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RESULTS OF INSTRUMENT RELIABILITY STUDY FOR HIGH-LEVEL NUCLEAR WASTE REPOSITORIES*

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Abstract

Reliable instrumentation will be needed to monitor the performance of future high-level waste repository sites. A study has been made to assess instrument reliability at Department of Energy (DOE) waste repository related experiments. Though the study covers a wide variety of instrumentation, this paper concentrates on experiences with geotechnical instrumentation in hostile repository-type environments. Manufacturers have made some changes to improve the reliability of instruments for repositories. In this paper, we will review the failure modes, rates, and mechanisms, along with manufacturer modifications and recommendations for additional improvements to enhance instrument performance.

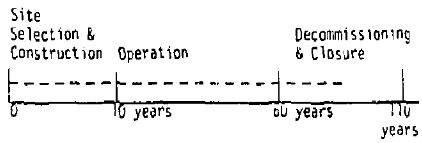
Introduction

In June 1981, the U.S. Nuclear Regulatory Commission (NRC) published proposed rules requiring the measurement of specific geotechnical parameters for high-level nuclear waste repositories. To provide guidance in complying with these proposed rules, the Geological, Environmental, and Radiological Field Measurement System Evaluation Project of the Lawrence Livermore National Laboratory (LLNL) has been conducting studies for the NRC Office of Research.

The purpose of one of the studies is to examine the reliability of instrumentation which may be used at future waste repository sites. Using studies of instrument reliability and failure mechanisms and on-site observations, this paper reports on the status of instrument reliability in specific areas of waste repository instrumentation and identifies needed geotechnical instrumentation improvement. Site visits to Department of Energy (DOE) waste repository experimental sites have yielded first-hand observations of problems and progress made by DOE experimenters in solving some of these problems. The major sources of instrumentation experience reported herein was obtained from individuals, and reports of their work on the Stripa Project conducted by the Lawrence Berkeley Laboratory, the Climax Spent Fuel Test conducted by the Lawrence Livermore National Laboratory, the BWIP Project conducted by Rockwell at it's Hanford Operations site, and RE/SPEC at Avery Island, Louisiana.

Instrumentation will play an important part in monitoring the operation and integrity of future high-level waste repositories. Once a repository is built, instrumentation will be vital to ensuring the integrity of the site by monitoring critical geological, environmental, and radiological parameters.

Due to the long operational phase of the repository, instrumentation selected for use should be the most reliable state-of-the-art instrumentation available. The following figure illustrates the repository time line.



During the course of the LLNL study, it was found that geotechnical instruments appeared to have numerous reliability problems. In the following sections we discuss some general findings, the types of problems encountered, improvements made by manufacturers, and areas where improvements are still needed to enhance and improve performance and reliability.

A major problem which has contributed to poor instrument performance has been the transfer of technology from instruments designed for ambient temperature civil engineering applications into high temperature hostile environment repository applications. This technology transfer is a logical first step; however, many of the instruments have not proven to be adequate in the more hostile environments.

General Findings

The more sophisticated electronic data acquisition systems and computer-based control and monitoring systems performed well in most repository related experiments. Radiological monitoring and environmental monitoring systems also performed reliably. The geotechnical instrumentation appeared to be the weakest link in repository instrumentation.

One of the major problems was the impact of the high temperatures encountered in the repository simulated experiments. Many instruments required large corrections to acquired data due to the effects of the high thermal environments. The large temperature corrections in some cases exceeded the actual measurements.

Other failure mechanisms which plagued the applications of geotechnical instruments included water intrusion and corrosion. In the short-term experiments, these mechanisms created a number of reliability problems and could prove to be a major problem in future long-term applications of instrumentation in high-level nuclear waste repositories.

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Multiple Position Borehole (Rod) Extensometer (MPBX)

The rod extensometer is a common device for measuring changes in axial length along a borehole. The reliability information presented here was gained from field experiences involving 125 multiple position rod extensometers at four DOE experiment sites.

The four major components of these MPBXs are: (1) the anchor, (2) the anchor-to-head rod connection mounted inside a waterproof flexible conduit, (3) a rod tensioning system, and (4) a head assembly which can include displacement transducers. The 112 extensometers installed in basalt and granite experiments used hydraulic anchors and electronic sensors, while the 13 extensometers installed in the Avery Island salt experiments used mechanical anchors and dial gauge readouts. Extensometers with three, four, or six anchor positions were used, as shown in Table 1. We will concentrate on experiences with those systems used in the basalt and granite experiments.

Two types of electronic sensors have been used: linear potentiometers and linear variable differential transformer (LVDT) type transducers. Of the 315 LVDTs used in basalt and granite experiments, there have been no confirmed catastrophic failures reported. However, there has been one reported experience indicating complete failure in attempts to use LVDTs in experiments at one of the salt sites.

Patrick et al. (198?) has reported the failure of 23 linear potentiometers from a total of 56 transducers (i.e., 41%) used on 14 four-anchor rod extensometers at one experiment located in granite. Another 60 linear potentiometers on similar extensometers, at the same site but in parallel drifts, have performed without failure. The failure mode was a nonlinear change in the electrical resistance of the potentiometers with time, resulting in the data acquisition system recording erroneous indications of several millimeters of displacement (some indications exceeding 5 mm). All of the failed transducers were on vertically installed extensometers located in the main canister drift, and all were located 1.4 to 2.0 m from the heat sources. It is also worth noting that there was a high failure rate of vibrating wire stressmeters located in the same general area. A number of tests have been conducted to determine the cause of failure of the potentiometers, and a number of possibilities prevail, but no definite cause has been identified. The linear potentiometers on extensometers where failures occurred have been replaced with a selection of other linear potentiometers, LVDTs, and electromagnetic proximeters to evaluate their performance under similar conditions.

Hydraulic anchoring systems, in which a copper bladder is inflated against the borehole wall to set each anchor, were used on MPBXs in the granite and basalt experiments (see Table 1). It was felt that hydraulic anchors would provide good compliance to borehole deformations. Grouting was used in the granite experiments to supplement the anchors. At Stripa the boreholes were completely filled with grout (Schrauf et al., 1979), and at Climax, the grout columns were interrupted by closed-cell foam rubber expansion joints to isolate axial displacements (Brough and Patrick, 1982). Of the 370 anchor systems where hydraulic pressures were monitored, approximately 115 (i.e., 31%) have gone to zero pressure or failed to maintain a minimum pressure over a 24 hour period. It has not been individually determined whether the failures were in the bladders, hydraulic tubings, or fittings. A few anchor systems failed when initially inflated and a few more failed with increased hydraulic pressures during heating, however, the majority of failures have occurred under controlled pressures as the experiments progressed. Some of the bladders may simply have burst into voids or fractures intersecting the boreholes, which is more likely in a highly fractured media. Other pressure failures may have occurred at fittings or in tubing, or in the bladder surface within the borehole, which is more likely where grouting did not surround the hydraulic system. Both of these

Table 1. Multiple Position Borehole (Rod) Extensometer (MPBX) Failure Rate

					Transducers			Anchors		
User (Media)	No. Used and Positions	Total Positions	Slope	Period	Type	No. Failed (1)	% Failed	Type	Loss of Pressure	% Loss
BWIP-NSTF (Basalt)	21-4 pt. / 1-3 pt.	87	Vert.	450 days	LVDT	0	-	Hydraulic	87	50%
	29-3 pt.	87	Horiz.	↓	↓	0	-	↓		
LLNL-Climax (Granite)	14-4 pt.	56	Vert.	365 days	Linear Pot.	23	41%	Hydraulic & Grouted	17	30%
	4-3 pt.	12	Horiz.	↓	↓	0	-	↓	(2) unknown	
	8-6 pt.	48	Incline	↓	↓	0	-	↓		
LBL-Stripa (Granite)	17-4 pt.	68	Vert.	550 days	LVDT	0	-	↓	11	8%
	18-4 pt.	72	Horiz.	↓	↓	0	-			
RE/SPEC-Avery (Salt)	13-6 pt.	78	-	1000 days	Dial			Mechanical	2 failures	2.5% (3)

(1) Erroneous readings.

(2) Used hydraulic anchors with check values and no pressure monitoring. Anchors were also grouted.

(3) *Suspicious readings, possible anchor movement.*

two possibilities may explain the higher incidence of anchor pressure failures in the basalt experiments (Table 1). Despite the number of anchor system pressure failures, there have been only two cases reported where anchor slippage may have occurred.

Wilder et al. (1982) reported that the majority of rod extensometers in waste isolation projects used Superinvar (a nickel-cobalt steel alloy) rods, because at temperatures below approximately 150°C to 200°C, Superinvar has a low coefficient of thermal expansion relative to mild steel. However, mild steel rods were used in some cases where only moderate temperature rises were expected. It was also recommended that Superinvar rods be put through the full MIT three-cycle heat treatment to reduce hysteresis. For accurate measurements at elevated temperatures, the thermal expansion characteristics of the rods must be carefully determined. This is particularly important with Superinvar where the thermal expansion is non-linear with temperature. During use, temperatures must be measured at a sufficient number of points along the rods to provide a temperature profile adequate for thermal expansion corrections.

Friction, or "stiction", within extensometer systems has also been reported as a problem that has resulted in a stick-slip response at the sensors. Tests done at Stripa released as much as 80 µm of stored rod displacement by lightly rapping the extensometer head assemblies. A routine was then instituted to periodically rap each instrument head to continuously release the friction (Binnall, 1980). Several laboratory tests have followed to determine sources of this friction, and a number of design improvements have been made in later extensometers to help reduce the problem.

Cases of failures in the waterproof conduit systems have been observed, allowing water or moisture to reach the rods. In some cases, rusty water has flowed from the rod conduit into the head assemblies causing damage there and indicating the possibility of rod oxidation and corrosion. There have been no confirmed catastrophic rod failures, and only two cases reported where either a rod or anchor might have failed; however, rod corrosion and anchor system corrosion must be carefully considered where long-term reliability is required.

Despite the numerous problems, most of the MPBXs used in the DOE experiments have been fairly reliable considering they were not designed to last for several years, nor to operate unattended and unmaintained in a repository-type environment. However, it must be noted that the performance experienced to date would be unacceptable for repository monitoring where it is expected that long-term monitoring, tens of years, will be required (Wilder et al., 1982).

Numerous improvements have been made since the first extensometers were installed at Stripa. The latest designs have yet to be tested in actual repository experiments. Attempts have been made to reduce friction with every design iteration; some of the latest include an individual conduit for each rod. Improved anchor systems have also been designed. Well designed mechanical, grouted anchors may ultimately be the best solution. At least one of the latest designs includes rods that can be easily decoupled from the anchor for removal or for movement to a second level at the anchor to aid in extensometer calibration.

There is still need for additional improvements. This includes transducers that can function reliably and accurately at actual repository temperatures. Moisture intrusion and corrosion problems must be solved. Also needed is a method to perform a simple in-situ calibration; the ideal calibration would move the rod at the anchor end to simulate actual rock displacement. At least one manufacturer (European) produces a single rod extensometer with a transducer located at each anchor for multiple position measurements. Unfortunately, the present design is not suitable for use in a repository environment, but the basic idea has a number of merits.

USBM Borehole Deformation Gauge

The three-component borehole deformation gauge was originally developed by the U.S. Bureau of Mines for short-term use at ambient temperatures to measure in-situ stresses by the overcoring method (Hooker et al., 1974), and is highly reliable in that application. The gauge is typically used in a 38 mm borehole to measure three components of diametrical change 120° apart. Deformations are measured by strain gauges mounted on three pairs of opposed cantilever beams, which in turn are coupled to the borehole wall by six pistons 60° apart. Laboratory tests in aluminum and steel have yielded accuracies of 0.002 mm and sensitivites of 0.001 mm.

DOE experimenters elected to use USBM gauges at Stripa and BWIP to make borehole deformation measurements for in-situ stress change calculations. The experiments, unlike previous applications of this gauge, were longer term (about 2 years) and in hostile environments. A number of modifications were made to meet the anticipated high temperatures (up to 200°C); however, gauge deficiencies still resulted in high failure rates as shown in Table 2.

Table 2. USBM Gauge Failure Rates

User	Qty.	No. Failed	% Failed	Period
BWIP-NSTF	28	19(1)	68%	450 days
LBL-Stripa	30	19	63%	550 days

(1) Failed or suspect (Deju, Nov. 1981)

The failure rates are actually worse than indicated by the table. Many of the failed gauges were repaired and reinstalled, failed again, and were repaired a second or even third time.

The major factors affecting USBM gauge survival have been attributed to moisture and corrosion. Even small amounts of moisture within the gauge can affect the strain gauge readings. There have been cases where large amounts of water have entered the gauges causing catastrophic failures. A number of failures have been attributed to corrosion of the wiring, connections, and strain gauges. There have also been signs of corrosion of some of the internal mechanical components, such as at the piston/cantilever interfaces. Though there has been no evidence of external corrosion of the gauge's stainless steel body, corrosion has attacked other external components such as pistons and centering springs. Corrosion of the pistons can reduce the effective piston length and be interpreted as borehole deformation, and failure of a centering spring can allow the gauge to pitch in the borehole, also affecting measurements.

USBM gauge accuracy and reliability are also affected by temperature. There have been cases where thermal expansion of epoxies have broken very fine strain gauge wires. Gauge sensitivity and offset as a function of temperature and gauge thermal expansion are relatively easy to characterize; however, sensitivity and offset are subject to long-term drift which is greatly influenced by temperature. The magnitude of drift is not predictable and must be quantified by some method such as periodic recalibration in order to accurately measure deformation (Wilder et al., 1982).

As gauges have been removed and rebuilt, a continuous progression of improvements have been made and new designs have evolved: moisture barriers have been improved, electrical connectors have been replaced with electric feed-through pins, electrical cables have been made more water tight or replaced with more water tight cables, internal components have been coated with moisture barriers, strain gauge mounting techniques have been improved, and improved strain gauge adhesives have been used. One improved version included filling the gauge body with a silicone oil to displace moisture, which appears to have increased gauge life.

The most likely locations for water intrusion into the gauge are at the pistons and the cable. One of the latest designs, yet untested, provides a bellows between the pistons on the outside and the internal cantilevers. It also includes a water tight flexible stainless steel conduit welded to the gauge for the electrical cable. One other recent improvement is that the gauge can now be manufactured from titanium which reduces its weight by 43% (Rogue, 1982).

Despite the many significant improvements, the USBM gauge is still not at that point where it can be used unattended over long periods of time in a repository environment. The corrosion and moisture intrusion problems must be eliminated, and the long-term drift problems greatly reduced. Additionally, some techniques should be employed so that in-situ calibrations can be performed. Previous investigators have used a gauge with cantilevers activated by internal air pressure. The USBM gauge should continue to be developed unless a more promising instrument comes along.

Vibrating Wire Stressmeter (VWS) Gauge

The vibrating wire stressmeter operates on the principal that a change in tension on a wire causes a change in its fundamental period of vibration. The gauge body consists of a hollow steel cylinder with a highly stressed steel wire stretched across its diameter. In use, the cylinder is installed in a borehole and substantially preloaded in the direction of the wire axis by means of a sliding wedge and platen assembly, thus forming a rigid inclusion. Stress changes in the surrounding rock slightly deform the cylinder causing changes in the natural period of vibration of the wire (Hawkes and Bailey, 1973). The natural period is measured, periodically, by electromagnetically exciting the steel wire and monitoring it for 100 oscillations.

Although VWS gauges have proven reliable in a wide variety of geotechnical applications, numerous problems have been encountered with their use at elevated temperatures in waste isolation experiments. The hostile environments have resulted in excessively high failure rates as shown in Table 3. The primary cause of failures has been either moisture leakage into the gauge body-cavity or into the electromagnetic coil assembly; or possibly entrapped humidity in the gauge at the time of manufacture (Wilder et al., 1982). The mechanism of failure within the body-cavity has been identified as corrosion, especially to the wire itself (Patrick et al., 1981). In addition to failures, internal corrosion involving the wire can influence the basic calibration and response of the unit.

Table 3. VWS Gauge Failures

User	Qty. (1)	No. Failed	% Failed	Period
BWIP-NSTF	40	31(2)	78%	450 days
LLNL-Climax	18	13	72%	365 days
LBL-Stripa	26	6	27%(3)	550 days
RE/SPEC-Avery	84	24	29%	1000 days

(1) Quantities initially installed, not including replacements

(2) Failed or suspect (Deju, Nov. 1981).

(3) Four gauges removed early are not included in this calculation.

Aside from the internal corrosion problems, numerous other problems have plagued the performance of the VWS gauges. Gauges used in the earlier experiments, conducted at Stripa, also experienced severe external corrosion of the mild steel bodies. To avoid this problem, BWIP and Climax experimenters suggested improvements in design which included addition of a 5 mil electroless nickel plating on the inside and outside of the gauge body to inhibit corrosion. However, O-ring seals were still used. It was later discovered that plating the inside of the gauge body may have exacerbated the wire corrosion problem by removing a rustable surface within the gauge which otherwise might have acted as a "getter" for small amounts of water (Patrick et al., 1982). The manufacturer has subsequently designed and tested a hermetically sealed, evacuated version of the gauge in which the cavity containing the steel wire is sealed by electron-beam welding thin stainless steel cups inside the body. Concurrently, the manufacturer developed a new technique for sealing the electromagnetic coil assembly. Nine of these gauges have been in use at Climax since June 1981, with no reported failures, and others are in use in BWIP experiments.

Other problems arise in the complexity of the data analysis. Gauge response is a function of rock modulus and rock/gauge moduli interactions, which in turn are temperature and measurement history dependent. Thermal expansion characteristics of the rock and gauge must be taken into account. Operating at elevated temperatures can require corrections to field data several times larger than the expected in-situ stress changes. It has also been observed that misalignment between the platen, wedge, gauge body, and borehole can cause wide measurement variations. Measurements are also sensitive to gauge preload, body corrosion, modulus change in the steel, and localized rock crushing and microcracking under high inclusion forces. Installation setting techniques need to be improved and gauge drift problems decreased.

Though significant improvements have been made to the vibrating wire stressmeter, it is obvious that there are still numerous problems to be solved before the gauge can be effectively used to measure stress for long periods in a repository environment.

Thermocouples

Thermocouples have been the principal temperature measuring device used in nuclear waste isolation experiments. A total of 1310 type K (Chromel-Alumel) and type E (Chromel-Constantan) thermocouples were installed at the three DOE experiment sites in granite and basalt (see Table 4). These devices are mechanically simple and rugged, and have been relatively reliable in operation over the periods of the experiments (1-1/2 to 3 years).

As shown in Table 4, three types of thermocouple wire coverings were used: Inconel-600 and 304-stainless steel sheaths where higher temperatures were expected, and Teflon (type TFE) insulation where initial calculations predicted temperatures below 200°C.

Table 4. Thermocouple Failure Rates

User	Type	Qty.	No. Failed	% Failed	Clad (1)	Ref. (2)
BWIP-NSTF	K	72	0	-	I	RTD
	E	371	0	-	T	RTD
LLNL-Climax	K	482	0	-	I	RTD
LBL-Stripa	K	385	48	12.5%	I,T,S	IPR
TOTAL		1310	48	3.7%		

(1) I = Inconel-600 sheath
T = Teflon (TFE) insulation
S = 304-stainless steel sheath

(2) RTD = RTD monitored isothermal blocks
IPR = Ice point reference.

Experience has shown that temperature accuracies of 1°C or 2% of reading, whichever is greater, are easily obtained. With computer-based thermocouple conversion routines that include a complete temperature measuring system calibration, these accuracies are improved to better than 0.5°C or 0.5%, whichever is greater. Thermocouple limits-of-error and individual calibration criteria have been selected to meet specific accuracy requirements. Experiences to date have shown that the selected TCs and temperature references have been sufficiently accurate and stable to meet application requirements (Wilder et al., 1982).

There have been no catastrophic failures of thermocouples under normal operating conditions at either Climax or BWIP. Catastrophic failures, however, were experienced at Stripa under one particular operating condition. Intergranular corrosion of 304-stainless steel sheaths necessitated replacement of 60 thermocouples installed in 12 sand backfilled boreholes in close proximity to two full-scale heaters. Only 23 of these completely failed, but all were replaced with (50) Teflon insulated and (10) Inconel-600 sheathed thermocouples. Had the replacements not been made, it has been predicted that 48 thermocouples would probably have failed as shown in Table 4. All of the failures occurred within the first 100 days of experiments that ran for nearly 600 days. Upon removal at the end of the experiments the Inconel sheathed replacements also showed signs of corrosion. Three observations should be noted here. First, all sheathed thermocouples used at Stripa had been heat treated to stabilize their thermal-electric characteristics, inadvertently making the sheath material more sensitive to intergranular corrosion (Binnall, 1980). Second, only those thermocouples in sand backfilled holes were effected by corrosion. Third, since the Stripa experiments were well below the water table, the corroded thermocouples were initially in a wet, heated environment.

Some of the Teflon insulated thermocouples at Stripa developed water leakage at the RTV coated junctions. This caused no problem in itself, but in some of the grouted boreholes, head pressure forced water along the thermocouple wire between layers of insulation and into the electronics enclosures. Even so, temperature readings seemed to remain valid when compared with predicted data.

Another phenomenon was observed at two experimental sites when small quantities of water were captured in closed bottom thermocouple tubes. This resulted in a boiling and condensing cycle within the tubing, which caused thermocouple readings to oscillate erratically between 100°C and the valid temperatures. This continued until the tubes were cleared of the moisture.

Wilder et al. (1982), makes the following design recommendations resulting from experiences with thermocouples in DOE experiments:

- Use thermocouple sheath and insulation material that will survive the environmental conditions without corrosion or decomposition.
- Use grounded junctions in enclosed sheaths.
- Obtain all thermocouple wire from single material melts.
- Retain control samples of thermocouples to check long-term stability.
- Install tubing whenever possible for traveling thermocouples. Take care that this tubing does not collapse during installation or grouting.
- Thermocouples should be removable for recalibration and/or replacement.
- Provide a means to drain or remove moisture from long thermocouple wells (tubes).
- Provide periodic loop resistance measurements to verify that TCs have not electrically opened or shorted somewhere along their length.

Conclusions

Geotechnical instruments originally designed for laboratory and civil engineering applications have been used for scientific measurements in high temperature repository experiments. The use of modified, off-the-shelf instruments, with a minimum investment in design improvements and testing programs, have resulted in excessively high failure rates. Manufacturers have made numerous improvements in their instrument designs resulting from the experiences in DOE repository experiments. Even so, it appears that further significant improvements in geotechnical instruments, testing programs, and measurement and analysis techniques are needed before these instruments can be used with confidence, over long periods, in high-level nuclear waste repositories.

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