INSTRUMENT RELIABILITY FOR HIGH-LEVEL NUCLEAR WASTE REPOSITORY APPLICATIONS

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ABSTRACT

Reliable instrumentation will be needed to evaluate the characteristics of proposed high-level nuclear waste repository sites and to monitor the performance of selected sites during the operational period and into repository closure. A study has been done to assess the reliability of instruments used in Department of Energy (DOE) waste repository related experiments and in other similar geological applications. The study included experiences with geotechnical, hydrological, geochemical, environmental, and radiological instrumentation and associated data acquisition equipment. Though this paper includes some findings on the reliability of instruments in each of these categories, the emphasis is on experiences with geotechnical instrumentation in hostile repository-type environments. We review the failure modes, rates, and mechanisms, along with manufacturers modifications and design changes to enhance and improve instrument performance; and include recommendations on areas where further improvements are needed.

INTRODUCTION

In June 1981, the U.S. Nuclear Regulatory Commission (NRC) published proposed rules requiring the measurement of specific 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(1) was to examine the reliability of instrumentation which may be used at future waste repository sites. This paper reports on results from this study and identifies areas where instrument improvement and development are needed for reliable in-situ measurements in high-level nuclear waste repository environments.

Visits to Department of Energy (DOE) waste repository experimental sites have yielded first-hand observations of problems, and progress made by DOE experimenters and instrument manufacturers in solving some of these problems. The major sources of instrumentation experience reported herein were obtained from individuals and reports of their work on the Stripa Project conducted in granite by the Lawrence Berkeley Laboratory, the Climax Spent Fuel Test also conducted in granite by the Lawrence Livermore National Laboratory, the Basalt Waste Isolation Project (BWIP) conducted by Rockwell at the Hanford Operations site, and salt dome experiments conducted by RE/SPEC at Avery Island, Louisiana. Instrument manufacturers and consulting organizations have also provided valuable information for this study. Applicable work conducted by state and federal agencies, public utilities, and private companies was also looked at for additional in-situ instrumentation reliability data.

Instrumentation will play an important part in site characterization and evaluation during the initial ten year period representing site selection and construction. During the 50-year repository operation period that follows, reliable instrumentation will be vital in ensuring repository integrity by monitoring critical geological, hydrological, geochemical, environmental, and radiological parameters. Continued in-situ measurements may also be required well into the final 50-year phase that represents repository decommissioning and closure.

Due to the necessity to accurately monitor and understand the performance of a repository, and because of the long exposure of instruments to hostile environments, the most reliable state-of-the-art instrumentation available should be selected for use. A continuing development program will be needed to provide new generations of improved instruments to replace or supplement those that fail or are found to provide inadequate data.

During the course of the LLNL study, it was found that experiences with geotechnical instruments provided the preponderance of reliability data for equipment that has been in use continuously over periods of several years for in-situ measurements in simulated repository environments. There were numerous problems with the reliability reported for these geotechnical instruments. Only one of the DOE experiments, a large-scale permeability experiment at Stripa, used a significant number of continuously installed instruments for hydrological measurements over a period exceeding a year. This provides a rather limited data base for the evaluation of the reliability of hydrological instruments. However, their reliability and failure mechanisms appear to be roughly the same as for geotechnical instruments. Experience with instrumentation for continuous in-situ geochemical measurements in a repository environment is essentially nonexistent since such measurements in the previous DOE experiments were made by taking samples into laboratories for analysis, though this may not always be a practical approach for some types of measurements in an actual repository.

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Because of the limited experiences with hydrologic and geochemistry instrumentation in simulated repository environments, this paper concentrates on the specific findings associated with geotechnical instrumentation reliability. In doing this, 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 instrumentation performance and reliability. The general findings can be extrapolated to the other classes of instrumentation that may be used in a repository environment.

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.

Radiological instrumentation was installed and operated at only one DOE site since none of the others involved tests with radioactive waste. To date, no major reliability problems have been encountered with these instruments. This is likely attributable to the fact that such instruments have been developed and used for long-term laboratory monitoring for many years, and the conditions in the Climax Mine where the instruments are installed reasonably approximate laboratory conditions. Similar ideal conditions may not be encountered under all circumstances in active repository environments.

Similarly, the environmental measurement instruments, such as temperature monitors, hygrometers, and turbine air flow monitors, have operated in the relatively short-term DOE experiments with no major reliability problems. Again, these continuous-duty instruments were operating in an environment for which they had been extensively designed and tested.

One of the major problems was the impact on geotechnical instruments of high temperatures encountered in the repository simulated experiments. Many instruments required large thermal corrections to acquired data. In some cases the corrections exceeded the actual measurement data(2).

The major failure mechanisms which plagued geotechnical and hydrological instruments were water intrusion and corrosion, both of which were accelerated by elevated temperatures. Instruments were exposed to the highest temperatures in the BWIP experiments with the second highest temperatures encountered in the Stripa experiments. This reflects itself in the instrument failure rates. In the relatively short-term DOE experiments, these mechanisms created numerous reliability problems sometimes causing instrument failures within a few months, and could prove to be a major problem in future long-term applications of instrumentation in high-level nuclear waste repositories.

The mode of failure varies from the complete failure of an instrument all the way to the point at which the instrument appears to function but is, in fact, giving erroneous data. The latter failure mode is perhaps of greater concern since it is often detected only when the experiment is complete and the instrument has been removed for calibration. The implications of this type of failure for long-term repository monitoring are obvious.

Table 1. California Department of Water Resources (DWR) long-term monitoring

Measurement	Instrument	Manufacturer	Model	No. In Use	No. Failed	Failure Mode	Failure Mechanism	Time In Use	Percent Failed	Remarks
Soil stress	Carlson Gauge	Carlson Inst. Inc.	Soil type	24	20	Erroneous[a] readings	Unknown[b]	13 years	83%	Edmonston Pump Station
Concrete stress			Concrete type	14	14				100%	
Water pressure			Pore pressure	4	3			↓	75%	↓
Soil stress			Soil type	26	9			12 years	35%	Wheeler Ridge Pump Station
Water pressure			Pore pressure	2	2			↓	100%	↓
Soil stress			Soil type	9	1			10 years	11%	Devil Canyon Pump Station
Concrete stress			Concrete type	20	20				100%	
Water pressure			Pore pressure	2	1			↓	50%	↓
Soil stress			Soil type	21	8			12 years	38%	Pear Blossom Pump Station
Concrete stress			Concrete type	20	12				60%	
Water pressure	↓	↓	Pore pressure	3	2	↓	↓	↓	67%	↓
Soil stress	Maihak Gauge SG3	Aerojet General	Soil type	15^c	0	None	-	11 years	0	Castaic Dam
	Carlson Gauge			15^c	12	Erroneous[a] readings	Unknown[b]	↓	80%	↓
	Maihak Gauge			15^c	3	Open	Lightning strike	14 years	20%	Oroville Dam
↓	Carlson Gauge	↓	↓	15^c	?	↓	↓	↓	Unknown	↓

[a] All gauges still active but read in apparent tenstion mode instead of compression.
[b] Gauges are not accessible for failure analysis.
[c] Vibrating wire and unbonded strain gauge make up 1 large soil stress gauge (13").

LONG-TERM INSTRUMENTATION RELIABILITY EXPERIENCES

This paper concentrates on the reliability experiences with four types of geotechnical instruments because of the preponderance of data available about them from the DOE waste isolation experiments in hostile environments similar to those that may be encountered in an actual repository. The DOE experiments, however, were limited in time to just a few years. To broaden the data base and provide additional reliability statistics on geotechnical and hydrological type instruments used for in-situ measurements over longer periods of time, data was also collected at other facilities not related to waste isolation. In this regard, the California Department of Water Resources (DWR) has provided information on instrumentation reliability at their facilities where instruments have been installed for periods of up to 14 years. This information is summarized in Table I.

It must be emphasized that the principal similarity between the DWR and DOE instrumentation is that the DWR instruments were permanently installed for in-situ measurements, possibly in a wet or moist environment. They were not exposed to the elevated temperatures that were so detrimental to instruments in the DOE experiments. Even at that, the percentage failures with instruments at DWR facilities were high.

RELIABILITY OF GEOTECHNICAL INSTRUMENTS AT DOE SITES

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 anchors, (2) the rods for anchor-to-head 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 II. 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, attempts to use LVDTs on extensometers at the salt experiment site has resulted in failure of 100 percent of the transducers.

Patrick et al.(3) 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 2.2 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, and, though probably not a factor, all these instruments were located near canisters containing radioactive waste. 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

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

					Transducers			Anchors		
User (Media)	No. Used and Positions	Total Positions	Slope	Period	Type	No. Failed[a]	% 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	-			
	8-6 pt.	48	Incline	↓	↓	0	-	↓	unknown[b]	
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%[c]

[a] Erroneous readings.

[b] Used hydraulic anchors with check valves and no pressure monitoring. Anchors were also grouted.

[c] Suspicious readings, possible anchor movement.

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. After about six months to a year, four of the linear potentiometers used to replace failed units, but from a different manufacturer, have failed. These were on extensometers using the closed head covers provided with the instruments. There have been no failures with linear potentiometers where extensometer head assemblies were vented or purged with nitrogen, nor have there been any failures with the LVDT type transducers or the electromagnetic proximeters(4).

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 II). 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(5), and at Climax, the grout columns were interrupted by closed-cell foam rubber expansion joints to isolate axial displacements(6). 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 possibilities, along with the higher temperatures encountered at BWIP, may explain the higher incidence of anchor pressure failures in the basalt experiments (Table II). Despite the number of anchor system pressure failures, there have been only two cases reported where anchor slippage may have occurred.

Wilder et al.(7) 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 causing vibration to release movement restrained by the friction(8). 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 only two confirmed catastrophic rod failures, and 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. The two catastrophic rod failures occurred in two extensometers at the Climax site 34 months after installation. In both cases, the rods broke near the anchors just above their threaded ends. Investigations at LLNL have shown the failures to be due to stress corrosion cracking with signs of both intergranular and transgranular corrosion(4). The two failures occurred within a few weeks of each other and were located in the same area where the numerous extensometer transducer and vibrating wire stressmeter failures have occurred.

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(7).

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. Another design provides self compensation for thermally induced changes in rod length.

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(9), and is highly reliable in that application. The gauge is typically used in a 38 mm borehole to measure three components of diametral 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 III.

Table III. USBM Gauge Failure Rates

User	Qty.	No. Failed	% Failed	Period
BWIP-NSTF	28	19[a]	68%	450 days
LBL-Stripa	30	19	63%	550 days

[a] Failed or suspect(10)

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. 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(7).

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 cables that are more water tight, 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%(11).

Despite the many significant improvements, the USBM gauge is still not at the 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(12). 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 IV. 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(7). The mechanism of failure within the body-cavity has been identified as corrosion, especially to the wire itself(3). In addition to failures, internal corrosion and creep involving the wire can influence the basic calibration and response of the unit.

Table IV. VWS Gauge Failures

User	Qty.[a]	No. Failed	% Failed	Period
BWIP-NSTF	40	31[b]	78%	450 days
LLNL-Climax	18	13	72%	365 days
LBL-Stripa	26	6	27%[c]	550 days
RE/SPEC-Avery	84	24	29%	1000 days

[a] Quantities initially installed, not including replacements

[b] Failed or suspect(10).

[c] Four operational 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(3). 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 V). 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 V, 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 V. Thermocouple Failure Rates

User	Type	Qty.	No. Failed	% Failed	Clad[a]	Ref.[b]
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%		

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

[b] 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 thermocouples and temperature references have been sufficiently accurate and stable to meet application requirements(7).

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 V. 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(13). 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.(7), 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 thermocouples 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.

The experiences with geotechnical instruments should be extended to benefit the other classes of instruments (hydrological, geochemical, environmental, and radiological) that will ultimately be used in the hostile repository environments. For the most part, their present development significantly lags that of the geotechnical instruments for in-situ repository applications.

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