CAES Monitoring to Support RMRCT

(DE-FC26-01NT40868)

CAES Development Co.
In conjunction with
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Sandia National Laboratories

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Executive Summary

The **CAES Monitoring to Support RMRCT** (DE-FC26-01NT40868) was to have been conducted by CAES Development Co. and Sandia National Laboratories. This document, covering task 1.0 and subtasks 2.1, 2.2, and 2.5, constitutes the final project deliverable of the Statement of Project Objectives. The proposed work was to have provided physical measurements and analyses of large-scale rock mass response to pressure cycling. The goal was to develop proof-of-concept data for a previously developed Refrigerated-Mined Rock Cavern Technology (RMRCT, sponsored by the DOE). In the RMRCT concept, a room and pillar mine developed in rock serves as a pressure vessel. Such a vessel needs a pressure of about 1370 psi that cycles down to 300 psi. The measurements gathered in this study would have provided a means to directly determine rock mass response during cyclic loading on the same scale, under similar pressure conditions.

Introduction

The DOE studied the potential for development of a Refrigerated-Mined Rock Cavern Technology (RMRCT) for storage of natural gas in granitic rock in the northeast U.S [1]. The concept involves mining space deep in crystalline unfractured rock and storing natural gas by chilling and compressing it to reduce the storage space required. Considerable technical risk is associated with a facility of this type, a portion of which is derived from unknowns associated with large-scale cyclic internal pressurization of a mined cavern in hard rock. The technical risk can be dramatically reduced by completing measurements and analyses of rock mass displacements in hard rock at the same scale as the RMRCT to quantify the effects of the pressurization and pressure variations at low temperatures. Both the compressed air energy storage facility (CAES, being built in Norton Ohio) and RMRCT facilities exhibit similar *In situ* conditions, rock mass properties, pressurization range, causing similar deformities. For this reason, measurements of these pressure-induced deformations had been planned in the CAES facility. The analogous nature of this planned work makes it directly applicable to understanding the physical nature of deformations likely to be induced in a RMRCT facility and thus reduce the technical risk.

This document, covering task 1.0 and subtasks 2.1, 2.2, and 2.5, constitutes the final project deliverable of the Statement of Project Objectives.

Note: Since the CAES project has been delayed due to national economic unrest in the energy sector, the plans and methods discussed here are no longer being actively sought, and the report should be read with this delay in mind.

Task 1.0: ***Review RMRCT facility concepts***

The concepts for the RMRCT feasibility design shall be reviewed in detail to assure that monitoring of the CAES facility meets the important engineering design and performance needs of a RMRCT facility.

The proposed work will provide physical measurements and analyses of large-scale rock mass response to pressure cycling. The goal is to develop proof-of-concept data for a previously developed Refrigerated-Mined Rock Cavern Technology (RMRCT, sponsored by the DOE). In the RMRCT concept, a room and pillar mine developed in rock serves as a pressure vessel. Such a vessel needs a pressure of about 1370 psi that cycles down to 300 psi. The measurements gathered in this study would have provided a means to directly determine rock mass response during cyclic loading on the same scale, under similar pressure conditions. The measurements gathered in this study will provide a means to directly determine rock mass response during cyclic loading on the same scale, under similar pressure conditions. The *in situ* conditions and rock mass properties, pressurization range, and thus deformations for both the CAES and RMRCT facilities will be similar.

The RMRCT storage involves understanding a large-volume rock mass's mechanical and transport response to a cyclic pressure load and thermal variations. Public health and safety in underground natural gas storage is an unmeasured risk. This risk is sometimes judged as very high because of the volatile nature of the material being stored and the uncertainties of the geologic materials proposed as the storage media. A portion of the natural gas storage risk can be reduced by increasing the fundamental understanding of very large-scale rock mass response to significant cyclic pressure loads, in a manner similar to those that a RMRCT facility may experience.

The thermal/mechanical rock mass response effects for the proposed RMRCT have been discussed and modeled [1]. The results indicate a favorable set of conditions for stability, given the simplifying assumptions made. At some point coupled 3-D thermomechanical (and possibly hydrologic) analyses will be required to fully understand the physics of an operating facility design. These analyses should include potential changes in the mechanical and hydrologic transport properties of the host rock resulting from thermal and pressure changes. The temperature changes indicated [1] for RMRCT are on the order of 50^oC. Uniform and non-uniform temperature changes (increases or decreases) are known to affect the mechanical and transport properties of igneous rock [e.g. 2 and 3, respectively]. The non-uniform temperature field thermal effects are considered to a certain degree in the analysis results presented [1], although simplifying geometric assumptions facilitated the analysis. The non-uniform effects would be transient for some time until a steady-state heat transfer environment evolved. Also, pressurization has the potential to modify the effective stress field by altering the pore pressure in the rock, which would affect the stress state.

The conceptual design and supporting analyses completed thus far indicate that fluid pressures within the RMRCT will range from 1370 psi to about 300 psi, a range of almost

1100 psi. The minimum vertical and minimum horizontal *in situ* stresses are about 3000 psi, while the maximum horizontal *in situ* stress is about 6000 psi. These stresses and pressure changes constitute mechanical loads on each underground opening in the RMRCT. Modeling shows small load cycling pressure change relative to both the strength, *in situ* stress, and excavation induced loads. The underground structure is presented as stable in the RMRCT report and considered to be within a safe operating limit, with the potential to add ground support.

The conclusions reached to date for RMRCT storage are based solely on assumed rock properties and analyses. Although analyses are used routinely in underground design under ambient, relatively steady state conditions, a project of this magnitude will require substantial investment. The inherent unknowns of geologic systems, resulting in perceived risk for regulators, the public, and investors will need to be determined. Attempts should be made early on in the conceptual design process to decrease that risk. One way to accomplish this risk reduction, as proposed for the Norton CAES project, is to measure large-scale rock mass response to cyclic pressure.

A CAES facility is being built in Norton, Ohio, will begin operation within 2 years at 300 MW electric generating capacity, with design plans to increase to 2700 MW during the subsequent 5 years. The underground portion of the facility is an inactive room-and-pillar limestone mine that is 2200 ft deep. The volume of the mine is approximately 338 million cf with a footprint of about 1 mile by 1.5 miles (Figure 1). Rooms are ~32 ft wide and range in height from 17 ft, 28 ft, to 47 ft. Fourteen long boreholes (at ~100 ft) exist in the mine (at various orientations) and could also be used for monitoring sites. The mine will be cycled in pressure from about 1650 psi to 900 psi on a weekly basis. Monitoring the rock mass during pressurization cycles of the mine will provide a means to evaluate large-scale rock mass mechanical and hydrologic responses. Measurements and analyses will be made of pressure, temperature, and rock mass displacements from within the mine during initial pressurization, and during pressure cycling. *In situ* monitoring of the mechanical and hydrologic response of this facility will provide the DOE a means to reduce risk and thus increase the flexibility (create a better opportunity), and further considerations of RMRCT underground gas storage technology in the U.S., especially in areas where other media are not available.

The measurements conducted in this study will provide a means to directly determine rock mass response during cyclic loading, on the same scale, under similar pressure conditions. Table 1 compares a potential granite site for RMRCT with recently measured physical properties (lab and *in situ*) for the Norton site. The Norton site has very little ground support (occasional spot bolting at high traffic intersections) and the RMRCT facility is intended to have minimal ground support. Thus the Norton site offers the opportunity to monitor rock mass response without the added complexity of ground support interactions. Except for rock types and operating temperatures, the two facilities are remarkably similar, and thus the mechanical response of the two rock types is expectedly analogous. This similarity is apparent through examination of values in Table 1, where material properties of the host rock, *in situ* conditions and operating conditions are listed side by side.

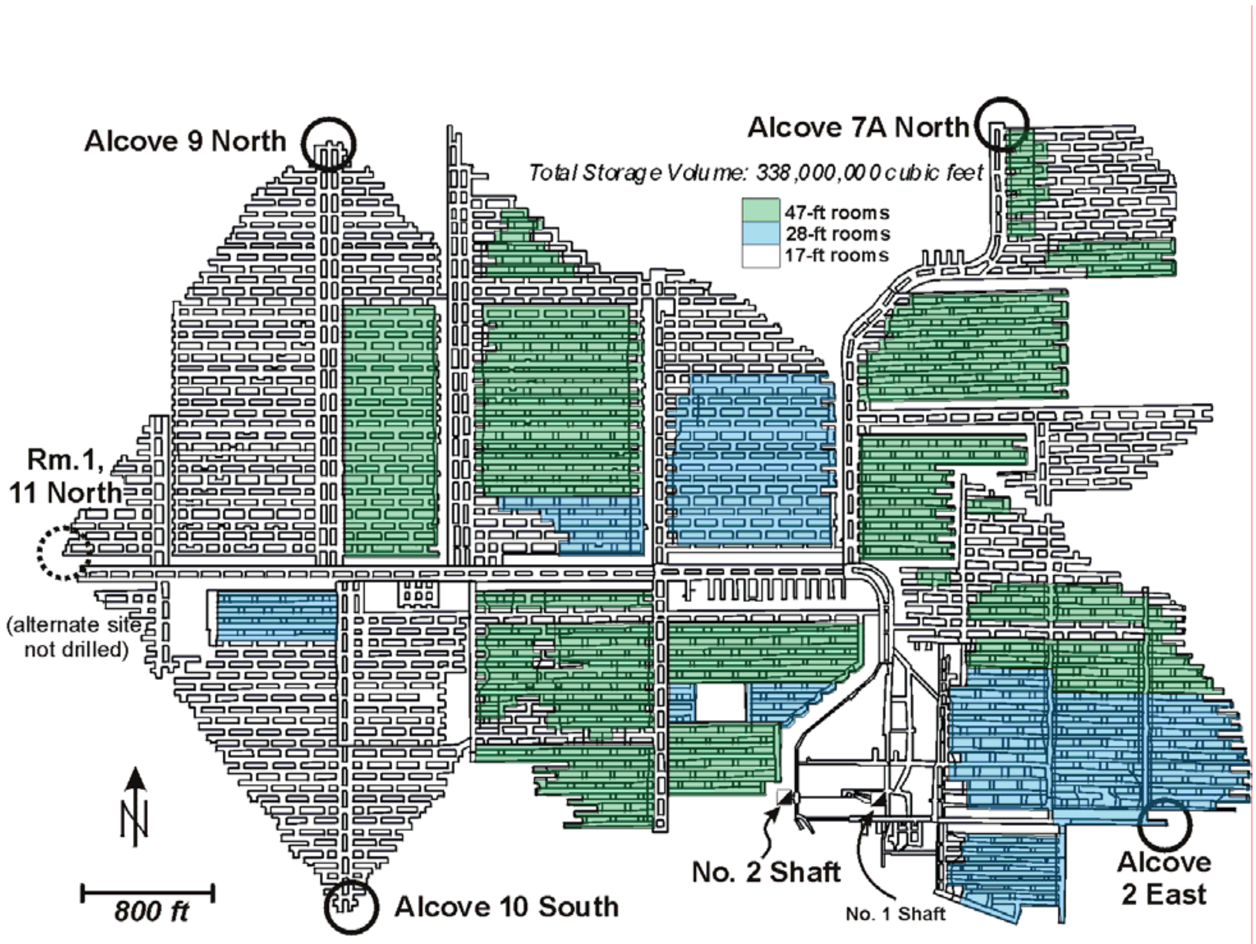


Figure 1. Footprint of the Norton Mine, showing location and distribution of room sizes.

Property	Granite[1]	Limestone[2]
Unconfined compressive strength	2,000-20,000 psi; Average=10,000 psi	27,000 psi
Tensile strength	700 psi	1600 psi
Young's modulus	7,500,000 psi	8,400,000 psi
Poisson's ratio	0.27	0.25
Bulk density	2.80 g/cc	~2.7g/cc
Porosity	1%	0.75%
Average RQD index value	85 at 3,000 foot depth	80-90
Permeability	10^{-16} m^2	10^{-19} m^2
Vertical Stress	3030 psi	3030 psi
Horizontal Stresses (anisotropic)	3030, 6060psi	3630, 6110psi
Temperature	73°F at 3,000 ft	90°F at 2,200 ft
Working Temperature	-20°F	90°F
Gas storage pressure, maximum	1370 psi	1650 psi
Gas storage pressure, minimum	250 psi	800 psi
	[1]estimated and assumed ref. 1	[2]measured ref. 4-15

Table 1. Comparison for Granite and Columbus Limestone

Specifically, displacements across rooms and within existing long boreholes from rooms will be measured with extensometers. The cross-room measurements (floor to ceiling primarily) will provide an indication of the rock mass displacements, which are a consequence of far-field response (the free surface of the earth is the only unconstrained surface). Along with these measurements, measurements of pressure, moisture, and temperature in the mine will be made to define the *in situ* loadings on the rock mass. The displacement measurements within long boreholes will provide an indication of the displacement gradient. If a strain gradient exists with distance from rooms, this could be the result of a damaged rock zone (DRZ) around the openings. These measurements will provide insight into large-scale rock mass response of mined openings to internal pressurization by a gas of mined openings, directly applicable to the RMRCT facility rock mass response.

Thus, the compressed air facility in operation could serve as a model for the RMRCT facility. The benefits of making these measurements and analyses are many. The CAES facility will be cycled weekly (more often than the RMRCT facility), thus there will be less wait time for seeing the effects of load cycling. The CAES facility will be subjected to pressures greater than the RMRCT facility, thus a greater portion of the stress-strain curve will be exercised. If a RMRCT facility is ever developed it will have to be monitored internally, monitoring the Norton Mine will provide a means to evaluate equipment and instrumentation techniques for long-term operation. The Norton Mine rock mass is well characterized [see references 4-15]; therefore, the measurement system could provide focus for characterization funding of the RMRCT development. Finally, internal pressurization of hard rock to this magnitude has never been attempted. Geologic uncertainty dictates the possibility of unknowns. Air, a ubiquitous and safe medium, will pressurize the CAES facility, making the consequences of a leak benign to the public. A natural gas leak, as has been experienced recently in Kansas, can be catastrophic. Clear understanding of every detail of rock mass response is critical. This study will greatly enhance understanding of important unknowns for a RMRCT facility.

The planned work is directly analogous to that needed for the RMRCT. This makes it directly applicable to understanding the physical nature of the deformations at the RMRCT facility. It offers the potential to reduce the risk, both technical and financial, if a facility of this type is ever to be constructed.

Task 2.0: ***Design and procure instrumentation system***

Subtask 2.1: ***Identify performance requirements***

Specific requirements shall be identified for measurement performance and instrumentation to meet those requirements shall be selected.

The planned measurement requirements are focused on developing a good understanding of the potential "actual" physical response of the internally pressurized rock mass in the context of temporal operations of the CAES facility. Figure 2 shows an example of the planned pressurization history for the facility, with 0 hours representing 8:00 AM on Monday morning. Compressed air pressure will be used to drive a turbine for about eight peak use hours, with recharge of the facility taking place through compression during off-peak hours each day. The net loss in pressure at the end of the week on Friday afternoon is made up by air compression through the weekend to recharge the facility. The pressure cycles presented below were modeled using finite element analyses.

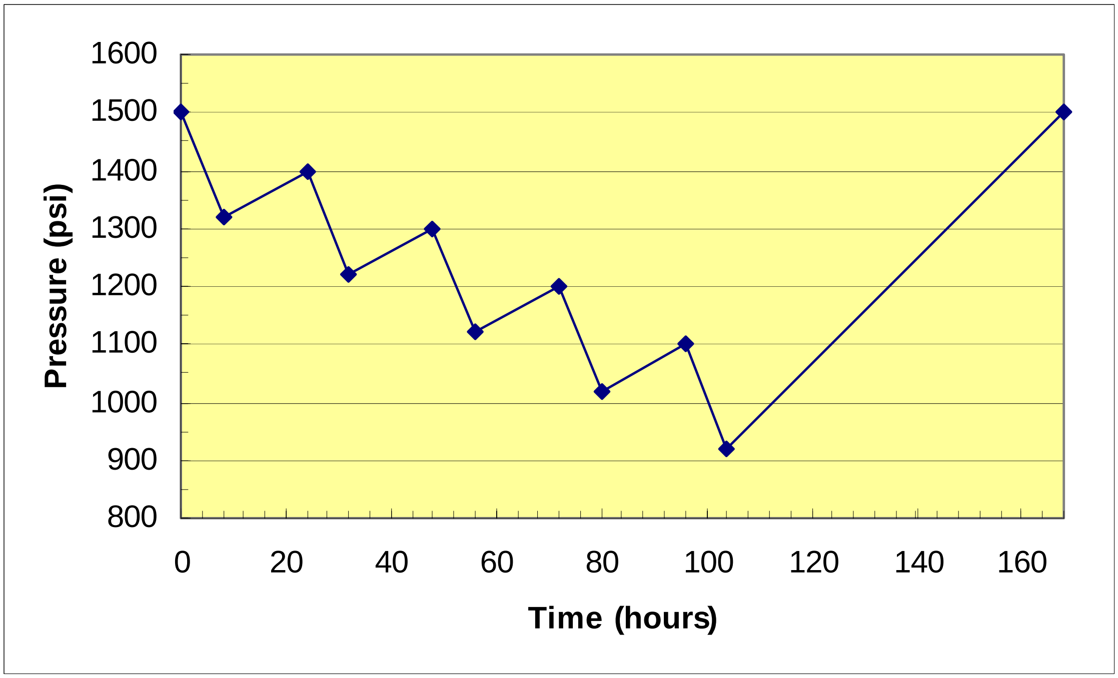
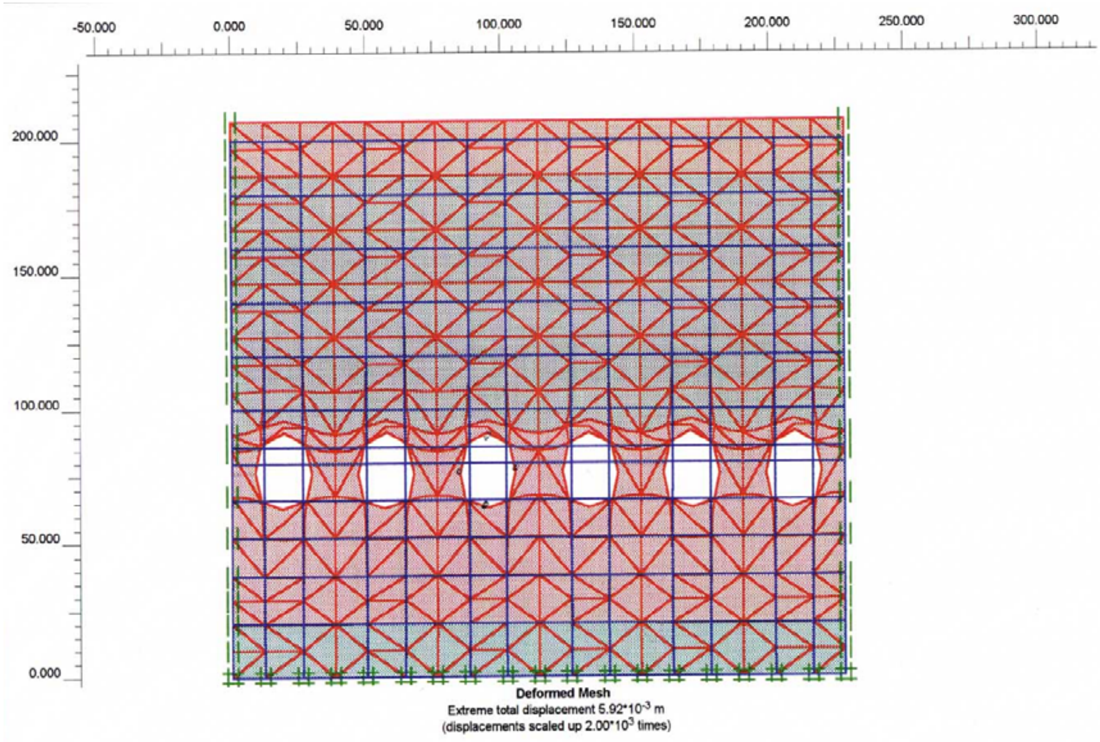


Figure 2. Planned "typical" weekly pressure cycling of the Norton CAES facility.

The analyses were both near and far-field representations that used an elastic-plastic material model in two- and three-dimensional realizations. In the analyses, the *in situ* stresses were first imposed on a large representative volume of rock. Then the mined rock areas/volumes were removed to simulate the excavation process, allowing the rock to deform into the space created by excavation. Figure 3 is a representation of a portion of the mesh used in one of the 2-D room and pillar analyses. Pressures were applied from inside the rooms pushing out in all directions to simulate the planned "typical" weekly pressure cycling as shown in Figure 2. All deformations calculated are within elastic limits and predicted displacements were: horizontal: 0.03 to 0.11 cm, vertical: 0.09 to 0.57 cm, depending on the type of room, where in the mine the room is located, and the location of the point being displaced. The vertical displacements are potentially the greatest because above the mine roof is the free surface, 2200 ft away (the surface of the earth), whereas horizontally, the mine is everywhere constrained by rock. These calculations were used to support determinations of the range, sensitivities and locations of instrumentation used to measure the rock mass response.



Room and pillar finite element mesh for Norton Mine

Figure 3. Typical room and pillar finite element mesh of the Norton mine.

Subtask 2.2: ***Select instrumentation locations***

Target areas for instrumentation locations shall be identified. Target areas shall provide optimum opportunity to measure large-scale rock mass response to pressure cycling.

Subtask 2.5: ***Formalize instrumentation test plan.***

Final instrumentation types and locations necessary to maximize collection of displacement, pressure, moisture, and temperature data in the mine shall be determined.

The locations of instrumentation (Figure 4) were chosen to provide optimum opportunity to measure large-scale rock mass response to pressure cycling. The wiring and data collection runs from the surface down through a dedicated borehole. The types of electrical/pressure connections planned are detailed in Appendix 1. The type, range and sensitivities of instrumentation were chosen to measure an average rock mass response in ways that are consistent with the orientations and magnitudes of maximum displacements predicted by the room and pillar finite element models. For example, extensometer measurements are to be made across rooms (vertical and horizontal) in areas well within the mine, away from mine "edge effects". The convergence meter is a modified MPBX using one anchor installed in a vertical and one in a horizontal direction, each with extension rods. The specific instrumentation selected is detailed in Appendix 2, and contains the range and sensitivity of each instrument. Also, taking advantage of existing long borehole drilled from the mine periphery, deformations within the more virgin rock mass away from the mine opening could be measured. Pressure and temperature measurements are planned at all of the displacement measurement locations because mine deformations also depend on spatial and temporal thermal and pressure fluctuations.

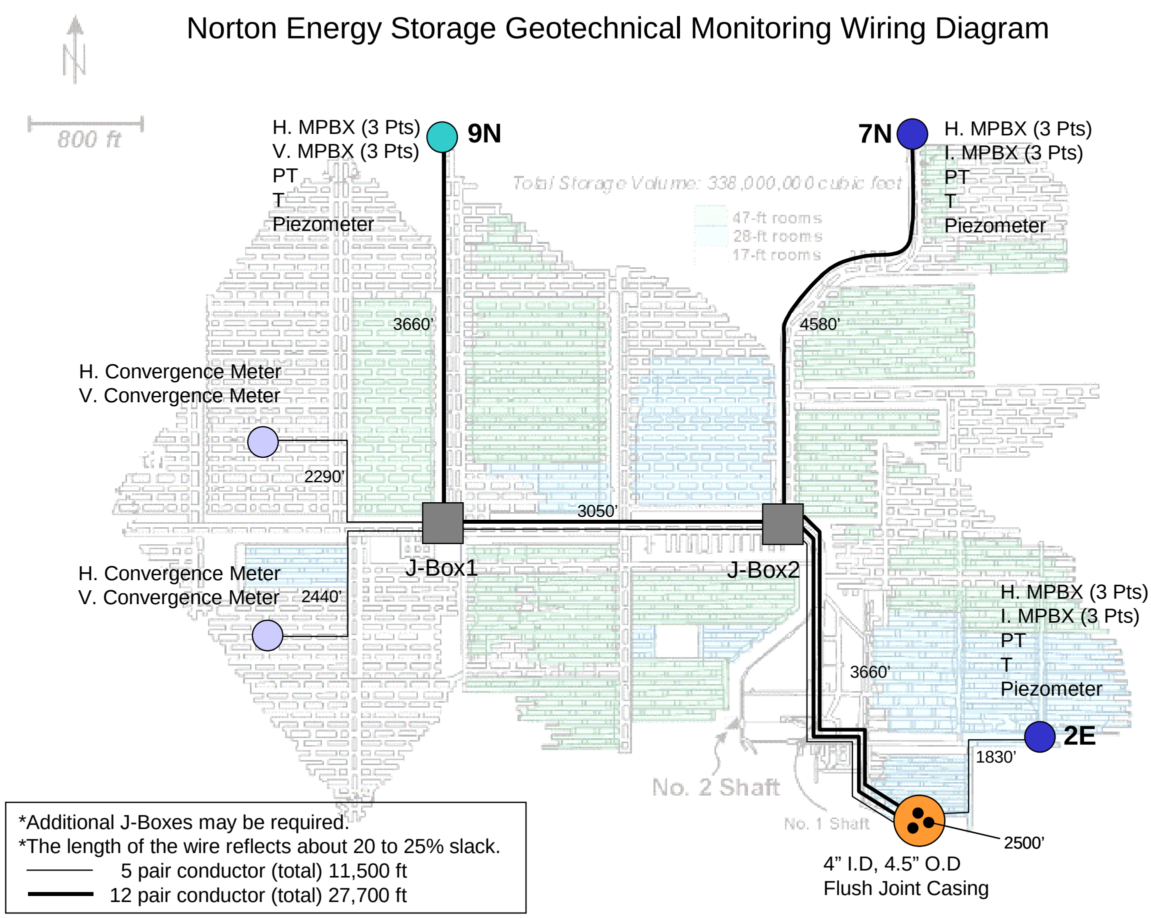


Figure 4. Footprint of the Norton Mine, showing location, distribution and type of instrumentation planned for the facility (MPBX-Multiple Point Borehole Extensometer; PT-Pressure Transducer; and T- Thermocouple).

Conclusions

This study ended without completely getting off the ground. The work was terminated solely because of a hiccup in national economics within the energy sector, resulting in a delay in the compressed air energy project. The work presented clearly connects the RMRCT and CAES projects in terms of the needs to further understand large-scale rock mass response. The information in this report, and the fact that the work was funded, further demonstrates the technical feasibility, constructability, etc. of the CAES project in Norton, Ohio. The fundamental rationale for a rock mass monitoring system, and the sensitivities, ranges and the layout of that system in the facility have been detailed.

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Appendix 1

Connectors and Receptacles

D. G. O'Brien 128 Series Connectors

A high density, instrumentation connector series for submerged applications. Size and cost are major drivers in selection. The plugs are designed to be molded to cables.

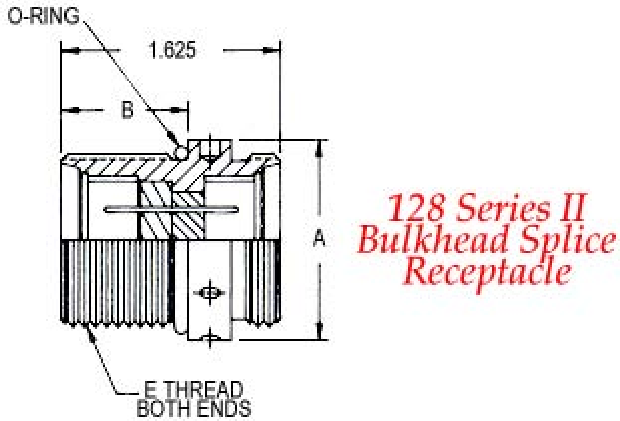
Product Features

- Glass-to-metal sealed pressure barrier in receptacles
- Single O-ring seal between plug and receptacle
- Operating pressure: 0 to 2,000 psig (138 bar)
- Basic body material: 316/316L stainless steel (others available)

Product Options

- Plugs
- Bulkhead Receptacles
- Bulkhead Splice Receptacles

D. G. O'Brien 128 Series Bulkhead Splice Receptacles



Dimensions in inches

Contacts	Part Number	"A"	"B"	"C" Thread	O-ring
6#20	1280231-101	1.062	0.940	7/8-14UN	M83461/2-910
10#20	1280232-101	1.250	0.940	1 1/16-12UN	M83461/2-912
14#20 & 1#16	1280233-101	1.375	0.940	1 3/16-12UN	M83461/2-914
26#20	1280234-101	1.500	0.940	1 5/16-12UN	M83461/2-916
32#20	1280235-101	1.710	0.890	1 1/2-12UN	M83461/2-918
55#20	1280237-101	1.812	0.890	1 5/8-12UN	M83461/2-920

Appendix 2

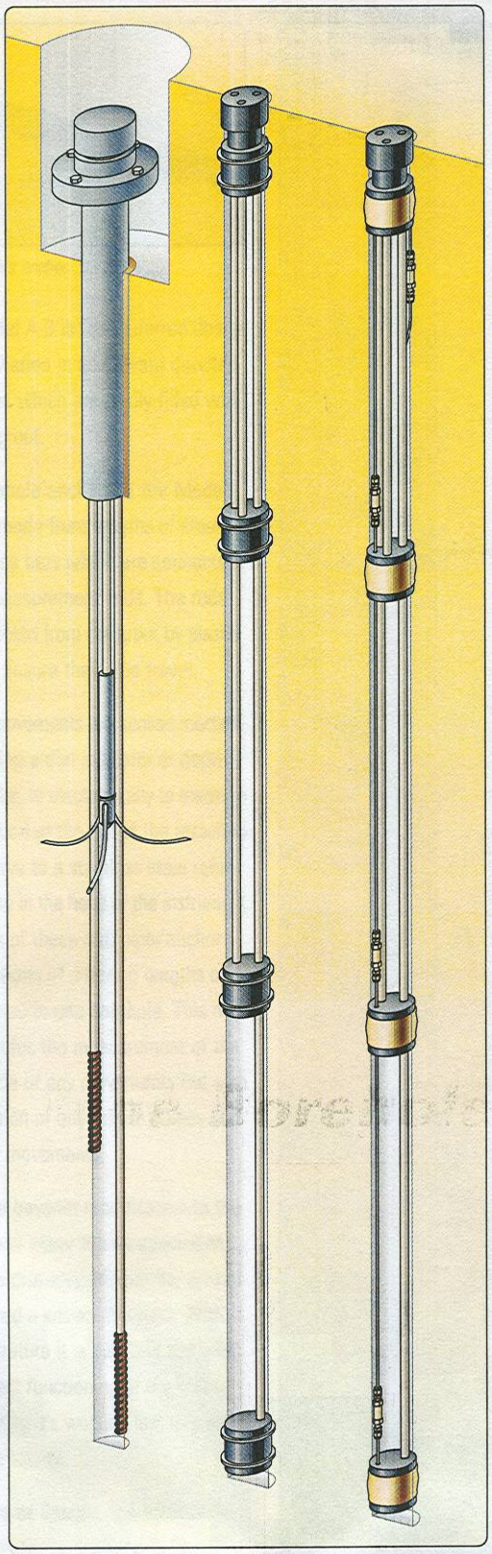
Extensometers, Piezometers, Pressure Transducers and Temperature Sensors

Rod-Type Borehole Extensometers

Applications

Rod Type Extensometers measure displacement or deformation in soil, rock and concrete structures. Typical applications include the measurement of...

- **Ground movements around tunnels**
- **Deformation of dam abutments and foundations**
- **Ground movement behind retaining walls, sheet piling, slurry walls, etc.**
- **Ground movements in the walls of open pit mines**
- **Deformation of concrete piles (tell-tales)**
- **Fracturing in the roofs and walls of underground caverns**
- **Subsidence above tunnels and mine openings**
- **Settlement and heave of foundations in soft soil**



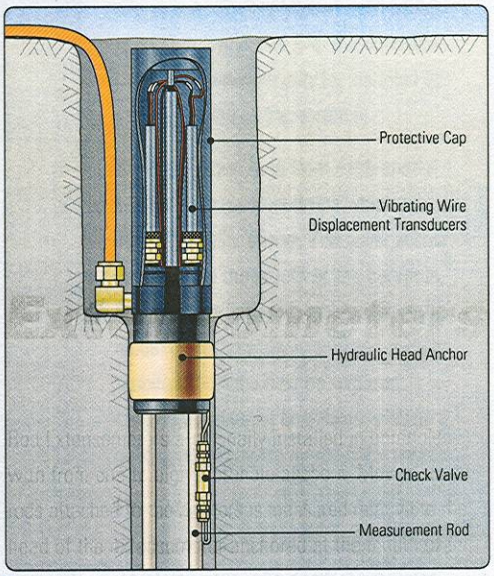
Model A-3, A-4 and A-5 Multiple Point Extensometers (left to right).

Operating Principle

Rod Extensometers are usually installed in boreholes with from one to eight borehole anchors. Movement of rods attached to the anchors is measured relative to the head of the extensometer anchored at the mouth of the borehole and can be analyzed to reveal the magnitude of the deformation between the anchors.

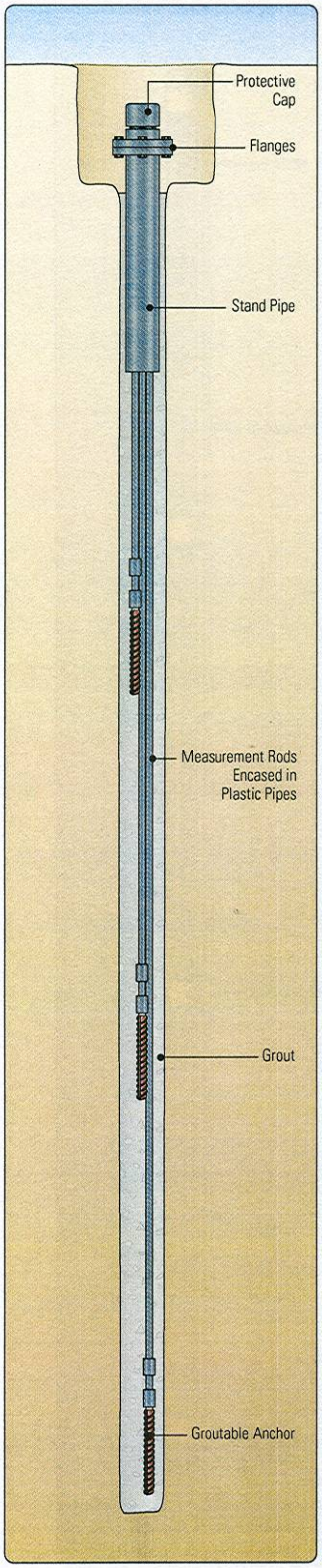
Installation is accomplished by assembling the anchors, rods and pipes outside the borehole, placing the assembly in the borehole then fixing the anchors in place. The head of the extensometer can be configured for manual readout using a dial indicator and/or for electronic readout using vibrating wire sensors, linear potentiometers or DCDT's.

Two main types of extensometer heads can be identified. The *Flange* type is designed to sit on the surface of the rock, soil or concrete structure at the mouth of the borehole. The *Flangeless* type is designed to be recessed into the borehole or into an enlarged section of the borehole; usually to provide protection of the head from traffic, vandalism or from blasting, construction activity, etc.

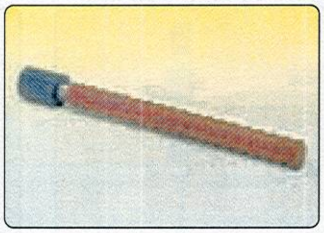


Flangeless type head assembly.

Model A-3 Multiple Point Groutable Anchor



Model A-3 with groutable anchors.


Groutable anchor.

The Model A-3 is the preferred design for installation in downward directed boreholes which are easily filled with cement grout.

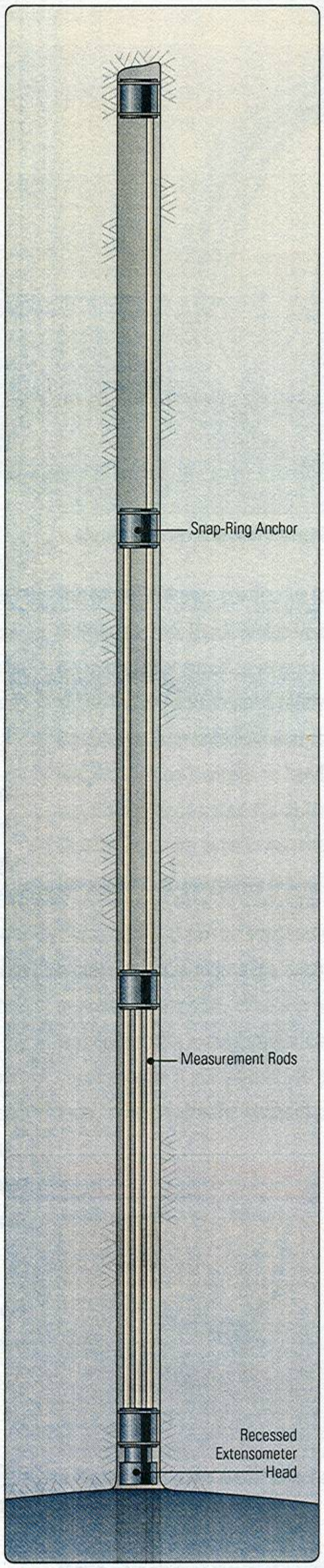
The borehole anchors of the Model A-3 are made from lengths of steel reinforcing bars which are connected to the measurement rods. The rods are protected from the grout by plastic pipes to ensure their free travel.

Anchor movements are sensed mechanically using a dial indicator or depth micrometer, or electronically to measure the position of the top of the attached rod relative to a stainless steel reference plate in the head of the instrument. Up to six of these rod/pipe/anchor combinations of differing lengths can be installed in one borehole. This not only enables the measurement of the magnitude of any movements but also the location of any failure planes and zones of movements.

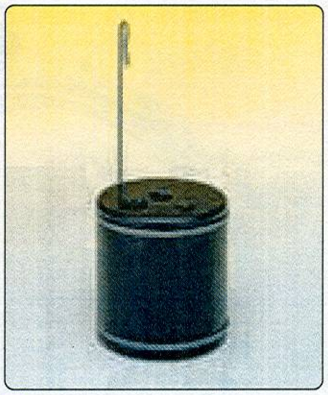
A special bayonet modification to the anchor will allow the measurement rod to be disengaged from the anchor and moved a known distance. With such a feature it is possible to check the correct functioning of the instrument during it's working life; this adds to it's reliability.

By means of flanges, the head of the extensometer is designed to fit a 3" standpipe that is firmly anchored in the mouth of the borehole at the surface.

Model A-4 Multiple Point Snap-Ring Anchor



Model A-4 with snap-ring anchors.


Snap-ring type anchor.

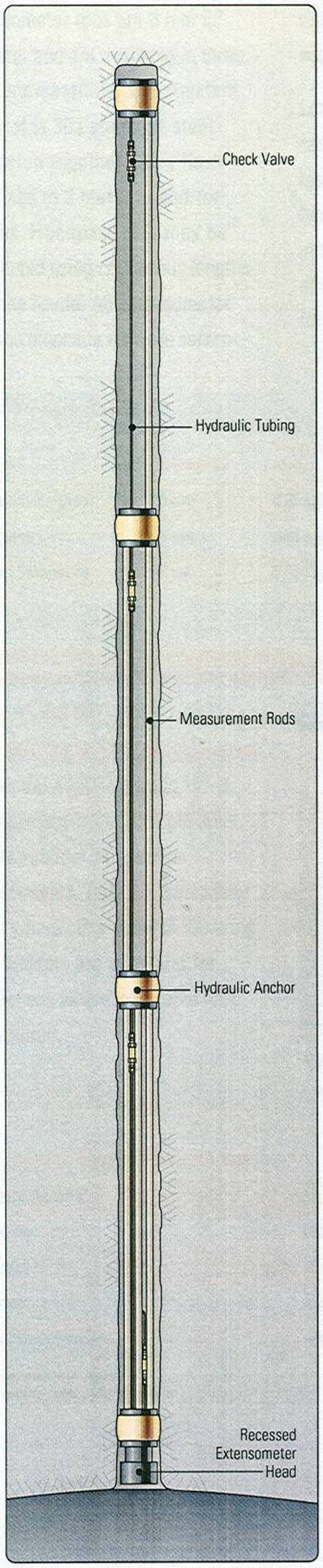
The Model A-4 is designed for upward directed boreholes, in hard or competent rock, that are smooth, uniform in diameter and will stay open.

Anchors are easily installed by pushing them to the required depth on the end of the setting rods and then pulling on a cord to remove the locking pin. This allows two retaining rings on each anchor to snap outward and grip the borehole. Up to eight anchors may be installed at various depths in the borehole.

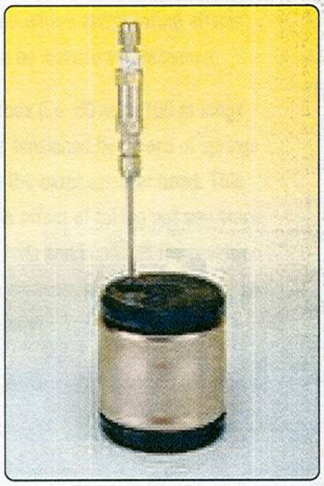
Stainless steel rods from each anchor terminate in machined tips which rest inside the collar anchor. This collar anchor is set inside the mouth of the borehole, again using a snap-ring type anchor. If the mouth of the borehole is enlarged, a collar stabilization tube may be required; it is cemented inside the borehole to provide a good gripping surface for the collar anchor.

The collar anchor has a stainless steel reference plate containing holes through which the stem of a depth micrometer or dial indicator can be inserted to measure the position of the rod tips. Alternatively, or additionally, the collar anchor can be configured for electronic readout. Intermediate borehole anchors tend to support and space the longer rods, however additional spacers may be installed as required.

Model A-5 Multiple Point Hydraulic Anchor



Model A-5 with bladder anchors.



Bladder type hydraulic anchor.

The Model A-5 uses hydraulic borehole anchors and can be easily installed in boreholes oriented in any direction. They are particularly useful in boreholes which are fractured or oriented upwards and which are difficult to grout.

The hydraulic bladder type anchors consist of a spool of high strength plastic around which a sealed, pressure tight soft copper tube is wrapped. Attached to the copper bladder is a high pressure nylon inflation line and check valve. The inflation of the anchors is accomplished with a hydraulic pump which causes the copper bladder to expand and "unwind", filling the space between the spool and the borehole wall. The copper permanently deforms so that the shape does not change and the grip is not lost even if the check valve fails.

The hydraulic bladder type anchors are designed for nominal borehole diameters but can accommodate up to 30 mm of oversize without loss of grip.

Readout is achieved using dial indicators, depth micrometers or electronically.

Model A-6 Flexible Rod Type

Model A-6 assembled with groutable anchors and coiled for shipment.

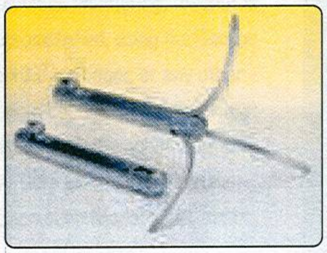
The Model A-6 uses continuous lengths of fiberglass rods (inside protective tubing), cut to customer specified lengths, coiled at the factory and shipped ready for installation. The extensometer is lightweight, making it easier to handle for installation and less costly to ship. On-site assembly time is minimal and the installation procedure is simplified.

The Model A-6 can be supplied with either groutable rebar-type anchors or hydraulic anchors. Where grouting is required, the extensometer can be supplied with a pre-assembled grout tube. When hydraulic anchors are used, the extensometer is supplied with oil-filled tubes attached.

To install the extensometer, the assembly is uncoiled on the surface and fed into the borehole. The assembly is usually lightweight enough so that this operation can be carried out easily by one person (even for overhead installations). With the extensometer in position, the borehole is either grouted, or the hydraulic anchors actuated (and then grouted, if necessary).

Readout can be either manual, electronic or both.

Borros Type Anchors



Single-action borros anchor before and after prong extension.

Borros type anchors are recommended for soft soils where deep penetration of the prongs is required for good anchorage.

With the borros type anchor, hydraulic pressure is applied to extend 3 (single action) or 6 (double action) prongs from the anchor body into the borehole wall. Fully extended, the prongs protrude approximately 150 mm from the anchor body at 3 places, spaced 120° from one another. This helps to ensure positive, end bearing anchorage as opposed to friction bearing anchorage in the case of the bladder anchor.

Rod Types

Extensometer rods are 6 mm in diameter and are available in three different materials. The standard material is 303 stainless steel connected together using flush couplings in 3 meter or shorter lengths. Fiberglass rods may be substituted using continuous lengths as in the Model A6 Extensometer. Carbon composite rods are recommended where temperature effects need to be reduced to a minimum.

Long rods (i.e. 50 m to 100 m long) can be tensioned by means of springs inside the extensometer head. This has the effect of taking out any slack in the rods and improves the precision of the measurement (contact Geokon for details).

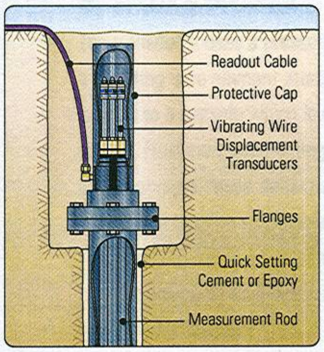
Rod Properties

Material	Diameter	Weight/ Meter	Young's Modulus	Temperature Coefficient
303 Stainless Steel	6 mm	0.25 Kg/m	200 GPa	17.5 ppm/°C
Fiberglass	6 mm	0.06 Kg/m	20 GPa	3.0 ppm/°C
Carbon Composite	6 mm	0.05 Kg/m	130 GPa	< 1.0 ppm/°C

Sensors

Model 4450 VW Displacement Transducer

The Model 4450 Vibrating Wire Displacement Transducer provides remote readout for Geokon extensometers. They are particularly useful where other types of Vibrating Wire sensors are used and for installations where long cable runs are required.



Model 4450 Extensometer Head Assembly with vibrating wire transducers.

Technical Specifications

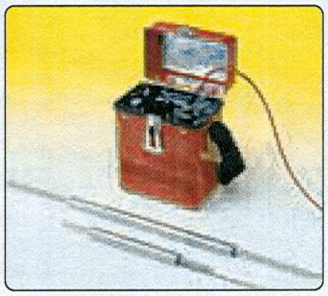
Standard Ranges[1]	12, 25, 50, 100 mm (0.5, 1, 2, 4 in.)
Sensitivity	0.02% F.S.
Accuracy	±0.1% F.S.
Nonlinearity	< 0.5% F.S.
Temperature Range[2]	−20°C to +80°C

[1]Other ranges available on request.
[2]Other temperature ranges available on request.

Sensors (Continued)

Model 1500 Linear Potentiometer

The Model 1500 Linear Potentiometer utilizes a sturdy 6.5 mm (0.25 in.) diameter rod which protrudes from both ends as the actuating shaft. This facilitates connection of the linear potentiometer to extensometer rods and also permits a mechanical check on the readings using either a dial indicator or a depth micrometer.



Model 1500 Linear Potentiometer pictured with Model RB-100 Readout Box.

Technical Specifications

Standard Ranges	50, 100, 150, 200, 250 mm (2, 4, 6, 8, 10 in.)
Least Reading	0.025 mm (0.001 in.)
Accuracy	±0.25% F.S.
Nonlinearity	< 0.5% F.S.

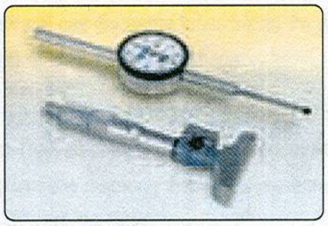
Model 1450 DC-DC LVDT

DC-DC LVDT's for dynamic and/or high temperature applications are also available. Standard ranges are 50 mm, 100 mm and 150 mm. Other ranges available on request.

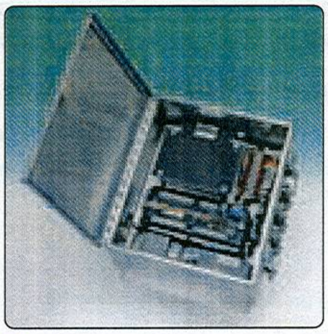
Readout Instruments

Manual Readout is performed using the Model 1400-1 Dial Indicator (50 mm range) or 1400-4 Digital Depth Micrometer (50-150 mm range). Electronic readout is achieved using the Model GK-401 or GK-403 VW Readout Box (Model 4450) or the Model RB-100 Linear Potentiometer Readout Box (Model 1500).

For automatic monitoring, readout is best accomplished, using the Geokon Micro-10 Datalogger, or any other datalogger capable of reading vibrating wire sensors (Campbell Scientific CR10X, Data Electronics Datataker 600, Geomation Model 2380, etc.).



Model 1400-1 Dial Indicator (top) and Model 1400-4 Digital Depth Micrometer.



Geokon Micro-10 Datalogger.

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VW Piezometers & Pressure Transducers

Applications

For the measurement of...

- Ground Water elevations
- Pore Water pressures
- Pump Tests
- Uplift Pressures in dam foundations
- Hydraulic Pressures in tanks and pipelines
- Wick Drain efficiency
- Water Pressures behind tunnel linings

• Model 4500C, 4500S, 4500H, 4500DP and 4500HD Vibrating Wire Piezometers (front to back).

Operating Principle

The transducer uses a pressure sensitive diaphragm with a vibrating wire element attached to it. The diaphragm is welded to a capsule which is evacuated and hermetically sealed. Fluid pressures acting upon the outer face of the diaphragm cause deflections of the diaphragm and changes in tension and frequency of the vibrating wire. The changing frequency is sensed and transmitted to the readout device by an electrical coil acting through the walls of the capsule.

Piezometers incorporate a porous filter stone ahead of the diaphragm, which allows the fluid to pass through but prevents soil particles from impinging directly on the diaphragm.

Advantages and Limitations

The 4500 Series Vibrating Wire Piezometers and Pressure Transducers have outstanding long-term stability and reliability, and low thermal zero shift. Cable lengths of several kilometers are no problem and the frequency output signal is not affected by changing cable resistances (caused by splicing, changes of length, terminal contact resistances, etc.), nor by penetration of moisture into the electronic circuitry.

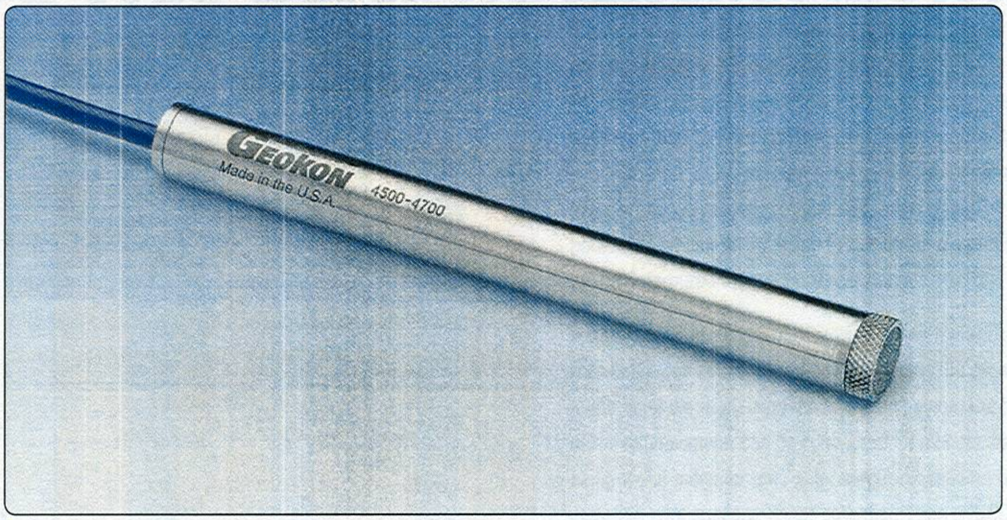
A thermistor located in the housing permits the measurement of temperatures at the piezometer location.

All-stainless steel or titanium construction and evacuation of the capsule guarantees a high level of corrosion resistance. Integral gas discharge tubes inside the main housing protect against lightning damage.

Standard porous filters are made from sintered 316 stainless steel. High air-entry ceramic filters are available for use in applications requiring that air be prevented from passing through the filter.

Vented versions of all models are available to provide automatic compensation for barometric pressure fluctuations. Negative pressures up to 1 Bar can be measured.

Vibrating wire pressure transducers are not suitable for the measurement of rapidly changing pressures: for these purposes Model 3400 transducers should be used.



• *The Model 4700 incorporated into the Geokon Model 4500 Vibrating Wire Piezometer (Model 4500-4700).*

System Components

The basic transducer is packaged inside a sealed stainless steel tube for protection against mechanical damage and water intrusion. An internal thermistor and gas-discharge tube, (for lightning protection), are also included. The Model 4700 is supplied with a 4-conductor cable attached.

Accessories

The Model 4700 can be read using either the Model GK-403 Readout Box or the Model 8020 Micro-10 Datalogger. Terminal boxes and Junction boxes are also available for multiple temperature sensor installations. Mounting brackets for installations on various structures are available as well.

Technical Specifications

Standard Range	100°C (–20°C to +80°C)
Optional Range	200°C (–200°C to 0°C or 0°C to +200°C)
Sensitivity	0.034°C
Accuracy[1]	±0.5°C
Response Time[2]	2.5 minutes
Thermal Equilibrium[3]	15 minutes
Cable	4-conductor shielded 22 AWG
Weight	115 g
Length × Diameter	127 × 19 mm

[1]*Established under laboratory conditions.*
[2]*Time required to reach 63.2% of an instantaneous temperature change.*
[3]*Maximum time required to reach thermal equilibrium.*

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Geokon maintains an ongoing policy of design review and reserves the right to amend products and specifications without notice.

Vibrating Wire Temperature Sensor

Applications

The Model 4700 is used to measure the temperatures in and around...

- **Dams**
- **Concrete structures**
- **Geothermal wells**
- **Landfills**

• *Model 4700 Vibrating Wire Temperature Sensor.*

Operating principle

A tensioned steel wire is clamped axially inside a cylindrically shaped, stainless steel body and is made to vibrate at its fundamental frequency by means of electrical pulses fed from a readout box, through a cable, to an electronic coil and permanent magnet assembly mounted close to the wire. Temperature changes cause the stainless steel body to expand and contract at a different rate than the vibrating wire. This causes a corresponding change in the wire tension and in its vibrational frequency. Vibration of the wire in the permanent magnetic field induces an alternating current in the electronic coil with the same frequency. The readout box used to pluck the wire is now used to measure this frequency, which can then be related to the temperature by means of a calibration factor supplied with each gage.

Advantages and Limitations

The Model 4700 enjoys all the advantages of vibrating wire sensors: i.e., excellent long term stability, maximum resistance to the effects of water and a frequency output suitable for transmission over very long cables.

All components are made from stainless steel for corrosion protection. The gages are waterproof and contain internal protection against lightning damage.

Each gage also incorporates a thermistor for use as a backup or as an independent check on the temperature reading.

The Model 4700 is of particular value where cables are very long, (lengths of up to 3 km are possible), and where other types of vibrating wire sensors are in use. In addition, it can be incorporated into the Geokon Model 4500 Piezometer and Model 4800 Pressure Cell.

Special high and low temperature versions are available for temperatures varying from –80°C to +230°C.

The thermal response of the Model 4700 is quite slow so it is not suitable for the measurement of rapidly changing temperatures.

Technical Specifications

Model	Standard Ranges	Over Range	Sensitivity	Accuracy	Linearity	Temperature Range[1]	Thermal Zero Shift	Diaphragm Displacement	Length x Diameter	Mass
4500S	0.35, 0.7, 1.0, 2.0, 3.0, 5.0, 7.5 MPa	2 x rated pressure	0.025% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	133 x 19.1 mm	0.12 kg
4500AL	70, 175 kPa	2 x rated pressure	0.025% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	133 x 25.4 mm	0.25 kg
4500ALV	70, 175 kPa	2 x rated pressure	0.025% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	133 x 25.4 mm	0.25 kg
4500B	0.35, 0.7, 1.0, 2.0, 3.0, 5.0, 7.5 MPa	2 x rated pressure	0.025% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	133 x 17.5 mm	0.10 kg
4500C	0.35, 0.7 MPa	2 x rated pressure	0.05% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S.	−20°C to +80°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	165 x 11 mm	0.09 kg
4500DP	0.07, 0.175, 0.35, 0.7, 1.0, 2.0, 3.0, 5.0, 7.5 MPa	2 x rated pressure	0.025% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	187 x 33.3 mm	0.90 kg
4500HD	0.07, 0.175, 0.35, 0.7, 1.0, 2.0, 3.0, 5.0, 7.5 MPa	2 x rated pressure	0.025% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	203 x 38.1 mm	1.50 kg
4500H	0.35, 0.7, 1.0, 2.0, 3.0 MPa	2 x rated pressure	0.025% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	140 x 25.4 mm	0.30 kg
4500HH	5.0, 7.5, 10, 25, 50, 75, 100 MPa	2 x rated pressure	0.025% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	143 x 25.4 mm	0.30 kg
4500HT	0.35, 0.7, 1.0, 2.0, 3.0, 5.0, 7.5, 10, 25, 50, 75, 100 MPa	2 x rated pressure	0.025% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +200°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	133 x 19.1 mm	0.12 kg
4500Ti	0.35, 0.7, 1.0, 2.0, 3.0, 5.0, 7.0 MPa[1]	2 x rated pressure	0.025% F.S. (minimum)	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	< 0.001 cm³ at F.S.	125 x 25.4 mm	0.19 kg
4580-1 (Sealed)	15, 35 kPa	2 x rated pressure	0.025% F.S.[2]	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	n/a	165 x 38 mm	0.86 kg
4580-2 (Vented)	15, 35 kPa	2 x rated pressure	0.025% F.S.[2]	±0.1% F.S.	< 0.5% F.S. (±0.1% F.S. optional)	−20°C to +80°C	< 0.05% F.S./°C	n/a	165 x 38 mm	0.86 kg
4580-3	7 kPa	2 x rated pressure	0.025% F.S.[2]	±0.1% F.S.	< 0.5% F.S.	−20°C to +80°C	< 0.05% F.S./°C	n/a	165 x 63.5 mm	1.72 kg
4580-4	7 kPa differential	2 x rated pressure	0.025% F.S.[2]	±0.1% F.S.	< 0.5% F.S.	−20°C to +80°C	< 0.05% F.S./°C	n/a	196 x 63.5 mm	2.04 kg

Note: PSI = kPa x 0.14503, or MPa x 145.03

[1]Other ranges available on request.

[2]Depends on readout system.

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Model 4500H(H) Pressure Transducers

• *Model 4500H Pressure Transducer.*

The Model 4500H and 4500HH Pressure Transducers are supplied with a ¼-18 NPT male or female pipe thread fitting to permit the transducer to be coupled directly into hydraulic or pneumatic pressure lines. Other pipe thread sizes are also available.

Model 4500HT High Temperature Piezometer

• *Model 4500HT High Temperature Piezometer (shown coiled for shipping (inset)).*

The Model 4500HT High Temperature Piezometer is designed for applications where the temperature may be as high as 230°C. Two versions are available, one for continuous use up to 200°C and one for up to 230°C. Teflon cables inside stainless steel tubing are normally supplied with these sensors.

Model 4500Ti Titanium Piezometer

• *Model 4500Ti Titanium Piezometer.*

The Model 4500Ti is designed specifically for use in highly corrosive environments such as landfills and leach fields. Also used in critical areas where long term survivability is essential, for example, as in nuclear waste repositories and aggressive mine tailings. All exterior surfaces are made from titanium.

Model 4580 Pressure Transducer

• *Model 4580 Pressure Transducer.*

The Model 4580 Pressure Transducers are designed for very low fluid pressure measurements, such as groundwater elevations in wells, water levels in streams, weirs, flumes, etc. Changes in water levels of as little as 0.2 mm can be measured. Non vented types can be used as a barometer to measure atmospheric pressure changes.

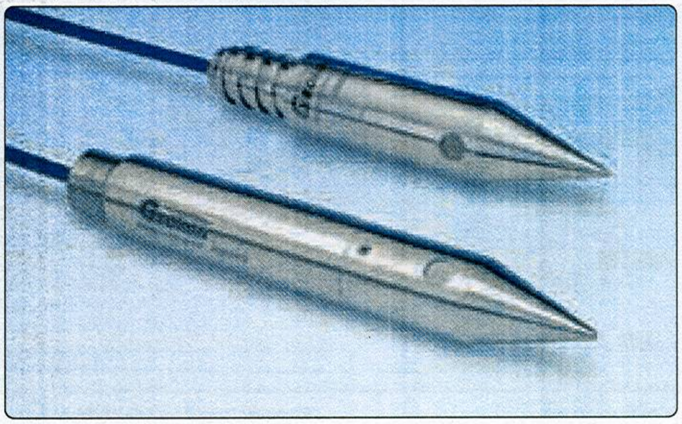
Model 4500S, 4500AL(V) Standard Piezometers

• *Model 4500S (front) and Model 4500AL (rear) Standard Piezometers.*

The Model 4500S Standard Piezometer is designed to measure fluid pressures such as ground water elevations and pore pressures when buried directly in embankments, fills, etc. It is also suitable for installation inside boreholes, observation wells and standard (>19 mm diameter) piezometer riser pipe.

The Model 4500AL is designed for low-pressure ranges. The vented version (Model 4500ALV) provides automatic compensation for barometric pressure changes. Thermistors are included to measure temperatures.

Model 4500DP Drive Point Piezometers



• *Model 4500DP Drive Point Piezometers.*

The Model 4500DP Drive Point Piezometer has the transducer located inside a housing with an EW drill rod thread and removable pointed nose cone. When threaded onto the end of EW drill rods, the unit can be pushed directly into soft ground with the signal cable located inside the drill rod. This model is ideally suited for use in soft clays and landfills. The piezometer may be recovered at the end of the job.

Models are also available that are similar in construction to the 4500DP but which use standard metric threads allowing for installation using cone penetrometer and other drill rods with adapters.

Model 4500B, 4500C Small Diameter Piezometers

• *Model 4500C (front) and Model 4500B (rear) Small Diameter Piezometers.*

These piezometers are designed to enable the automation of small diameter piezometer standpipes. The 4500B fits inside 19 mm pipe and the 4500C inside 12 mm pipe.

Model 4500HD Heavy Duty Piezometer

• *Model 4500HD Heavy Duty Piezometer.*

The Model 4500HD Heavy Duty Piezometer is designed for direct burial in fills and dam embankments. The 4500HD is used in conjunction with heavily armored cable to withstand earth movements during construction. Recommended for use in earth dams.