Constructing Hydraulic Barriers in Deep Geologic Formations -8278

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ABSTRACT

Many construction methods have been developed to create hydraulic barriers to depths of 30 to 50 meters, but few have been proposed for depths on the order of 500 meters. For these deep hydraulic barriers, most methods are potentially feasible for soil but not for hard rock. In the course of researching methods of isolating large subterranean blocks of oil shale, the authors have developed a wax thermal permeation method for constructing hydraulic barriers in rock to depths of over 500 meters in competent or even fractured rock as well as soil. The technology is similar to freeze wall methods, but produces a permanent barrier; and is potentially applicable in both dry and water saturated formations.

Like freeze wall barriers, the wax thermal permeation method utilizes a large number of vertical or horizontal boreholes around the perimeter to be contained. However, instead of cooling the boreholes, they are heated. After heating these boreholes, a specially formulated molten wax based grout is pumped into the boreholes where it seals fractures and also permeates radially outward to form a series of columns of wax-impregnated rock. Rows of overlapping columns can then form a durable hydraulic barrier. These barriers can also be angled above a geologic repository to help prevent influx of water due to atypical rainfall events. Applications of the technique to constructing containment structures around existing shallow waste burial sites and water shutoff for mining are also described.

INTRODUCTION

Construction of effective hydraulic barriers hundreds of meters deep in mixed formations of rock and soil is a difficult engineering challenge for nuclear waste repository design. At many repository sites, site characterization research often reveals networks of fractures and faults that reduce the long-term integrity of a waste disposal facility that must sequester the waste for many thousands of years [1, 2]. The presence of these fracture networks necessitates the construction of secondary engineered barriers to mitigate water infiltration and achieve the required level of reliability and durability. This paper introduces a new method of constructing hydraulic barriers or seals in deep geologic formations. This wax thermal permeation method can be used in a wide range of formation types, and offers a potentially viable solution to a number of intractable challenges in the is construction of permanent engineered barriers. These new methods are made possible by a new class of permeation grouting material based on molten wax.

Wax As a Permeation Grout

A special wax grout, known as Waxfix 125, developed for jet grouting of buried radioactive waste at the Idaho National Engineering laboratory [3, 4], may have unexpected applications in sealing waste repositories. The molten wax can permeate through soil and rock that were only marginally permeable to water. Upon further study, it was determined that the surface active properties of the wax not only allowed the wax to displace water in jet grouted soil but also helped the wax to "wick", by capillary action, through clay and rock. This wicking phenomenon occurs when the wax is a molten liquid, but ceases when the wax cools to its congealing point. Upon cooling, the wax remains malleable but is highly impermeable to water and gas and has a sticky adhesive quality. These properties allow the material to be used as an advanced type of waterproofing grout.

Fig. 1. Capillary wicking of wax (wet areas) upward through shale rock core sitting in pan of wax. Only the small light colored area in the upper right corner is not yet saturated.

Molten wax is essentially a new class of grouting material. It is a super permeation grout that is controlled by thermal heat loss instead of a chemical reaction. Thermal heat transfer controls the change from a permeating liquid to a waterproof wax solid. This allows a type and degree of placement control not possible with conventional chemical grouts. The distance from the injection point that the molten wax grout can travel is limited by heat rather than pressure and viscosity. If a subterranean volume of soil is pre-heated, molten wax poured from the surface will flow into and saturate only the heated zone; filling it like a glass with heat gradients preventing the wax from flowing an uncontrolled direction. This heat sensitivity makes it possible to perform effective waterproofing a fixed depth into a soil or rock, or precisely along a heated zone. It also makes it possible to create barriers in fractured rock formations. The molten wax will flow only a limited distance into a fracture before it cools and seals off the fracture. The grout can also permeate through low porosity rock to reach and seal fractures that are not even directly connected to the injection point [5].

Molten wax can permeate into soil materials that are relatively impermeable to water, such as clay and shale; and tests have shown that the wax also permeates through basalt rock and concrete [3]. 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 more impermeable than cement or clay, 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 do.

Wax Grout Durability

Wax is an ancient material that occurs naturally in near surface deposits such as ozokerite and in rocks saturated with waxy material. Historically, wax was recovered by boiling these rocks in water. The durability of large masses of such natural wax in the environment is well established. Wax naturally occurs in some crude oil and tends to plug pipes and production equipment. Mineral wax, as well as insect and plant derived wax, have also been used as waterproofing, sealing, and preservative material since the beginning of recorded history. For example, even before 3000 BC, ancient Mesopotamians developed a wax-casting technology that reduced the amount of metal needed for bronze-working. Wax is a complex mixture that can be engineered to have different properties. Household wax, such as common paraffin, can be brittle; while more complex waxes, such as Waxfix 125, are more similar to synthetic ozokerite and contain multi-branched chains that make these materials malleable and resistant to degradation [3, 6-8]. These complex wax materials can also be modified with boron or other biocides to further increase the material's resistance to biodegradation. Recent studies have shown that while dispersed wax can be biologically degraded under laboratory conditions, the maximum degradation rate for large underground masses is slow enough to preclude significant degradation of the 1 meter thick barriers described herein over the 10,000-year design life for radioactive waste repositories [4].

Thermal Permeation Grouting

Thermal permeation grouting is a new technology for constructing a hydraulic barrier in fractured rock or similar underground formations. Barriers are constructed by drilling a row of closely spaced small diameter holes along the desired perimeter. The holes are then heated and molten wax is introduced into the holes to permeate the rock within the heated zone and form a wall of overlapping cylindrical columns of wax-impregnated rock. Two heating methods are being developed.

If electric heating is used (Figure 2), heating elements are first inserted into the drill holes until the formation reaches the temperature needed to enable wax permeation into fractures and pore spaces. The heaters are withdrawn, and molten wax is injected until all pore spaces are filled.

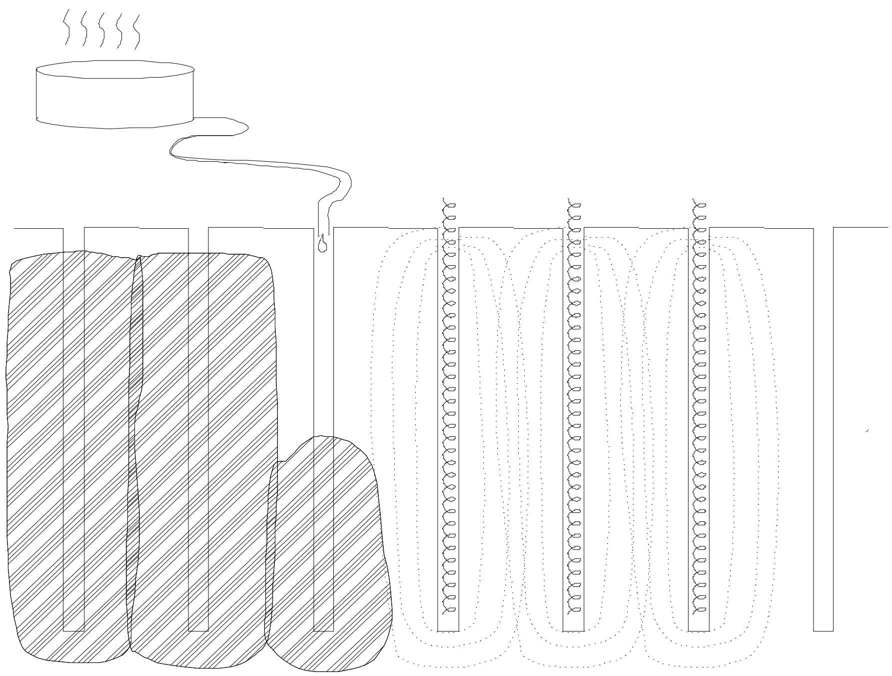

Fig. 2. Thermal permeation barrier in rock with electric heating

Alternatively, molten wax can be circulated through the drill holes until the wax transfers sufficient heat to the rock to heat the formation to the desired temperature and overlap radius (Figure 3). In this method, the barrier may be formed by first drilling a series of small diameter holes on 1 or 2 meter centers along the desired plane of the barrier. After the small diameter holes are drilled, a tubing circulation pipe is inserted in every other hole and molten wax is circulated within the hole for 8 to 12 weeks. These holes are labeled "primary" and the ones in-between are "secondary". As the wax is circulated, the rock heats up around the radius of the primary holes and the wax permeates and fills the heated zone. The net wax and heat loss can be measured and the wax reheated at the surface as it is circulated. During this period, thermal imaging measurement instruments can be inserted periodically in the secondary holes to verify whether the heat is spreading uniformly from both adjacent primary holes. Such measurements both verify the uniformity of hole spacing at deep depths, and provide a quality-control measure to help ensure that wax can fully permeate the formation. Areas with reduced heat signature may indicate non-uniform hole spacing and can be flagged for a longer heating cycle.

When the heated zone reaches a one-meter radius around the holes, wax will begin to flow into the secondary holes. When the molten wax begins to flow from the rock into the secondary hole, circulation pipes are then inserted in the secondary holes and molten wax is circulated within these holes also until the total heat loss and wax usage indicate that the barrier has reached the desired thickness. Data from the thermal logs and wax usage will allow calculation of how long circulation must be continued in the secondary holes. When the formation has been fully permeated, circulation will stop and the molten wax will be allowed to cool and seal the drilled holes.

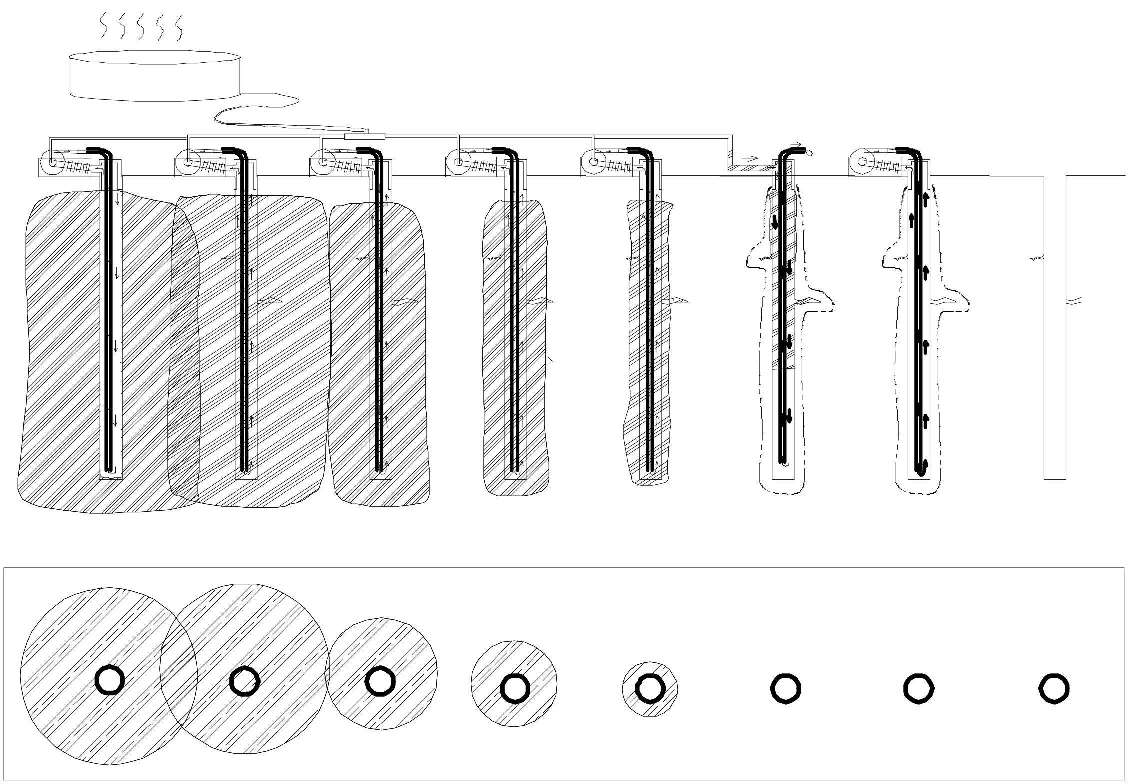

Fig. 3. Heating boreholes by circulating molten wax

In dry rock, closely spaced holes would be drilled dry and then treated with the permeating wax grout to form a continuous waterproof barrier. In a saturated formation, the closely spaced holes would be heated significantly before introducing the molten wax. This can be done with electric heaters, or circulation of hot water. In highly fractured formations much of the heating can be done with simple injection of steam or hot water. After the hole is warm, molten wax is injected under pressure from the surface. The wax, which is lighter than the water in the hole, displaces the water downward and outward into the formation. As the wax follows the water radially away from the borehole, it reaches the unheated rock and cools and solidifies. As the wax reaches the bottom of the hole it forms a cylinder of molten wax impregnated rock with an external case of solidified wax. A circulation tube can then be lowered into the hole and hot molten wax is circulated in the hole to add additional heat to the system and expand the diameter of the wax-impregnated cylinders around the primary holes.

Thermal probes can be periodically inserted into the secondary holes in wet rock to monitor the uniformity of heating between holes in much the same manner as in the dry rock. It is also possible to accelerate heating in wet rock by circulating water in these secondary holes as they warm. When wax begins breaking through into the secondary holes, it will be detected in the circulated water. At this point, wax will be injected into the secondary holes to displace the water out into the formation. Wax circulation will then be maintained in the secondary holes for a duration based on the observed heat flow from the primary 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. To help assure that the heated zones overlap properly, a special verification technique may be used. The construction sequence can be as depicted in Figure 4 and described below:

1. Drill a line of approximately straight holes along a boundary where a barrier wall is needed, installing perforated or screen casing through any unconsolidated zones.
2. 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 some applications steam or hot water may be injected to rapidly pre-heat the holes. This is especially useful if working below the water table.*)
3. Switch from hot air to circulation of hot molten wax and circulate the re-heated molten wax to increase the heated radius. (*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.*)
4. Drill secondary holes midway in between each primary 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.
5. Begin circulating molten wax in the secondary holes long enough to assure that the wax saturated zones overlap.

Barriers do not need to be vertical, and can be in any orientation where drilling the closely spaced holes is feasible. Slant hole drilling or directional drilling techniques may make it feasible to augment the permeability of a formation by building impermeable barriers within the rock in horizontal or even cylindrical shapes outside of the desired isolation zone. Nominal thickness of the barriers formed by the permeation method would likely be between 1 and 2 meters.

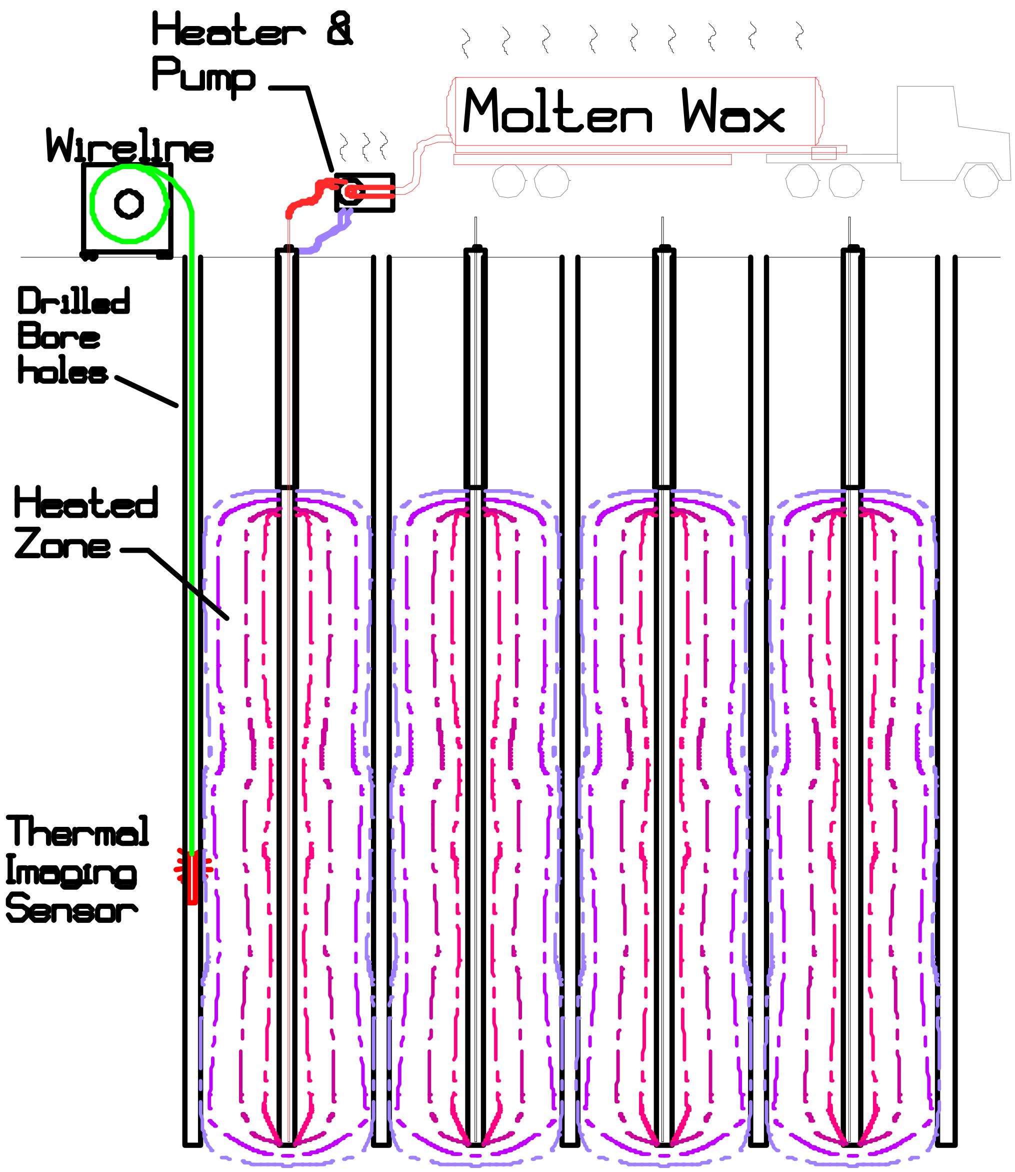

Fig. 4. Thermal imaging method of verifying uniform heating between adjacent boreholes

Wax permeation has been tested with a number of rock cores including shale, basalt, tuff, limestone and concrete [3, 5]. The wax volume required to form the barrier is roughly equal to the accessible void space in the rock. If rock void space were 20% the wax grout volume would be 20 % of the volume of the total barrier. In harder rock, such as shale, the void space is mostly accessible through microscopic fractures and so much less wax is required. In shale cores such as fig 1, saturation appears to require less than 6 percent. In igneous fractured lava rock like basalt the wax permeates only within the fractures and vesicles so the wax volume would depend mainly on the volume of the fractures.

Mitigating Water Infiltration into Waste Repositories

Avoidance of water infiltration is a primary design objective for most waste disposal projects. Legacy buried waste in pits and trenches are seldom as secure or as immobile as was anticipated when it was emplaced, and excavation or additional *in situ* remediation is needed to ensure protection of water resources and environmental quality. Waste repositories from surface trenches and shafts at the Los Alamos National Laboratory (LANL) site in New Mexico and drilled tunnels at the Yucca Mountain site in Nevada are being built in volcanic tuff, a soft compacted material that is permeable to water and air. U.S. Department of Energy (DOE) documents on repository design identify the primary design goal of "*preventing water from reaching the waste canisters, dissolving the canisters and carrying the radioactive waste particles away from the repository*" [9]. The DOE currently plans to achieve this by use of multiple barriers along with careful placement of the repository both well above the water table and well above the ground level in Yucca Mountain. This area has a historically dry climate, but climate change phenomena may have the potential to alter regional climate patterns [10, 11] and geologic movement may create new fractures and cracks. The combination of these two processes, operating over thousands of years, may lead to higher infiltration rates than currently projected.

Wax thermal permeation grouting method performed in slant-drilled holes offer an additional means of mitigating water infiltration into the mountain, and can help mitigate these potential future impacts. Currently, titanium-based drip shields are planned within the Yucca Mountain tunnel to prevent dripping water from reaching the waste containers. Additional impermeable roofs, or *in situ* "drip shields", could be constructed deep in the rock above the repository to divert water away from the waste storage chamber. Thermal permeation grouting with wax grout can form a robust drip shield within the rock itself, tens to hundreds of meters above the tunnel drifts. Such a structure could be installed either before or after waste is emplaced since it does not require access to the tunnel drifts, and can be emplaced either from the tunnel drifts or land surface and. Such *in situ* drip shields made by wax thermal permeation may be shaped in various "roof" configurations to channel water away from the repository. The simplest would be an angled flat plane to direct water away from the drifts. Such a structure would allow moisture from heating the rock to escape upwards; while diverting water moving downward from above.

The drip shield could be formed in-situ by drilling a series of 100 mm diameter holes on 1-meter centers along the desired plane well above the repository drifts – far enough that they would not be significantly heated by the waste, or significantly damaged by neutron and gamma radiation. The closely spaced holes would be drilled dry and then treated with permeating wax grout to form a continuous waterproof roof over the repository area. This method would work equally well in volcanic tuff or in fractured or faulted rock, and the elasticity of the wax [3] allows the barrier flex with the mountain to prevent future geologic shifts from creating new fractures that channel water into the repository drifts. If future shifts are of sufficient magnitude to break through the flexible wax barrier, then the barrier can be easily strengthened and/or repaired through additional heating and injection of wax.

Legacy Waste in Drilled Shafts

Drilled shafts in volcanic tuff and other soil types have often been used to dispose of waste that have no alternative disposal path [12]. This waste sometimes includes activated metals and classified objects. The wastes are deposited and the shaft backfilled with crushed tuff. The long-term containment isolation of these shafts may be dramatically improved by saturating the shaft with molten wax. The preferred method is to pre-heat the shaft and soil before adding the molten wax. Heating means can be sonic drilled or mechanically driven into the backfill or drilled around the perimeter of the shaft. The tuff is a thermal insulator so it does not require much power to slowly heat the earth to optimum temperature. There are commercial vendors in the soil thermal treatment business that have with the equipment to perform this work. After slowly heating the waste zone to approximately 60 degrees Celsius over a period of weeks, molten wax is introduced from the surface or to the bottom of the shaft through one of the heater pipes. The molten wax will bond to the waste and fill all the void space within the heated zone producing a waterproof durable mass.

CONCLUSION

Thermal permeation grouting with molten wax provides an exciting new tool to facilitate engineering improvement or waterproofing of soil and rock formations around radioactive waste repositories, groundwater contamination, mining tunnels, oil shale reserves, and subterranean civil construction applications. The thermal application techniques allow an unprecedented degree of control in forming uniformly thick and durable barriers within solid rock as well as fractured rock and granular formations. Initial tests for nuclear waste encapsulation and remediation have been successful, and this method is currently being further developed for oil shale recovery applications. Persons and institutions interested in partnering and developing the nuclear, geotechnical, and waste management applications of the technology described herein are encouraged to contact the authors.

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