MONITORING OF SURFACE DEFORMATION AND MICROSEISMICITY APPLIED TO RADIOACTIVE WASTE DISPOSAL THROUGH HYDRAULIC FRACTURING AT OAK RIDGE NATIONAL LABORATORY*

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ABSTRACT

Low-level liquid nuclear wastes are disposed of at Oak Ridge National Laboratory by the hydrofracture process. Wastes are mixed with cement and other additives to form a slurry that is injected into shale of low permeability at 300 m depth. The slurry spreads radially along bedding plane fractures before setting as a grout. Different methods for monitoring the location and behavior of the fractures have been investigated. Radioactive grout sheets can be located by gamma-ray logging of cased observation wells. Two other methods are based on the fact that the ground surface is deformed by the injection. The first entails surface leveling of a series of benchmarks; uplift up to 2.5 cm occurs. The second method involves use of tiltmeters that are sensitive and measure ground deformation in real time during an injection. Both methods show subsidence during the weeks following an injection. Interpretive models for the tiltmeter data are based on the elastic response of isotropic and anisotropic media to the inflation of a fluid-filled fracture. A fourth monitoring method is based on microseismicity. Geophone arrays were used to characterize the fracture process and to provide initial assessment of the feasibility of using seismic measurements to map the fractures as they form. An evaluation of each method is presented.

INTRODUCTION

At Oak Ridge National Laboratory (ORNL), the hydrofracture technique has been used for over two decades for permanent geologic disposal of liquid low-level radioactive waste. A description of the technique is found in Weeren et al.[1] The technique is basically quite simple and consists of mixing liquid waste with cement and other additives to form a slurry that is injected under pressure into a highly impermeable shale, where the slurry sets to form a solid grout. The injection is through a slot in the cased injection well at approximately 300 m depth; the slurry spreads outward from the well to form a thin ($<$a few cm) sheet parallel to the bedding of the shale. The radius of the grout sheet is up to 200 to 250 m from the injection well. Over 1.5 million curies of wastes have been disposed of in this fashion. The major radioelements are Sr^{90} and Cs^{137}, although a number of other isotopes are also disposed of. Each injection involves disposal of 400,000 to 800,000 liters of slurry.

One of the most important aspects of the technology is that the radioactive slurry spreads along horizontal or near-horizontal bedding plane fractures in the shale before setting. Thus, the wastes are confined to the host formation and do not come into contact with more permeable strata that might provide a hydrologic pathway to the accessible environment. The possibility exists, however, that the slurry could follow vertical fractures and containment within the low permeability shale could be lost. Thus, there is a need to monitor the extent and orientation of the grout sheets to help assure that geologic isolation has occurred. The geology of the site is discussed by Haase et al.[2]

MONITORING TECHNIQUES

A variety of techniques can be used to determine the location of a grout sheet. The most accurate method involves drilling a large number of boreholes to intersect the emplaced grout. Such a method, however, is expensive, time-consuming, and jeopardizes the ability of the site to geologically isolate future slurry injections.

Therefore, it is desirable to consider other methods of determining the orientation and extent of the grout sheets. Methods are being developed at

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ORNL that entail both post-injection and real-time monitoring. Post-injection methods consist of gamma-ray logging of cased observation wells and accurate leveling of benchmarks in the vicinity of the hydrofracture facility. Real-time monitoring methods entail use of tiltmeters installed at the ground surface and geophone arrays at the surface and in deep wells at the site.

The purpose of this paper is, thus, to review recent advances made in these instrumental monitoring techniques; little discussion will be devoted to the gamma-ray logging technique, which has been used for some years. We shall discuss: monitoring data acquired from recent waste injections; limitations and relative comparisons of each; and future work that needs to be undertaken to more fully refine each technique.

SURFACE DEFORMATION TECHNIQUES

When wastes are injected at 300 m depth, the ground surface undergoes slight, but measurable, deformation.[3,4] The shape and location of this ground deformation reflect the orientation and extent of the subsurface grout sheet (Fig. 1). By accurately measuring the surface deformation, either during or after an injection, and comparing it to elastic models, the geometry and orientation of the subsurface sheet can be estimated.

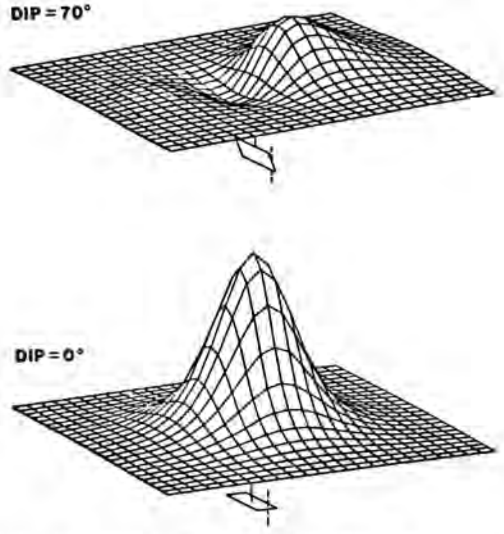

Fig. 1. Idealized configuration of surface deformation resulting from formation of fractures with different orientations in anisotropic and homogeneous half-space, modified from Evans.[5] The lower figure depicts a symmetrical deformation centered directly over the fracture when the fracture is horizontal. As the fracture dips, the shape of the deformation becomes asymmetrical and the area of maximum swelling shifts in the direction of increasing dip of the fracture (top figure).

Leveling Surveys

At ORNL, a series of 75 benchmarks has been installed along roads in a radial pattern up to 650 m from the injection facility (Fig. 2). During eight bimonthly injections in 1982 and 1983, precise leveling surveys were made before and after each injection to determine the amount of surface deformation.

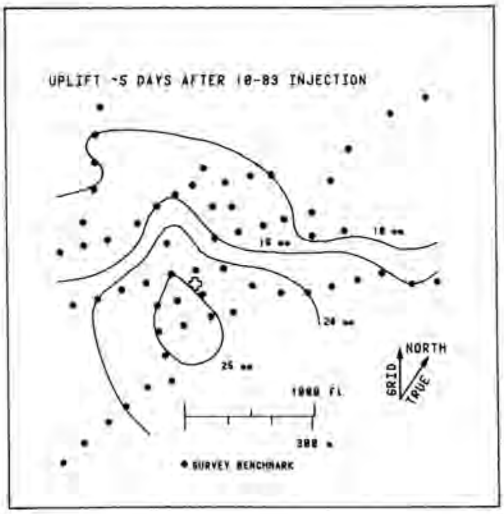

Fig. 2. Net surface uplift immediately after the October waste injection at ORNL. The cross indicates the projected position at the ground surface of the injection point, some 300 m below ground surface. Contour interval is 5 mm.

Systematic uplift patterns have been observed after each of the injections. The uplift pattern from the October, 1983, injection is shown in Fig. 2. This pattern is representative of those associated with other injections, although the extent and shape of the surface deformations vary with each injection. For the October injection, it is noted that the area of maximum uplift is offset by some 100 m to the southwest from the injection well and that the maximum uplift is over 2.5 cm. The uplift decreases in a fairly systematic way outward from the highest point and, although not shown in Fig. 2, extends beyond the 650-m limit of the benchmarks. The volume of the uplift significantly exceeds the volume of the injected grout.

The geometry of the uplift pattern indicates that the grout sheet spread to the north, which is in an updip direction. This orientation would be expected because the slurry should preferentially migrate in the direction of least lithostatic pressure, i.e., in an updip direction along bedding planes. Post-injection gamma-ray logging in the observation wells within 150 m of the injection well confirms the extension of the grout sheet in a northerly direction.

Thirty days after the October injection, the leveling survey was rerun; noticeable changes had occurred over this time period (Fig. 3), similar to those detected after other waste injections. The area of maximum uplift was found to correspond to the location of the downhole injection point and the maximum uplift had decreased to approximately 10 mm in this area. The subsidence of the uplift after the injections is yet being investigated, but is thought to result from an attempt toward mechanical relaxation of the stressed strata following the injection. As noted later, microseismic signals continue for weeks after an injection. It is important to note that the volume of the uplift measured 30 days after an injection roughly corresponds to the volume of radioactive slurry injected.

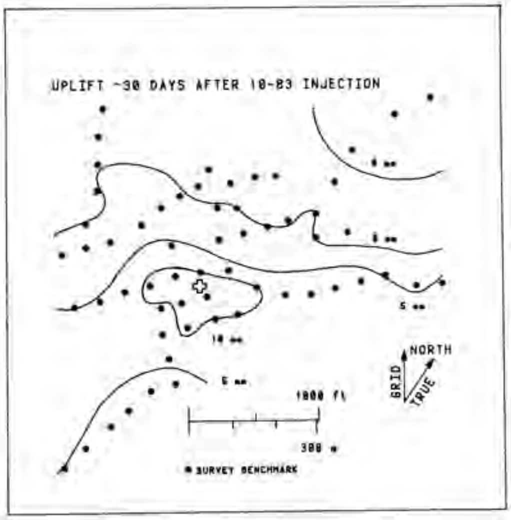

Fig. 3. Net surface uplift 30 days after the October 1983 waste injection at ORNL. Map symbols are the same as in Fig. 2.

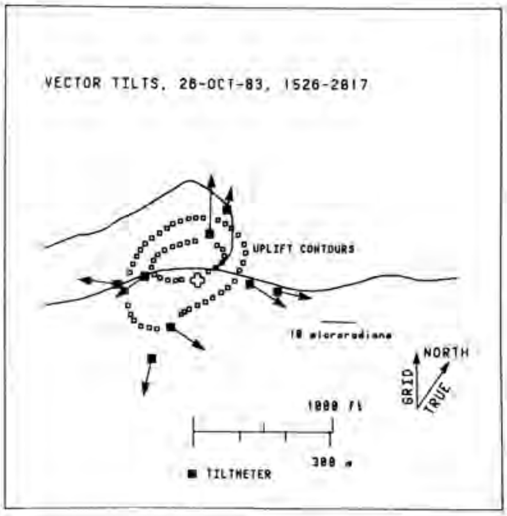

Fig. 4. Net ground tilting resulting from the October 1983 waste injection at ORNL. The arrows for each tiltmeter represent the net vector of tilt measured in an X and Y direction. Solid lines represent roads. Other map symbols are the same as in Fig. 2.

Tiltmeter Surveys

Tiltmeter measurements represent a monitoring technique that provides information on the ground deformation that occurs during and after an injection.[6,7] Eight tiltmeters were installed in September 1983 in shallow wells at radii of 120 and 180 m from the injection point. Measurements were taken for the October and November injections and for the intervening period. The net ground deformation resulting from the October injection is shown in Fig. 4. The arrows indicate the vector tilt of the ground surface at each site. The length of each arrow is proportional to the amount of tilting, measured in microradians. The October injection covered two days. Tilt rates for the second day significantly exceeded those of the first day, suggesting a nonlinear response of the strata over the injection zone. The data reveal that maximum uplift is slightly north of the injection point. Elastic modeling of a purely dilatational fracture would suggest that this uplift pattern corresponds to a grout sheet that propagated upward and to the south.[3] This result is obtained using both an isotropic elastic model and a transversely isotropic model in which rock stiffness parallel to bedding is five times greater than stiffness perpendicular to bedding. This conclusion does not, however, agree with that drawn on the basis of leveling surveys and on the gamma-ray logging of observation wells.

A possible explanation for this northward shift of the center of uplift may be related to shear induced in the hydraulic-fracture plane during grout injection. Horizontal crustal compression in the Oak Ridge area should induce an in-plane shear component because the grout sheets are inclined to this inferred principal stress direction. In-place shear on a southward-dipping fracture would result in maximum uplift to the north of the injection well. When added to the uplift caused by fracture dilation, the net tilt would resemble that measured during the October and November 1983 injections. A more complete discussion of the interpretation of the tiltmeter data are found in a recent article by Holzhausen et al.[8]

Tiltmeter data were also gathered during the month between the October and November injections. Figure 5 shows the net tilt change for the first eight days of this period. Vector directions indicate that subsidence occurred, an observation that corresponds closely with the results of the leveling surveys (Fig. 3). Apparently, this subsidence caused a shift in the center of uplift from slightly north of the injection point to slightly south of the injection point.

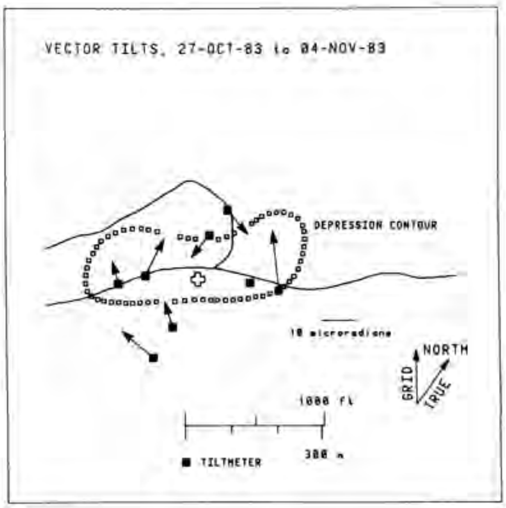

Fig. 5. Net ground tilting during an eight-day period following the October waste injection at ORNL. Map symbols are the same as in Fig. 2 and 4.

Because the tiltmeter data are acquired on a continuous basis, it is possible to monitor ground deformation in real time during an injection.

During the October and November injections, it was observed that surface deformation patterns changed continuously with time and that areas of maximum deformation shifted on a frequent basis. These observations suggest that the injected grout sheet forms in a discontinuous fashion as lobes that are extended in different directions during an injection.

In evaluating their use for monitoring, it is important to note the sensitivity of the tiltmeters. The instruments used during the October and November injections can resolve 5 nanoradians (5×10^{-9} radian) of movement. Figure 6 depicts tilting on the orthogonal X and Y axes for one of the eight instruments during the October injection. On October 25, fracture initiation was caused by injection of a few thousand liters of water at the 300 m depth; tilting was immediately detected. Cessation of tilting was noted immediately when injections were ceased, and a slight reversal of tilt was noted between the night of October 25 and the morning of October 26 on the X axis. These data indicate that tiltmeters are a very sensitive indicator of surface deformation associated with subsurface injections. With appropriate modeling of the data, tiltmeters may represent a feasible method of real-time monitoring of the orientation and extent of the grout sheet.

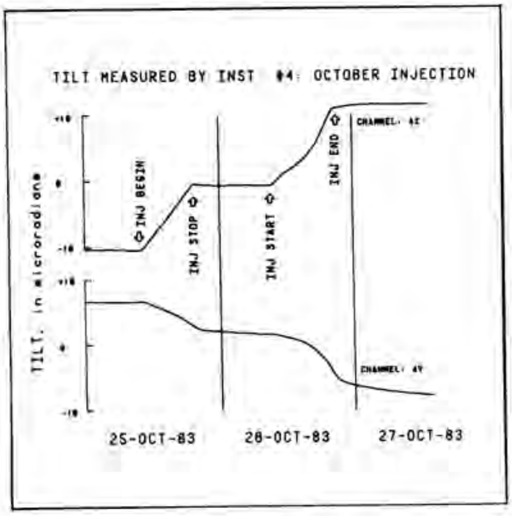

Fig. 6. Graph showing tilt amount, in micro-radians, versus time for instrument no. 4 from October 1983 waste injection at ORNL. Times at which the injection was started and stopped are shown.

MICROSEISMIC MONITORING

It was anticipated that detection of microseismic signals resulting from a propagating fracture might provide a basis for determination of the location and rate of formation of the fracture, and for the failure mechanism by which the fracture propagates. Three geophone arrays were used; two high-frequency (20-250 Hz) arrays were placed 125 to 180 m down in drillholes overlying the injection zone. The geophones were "sanded into" the wells to assure good transmission of signals from the rock. A third array was placed at the ground surface. Low frequency (0.03 Hz) signals were also recorded with a surface-mounted vertical component seismometer.

Numerous microseismic events occurred during the injection; most represent shear failure associated with stress field changes in the rock envelope surrounding the fracture. Few tensile events--those that could be created by bedding plane opening--were detected. Long-period events occurred throughout the injection and correlated closely with slight decreases in pumping pressure. Events also were noted for days after an injection ceased, suggesting that a physical readjustment of the slurry and/or overlying strata was taking place. These post-injection events gradually decreased with time.

Progress to date has not been successful in mapping the fractures as they form. The chief reason for this is that the events associated with fracture propagation are of very low energy and geophones must be close to the fracture for detection of the events. In the case at ORNL, the geophones were over 100 m above the fracture; most of the energy from the fracturing apparently was absorbed by the intervening strata.

RELATIVE EVALUATION OF THE TECHNIQUES

In the evaluation of the relative potential of the monitoring techniques, one must consider the objective of the monitoring. If the objective is simply to determine the orientation of the wastes after injection, then surface leveling surveys may be applicable and could be conducted at relatively low costs. Also a small number of properly located cased observation wells offers a relatively inexpensive method of directly determining the exact depth of a radioactive grout sheet, although there may be considerable capital costs in drilling and installation of the wells. Neither of these methods, however, allows for the determination of the behavior of injected wastes during the actual disposal operation.

It may be desirable that a monitoring program be in place that provides sufficient real-time data to allow continuous subsurface "mapping" of the extent and orientation of the injected wastes during disposal. Because the objective of the disposal technique is to geologically isolate wastes from aquifers, a breaching of an impermeable containment horizon--possibly by the unexpected formation of vertical fractures--might represent loss of isolation and constitute grounds for cessation of operations. In such a case, real-time monitoring techniques, such as the tiltmeter surveys or microseismic detection, would be necessary.

At present, neither the tiltmeter nor the seismic technique is sufficiently developed to fulfill the need for highly accurate real-time monitoring. From our experience, both appear to have great potential and may prove to be complementary to each other. At present, it appears that the tiltmeter technique is the more developed method and is highly sensitive to subsurface deformation. A properly designed tiltmeter array would likely detect subsurface fractures that deviate significantly from the containment horizon. It is possible to process and to automatically display the tiltmeter data as they are acquired. Development of additional real-time analysis and interpretation capabilities would certainly be more rapid for the tiltmeter method than for the microseismic method. Another limitation of the microseismic method is that the fracturing of the rock during waste injection must produce signals that can be identified and measured. In rocks with essentially no tensile strength, the actual mapping of fracture propagation may be difficult.

The costs of either of the real-time monitoring techniques are considerable compared to the leveling surveys and gamma-ray logging. Tiltmeters cost up to $10,000 each; to this, must be added the cost of the data management system and system maintenance. While geophone arrays might be constructed for significantly less than tiltmeter arrays, our experience indicates that geophones submersed in deep wells, as is necessary to detect signals, may fail if the wells are full of water. Also, data management systems for seismic research are typically quite expensive. Nevertheless, for a major waste disposal operation, the capital and maintenance costs of these monitoring techniques may not be unreasonable. It is also probable that such an operation would require a series of monitoring wells for post-injection logging, in addition to a real-time technique.

CONCLUSIONS

Recent development work at ORNL on monitoring techniques for tracking subsurface grout sheets from the hydrofracture waste disposal operations indicates that several methods provide information on the behavior of the waste-bearing grouts. Leveling surveys appear to be a reasonably good method of post-injection monitoring and yield data on surface uplift and the orientation of the grout sheet. Tiltmeter surveys provide highly sensitive real-time data on ground deformation during an injection, and can be interpreted using isotropic and transversely isotropic models. Seismic methods also provide real-time information on the behavior of fracture formation and on the failure of rocks surrounding the injection zone. Both the tiltmeter and seismic methods appear to have considerable potential for future application.

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