Waterproofing and Strengthening Volcanic Tuff in Waste Repositories

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ABSTRACT

Conventional methods of sealing fractures within volcanic tuff may not be perfect enough or long lived enough to isolate a waste repository or a repository shaft from water for the required duration. A new grouting technology based on molten wax shows significant promise for producing the kind of long-term sealing performance-required. Molten wax is capable of permeating a significant distance through volcanic tuff as well as sealing fractures by permeation and is thermally dependent instead of chemically or time dependent. The wax wicks into and saturates tuff even if no fractures are present, but penetrates and fills only the heated area. Heated portions of the rock fill like a vessel. The taffy-like wax has been shown to waterproof the tuff as well as dramatically increasing its resistance to fracture. This wax was used in 2004 for grouting of buried radioactive beryllium waste at the Idaho National Engineering Laboratory chiefly to effectively stop the water-based corrosion reactions of the waste. The thermoplastic material contains no water and does not dry out or change with age. Recent studies indicate that this kind of wax material may be much more resistant to bio-degradation than previously thought. This paper introduces several novel concepts using wax for improvement of radioactive waste containment underground.

INTRODUCTION

Avoiding water infiltration is a key part of most radioactive waste disposal concepts. Legacy buried waste in pits and trenches are seldom as secure or as immobile as was anticipated when it was emplaced. Waste repositories from surface trenches and shafts at the Los Alamos National Laboratory (LANL) site in New Mexico to 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.” Designers expect 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 a mountain. Though repositories are located in areas that have a historically dry climate to minimize the impact of rainfall infiltration, scientific reports allege that global warming phenomena has the potential to change climate norms radically.

Conventional cement and clay grouting materials are good at producing seals in the right conditions but are less than certain of producing seals that can last 10,000 years. The chief reason for this is that these grout materials are chemically interactive with their environment and subject to damage from wet/dry cycles, freeze/thaw cycles, thermal expansion rock movement, seismic rock movement and chemical attack from acid rain and carbon dioxide. A new grouting technology based on molten wax shows significant promise for producing long-term sealing of pits, trenches, packages and large waste repositories. This grout material technology is first described in general and then several possible applications are discussed.

Wax As a Grout

A special wax grout, know as Waxfix, originally developed for jet grouting of buried radioactive waste at the Idaho National Engineering Laboratory (INEL) site in Idaho, may have unexpected applications in sealing nuclear waste repositories. It was discovered that the molten wax sometimes had the ability to flow 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, which were developed to allow the wax to displace water in jet grouted soil, caused 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 wax to be used as an advanced type of waterproofing grout.

Thermal heat transfer rather than chemical reactions control the change of the wax from a permeating liquid to a waterproof solid. This material characteristic allows a type and degree of placement control not possible with conventional grout. The distance from the injection point the molten wax grout can travel may be controlled by heat instead of 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 open spaces in the heated zone and filling them like a cup without flowing away in an uncontrolled fashion. This makes it possible to perform effective waterproofing of a fixed depth into a soil or rock or precisely along a heated zone. This effect also makes it possible to create barriers in fractured soil and 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 migrate through solid but slightly porous rock that is within the heated zone to reach and seal fractures that are not even directly connected to the injection point.

Waste Stabilization Properties

Since the wax does not contain water and displaces water, it tends to stop the water-based geochemical reactions that normally occur in buried waste. This was a key factor in DOE's decision to use this wax grout to seal activated-beryllium reactor blocks buried at the INEL site in the Idaho desert. These intensely radioactive objects were subject to corrosion that released radioactive materials into the surrounding soil. Scientists determined that molten encapsulation of the waste with Waxfix 125 would be the best way to stop the chemical corrosion process and to prevent water from contacting the waste. In order for this encapsulation process to work effectively on buried waste, the wax must remain molten as it saturates the waste. This may be accomplished by heating the wax to a sufficiently high initial temperature or by pre-heating the waste itself. The relative volume of wax and the heat capacity of the waste/soil volume to be treated is also a factor in the thermal design of such a project. If mistakes are made in the application, re-heating of the wax treated area, to more fully saturate the waste, may be done at a later date by driving heater pipes into the waste zone.

The same properties that make for good waste stabilization also make the grout potentially much more durable than conventional grouts. Since the wax does not interact with water-based chemistry, there is less potential for it to be altered over time.

Wax Grout Durability

Wax is an ancient material that occurs naturally in near surface deposits as Ozokerite and large chunks and in rocks saturated with the waxy material. Historically, the wax was recovered by boiling these rocks in water. The durability of large masses of such natural wax in the environment is well proven. Wax naturally occurs in 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. Wax has been used as a sealing and waterproofing agent for at least 4,000 years and many ancient artifacts such as erasable writing tablets, rope, wood, and leather contained wax. While familiar household wax such as common paraffin can be brittle, more complex waxes such as Waxfix 125 are substantially like a synthetic Ozokerite and are characterized by multi-branched chains, which makes them malleable and resistant to degradation.

Recent studies have shown that while most waxes can be degraded and metabolized by certain bacteria in a laboratory under optimal conditions, the rate of degradation progress for large underground masses is sufficiently slow to meet a 10,000-year design life. Complex branched chain wax is significantly more resistant to biodegradation and can be modified with boron or other biocides to make it even more so. A long-term study was performed by Microbe Innotech Laboratories to determined the maximum degradation rate for two grades of plain Waxfix with no biocide or boron under optimal moisture and circulation conditions in a bioreactor. The degradation rates varied from 0.00018 to 0.00061 grams per square centimeter per week. At this rate a 1 meter thickness would last 40,000 to 140,000 years if bio-degradation conditions remained optimal and nutrient transport circulation conditions persist. In real world conditions the wax is expected to last much longer. Wax filling the pores of a rock is also expected to be more durable because the transport conditions to bring nutrients to the wax surface are absent.

Organic-based grouts have not been adequately considered for nuclear applications because of concerns about radiolysis generation of hydrogen or criticality concerns over neutron moderation. While this should always be evaluated, in most cases these concerns are unfounded. It should be noted that even cement grouts contain enough water to offer the potential for hydrogen generation and neutron moderation. Cement grout is permeable to hydrogen while wax is only marginally so. Hydrogen generated from exposure of large masses of wax to radiation is mostly retained within the wax matrix. However, since hydrogen generated on the wax surface may still escape, it is desirable not to allow a head space where gas could collect.

Waterproofing Tuff

Volcanic tuff is a relatively low-strength, fragile, rock comprised by compacted volcanic ash. Massive tuff deposits cover many areas of New Mexico such as the area around LANL and the Yucca Mountain area. Tuff is a low-density rock that is permeable to water and often has small fractures that can channel water through it. Tuff is highly permeable to molten wax and has a low heat capacity and high void ratio so wax will permeate a significant distance into the rock before loosing enough heat to solidify.

If molten wax is poured into a new excavation in tuff, the wax will uniformly permeate a foot or two into the rock and then stop. Wax will flow into fractures for a greater distance and seal them off. The wax will remain molten in the trench for a long time because both the solidified wax and the tuff are thermal insulators. If the remaining molten wax is then pumped back out of the trench, it will leave a lining of wax-impregnated tuff several feet thick. This wax-impregnated tuff is waterproof, fracture resistant and has a much higher strength and toughness then the virgin tuff.

Sealing openings and shafts in volcanic tuff and rock salt formations with conventional grouts is difficult because the grout has difficulty bonding to the rock and the rigidity of the grout allows microscopic fractures to form that can enlarge over time. However, molten wax grout actually flows some distance into a rock face and is able to stretch and deform without cracking. Conduits, shafts and sensor lines can be reliably and permanently sealed with molten wax. Molten wax penetrates microscopic fractures in bedded and domal salt rocks, shale, limestone, clay, granite, and basalt, allowing the grout to permeate into the rock formation.

The Yucca Mountain Repository

Waste repository design thinking often changes as a potential site is studied and political goals change. When the tuffs at the Yucca Mountain site were first proposed as a potential host rock for a geologic repository for safe disposal of high-level radioactive waste in the 1970s, they were thought to be dry with little or no local rainfall or infiltration. Further study indicated that perched water zones and fracture systems in the rock existed that could allow surface precipitation to eventually reach the repository. The current hot repository design plan deals with this moisture issue by packing the waste so densely that the rock around and between the tunnel drifts becomes hot enough to boil away the small amounts of water expected to filter down from the surface into the repository. However, if the local weather patterns change due to global warming, it is possible that sites that have been dry for thousands of years may not always remain that way. Recent reports on climate change indicate that it is no longer reasonable to assume that rainfall averages will remain constant over the lifetime of the repository. In view of the possibility of radical climate changes over the very-long time of concern at the Yucca Mountain site, it is prudent to consider just how much water inflow the system can handle.

Thermal Permeation Grouting for Yucca Mountain Drip Shield

Thermal permeation grouting is a new technology for constructing a hydraulic barrier in fractured rock or similar underground formations. The technology is being commercialized for construction of hydraulic barriers to facilitate in situ oil shale development requiring hydraulic barriers in to be formed in fractured rock to depths of up to 600 meters. However the authors believe that the technique is also capable of constructing permanent barriers in volcanic tuff to improve performance of radioactive waste repositories of various kinds. As illustrated in Fig. 1, impermeable barriers are constructed by the initial drilling of a row of closely spaced small diameter holes along the desired perimeter from the surface. 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. The relatively small diameter drilled hole will produce a very large diameter column of wax-saturated rock. The holes can be heated by electric resistance cable but the most convenient method is to simply circulate molten wax in them until they heat up to the desired overlap radius. Molten wax conducts heat quite well while solidified wax is a thermal insulator. As more and more thermal energy is loaded into each molten column, the outer skin of congealed wax insulates the column and limits the heat loss to the formation. Periodically the hot molten wax breaks through the cooler skin and increases the radius of the column, until the column reaches critical size and stops growing. The radius of the column depends on the diameter of the initial hole, the temperature of the circulated wax and the thermal conductivity of the rock.

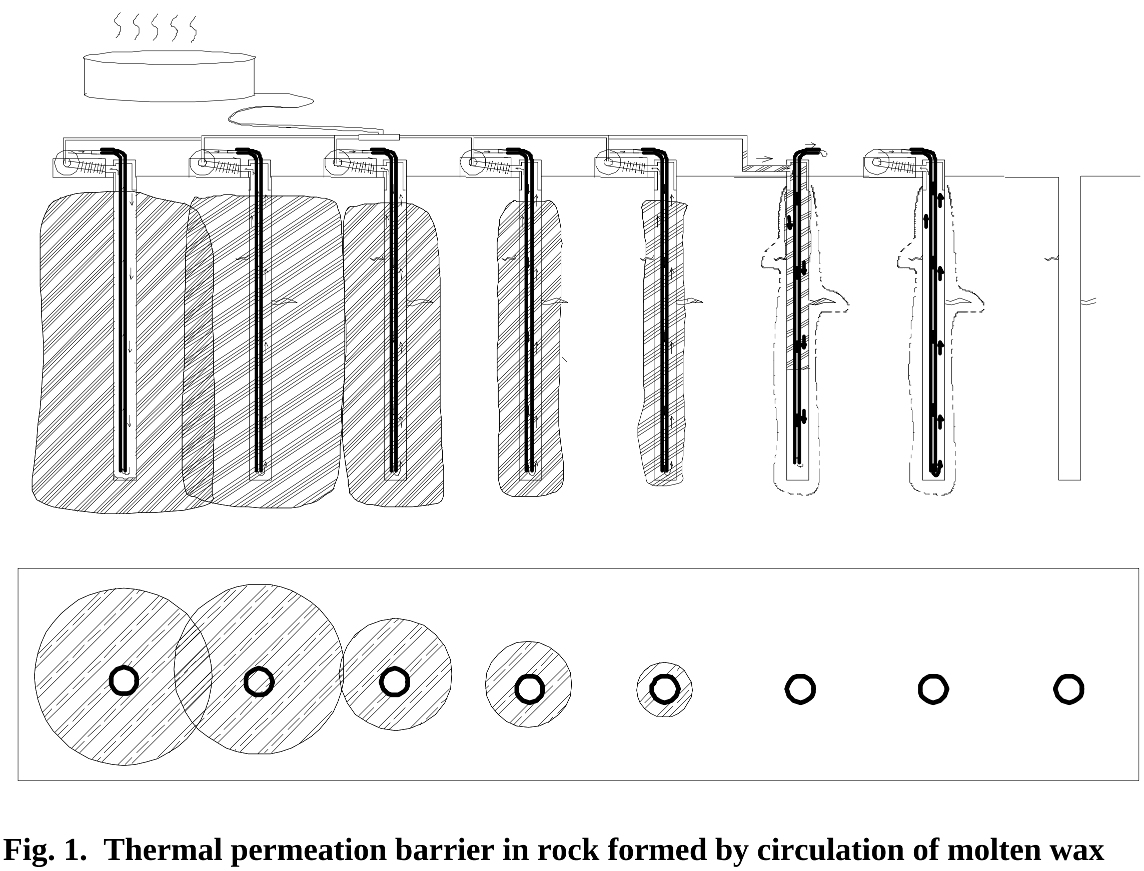

Fig. 1. Thermal permeation barrier in rock formed by circulation of molten wax

The wax thermal permeation grouting method performed in slant-drilled holes may offer an additional means of mitigating water infiltration into the mountain. As illustrated in Fig. 2, impermeable roofs or “drip shields” could be formed in-situ in the rock above the repository to divert water away from the repository. Currently, titanium-based drip shields are planned within the tunnel. Thermal permeation grouting with wax grout may make it possible to form a robust drip shield within the rock itself 50 to 100 meters above the above the tunnel drifts. Such a structure could be installed either before or after waste is emplaced since it is done from the surface and does not require access to the tunnel drifts. 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 a simple flat plane on perhaps a 15 to 20 degree angle so that the water would be directed away from the drifts. Such a simple structure would allow moisture from heating the rock to escape upwards but would still divert water moving downward from above. Fig 2 shows a second panel added to from a vaulted roof concept.

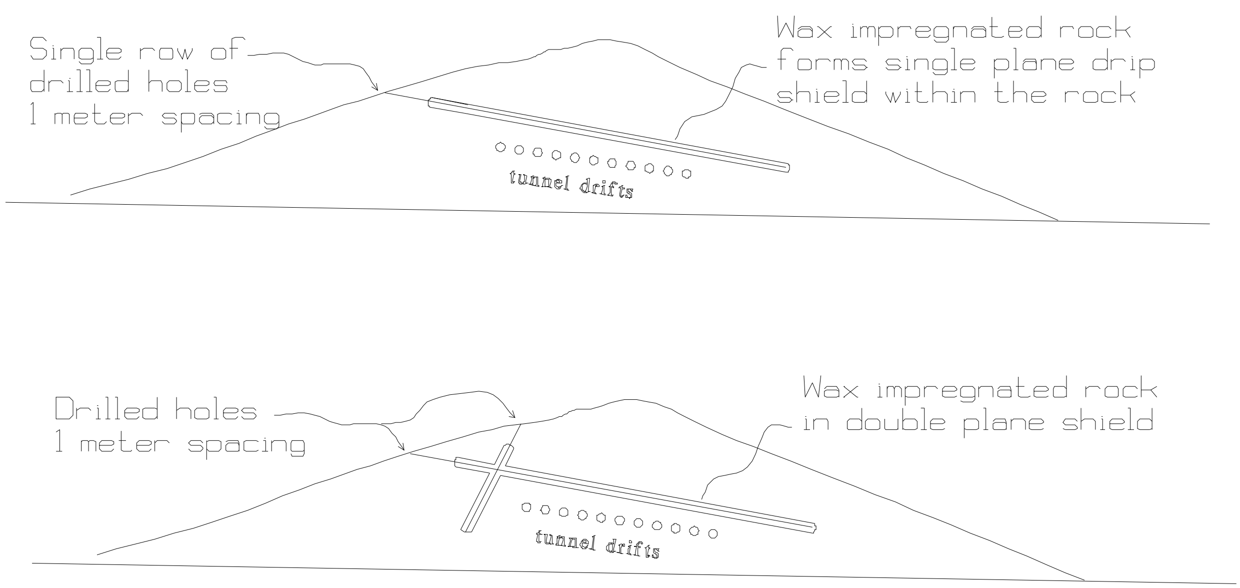

Fig. 2. Drip shield formed in-situ in mountain rock above the repository

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 of the barrier fifty to one hundred meters above the repository drifts as in Fig 2. They would be far enough above that they would not be significantly heated by the waste. 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. If the drilling conditions and measurement technology is good enough to drill straight holes and maintain a uniform spacing then the molten wax would simply be re-circulated through a tubing from the bottom of each hole for several weeks to form overlapping areas treated with wax as in Fig 1. This would likely be the case with holes that are not very deep however holes that are very deep are seldom straight. If the drilling technology cannot guarantee uniform spacing a two-step wax treatment method can physically verify the successful permeation of wax between holes and compensate for holes that are further apart.

Verifying Wax Barrier Continuity

In the first step, after the holes are drilled, a tubing circulation pipe is inserted in every other hole and molten wax is circulated within the hole for 6 to 8 weeks. These holes are labeled "primary" and the ones in-between are "secondary". The net wax and heat loss are measured and the wax is reheated at the surface and re-circulated. As the wax is circulated, the tuff heats up around the radius of the primary holes and the wax permeates and fills the heated zone. Thermal imaging measurement instruments inserted periodically in the secondary holes verify that the heat is spreading uniformly from both adjacent primary holes. Instrument surveys of the uniformity of the hole spacing provide useful data but when the heat from the primary borehole reaches the melting temperature for the wax in the secondary borehole we may be certain that the wax will reach it as well. Areas with reduced heat signature will be flagged for a longer heating cycle.

In the second step, 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 also inserted in the secondary holes and molten wax is circulated within these holes until the total heat loss and wax usage indicate that the barrier has reached the desired continuity and thickness. Data from the thermal logs and wax usage will allow us to calculate how long time circulation must be continued in the secondary holes. The molten wax will then be allowed to cool and seal the drilled holes.

The wax barrier will be a ridged shape since it is formed from overlapping cylindrical areas that are impregnated with wax. This shape will also help channel water away from the repository. Nominal thickness of the barrier would be between 1 and 2 meters. This drip shield barrier could be quite large covering the entire repository area rather than just one tunnel drift. Since the barrier is a long way from the waste canisters, the barrier will not have to endure elevated temperatures or radiation from the disposed waste. This in-situ drip shield within the matrix of the rock should be more durable than a metal shield within the tunnel and able to perform even if the average rainfall increases by an order of magnitude.

The wax volume required to form the barrier is roughly equal to the accessible void space in the tuff because the wax is typically able to saturate the pores in the tuff. If the pore volume of the rock (void space) were 20%, the wax grout volume would be 20 % of the volume of the total drip shield. At a delivered cost on the order of $10 per 3.8 liters (1 gallon) and with an energy cost of $3 per 3.8 liter (1 gallon) of diesel fuel, and drilling costs of $100 per 0.3048 meters (1 foot) it is estimated that large barriers would cost about ten million dollars per 4046 square meters (1 acre) In harder rock, such as shale, the void space is mostly accessible through microscopic fractures and much less wax is required so the cost could be less. Barriers in hard fractured rock like basalt would be less costly in wax volume but require significantly more energy to heat the rock.

Fault Lines

Wax is an excellent sealing material that has the desirable property of flowing under and applied load, while retaining a seal. It should be possible to seal fractures and fault lines against water influx even if adjacent areas move from time to time. The malleable and sticky properties of the wax may even allow a drip shield to be constructed across fault lines that continue to move. The wax-impregnated rock increases the ductility of the tuff and may also be able to automatically re-seal across shear planes.

Barriers formed by this technique could take any shape that can be outlined by the drilled holes. The barrier could be horizontal or vertical. A barrier could also be formed in a basin shape under a waste disposal burial site. The barrier method is applicable to most rock formation types and also to soil. The method has been studied for work in fractured or karst rock formations below the water table as well. After pre-heating of the holes with a circulation pipes, resistance heaters or hot water flush, the molten wax is injected from the top of each well. The lower density molten wax floats on the water as the wax is injected under pressure and displaces the water back into the formation. Then tubing is inserted in the well and molten wax is circulated in the hole as in the method above until the wax treated zone reaches the desired diameter.

Sealing and Toughening Tunnels in Tuff

Volcanic tuff that has been treated with wax has very different properties from the natural tuff. The natural tuff is very permeable to air and water but the treated tuff is waterproof and gas tight just like the wax. Tuff struck with a hammer will normally fracture but wax treated tuff just dents. Compressive strength of the material also seems to be increased though the reason for this is not known. It is possible that the increase in strength of the tuff due to wax impregnation is technically an increase in fracture toughness, just as adding polymer fibers to cement can increase its apparent strength. The wax appears to create a continuous phase within the porosity of the rock. The wax, which is not very high is compressive strength, does have the ability to adsorb a lot of shear energy. It may be that the wax is connecting the strong grains of the tuff together so that shear energy is more evenly distributed.

There may be various shaft, instrument lines or even tunnel shafts that would benefit from a sealing grout that will tolerate earth movements and wet/dry and freeze/thaw conditions with out cracking. Many of the Yucca Mountain tunnels will never house waste but will still be needed for access for a long time. In geological time scales wax may have a limited life but thick layers of branched chain wax such as Waxfix should be able to last for the 10,000-year design life of most repository facilities.

Molten wax thermal permeation grouting may even provide an effective method of uniformly strengthening and sealing the tunnel walls in tuff. As illustrated in Fig. 3, a movable fixture placed in the tunnel would allow a section of tunnel to be heated and permeated by circulating molten wax while still allowing travel through the tunnel. In a cold repository design, tunnel walls made of volcanic tuff could be impregnated with wax up to 2 meters deep to create a more geologically durable and waterproof tunnel. The waste container and its distance from the tunnel walls could prevent heating of the tunnels and radiolysis hydrogen generation. The wax-impregnated tunnel walls could also be lined with other structural shield materials or the tunnels backfilled with crushed tuff to shield the wax from long-term radiation exposure. In large tunnels, a special tubular fixture would be used to treat the tunnel one section at a time operating behind the tunnel-boring machine (Fig. 3). The wax treatment will produce a stronger and more durable tunnel wall as well as making it waterproof and substantially gas tight. This treatment could also prevent radon gas from entering the tunnel drift. In some cases wax treatment may eliminate the need for rock bolts. If rock bolts are used, they could also be sealed with additional wax (Fig. 3).

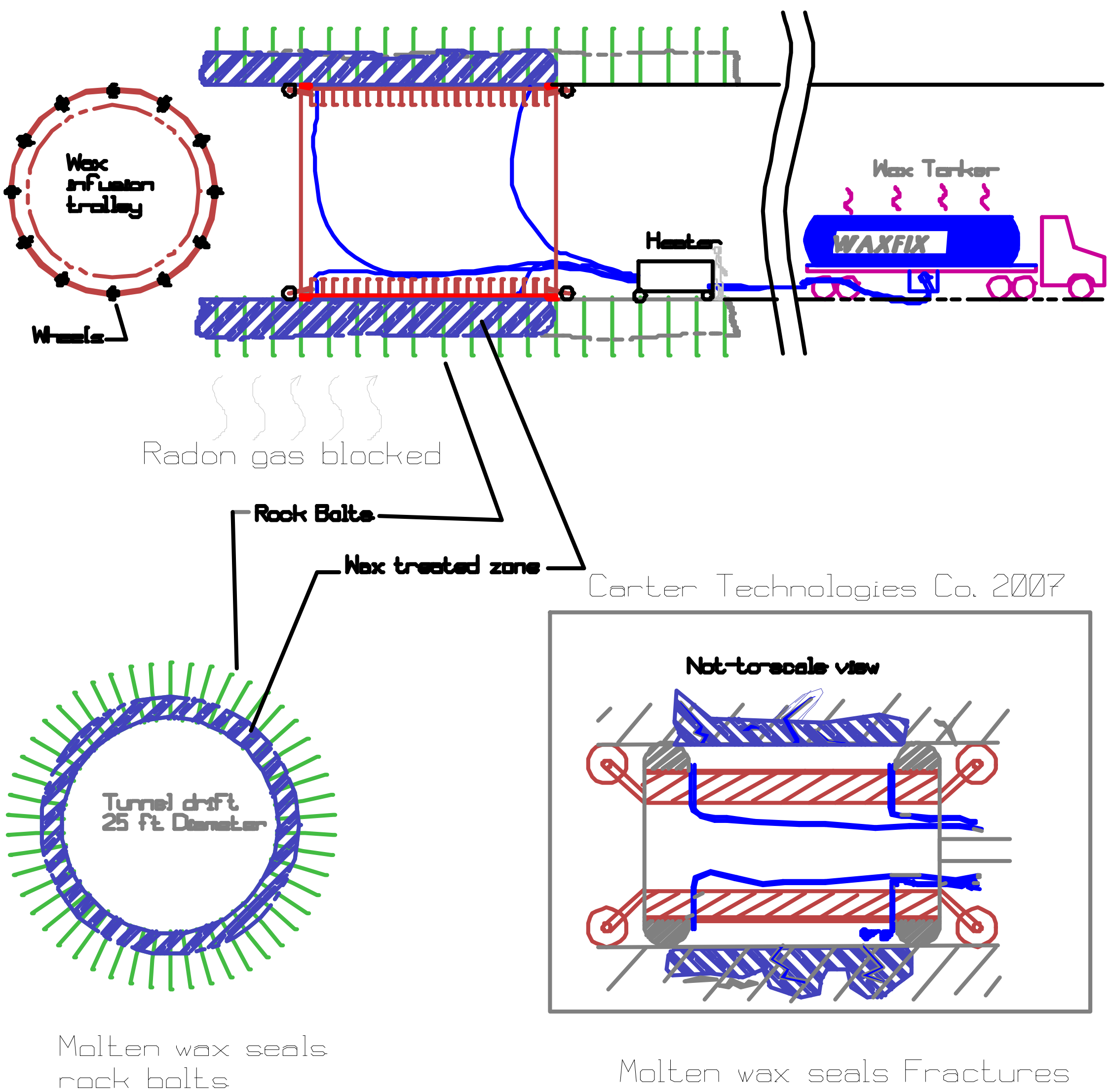

Fig. 3. Trolley apparatus for infusing molten wax to seal and strengthen tunnel walls

Waste Packaging

Contact-handled transuranic waste packages often emit only a small amount of heat, but do so for a very long time. Corrosion of metal containers can occur even in a dry environment if there is water vapor in the air (humidity greater than zero percent). Metal encapsulated with molten wax at temperatures well above the boiling point of water are well protected from geochemical corrosion. The durability of the metal containers could be improved by encasing them directly in wax to prevent contact with moisture. A nominal wax thickness of 5 centimeters around a drum will provide long-term protection. Standard waste drums may be placed in an overpack drum. The space between the drums may be filled completely with malleable waterproof wax. For this application, the wax would be designed with a melting point above 80 degrees Celsius (176F) but it would still be a tough malleable material at the repository temperature.

Legacy Waste Trenches in Tuff

Generally, treatment of an existing buried waste area requires that the waste be pre-heated so that the wax will remain molten as it permeates and saturates the waste. When radioactive waste repositories such as trenches and drilled shafts are backfilled, the backfill may not be compacted so the void space may be significantly greater than the native tuff. In some cases, trench waste can be treated and impregnated with molten wax without pre-heating the waste. A study performed for DOE in 2004 described a method for treating a particular waste trench at LANL containing containerized waste. The technique called for pipes to be driven along the edges of the trench to allow molten wax to be poured directly to the bottom of the trench. Wax would be installed in a series of lifts to prevent floating of the waste. Such a treatment would convert the entire trench into a flexible waterproof zone.

Some existing trench waste is randomly distributed with poor records. This type of trench can be treated in place by driving closed-end heat pipes into the waste and slowly heating the waste trench to 60 degrees Celsius, (140F). Molten wax is then allowed to enter the trench in lifts spreading out and saturating or encapsulating all the waste and soil in the trench.

Legacy Waste in Drilled Shafts

Drilled shafts in volcanic tuff and other soil types have often been used to dispose of wastes that have no alternative disposal path. These wastes sometimes include activated metals and classified objects. The wastes are deposited and the shaft is then backfilled with crushed tuff. The long-term containment and isolation characteristics 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. As illustrated in Fig. 4, heating means can be 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 the equipment to perform this work. After slowly heating the waste zone to approximately 60 degrees Celsius (140F) 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 fill all the void space within the heated zone and for a waterproof durable mass.

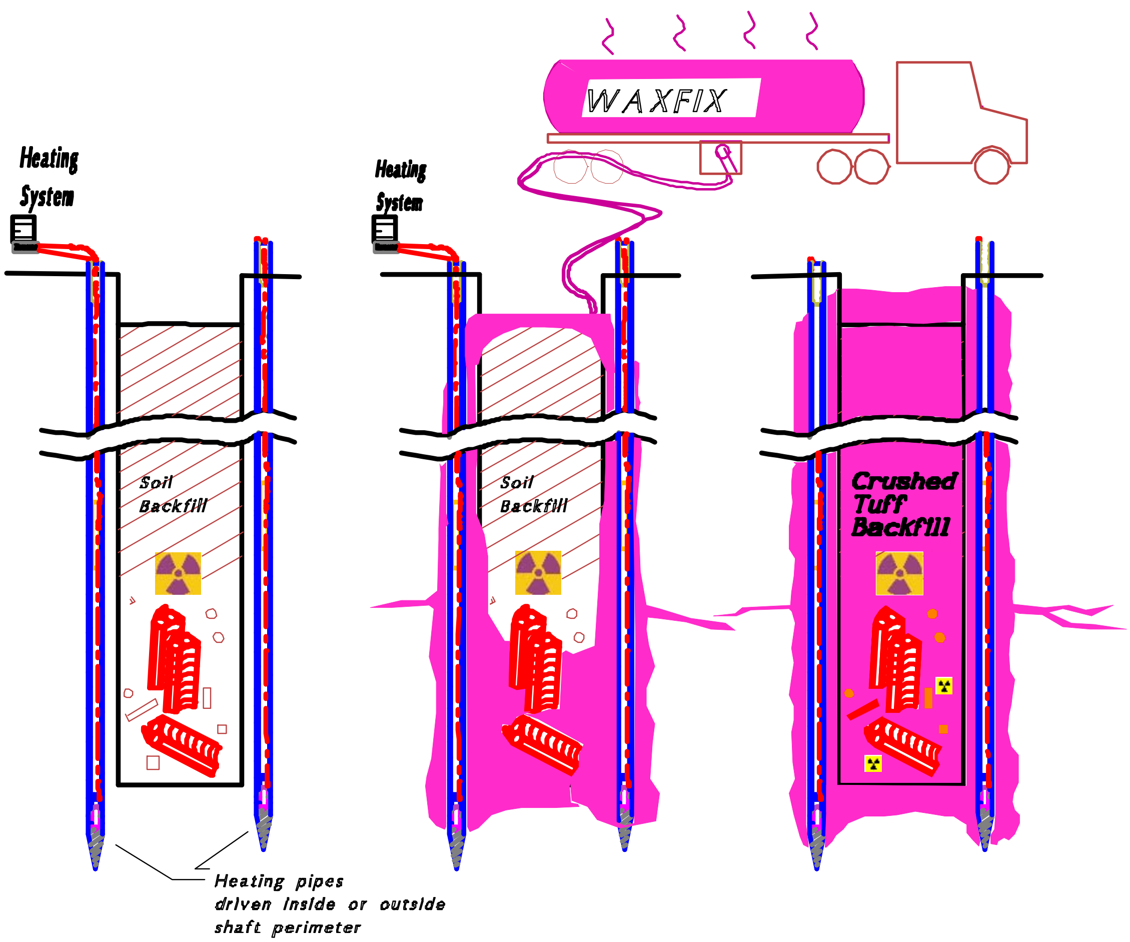

Fig. 4. Waterproofing legacy waste in a drilled shaft by preheating the waste and saturating with molten wax

CONCLUSION

Thermal permeation grouting with molten wax provides an exciting new tool for constructing engineered barriers in volcanic tuff and other semi-permeable formations. The technology is being developed for oil shale production needs but it appears to have many potential applications in the field of radioactive waste containment. The authors are currently investigating possible sources of funding to demonstrate the method in dry arid environments such as those common for waste repositories. While this paper focuses on volcanic tuff, it should be noted that the methods appear to be applicable in sand, clay as well as many types of porous or fractures rock.