21
10-30-79
7/11/15

SAND79-0114
Unlimited Release

MASTER

Indirect Deformation (Strain) Measurements and Calibrations in Sandia Triaxial Apparatus for Rock Testing to 250°C

Wolfgang R. Wawersik

Sandia Laboratories

SAND 80-0114

Indirect Deformation (Strain) Measurements and Calibrations
in Sandia Triaxial Apparatus for Rock Testing to 250°C*

by

W. R. Wawersik
Sandia Laboratories**
Albuquerque, New Mexico 87185

ABSTRACT

Indirect procedures for axial and radial strain measurements on rock in triaxial tests to 250°C are presented. The description of techniques includes discussions of all calibrations and of the accuracies of measurements. In addition, two examples are given to show how the techniques are implemented in triaxial compression and triaxial extension experiments.

*This work was supported by the U.S. Department of Energy (DOE) Division of Waste Management (ETW), under Contract DE-AC04-76DP00789.
**A U.S. DOE facility.

DISCLAIMER

TABLE OF CONTENTS

	Page
INTRODUCTION	i
REVIEW OF TRIAXIAL EXPERIMENTS	ii
AXIAL DEFORMATION (STRAIN) MEASUREMENTS.	iii
The Method.	iii
Calibrations.	iv
Determination of Platen Displacement Component ϵ'_{PL}	iv
Determination of Platen Displacement Component ϵ''_{PL}	v
Resolution and Accuracy of Measurement.	v
LATERAL (RADIAL) DEFORMATION MEASUREMENTS.	vi
Method 1 - Ring Transducer.	vi
Method 2 - Dilatometric Measurement.	vi
Case 1	vi
Case 2	vii
Corrections for Tests at Elevated Temperature	vii
Low Load Corrections.	viii
Calibrations for Dilatometric Method.	viii
Resolution and Accuracy of Dilatometric Measurements.	viii
IMPLEMENTATION OF MEASUREMENT TECHNIQUES - EXAMPLES.	ix
Strain Computations in Triaxial Compression Tests at Constant Confining Pressure.	ix
Strain Computations in Triaxial Extension Tests at Variable Confining Pressure.	x
SUMMARY.	xi
REFERENCES	xii
FIGURES	xiii

ILLUSTRATIONS

Page

- Figure 1 Typical experiment configuration for (a) tri-axial compression and (b) extension tests.
- Figure 2 End-cap and sample configurations used in some triaxial extension experiments.
- Figure 3 Schematic of system and transducer gauge points (gauge #1 and #2) in Sandia triaxial apparatus.
- Figure 4 Idealized (a) and force-displacement record, F versus δ in Figure 3.
- Figure 5 Realistic force-displacement curves, F vs. δ (cf. Figure 3), with differing degrees of nonlinearities indicating possible "ice" correction. F_{lin} linear approximation of actual data and maximum error e between data and approximation.
- Figure 6 Actual (a) and idealized (b) force-displacement curves for metal standards used in transducer and system calibrations.
- Figure 7 Schematic of gauge point transfer button for measurement of radial sample deformation.
- Figure 8 Typical surface profile of deformed rock salt specimen parallel to sample axis (direction of σ_1)
x: Distance from specimen ends
y: Relative amplitude proportional to radial deformation (1.13×10^{-3} in (28.6 μ m) per smallest division).
Records #2 and #3 correspond to gauge lines radians apart.

	Page
Figure 9	40
Schematic of triaxial sample - piston arrangement with matched diameters, $D_R = D_S$ for interpretation of dilatometric measurements.	
Figure 10	41
Schematic configuration of specimen, loading piston, and end-caps in Sandia triaxial apparatus. Ports through piston and end-caps provide access to specimen for venting, pore pressure control, etc.	

INTRODUCTION

Since 1975 Sandia Laboratories has developed several triaxial apparatuses to determine the thermomechanical behavior of rock in quasi-static compression and in creep up to 250°C temperature. The most difficult aspect of this task involved the experimental measurement of rock deformations (strains) particularly if large deformations are encountered. This is the case in rock salt for example. The measuring system must accommodate strains in excess of 30% which are typically observed in the advanced stages of rock salt deformation at elevated temperature. At the same time the intrinsic elastic modulus of rock salt is approximately 5×10^6 psi; to ascertain this value it is necessary to resolve small strains. Deformation measurements under pressure and at elevated temperature create additional difficulties.

Strain gauges bonded to the rock can be utilized to determine strains in the new Sandia triaxial systems. However, routinely, strains are inferred from measurements of changes in the length and in the diameter of cylindrical samples. To facilitate testing further, dimensional changes are often monitored indirectly, e.g., by tracking the motion of loading pistons. Such indirect approaches render satisfactory results provided the length of extraneous material within the active gauge length of each transducer is minimized and provided care is taken in instrumentation setup and calibration.

The purpose of this report is to document the procedures for indirect strain measurements on rock during tests in the new

Sandia triaxial apparatus. At the same time, this report provides a manual for those who wish to use the equipment. It is divided into four parts: (1) a general review of triaxial compression and extension tests, (2) a description of axial strain measurements on rock cylinders, (3) a discussion of radial strain measurements, and (4) two examples which demonstrate how the measurement techniques are implemented in particular experiments.

REVIEW OF TRIAXIAL EXPERIMENTS

A brief review of so-called triaxial experiments is given here to avoid confusion among users who are unfamiliar with rock testing. The name triaxial test defines two types of experiments which are performed on cylindrical specimens such that two principal stresses are always equal. Denoting compressive stresses as positive the following conditions can be obtained: (1) $\sigma_1 = \sigma_2 = \sigma_3$ or (2) $\sigma_1 = \sigma_2 > \sigma_3$. Case one is called triaxial compression. Case two is known as triaxial extension where σ_3 may, but does not have to be tensile (negative). In the non-English literature both types of triaxial tests are often referred to as von Kármán experiments.

To produce states of triaxial compression or extension, typically rock cylinders are positioned between anvils, jacketed and placed inside a pressure vessel as shown in Figure 1. Each specimen can be subjected to hydrostatic and deviatoric loading. Hydrostatic loading is accomplished directly in Figure 1a by pressurizing the pressure vessel. Alternatively, for the setup in Figure 1b hydrostatic pressure may be generated by applying simultaneously a ram force, F , and a pressure, p , inside the vessel. The schematic in Figure 1b indicates that the pressurizing medium (liquid or gas) does not enter the interface between the loading piston and the specimen ends. Therefore, the applied radial pressure and the axial stress are decoupled; this is necessary to conduct triaxial extension experiments.

After a hydrostatic stress state is induced, deviatoric loading can commence as triaxial compression or triaxial ex-

tension. To do so three possibilities exist: (1) the ram force is changed (increased or decreased) at constant confining (radial) pressure (2) the confining pressure is altered at constant axial stress or (3) both axial stress and confining pressure are varied at the same time, for example, to maintain states of uniaxial strain or constant mean stress in the rock specimen.

Figures 2a and b depict the configuration of endcaps and/or specimens which are sometimes used in triaxial extension tests where net tensions are to be induced along the rock cylinder axes.

AXIAL DEFORMATION (STRAIN) MEASUREMENTS

The Method

Axial rock deformation in the Sandia apparatus is measured by means of one or two Linear Variable Differential Transformers (LVDT) external to the pressure vessel (Figure 3). The transducers track the relative displacements between one or two sets of points, A, on the loading piston and on reference points, B, at one end of the pressure vessel.

For the experiment setup in Figure 3, changes in position δ between the pairs of points A and B are used to compute the changes in length, δ_R , of the rock sample which is subjected to an axial force F and confining (hydrostatic) pressure p. The temperature of the experimental system is arbitrary but assumed constant. The rock deformation is obtained by subtracting all non-rock contributions from the total measured displacement. The total non-rock contribution will be called "platen displacement," δ_{PL} . It derives from the deformation of end-caps, loading pistons and interfaces, δ'_{PL} , with varying F. It is also affected by changes in the length of the pressure vessel, δ''_{PL} , with changes in pressure p. Thus,

$$\delta_R = \delta - \delta_{PL} \quad (1)$$

where

$$\delta_{PL} = \delta'_{PL} + \delta''_{PL} \quad (2)$$

If two diametrically opposed transducers are employed then δ represents average displacement readings. This average elimi-

rates some or all of the influence of piston rotations. If only one transducer is utilized it is essential that the rock sample be machined to close tolerances and that the test system be accurately aligned.

Both δ_{PL} and δ_{PL} must be determined by calibration. Calibrations are mandatory to establish δ_{PL} because of the nonlinear force-displacement behavior of various interfaces between rock specimen and end caps etc. as indicated in Figure 3.

Once δ_R is known, the axial rock strain, ϵ_a is calculated as

$$\epsilon_a = \frac{\delta_R}{L_R} \quad , \quad \text{or} \quad \epsilon_a = -\ln\left(1 - \frac{\delta_R}{L_R}\right) \quad , \quad (3)$$

using the initial specimen length, L_R . In either case compressive strain is denoted positive. The two strain definitions yield so-called engineering strain and true (logarithmic) strain, respectively. Note the tacit assumption that the rock deformation is homogeneous along the sample axis. Although this condition does not ordinarily prevail, it can be approached by the choice of appropriate ratios of sample length to sample diameter.

Calibrations

Determination of Platen Displacement Component δ_{PL}

Platen displacement calibrations are carried out by means of steel and aluminum standards of identical size and of known Young's moduli and Poisson's ratios. If these standards are tested in lieu of a rock sample, ideally, linear records are obtained of force, F , versus total displacement (Figure 4). Under such conditions δ_{PL} can be defined readily in terms of

an average calibration factor

$$C = \frac{F_1}{\delta_1} \left[\left(1 - \frac{F_1}{F_{ST}} \right) + \left(1 - \frac{F_1}{F_{AL}} \right) \right] \frac{1}{2} \quad (4)$$

The quantities δ_1 and δ_2 are the total displacements for calibrations on steel and aluminum. The subscripts "ST" and "AL" refer to steel and aluminum, respectively. L and A denote the equal lengths and the cross-sectional areas of the metal standards. As a precaution, area A should be approximately equal to the cross sectional area of prospective rock specimens. Here F_1 is the value of axial force corresponding to any arbitrary value of displacement δ .

In reality, because of the presence of interfaces, any plot of F vs. δ or F vs. δ_{PL} always contains a nonlinear toe as indicated schematically in Figure 5a. This toe results from the closure of interfaces at $F \leq F_C$. It can seriously affect the accuracy of rock deformation measurements depending on the magnitude of the ratio F_M/F_C , where F_M is the anticipated maximum force in particular experiments of interest (Figure 5). If F_M and F_C have the same order of magnitude; then δ_{PL} cannot be determined by use of a fixed calibration value Δ_1 . Instead the curve F versus δ_{PL} is described by a suitable nonlinear curve fit. In addition, the relationship between F and δ_{PL} is recorded in repeated tests on steel, aluminum, and brass standards to define the uncertainty in δ_{PL} due to differences in surface conditions between samples. If $F_C \ll F_M$, generally the nonlinear toe in Figure 5b is considered by means of a single displacement offset ($-\delta_{PL}$) in the interval $0 \leq F \leq F_C$ (Figure 5b). Then the straight line slope is obtained using Equation (4).

If errors in rock deformation δ_R on the order of 3-10% can be tolerated, the following third choice exists. A curve F versus δ_{PL} which is nonlinear throughout can be approximated by a linear fit for $F > F_C$ while the highly nonlinear toe within $0 \leq F \leq F_C$ is eliminated by a correction ($-D_{PL}$) as shown in Figure 5c. In this case calibrations must yield the value of the maximum possible error in deformation, e , for $F \leq F_m$ (Figure 5c). The error e constitutes the maximum error between actual readings and their linear approximations.

.. Determination of Platen Displacement Component δ_{PL}

According to Figure 3 rock deformation can be determined by monitoring changes in relative displacement between the sets of reference points A and B. It follows from the pressure vessel configuration shown that points B are fixed only if the pressure inside the vessel is constant. Although it may be possible to calculate changes of B with respect to the base line LL (Figure 3), subsequent calibration tests are advisable. For the experimental setup in Figure 3, for example, a pointwise determination of the (linear) relationship between F and δ_{PL} can be performed by means of the steel or aluminum standards which were described earlier. At $p = 0$ (ambient pressure) the loading piston is advanced until contact is made between the loading piston and the sample as indicated by a small piston force $F_0 \ll F_C$. Then the vessel pressure is increased to some value p which produces a reaction along the loading piston, F_H . At that point the loading piston is advanced again until piston force $F = F_H + F_0$

is registered, thus contact between calibration sample and loading piston is reestablished and the change in the gauge length, δ , between points A and B is recorded. This procedure is repeated in at least five steps up to the maximum operating pressure of the system. For linear relationships between P, δ , and ϵ , the resulting data for steel, for example, can be related to a calibration factor

$$\epsilon_2 = \frac{\delta_2}{L} = \frac{1}{F} \left[\delta_1 - \Delta_1 F - \frac{L}{E_{ST}} F (1 - \nu) \right] \quad (5)$$

p and δ represent arbitrary values of pressure and deflection. F equals the sum of the contact force, F_0 , plus the piston reaction, F_H , due to p . Δ_1 is given by equation (4).

Resolution and Accuracy of Measurement

The resolution of axial deformation (strain) measurements as described depends on the resolution of the transducers employed and on the quality of signal conditioners and recording equipment. The resolution of LVDT transducers is unlimited. On the other hand, the accuracy of measurement is directly related to both the number and the condition of interfaces within the active gauge length and to the alignment of the entire experimental load train. Interfaces and misalignment lead to nonlinear readings which were discussed previously.

The accuracy of axial deformation (strain) measurements in the Sandia apparatus was ascertained in two ways. First, the combination of force-displacement records for steel and aluminum was used to calibrate the LVDT transducers. This procedure was

described by Fairhurst (1961) and is indicated in Figures 6a and b. Figure 6a depicts the schematic of typical force-displacement records. Figure 6b shows the same curves minus "toe" corrections, (D_{PL}). Here force is defined in pounds, and displacement equals the transducer output in volts. Because the dimensions (A , L) and the elastic moduli, E_{ST} and E_{AL} , of the two standards are known, Figure 6 implies a LVDT calibration factor

$$\Delta_3 = \frac{AL}{F_L} \left(\frac{1}{E_{AL}} - \frac{1}{E_{ST}} \right) \quad (6)$$

The value of Δ_3 (eq. 6) was then compared with that value, $\bar{\Delta}_3$, which was established by direct calibration using a micrometer. As an example, a typical comparison showed

$$\Delta_3 = 1.025 \text{ (V/in)}$$

$$\bar{\Delta}_3 = 10.000 \text{ (V/in)}$$

Hence, the discrepancy was only 0.25%.

Referring back to Figures 5 and 6a, a more rigorous way to evaluate measurement accuracy follows from a detailed evaluation of the consistency of necessary "toe" corrections, D_{PL} , and of possible nonlinearities above the force F_C . Such checks were again performed by means of a steel standard for which errors become most apparent because of the high elastic modulus, E_{ST} . Omitting details, the foregoing comparison provided maximum and typical errors in measured displacement of $e_{\max} = 4 \times 10^{-4}$ in (0.01 mm) and $e_{\text{typ}} = 2 \times 10^{-4}$ in (0.005 mm), respectively. These numbers translate into axial strains of 5×10^{-5} and 2.5×10^{-5}

for eight inch long samples. In some cases these accuracies can be improved, particularly during deviatoric unloading and reloading cycles which are often used to determine elastic rock constants.

It is emphasized that the accuracies which are reported here were attained only after careful alignment of all apparatus. Quality alignment is especially important for tests on rock with high elastic moduli.

LATERAL (RADIAL) DEFORMATION MEASUREMENTS

Method 1 - Ring Transducer

In many tests radial rock deformations are measured by means of one or two ring transducers which are suspended at various distances from the specimen ends. The transducer was developed and described by Schuler (1978). Since each specimen is enclosed in a 1/16" (1.6 mm) thick, compliant jacket, appreciable errors in measurements could arise if any jacketing material lay within the active gauge length of the transducers. To avoid this problem, special buttons are utilized which are inserted through holes in the jacket as shown schematically in Figure 7.

The ring transducers employed are remarkably compact and have a relatively large linear range. They are also well suited to monitor diameter changes at different points on the specimen circumference. However, if the rock deforms inhomogeneously then readings provided by individual transducers may differ considerably from the average diameter changes along the specimen height. This point is demonstrated by the record of a deformed sample after testing in Figure 8.

Method 2 - Dilatometric Measurement

The dilatometric method is applied readily to track average radial rock deformation in triaxial experiments at constant confining pressure. The principles of the method are described elsewhere (Wawersik, 1975). In a leakproof system radial deformation can be calculated from volume adjustments of the confining pressure medium which are needed to keep the confining pressure con-

stant. Details of the method are easily explained by means of Figure 3. Figure 3 shows the schematic of a cylindrical rock sample between cylindrical loading pistons inside a pressure vessel subjected to pressure p . Relevant undeformed sample and piston geometries are defined by the diameters D_R , D_S and the length L_R . The subscripts R and S stand for rock and (steel) pistons. The elastic constants of the piston material are E_S and ν_S . The internal length of the pressure vessel between the seal and the vessel bottom is denoted L_P .

The piston force F in Figure 3 can be split into two components, F_H and F_D . F_H constitutes the reaction to the pressure p . F_D is the axial force required to subject the specimen to a deviatoric stress and is proportional to the difference in maximum and minimum principal sample compression, $(\sigma_1 - p) = (\sigma_1 - \sigma_3)$.

Case 1

Consider the axisymmetric configuration of Figure 9 where rock and loading piston have equal undeformed diameters $D_R = D_S$. If the rock deformations due to hydrostatic loading are neglected, then the differences between the solid and dashed lines in Figure 9 result from deformations due to the force F_D . However, because of friction along the rock/piston interface, the deformed specimen will not be a perfect cylinder but more or less barrel-shaped. Therefore, the cylindrical configuration which is indicated only corresponds to the equivalent deformed shape at constant diameter which, together with the same axial shortening, gives rise to the correct volumetric deformation of the specimen.

Since fluid is displaced with the application of F_D , the volume of the confining pressure system must be adjusted to maintain the confining pressure constant. Treating compressions as positive, Figure 9 implies that this volume adjustment, ΔV , under isothermal conditions is

$$\Delta V = \left[\frac{\pi}{4} (D_R + \Delta D_R)^2 (L_R - \Delta L_R) - \frac{\pi}{4} D_P^2 L_P \right] + \left[\frac{\pi}{4} D_S^2 (L_P + \Delta L_P) - (L_P - L_R + \Delta L_R) - \frac{\pi}{4} D_S^2 (L_P - L_P) \right] \quad (7)$$

ΔD_R , ΔD_P and ΔD_S denote changes in length and diameters with the force F_D . Furthermore, assuming that the lateral strains in rock and piston are homogeneous:

$$(\epsilon_2)_R = (\epsilon_3)_R; (\epsilon_2)_S = (\epsilon_3)_S$$

Therefore, neglecting second order terms in lateral strains

$$\Delta V = \frac{\pi}{4} D_R^2 \left\{ \left[1 + 2(\epsilon_2)_R \right] (L_R - \Delta L_R) + \left[1 + 2(\epsilon_2)_S \right] (L_P - L_R + \Delta L_R) - L_P \right\} \quad (8)$$

Substituting

$$(\epsilon_2)_R = -\frac{V_R}{E_R A_R} = -\frac{V_P}{E_P A_P} \quad (9)$$

getting

$$\epsilon_2 = (\epsilon_2)_R \quad ; \quad \epsilon_3 = (\epsilon_3)_R \quad ,$$

and omitting simple algebra it follows that

$$\frac{F_D}{A_R} = -\frac{1}{1 - \nu_R} \left[\frac{V_R}{A_R L_R} - \frac{V_P}{A_P L_P} \left(\frac{L_P - L_R}{L_R} + \nu_P \right) \right] \quad (10)$$

where

$$\Lambda_R = \frac{\pi}{4} D_R^2 = \frac{\pi}{4} D_S^2$$

and

$$1 - \frac{D_R^2}{D_S^2}$$

To consider higher order terms in the strains $\epsilon_2 = \epsilon_3$, eq. (10) can be corrected to obtain

$$\epsilon_2^{cor} = \epsilon_3^{cor} = - (\sqrt{1 + 2\epsilon_2} - 1) \quad (11)$$

Neglecting the effect of hydrostatic loading generally results in errors of less than .5%. If such an error is excessive it is possible to make appropriate corrections. The difference between ϵ_2^{cor} and ϵ_2 is + 0.5% at $\epsilon_2 = -1\%$. It increases rapidly to + 13.2% at $\epsilon_2 = -30\%$.

Case 2

In most experiments at Sandia Laboratories the experimental geometry of Figure 10 is more typical. In this case the rock sample is jacketed between end-caps. Also, the piston diameter is smaller than the diameters of both rock sample and end-caps. Lastly each end-cap is equipped with a sealed nipple of diameter D_N , to vent the specimen (Fig. 10a).

Idealizing Figure 10a and neglecting deformations due to hydrostatic loading again, Figure 10b leads to isothermal volume adjustments, ΔV , for constant confining pressure experiments. Specifically, if

$$\begin{aligned}
A_R &= \frac{\pi}{4} D_R^2 & E_C &= E_S \\
A_S &= \frac{\pi}{4} D_S^2 & \nu_C &= \nu_S \\
A_C &= \frac{\pi}{4} D_C^2 & (\epsilon_2)_R^2 &= (\epsilon_2)_S^2 = (\epsilon_2)_C^2 = 0 \\
A_C &= A_R & \epsilon_2 &= \epsilon_3 = (\epsilon_2)_R = (\epsilon_3)_R
\end{aligned}$$

previous logic yields

$$\epsilon_2 = \frac{1}{1 - \frac{A_C}{A_R}} \left[\frac{\Delta V}{V_1} - C_1 \epsilon_1 + C_2 \epsilon_1 + C_3 \epsilon_1 + C_4 \epsilon_1 + C_5 \epsilon_1 \right] \quad (12)$$

where compressive strains are positive and

$$\begin{aligned}
C_1 &= 2A_R/L_R & C_4 &= \frac{1}{2} \left(1 - \frac{A_C}{A_R} \right) \\
C_2 &= \frac{\nu}{1 - \frac{A_C}{A_R}} & C_5 &= \frac{L_C}{L E_S} \left(1 - \frac{A_C}{A_R} \right) \\
C_3 &= C_2 \left(\frac{L_P}{L_R} - 1 \right)
\end{aligned}$$

Including second order terms $(\epsilon_2)^2$, the corrected result becomes

$$\epsilon_2^{cor} = \epsilon_3^{cor} = - \left(\sqrt{1 + 2} \right) (\epsilon_2) - 1 \quad (13)$$

Note that the dominant terms in eq. (12) are $\frac{\Delta V}{V_1}$ and $C_4 \epsilon_1$.

Corrections for Test at Elevated Temperature

Eqs. (10) and (12) apply directly to tests at elevated temperature if the volume adjustments can be affected without changing the temperature of the confining pressure fluid. This is not always possible nor is it necessarily advantageous. In the Sandia setup, triaxial tests at elevated temperature are performed in such a manner that only the pressure vessel is heated. The dilatometer which is used to regulate pressure and to measure ΔV remains at ambient temperature. Thus, when a volume adjustment

is made, hot fluid is extracted from the vessel or cold fluid injected into the pressure vessel depending on the sign of the deformation-induced pressure change. To account for thermal contractions or expansions, the actual volume adjustment ΔV is calculated from the registered volume change ΔV_M as

$$\Delta V = \frac{\Delta V_M}{1 - \alpha(T - T_0)} \quad (14)$$

α denotes the coefficient of volumetric thermal expansion of the confining pressure fluid per $^{\circ}\text{C}$. T_1 and T_0 are the test temperature in the pressure vessel and the ambient reference temperature in $^{\circ}\text{C}$, respectively. The factor α is evaluated in separate calibration tests as a function of temperature and pressure.

Low Load Corrections

Corrections are necessary if the confining pressure fluid can enter any of the interfaces between the specimen ends and the loading piston or spacers (Figure 1a). Fluid is expelled from these interfaces as they are closed with increases in ram force. This fluid displacement contributes to an increase in confining pressure which is unrelated to specimen deformation. Therefore, it introduces an error in dilatometric readings which manifests itself in terms of a nonlinear toe if force is plotted versus dilatometer output. The easiest way to correct this error is by a toe adjustment analogous to the toe adjustment ($-D_{PL}$) which was described in an earlier section on axial deformation measurements (Figure 5). The upper bound and the uncertainty of

the toe adjustment must be evaluated in calibration tests by means of metal standards.

Calibrations for Dilatometric Method

In principle, dilatometric strain measurements can be performed without calibrations because the reduction equations depend only on known geometric parameters and on the known properties of all pressure vessel materials. However, in practice calibration tests are recommended to demonstrate the validity of eqs. (10) and (12). This can be accomplished by validating the magnitudes of $C_1 = 2 \nu_R L_R$ and of L_P , which can be determined by means of eq. (12) using measured volume changes, ΔV , and calculated (theoretical) strain values ϵ_1 and $\epsilon_2 = \epsilon_3$.

Using steel and aluminum standards again,

$$\frac{V_{AL} - V_{ST}}{V_{AL} - V_{ST}} = \frac{V_{AL} - V_{ST}}{V_{AL} - V_{ST}} \quad (15)$$

V_{AL} and V_{ST} are measured dilatometric readings for aluminum and steel, respectively. E_s , ν_s are assumed to be known. $(\epsilon_1)_{AL}$, $(\epsilon_2)_{AL}$, $(\epsilon_1)_{ST}$, etc., are the calculated strain magnitudes for the steel and aluminum standards subjected to the axial force F_D .

Once C_1 is determined L_P can be found by substituting the measured values ΔV_{AL} , ΔV_{ST} and the calculated values $(\epsilon_1)_{AL}$, $(\epsilon_2)_{ST}$ etc., into eq. (12). Finally, temperature corrections according to eq. (14) can be validated by repeating some calibration runs at elevated temperature. To accomplish this with acceptable resolution, the most compliant standard available should be employed.

Calibrations in two large sample Sandia apparatus rendered values of C_1 which agreed to better than 0.1% with the theoretical value $C_1 = 2A_R L_R$. In turn, the average calibrated value of L_R was 13.39 in (34.01 cm) versus $L_P = 13.50$ in (34.29 cm) according to design drawings. This discrepancy of approximately 1% causes an error in measured radial strains of less than 0.1%.

Resolution and Accuracy of Dilatometric Measurements

The resolution of dilatometric measurements depends on the resolution of small departures away from a reference pressure and on the ability to make small volume adjustments, ΔV . To maximize the resolution it is advisable to measure pressure changes between 2 psi (14 kPa) and 10 psi (69 kPa). Furthermore it is necessary to balance the specimen size, the fluid capacity of the confining pressure system, the dilatometer dimensions and the required response time of the apparatus. At present the Sandia equipment allows reliable volume resolutions of $\Delta V = 2 \times 10^{-3} \text{ in}^3$ (3.3 mm^3). This corresponds to $(\epsilon_2)_{ST} = (\epsilon_3)_{ST} = 10^{-5}$ for $L = 8 \text{ in}$ (20.3 cm) and $A = 11.3 \text{ in}^2$ (76.1 cm^2).

The accuracy of dilatometer measurements is more difficult to determine. Obviously, the absence of leaks is mandatory. Besides that, the measurement accuracy depends on whether the temperature of the confining pressure fluid remains constant or not. Temperature changes result in significant thermal expansion and erroneous dilatometer adjustments. Deformation induced temperature changes usually are negligible. On the other hand, diurnal temperature changes around the Sandia apparatus lead to

apparent short-term and long-term strain variations between 5×10^{-6} and 2×10^{-4} , respectively. Because of the diurnal nature of long-term temperature changes ($\pm 0.8^{\circ}\text{C}$) the average error is considerably smaller than 2×10^{-4} .

The accuracy of dilatometric measurements is also a function of the homogeneity of specimen deformation. Because of end effects most specimens will barrel to greater or lesser extent. Therefore, the radial strain readings obtained by means of eqs. (10) through (13) only provide average strain values. These averages are lower bounds of the radial strains across the largest specimen diameter. However, it should be borne in mind that maximum diameter changes, usually at the center of each specimen, are merely upper bounds of the radial strains which would result if the same resultant forces had produced homogeneous states of deformation (Raleigh, 1973). It is also noted that slight material inhomogeneities, for example in rock salt, may lead to imperfect barrelling. As a result maximum radial strains occur away from the specimen center. This fact creates difficulties in determining the optimum positions for transducers which only measure changes across discrete sample diameters.

In spite of existing difficulties, comparisons between dilatometric measurements according to eqs. (10) through (13) with ring gauge readings converted to radial strains proved favorable. Maximum observed variations on rock salt amounted to 7% at $\epsilon_2 = -9.1\%$. In some cases the two sets of measurements agreed to within better than 2% at $\epsilon_2 = -7.5\%$. Finally, the comparison of ring gauge readings at midheight and at 1/3 the

sample length from one end led to discrepancies between 0.6% and 18% of the smallest observed values. The radial strain at $1/3$ length exceeded the center strains in four of nine experiments indicating a "double barrel" configuration.

* χ^2 -test results are given in parentheses.

* χ^2 -test results are given in parentheses.

[illegible]

EXCERPTS FROM DATA RED. PROGRAM QSTAT

```

10 REM -REDUCTION PROGRAM FOR TRIAXIAL TESTS AT CONSTANT OR VARYING CON-
20 REM FINING PRESSURE WHERE LATERAL DEFORMATION IS MEASURED EITHER
30 REM DILATOMETRICALLY OR NOT AT ALL
40 PAGE=PRINT TAB(50);"PROGRAM: QSTAT.BAS"\PRINT
50 REM -IDENTIFICATION OF DATA FILE AND CORRESPONDING EXPERIMENT
70 PRINT "INPUT FILENAME: ";\INPUT N1$
80 PRINT "OUTPUT FILENAME: ";\INPUT N2$
100 PRINT "TEST SYSTEM USED: ";\INPUT TS$
130 PRINT TAB(10);"SOURCE OF CORE (HOLE #): ";\INPUT CH$
140 PRINT TAB(10);"DEPTH OF CORE (FT): ";\INPUT B1
150 PRINT TAB(10);"TEST CODE (Q# ETC.): ";\INPUT B$
160 PRINT TAB(10);"NOMINAL CONF. PRESSURE (KSI): ";\INPUT B1$
170 PRINT TAB(10);"TEST TEMPERATURE (DEG. C): ";\INPUT B2
190 PRINT "SPECIMEN DIAMETER (IN): ";\INPUT DR
200 PRINT "SPECIMEN LENGTH (IN): ";\INPUT LR
210 REM -DEFINE TEST I.D. IN THE FOLLOWING FORMAT:
220 REM (TEST SYS. #XNOM SP. DIAM.XTEST CODE)X(HOLE #)XDEPTH OF
230 REM CORE)X(NOM. CONF. PR. (KSI))X(TEST TEMP. (C))
290 PRINT "ENTER SYSTEM PARAMETERS FOR TEST SYSTEM ";TS$
300 PRINT TAB(10);"GROSS AREA OF LOADING PISTON (SQIN): ";\INPUT AP
310 PRINT TAB(10);"NET AREA OF LOADING PISTON (SQIN): ";\INPUT AE
320 PRINT TAB(10);"EFFECTIVE LENGTH OF PR. VESSEL (IN): ";\INPUT LP
340 PRINT "DO YOU WISH TO CONSIDER EFFECT OF END CAPS (Y OR N) ";
350 INPUT V1$
360 IF V1$="N" THEN 410
370 PRINT TAB(10);"END CAP DIAMETER (IN): ";\INPUT EC
380 AC=KEC/2)*3.1416/4
390 PRINT TAB(10);"END CAP LENGTH (IN): ";\INPUT LC
400 GOTO 420
410 AC=1\LC=0
420 PRINT

```

```

430 PRINT "PLATEN CALIBR. FACTOR (IN/LB): "; INPUT PF
440 PRINT "SYSTEM DEFORMATION FACTOR (IN/PSI): "; INPUT EU
460 PRINT "ENTER INSTRUMENTATION PARAMETERS FOR TEST SYSTEM: ", TS$
470 PRINT TAB(10); "LUOT CALIBR. FACTOR (U/IN): "; INPUT LF
480 PRINT TAB(10); "LUOT SCALE FACTOR (U LUOT/U RECORD): "; INPUT F1
530 PRINT TAB(10); "POTENTIOM. (DILATOM.) CALIBR. FACTOR (CUIN/U) ",
540 INPUT UF
550 PRINT TAB(10); "POTENTIOM. SCALE FACTOR (U POT/U RECORD): "; INPUT F2
560 PRINT TAB(10); "THERM. EXP. COEFF. OF PR. FLUID (CUIN/DEGR C) ",
570 INPUT EX
630 REM -ENTER DATA TO ALTER TOE REGIONS IN PLOTS FORCE-DISPL. OR
640 REM FORCE-VOL. ADJ. THE DATA D1, P1 ETC. ARE OBTAINED FROM
650 REM DATA IN OUTPUT FILES OF OFSED OR OFESET; THEY HAVE THE
660 REM DIM'S OF (VOLT) AND (LB)
670 REM (VOLT) AND (LB)
730 PRINT "DO YOU WISH TO ALTER TOE IN FORCE-DISPL. DATA OF INPUT "
740 PRINT "FILE (Y OR N): "; INPUT Y4$
750 IF Y4$="N" THEN 790
760 PRINT TAB(10); "ENTER ZERO SHIFT IN DISPL., D1 (VOLT): "; INPUT D1
770 PRINT TAB(10); "ENTER UPPER BOUND FORCE OF TOE REGION, P1 (LB) ";
780 INPUT P1
790 IF Y2$="N" THEN 870
810 PRINT "DO YOU WISH TO ALTER TOE IN FORCE-VOL. ADJ. DATA OF INPUT "
820 PRINT "FILE (Y OR N): "; INPUT Y5$
830 IF Y5$="N" THEN 870
840 PRINT TAB(10); "ENTER ZERO SHIFT IN VOL. ADJ., D2 (VOLT): "; INPUT D2
850 PRINT TAB(10); "ENTER UPPER BOUND FORCE OF TOE REGION, P2 (LB) ";
860 INPUT P2
1120 REM -DEFINE COUNTER Z1 TO DISTINGUISH FIRST (Z1=0) FROM
1130 REM SUBSEQUENT DATA LINES (Z1=1) IN INPUT FILE
1140 Z1=0
1160 REM -CALCULATE CONSTANTS DEFINED BY INPUT DATA AND NEEDED FOR
1170 REM E3 REDUCTION CALCULATIONS
1180 AR=(DR-2)*3.1416/4
1190 C1=2*AK*LR

```

```

1200 C2=(1-AP/AR)/2
1210 C3=.29/(2.8E+07*AR)
1220 C4=LC*(AR-AP)/(C1*2.8E+07*AC)
1230 C5=C3*(LP/LR)-1)
1240 TC=(1-(B2-22)*EX)
1250 REM -BEGIN TO READ AND REDUCE DATA (T=TIME; P=LOAD; CP=CONF. PR.
1260 REM D=DISPL.; U=VOL. ADJ.)
1270 INPUT #1,TI,P,CP,D,U
1300 REM -CALCULATE STRAIN E1 (IN/IN) CONSIDERING SHIFT FACTOR D1
1310 REM AND PLATEN DISPLACEMENT
1320 IF P>P1 THEN IF P>P2 THEN 1360
1330 IF Z1=1 THEN 1270
1340 E1=0/E3=0
1350 GOTO 1460
1360 D=(D+D1)/LF)*F1
1370 C7=P-CP*AE
1380 E1=(D-C7*PF-(CP-SR)*EU)/LR
1390 REM -CALCULATE E3 CONSIDERING THERMAL EXPANSION OF PR. FLUID AND
1400 REM SHIFT FACTOR D2
1410 IF Y2#="N" THEN 1490
1420 U=U+D2
1430 U=U*F2/TC
1440 C6=(U/C1+(C2-C3P)*E1+(C4-C5)*P)/(1-E1)
1450 E3=(SQRT(1+2*C6))-1
1460 REM -CALCULATE SHEAR AND VOLUMETRIC STRAINS
1470 E4=E1+E3
1480 E=(1-E1)*((1+E3)/2)-1
1490 REM -CALCULATE PRINC. STRESS DIFF. AND MEAN STRESS
1500 C8=AR*(1+E3)/2
1510 S4=C7/C8
1520 S=(S4+3*CP)/3
2070 REM -DISPLAY ON SCREEN FILE NAME, TEST I.D. AND DIMENSION OF DATA
2080 REM ARRAY (# OF DATA SETS) IN OUTPUT FILE. THEN DISPLAY MAX. VALUES
2090 REM OF TIME, (S1-S3) ETC.

```

TYPICAL OUTPUT FILE OF DATA REDUCTION PROGRAM QSTAT

The abbreviated file name Q30 designates the file as an output file of the data reduction program QSTAT. The letter A refers to rock salt from a site in southeastern New Mexico. The file number 30 (between 0 and 99) identifies a quasistatic experiment.

FILE QA30

TEST I.D. A1 40/9-2604/ 5/200

TIME (HRS)	S1-S3 (PSI)	S3 (PSI)	S (PSI)	E1 (%)	-E3 (%)	E1-E3 (%)	E (%)
000,	000,	529,	529,	000,	000,	000,	000
0111,	265,	527,	615,	05,	000,	050,	034
0333,	265,	528,	616,	055,	000,	064,	038
0667,	260,	529,	616,	057,	000,	065,	039
1,	263,	530,	618,	057,	000,	065,	039
1375,	511,	528,	698,	097,	028,	125,	041
1667,	516,	525,	697,	11,	04,	15,	029
2,	506,	526,	695,	112,	04,	153,	031
2333,	500,	527,	694,	114,	04,	155,	032
2667,	498,	527,	693,	114,	041,	155,	032
2795,	527,	526,	702,	114,	04,	154,	033
2828,	757,	517,	769,	132,	046,	178,	04
2942,	763,	523,	777,	147,	068,	214,	01
3,	758,	524,	777,	149,	068,	216,	012
3333,	747,	527,	776,	16,	069,	229,	021
3667,	764,	524,	779,	165,	081,	245,	002
4,	757,	521,	773,	17,	093,	263,	-015
4045,	1011,	524,	861,	236,	126,	362,	-016
4333,	1006,	527,	862,	312,	169,	48,	-025
4667,	994,	526,	857,	355,	195,	551,	-034
5,	1005,	524,	859,	393,	221,	614,	-046
5333,	1011,	523,	860,	428,	246,	674,	-062
5392,	1247,	527,	943,	562,	318,	88,	-07

stresses are included. Among the input parameters the gross (cross-sectional) area of the loading piston corresponds to the outer diameter of the loading piston, D_S (Fig. 10). Therefore $AP = A_S$ in equation (12). Given the diameter of the sealed nipples, D_N , of most Sandia end-caps (Fig. 10a) the net piston area is $AP = A_S - \frac{\pi}{4} D_N^2$. Hence, AE equals that area of the loading piston which is subjected to the confining pressure $CP = \sigma_2 = \sigma_1$. The magnitude of AE determines the magnitude of the initial pressure reaction along the loading piston, F_H . In most experiments in the Sandia apparatus $AE = 0.95 AP$.

The variables AP , AC , etc. and the actual computations of strains and stresses are consistent with equations (10) through (13) using the platen calibration factors Δ_1 and Δ_2 in equations (4) and (5). In the enclosed program excerpts $PF = \Delta_1$ and $FV = \Delta_2$.

Finally, the definitions and implementation of the toe adjustments of axial and dilatometric deformation measurements follow from earlier discussions setting $D1 = D_{PL}$, $PL = F_C$, etc. Parts of the data reduction program QSTAT are followed by the first page of a typical output file.

Strain Measurements in Triaxial Extension Tests at Variable Straining Pressure

During the course of the triaxial extension tests, axial and radial strain measurements are conducted by means of LVDT transducers attached to reference points A and B. The points A and B are placed at the top of the pressure vessel flange. On the other hand, radial deformations are monitored by means of one or two disk potentiometers with outputs 11 and 12. The present experimental technique does not permit dilatometric measurements at variable confining pressure. Note that the radial strains now denote the in-situ compressive strains $\epsilon_1 = \epsilon_2$ while the axial sample strain equals the least compressive principal strain ϵ_3 . Further details follow immediately from an inspection of the original sections of the data reduction program (STAT) using the variables which were introduced in the reduction program (STAT).

EXCERPTS FROM DATA RED. PROGRAM QSTAT3

```

10 REM -REDUCTION PROGRAM FOR TRIAXIAL EXTENSION TESTS WHERE LATERAL
20 REM STRAIN IS MEASURED BY MEANS OF ONE OR TWO DISC GAUGES
30 PAGE=PRINT TAB(50);"PROGRAM: QSTAT3.BAS"PRINT
40 REM -IDENTIFICATION OF DATA FILE AND CORRESPONDING EXPERIMENT
50 PRINT "INPUT FILENAME: ";INPUT N1$
60 PRINT "OUTPUT FILENAME: ";INPUT N2$
80 PRINT "TEST SYSTEM USED: ";INPUT TS$
110 PRINT TAB(10);"SOURCE OF CORE (HOLE #): ";INPUT CH$
120 PRINT TAB(10);"DEPTH OF CORE (FT): ";INPUT B1
130 PRINT TAB(10);"TEST CODE (ON ETC.): ";INPUT B$
140 PRINT TAB(10);"CONF. PRESSURE (KSI): ";INPUT B1$
150 PRINT TAB(10);"TEST TEMPERATURE (DEG. C): ";INPUT B2
170 PRINT "SPECIMEN DIAMETER (IN): ";INPUT DR
180 PRINT "SPECIMEN LENGTH (IN): ";INPUT LR
190 REM -DEFINE TEST I.D. IN THE FOLLOWING FORMAT:
200 REM (TEST SYS. #XNOM. SP. DIAM.XTEST CODE)/(HOLE #)-(DEPTH OF
210 REM CORE)/(NOM. CONF. PR. (KSI))/(TEST TEMP. (C))
270 PRINT "ENTER SYSTEM PARAMETERS FOR TEST SYSTEM ";TS$
280 PRINT TAB(10);"CROSS AREA OF LOADING PISTON (SQIN): ";INPUT AP
290 PRINT TAB(10);"PLATEN CALIBR. FACTOR (IN/LB): ";INPUT PF
300 PRINT TAB(10);"SYSTEM DEFORMATION FACTOR (IN/PSI): ";INPUT EU
310 PRINT
320 PRINT TAB(10);"LUOT CALIBR. FACTOR (U/IN): ";INPUT LF
330 PRINT TAB(10);"LUOT SCALE FACTOR (U LUOT/U RECORD): ";INPUT F1
350 PRINT TAB(10);"NO. OF DISC TRANSDUCERS USED (1 OR 2): ";INPUT M
360 PRINT
370 PRINT TAB(15);"CALIBR. FACTOR (U/IN) FOR DISC #1 (CH. X+4): ";
380 INPUT UF
390 PRINT TAB(15);"SCALE FACTOR FOR DISC #1 (U DISC/U RECORD) ";
400 INPUT F2
410 IF M=1 THEN 400
430 PRINT TAB(15);"CALIBR. FACTOR (U/IN) FOR DISC #2 (CH. X+5): ";

```

```

440 INPUT WF
450 PRINT TAB(15); "SCALE FACTOR FOR DISC #2 (U DISC/U RECORD): ";
460 INPUT F3
480 REM -ENTER DATA TO ALTER TOE OF FORCE-AX. DISPL. CURVE OR TO
490 REM ZERO-SHIFT ALL AX. AND/OR LAT. DISPL. VALUES. THE DATA
500 REM D1,P1 ETC. ARE OBTAINED FROM DATA IN OUTPUT FILES OF
510 REM OFSED2 OR OFSET2; THEY HAVE THE DIM'S OF (VOLT) AND (LB)
540 PRINT "DO YOU WISH TO ALTER AX. DISPL. DATA OR TOE IN FORCE-DISPL. ";
550 PRINT "OF INPUT FILE (Y OR N): "; INPUT Y1$
560 IF Y1$="N" THEN 600
570 PRINT TAB(10); "ENTER ZERO SHIFT IN DISPL., D1 (VOLT): "; INPUT D1
580 PRINT TAB(10); "ENTER UPPER BOUND FORCE OF TOE REGION, P1 (LB): ";
590 INPUT P1
600 PRINT
610 PRINT "DO YOU TO ZERO SHIFT LAT. DISPL. DATA (Y OR N): "; INPUT Y2$
620 IF Y2$="N" THEN 680
630 PRINT TAB(10); "ENTER ZERO SHIFT IN LATD1 DATA (DISC #1): ";
640 INPUT D2
650 IF M=1 THEN 710
660 PRINT TAB(10); "ENTER ZERO SHIFT IN LATD2 DATA (DISC #2): ";
670 INPUT D3
680 PRINT
690 PRINT "DO YOU WISH TO RETAIN ONLY AVG. LATD VALUES OR BOTH INDIV. ";
700 PRINT "AND AVG. " INPUT Y3$
710 PRINT
940 REM -DEFINE COUNTER Z1 TO DISTINGUISH FIRST (Z1=0) FROM
950 REM SUBSEQUENT DATA LINE (Z1=1) IN INPUT FILE
970 Z1=0
1110 REM -CALCULATE SAMPLE AREA
1120 AR=(DR~2)*3.1416/4
1130 REM -BEGIN TO READ AND REDUCE DATA (T=TIME; P=LOAD; CP=CONF PR.
1140 REM D=AX. DISPL.; L1=LATD1; L2=LATD2)
1150 INPUT #1,T1,P,CP,D,L1,L2
1160 IF Z1=1 THEN 1180
1170 GOSUB 1940

```

```

1180 REM -CALCULATE (AXIAL) STRAIN -E3 (IN/IN) CONSIDERING SHIFT FACTOR
1190 REM D1 AND PLATEN DISPLACEMENT
1200 IF P>P1 THEN 1230
1210 IF Z1=1 THEN 1150
1220 GOTO 1350
1230 D=(D+D1)/LF)*F1
1240 E3=(D+(P-PR)*PF+(CP-SR)*EV)/LR
1250 REM -CALCULATE (LATERAL) STRAIN E1 CONSIDERING POSSIBLE SHIFT
1260 REM FACTORS D2,D3
1270 L1=L1+D2
1280 G1=(L1/(DR*F))*F2
1290 IF M=1 THEN 1340
1300 L2=L2+D3
1310 G2=(L2/(DR*F))*F3
1320 E1=(G1+G2)/2
1330 GOTO 1350
1340 E1=G1
1350 REM -CALCULATE SHEAR AND VOLUMETRIC STRAINS
1360 E4=E1+E3
1370 E=(1-E1)^2*(1+E3)-1
1380 REM -CALCULATE PRINC. STRESS DIFF. AND MEAN STRESS
1400 C8=AR*(1-E1)^2
1410 S3=CP+(P-CP*AP)/C8
1420 S4=CP-S3
1430 S=(2*S4+3*S3)/3
1440 REM -INITIAL VALUE DETERMINATIONS
1460 SR=CP
1470 PR=P
2010 RETURN
2020 REM -DISPLAY ON SCREEN FILE NAME, TEST I.D. AND DIMENSION OF DATA
2030 REM ARRAY (# OF DATA SETS) IN OUTPUT FILE. THEN DISPLAY MAX. VALUES
2040 REM OF TIME, S4=(S1-S3) ETC.

```

SUMMARY

Indirect procedures were presented which are used at Sandia Laboratories to determine axial and lateral (radial) strains on rock cylinders in triaxial experiments to 250°C. The techniques are employed in quasi-static tests as well as in long-term creep experiments. Descriptions of all techniques included discussions of (1) methodologies, (2) calibration procedures and (3) accuracies of measurements. In addition, two examples were presented which demonstrate how various sets of raw data are reduced by means of computer programs for triaxial compression tests and for triaxial extension experiments.

REFERENCES

- Baligh, M. M. "Numerical Study of Uniaxial and Triaxial Rock Compression Tests," Report No. SSS-R-73-1658, System, Science and Software, La Jolla, CA, 1973.
- Fairhurst, C., "Laboratory Measurements of Some Physical Properties of Rock, "Proc. 4th Symp. Rock Mech., Penn. State Univ., 1961.
- Schuler, K. W., "Lateral-deformation Gage for Rock-mechanics Testing," Exper. Mech., 18, 12, 1978
- Wawersik, W. R., "Technique and Apparatus for Strain Measurements on Rock at Constant Confining Pressure," Rock Mech., 7, 231, 1975.

Figure 1 Typical experiment configuration for (a) tri-axial compression and/or (b) extension tests.

Figure 2 End-cap and sample configurations used in some triaxial extension experiments.

Figure 3 Schematic of system and transducer gauge points (pts. A and B) in Sandia triaxial apparatus.

Figure 4 Idealized (ram) force-displacement record, F versus δ in Figure 3.

Figure 5 Realistic force-displacement curves, $F_{max} = 100$ kN (Figure 3b), with differing degrees of nonlinearity indicating possible "top" and "tail" regions. Linear approximation of actual data and maximum error e between data and approximation.

Figure 6 Actual (a) and idealized (b) force displacement curves for metal standards used in transducer and system calibrations.

Figure 7 Schematic of gauge point transfer button for measurement of radial sample deformation.

Figure 8 Typical surface profile of deformed rock salt specimen parallel to sample axis (direction of σ_1)

x: Distance from specimen ends

y: Relative amplitude proportional to radial deformation (1.13×10^{-3} in (28.8 μm) per smallest division).

Records #2 and #3 correspond to gauge lines $\frac{\pi}{4}$ radians apart.

Figure 9 Schematic of triaxial sample - piston arrangement with matched diameters, $D_R = D_S$ for interpretation of dilatometric measurements.

Figure 10 Schematic configuration of specimen, loading piston, and end-caps in Sandia triaxial apparatus. Ports through piston and end-caps provide access to specimen for venting, pore pressure control, etc.

(b)

Figure 10 Schematic configuration of specimen, loading piston, and end-caps in Sandia triaxial apparatus. Parts through piston and end-caps provide access to specimen for venting, pore pressure control, etc.

Distribution:

U.S. Dept. of Energy, Headquarters
Office of Nuclear Waste Management
Washington, DC 20545

Eugene F. Beckett, Project Coord. (WIPP) (5)
Colin A. Heath, Dir., Div. Waste Isolation (2)
Sheldon Meyers
Raymond G. Romatowski
R. Stein
Carl R. Cooley

U.S. Dept. of Energy, Albuq. Operations
P.O. Box 5400
Albuquerque, NM 87185

D. T. Schueler, Mgr., WIPP Project Office (3)
R. Rudolph, Atty. Deputy Mgr., WIPP Project Office
G. Dennis, Dir., Public Affairs Division
S. C. Taylor, C&TI Div. (Public Reading Rooms) (5)

U.S. Dept. of Energy
Carlsbad WIPP Project Office
Room 113, Federal Building
Carlsbad, NM 88220

Mr. Jeff O. Neff
U.S. Dept. of Energy
c/o Battelle Office of Nuclear
Waste Isolation
505 King Avenue
Columbus, OH 43201

Battelle Memorial Institute
Office of Nuclear Waste Isolation
505 King Avenue
Columbus, OH 43201
Neil Carter, General Manager (2)
R. Heineman
Wayne Carbiner

Westinghouse Electric Corp.
P.O. Box 40039
Albuquerque, NM 87196
R. C. Mairson
D. Hulbert
A. K. Kuhn, D'Appolonia

Mr. J. Holloway
National Academy of Sciences
Committee on Radioactive Waste Management
2101 Constitution Avenue
Washington, DC 20418

Bechtel, Inc.
P.O. Box 3965
San Francisco, CA 94119
R. A. Langley
H. G. Taylor
P. K. Frobenius
D. L. Roberts
D. Duncan
J. Kirkmyer

Dr. Bruno Giletti, Co-Chairman
Environmental Protection Agency
Ad-Hoc Panel of Earth Scientists
Department of Geological Sciences
Brown University
Providence, RI

Dr. Raymond Siever, Co-Chairman
Environmental Protection Agency
Ad-Hoc Panel of Earth Scientists
Department of Geological Sciences
Harvard University
Cambridge, MA 02139

Dr. Marvin H. Wilkening, Chairman
Environmental Protection Agency
Ad-Hoc Panel of Earth Scientists
New Mexico Advisory Committee on WIPP
NMIMT Graduate Office
Socorro, NM 87801

Robert H. Neill, Director
State of New Mexico
Environmental Evaluation Group
320 Marcy Street
P.O. Box 968
Santa Fe, NM 87503

Dr. W. F. Brace
Dept. of Earth & Planetary Sciences
Massachusetts Inst. of Technology
Cambridge, MA 02139

Dr. N. G. W. Cook
University of California
Berkeley, CA 94720

Dr. Charles Fairhurst
University of Minnesota
Dept. of Civil & Mineral Eng.
112 Mines & Metallurgy Bldg.
Minneapolis, MN 55455

Dr. Paul F. Gnirk
RE/SPEC Inc.
PO Box 725
Rapid City, SD 57709

3141 T. L. Werner (5)
 3151 W. L. Garner,
 DOE/TIC (Unlim. Release) (3)
 3172-3 R. P. Campbell, DOE/TIC (25)
 3310 W. D. Burnett
 3311 D. R. Parker
 Attn: L. W. Brewer
 3312 G. E. Tucker
 Attn: J. H. Metcalf
 3313 A. L. Stanley
 4500 E. H. Beckner
 4510 W. D. Weart
 4512 T. O. Hunter
 4512 A. R. Sattler
 4512 J. R. Wayland
 4514 M. L. Merritt
 4540 M. L. Kramm
 4541 L. W. Scully
 4541 R. E. Stinebaugh
 4541 W. Wowak
 4542 J. W. McKiernan
 4542 Sandia WIPP Central Files (2)
 4732 D. E. Munson
 5000 J. K. Galt
 Attn: Directors
 5500 O. E. Jones
 Attn: Department Managers
 5521 R. Krieg
 5530 W. Herrmann
 Attn: Supervisors
 5531 L. D. Bertholf
 5531 P. R. Dawson
 5532 B. M. Butcher (2)
 5532 L. S. Costin
 5532 W. R. Wawersik (15)