water, 3) prevent vertical migration of ground water between strata, and 4) preserve confining conditions by preventing the upward migration of water along the casing. An effective seal requires that the annulus be filled completely with sealant and the physical integrity of the seal be maintained throughout the lifetime of the well (Aller et al., 1991).

MATERIALS

The sealant must be of very low permeability (generally 10^{-7} to 10^{-9} cm/sec), capable of bonding with casing, and chemically inert with the highest anticipated concentration of chemicals expected. Cuttings from the existing borehole, no matter what the type of materials, should never be used. They generally exhibit higher permeability and cannot form an adequate seal. The most common materials used are bentonite and neat cement grout. Each has specific, unique, and desirable properties. These materials are discussed briefly here. Additional information can be found in Michigan DEQ (2007), ASTM Method C-150 (2007), and Nielsen and Schalla (2006).

Bentonite

Bentonite is composed of clay particles that expand many times their original volume when hydrated. The most acceptable form is a sodium (Na) rich montmorillonite clay that exhibits a 10- to 12-fold expansion when hydrated. Other types, such as calcium (Ca) bentonite, are less desirable because they offer lower swelling ability and surface area to mass ratios. However, other types should be considered if Na bentonite is incompatible with the formation or analyses of concern. For example, the capability of bentonite may be adversely affected by chloride salts, acids, alcohols, ketones, and other polar compounds. Ca bentonite may be more appropriate for calcareous sediments.

Bentonite is available in a variety of forms, including pelletized, coarse grade, granular and powder. ***Pellets*** are uniform in size and consist of compressed, powdered Na montmorillonite. They typically range from 1/4 to 1/2 inch in size. Pellets expand at a relatively slower rate when compared to other forms. ***Coarse grade***, also referred to as crushed or chipped, consists of irregularly shaped, angular particles of montmorillonite that range from 1/4 to 3/4 inches in size. ***Granular*** particles range from 0.025 to 0.10 inches in size. ***Powdered*** bentonite is pulverized montmorillonite, factory-processed after mining. Powered and granular forms are generally mixed with water to form a slurry.

Risk of losing a slurry to the underlying filter pack and surrounding formation should be considered. Bentonite slurry with less than 30 percent solids can lose its affinity for water, thus losing water to the formation (Listi, 1993). Bentonite used for drilling fluids/drilling fluid mud has a low solids content and therefore forms poor seals, so they are not suitable as annular seal materials (Edil et al., 1992). High-solids bentonite (>30% clay solids) has been developed specifically for monitoring well construction and provides an effective seal. High-solids bentonite slurries may also be formed by the addition of a swelling inhibitor to slow the swelling of the bentonite power, or addition of granular bentonite to bentonite slurry just prior to emplacement with a tremie pipe (Nielsen and Schalla, 2006).

Neat Cement Grout

Neat cement grout is comprised of portland cement and water, with no aggregates added. It is a hydraulic cement produced by pulverizing cement clinker consisting essentially of hydrated calcium silicates, and usually containing one or more forms of calcium sulfate as an interground addition. Several types of portland cements are manufactured to accommodate various conditions. Table 7.2 lists the types as classified by ASTM C150-07(2007). Type I is most commonly used for monitoring wells.

Air-entraining portland cements have been specially processed to form minute air bubbles within the hardened structure. The air-entraining materials are added during the grinding of the clinker. The finished product is more resistant to freeze-thaw action. Air-entraining cements are designated with an "A" after the ASTM cement type. They have been used to construct water supply wells; however, they are less desirable than standard cements because of their greater permeability. Therefore, air-entraining varieties are not recommended for subsurface sealing of monitoring wells.

Water added to the neat cement should be potable and contain less than 500 ppm total dissolved solids (Nielsen and Schalla, 2006). Low chloride and sulfate concentrations also are desirable (Campbell and Lehr, 1973). As the water to cement ratio increases, the compressive strength of the cement decreases and shrinkage increases. The American Petroleum Institute recommends a ratio of 5.2 gallons of water per 94 pound sack of cement. Additional water makes it easier to pump, but adversely affects the grout's sealing properties. Excess water can cause shrinkage and separation of the cement particles, which compromises seal integrity (Nielsen and Schalla, 2006).

Table 7.2 ASTM cement designation (modified from Michigan DEQ, 2007).

CEMENT TYPE	DESCRIPTION
Type I	General purpose cement suitable where special properties are not required. Most common type of cement used for grouting.
Type II	Moderate sulfate resistance. Lower heat of hydration than Type I.
Type III	High early strength. Not commonly used. Ground to finer particle size, which increases surface area and reduces curing time period before drilling may resume from 48 hours to 12 hours.
Type IV	Low heat of hydration cement designated for applications where the rate and amount of heat generated by the cement must be kept to a minimum. Develops strength at a lower rate than Type I. Not commonly used.
Type V	Sulfate-resistant cement for use where ground water has a high sulfate content.
Type IA, IIA, and IIIA	Air entraining cements for the same use as Types I, II, and III. Not recommended for monitoring well construction.

The major disadvantages of neat cement are its heat of hydration, shrinkage upon curing, and its effect on water quality. During curing, heat is released, which is generally of little concern for monitoring wells. If large volumes of cement are used or the heat is not rapidly dissipated, the resulting high temperatures can compromise the integrity of PVC casing. However, the borehole for most monitoring wells is small, and heat significant enough to cause damage generally is not created.

Shrinkage is undesirable because it causes cracks and voids. Bentonite is sometimes added to cement slurry to reduce shrinkage, the bentonite causing the mixture to expand as it hydrates and swells. Bentonite is also added to improve the cement’s workability, reduce the weight and density of the slurry, and reduce the set strength of the cement seal. Several authors, however, have shown bentonite to be chemically incompatible with cement so that the bentonite does not swell, and indeed reduces the capacity of the slurry to swell (Calhoun, 1988, Listi, 1993). Sodium ions in the bentonite are replaced by calcium ions in the cement through ion exchange, reducing the capacity of the bentonite to swell. Cement also releases OH^- ions as it sets, which causes the bentonite to flocculate, reducing its swelling ability. Christman et. al (2002) found that cement-bentonite grout showed evidence of dryness and variable consistency. If used, cement-bentonite grout should be used with care (ASTM 5092-04, Cristman, et. al, 2002).

Upon setting, neat cement grouts often lose water into the formation and affect water quality. Neat cement typically ranges in pH from 10 to 12; therefore, it is important to isolate the annular seal from the screen and filter pack. This may be accomplished by placing a very fine-grained secondary filter pack, 2 to 3 feet thick, above the primary filter pack (Nielsen and Schalla, 2006).

SEAL DESIGN

Annular seals should incorporate measures to prevent infiltration into the filter pack. Contact with the seal can cause sampled ground water to be artificially high in pH. Additionally, bentonite has a high cation exchange capacity, which may affect the chemistry of samples (Aller et al., 1991). In the saturated zone, a 2-foot pure bentonite seal can minimize the threat of infiltration. Above the bentonite seal, neat cement or bentonite grouts should be placed in the remainder of the annulus to within a few feet of the surface.

SEAL INSTALLATION

Bentonite

Annular seals should be installed using techniques that prevent bridging, which may cause gaps, cracking or shrinking. Surface water and/or contaminants potentially can migrate through any voids created. Bentonite that comes in contact with ground water may affect the chemistry of the ground water due to its high pH and high cation exchange capacity. Cations in the molecular structure of the bentonite may exchange with cations existing in the ground water. Because of this, bentonite sealing material should be placed a minimum of 3 to 5 feet above the top of the well screen. Use of a secondary filter pack above the primary filter is also recommended (Nielsen and Schalla, 2006). The bentonite seal above the filter pack is commonly installed by placing granular bentonite, bentonite pellets, or bentonite chips around the casing by dropping them directly down the annulus. If feasible, this practice is acceptable for wells less than 30 feet deep if a tamping device is used. However, for wells deeper than 30 feet, coarse-grained bentonite should be placed by means of a tremie pipe.

The bentonite should be allowed to hydrate or cure prior to sealing the remainder of the annular space. This will help prevent the grout from penetrating into the screened interval. Because bentonite chips or pellets require~~s~~ a sufficient quantity and quality of water in order to achieve and retain hydration, bentonite chips or pellets generally should only be used in the saturated zone. If a two foot bentonite seal is desired in the unsaturated zone, granular bentonite should be used. It should be added and hydrated in lifts of 2 to 3 inches using water that is potable and free of analytes of concern (Nielsen and Schalla, 2006).

For the remainder of the annulus, sealants should be in slurry form (e.g., cement grout, bentonite slurry) and should be placed with a tremie pipe (Figure 7.4). The grout should be mixed using a paddle-type mechanical mixer or by circulating the grout through a pump to disintegrate the lumps (ASTM 50-92-04). The grout should be placed with a tremie pipe. The bottom of the pipe should be equipped with a side discharge deflector to prevent the slurry from jetting a hole through the filter pack. The seal should be allowed to completely hydrate, set, or cure in conformance with the manufacturer's specifications prior to completing the surface seal and developing the well.

Neat Cement

Neat cement should not be poured into the annulus unless there is at least 3 inches between the casing and borehole, the annulus is dry, and the grout is being placed within 30 feet of the surface. If the neat cement grout is poured through standing water the mixture may be diluted or bridging may occur (Nielsen and Schalla, 2006). A neat cement grout should be mixed as with bentonite grout. A tremie pipe should be used for placement and inserted in the annulus to within a few inches of the bottom of the space using a side discharge port.

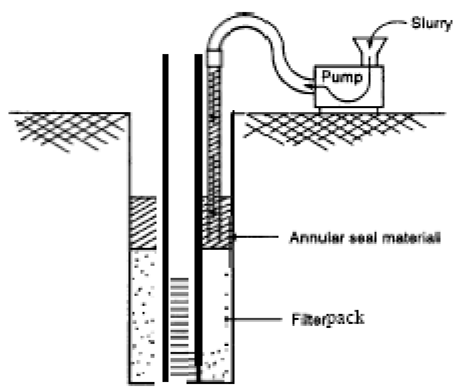

Figure 7.3 Tremie pipe emplacement of annular seal material (Source: Aller et l., 1991).

SURFACE SEAL/PROTECTIVE CASING COMPLETIONS

A surface seal is used to prevent surface runoff from entering the well annulus. The surface seal and protective casing also serve to provide protection from accidental damage or vandalism.

SURFACE SEAL

A neat cement or concrete surface seal should be placed around a protective casing to a depth just below the frost line (3-5 ft.). If the same material was used in the annular seal, the surface seal can be a continuation; otherwise, the surface seal is installed directly over the annular seal after settling and curing. The surface seal should slope away from the well and extend beyond the edge of the borehole to divert surface water. Air-entraining cements may be desirable in cold climates to alleviate cracking caused by freezing and thawing.

ABOVE-GROUND COMPLETIONS

Whenever possible, monitoring wells should extend above the ground surface to prevent surface water from entering and to enhance visibility. From the frost line upward, a steel protective casing should encompass the well. The protective casing should be at least two inches larger in diameter than the inner casing, extend above it, and have a locking cap. The lock should be protected by plastic or rubber covers so the use of lubricants to free and maintain locking mechanisms can be avoided. A small drain or "weep hole" should be located just above the surface seal to prevent the accumulation of water between the casings (See Figure 7.1). This is especially useful in cold climates, where the freezing of trapped water can damage the inner casing. In areas susceptible to flooding, the protective casing should extend high enough to be above flood level (Nielsen and Schalla, 2006). A permanent reference point on the well inner casing must be surveyed to the nearest 0.01 ft. This permanent marker should be used for all water level measurements. Additionally, the well identification number or code should be marked permanently and clearly.

Bumper or barrier guards should be placed beyond the edge of the surface seal or within 3 to 4 feet of the well (See Figure 7.1). These guards are necessary to reduce and prevent accidental damage from vehicles. Painting the guard posts yellow or orange and installing reflectors can increase visibility and help prevent mishaps.

FLUSH-TO-GROUND COMPLETIONS

Flush-to-ground completions are discouraged because the design increases the potential for surface water infiltration; however, they are occasionally unavoidable. This type of completion is generally used only when the location of a well would disrupt traffic areas such as streets, parking lots, and gas stations, or where easements require them (Nielsen and Schalla, 2006).

If flush-to-ground completion is installed, very careful procedures should be followed. A secure subsurface vault generally is completed in the surface seal, allowing the well casing to be cut below grade. The vault should be traffic-rated, and constructed of steel, aluminum, or a high-strength plastic composite material (Nielsen and Schalla, 2006). An expandable locking cap on the casing and a water-proof gasket should be installed around the vault lid to prevent surface water infiltration. The gasket should be inspected at regular intervals and properly maintained to ensure a watertight seal (Nielsen and Schalla, 2006). The completion should be raised slightly above grade and sloped away to help divert surface water. It should be marked clearly and locked to restrict access. This is especially important at gas stations to prevent the misidentification of wells as underground tank filling points. In cold-weather areas where parking lots and roads may be cleared of snow with snowplows, the well vault should be set slightly below the surrounding concrete or asphalt to prevent shearing off of the vault lid by the blade of a snowplow. Flush-to-ground well completions should never be installed in low-lying areas that undergo flooding (Nielsen and Schalla, 2006).

DOCUMENTATION

During monitoring well installation, pertinent information should be documented, including design and construction, the drilling procedure, and the materials encountered (see Chapter 3 for a listing of the particular geologic information needs). Accurate "as-built" diagrams should be prepared that, in general, include the following:

- Date/time of start and completion of construction.
- Boring/well number.
- Drilling method and drilling fluid used.
- Borehole diameter and well casing diameter.
- Latitude and longitude.
- Well location ($\pm$ 0.5 ft.) with sketch of location.
- Borehole depth ($\pm$ 0.1 ft.).
- Well depth ($\pm$ 0.1 ft.).
- Casing length and materials.
- Screened interval(s).
- Screen materials, length, design, and slot size.
- Casing and screen joint type.
- Depth/elevation of top and bottom of screen.
- Filter pack material/size, volume calculations, and placement method.
- Depth/elevation to top and bottom of filter pack.
- Annular seal composition, volume, and placement method.
- Surface seal composition, placement method, and volume.
- Surface seal and well apron design/construction.
- Depth/elevation of water.
- Well development procedure and ground water turbidity.
- Type/design of protective casing.
- Well cap and lock.
- Ground surface elevation ($\pm$ 0.01 ft.).
- Surveyed reference point ($\pm$ 0.01 ft.) on well casing.
- Detailed drawing of well (include dimensions).
- Point where water encountered.
- Water level after completion of well development.

In addition, the following should be documented in work plans (when appropriate) and reports:

- Selection and rationale materials for selection of casing and screen.
- Selection and rationale for well diameter, screen length, and screen slot size.
- Filter pack selection and emplacement.
- Annular sealant selection and emplacement.
- Security measures.
- Locations and elevations of wells.
- Well development.

A complete, ongoing history of each well should be maintained. This can include sample collection dates, dates and procedures for development, water level elevation data, problems, repairs, personnel, and methods of decommissioning. This information should be kept as a permanent on-site file, available for agency review upon request.

On July 18, 1990, Ohio House Bill 476 went into effect. This bill requires that all logs for monitoring wells drilled in Ohio be submitted to the Ohio Department of Natural Resources, Division of Water (ODNR). The ODNR can be contacted for further information.

MAINTENANCE AND REHABILITATION

The condition of wells must be maintained to keep them operational and insure that representative samples can be obtained. The maintenance program should be site-specific and take into account all information that could affect well physical and chemical performance (ASTM Method D 5978-96(2005)).

Maintenance consists of conducting inspections and periodic checks on performance. Proper documentation (see previous section) is needed to serve as a benchmark for evaluation, as well as to track well maintenance activities. Current conditions should be compared to as-built diagrams and previous measurements. Maintenance includes, but is not limited to, the following:

- Ensuring visibility and accessibility.
- Inspecting locks for rusting.
- Inspecting surface pad and seals for cracking.
- Checking survey marks to insure visibility.
- Determining depth (see Chapter 10 for recommended procedures).
- Removing sediments (if needed).
- Evaluating performance by doing hydraulic conductivity tests.
- Evaluating turbidity and re-developing or replacing well if turbidity increases.
- Evaluating well construction using geophysical logs or down hole cameras.

Routine inspections generally can be conducted during sampling. Additional evaluation can be conducted by comparing new ground water quality data and with previous data. If the maintenance check indicates a problem, rehabilitation should be conducted. Well rehabilitation activities include redevelopment to remove fine-grained materials or entrapped pollutants from the well. See Chapter 8: Monitoring Well Development for further information on well development.

REFERENCES

Aller, L., T. W. Bennett, G. Hackett, R. J. Petty, J. H. Lehr, H. Sedoris, D. M. Nielsen, and J. E. Denne. 1991. Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells. Environmental Monitoring Systems Laboratory, Office of Research and Development, U.S. Environmental Protection Agency. Las Vegas, Nevada. EPA/600/4-89/034. (In cooperation with the National Water Well Association, Dublin, Ohio).

American Society For Testing and Materials (ASTM), Method C150 07. Standard Specification for Portland Cement. Annual Book of American Society For Testing and Material Standards. Philadelphia, Pennsylvania Vol. 4.01, pp. 11-125.

ASTM, Method D5092-~~90~~ -04e1. Standard Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers. Annual Book of American Society for Testing and Material Standards. Philadelphia, Pennsylvania. Vol. 04.09, pp. 162-173.

ASTM Method D 5978-96 (2005). Standard Guide for Maintenance and Rehabilitation of Ground-Water Monitoring Wells. American Society for Testing and Material Standards. West Conshohocken, Pennsylvania.

ASTM D 6725-04, Standard Practice for Direct Push Installation of Prepacked Screen Monitoring Wells in Unconsolidated Aquifers. American Society for Testing and Material Standards. West Conshohocken, Pennsylvania.

ASTM, Method F480-90. Standard Specifications for Thermoplastic Well Casing Pipe and Couplings Made in Standard Dimension Ratios (SDR) SCH40 and SCH80. Annual Book of American Society for Testing Material Standards. Philadelphia, Pennsylvania. Vol. 04.08, pp. 792-805.

Barcelona, M. J., J. P. Gibb and R. Miller. 1983. A Guide to the Selection of Materials for Monitoring Well Construction and Ground Water Sampling. Illinois State Water Survey, SWS Contract Report 327. Champaign, Illinois.

Barcelona, M. J. and J. A. Helfrich. 1988. Laboratory and Field Studies of Well Casing Material Effects. Proceedings of the Ground Water Geochemistry Conference. National Water Well Association. Dublin, Ohio. pp. 363-375.

Campbell, M. D. and J. H. Lehr. 1973. Water Well Technology. McGraw-Hill Book Company. New York, New York.

Calhoun, D. E., Sealing well casings: and idea whose time has come, 1988. Water Well Journal, Volume 42, Number 2, pp. 25-29.

Christman, M., C.H. Benson, T.B. Edil. 2002. Geophysical Study of Annular Well Seals. Ground Water Monitoring and Remediation. Volume 22, Number 3, pp. 104-12.

Curran, C. M. and M. B. Tomson. 1983. Leaching of Trace Organics into Water from Five Common Plastics. Ground Water Monitoring Review. Vol. 3, No. 3, pp. 68-71.

Dablow, J.S. III, D. Persico and G.R Walker. 1988. Design Considerations and Installation Techniques for Monitoring Wells Cased with Teflon PTFE. In: A. J. Collins and A. I. Johnson (editors), Ground-Water Contamination Field Methods. ASTM STP 963. American Society for Testing Materials. Philadelphia, Pennsylvania. pp. 199-205.

Driscoll, F.G. (editor). 1986. Ground Water and Wells. Second Edition. Johnson Division. St. Paul, Minnesota.

Edil, T.B., M.M.K. Chang, L.T. Lan, T.V. Riewe. 1992. Sealing Characteristics of Selected Grouts for Water Wells. Ground Water. Volume 30, Number 3, pp. 351-361.

Einarson, Murray D., and John A. Cherry. A New Multilevel Ground Water Monitoring System Using Multichannel Tubing, 2002. Ground Water Monitoring and Remediation, Volume 22, Number 4, pp. 52-65.

Gaber, M. S. and B. O. Fisher. 1988. Michigan Water Well Grouting Manual. Division of Water Supply, Bureau of Environmental and Occupational Health, Michigan Department of Health. Lansing, Michigan.

Gillham, R. W. and S. F. O'Hannesin. 1990. Sorption of Aromatic Hydrocarbons by Materials Used in the Construction of Groundwater Sampling Wells. Institute of Groundwater Research, University of Waterloo. Ontario, Canada.

Hewitt, A.D. 1994. Dynamic Study of Common Well Screen Materials. Ground Water Monitoring and Remediation. Vol. 14, No. 1, pp. 87-94.

Hewitt, A.D. 1992. Potential of Common Well Caseing Materials to Influence Aqueous Metal Concentrations. Ground Water Monitoring Review. Vol. 12, No. 2, pp. 131-136.

Jones, J. N. and G. D. Miller. 1988. Adsorption of Selected Organic Contaminants Onto Possible Well Casing Materials. In: A. G. Collins and A. I. Johnson (editors), Ground-Water Contamination Field Methods. ASTM STP 963. American Society for Testing and Material Standards. Philadelphia, Pennsylvania. pp. 185-198.

Lehr, J. H., S. Hurlburt, B. Gallagher and J. Voytek. 1988. Design and Construction of Water Wells. Van Nostrand Reinhold. New York, New York.

Listi, R., Monitoring Well Grout: Why I think bentonite is better, 1993. Water Well Journal, May, 5-6, 1993.

Michigan Department of Environmental Quality, 2007. Ground Water & Wells Fundamentals and Water Well Inspector's Manual. Lansing, Michigan.

Miller, G. D. 1982. Uptake and Release of Lead, Chromium, and Trace Level Volatile Organics Exposed to Synthetic Well Casings. Proceedings of the Second National Symposium on Aquifer Restoration and Ground-Water Monitoring. National Water Well Association. Dublin, Ohio. pp. 236-245.

NSF International. 2004. Plastic Piping Components and Related Materials, NSF Standard Number 14. Ann Arbor, Michigan.

Nielsen, D. M. and R. Schalla. 2006. Design and Installation of Ground Water Monitoring Wells. In: David M. Nielsen (editor), Practical Handbook of Ground-Water Monitoring. Lewis Publishers, Inc. Chelsea, Michigan. pp. 639-806.

NWWA/Plastic Pipe Institute. 1981. Manual on the Selection and Installation of Thermoplastic Water Well Casing. National Water Well Association. Worthington, Ohio.

Parker, L. V. and T. F. Jenkins. 1986. Suitability of Polyvinyl Chloride Well Casings for Monitoring Munitions in Ground Water. Ground Water Monitoring Review. Vol. 6, No. 3, pp. 92-98.

Parker, L. V., A. D. Hewitt, and T. F. Jenkins. 1990. Influence of Casing Materials on Trace-Level Chemicals in Well Water. Ground Water Monitoring Review. Vol. 10, No. 2, pp. 146-156.

Parker, L.V. and T.A. Ranney, 1994. Effect of Concentration on Sorption of Dissolved Organics by PVC, PTFE, and Stainless Steel Well Casings. Ground Water Monitoring and Remediation. Vol. 14, Vo. 3, pp. 139-149.

Reynolds, G. W. and R. W. Gillham. 1985. Absorption of Halogenated Organic Compounds by Polymer Materials Commonly Used in Ground Water Monitoring. Proceedings of the Second Canadian/American Conference on Hydrogeology. National Water Well Association. Dublin, Ohio. pp. 198-204.

Rinaldo-Lee, M.B. 1983. Small vs. Large Diameter Monitoring Wells. Ground Water Monitoring Review. Vol.3, No. 1, pp. 72-75.

Schalla, R. and P. L. Oberlander. 1983. Variation in the Diameter of Monitoring Wells. Water
Well Journal.Vol. 37, No. 5, pp. 56-73.

Schmidt, K. D. 1982. The Case for Large Diameter Monitoring Wells. Water Well Journal. Vol. 36, No. 12, pp. 28-29.

Schmidt, G. W. 1987. The Use of PVC Casing and Screen in the Presence of Gasolines on the Ground Water Table. Ground Water Monitoring Review. Vol. 7, No. 2, p. 94.

Sykes, A. L., R. A. McAllister and J. B. Homolya. 1986. Sorption of Organics by Monitoring Well Construction Materials. Ground Water Monitoring Review. Vol. 6, No. 4, pp. 44-48.

Tomson, M. B., S. R. Hutchins, J. M. King and C. H. Ward. 1979. Trace Organic Contamination of Ground Water: Methods for Study and Preliminary Results. Third World Congress on Water Resources. Vol. 8. Mexico City, Mexico. pp. 3701-3709.

U.S. EPA. 1975. Manual of Water Well Construction Practices. Office of Water Supply. EPA/ 570/9-75-001.

U.S. EPA. 1992. RCRA Ground-Water Monitoring: Draft Technical Guidance. Office of Solid Waste. EPA/530/R/93-001, Dockette #F/93/GWMA/FFFF. Washington, D.C.

Wisconsin Code. 1990. Ground Water Monitoring Requirements. Wisconsin Department of Natural Resources. Chapter NR 141.01 to NR 141.31. Wisconsin Register No. 409.