Construction of Flexible Subterranean Hydraulic Barriers in Soil and Rock - 8281

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ABSTRACT

In the management of radioactive waste sites, there is sometimes a need to divert infiltration water; or contain or divert contaminated groundwater. This paper discusses several experimental techniques based on super permeating molten wax. Many of the methods are suited to form both vertical or horizontal barriers in-situ in the ground. The first method is based on thermally controlled permeation grouting between drilled holes that produces a very thick barrier in soil, rock, or even fractured rock up to 600 meters deep. The second method is a variation on jet grouting for producing a thin low cost barrier in soil. Also discussed is a technique for forming an infiltration barrier within the surface soil over an underground tank farm and a method for encapsulating a buried waste without excavation.

These new methods can produce durable subterranean barriers of high integrity. These barriers are made with a special malleable wax that soaks into the soil or rock matrix. The wax is far more impermeable than clay or cement and can flex and stretch in response to soil movements. The wax contains no water and is not prone to damage from soil moisture changes.

INTRODUCTION

Pollution prevention or remediation often requires construction of subterranean barriers. Barriers may be installed to isolate contaminated groundwater, divert water infiltration, or to facilitate remediation operations. Conventional civil construction methods have limitations in depth, permeability, and durability. Local geologic features such as rock, gravel, fractured rock, soil types and ground water may interfere with construction of an effective barrier. Lack of any geologic confining layer within the first 100 meters tends to limit the usefulness of conventional vertical barrier technology such as slurry walls or sheet piles at many arid sites. This is especially true in the varied strata at government radioactive wastes sites in Washington State, Idaho, and Nevada. Durability of common grout materials, such as cement and water-saturated bentonite clay, is also problematic in dry climates.

At the Hanford site in Washington, layers of sand, gravel and large cobbles in the earth can make slurry trenching problematic [1, 2]. Jet grouted barriers and other mixed in place technologies are more limited in depth because it is difficult to maintain continuity as depth increases. The Idaho sites are characterized by layers of fractured basalt separated by sedimentary interbeds and dynamic perched water zones [3]. Completely sealing these fractures with conventional pressure grouting is extremely difficult due to the random size and often-vertical orientation of fractures. Sealing tunnels or creating waterproof barriers in porous volcanic tuff is also difficult with conventional grouting materials. Verifiable construction of geologically durable barriers sufficient to contain contamination or prevent groundwater intrusion remains an illusive goal in these formations. Construction of barriers more than 100 meters deep or horizontal under a waste site is an even greater challenge.

This paper provides a brief overview of some experimental methods of barrier construction based on a unique super permeation grout based on molten wax, that have the potential to form deep barriers to great depths on the order 600 meters deep in many types of strata including fractured basalt, shale, and inter-bedded layers coarse and fine grain soils with cobbles. One of these methods is being developed to facilitate in situ thermal conversion and recovery of oil from oil shale formations at depths of 600 meters. The authors believe these methods are applicable to most formations that can be drilled with reasonably straight holes. The methods are based on a unique thermoplastic grout made of molten wax that was first utilized for grouting radioactive sites in 2004 [4, 5].

Molten Wax Grout Properties

Molten wax is essentially a new class of grouting material. It is a type of super permeation grout that is controlled by thermal heat loss instead of a chemical reaction. Permeation grouts are those that can flow into the permeability of a soil and then solidify. The viscosity and set time of such grouts normally limits how far they can permeate. Molten wax grouts are able to penetrate earthen materials far more readily and completely than any known chemical grout including acrylamide and colloidal silica. Molten wax as a grout material is comparable in cost to acrylamide and therefore more costly than mixtures of clay and water, but has desirable properties whose benefits can far outweigh the higher material costs. With conventional grouts, the direction and extent of travel are not controllable because the grout will follow the path of least resistance until enough time passes for it to set. In contrast, molten wax grout will only flow into a pre-heated volume of soil and fill it like water filling a cup. The wax will not move out of the heated area, because as it does so it quickly cools and solidifies [6]. Unlike water based grouts, wax contains no water and does not dry out during wet/dry cycles.

Molten wax can permeate into soil materials that are relatively impermeable to water, such as clay and shale. Tests have shown that the wax also permeates through heated basalt rock and some concrete grout [4]. Properly formulated wax is flexible and malleable at typical soil temperatures, will bond to wet soil or rock, and can displace water without diluting the grout. Wax is significantly more impermeable than cement or clay [4], and its ability to extrude or flow under applied loading means that it will not crack or fracture due to earth movements. The non-toxic wax contains no water so it does not suffer drying shrinkage cracks as water based grout can.

Molten wax is capable of either permeating soil or sealing and plugging the face of an excavation depending on heat flow. The molten wax moves easily through soil up to the point it loses enough heat to solidify. Molten wax will flow indefinitely through a formation heated above the melting point of the wax. Thus, as molten wax enters a cooler formation, a cold subterranean fracture network or a zone of open porosity, the wax will cool and seal the openings. Even vertical fractures can be sealed. Molten wax in an open trench will permeate a few inches into the soil and then form a seal that allows hydrostatic pressure to support the walls of the excavation. However, if soil is preheated, or heat is added by circulation of molten wax, the wax can permeate a great distance into the heated soil. Radioactive contaminated soil can be heated in place by driving metal rods or pipes into the soil and then using electrical or physical heat transfer means to heat the soil. Molten wax introduced into such a heated soil will permeate and micro-encapsulate the soil in the heated zone forming a waterproof and gas-tight mass [4-6].

Wax is not strongly affected by chemical contamination and is naturally resistant to biological degradation. There are many ways to utilize molten wax in managing underground radioactive contamination. This paper discusses four very different methods and types of barriers formed with molten wax that are suited to very different applications.

Barrier Applications

- *Thermal Permeation Barrier Method*: This method requires a series of closely spaced holes. The holes are heated and treated with molten wax that permeates up to a 2-meter radius around each hole, overlapping the heated area of the adjacent holes regardless of the type of strata. These overlapping wax saturated areas form a thick waterproof barrier. This method forms a thick and highly durable barrier and will work in rock as well as soil. Barriers may also be formed in fractured rock and below the water table. Barriers may also be horizontal when formed from horizontal directionally drilled holes.

- *Jet Grouted Thin-Wall Barrier Method*: This method uses a form of linear jet grouting but also includes a mechanical proving mechanism that helps assure that the barrier is indeed continuous and has no gaps even when applied to great depth. This mechanical verification helps assure high quality even when operating at great depths. This method can form thin economical barriers in soil but is not suitable for rock. This method is well suited as a cost-effective barrier to facilitate other water control or remediation work in soil.

- *Tank Farm Surface Infiltration Barriers*: These barriers may be formed just below the surface simply by pooling molten wax over the surface and allowing it to soak in to the soil just below the surface. This method is intended for construction of infiltration barriers over legacy underground tank farms that typically are covered with multiple layers of gravel with multiple wires, sensors and pipes embedded in the contaminated lower layers.

- *Buried Waste Micro-Encapsulation*: This technique is performed *in situ* by pre-heating subterranean soil containing the contamination and adding the molten wax from the surface. The molten wax will flow down through the heated soil and fill the pre-heated volume encapsulating the waste completely. Technically this is a form of macro+micro encapsulation rather than a barrier, because the waste and the surrounding soil are intimately permeated and saturated with waterproof wax instead of just being surrounded. This method is also applicable to warehouse stored waste in steel drums. The drums may be slowly heated in a hot room and wax infused through the drum vent without increasing the net volume of the waste.

Thermal Permeation Barrier Construction Technique

Thermal Permeation Barriers could be formed in salt formations, hard rock, shale, fractured rock, volcanic basalt, or in volcanic tuff. It should be possible to construct durable barriers 600 meters deep in both dry and water saturated formations. The special wax is malleable and can withstand significant earth movement without damage [4]. The basic method is illustrated in Figure 1 wherein molten wax is injected into closely spaced boreholes and then additional wax is circulated to add additional heat until the wax permeated columns overlap.

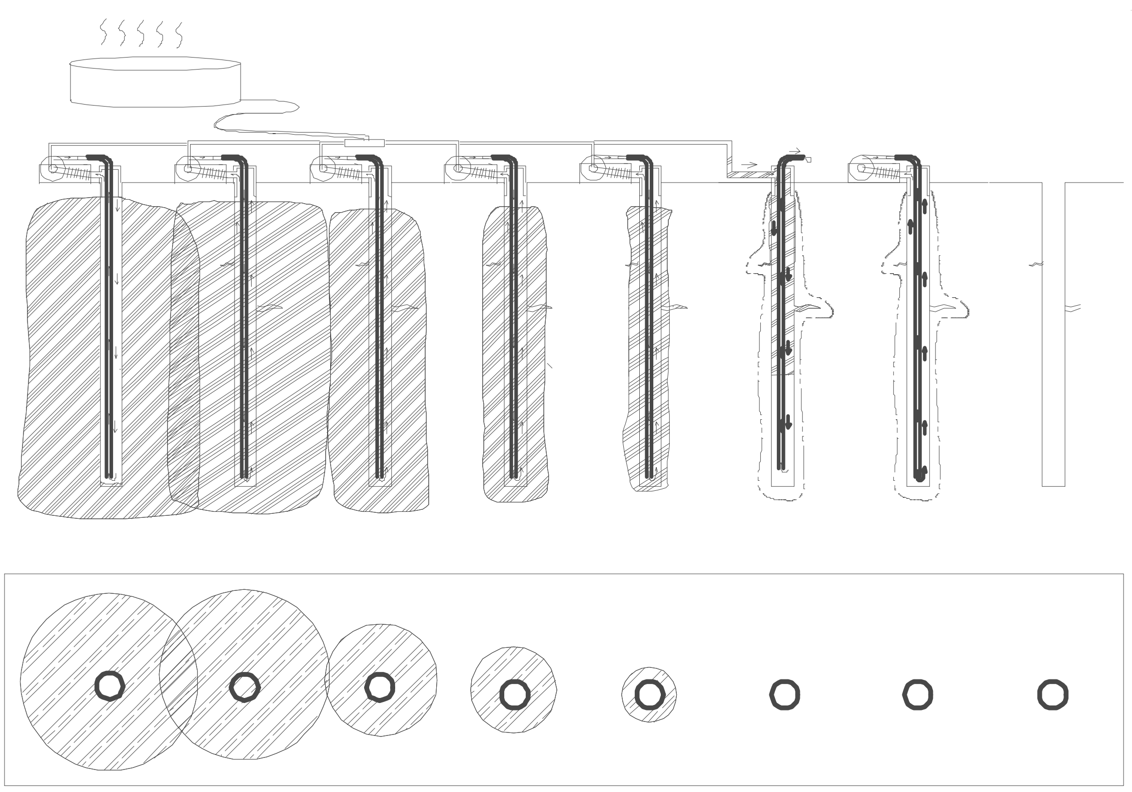

Figure 1, Thermal Permeation Barriers formed by circulation of molten wax in closely spaced drilled holes

This technique is being developed to construct 600-meter deep geologic barriers around oil shale formations so that they can be dewatered and heated to recover the oil. These formations are made of many isolated layers of fractured shale rock, and the spacing accuracy of the drilled holes may vary with depth. Verification techniques are needed to assure that the heated zones overlap properly. The construction sequence is as follows:

- Drill a line of straight holes along a boundary where a barrier wall is needed; installing perforated or screen casing through any unconsolidated zones.
- Place electric heaters in the boreholes, or lower a tubing pipe to the bottom of the holes and circulate hot air into the hole to warm up the walls of the hole. (*Note than in non-nuclear applications steam or hot water may be injected to rapidly pre-heat the holes. This is especially useful if working below the water table.*)
- Switch from hot air to circulation of hot molten wax and circulate the re-heated molten wax to allow the heated radius to increase. (*Note that in saturated formations the molten wax is injected from the surface such that it displaces the water downward and outward into the formation.*)
- Drill secondary holes midway in between each hole and log these holes with thermal imaging to verify that the heat is reaching both sides of the hole evenly at various depths. Continue until entire hole reaches minimum temperature.
- Begin circulating molten wax in the secondary holes to assure that the wax saturated zones overlap.

Thermal Permeation Barriers can also form barriers in fractured rock even when the fractures do not intersect the drilled boreholes. The molten wax will first seal the fractures outside the heated zone. Then it will slowly permeate through the heated rock until it reaches the non-connected fractures within the heated zone. It will slowly flow into the fracture and seal it off just outside the heated zone.

The permeation distance of molten wax is controlled by the temperature and heat capacity of the soil, and the injection temperature of the wax. In certain fractured hard rock formations, pre-flushing the fractures with hot water can provide enough pre-heating to achieve results. Most projects will require extensive preheating of the formation to at least 60C to achieve a perfect barrier. Uniform spacing of boreholes can be confirmed by thermal logging, but in deeper holes verifying the spacing of holes can be complex. In these situations, geophysical techniques such as inclinometers, sonar, electrical resistivity or seismic surveys may provide the needed information but these techniques are not commercially available for continually verifying the distance between adjacent holes by depth. A key issue in Thermal Permeation Barriers is to verify that the soil between the drilled holes is being heated to the required temperature while minimizing overheating; which creates a thicker and more costly barrier. Figure 2 illustrates the method of heating only every other borehole and monitoring the temperature profile of both sides of the borehole in between. Infrared thermal imaging sensors may be run down this middle borehole to monitor the heat profile propagating from the adjacent heated boreholes. If the sensors find a cold spot, additional heat would then be added at the depth of any such cold spots to develop the desired heat profile. Heating of the initial boreholes could even be continued until the wax begins flowing into the middle boreholes.

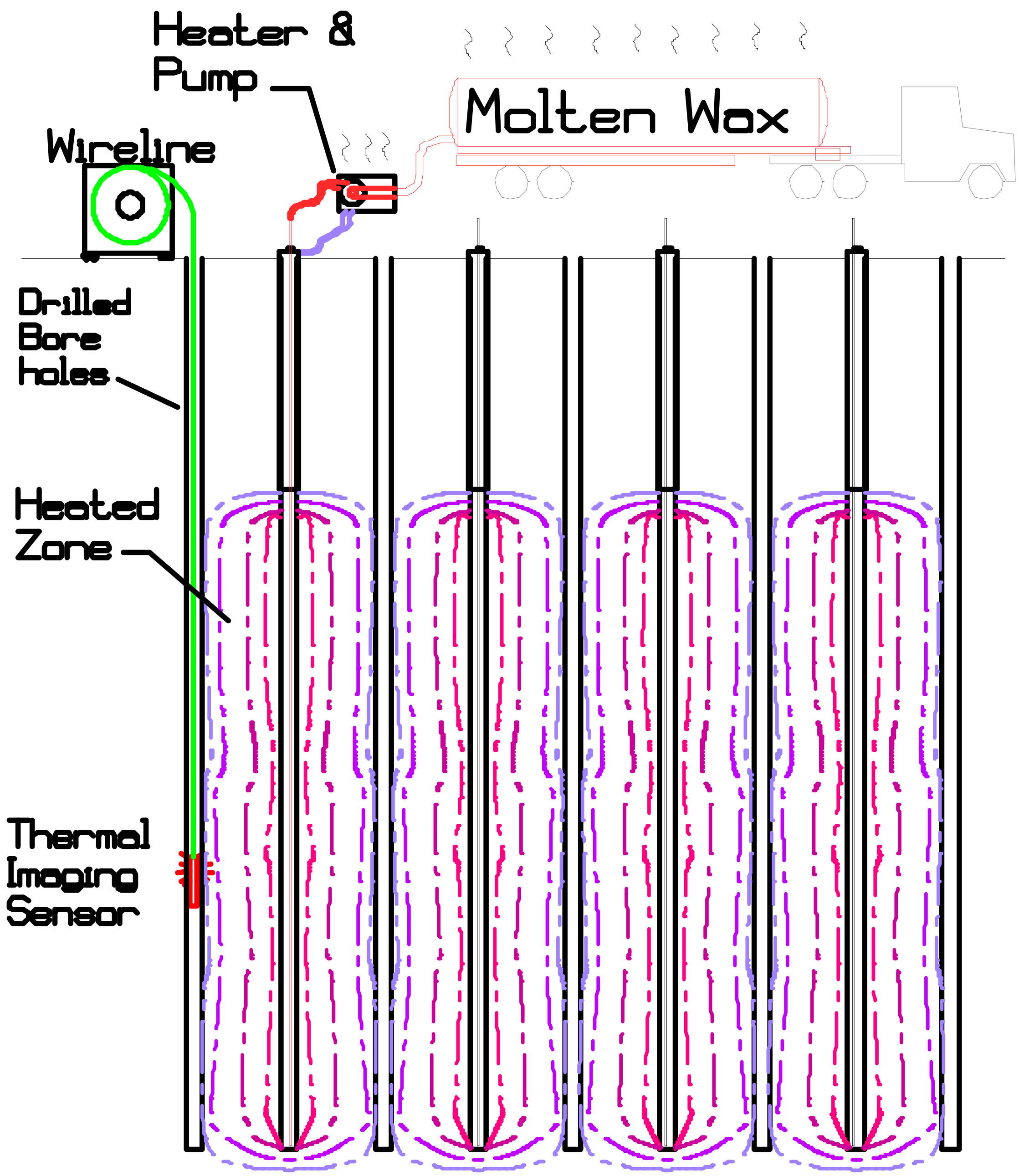

Figure 2, Imaging Heat Transfer Uniformity While Heating Primary Boreholes For Thermal Permeation Barrier

Barriers formed by the Thermal Permeation Method could be several meters thick and durable enough to last for several thousand years. The boreholes for Thermal Permeation Barriers do not have to be vertical and could instead be angled to form a V or directionally drilled to form a bottom under the area to be contained. Drillers running sonic rigs at the Hanford site report that they are capable of drilling very straight holes as close as 1 meter apart to depths well over a hundred feet. It is also possible to drill 45-degree slant holes, though these must be cased in some areas to prevent sloughing of unconsolidated formations. Holes for Thermal Permeation

Barriers must be of relatively uniform spacing so that the soil between them has sufficient heat to draw in the molten wax. The wax penetrates and seals the connected porosity of the rock or soil. In shale or basalt rock, the volume of wax required may be less than 5 percent of the volume of the barrier; while in a sandy Hanford type soil the wax volume may be as high as 25 percent. In some cases, boreholes spaced more closely together may be more economic because this reduces the volume of wax required to form the barrier.

Constructing Thin Barriers With Jet Grouting

In the Jet Grouted Method, a wax barrier only a few centimeters thick can be formed using a ”thin panel” jet grouting technique. The thinner barriers are much faster to install and cost much less since they use only a fraction of the wax required for other techniques. This method is intended for work in soil with some rocks but not in solid rock, as high pressure wax streams cannot fully permeate solid rock. In this method, two drill pipes a few feet apart are driven into the ground at the same time without rotation. The holes may be pre-drilled by any method or the pipes may be forced into the ground by hammer drill or resonant sonic methods. These pipes each have a jet nozzle aimed at each other. The jet nozzle is fed a grout material, such as molten wax, at pressures of over 400 bars. This jet blast carves a pathway through the soil toward the jet from the other pipe. A tether line made of flexible steel wire rope connects the two pipes so that they cannot move too far apart and the jets remain pointed at each other. A continuous pathway is normally carved by the powerful jet blast, but when an obstruction such as a rock, or hard soil prevents the opposed jet blasts from connecting, the tether cable will cut the soil, mechanically nudge the rock aside, or stop the progress of the two pipes. If the downward travel stops or slows down the operator can then momentarily raise up a few inches and allow the jets to erode a complete pathway.

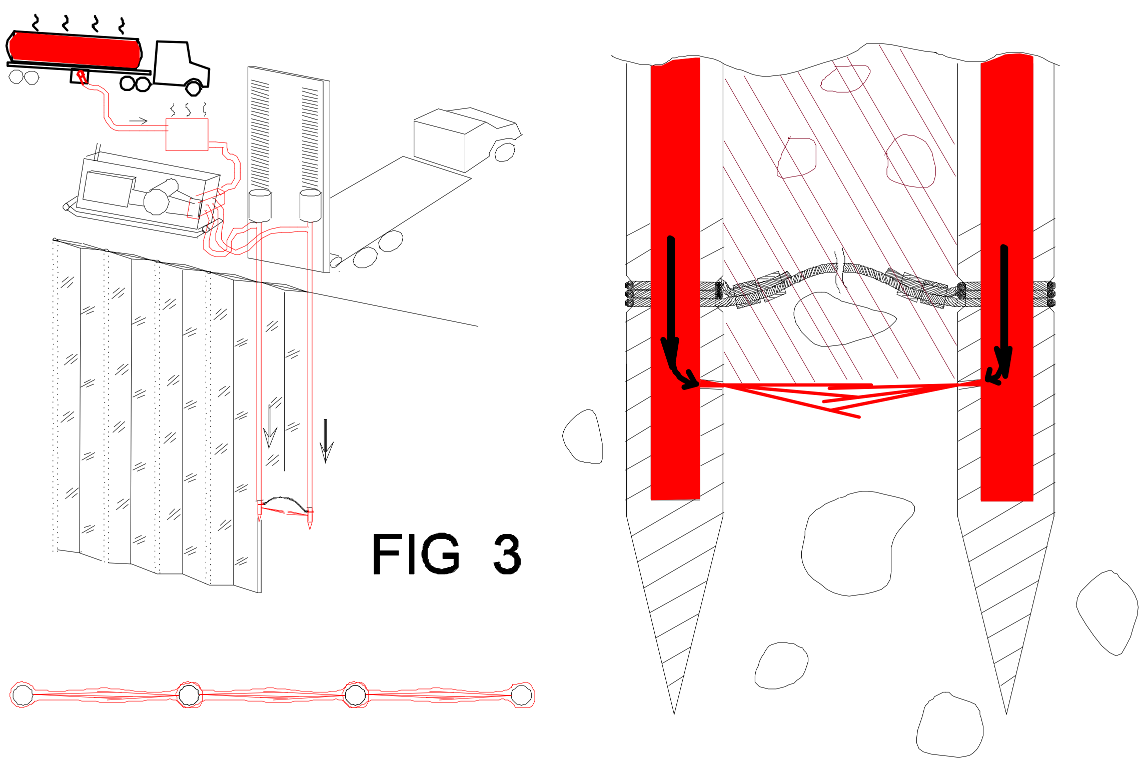

FIG 3

Fig 3: Jet Grouting Thin Flexible Panels

Conventional grouts, such as clay and cement based material; or even chemical grouts do not have the ability to penetrate into the soil. Therefore, if soil movement or hydraulic forces should pinch out the initial cut through the soil, there is no longer any barrier. In contrast, the molten wax penetrates into the soil on each side of the path initially cut through the soil. Since the barrier extends a short distance into the undisturbed soil, it will remain intact even if soil movement closes the initial cut through the soil. The cut is typically 2 to 3 centimeters in thickness while the permeation barrier is nearly twice that thick. Wax permeated soil is much less permeable than clay or concrete so the barriers do not need to be as thick.

The connection between the two pipes provides a positive verification that a continuous pathway has been formed. The optimal economic distance between adjacent drilled holes varies with the formation type. It is often best to make the spacing between holes very close so that the vertical stroke may be quite rapid. Ideally, the spacing should be such that the jets can cut the pathway between the pipes at least as fast as the pipes can be driven downward. Holes are generally less than a meter apart. Higher pressure and/or air injection can allow this spacing to be extended to 2 meters, but requires significantly more wax in the jetting process. The excess molten wax circulates to the surface and may be re-cycled and by filtering and re-heating the wax. Wax is expensive, and thus it is usually more cost-effective to recycle wax that returns to the surface.

Surface Infiltration Barriers

Surface Infiltration Barriers may be constructed in place by inundating the gravel surface with molten wax. In order to accomplish this, a shallow berm would be placed around the perimeter of the tank farm surface and then flooded with molten wax. The berm could be constructed by pouring molten wax on the surface slowly to fill the void space in the gravel and form a liquid tight perimeter as shown in Fig 4. This is done with a relatively slow flow so that the wax cools quickly and builds up into a wall. Sand bags would then be placed on top of this perimeter and sealed with more wax and soil. The perimeter wax may optionally be of a higher melt point. The perimeter may be constructed anytime of year but main barrier construction will preferably be performed during the summer when the surface soil is dry and warm and the net weight over the tank dome has been reduced by seasonal evaporation.

Molten wax is delivered in tanker trucks and flooded into the enclosed area and allowed to permeate into the surface. Ten centimeters of pooled molten wax will become a barrier 20 to 30 centimeters thick in most disposal sites; because wax only fills the void spaces. If deeper surface penetration into the underlying soil is desired the wax may be fed through an industrial instant heater to increase its delivery temperature. The wax has a flash point of over 260C and a relatively high heat capacity. The wax will flow readily through the gravel layer and soak into the native soil until it is cooled to its congealing temperature of about 52C.

The existing surface topography may determine the optimal surface contour for the barrier. Contaminated gravel and sand particles will be coated with the impermeable wax and bonded together so runoff water will be relatively clean. In most cases, it will be possible to form an integrated rainfall collection sump. However, at the Hanford site this may be unnecessary because the rainfall that collects on top of the barrier will evaporate in a few days.

Most of the Hanford tanks have several pipes leading from the top of the tank to the surface. The Molten wax barriers will naturally seal around these pipes. The wax is relatively flexible and malleable so it is able to adjust to earth movement and thermal expansion of materials. The wax saturated soil and gravel is durable enough that vehicles can drive over it. Local repairs to the barrier may be needed from time to time due to equipment maintenance or new excavations. These repairs can be made readily even in winter by preheating the ground surface with forced air heaters and pumping additional molten wax from heated drums onto the surface.

Damage to the barrier caused by heavy equipment or excavations can be readily repaired with additional molten wax. If cracks should form in the barrier over time the wax will tend to self-heal during the relatively warm summers.

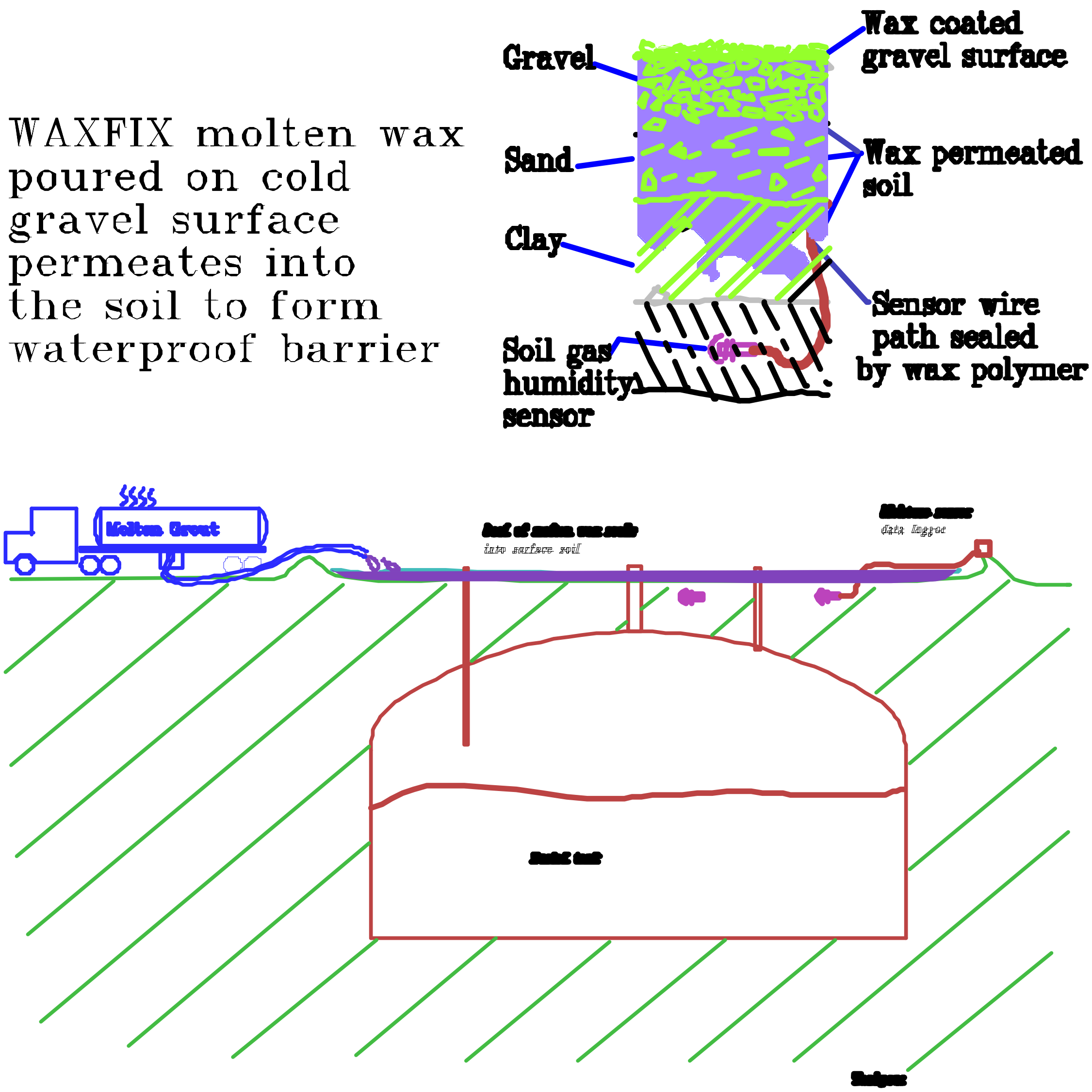

Fig 4: Infiltration Barrier Over Tank Farm

Encapsulating Buried Waste

Buried waste, or contaminated soil such as that from a spill or a leak in a buried line, may be completely encapsulated *in situ* by molten wax via thermal permeation. Heating means are first driven into the contaminated zone to pre-heat the soil to at least the melting point of the wax. Molten wax is then allowed to gravity flow into the heated soil volume and saturate the waste and adjacent soil to form a waterproof mass. Heating means may include electric resistance heating, impedance heating, microwave heating or circulation of hot matter in a heat exchanger mode. Heating is preferably done gradually, in order to slowly raise the temperature to between 65C and 80C over a period of weeks or months. This is below volatilization temperatures of virtually all contaminants, and should not present a hazard. If the waste is deep, it may be desirable not to heat the soil all the way to the surface. The molten wax may be injected at the bottom through a heating pipe. With shallow buried waste, the surface soil will also be heated so the molten wax may simply be poured from a tanker truck into a shallow depression at the surface. Water in the waste and surrounding soil will be displaced or emulsified by the molten wax as the wax permeates through the soil. The hydrostatic head of the molten wax injected from the surface is sufficient to push the molten wax into the entire heated zone. The encapsulated waste form will be completely waterproof and gas tight. Any gas evolved from the waste will form microscopic bubbles within the malleable wax matrix. The treated waste may be left in place or it can then be excavated in open air without the release of contaminated dust.

CONCLUSIONS

Molten wax represents a new class of grouting materials, which are thermally applied. These super-permeation grouts can readily permeate through clay and rock. Unlike chemical grouts, they have a thermally controllable limit to how far they can travel. Even in permeable soil, they will fill up a hydrostatic column in a pre-heated zone in a well-defined manner. These grouts enable new ways of emplacing waterproofing barriers in soil and rock at both near the surface and at great depths. Methods have been described that will allow construction of ultra deep barriers in both dry and saturated formations having a wide variation of geologic formation types. The barriers need not replace the existing earth material, but rather permeate into it to micro-encapsulate and waterproof it. The permeation is directly controlled by thermal means. The molten wax forms a hydrostatic column and fills the void space within the preheated soil and rock creating a very uniform treated diameter. Barriers of very high quality and durability can be formed along a line of holes drilled into the formation by allowing the wax to form overlapping joined columns of wax impregnated soil or rock. The flexible and malleable wax appears to be well suited for constructing thick durable barriers over a meter thick in fractured rock as well as porous rock such as volcanic tuff.

A jet grouting based variation of the method allows thin flexible barriers to be installed in soil using a variation on the dual string jet grouting method. These thin barriers may be formed very rapidly in a series of pre-drilled holes. A cable mechanically tethers the two small diameter jet grouting strings to assure correct alignment even at extreme depth. The tether cable mechanically verifies the continuity of the jet-blasted pathway and the molten wax permeates into undisturbed soil on each side of the cut to increase the thickness of the barrier.

The molten wax may also be used to construct near surface infiltration barriers over tank farms without damage to existing control and measurement systems. Other applications include a simple method of micro-encapsulation of buried waste without excavation or as a pre-excavation dust control measure.

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