SITE CHARACTERIZATION AND CONTAINMENT/REMEDIATION OF ACID MINE DRAINAGE AT AN ABANDONED MINE WASTE DUMP

by

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Abstract. This paper focuses on the preliminary results of laboratory tests to evaluate a new suspension grout consisting of a mixture of a naturally occurring lignite coal based wax "montan wax", sodium bentonite "pure gold grout", and water. The test program assesses the suitability of the grout for creating subsurface containment barriers in coal waste dump sites for acid mine seepage control to surface and ground waters. The laboratory activities evaluated the reduction in permeability that could be achieved in a coal waste dump site under optimum conditions and the compatibility of the grout with representative waste from the test site. Information on geological, geochemical and geophysical about the test site is presented. Laboratory formulation of the grout is complete and simulation of field condition is in progress. Pregrout geophysical surveys for determination of hydrogeologic conditions at the site are also completed. Based on geophysical surveys, a grout curtain is proposed which will consist of two rows of grout placement holes in an array across the seepage area toward Belt Creek in Montana. Post-grout geophysical survey will be carried out immediately after grouting work. Performance of the grout curtain will be monitored by collection of water samples from monitoring wells in the Belt Creek and seepage area.

Additional Key Words: grouting, sealing, barriers, seepage control, grout formulation, montan wax, bentonite, permeability, compatibility tests, coal waste dump site, ground water contamination, geophysical, geochemical, etc.

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Introduction

Acid mine drainage (AMD) from past mining practices is a major source of contamination of rivers, streams, and aquifers throughout the United States. The migration of surface and groundwater through active and abandoned mine workings and tailing piles, combined with bacterial oxidation of sulfides, is the major cause of the formation of AMD. In the eastern United States, there are thousands of abandoned surface and underground, high-sulfur, coal mines. As a result, AMD is a significant source of pollution of surface and ground water. However, in the western United States, AMD is primarily the result of hard-rock mining. For example, the state of Colorado has over 20,000 abandoned mines, some of which are sources of contamination of rivers and streams.

Montan Wax is essentially a mixture of waxy constituents consisting of monohydric alchohol esters and high-molecular-weight acids with some resinous and asphaltic material.

The idea of using Montan wax to construct containment barriers began because of serious environmental problems in Bitterfeld, Germany. MIBRAG is a large industrial company with headquarters in Bitterfeld that developed the montan wax grout. MIBRAG was responsible for lignite coal mining operations in the area. Montan wax deposits are present in these coal fields.

In the Bitterfeld area, there are several industrial waste disposal pits where leachates are entering the local aquifer, contaminating the drinking-water supply. (Voss, et. al., 1994). MIBRAG researchers began testing the feasibility of constructing containment barriers with montan wax grouts in several field demonstration projects at the disposal sites. The sites contained unconsolidated soils with relatively high rates of hydraulic conductivity (e.g., 10^{-3} cm/s). After permeating the soils with a mixture of montan wax, water, and bentonite, the conductivity of the soil was reduced by as much as five orders of magnitude (Caldonazzi, et. al., 1993).

Based on the positive results of the field demonstration projects in Germany, the U.S. Department of Energy's (DOE) Office of Technology Development (OTD) is evaluating the montan-wax emulsion as a containment material for remediating contaminated DOE sites. Hydraulic conductivity tests have been conducted on soil specimens from the Hanford and Sandia sites. Laboratory studies, namely hydraulic conductivity, penetration rate, waterproofing characteristics, chemical compatibility, and durability have shown that these soils are groutable with montan wax emulsions. After permeating the soils with straight montan wax (no added bentonite), the hydraulic conductivity of soil has been reduced by as much as five orders of magnitude. (Voss, et al., 1993)

Chemistry of Montan Wax

Montan wax is found in lignite which is not far advanced into the carbonization process. The resistant fossil plant leaf wax has remained uncoalified as a result. It is thought that montan wax results from fossil palms similar to modern carnauba wax palms. Montan wax is recovered by pulverizing the lignite and placing it in a solvent extractor for removal of the plant wax. Montan wax is a complicated mixture of primarily wax, resin, and asphaltene - like substances. The typical dark color of the base montan wax is due to the small percentage of asphaltene - like substances. Montan wax has a distribution of C24 - C32 carbon chain esters of long-chained acids and long-chained alcohols. Hydrocarbons, free alcohols, and ketones exist only in small quantities.

Because the wax is extracted from the mining of lignite, it is classified as a mineral wax. But, it is a fossil plant wax, not a petroleum wax, and the properties are comparable to natural plant waxes. The asphaltene-like material contained in the wax is so named because it is black; it does not have the same chemistry as asphalt.

Montan waxes are used for their hydrophobic and lubricating properties as well as their hardness and high melting point. Montan wax has a natural acid number and a long chain hydrophobic molecule with a short hydrophilic section. For water-proofing of aggregates, the hydrophilic section wets the aggregates and the hydrophobic section provides the water repellency. This property is not found in paraffin waxes.

Montan wax grout in comparison to conventional cement grouts offers superior sealing characteristics because ground water does not wash it out and pore cavities are sealed by wax deposition. If large pore sizes exist in the rock mass, bentonite is added to the wax to improve sealing performance. Montan wax is not brittle and has non-desiccant characteristics. It is environmentally safe and chemically and micro-biologically stable. (Karabon, 1978)

General Characteristics and Uses of Montan Waxes

Montan wax is composed of hard, friable, lustrous materials ranging in color from black to amber. The natural ester wax is derived from fossilized plants and is a complex mixture of components. Montan wax products in the United States are named ALPCO by the producer of crude montan wax. ALPCO produces several waxes. ALPCO 16, 1600, and 1650 are suitable for environmental applications. For formulations of montan wax and bentonite, only ALPCO 16 is being used. ALPCO 16 is a black, hard and lustrous wax. Its moderate acid number makes it easily saponified and suitable for emulsions for mold releases, polishes, water-proofing applications, asphalt emulsions, cable dressing, lubricants and grease. ALPCO 16 is a modifier for asphalts, temporary soft coatings, sealants, and undercoating materials.

ALPCO 16 has a specific gravity of 1.01 at 25 C°, bulk density from 4.9×10^2 to 5.3×10^2 kilograms per cubic meter, melting point from 81 to 85 C°, and flash point of 345 C°. All ALPCO waxes are resistant to oxidation but will biodegrade. All ALPCO waxes are non zardous by U.S. Department of Transportation regulations.

Potential Benefits of Montan Wax Grout as a Sealing Material

When injected into the fractured rock mass, montan wax emulsions containing polymer silicate creates an elastic block which firmly bonds with the pore walls. The sealing characteristics of montan wax grout can be adjusted for mobility, precipitation, and configured for the individual geological conditions. An example of this type of application is sealing of the drill hole walls by introducing montan wax emulsion into the drilling fluid containing polymer silicate. As a result, the introduction of heavy metals into the drill hole while drilling is stopped. Montan wax emulsion, containing bentonite, and containing large pore openings is also used for soil stabilization. This application improves water isolation properties of the soil mass even in high permeability environments.

The properly designed montan wax grouts are insoluble in ground water, neutral, and biologically nondegradable in the saturated fractured rock mass environment. The montan wax does not stratify during hardening nor stabilize during injection and it has excellent flow-ability characteristics. It develops strength quickly after injection and it is used for soil stabilization of hazardous waste sites in the Lausitz region, Bad Erna, Germany. Sealing characteristics of montan wax placed within fractures for isolating ground waters in the central German mining area of Lochau and Meserburg - OST have been documented, (Voss, et al., 1993).

The montan wax grouting technique is used for encapsulation of contamination sources or to prepare it for a subsequent restoration purpose. For control of contaminant migration in lateral, horizontal and inclined directions, injection of montan wax is practiced in the brown coal fields of the former East Germany.

General Characteristics of Pure Gold Grout (Bentonite Clay Grout)

Pure Gold Grout (PGG) is a specifically formulated, high solids, sodium bentonite grout. PGG is an easy mixing, single component, organic free bentonite clay grout. It was engineered to form a contaminant resistant seal without affecting ground water chemistry. PGG is a technically superior replacement for traditional cement grouts. It will form a low permeability and a flexible clay seal which impedes interaquifer fluid movement and infiltration of surface contaminants into the borehole.

PGG is commonly used in sealing boreholes or the annular space of monitoring wells to control contaminant infiltration and preserve ambient groundwater quality. PGG's pH ranges from 5 to 6-standard units. PGG is contaminant free and chemically stable. PGG has a low permeability with test results ranging from $1x10^{-7}$ to $1x10^{-9}$ cm/s against permeants ranging from a pH of 2 to 12. PGG has a low formation loss, and minimum flow through highly permeable soils. It remains flexible, maintains putty-like consistency over time and will re-hydrate. PGG is mixed with a grout mixer and trimmed with a positive displacement pump. It can be mixed in a slurry up to 30% solids, remains placeable for up to two hours, and sets in eight hours. PGG is manufactured by American Colloid Company. (CETCO, 1994).

Site Characterization

Site characterization for planning the grout test involved drilling, coring and mapping, the installation of monitoring wells, the collection of geochemical data from the monitoring wells, diversion ditching and performing geophysical surveys.

Site Survey

The field site selected for this study is the Anaconda Coal Mine's reclaimed coal processing waste dump near Belt, MT. AMD is a major source of contamination of Belt Creek and the unconfined aquifers at the site. The mine was an active underground coal mine from the 1890s to the 1920s, and at one time, was the largest coal mine in Montana, with daily production of 2,500 tons. The mined coal was transferred about 914 m from the adit to a coal processing plant. Washed coal was coked and coal waste dumped on the banks of Belt Creek. In the 1980s, $6.5x10^5 m^2$ of the site was reclaimed by the Abandoned Mine Reclamation Bureau, Department of State Lands, State of Montana.

The 8,100 m^2 testing site is bounded by Belt Creek, an all-weather road, and a diversion ditch which discharges flow of about 378 lpm from the mine adit into Belt Creek. AMD from the diversion ditch flows through the mine waste dump and seeps to Belt Creek. Aquatic life has disappeared up to 8 kilometers down the creek. The site is presently used by the Department of Transportation, State of Montana to store railroad ties and gravel for making asphalt. The site is leveled, and a foot of top soil covers the area.

Drilling

Six hydrologic monitoring wells (MW) have been drilled using a hollow stem auger drill (Figure 1). The wells were all drilled to bed-rock and range from 4.2 to 7.2 m (Table 1). During drilling, subsurface materials were characterized by examining materials coming up the outside of the auger flights. Split spoon sampling was not conducted during drilling. Materials encountered were in no way uniform throughout the site and ranged from gravel to clay to coal to a reddish "muddy" material which may have been decomposed, liquified scoria and mine waste. Drilling at every location except MW-4 was stopped when augers began scraping on a compact solid surface at depth. It was postulated that this solid surface may be cemented gravel underlying the coal wastes. The cemented gravel could be caused by precipitation of minerals due to pH changes in the water migrating through the coal wastes into native materials. A surface exposure of cemented gravel is located adjacent to Belt Creek a short distance upstream from the diversion ditch discharge point. At MW-4 gravel, clay and silt were encountered at depth rather than the "cemented gravel". Once the drilling was complete, groundwater monitoring wells were installed with 10 cm diameter 40 PVC pipe. Three meter screened sections were used in each well to intercept the groundwater table. Screened sections were filter packed with sand. Above the sand, bentonite chips were used to fill the remaining annular space. A flushmount with concrete seal was then installed at the surface. After installation activities, the wells were developed by blowing water and sediment from the well using pressurized air from the drill rig and then surging and bailing with a disposable bailer to purge the wells of fine material (Tetra Tech, Inc., 1995). This work was sponsored by the Department of Environmental Quality, Reclamation Division, State of Montana. Drilling of monitoring wells was contracted to Boland Drilling, Great Falls, MT., and hole logging was done by the Tetra Tech, Inc. Helena, MT.

Geochemical Data

Water samples collected from monitoring wells were analyzed and scanned for their metal contents. Conductivity ranged from 8,200 (MW-4) to 26,000 (MW-3) micro mhos/cm and pH ranged from 1.9 (MW-3) to 4.0 (MW-4). At about 6 meters from MW-2 (Figure 1) on the bank of Belt Creek, decolorization and bubbling of water was in progress and a water sample was collected from this location. Conductivity and pH measured for this location were 566 micromohs/cm and 4.7 respectively. An additional water sample was taken from surface diversion ditch and it had conductivity and pH of 2,800 micromohs/cm and 2.4 respectively. Water samples taken from Belt Creek, upstream from the test site have conductivity and pH content of 415 micromohs/cm and 7.4 respectively. Water analysis for the contaminated samples show that pH was quite low and dissolved solids moderately high. The dissolved solids are largely composed of sulfates. Iron, magnesium and calcium are the most common cations detected, but there are probably other cations present that were not tested for. The main concern is the low pH but there were small amounts of toxic metals, mainly lead and zinc. Lead and zinc metal ions were detected in all of monitoring wells above limits for drinking water established by Environmental Protection Agency in mg/l.

Compatibility Test Results

Chemical compatibility testing was conducted in order to provide a preliminary indication of the performance of the grout when exposed to a variety of metals that are representative of typical AMD constituents present at the coal waste dump test site. The analysis of water samples is not complete enough to simulate exactly the potential effects on the grout; however, the simulated solution's pH is 2, which will be a tougher test for the grout, but the total dissolved solids will have about 2,000 ppm, which would make an easier test for the grout.

Grout Cost Comparison

Cost estimation for grouting projects is an art and much depends on site-specific conditions, materials availability, grouting contractors mobility and experience. However, the cost data, presented in Table 2, are for material cost comparisons purpose for the various grouts. These costs include the cost of material and shipment to Denver only, and exclude labor cost for preparation of grouts.

Portland Cement Type II grout is the cheapest one but it has its own limitations for environmental applications. The second cheapest grout is montan wax and bentonite clay-based (Pure Gold Grout) materials with unique properties. These materials may have a wide application in the environmental field for containment and stabilization of abandoned coal, uranium and hard-rock mines. The most expensive grouting materials are microfine cement and sodium silicate. These materials are routinely and successfully used at civil engineering projects, however, economically they would have limited application in large volume mining operations for AMD control.

Laboratory Formulation

American Colloid Company has been active in formulation of montan wax and bentonite grout for acid mine seepage control at the test site. The first phase of this effort focused on formulation of grout in the laboratory; and the second phase of this effort will consist of field injection of the formulated grout in the Anaconda Coal Mine waste dump site near Belt, MT., where performance of injected grout will be determined by post-grout geophysical surveys and hydrologic monitoring.

Laboratory formulation of montan wax and bentonite grout is complete. A total of nineteen formulated samples of montan wax and bentonite (Pure Gold Grout) were prepared in the laboratory and all of these samples were subjected to standard cone penetration testings. Pure Gold Grout (PGG) is the type of bentonite grout used for laboratory testing. PGG is used as the standard basis for core penetration testing of all formulated samples. Two formulated samples out of nineteen were closely comparable to PGG's cone penetration results. The results of these two formulated samples are presented in Table 3.

The two formulated samples are composed of 1) 1% montan wax, 30% PGG, and 69% deionized water, 2) 5% montan wax, 25% PGG, and 70% deionized water. Permeability studies resulted in the measurement of hydraulic conductivity of 2.04×10^{-8} cm/s after 142 days for 1% Montan wax mixture.

The permeability measured for 5% Montan wax was 1.12×10^{-7} cm/s after two weeks. For both grout formulations, falling head permeability tests were used and the permeant had a pH of 2. Furthermore, 1% montan wax, PGG 30%, and 69% deionized water formulated grout was mixed with augered coal waste dump samples from the testing site at a ratio of 1:1. This mixture is permeated with tap water in the laboratory. The average hydraulic conductivity measured after 56 days was 2.71×10^{-8} cm/s. This test is still in progress. This is considerably less than the level of 10^{-5} cm/s specified by EPA for use in liner systems. Nevertheless, the reduction in permeability afforded by the montan wax based grout is significant and it may be a useful barrier material for applications where the containment time is limited, or where a lower degree of containment can be tolerated.

Geophysical Surveys

AMD from the sealed adit of the abandoned Anaconda coal mine is directed east through a drainage pipe downslope to a diversion ditch which brings AMD from other mines upstream. Flow is then directed northeasterly and discharges into Belt Creek, which flows in a northwesterly direction at this location. The diversion ditch is constructed on top of wastes from coal processing and angles toward Belt Creek where it discharges over a riprap embankment to prevent erosion. Consequently, a positive hydraulic gradient is established along the ditch which is approximately normal to the topographic gradient of the old surface drainage.

The seepage of AMD that has been observed in Belt Creek, upstream from the discharge point of the diversion ditch, thus could be due to leakage from the ditch, or the near surface groundwater moving through the waste materials, or a combination of both. Geophysical surveys were performed on the site to characterize the hydrology and attempt to delineate the primary source of the AMD seep into the creek.

Electromagnetic (EM34) surveys were performed to map the subsurface conductivity of the site, and self-potential (SP) surveys were made to determine direction of significant ground water movement in the area. Additionally, a ground-penetrating radar method was evaluated as a potential characterization technique. The EM34 data were taken using the 10m coil spacing in the horizontal and vertical dipole configurations to investigate both the fill material, which varied in thickness from about 3m to 8m, and the buried geologic formation beneath the fill. The horizontal dipole configuration has a depth of investigation up to approximately 7.5m, whereas the vertical dipole configuration responds to conductive layers up to 15m depths.

Geophysical surveys were made in August and again in October, 1995. Surface conditions at the site were significantly different between the two dates. These conditions affected the SP surveys with excessive noise because of the electrode coupling problems. Also, the surface of the site has been capped, revegetated, and used by the County for storage of gravel and asphalt for road construction, compounding the coupling problem. EM34 surveys, however were highly repeatable, indicating little change in subsurface groundwater conditions between the two survey dates.

Figures 2, 3, and 4 illustrate the horizontal dipole, vertical dipole, and SP data, respectively, from the later surveys in October, 1995. Included on the maps are the survey line data points (small circles), sample well locations, and the approximate boundary of the property (heavy solid line). The boundary line is a barbed wire fence which affects the response of the EM34, and data near this boundary is not diagnostic; however, in the central portion of the site on the horizontal dipole data map (Figure 2), a high conductivity ridge originating at the diversion ditch between 50-60m, and oriented toward the approximate location of the seep into Belt Creek, is apparent. The vertical dipole data (Figure 3), which is responding proportionately greater to deeper ground conductivity, does not show a prominent high anomaly at this location, and the SP map (Figure 4) is also relatively non-descript.

Interpretation of these geophysical surveys indicates potential leakage from the central portion of the diversion ditch, accumulation and very slow percolation of the already acidic water through the coal processing wastes just above the bedrock surface (which is an impermeable cemented conglomerate), dissolution of metals in the wastes, and seepage below the water level at the bank of Belt Creek. The self potential data is non-diagnostic because the rate of flow and hydraulic gradient (pressure) is minimal, generating no streaming current. Horizontal dipole survey data indicate the primary water movement is at or above the bedrock layer, and the vertical dipole data indicates little likelihood of communication with any deeper groundwater regime.

The conclusion from the interpretation of the geophysical surveys is that the objective of the project, i.e., evaluating the effectiveness of a montan wax bentonite grout curtain (Figure 5), can be achieved by configuring the placement holes in an array across the channel of acid mine drainage and monitoring the effect on the location and rate of seepage into Belt Creek.

Summary

The laboratory results of the preliminary evaluation of montan wax and bentonite (Pure Gold Grout) for constructing containment barriers at an unconsolidated coal waste dump site for seepage control is promising. Permeability testing for a formulated 1% montan wax, 30% PGG, and 69% dionized water had average hydraulic conductivity of 2.04×10^{-8} cm/s after 142 days. The permeant had pH of 2. This formulated grout is mixed with an augered coal waste dump sample in the laboratory at a ratio of 1:1. This mixture was permeated with tap water. The average hydraulic conductivity measured was 2.71×10^{-8} cm/s after 56 days. This test will be repeated soon and permeance will be replaced with an acid solution of pH2. Laboratory measured hydraulic conductivities exceed the maximum level of 10^{-6} cm/s specified by EPA for use in liner systems. Geophysical surveys were performed at the site to characterize the hydrology in an attempt to delineate the primary source of the AMD seep into the creek. Interpretation of these geophysical surveys indicates potential leakage from the central portion of the diversion ditch, accumulation and very slow percolation of the acidic water through the coal waste dump just above the bed rock surface, dissolution of metals in the wastes, and seepage below the water level at the bank of Belt Creek.

In summary, the interpretation of geophysical surveys have resulted in configuring the grout placement holes in an array across the acid mine drainage channel. Grouting work will be completed soon and a post-grout geophysical survey will be carried out for determination of grout effectiveness. Finally, performance of grouting work will be monitored by collecting water samples from wells and by monitoring the rate of seepage into Belt Creek.

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TABLE 1. LABORATORY FORMULATION RESULTS FOR MONTAN WAX(MW) AND PURE GOLD GROUT(PPG)

Grout Type	PGG gram	MW ml	Deionized water ml	Cone Penetration** 15 min mm	24 hr mm	Hydraulic Conductivity cm/s
PGG Grout Standard	300		700	>100	24	1.0×10^{-7} - 1.0×10^{-6}
MW/PGG 1	300	10	690	>100	22	2.04×10^{-8} after 142 days*
MW/PGG 2	250	50	700	>100	36	1.12×10^{-8} after 14 days*

*Simulated site water sample had a pH 2.0 Falling Head Permeability Test were based on Rigid Wall Method (ASTM: D2434-68)

**Standard Test Method for Cone Penetration of Lubricating Grease (ASTM: D217-86)

TABLE 2. GROUT COST ESTIMATE*

Grout Type	$/m³
Montan Wax (MW) and Pure Gold Grout (PGG)**	
1: 1% MW, 30% PGG, 69% Deionized Water	120
2: 5% MW, 25% PGG, 70% Deionized Water	90
Portland Cement Grout Type II, mixed at ratio of 1 to 1	70
Microfine Cement, mixed at ratio of 1 to 1	1,170
Sodium Silicate	1,250

*These cost estimates include cost of material and shipment to Denver and excludes labor costs for preparation of grouts.

**Pure Gold Grout is a registered trade mark of the American Colloid Company.

TABLE 3. MONITORING WELL DATA FROM ANACONDA MINE RECLAIMED WASTE DUMP, BELT, MONTANA

Monitoring Well	pH	Conductivity micromhos/Cm	Temperature C°	Well Depth m	Well Evaluation m	Depth to Water m	Water Evaluation m	Depth of Water m
MW - 1	3.9	9,000	11.8	4.2	30.3	3.7	26.6	0.48
MW - 2	3.4	14,500	10.7	4.8	29.8	3.2	26.7	1.64
MW - 3	1.9	26,000	12.2	4.4	30.6	3.5	27.0	0.79
MW - 4	4.0	8,200	10.6	7.2	31.4	3.4	27.0	2.84
MW - 5	2.4	8,900	10.1	5.2	31.9	4.8	27.0	0.06
MW - 6	3.8	12,000	10.3	5.4	32.3	4.6	27.6	0.70

This information was collected from testing site on August 09, 1995

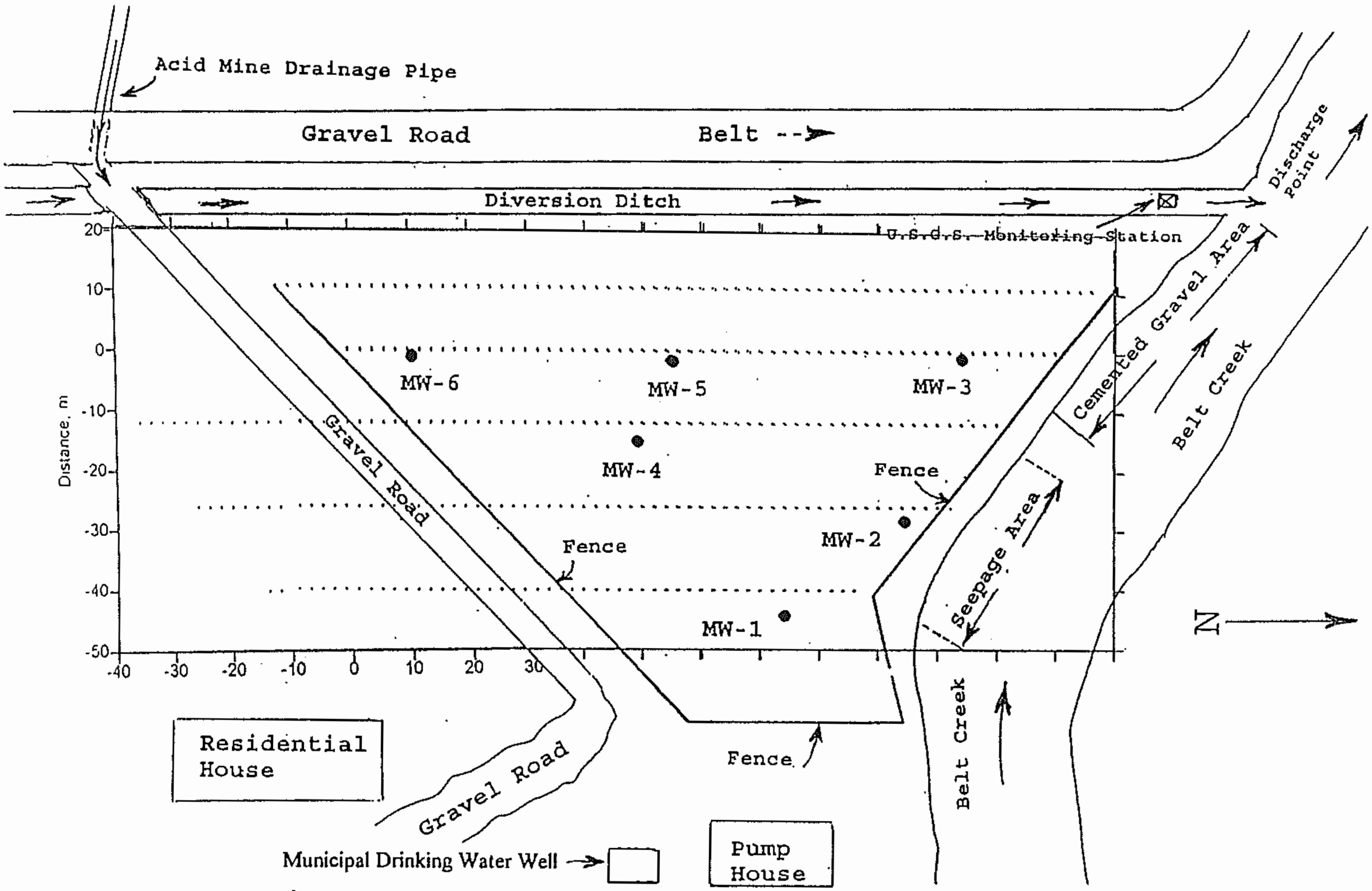

Figure 1. Monitoring Well Locations at Anaconda Coal Mine's Waste Dump Site, Cascade County, Belt, MT.

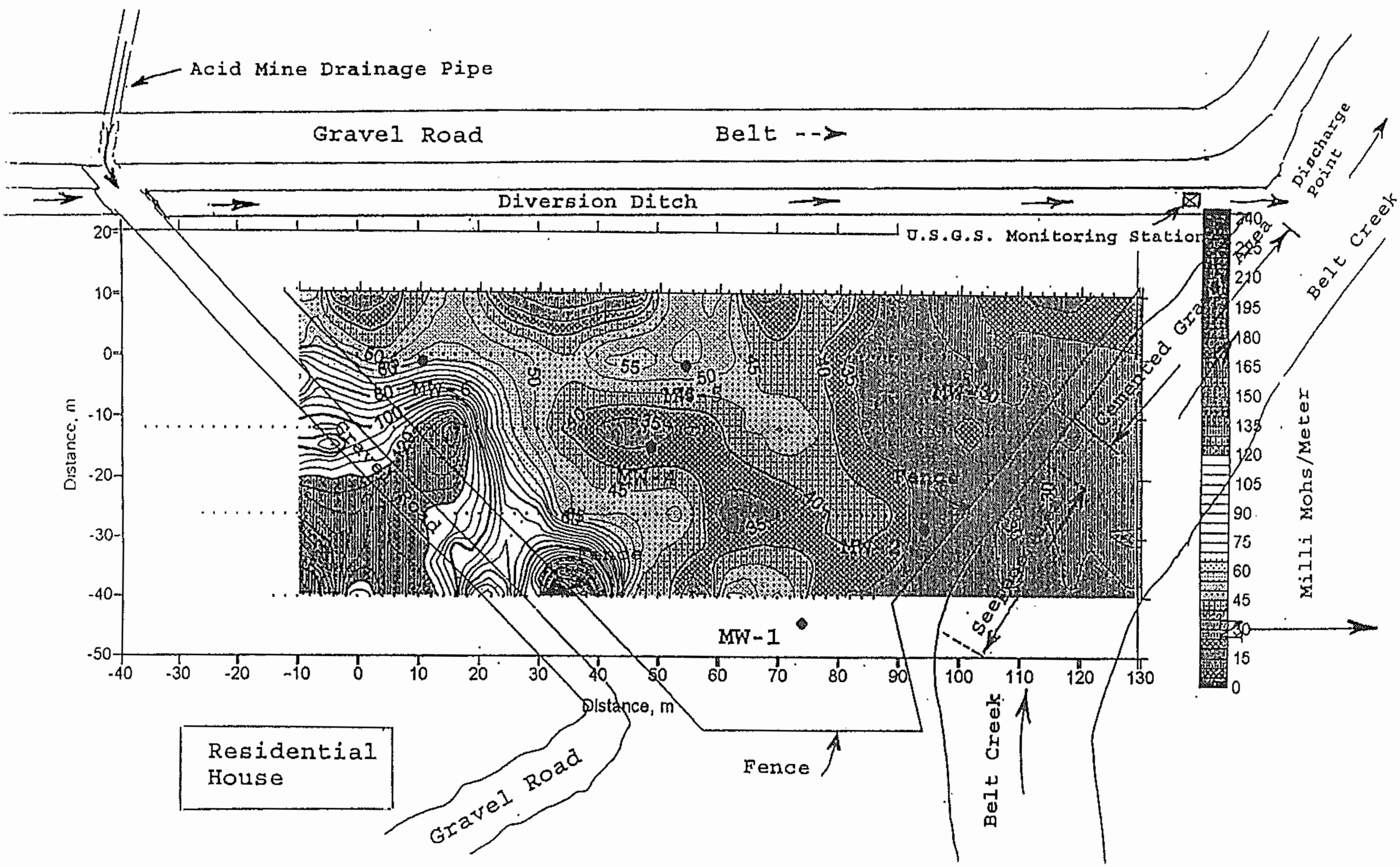

Figure 2. Geophysical Survey, EM34, Horizotal Dipole, Anaconda Coal Mine's Waste Dump Site, Cascade County, Belt, MT.

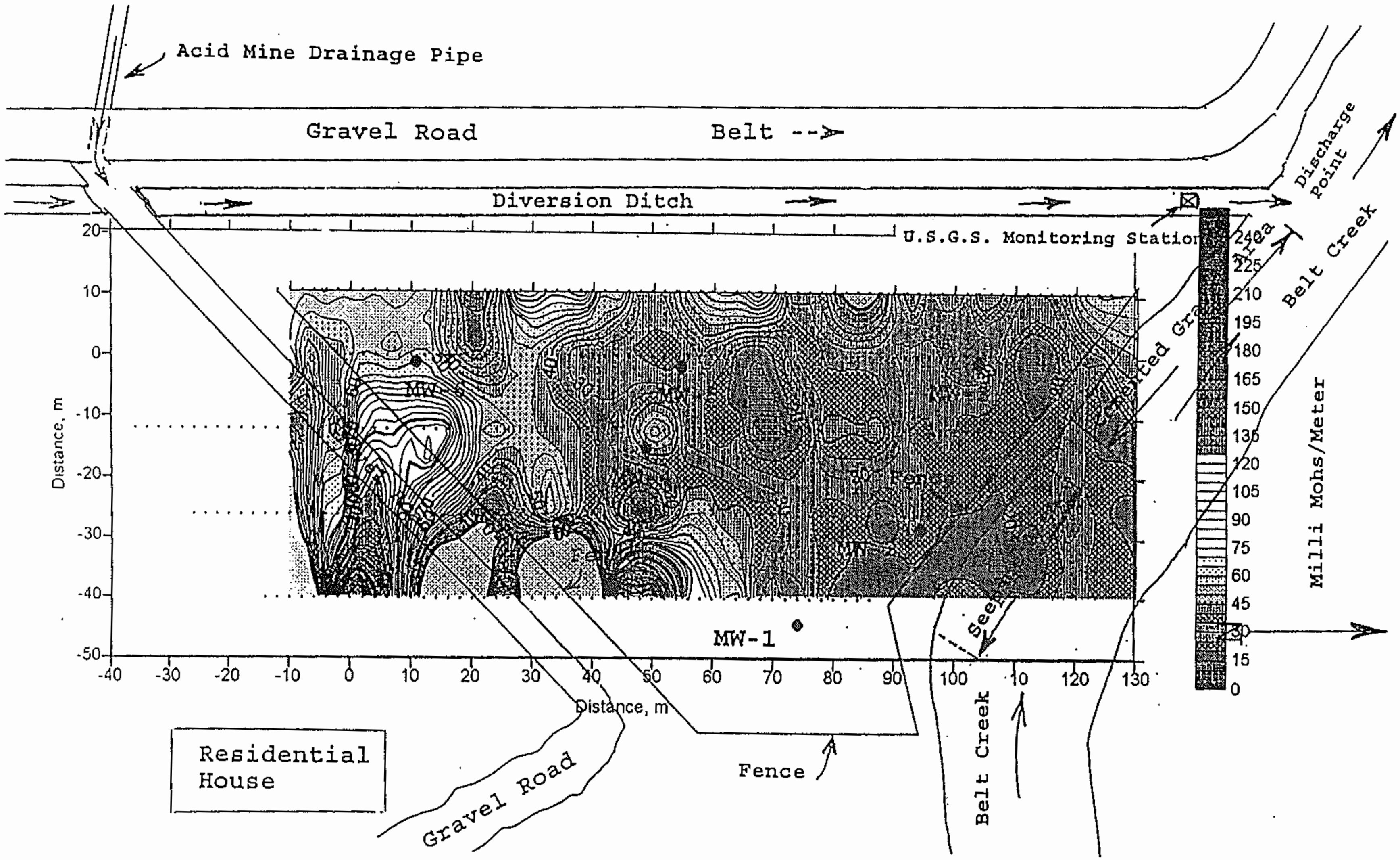

Figure 3. Geophysical Survey, EM34, Vertical Dipole, Anaconda Coal Mine's Waste Dump Site, Cascade County, Belt, MT.

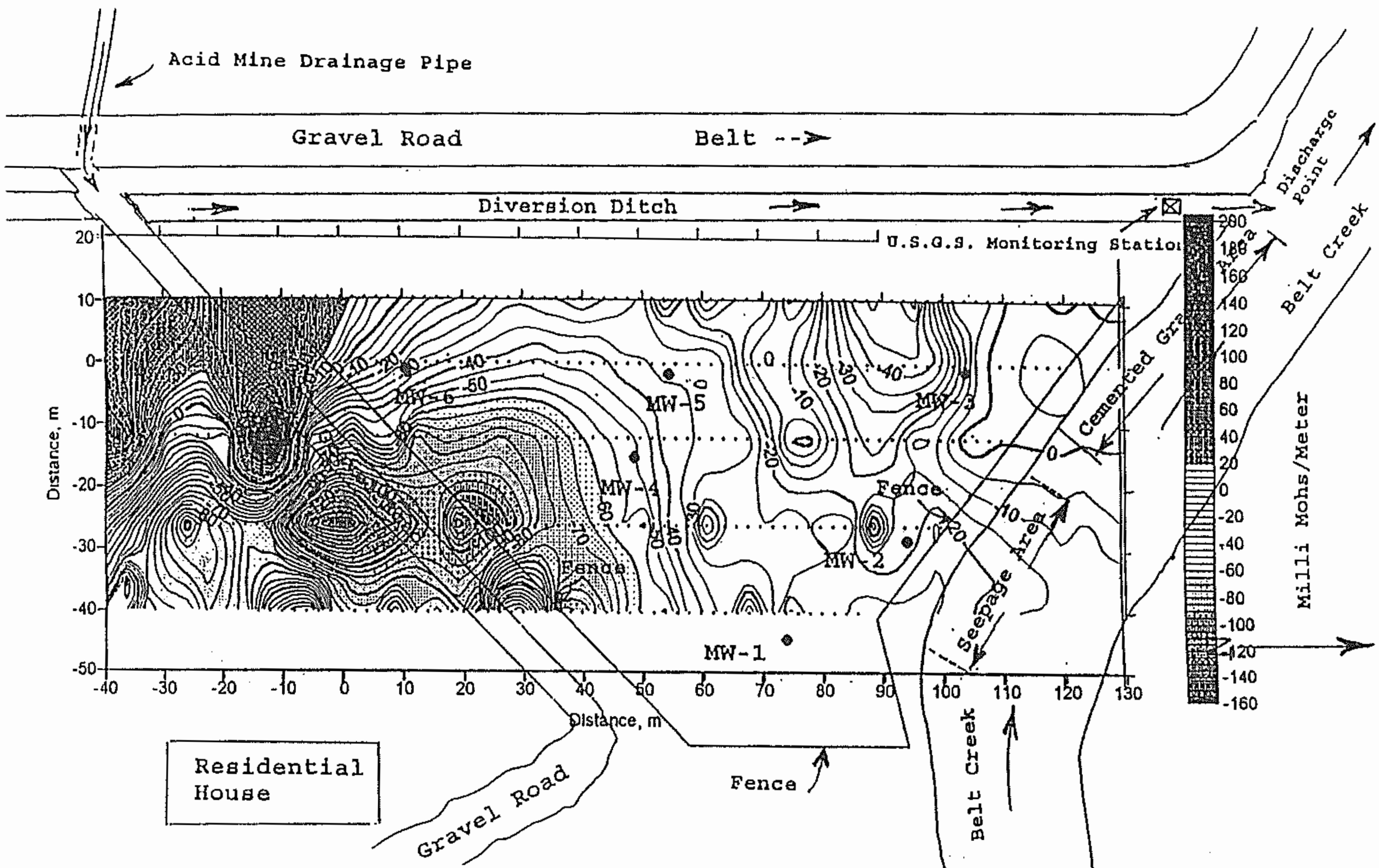

Figure 4. Geophysical Survey, Self-potential, Anaconda Coal Mine's Waste Dump Site, Cascade County, Belt, MT.

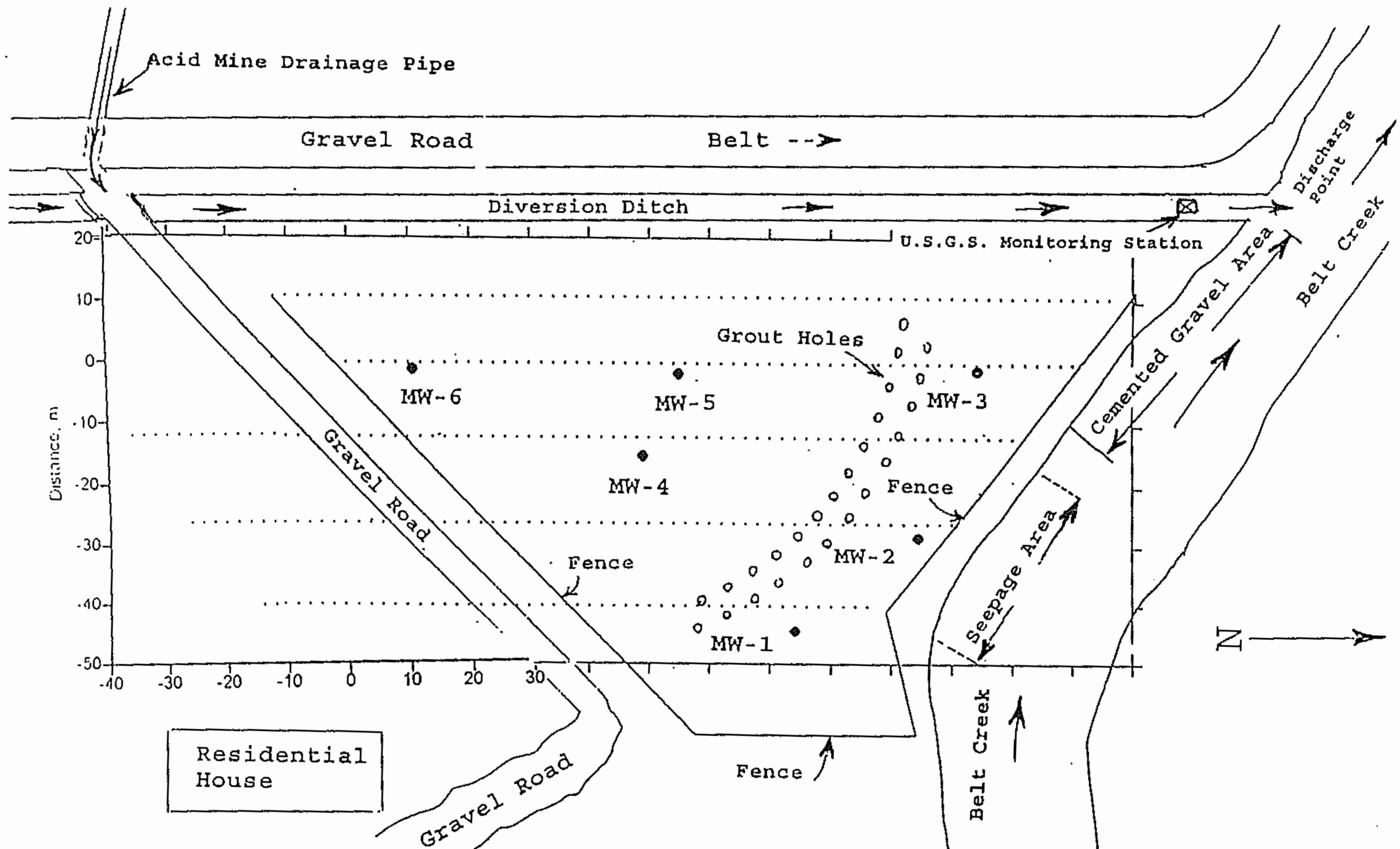

Figure 5. Proposed Locations for Grout Curtain at Anaconda Coal Mine's Waste Dump Site, Cascade County, Belt, MT.