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Public Draft

Laboratory Rock Mechanics Testing Manual

Technical Report

October, 1981

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ABSTRACT

Standardized laboratory rock mechanics testing procedures have been prepared for use in the National Terminal Waste Storage Program. The procedures emphasize equipment performance specifications, documentation and reporting, and Quality Assurance acceptance criteria. Sufficient theoretical background is included to allow the user to perform the necessary data reduction. These procedures incorporate existing standards when possible, otherwise they represent the current state of the art. Maximum flexibility in equipment design has been incorporated to allow use of this manual by existing groups and to encourage future improvements.

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1.0 Introduction

1.1 Background.

The National Waste Terminal Storage (NWTS) program includes several rock mechanics testing studies to fully characterize rock at candidate nuclear waste repository sites. Because of the nature of the NWTS program, these rock mechanics studies must fulfill several requirements:

- The studies should provide technically sound, high-quality data.
- Studies conducted by individual groups should be usable by other researchers and easily integrated into the overall NWTS program.
- The studies should satisfy the data defendability, preservation, and retrievability requirements of the NWTS program.

To satisfy these requirements, standardized rock mechanics test procedures are necessary. While standard procedures are in existence for certain tests, there are many tests, particularly high temperature mechanical tests, for which no such procedures exist. In addition, existing procedures do not address such areas as equipment performance, calibration and documentation requirements, and level of reporting in sufficient detail to be directly usable in the NWTS program. Therefore, a set of standard procedures incorporating the state of the art of rock testing and oriented toward the NWTS program requirements was commissioned by the Office of Nuclear Waste Isolation (ONWI). This testing manual is the result of that effort.

The manual was prepared by Foundation Sciences, Inc., Portland, Oregon. Accepted standards and procedures, particularly from the American Society for Testing and Materials (ASTM) and International Society for Rock Mechanics (ISRM), are incorporated wherever possible. Where these are lacking, the procedures are based on the state of the art techniques used by research laboratories, universities, and the geotechnical industry. This manual should be considered a living document. It was the intention of the authors that changes in technology and methodology could be incorporated into these procedures while maintaining the general intent and level of quality.

1.2.1 To provide a standard approach for conducting tests. The method of testing can have a significant effect on the data

generated by the test. A major purpose of these procedures is to describe in general terms a standard approach for measuring specific rock properties. These procedures are as flexible as possible while establishing common ground for comparison and evaluation of results.

1.2.2 To establish performance requirements for apparatus. Two important areas in rock mechanics testing that have not received sufficient emphasis in state-of-the-art testing programs are the level of accuracy for measurement of test parameters and the effect of physical measurement errors on the quality of the final data. A primary purpose of these procedures is to establish performance criteria for all relevant equipment and instrumentation, in order to provide high-quality data consistent with repository site characterization requirements. Another purpose of these procedures is to identify and minimize the limitations placed on the resulting data by uncertainties due to measurement system error and sample variability. The intent is to provide the person using the data with an idea of how good the data really are.

1.2.3 To establish Quality Assurance acceptance criteria and checkpoints. The results of rock mechanics testing in the NWTS program must be defendable, traceable, and recoverable. These are responsibilities of a Quality Assurance program. The procedures in this manual identify the relevant areas of qualification, verification, inspection, and documentation so that each test can successfully fulfill Quality Assurance requirements.

1.2.4 To define reporting requirements. The potentially widespread application of the results of the testing programs requires that reports be complete, understandable, and usable to workers who may or may not have a background in rock mechanics. The procedures in this manual emphasize reporting requirements in order to produce a document which can stand alone and be correctly applied.

1.3 Limitations of the manual.

1.3.1 Data interpretation and application. The procedures in this manual are designed to produce usable data. The interpretation and application of these data depend on the nature of the project and are highly site specific. More importantly, interpretation and application are in part creative processes which draw heavily on the experience, judgment, and capability of the individual, and are not amenable to reduction to a standard procedure.

1.3.2 Technical expertise. Even in well-defined and repetitive processes such as laboratory rock mechanics testing, contin-

gencies will arise which are not and cannot be covered by a procedure. These require an understanding of the physical processes involved in the test and the equipment used. The procedure is not a substitute for technical knowledge and experience.

1.3.3 Equipment specifications. To keep these procedures timely and avoid hardship on testing laboratories, no equipment or apparatus has been specified by brand name. Equipment requirements have been approached through performance specifications, to allow workers maximum flexibility. It is not the intent of these procedures to restrict future improvements in testing techniques in any way.

1.4 Acknowledgments.

The authors wish to acknowledge the various organizations involved in rock mechanics testing which have produced testing procedures in the past. In particular, the following supplied background information which was incorporated into this manual:

The American Society for Testing and Materials, Book of Annual Standards, Part 19: Soil and Rock; Building Stones; Peats.

The International Society for Rock Mechanics, Commission on Standardization of Laboratory and Field Tests

U. S. Army Corps of Engineers, Rock Testing Handbook (Standard and Recommended Methods)

U. S. Bureau of Mines, Bureau of Mines Test Procedures for Rocks

Vutukuri, V.S., Lama, R.D., and Saluja, S.S., 1974, Handbook on Mechanical Properties of Rocks, Testing Techniques and Results, 1, Trans Tech Publications, Clausthal, Germany.

The authors also wish to extend their appreciation to the following individuals who supplied material pertaining to the state of the art in rock mechanics testing:

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2.0 Generalized laboratory operations

2.1 Basic skills assumed by the procedures.

This manual presupposes familiarity with basic laboratory operations such as weighing, volume and length measurements, etc., so these skills are not included in the procedures. The prequalification of technicians and supervisors required in the procedures and implemented in a basic Quality Assurance pro-

gram is an implicit recognition that capable individuals will be performing the tests.

2.2 Error in laboratory measurements.

2.2.1 Definition of terms.

2.2.1.1 Accuracy - the deviation of the measurement from the "true" value of the parameter being measured. For example, a pressure gage that reads 102 psi (0.703 MPa) at a known pressure of 100 psi (0.689 MPa) has an accuracy of 2% at that point.

2.2.1.2 Precision - the ability to reproduce a certain measurement, regardless of the accuracy. For example, if the pressure gage of section 2.2.1.1 is read five times and the readings are 102, 101, 102, 102, and 101 psi (0.703, 0.696, 0.703, 0.703, and 0.696 MPa), the precision is 1% of the measured value.

2.2.1.3 Resolution - the smallest measurement interval which an instrument is capable of reading. For example, if the smallest graduations on a pressure gage are at 10 psi (0.069 MPa) intervals, it is possible to interpolate to the nearest 1 psi (0.007 MPa), thus giving a resolution of 1 psi (0.007 MPa).

2.2.1.4 Sensitivity - the ratio of instrument output per change in the measured parameter. For example, two different model LVDTs have sensitivities of 10 V/in. (25.4 V/cm) and 5 V/in. (12.7 V/cm).

2.2.1.5 Systematic errors - reproducible errors introduced by faulty equipment, calibration, or technique. For example, a pressure gage which reads 5% too high introduces a systematic error of 5% into all pressure readings unless this inaccuracy is determined by calibration and the data corrected. Another example is a lab technician who always reads the pressure gage 100 psi (0.689 MPa) too high because of parallax errors between the gage needle and scale. Systematic errors can seriously affect the accuracy of a measurement.

2.2.1.6 Random errors - the fluctuation in the measurement due to the finite precision of the test equipment. For example, the measurement of a constant flow in a permeability test can vary due to the uncertainties in the measurement of volume and elapsed time.

2.2.1.7 Uncertainty - the combined effect of random errors in a measurement. For a suite of several samples, it is the combined effects of random variations of the average material properties.

2.2.2 Measurement uncertainties. Each piece of data obtained from a laboratory test has an uncertainty associated with it that is the combination of the individual uncertainties of the

measurements required to obtain the data. A detailed discussion of uncertainty analysis is highly complex and beyond the scope of this manual. The user is referred to standard statistics texts. However, a few concepts will be defined to provide the background for the error analysis requirements in the procedures.

The basis for uncertainty estimates of measurements is the standard theory of propagation of errors. If a value, y, is a function of several independent measurements:

$$y = f(u,v,x...) \tag{1}$$

The theory of propagation of errors relates the uncertainty of each measurement to the uncertainty of the total measurement by:

$$w_y^2 = \left(\frac{y}{u}\right)^2 w^2 + \left(\frac{y}{v}\right)^2 w_v^2 + \left(\frac{y}{x}\right)^2 w_x^2 \quad ... \tag{2}$$

where w_y = uncertainty of the value of y

w_u, w_v, w_x = uncertainties in measurements of u, v, and x.

For example, a modulus of deformation test is run on a basalt core. The following equipment is used:

pressure gage:	range: 0-200 psi (0-1.38 MPa) accuracy: 1% of full scale
hydraulic ram:	area: 25.00 $in.^2$ (161.25 cm^2)
LVDTs:	calibration factor: 0.200 in./V (0.51 cm/V) gage length: 2.000 in. (5.08 cm)
voltmeter:	accuracy: 0.05% of reading
diameter:	2.050 in. (5.207 cm)

The samples are stressed from 0 to 5000 psi (0 to 34.48 MPa) and the deformation is linear. The initial voltmeter reading is 7.500 mV and the total change in output is 5.076 mV. The rock modulus is calculated to be 9.85×10^6 psi (6.79×10^4 MPa). How accurate is that figure?

The modulus, E, is calculated using:

$$E = \frac{\sigma}{\varepsilon} \tag{3}$$

where σ = stress in the sample
ε = strain in the sample.

The stress in the sample, σ, is calculated using:

$$\sigma = \frac{SA_r}{A_s} \tag{4}$$

where S = pressure gage reading
A_r = area of ram
A_s = area of sample.

The strain in the sample, ε, is calculated using:

$$\varepsilon = \frac{\Delta VC}{L} \tag{5}$$

where ΔV = change in output voltage from LVDT
C = LVDT calibration factor
L = gage length.

The area of the sample, A_s, is calculated using:

$$A_s = \frac{\pi}{4} d^2 \tag{6}$$

where d = the measured diameter.

Applying Equation 2 to Equation 6, the error, w_{A_s}, associated with the sample area may be calculated using:

$$w_{A_s}^2 = \frac{\pi^2}{4} d^2 w_d^2 \tag{7}$$

where w_d = the uncertainty in the sample diameter.

The sample diameter was measured with a micrometer caliper capable of reading to 0.001 in. (0.03 mm) and accurate to 0.001 in. (0.03 mm). Therfore, w_{d2} is $0.001_2(0.03)$. Working through the algebra, w_{A_s} is (0.003 in.^{2} (0.2 mm^2).

To calculate the error associated with the stress measurement, w_σ, Equation 4 is combined with Equation 2:

$$w_\sigma^2 = \frac{A_r^2}{A_s^2} w_s^2 + \frac{S^2}{A_s^2} w_{A_r}^2 + \frac{S^2 A_r^2}{A_s^2} w_{A_s}^2 \tag{8}$$

where w_{A_r} = error associated with the area of the hydraulic ram
W_s = error associated with the pressure gage reading

The value of S is chosen to correspond to 2500 psi (17.24 MPa) sample stress, the average value over the pressurization cycle. The following parameters are input into Equation 8:

S = 100 psi (0.689 MPa)

w_s = 2 psi (0.014 MPa) (from performance verification test)

A_r = 25.00 in.^{2} (161.25 cm^2)

w_{Ar} = 0.01 in.^{2} (0.645 mm^2) (from manufacturer; subsequently verified)

A_s = 3.301 in.^{2} (21.29 cm^2)

w_{As} = 0.003 in.^{2} (0.2 mm^2) (from above)

Solving Equation 8, w_σ is found to be approximately 15 psi (0.103 MPa).

To calculate the error associated with the strain measurement, w_ε, Equation 5 is combined with Equation 2:

$$w_\varepsilon^2 = \frac{C^2}{L^2} w_{\Delta V}^2 + \frac{\Delta V^2}{L^2} w_C^2 + \frac{\Delta V^2 C^2}{L^4} w_L^2 \qquad (9)$$

The value of ΔV is chosen to correspond to the average change in voltage over the pressurization cycle. The error in the voltage reading, $w_{\Delta V}$, may be approximated by the root mean square of the errors of the initial and final voltage, or 0.007 mV. The following parameters are input into Equation 9:

ΔV = 2.538 mV

$w_{\Delta V}$ = 0.007 mV

C = 0.0002 in./mV (0.005 mm/mV)

w_C = 0.000001 in./mV (2.5×10^{-5} mm/mV) (from calibration)

L = 2.000 in. (5.08 cm)

w_L = 0.001 in. (0.03 mm) (accuracy of dial micrometer)

Solving Equation 9, the error associated with the strain measurement is 1.5×10^{-6}.

Finally, to calculate the error associated with the modulus value, w_E, Equation 3 is combined with Equation 2:

$$w_E^2 = \frac{w_\sigma^2}{\varepsilon^2} + \frac{\sigma^2}{\varepsilon^4} w_\varepsilon^2 \qquad (10)$$

The stress and strain are evaluated at the midpoint of the pressurization cycle. The following parameters are input into Equation 10:

σ = 2500 psi (17.24 MPa)

w_σ = 15 psi (0.103 MPa) (from above)

ε = 254×10^{-6}

w_ε = 1.5×10^{-6} (from above)

Solving Equation 10, w_ε is 0.83×10^5 psi (5.72×10^2 MPa). Thus the error associated with the modulus determination is $\pm 0.08 \times 10^6$ psi (0.06×10^4 MPa).

For this test, then, E = $9.85 \pm 0.08 \times 10^6$ psi ($7.79 \pm 0.06 \times 10^4$ MPa).

2.2.3 Sources of error. Measurement accuracy is determined primarily by the ability to control systematic errors. Precise calibration of test equipment, adequate training of test personnel, control of the test environment, and design of experiments with redundant systems are areas of major importance in performing accurate tests.

Random errors primarily reflect the limitations of the test equipment. Certain environmental factors, such as radio interference or vibration, can also influence measurements in quite random ways. Careful experiment design and environmental control are the two primary means of minimizing random errors.

3.0 Test equipment performance verification

3.1 Definition of terms and concepts.

3.1.1 Performance verification. The procedures in this manual specify certain accuracies, resolutions, and other requirements for the equipment used in the tests. Performance verification means demonstrating that the equipment does indeed perform within the required specifications. The demonstration must be conducted according to standard, accepted, defendable procedures. In general, calibration of the equipment is the method of performance verification.

3.1.2 Calibration. Calibration means subjecting a piece of equipment to a change in the parameter of interest by means of a known input, and monitoring the actual output. The variation between the input and output is used to calculate the correct reading of a measured value in an actual test. Alternatively, the calibration can verify that the equipment performance is within a certain acceptable limit of error which will be used when evaluating the test data.

3.2 Standards.

During calibration, the equipment is effectively being measured against a known standard. Clearly, the accuracy of the standard will be the limiting factor in the calibration. The most accurate standards are maintained by the U.S. National Bureau of Standards (NBS).

Not all equipment, of course, can be calibrated directly against NBS standards. Most equipment is calibrated against standards that are traceable to NBS standards. This means that the standard was calibrated against another standard which was calibrated against another standard and so forth until the last standard is the NBS standard. Traceability to NBS is the best practical way to ensure a minimum level of accuracy in the equipment calibration.

All calibration of equipment used in these procedures shall be against standards traceable to NBS unless otherwise stated.

3.3 Performance specifications.

3.3.1 Specific requirements. Specific performance requirements for equipment are listed in each test procedure.

3.3.2 Manufacturer's specifications. For equipment which does not have specific requirements stated in the procedures, the performance specifications supplied by the manufacturer shall be the basis for performance verification. This is particularly relevant for electronic equipment, such as voltmeters and oscilloscopes. This type of equipment is generally calibrated before it leaves the factory. The manufacturer can recommend the time intervals and procedures for recalibration.

3.4 Error estimates.

As discussed in Section 2.2, the accuracy of a piece of equipment influences the error associated with the data. The error contributions from several pieces of equipment in a test setup can be estimated by performing a propagation-of-error analysis on the system, similar to that in Section 2.2.2. Not all instrument uncertainties contribute the same amount to the final error, and the accuracy of the test can often be improved by upgrading those pieces of equipment which control the error, or by improving their calibration.

3.5 System calibrations.

Because of the complex nature and possible interaction of error-producing factors in a test system, calibration of the entire system is preferred where possible to produce a more accurate error estimate. For example, calibrating an ultrasonic velocity test system by using standards of known material properties is preferable to performing a propagation-of-error analysis on individual pieces of electronic equipment.

3.6 Specific calibration procedures.

(Specific calibration procedures will be included at a later date.)

4.0 Statistical methods

4.1 Sample variability.

No two rock samples will give the same results when tested, even if cut from the same piece of core adjacent to each other, because there are differences in composition, history, and structures such as fractures and pores. The results of tests in a single suite of rocks, then, will show a range of values. When applying these results, the uncertainty due to this sample variability must be appreciated as well as the measurement error of the individual data points. To quantify the uncertainty due to sample variability, the following statistical methods are useful.

4.1.1 Average. The average, $\overline{X}$, for a group of data is calculated:

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} Xi \tag{11}$$

where:

N = number of data points

X_i = values of individual data points.

For example, modulus tests are run on a suite of basalt samples and the results are 9.85, 8.97, 9.11, 10.24, and 9.90 x 10^6 psi (6.79, 6.18, 6.28, 7.06, and 6.83 x 10^4 MPa). The average value is 9.61 x 10^6 psi (6.63 x 10^4 MPa).

4.1.2 Range. The range of the data is expressed by the lowest and highest values. Thus, the range of the data in Section 4.1.1 is 8.97 to 10.24 x 10^6 psi (6.18 to 7.06 x 10^4 MPa).

4.1.3 Standard deviation. The standard deviation, s, for a group of data is a measure of the variation of each data point from the average:

$$S = \sqrt{\frac{\sum_{i=1}^{N} (X_i - \overline{X})^2}{N - 1}} \tag{12}$$

In practice, s is more easily calculated from the algebraically equivalent form of Equation 12:

$$s^2 = \frac{\sum_{i=1}^{N} X_i^2 - \left(\sum_{i=1}^{N} X_1^2\right)^2}{N(N-1)} \tag{13}$$

The standard deviation of the data in Section 4.1.1 is 0.55 x 10^6 psi (0.38 x 10^4 MPa).

4.1.4 Uncertainty. The uncertainty of the data is an estimate of the expected values of more tests conducted on the same suite of samples. Uncertainties are evaluated with various degrees of confidence based on probability theory and on assumed distribution of the data. In most rock mechanics testing, the individual data points can deviate from the average by any value because of the complexity of the material and the test procedures. However, large deviations are relatively less frequent than smaller deviations. In this case, the data is assumed to have a normal distribution of values about the average.

The uncertainty of the test data, U, is calculated by:

$$U = t \frac{s}{\sqrt{N-1}} \tag{14}$$

where s = standard deviation
N = number of tests
t = confidence coefficients for the Student's t distribution,* from Table 4.1

For the data given in Section 4.1.1, the number of degrees of freedom (N-1) is 4. The confidence coefficient is thus 2.13 at the 95% level. Using the standard deviation calculated above, the uncertainty is 0.59 x 10^6 psi (0.41 x 10^4 MPa). The average modulus value for the sample suite may thus be written:

$$E = 9.61 \pm 0.59 \times 10^6 \text{ psi} \quad (6.63 \pm 0.41 \times 10^4 \text{ MPa})$$

This means that if more samples were tested from the same rock suite, the mean modulus values of other test groups would have a 95% probability of falling within the range of 9.02 to 10.20 x 10^6 psi (6.22 to 7.04 x 10^4 MPa).

*The Student's t distribution is similar to the standard normal distribution, approaching it as the number of tests approaches infinity.

TABLE 4.1[1]

Confidence Coefficients for Student's t Distribution

Degrees of freedom (N-1)	t, at confidence level 99%	95%	90%
1	31.82	6.31	3.08
2	6.96	2.92	1.89
3	4.54	2.35	1.64
4	3.75	2.13	1.53
5	3.36	2.02	1.48
6	3.14	1.94	1.44
7	3.00	1.90	1.42
8	2.90	1.86	1.40
9	2.82	1.83	1.38
10	2.76	1.81	1.37
11	2.72	1.80	1.36
12	2.68	1.78	1.36
13	2.65	1.77	1.35
14	2.62	1.76	1.34
15	2.60	1.75	1.34
16	2.58	1.75	1.34
17	2.57	1.74	1.33
18	2.55	1.73	1.33
19	2.54	1.73	1.33
20	2.53	1.72	1.32
21	2.52	1.72	1.32
22	2.51	1.72	1.32
23	2.50	1.71	1.32
24	2.49	1.71	1.32
25	2.48	1.71	1.32
26	2.48	1.71	1.32
27	2.47	1.70	1.31
28	2.47	1.70	1.31
29	2.46	1.70	1.31
30	2.46	1.70	1.31
40	2.42	1.68	1.30
60	2.39	1.67	1.30
120	2.36	1.66	1.29
∞ (normal distribution)	2.33	1.65	1.28

[1] Adapted from Miller, I. and Freund, J.E., 1965, Probability and Statistics for Engineers, Prentice-Hall, Inc. New Jersey, p. 399.

4.2 Group correlation.

If rock suites have been tested from several areas within a single formation, it may be of interest to determine whether differences in results are due to sampling uncertainties of a single material, or whether they represent distinct mechanical variations in the rock. To compare two groups, a confidence coefficient, t, is calculated from the statistics of the groups using:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{(N_1-1)s_1^2 + (N_2-1)s_2^2}} \sqrt{\frac{N_1 N_2 (N_1+N_2-2)}{N_1 + N_2}} \qquad (15)$$

where $\bar{X}_1$ = average value of group 1
s_1 = standard deviation of group 1
N_1 = number of tests in group 1
$\bar{X}_2$ = average value of group 2
s_2 = standard deviation of group 2
N_2 = number of tests in group 2.

The confidence level for the value of t calculated from Equation 15 is found from Table 4.1. The degrees of freedom in this case are equal to N_1+N_2-2. The confidence level is the probability that the two groups of tests are significantly different.

For example, two suites of basalt cores are tested to determine modulus of deformation. The two suites represent rock from two boreholes several hundred feet apart in the same rock formation. The following statistics are found for each group:

$\bar{X}_1 = 9.85 \times 10^6$ psi $(6.79 \times 10^4$ MPa)
$s_1 = 0.71 \times 10^6$ psi $(0.49 \times 10^4$ MPa)
$N_1 = 5$
$\bar{X}_2 = 8.66 \times 10^6$ psi $(5.97 \times 10^4$ MPa)
$s_2 = 1.20 \times 10^6$ psi $(0.83 \times 10^4$ MPa)
$N_2 = 8$

The t value calculated from Equation 15 is 1.99. For 11 degrees of freedom, the t value at the 95% confidence level is 1.81. Therefore, it is more than 95% probable that the rock suites from the two boreholes represent materials of distinctly different modulus.

4.3 Comparisons.

The uncertainty due to sample variability should be compared to the error of an individual measurement. The sample variability uncertainty should be significantly larger than the measurement error (at least 2 to 3 times) to allow comment on the test suite. For rocks, this will generally be the case. If not, the test system should be improved until the measurement error decreases sufficiently.

5.0 Quality Assurance

5.1 Purpose.

5.1.1 Conformance to standards. The Quality Assurance program is intended to ensure that the actual testing program satisfies the requirements and specifications established in these procedures. The specific tasks involved in implementing the program are discussed in Section 5.2.

5.1.2 Documentation. Documentation is a key part of the NWTS program. An effective Quality Assurance program will monitor project documentation so that the following requirements are satisfied.

5.1.2.1 Traceability. The history of each rock sample and piece of test equipment should be completely recorded. For rock samples, the history from initial recovery, logging, and storage through shipping, preparation, and testing must be available to verify the identity of the sample and allow evaluation of the test results in light of its previous history. For equipment, a history from manufacture through calibration and testing, with emphasis on repairs or modifications, should be available to aid in evaluating equipment performance.

5.1.2.2 Defendability. Test program documentation should provide a clear account of what equipment was used, how the test was performed, and how the results were derived. In this way it can be verified at a later date that the test program was conducted in accordance with recommended procedures and specifications.

5.1.2.3 Preservation. A complete set of documents on the testing program should be preserved separately from the working and reporting copies, so that no test information is lost.

5.1.2.4 Retrievability. The documentation should be organized and stored conveniently so that any piece may be easily recovered upon request.

5.2 Primary tasks.

5.2.1 Personnel prequalification. In rock mechanics laboratory testing, the primary personnel are the Test Supervisor, who

directs the overall program, inspects the testing apparatus, evaluates the measurements, and troubleshoots when necessary, and the Technicians, who prepare samples, assemble equipment, and perform the test. The Quality Assurance program should establish and verify the qualifications for each type of position. In general, the Test Supervisor should have performed the test previously, be able to reduce the data, have a good understanding of the theory and applications of the data obtained from the test, and be familiar with the equipment used. The Technicians should understand the purpose of each piece of test equipment, be able to assemble and operate the test equipment, understand in general the purpose of the data, and be thoroughly familiar with the test procedure. The Quality Assurance program can verify these qualifications by written and oral testing of candidate test personnel, by testing the candidate's ability to assemble and operate the equipment in the lab, and by evaluating the candidate's background.

5.2.2 Instrument calibration certification. The Quality Assurance program should verify that all equipment calibration and performance verification is conducted according to accepted procedures and that the standards are traceable to NBS as appropriate. Calibration certificates are generally issued identifying the piece of equipment, the calibration standard and its NBS traceability, the calibration data or results, and the time interval for which the calibration is acceptable. A complete set of calibration certificates should be maintained by Quality Assurance personnel.

5.2.3 Inspection during testing. Quality Assurance personnel should inspect the test setup prior to the start of any new type of test, and periodically thereafter, to verify that the correct equipment and procedure are being used. Deviations from standard procedure or equipment should be documented, justified, and approved by technical personnel before the test proceeds.

Procedure L-A.1

Bulk Density of Rock Samples

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines the bulk density of a rock sample at ambient temperature. The buoyancy method is used, which is suitable for both regularly and irregularly shaped samples.

1.2 General description of the test.

The sample is weighed either dry or at its natural moisture content. The sample is oven dried, then submerged in a suitable fluid and saturated. The submerged saturated mass is determined. The sample is surface dried and its saturated surface-dry mass is determined. Bulk volume and bulk density are then calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Bulk density - the mass of a unit volume of the sample. The bulk density includes the effects of all pores and fillings, alteration zones, joints, etc.

1.3.1.2 Bulk volume - the volume of the sample in its natural state, including the volume of pores, fractures, etc.

1.3.2 Equations.

1.3.2.1 Bulk volume, V_b, is calculated using:

$$V_b = \frac{M_{sat} - M_{sub}}{\rho_f} \qquad (1)$$

where:

M_{sat} = saturated surface-dry mass of the sample

M_{sub} = saturated submerged mass of the sample

ρ_f = density of the submergence fluid.

1.3.2.2 The bulk density, ρ_b, is calculated using:

$$\rho_b = \frac{M_a}{V_b} \qquad (2)$$

where: M_a = the mass of the sample, either dry or under natural conditions.

1.4 References.

1.4.1 ASTM, 1978, Test Designation C97, "Standard Test Methods for Absorption and Bulk Specific Gravity of Natural Building Stone," Annual Book of ASTM Standards, Part 19.

1.4.2 Foundation Sciences, Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI-310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.3 ISRM, Commission on Standardization of Laboratory and Field Tests, 1979, "Suggested Methods for Determining Water Content, Porosity, Density, Absorption, and Related Properties and Swelling and Slake-Durability Index Properties," Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 16, No. 2.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Fracture fillings, inclusions, or alteration zones may exhibit significantly different densities than the overall rock mass. These structures should be included in the test program to provide an estimate of their effect.

2.4 Preservation of moisture condition of samples.

If the density of the rock under natural conditions is to be determined, the moisture content of the rock core shall be preserved between the time of recovery and testing as described in Procedure GT-A.4, "Handling and Storage of Rock Core Samples," see Ref. 1.4.2.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Weighing device.

The device for measuring the mass of the sample shall have an accuracy of at least 7.0×10^{-4} oz $\pm$ (0.02 g) and a resolution of at least 3.5×10^{-4} oz (0.01 g). It shall be equipped to weigh the sample submerged.

3.2 Suspension device.

The sample is suspended in the test fluid and weighed. A simple fine-wire basket is suitable to support the sample.

3.3 Oven.

A circulating air oven shall be used to dry the sample. It shall be capable of maintaining a temperature of 221° $\pm$ 4°F (105° $\pm$ 2°C) over a period of at least 24 hours.

3.4 Submergence fluid.

For most rock types, distilled water shall be used. Should the sample contain minerals which are water soluble, change volume or otherwise deteriorate in water, an inert fluid, such as carbon tetrachloride, naphtha, toluene, etc. shall be used. The density of the fluid at the test temperature shall be known.

3.5 Vacuum equipment.

A vacuum system shall be used to saturate the sample by removing any air from the sample and its surface-connected pores. The system shall be capable of maintaining a vacuum of less than 0.1 psi for a period of at least 1 hour. A vacuum gage shall be used to monitor the pressure on the sample. The gage shall have an accuracy of at least 0.05 psi (345 Pa) and a resolution of at least 0.01 psi (69 Pa).

3.6 Temperature measurement.

The temperature of the submergence fluid shall be measured during the test. The transducer shall have an accuracay of at least $\pm$ 0.2°C (0.4°F) and a resolution of at least 0.2°F (0.1°C). An engraved stem thermometer is recommended.

4.0 Procedure

4.1 Sample dimensions.

Regularly or irregularly shaped samples may be used in this procedure. It is recommended that the surface of the sample be as smooth as possible to minimize air entrapment. The sample shall have a mass of at least 3.5 oz (100 g).

4.2 Testing.

4.2.1 Initial mass. Any loose material shall be carefully and completely removed from the sample prior to testing. The initial mass of the sample shall be determined to the nearest 3.5×10^{-4} oz (0.01 g). It is recommended that this step be performed with the sample at the natural moisture condition. If the sample is to be tested dry, its dry mass as described in Section 4.2.2 shall be the initial mass.

4.2.2 Drying. The sample shall be dried in the oven at 221° ± 4°F (105° ± 2°C) for not less than 24 hours. If the natural moisture condition is not used as the basis for the density, the mass of the sample shall be determined to the nearest 3.5×10^{-4} oz (0.01 g) after it has cooled.

4.2.3 Saturation. The sample shall be submerged in the test fluid and saturated by applying a vacuum of less than 0.1 psi for at least 1 hour. In any case, the vacuum shall continue until bubbles no longer form on the surface of the sample. The sample shall be agitated periodically to remove any trapped air. It is recommended that the sample be placed in the weighing basket prior to saturation.

4.2.4 Submergence during handling. The sample shall remain submerged at all times between saturation and measurement of submerged mass.

4.2.5 Submerged mass. The saturated submerged mass of the sample shall be determined to the nearest 3.5×10^{-4} oz (0.01 g). The basket shall be immersed to the same depth as when its tare was determined.

4.2.6 Fluid temperature. The temperature of the submergence fluid shall be determined to the nearest 0.2°F (0.1°C).

4.2.7 Surface drying. The sample shall be surface dried using a cloth moistened with the test fluid. Care shall be exercised that no portion of the sample is lost during the surface drying process.

4.2.8 Saturated mass. The saturated mass of the surface-dry sample shall be immediately determined to the nearest 3.5×10^{-4} oz (0.01 g).

4.2.9 Data recording requirements. The data shown on Form L-A.1-1 shall be recorded as a minimum for this test.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described, as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure varies from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary. A summary table of results including the test suites and average values with ranges and uncertainties shall be presented.

5.4.2 Individual results. A table of individual results including at least sample numbers, rock types and formations, bulk density, and bulk volume if appropriate, shall be presented.

5.4.3 Other. The following other types of analyses and presentations may be included as appropriate.

5.4.3.1 Bulk density compared to grain density.

5.4.3.2 Histogram of results.

5.4.3.3 Correlation with other rock properties such as porosity, strength, static properties.

5.4.3.4 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all temperature and mass determinations.

5.5.2 Sample variability. For each suite of rock samples, the mean bulk density, range, standard deviation and 95% confidence limits for the mean shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

Each completed test Form L-A.1-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, procedure, and performance verification of the equipment. After testing, the completed Form L-A.1-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-A.1-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-A.1-1.

Bulk Density of Rock Samples
Test Data Sheet - Form L-A.1-1

Project _____ Sample No. _____
Date _____ Rock Type _____
Tested By _____ Test Fluid
Test Temperature _____ Type _____
Density _____

Equipment Description	Serial No.	Date of Next Calibration

Mass of Sample, Initial _____
Mass of Sample, Saturated and Submerged _____
Mass of Sample, Saturated and Surface Dry _____

Remarks:

Test Supervisor _____ Date _____
Quality Assurance _____ Date _____
Project Engineer _____ Date _____

Procedure L-A.2

Grain Density of Rock Samples

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines the density of the solid portion of a rock sample by the pycnometric method.

1.2 General description of the test.

The sample is powdered and passed through a sieve. It is placed in the pycnometer and dried to a constant mass. The sample mass is determined. Fluid is added to the pycnometer. Trapped air is removed from the sample either by heating or by a vacuum system. The total mass of the fluid, sample, and pycnometer is determined. Grain density is then calculated.

1.3 Data Reduction.

1.3.1 Terms and definitions.

1.3.1.1 Grain density - the mass of a unit volume of the solid portion of a rock. Voids, fractures, and other discontinuities in the intact structure of the rock are not accounted for.

1.3.1.2 Pycnometer - a flask of 0.68 to 3.4 fl oz (20 to 100 cc) capacity with a narrow scribed neck and stopper. Its design allows an accurate volume of fluid to be reproducibly placed in the flask.

1.3.2 Equations.

1.3.2.1 Grain density, ρ_g, is calculated using:

$$\rho_g = \frac{m_s \rho_f}{\rho_f V_{fs} + m_s - m_{sf}} \qquad (1)$$

where:

m_s = mass of the grains in the sample

m_{sf} = mass of the sample and fluid

ρ_f = density of fluid

V_{fs} = volume of fluid and sample (volume of pycnometer).

1.3.2.2 The mass of the sample and test fluid, m_{sf}, is calculated as:

$$m_{sf} = m_t - m_p \qquad (2)$$

where:

m_t = total mass of pycnometer, sample, and fluid

m_p = mass of pycnometer.

1.4 References.

1.4.1 ISRM Commission on Standardization of Laboratory and Field Tests, 1979, "Suggested Methods for Determining Water Content, Porosity, Density, Absorption, and Related Properties and Swelling and Slake-Durability Index Properties," Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 16, No. 2.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Fracture fillings, inclusions, etc. may exhibit significantly different grain densities than the parent rock mass. Filling materials and intact rock should be tested separately as well as in their natural proportions.

2.4 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Sieve.

A 0.0098-in. (0.250-mm) mesh sieve (No. 60) shall be available.

3.2 Weighing device.

The weighing device shall have an accuracy of at least 7.0×10^{-4} oz ($\pm$ 0.02 g) and a resolution of at least 3.5×10^{-4} oz (0.01 g).

3.3 Pycnometer.

The pycnometer shall have a capacity of 0.68 to 3.4 fl oz (20 to 100 cc).

3.4 Oven.

A circulating air oven capable of maintaining a temperature of 221° $\pm$ 4°F (105° $\pm$ 2°C) for a period of 24 hours shall be available.

3.5 Test fluid.

For most rock types distilled water shall be used. Should the sample contain minerals which are water soluble or which change volume or otherwise deteriorate in water, an inert fluid, such as carbon tetrachloride, naphtha, toluene, etc. shall be used. The fluid shall have good wetting properties. The density of the fluid at the test temperature shall be known.

3.6 Vacuum system.

A vacuum system may be used to de-air the sample and test fluid. It shall be capable of maintaining a vacuum of at least 0.1 psi (689 Pa) for a period of at least 1 hour. A vacuum gage shall be used to monitor the pressure in the sample. The gage shall have an accuracy of at least $\pm$ 0.05 psi (345 Pa) and a resolution of at least 0.01 psi (69 Pa).

3.7 Temperature measurement.

The temperature of the submergence fluid shall be measured during the test. The transducer shall have an accuracy of at least $\pm$ 0.4°F ($\pm$ 0.2°C) and a resolution of at least 0.2°F (0.1°C). An engraved stem thermometer is recommended.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Cleanliness. The sample shall be free from impurities such as wrapping materials, soil, drilling mud, etc.

4.1.2 Grinding. The sample shall be ground to a fine powder using a clean grinding device. The grinding surface shall not contaminate the sample during the grinding process.

4.1.3 Sieving. The ground sample shall be passed through the No. 60 mesh (0.250-mm; 0.0098 in.) sieve. Only the portion of the sample passing through the sieve shall be used for the test.

4.1.4 Size. The amount of sample tested shall be sufficient to fill about 20% of the volume of the pycnometer. For a 1.7-fl oz (50-cc) pycnometer, 0.7 to 0.88 oz (20 to 25 g) of sample is recommended.

4.2 Testing.

4.2.1 Pycnometer calibration. The pycnometer shall be cleaned, dried and weighed to the nearest 3.5×10^{-4} oz (0.01 g). It shall be filled to the designated mark with de-aired, distilled water. The full pycnometer shall be weighed to the nearest 3.5×10^{-4} oz (0.01 g) and the temperature of the water measured to the nearest 0.2°F (0.1°C). The volume of the pycnometer shall then be calculated. The volume shall be determined at least three times and the average value used.

4.2.2 Sample drying. The sample shall be placed in the pycnometer and dried in the oven at 221°F $\pm$ 4°F (105° $\pm$ 2°C) for at least 24 hours.

4.2.3 Dry mass. The mass of the dry sample and pycnometer shall be determined to the nearest 3.5×10^{-4} oz (0.01 g).

4.2.4 De-airing. The pycnometer containing the dry sample shall be filled to between 1/3 and 1/2 its volume with the test fluid and de-aired. It is recommended that the system be de-aired by applying a vacuum of at least 0.1 psi (689 Pa) for at least an hour, with periodic agitation to remove trapped air. Alternatively, the system may be heated to force the air out. The allowable temperature depends on the type of fluid, but shall be low enough to avoid excessive evaporation. Periodic agitation is again recommended.

4.2.5 Saturated mass. Test fluid shall be added to fill the pycnometer to the designated mark. The pycnometer containing sample and fluid shall be weighed to the nearest 3.5×10^{-4} oz (0.01 g).

4.2.6 Temperature. The temperature of the test fluid shall be measured to the nearest 0.2°F (0.1°C).

4.2.7 Data recording requirements. The data shown on Form L-A.2-1 shall be recorded, as a minimum.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material testes.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and type of sample tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. Rock type, structure, fabric, grain size, discontinuities, voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications shall be listed for each major piece.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations and any limitations in their applications shall be noted, and their effects on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary table. A table of results including the test suite identification and average grain density values, with ranges and uncertainties, shall be presented.

5.4.2 Individual results. A table of individual results including, as a minimum, sample numbers, rock types and formations, and grain densities, shall be presented.

5.4.3 Other. The following other types of analyses and presentations may be included as appropriate.

5.4.3.1 Grain density compared to bulk density.

5.4.3.2 Calculated total porosity.

5.4.3.3 Grain density compared to apparent and total porosity.

5.4.3.4 Histogram of results.

5.4.3.5 Correlation with other rock properties such as permeability and strength.

5.4.3.6 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all temperature and mass determinations.

5.5.2 Sample variability. For each suite of rock samples, the mean grain density, the range, standard deviation and 95% confidence limits for the mean should be calculated, as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed differences between groups are significant at the 95% confidence level.

5.6 Appended data.

Each completed test Form L-A.2-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test where Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the test procedure, and the equipment performance verification. After testing, the completed Form L-A.2-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-A.2-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-A.2-1.

Grain Density of Rock Samples

Test Data Sheet - Form L-A.2-1

Project_____ Sample No._____

Date_____ Rock Type_____

Tested By_____ Test Fluid

Test Temperature_____ Type_____

Density_____

Equipment Description	Serial No.	Date of Next Calibration

Pycnometer Mass_____

Pycnometer Volume_____

Mass of Pycnometer and Sample (Dry)_____

Mass of Pycnometer, Sample, and Fluid_____

Remarks:

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Engineer_____ Date_____

Procedure L-A.3

Composition of Rock Samples by Petrographic Analysis

1.0 Background

1.1 Scope.

1.1.1 Objective of this analysis. The primary purpose of petrographic analysis using a polarizing microscope is to identify the component phases of a rock and determine the relative percentage of each phase. The petrographic analysis will also provide a basic chemical classification of a rock sample and, when used in conjunction with the grain size and fabric analyses (Procedures L-A.4 "Grain Size of Rock Samples by Petrographic Analysis" and L-A.5 "Texture and Fabric of Rock Samples by Petrographic Analysis"), will provide information on the history of the rock's formation and subsequent alteration or deformation.

1.1.2 Limitations.

1.1.2.1 A petrographic examination does not yield a complete chemical analysis of a rock sample. It does allow identification of the mineral phases and other phases such as mineraloids, elements, and glasses.

While the general composition of a mineral is fixed, ionic substitution causes the detailed composition to be highly variable. Bulk chemical analysis, x-ray flourescence, or other techniques of quantitative analysis are required for exact chemical analysis. Similarly, specific identification of a sample's mineral phases may require x-ray diffraction, microprobe or other analysis.

1.1.2.2 Petrographic examination provides only limited data on extremely fine-grained or cryptocrystalline minerals, such as glass, clays or opal. Opaque minerals, such as metallic sulfides and oxides, require special techniques involving reflected light. These components may be identified and quantified only in the most general way using a polarizing microscope.

1.1.2.3 Petrographic examination of extremely coarse-grained material which is mineralogically variable (e.g., breccia, conglomerate) is not practical. These rock samples may be identified by examination with a stereoscopic binocular microscope.

1.2 General description of the test.

Thin sections of rock samples are identified using a polarizing microscope. The component minerals are identified by their optical properties such as 2V, extinction angle, dispersion, etc. The relative amounts of each mineral are determined by counting the number of mineral grains within a given area of the sample.

1.3 Terms and definitions.

1.3.1 Phases - generally minerals, but can include mineraloids, such as a chert; elements such as copper or diamond; or glasses such as tachylite.

1.3.2. Thin section - a slice of mineral, rock or any other crystalline material ground down to a standard thickness of about 30 microns, for microscopic examination.

1.3.3 Polarizing microscope - a microscope which has an analyzer located above the stage and a polarizer below the stage (Bloss, 1966, Figure 4-1, p. 29).

1.3.4 Relief - appearance or visibility of outline and surface of a mineral. Relief is dependent on the difference between the index of refraction (N) of the mineral and the mounting medium. Minerals with indices of refraction differing considerably from that of the medium have high relief, while those with N values near that of the medium have low relief.

1.3.5 Color - the color of the mineral in the thin section in plane-polarized light.

1.3.6 Pleochroism - a change in the color of a mineral as the stage is rotated in plane-polarized light.

1.3.7 Isotropic - minerals through which light travels with the same speed regardless of its direction of vibration; includes isometric crystals and glass.

1.3.8 Anisotropic - minerals through which a light ray may travel at different speeds for different directions of vibration.

1.3.9 Birefringence - the refractive index of an anisotroic medium for the slow ray minus the refractive index for the fast ray; double refraction.

1.3.10 Interference colors - colors displayed by a birefringent crystal under crossed nichols.

1.3.11 Optic axes - those directions in anisotropic minerals along which there is no double refraction.

1.3.12 Uniaxial - minerals with one optic axis, coinciding with the c-axis of the crystal, as with tetragonal and hexagonal minerals.

1.3.13 Biaxial - minerals with two optic axes, found in the orthorhombic, monoclinic, and triclinic systems.

1.3.14 Optic angle (2V) - the angle between the two optic axes of a biaxial crystal.

1.4 Suggested references.

1.4.1 Allman, M. and Lawrence, D.F., 1972, Geological Laboratory Techniques, Blanford Press, London.

1.4.2 ASTM, 1975, Test Designation C295-65, "Standard Recommended Practice for Petrographic Examination of Aggregate for Concrete," Annual Book of ASTM Standards, Part 14.

1.4.3 ASTM, 1975, Test Designation C294-69, "Standard Descriptive Nomenclature of Constituents of Natural Mineral Aggregates," Annual Book of ASTM Standards, Part 14.

1.4.4 Bloss, F.D., 1966, An Introduction to the Methods of Optical Crystallography, Holt, Rinehart and Winston, New York, New York.

1.4.5 Dana, E.S., and Ford, W.E., 1964, Dana's Textbook of Mineralogy, 4th ed., John Wiley and Sons, New York, New York.

1.4.6 Deer, W.A., Howie, R.A., and Zussman, J., 1975, An Introduction to Rock Forming Minerals, 8th Impression, Longman Group Limited, London.

1.4.7 Durrell, C., 1949, A Key to the Common Rock-Forming Minerals in Thin Section, W.H. Freeman and Co., San Francisco, California.

1.4.8 Heinrich, E.W., 1965, Microscopic Identification of Minerals, McGraw-Hill, New York, New York.

1.4.9 ISRM Commission on Standardization of Laboratory and Field Tests on Rock, 1978, "Suggested Methods for Petrographic Description of Rocks," Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 15, No. 2.

1.4.10 Kerr, P.F., 1959, Optical Mineralogy, McGraw-Hill, New York, New York.

1.4.11 Phillips, W.R., 1971, Mineral Optics Principles and Techniques, W.H. Freeman and Co., San Francisco, California.

1.4.12 Slemmons, D.B., 1962, "Determination of Volcanic and Plutonic Plagioclase Using a Three- or Four-Axis Universal Stage," G.S.A. Special Paper, No. 69, New York, New York.

1.4.13 Troger, W.E., 1959, Optische Bestimmung der Gesteinsbildenden Minerale, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, W. Germany.

1.4.14 U.S. Army Corps of Engineers, 1980, Procedure RTH 102-80, "Recommended Practice for Petrographic Examination of Rock Cores," Rock Testing Handbook, Geotechnical Laboratory, Waterways Experiment Station, Vicksburg, Mississippi.

2.0 Prerequisites

2.1 Personnel prequalification.

An accurate petrographic analysis relies heavily on the knowledge, ability, and experience of the petrographer. All personnel involved in performing the analysis, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and type of rock samples analyzed depends partly on the ultimate application of the results of the analysis. For example, an initial site characterization might require several samples from a variety of formations, while a detailed geochemical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples analyzed should be sufficient to provide an adequate statistical basis for evaluation of the results.

2.3.2.1 Each rock formation should be characterized. Representative samples should be taken from each rock formation at the site, consistent with the scope of the project.

2.3.2.2 Variations of material within a single formation should be analyzed, consistent with the scope of the project. An adequate number of samples should be chosen to represent each mineralogical and/or structural relationship (e.g., in fine-grained igneous rocks the presence of opal, glass, and clay).

2.3.2.3 In anisotropic materials, thin sections should be cut from three mutually perpendicular directions within the same sample, oriented with respect to fabric, bedding, or cleavage.

2.4 Documentation.

Each sample shall be documented according to standard Quality Assurance procedures.

2.5 Sample preparation.

High-quality thin sections shall be prepared according to procedures discussed in Allman and Lawrence (1972).

3.0 Equipment

3.1 Polarizing microscope and accessories.

The polarizing microscope includes the microscope body, objectives, oculars, analyzer, polarizer and rotary specimen stage. The microscope shall be capable of several levels of magnification between 5X and 1,000X.

The microscope shall be assembled to manufacturer's specifications. The analyzer, polarizer, objectives, and stage shall be centered according to standard Quality Assurance procedures.

3.1.1 Oculars. Several oculars shall be available, including a cross-hair ocular and a micrometer scale ocular. Magnification ranges from 2X to 25X shall be available.

3.1.2 Objectives. At least three objectives able to produce low (4X), medium (10X to 20X) and high (40X to 100X) initial magnifications shall be available. A numerical aperture of 0.85 is necessary to use the standard determination tables in most reference manuals.

3.1.3 Bertrand lens. A Bertrand lens shall be available on the microscope. When inserted into the optic path, this lens is used to observe interference figures.

3.1.4 Condenser. Condensers supply a cone of light necessary to give maximum illumination. Two condensers shall be available; one with a numerical aperture equal to the medium-power objective and one with a numerical aperture equal to that of the high-power objective. (Some microscopes have a condenser which slides up or down to change its numerical aperture.)

3.1.5 Accessory plates. Full- and quarter-wave compensators and a quartz wedge are required for mineral identification.

3.2 Mechanical stage.

A mechanical stage shall be provided to permit the microscope slide to be moved smoothly in mutually perpendicular directions on the rotating stage. The movement shall be measured in both directions to an accuracy of at least $\pm$ 0.004 in. ($\pm$ 0.1 mm). The stage shall be capable of advancing the thin section in accurate, equal increments for point counting.

3.3 Monochrometer.

A monochrometer shall be available. A monochromatic source, such as a sodium arc light, is preferable; however, a standard tungsten light with filters may be used.

3.4 Camera and accessories.

A camera with the accessories necessary to produce photomicrographs for documentation shall be available.

4.0 Procedure

4.1 Mineral identification.

Minerals shall be described and identified, and notes shall be taken during the examination as indicated on Form L-A.3-1. Relevant properties for mineral identification include the following:

4.1.1 Opaque phases.

4.1.1.1 Color with reflected light

4.1.1.2 Habit

4.1.2 Transparent or translucent phases.

4.1.2.1 Color, pleochroism, and birefringence.

4.1.2.2 Relief and habit, including cleavage, twinning, and shape.

4.1.2.3 Appropriate optical properties including optic group, 2Vz, extinction angle, dispersion, index of refraction (Nxyz).

4.2 Relative percentages.

The relative (modal) percentages of constituent minerals shall be determined by point counting. The number of points to be counted depends on the number of phases, the grain sizes and distributions, and the frequency of occurrence. A minimum of 300 points should be counted.

4.3 Structures.

Rock structure shall be described as indicated on Form L-A.3-1, to aid in recognizing the properties that may be expected to influence the behavior of the material.

4.3.1 Primary structures. Jointing, voids, brecciation, cooling features, pseudomorphs, and discontinuities, as well as rate and order of crystallization, and reaction between phases.

4.3.2 Groundmass features. Percentage of glass, crystal size and form, voids.

4.3.3 Secondary features. Devitrification, microfractures, fracture filling, presence of amygdules.

4.3.4 Xenoliths. Mineralogy, xenolith-host reactions, size and percentage of xenoliths within the sample.

4.4 Weathering and alteration.
The degree of weathering and alteration shall be examined and described in detail.

5.0 Reporting

The results of a petrographic analysis for engineering purposes should be presented in a concise, objective, and usable format. The purpose of this section is to establish the minimum requirements for a complete

and usable report. Further details may be added as appropriate, and order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.
The introductory section of the report is intended to present the purpose and scope of the analysis, and the general characteristics of the material examined.

5.1.1 Scope of analysis.

5.1.1.1 Number of samples analyzed. In a large report covering the analysis of several rock types, the number of samples is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples analyzed shall be clearly stated.

5.1.1.3 Limitations of the program. The areas of interest which are not covered by the analysis program, and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief macroscopic description of the samples. The general rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Results.

5.2.1 Tabular presentation of composition. A tabular presentation of the phases present in the samples shall be included.

5.2.2 Rock identification. A discussion of rock samples, with a brief statement concerning the physical and chemical properties of each sample, shall be included.

5.2.3 Brief crystallization history. The crystallization history of igneous and metamorphic rocks should be included if it is relevant to the scope of the project. Crystallization history yields data on pressure-temperature conditions of rock formation which in turn yield data on stability in present environment.

5.2.4 Alteration products. A description of alteration products should be included, accompanied by a discussion of the observed changes and the processes that produced them.

5.3 Graphic presentations.

A map of sample locations, phase diagrams, cross sections, drawings of unusual or key mineral textures, or other graphics shall be included when appropriate.

5.4 Recommendations.

Recommendations for further chemical or mineralogical analysis may be included.

5.5 Appended data.

5.5.1 Example thin section photographs or drawings. Representative photomicrographs or drawings shall be included either separately or as part of the petrographic analysis forms.

5.5.2 Petrographic analysis forms. A clean copy of each petrographic analysis Form L-A.3-1 shall be included.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test where Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the test procedure, and the equipment performance verification. After testing, the completed Form L-A.3-1 shall be reviewed and signed-off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-A.3-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-A.3-1.

Composition of Rock Samples by Petrographic Analysis
Form L-A.3-1

Project_____
Sample Location_____
Sample Coordinates_____
Sample No._____
Thin Section No._____
Microscope Serial No._____
Rock Type_____
Field Classification_____
Petrographic Classification_____

Petrographer_____ Date_____
Quality Assurance_____ Date_____
Project Engineer_____ Date_____

Macroscopic Description
Degree of Weathering:
Texture (Crystallinity, Granularity, Fabric):
Discontinuities:
Major Minerals and Percentages:

Microscopic Description
Rock Structure - Primary Structures:

Ground Mass Features:

Secondary Features:

Xenoliths:

Alteration and Weathering:

Mineral Identification

Major Constituents	Habit	Color Pleochroism	Cleav-age	Relief (H,M,L + or -)	Optic Group (I,U,B)	+ or -	Biref.	2V and Dispersion	Other Observations	Relative Percentage
Minor Constituents										
Accessory Constituents										

Procedure L-A.4

Grain Size of Rock Samples by Petrographic Analysis

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. The primary objective of this test is to determine the grain size and the size distribution of the phases within a rock sample.

1.1.2 Limitations.

1.1.2.1 This procedure should not be applied to unconsolidated materials such as sediments or some volcanic materials. These samples should be disaggregated and sieved for a more accurate analysis (ASTM, 422). Hydrometer and grain mount analyses are applicable to the subsieve sizes (ASTM E-20, C-295).

1.1.2.2 Petrographic analysis is not suitable for extremely fine-grained or coarse-grained rocks. The lower limit is imposed by the resolving power of the microscope. The upper limit is imposed by the size of a thin section.

1.2 General description of the test.

Thin sections of each rock sample are examined using a polarizing microscope and micrometer scale. A graduated eyepiece or photomicrograph is used to determine grain size. The distribution of sizes is tabulated with a point counter.

1.3 Terms and definitions.

1.3.1 Phases - generally minerals, but can include mineraloids, such as chert; elements such as copper or diamond; or glasses, such as tachylite.

1.3.2 Thin section - a slice of mineral, rock or any other crystalline material ground down to a standard thickness of about 1.2×10^{-3} in. (30 microns), for microscopic examination.

1.4 References.

1.4.1 Allman, M. and Lawrence, D.F., 1972, Geological Laboratory Techniques, Blanford Press, London.

1.4.2 ASTM, 1975, Test Designation C294-69, "Standard Descriptive Nomenclature of Constituents of Natural Mineral Aggregates", Annual Book of ASTM Standards, Part 14.

1.4.3 ASTM, 1975, Test Designation C295-65, "Standard Recommended Practice for Petrographic Examination of Aggregate for Concrete", Annual Book of ASTM Standards, Part 14.

1.4.4 ASTM, 1964, Test Designation E20-62, "Recommended Practices for Analysis by Microscopical Methods for Particle Size Distribution of Particulate Substances of Subsieve Size", Annual Book of ASTM Standard, Part 30.

1.4.5 ISRM Commission on Standardization of Laboratory and Field Tests on Rock, 1978, "Suggested Methods for Petrographic Description of Rocks", Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 15, 2.

1.4.6 U.S. Army Corps of Engineers, 1980, Procedure RTH 102-80, "Recommended Practice for Petrographic Examination of Rock Cores", Rock Testing Handbook, Geotechnical Laboratory, Waterways Experiment Station, Vicksburg, Mississippi.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and type of rock cores tested dpend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirement. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results.

2.3.2.1 Each rock formation should be characterized. Representative samples should be taken from each rock formation at the site, consistent with the scope of the project.

2.3.2.2. Variations of material within a single formation should be analyzed, consistent with the scope of the project. An adequate number of samples should be chosen to represent each mineralogical and/or structural relationship (e.g., in fine-grained igneous rocks the presence of opal, glass, and clay).

2.3.2.3 In anisotropic materials, thin sections should be cut from three mutually perpendicular directions within the same sample, oriented with respect to fabric, bedding, or cleavage.

2.4 Documentation.

Each sample shall be documented according to standard Quality Assurance procedures.

2.5 Thin section prepared.

High-quality thin sections shall be prepared according to procedures described in Allman and Lawrence (1972).

2.6 Mineralogical composition determined.

Composition of the samples shall be predetermined as described in Procedure L-A.3, "Composition of Rock Samples by Petrographic Analysis."

3.0 Equipment

3.1 Polarizing microscope and accessories.

The polarizing microscope includes the microscope body, objectives, oculars, analyzer, polarizer and rotary specimen stage. The microscope shall be capable of several levels of magnification between 5X and 1,000X. The microscope shall be assembled to manufacturer's specifications. The analyzer, polarizer, objectives, and stage shall be centered according to standard Quality Assurance procedures.

3.1.1 Graduated oculars. For grain size analysis, a calibrated micrometer eyepiece with either graduated cross lines or a net micrometer shall be available in a selection of grid sizes. Several oculars shall be available ranging in power from 2X to 25X.

3.1.2 Objectives. At least three objectives shall be available capable of low (4X), medium (10X to 20X), and high (40X to 100X) initial magnifications. A numerical aperture of 0.85 is necessary to use the standard determination tables in most reference manuals.

3.1.3 Bertrand lens. A Bertrand lens shall be available on the microscope. When inserted into the optic path, this lens is used to observe interference figures.

3.1.4 Condenser. Condensers supply a cone of light necessary to give maximum illumination. Two condensers shall be available; one with a numerical aperture equal to the medium power objective and one with a numerical aperture equal to that of the high power objective. (Some microscopes have a condenser which slides up or down to change its numerical aperture.)

3.1.5 Accessory plates. Full- and quarter-wave compensators and a quartz wedge are required for mineral identification.

3.2 Stage micrometer.

A stage micrometer with a photographic scale is required for use with the graduated eyepiece.

3.3 Mechanical stage.

A mechanical stage shall be provided to permit the microscope slide to be moved in mutually perpendicular directions on the rotating stage. The movement shall be measured in both directions to an accuracy of at least 0.004 in. (0.1 mm). The stage shall be capable of advancing the section in accurate, equal increments for point counting.

3.4 Point counter.

A point counter shall be provided. One that attaches to the mechanical stage is recommended.

3.5 Monochrometer.

A monochrometer shall be available. A monochromatic light source, such as a sodium arc light, is preferable; however, a standard tungsten light with filters may be used.

3.6 Camera and accessories.

A camera with the accessories necessary to produce photomicrographs shall be available.

3.6 Grid cover sheet.

A clear, graduated overlay shall be available for grain size measurements from photomicrographs.

4.0 Procedure

4.1 Ocular calibration.

To calibrate the field of view of the eyepiece, the stage micrometer or grid of exact dimensions shall be examined at intervals during the counting procedure, and whenever the process is restarted after stopping.

4.2 Observation technique.

Since the petrographer's eyesight and the distance from the ocular will affect the field of view, this procedure shall be

accomplished without eye-glasses (if possible), and using a hard rubber eyepiece attachment to minimize variations in distance.

4.3 Grain size measurements.

4.3.1 Direct method. Grain size may be measured directly through the petrographic microscope using the graduated ocular.

4.3.2 Photographic method. Grain size may be measured from a photomicrograph or projection of the thin section. The photographic scale shall be accurately known to be within 2% of the field of view.

4.3.3 General.

4.3.3.1 The grain size shall be taken as the longest dimension of the grain.

4.3.3.2 Grain sizes shall be tabulated in regular size intervals, e.g. less than 0.02 in., 0.02 to 0.04 in., 0.04 to 0.06 in., etc., (less than 0.5 mm, 0.5 to 1.0 mm, 1.0 to 1.5 mm, etc.) The intervals shall be appropriate to the type of rock, to allow a size distribution curve to be drawn for the whole rock. The grain sizes tabulated shall be taken without regard for the composition of the grains, to give a whole rock grain size. The area sampled depends on the size and distribution of grains; in general, a square area with each dimension being 10 times the size of the largest grain shall be used. A tabulating device similar to that used in point counting is recommended.

4.4 Data recording requirements.

Data shall be recorded as shown on Form L-A.4-1.

5.0 Reporting

The results of a petrographic analysis for engineering purposes should be concise and objective. The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of this report.

The introductory section is intended to present the purpose and scope of the analysis and the general characteristics of the material tested.

5.1.1 Scope of analysis.

5.1.1.1 Number of samples analyzed. In a large report, covering the analysis of several rock types, the number of samples is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples analyzed shall be clearly stated.

5.1.1.3 Limitations of the program. The areas of interest which are not covered by the analysis program, and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief macroscopic description of the samples. The general rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described macroscopically, as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material, or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Results.

5.2.1 Summary tables of phases. A table including, as a minimum, the major phases in the sample and the range of grain sizes of each phase shall be presented.

5.2.2 Summary table of whole rock. A summary table including as a minimum, the interval sizes and relative percentage of grains in each interval for the whole rock shall be presented.

5.2.3 Graphic presentation. A histogram of the whole rock grain sizes shall be presented.

5.2.4 Other. Other analyses, such as correlation of grain size with mechanical properties, or the genetic history of the rock as indicated by the grain size, may be included as appropriate.

5.3 Error estimate.

The uncertainty of each interval shall be calculated and presented. Grain size may be treated by determining confidence limits for the proportion in each interval. The uncertainty, μ, is calculated using:

$$\mu = \pm Z_c \sqrt{\frac{P(1-P)}{N}} \qquad (1)$$

where:

Z_c = confidence coefficient for the desired confidence level, equal to 1.96 at 95%
P = proportion of grains in each interval
N = total number of grains counted.

For example, the following grain sizes are counted:

Interval	Number of Grains
0 to 0.04 in. (0-1 mm)	5
0.04 to 0.08 in. (1-2 mm)	9
0.08 to 0.12 in. (2-3 mm)	7

The total number of grains counted, N, is 21. The proportions in the three intervals are 0.24, 0.43, and 0.33, respectively. Substituting these values in Equation 1, the uncertainties for the three intervals are $\pm$ 0.18, $\pm$ 0.21, $\pm$ 0.20, respectively. As a relative percentage, the data may be expressed:

Interval	Relative Percentage
0 to 0.04 in. (0-1 mm)	24 $\pm$ 18%
0.04 to 0.08 in. (1-2 mm)	43 $\pm$ 21%
0.08 to 0.12 in. (2-3 mm)	33 $\pm$ 20%

The uncertainties are the percentage within which it is 95% confident that the measured frequency represents the true frequency for the whole rock. Clearly more grains need to be counted than in this simple example.

5.4 Appended data.

5.4.1 Photomicrographs. Typical photomicrographs shall be included as required as examples of the major rock types.

5.4.2 Grain size forms. Completed Forms L-A.4-1 shall be included for each sample.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, procedure, and equipment performance verification. After testing, the completed Form L-A.4-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-A.4-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-A.4-1.

Grain Size of Rock Samples by Petrographic Analysis

Form L-A.4-1

Project _____

Sample Location _____

Sample Coordinates _____

Sample No. _____

Thin Section No. _____

Microscope Serial No. _____

Rock Type _____

Field Classification _____

Petrographic Classification

(from Form L-A.3-1) _____

Granularity _____

Photomicrograph with scale

Phase	Max. Size	Min. Size	Average Size	Other Information

Complete Thin Section

Grain Size Intervals	Number	Percentage

Petrographer _____ Date _____

Quality Assurance _____ Date _____

Project Engineer _____ Date _____

Procedure L-A.5

Texture and Fabric of Rock Samples by Petrographic Analysis

1.0 Background

1.1. Scope.

1.1.1 Objective of the test. The objective of this analysis is to examine the crystallinity and granularity of constituents of a rock sample, and the geometrical relationships between them, using a polarizing microscope. The textural features are necessary to evaluate the history of a rock sample and identify relationships which may influence the mechanical behavior of the material.

1.1.2 Limitations.

1.2.1.1 The results of this analysis do not yield an analysis of the fabric in three dimensions, but rather describe the geometry of grain relationships. A universal stage and Schmidt net are necessary for a complete spatial analysis (e.g., Bureau of Mines, 1974, Slemmons, 1962).

1.1.2.2 Petrographic analysis is not suitable for extremely fine-grained (e.g., clay) or extremely coarse-grained (e.g., pegmatite, breccia) rocks. A stereoscopic binocular microscope may be necessary for these types of materials.

1.1.2.3 If a rock contains only a minor percentage of a texturally significant accessory mineral, a thin section may not contain grains of this constitutent.

1.2 General description of the test.

Thin sections are examined using a polarizing microscope. The texture and fabric are identified and each sample is classified using the accepted textural terminology for the rock type encountered.

1.3 Terms and definitions.

1.3.1 Texture - the degree of crystallinity, grain size and fabric of a rock.

1.3.2 Fabric - the shapes of, and relationships between, the constituents of a rock.

1.3.3 Igneous rock - a rock solidified from molten or partly molten material.

1.3.4 Pyroclastic materials - fragmental products of volcanoes formed by explosion or ejection.

1.3.5 Metamorphic rock - any rock derived from pre-existing rocks by mineralogical, chemical, and structural changes. These are essentially solid state changes in response to changes in temperature, pressure, and chemical environment. Changes caused by weathering and cementation are not considered metamorphism.

1.3.6 Sedimentary rock - a rock resulting from the consolidation of loose sediment (clastic rock), consisting of mechanically formed fragments of older rocks transported from a source area and deposited; or a rock formed by chemical precipitation from solution; or an organic rock consisting of remains or secretions of plants and/or animals.

1.3.7 Cataclastic - sedimentary, igneous, or metamorphic rocks produced by shearing, mechanical crushing, and differential movement of component grains.

1.3.8 Specific terms - for definition of individual textural terms, see Appendix L-A.5-A, Glossary of Textural Terms.

1.4 References.

1.4.1 Allman, M., and Lawrence, D.F., 1972, Geological Laboratory Techniques, Blanford Press, London.

1.4.2 ASTM, 1975, Test Designation C294-69, "Standard Descriptive Nomencluatre of Constituents of Natural Mineral Aggregates, "Annual Book of ASTM Standards, Part 14.

1.4.3 ASTM, 1975, Test Designation C295-65, "Standard Recommended Practice for Petrographic Examination of Aggregate for Concrete," Annual Book of ASTM Standards, Part 14.

1.4.4 Bates, R.L., and Jackson, J.A., eds., 1980, Glossary of Geology: 2nd ed., American Geological Institute, Falls Church, Virginia.

1.4.5 ISRM Commission on Standardization of Laboratory and Field Tests on Rock, , "Suggested Methods for Petrographic Description of Rocks," Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 15, No. 2.

1.4.6 Johannsen, A., 1939, Descriptive Petrography of Igneous Rocks, 1, 2nd ed., University of Chicago Press, Chicago, Illinois.

1.4.7 Nockolds, S.R., Knox, R.W., Chinner, G.A., 1978, Petrology for Students, Cambridge University Press, Cambridge, England.

1.4.8 Pettijohn, F.J., 1949, Sedimentary Rocks, 2nd ed., Harper & Brothers, New York, New York.

1.4.9 Slemmons, D.B., 1962, "Determination of Volcanic and Plutonic Plagioclase Using a Three- or Four-axis Universal Stage", G.S.A. Special Paper, No. 69.

1.4.10 Turner, F.J., and Verhoogen, J., 1960, Igneous and Metamorphic Petrology, 2nd ed., McGraw-Hill, New York, New York.

1.4.11 U.S. Army Corps of Engineers, 1980, P rocedure RTH 102-80, "Recommended Practice for Petrographic Examination of Rock Cores", Rock Testing Handbook, Geotechnical Laboratory, Waterways Experiment Station, Vicksburg, Mississippi.

1.4.12 U.S. Bureau of Mines, 1974, Bureau of Mines Test Procedures for Rocks, Information Circular 8628.

1.4.13 Williams, H., Turner, F.J., and Gilbert, C.M., 1954, Petrography, W.H. Freeman and Company, San Francisco, California.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigtion of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results.

2.3.2.1 Each rock formation shall be characterized. Representative samples should be taken from each rock formation at the site, consistent with the scope of the project.

2.3.2.2 Variations of material within a single formation should be analyzed, consistent with the scope of the project. An adequate number of samples should be chosen to represent each mineralogical and/or structural relationship (e.g., in fine-grained igneous rocks the presence of opal, glass, and clay).

2.3.2.3 In anisotropic materials, thin sections should be cut from three mutually perpendicular directions within the same sample, oriented with respect to fabric, bedding or cleavage.

2.4 Documentation.

Each sample shall be documented according to standard Quality Assurance procedures.

2.5 Thin section preparation.

High-quality thin sections shall be prepared according to procedures described in Allman and Lawrence (1972).

2.6 Composition determination.

The mineralogical composition of each sample shall have been determined using Procedure L-A.3, "Composition of Rock Samples by Petrographic Analysis"

3.0 Equipment

3.1 Polarizing microscope and accessories.

The polarizing microscope includes the microscope body, objectives, oculars, analyzer, polarizer and rotary specimen stage. The microscope shall be capable of several levels of magnification between 5X and 1,000X. The microscope shall be assembled to manufacturer's specification. The analyzer, polarizer, objectives, and stage shall be centered according to standard Quality Assurance procedures.

3.1.1 Oculars. Several oculars shall be available, including a cross hair ocular and micrometer scale ocular.

3.1.2 Objectives. At least three objectives shall be available with low (4X), medium (10X to 20X) and high (40X to 100X) initial magnifications. A numerical aperture of 0.85 is necessary to use the standard determination tables in most reference manuals.

3.1.3 Bertrand lens. A Bertrand lens shall be available on the microscope. When inserted into the optic path, this lens is used to observe interference figures.

3.1.4 Condenser. Condensers supply a cone of light to give maximum illumination. Two condensers shall be available; one with a numerical aperture equal to the medium-power objective and one with a numerical aperture equal to that of the high-power objective. (Some microscopes have a condenser which slides up or down to change its numerical aperture.)

3.1.5 Accessory plates. Full- and quarter-wave compensators and a quartz wedge are required for mineral identification.

3.2 Mechanical stage.

A mechanical stage shall be provided to permit the microscope slide to be moved smoothly in mutually perpendicular directions on the rotating stage. The movement shall be measured in both directions to an accuracy of at least 0.004 in. (± 0.1 mm). The stage shall be capable of advancing the section in accurate, equal increments.

3.3 Monochrometer.

A monochrometer shall be available. A monochromatic source, such as a sodium arc light, is preferable; however, a standard tungsten light with filters may be used.

3.4 Camera and accessories.

A camera with the accessories necessary to produce photomicrographs for documentation shall be available.

4.0 Procedure

Texture and fabric analysis is a descriptive process. Standard terminology is contained in the Glossary, Appendix L-A.5-A.

4.1 Degree of crystallization.

The extent of crystallization in the rock shall be described using standard terminology.

4.2 Granularity.

The grain size shall be described using the appropriate terminology for the rock type.

4.3 Fabric.

4.3.1 Description.

Fabric shall be described by crystal shapes and textures.

4.3.2 Genetic relationships.

Primary and secondary structures shall be distinguished if possible.

4.3.3 Mechanical features.

Structures such as fractures, voids, alterations, cementations, etc., which can influence the mechanical properties of the rock shall be emphasized in the fabric analysis.

4.4 Data reading.

The fabric and textural data shall be recorded as shown on Form L-A.5-1. Photomicrographs shall be taken for each sample, clearly showing the important features.

5.0 Reporting

The results of a petrographic analysis for engineering purposes should be presented in a concise, objective, and usable format. The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the purpose and scope of the analysis and the general characteristics of the material examined.

5.1.1 Scope of analysis.

5.1.1.1 Number of samples analyzed. In a large report, covering the analyses of several rock types, the number of samples is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples analyzed shall be clearly stated.

5.1.1.3 Limitations of the program. The areas of interest which are not covered by the analysis program, and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief macroscopic description of samples. The general rock type, macroscopic structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material, or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Results.

5.2.1 Data. A general statement of the degree of crystallinity, granularity, and fabric of the samples analyzed shall be included. If more than a few samples were analyzed, a tabular presentation shall be used.

5.2.2 Mechanical features. Those features which may affect the mechanical properties of the rock shall be described in detail and their effect discussed.

5.2.3 Graphical presentation. Representative photomicrographs or line drawings shall be included to illustrate important features.

5.3 Interpretation.

The history of the rock shall be interpreted from the results of the texture and fabric analysis.

5.4 Appended data.

A copy of each analysis Form L-A.5-1 shall be included for each thin section.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-A.5-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-A.5-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-A.5-1.

Texture and Fabric of Rock Samples by Petrographic Analysis
Form L-A.5-1

Project _____
Sample Location _____
Sample Coordinates _____
Sample No. _____
Thin Section No. _____
Microscope Serial No. _____

Photomicrograph
with scale

Rock Type _____
Field Classification _____
Petrographic
Classification _____

Degree of crystallinity _____
Granularity _____
Description of fabric:

Petrographer _____ Date _____
Quality Assurance _____ Date _____
Project Engineer _____ Date _____

Appendix L-A.5-A

Glossary of Textural Terms

Contents

1.0 Igneous Rocks

1.1 Degree of crystallinity.

holocrystalline - composed entirely of crystals.

holohyaline - composed entirely of glass.

hypocrystalline (merocrystalline) - composed of both crystals and glass.

crystallite - composed of small non-polarizing incipient crystals of various shapes which cannot be identified.

microlite - composed of small polarizing crystals of various shapes which can be identified. Crystallites and microlites represent successive stages of incipient crystallization.

1.2 Granularity.

cryptocrystalline - crystals are not distinguishable with a microscope.

aphanitic - individual components are visible only with a microscope.

phaneritic - individual components are visible to the unaided eye.

fine grained - diameter of most crystals is less than 0.04 in. (1 mm).

medium grained - diameter of most crystals is between 0.04 and 0.20 in. (1 mm and 5 mm).

coarse grained - diameter of most crystals is between 0.20 and 1.2 in. (5 mm and 3 cm).

very coarse grained - diameter of most crystals is greater than 1.2 in. (3 cm).

1.3 Fabric.

1.3.1 Crystal shape.

euhedral (idiomorphic, automorphic) - crystal entirely bounded by its own regular crystal faces.

subhedral (hypidiomorphic) - crystal incompletely bounded by its own crystal faces and partly bounded against other crystal faces.

anhedral (allotriomorphic, xenomorphic) - absence of crystal faces on grain.

1.3.2 Textural terms (relationships between grains).

granular - consisting of grains of approximately equal size.

panidiomorphic-granular (panautomorphic-granular, lamprophyric) - major phases euhedral.

xenomorphic-granular (allotriomorphic-granular, aplitic, sugary, saccharoidal) - most phases anhedral.

hypidiomorphic-granular (hypautomorphic-granular, granitic) - phases euhedral, subhedral and anhedral.

microgranitic-hypidiomorphic - granular texture developed on a microscopic scale.

porphyritic (phyric) - large crystals (phenocrysts) in a fine-grained or glassy matrix.

megaphenocrysts - macroscopic phenocrysts; that is, visible to the unaided eye.

microphenocrysts (microporphyritic) - microscopic phenocrysts.

vitrophyric - phenocrysts in a glass matrix.

felsophyric - phenocrysts in groundmass of densely packed quartz and felspar.

orthophyric - phenocrysts in groundmass with rectangular feldspars.

glomeroporphyritic (cumulophyric) - clustered phenocrysts.

protoclastic - crystals formed earlier have been broken or deformed due to differential flow of magma before solidification; found near margins of large intrusions, anorthosites, and ultrabasic rocks. Also, a texture characteristic of a very small amount of strain.

graphic - regular intergrowth of quartz and feldspar crystals. The arrangement of the quartz resembles cuneiform writing on a background of feldspar.

myrmekitic - similar to graphic, with minute worm-like or finger-like bodies of vermicular quartz enclosed in sodic plagioclase (usually oligoclase).

ophitic - lath-shaped plagioclase phenocrysts which appear to be enclosed in coarse, subhedral pyroxene, but whose average length does not exceed the diameter of the pyroxene crystals.

subophitic - ophitic texture in which the pyroxene and plagioclase are approximately the same size and the plagioclase is only partially surrounded.

hyalo-ophitic - ophitic texture with glass in the place of pyroxene.

poikilitic - numerous, randomly oriented grains of various minerals completely enclosed within a large, optically continuous crystal of a different composition; may display mottled luster.

reaction rim (corona) - a zone around one mineral composed of another mineral; it represents the reaction between a solidified crystal and the surrounding melt.

kelyphytic rims - rims of concentric shells with radial fibrous texture.

intergranular - the angular interstices between feldspars in lavas and hypabyssal rocks are occupied by ferromagnesian minerals.

intersertal - the interstices between feldspars are filled with glass, cryptocrystalline materials or non-granular deuteric and secondary minerals.

hyalophitic - minute spaces between randomly oriented microlites of feldspar are occupied by glass.

felty (felted) - matrix of tightly compressed microlites interwoven in an irregular fashion.

pilotaxitic (trachytic) - microlites of feldspar are oriented in a sub-parallel manner as a result of flow and the interstices are occupied by micro- and cryptocrystalline material.

diktytaxitic - the presence of randomly oriented, abundant, closely spaced, minute, angular cavities between feldspar laths; some crystals protrude into these cavities.

vesicles - cavities.

amygdules - vesicles filled with secondary minerals.

drusy cavities (miarolitic) - in plutonic rocks, irregular cavities into which large subhedral to euhedral crystals project.

spherulites - in siliceous lavas and shallow intrusive rocks, radial aggregates of acicular and fibrous minerals.

axiolites - spherulites that are elongated or that coalesce along a central axis.

variolitic - in basalt and diabase, radial and sheaf-like mineral forms when viewed under the microscope (varioles); usually divergent plagioclase microlites in a glassy matrix or intergrown with crystals of pyroxene, olivine, or iron oxide or sulfide.

bostonitic - in dike rocks, irregular interlocking laths of alkali feldspar arranged in crudely divergent groups.

ocellar - phenocrysts resembling an eye, partly or wholly enveloped by trangentially or radially arranged crystals of later growths.

sieve texture - abundant inclusions within large, spongy crystals.

2.0 Metamorphic rocks

blasto - prefix that signifies a relict texture in metamorphic rocks, e.g. blastoporphyritic.

blastic- suffix that signifies a texture formed by metamorphism, e.g. lepidoblastic.

2.1 Crystalloblastic fabrics - fabrics resulting from chemical reconstitution involving growth of new crystals in an essentially solid medium.

xenoblastic - grains with irregular outlines.

idioblastic - grains bounded with distinct crystal faces.

hypidioblastic (subidioblastic) - grains bounded only in part by characteristic crystal faces.

poikiloblastic - larger crystals packed with small inclusions.

porphyroblastic - large crystals of one or more minerals associated with smaller grains of other minerals.

diablastic - intricately intergrown and interpenetrating constituents with rod-like shapes.

heteroblastic - essential minerals are of two or more distinct sizes.

homeoblastic - essential minerals are of approximately equal size.

granoblastic, hornfelsic - homeoblastic texture type whose mineral constituents formed essentially equidimensional crystals with well-sutured boundaries.

nematoblastic - homeoblastic texture formed of slender prismatic crystals.

lepidoblastic - homeoblastic texture with crystals in a foliated or schistose orientation due to the development of minerals with flaky or scaly habit during recrystallization.

fibroblastic - homeoblastic texture with long crystals due to the development of minerals with a fibrous habit.

2.2 Cataclastic textures - textures in a dynamically altered rock produced by severe mechanical crushing and differential movement of component grains; often characterized by fragmentary, deformed or strained mineral grains.

fluxion banded - flow-banded.

helicitic - bands of inclusions which indicate original bedding or schistosity of parent rock, cutting through later-formed crystals of metamorphic rocks. Relict inclusions occur in porphyroblasts as curved and contorted strings.

mylonitic - flow structure having flinty, banded or streaked appearance, produced by intense microbrecciation and shearing; often contains undestroyed augens and lenses of parent rock in a granulated matrix.

phyllonitic (phyllite-mylonite) - fine-grained texture formed by extreme deformation of originally coarse-grained rocks.

mortar structure (murbruk structure, porphyroclastic structure) - mica-free aggregates of small, finely crushed grains of quartz and feldspar, occupying the interstices between, or forming the borders of, much larger, rounded relicts of the same minerals.

flaser structure - lenses and layers of original or relatively unaltered granular minerals which are surrounded by a matrix of highly sheared and crushed materials, giving the appearance of a crude flow structure.

augen structure - a structure in which minerals like feldspar, quartz or garnet have been squeezed into elliptical or lens-shaped forms resembling eyes. These are commonly enveloped by essentially parallel layers of contrasting constituents such as mica or chlorite.

autoclastic - broken or brecciated surfaces formed as the result of crushing, shattering, dynamic metamorphism, orogenic forces, or other mechanical processes, found near the margins of large intrusions, anorthosites and ultrabasic rocks.

3.0 Sedimentary rocks

3.1 Particulate textures.

Textures which result from the accumulation of discrete particles. They are characterized in the unaltered state by point contacts between particles and associated intergranular spaces. Detrital sediments and crystals or organic materials accumulated through gravity settling generally have particulate structures.

3.1.1 Granularity (grain size) - granularity is defined on the basis of size ranges shown in Table L-A.5-1.

3.1.2 Grain sorting - the degree to which the grains approach a uniform size.

well sorted - grains all having approximately the same size.

moderately sorted - between poorly and well sorted.

poorly sorted - grains of many sizes mixed together.

bimodal - grains of two distinct sizes without many intermediate sizes.

3.1.3 Grain form - the expression of the external morphology of the grain.

shape - measure of the proportions between a grain's three axial directions.

sphericity - measure of a grain's approach to the shape of a sphere.

roundness - the degree of angularity of a grain's surface projections. When quantitatively evaluated, it is the average radius of curvature of the corners of the grain divided by the radius of the maximum inscribed circle.

surface texture - textures resulting from surface diagenesis. Recognition is essential, as resulting angularity would otherwise be interpreted as indicating minimal transport and abrasion.

3.1.4 Grain packing - the arrangement of grains in a three-dimensional framework; commonly used to express the distributional relationship between grains and matrix.

grain-supported - grains appear to constitute a three-dimensional framework by virtue of intergranular contact.

grainstones - grain-supported sediments that are devoid of interstitial support.

packstones - loosely-packed grain-supported sediments in which the proportion of grain contacts is reduced by the presence of an interstitial matrix.

matrix-supported - grains are dispersed within a matrix to such an extent that three-dimensional continuity between grains does not exist.

wackestones - matrix-supported sediments with more than 10% grains.

mudstones - matrix-supported sediments with fewer than 10% grains. Not to be confused with the sedimentary rock "mudstone".

3.2 Non-particulate textures.

Crystalline textures which result from the partial or entire crystallization of a sediment, characterized by an interlocking crystal mosaic.

3.2.1 Accretionary textures - displayed in shells and other bodies of direct organic origin and in accretionary bodies of less certain origin.

oolitic (ooliths) - grains which show an internal structure of concentric shells with diameters to 0.08 in. (2 mm).

pisolitic (pisoliths) - ooliths with diameters greater than 0.08 in. (2 mm).

3.2.2 Crystalline textures

macrocrystalline (sparry) - crystals greater than 8.0×10^{-4} in. (20 microns).

microcrystalline - crystals less than 8.0×10^{-4} in. (20 microns).

cryptocrystalline - individual crystals cannot be distinguished under the microscope.

equicrystalline - crystals of relatively uniform size.

inequicrystalline - crystalsof different sizes.

porphyroblastic - a few crystals are distinctly larger than those of the groundmass.

poikiloblastic - one crystal encloses smaller crystals or grains of another material.

fibrous - bladelike crystals arranged in subparallel fashion.

radial fibrous - radiating aggregates of fibrous crystals.

spherulitic - a coarsely crystalline aggregate with a radial internal structure arranged around one or more centers.

cementation - chemical precipitation of minerals into pre-existing pore spaces of a crystalline aggregate.

enfacial junction - two crystals form about a third along a planar surface.

fringe - incomplete cementation around a grain.

syntaxial rims (overgrowths) - cement has been precipitated in optical continuity with the grains and is of the same mineral composition.

cone-in-cone - displacive crystal growth which separates layers of the host sediment and rearranges the layers along crystal boundaries.

3.2.3 Solution textures.

passive solution - purely chemical action on a sedimentary component.

pressure solution - solution resulting from or related to direct pressure.

solution transfer - solution of grains at points of contact accompanied by reprecipitation in immediately adjacent areas.

stylotitic texture - interlocking columns attached to the opposing bodies of the rock.

Table L-A.5-1

Nomenclature for Grain Size in Clastic Sedimentary Rock

U.S. Standard Sieve Mesh Number	Diameter in mm	Phi (Ø)	Sediment Grain Size
			Boulder
-	256	-8	
			Cobble
-	64	-6	
			Very coarse pebble
-	32	-5	
			Coarse pebble
-	16	-4	
			Medium pebble
-	8	-3	
			Fine pebble
5	4	-2	
			Granule
10	2	-1	
			Very coarse sand
18	1	0	
			Coarse sand
35	1/2	1	
			Medium sand
60	1/4	2	
			Fine sand
120	1/8	3	
			Very fine sand
230	1/16	4	
			Coarse silt
-	1/32	5	
			Medium silt
-	1/64	6	
			Fine silt
-	1/128	7	
			Very fine silt
-	1/256	8	
			Clay

Phi (Ø) = $-\log_2$ diameter (mm)

Procedure L-B.1

Uniaxial Compressive Strength of Rock Core -

Ambient Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines the compressive strength of a cylindrical rock specimen at ambient temperature under uniaxial loading.

1.1.2 Limitations. Only the peak compressive strength is evaluated. No information on residual strength or deformation prior to failure is obtained. This test may be combined with Test L-C.1, "Uniaxial Compressive Modulus of Deformation of Rock Core - Ambient Temperature," to obtain detailed deformation data.

1.2 General description of the test.

A rock core sample is cut to length and the ends are machined flat. The sample is loaded axially until it fails. The strength is then calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Load - the total axial force acting on the sample.

1.3.1.2 Pressure, stress - force per unit area.

1.3.1.3 Failure - the inability of the sample to sustain increased load without rapidly increasing deformation or destructive fracturing.

1.3.1.4 Strength - the stress in the rock at which failure occurs.

1.3.2 Equations.

1.3.2.1 The compressive strength, σ_1, is calculated using:

$$\sigma_1 = \frac{P}{A} \qquad (1)$$

where:

P = load at failure

A = cross-sectional area of sample

1.4 References.

1.4.1 ASTM, 1978, Test Designation D2938, "Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens," Annual Book of ASTM Standards, Part 19.

1.4.2 Foundation Sciences, Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI -310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.3 ISRM Commission on Standardization of Laboratory and Field Tests, 1979, "Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials", Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 16, No. 2.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities in the rock mass, such as joints, inclusions, voids, etc., can significantly influence the mass strength of the rock. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Preservation of moisture condition of samples.

The moisture condition of the rock can influence the measured strength. The moisture content of the rock core shall be preserved between the time of recovery and the time of testing as described in Procedure GT-A.4, "Handling and Storage of Rock Core Samples," see Ref. 1.4.2.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanism for applying axial load to the sample, the reaction frame containing the load mechanism, and the control system for the load mechanism. The loading frame shall be constructed to apply a continuously increasing load to the sample at either a constant strain or constant stress rate.

3.2 Platens.

The diameter of the platens shall be equal to, or greater than the diameter of the sample. Rock materials subject to large deformations prior to failure, such as salt and some shales, shall be tested using platens sized so that the lateral expansion of the sample does not exceed the diameter of the platen. The platens shall be at least 0.625 in. thick[1] (15.9 mm). The surfaces shall be flat to within 0.0002 in. (0.005 mm) and hardened to at least Rockwell HRC 58.[1,2] One of the two platens shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.3 Axial load transducer.

An electronic load cell is recommended to measure axial load on the sample. The cell shall have an accuracy of at least ± 100 lb (±45.4 kg), including errors introduced by the excitation and readout system, and a resolution of at least 50 lb (22.7 kg). Alternatively, a pressure gage or electronic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Core size. Rock cores of NX size (2 in. nominal diameter; 51 mm) or larger are recommended. However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.[1]

4.1.2 Length-to-diameter ratio. Cores shall be cut to a length-to-diameter ratio of 2.0 to 3.0.[1,2]

4.1.3 Smoothness. The sides of the core shall be relatively smooth, free of abrupt irregularities and straight to within 0.01 in. over the length of the sample.[1]

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in.[(2)] (0.25 mm over 51 mm).

4.1.5 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in.[(2)] (0.05 mm).

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[1] ISRM, 1979 (see Ref 1.4.2)
[2] ASTM, 1979 (see Ref 1.4.1)

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in.[1,2] (0.025 mm).

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally, water is used for hard rock but other materials may require special fluids, such as saturated brine for salt or glycerin for expansive shales.

4.1.8 Measurements. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of measuring to 0.001 in. (0.025 mm). The diameter of the specimen shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measurements shall be recorded as shown on Form L-B.1-1.

4.2 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platens and sample are aligned with the loading axis to within 0.05 in. (1.27 mm).

4.2.2 Axial loading. The axial load shall be applied smoothly and continuously at either a constant strain or constant stress rate. For hard rock, the loading rate should produce failure within 5 to 15 minutes;[1] a typical constant stress rate is 25 psi (0.17 MPa) per second, while constant strain rates are on the order of 1 to 100με per second. For rocks which exhibit significant non-elastic behavior, such as salt and some shales, constant stress loading rates are generally slower, for example in the range of 0.5 to 4 psi (0.003 to 0.03 MPa) per second; constant strain rates will depend on the material type. The same loading rate shall be used for all samples in a particular suite of tests.

4.2.3 Sample failure. Failure is recognized when the load on the sample becomes constant or decreases. The maximum load sustained by the sample before this occurs is the failure load.

4.2.4 Data recording requirements. The data shown on Form L-B.1-1 shall be recorded as a minimum for this test.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

[1] ASTM, 1979 (see Ref 1.4.1)
[2] ISRM, 1979 (see Ref 1.4.2)

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and type of sample tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program, and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary table. A summary table including, as a minimum, rock types, average strengths, ranges and uncertainties shall be presented.

5.4.2 Individual results. A table including, as a minimum, sample numbers, rock types, and strengths shall be presented.

5.4.3 Other. The following other types of analysis or presentation may be included as appropriate.

5.4.3.1 Histograms of results.

5.4.3.2 Correlation of results with other rock properties such as modulus of deformation or specific gravity.

5.4.3.3 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean value of the compressive strength, range, standard deviation and 95% confidence limits for the mean shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

Each completed test Form L-B.1-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test Inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-B.1-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-B.1-1.

6.3.3 Test sign offs. Quality Assurance shall maintain signed-off copies of Form L-B.1-1.

Uniaxial Compressive Strength of Rock Core -
Ambient Temperature

Test Data Sheet - Form L-B.1-1

Project_____ Sample No._____

Date_____ Rock Type_____

Tested By_____ Test Temperature_____

Equipment Description	Serial No.	Date of Next Calibration

Sample Height_____ Sample Diameter_____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____ Sketch of Sample After Failure

Time Required for Failure_____

Loading Rate_____

Failure Load_____

Strength_____

Remarks:

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Engineer_____ Date_____

Procedure L-B.2

Uniaxial Compressive Strength of Rock Core -

Elevated Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines the compressive strength of a cylindrical rock specimen at elevated temperature under uniaxial loading.

1.1.2 Limitations. Only the peak compressive strength is evaluated. No information on residual strength or deformation prior to failure is obtained. This test may be combined with Test L-C.2, "Uniaxial Compressive Modulus of Deformation of Rock Core - Elevated Temperature", to obtain detailed deformation data.

1.2 General description of the test.

A rock core sample is cut to length and the ends are machined flat. The sample is heated to a specified temperature and is loaded axially until it fails. The strength is then calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Load - the total axial force acting on the sample.

1.3.1.2 Pressure, stress - force per unit area.

1.3.1.3 Failure - the inability of the sample to sustain increased load without rapidly increasing deformation or destructive fracturing.

1.3.1.4 Strength - the stress in the rock at which failure occurs.

1.3.2 Equations.

1.3.2.1 The compressive strength, σ_1, is calculated using:

$$\sigma_1 = \frac{P}{A} \qquad (1)$$

where:

P = load at failure

A = cross-sectional area of sample

1.4 References.

1.4.1 ASTM, 1978, Test Designation D2938, "Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens," Annual Book ASTM of Standards, Part 19.

1.4.2 ISRM Commission on Standardization of Laboratory and Field Tests, 1979, "Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials", Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 16, No. 2.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities in the rock mass, such as joints, inclusions, voids, etc., can significantly influence the mass strength of the rock. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanism for applying axial load to the sample, the reaction frame containing the load mechanism and the control system for the load mechanism. The loading frame

shall be constructed to apply a continuously increasing load to the sample at either a constant strain or constant stress rate.

3.2 Platens.

The diameter of the platens shall be equal to, or greater than, the diameter of the sample. Rock materials which are subject to large deformations prior to failure, such as salt and some shales, shall be tested using platens sized so that the lateral expansion of the sample does not exceed the diameter of the platen. The platens shall be at least 0.625 in. thick[1] (15.9 mm). The surfaces shall be flat to within 0.0002 in. (0.005 mm) and hardened to at least Rockwell HRC 58.[1,2] One of the two platens shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.3 Transducers.

3.3.1 Axial load. An electronic load cell is recommended to measure axial load on the sample. The cell shall have an accuracy of at least ± 100 lb (45.4 kg), including errors introduced by the excitation and readout system, and a resolution of at least 50 lb (22.7 kg). Alternatively, a pressure gage or electronic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.3.2 Temperature. The instrument chosen to monitor temperature depends primarily on the test apparatus and the maximum test temperature. Special Limits of Error thermocouples or platinum resistance thermometers (RTD's) are recommended. The temperature transducer shall be accurate to at least ± 0.9°F (± 0.5°C) with a resolution of at least 0.18°F (0.1°C). The temperature shall be measured at three locations, with one sensor near the top, one at mid-height, and one near the bottom of the sample.

3.4 Heating unit.

The heating unit shall be capable of maintaining a uniform temperature throughout the sample to within 7.2°F (4°C). The unit shall incorporate controls so that the sample may be heated at a rate no greater than 3.6°F (2°C) per minute. The mean temperature of the sample shall vary by no more than 3.6°F (2°C) during the test.

4.0 Procedure

4.1 Sample preparation

4.1.1 Core size. Rock cores of NX size (2 in. monimal diameter; 51 mm) or larger are recommended. However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.[1]

[1] ISRM, 1979 (see Ref 1.4.2)
[2] ASTM, 1978 (see Ref 1.4.1)

4.1.2 Length-to-diameter ratio. Cores shall be cut to a length-to-diameter ratio of 2.0 to 3.0.[1,2]

4.1.3 Smoothness. The sides of the core shall be relatively smooth and free of abrupt irregularities and straight to within 0.01 in. (0.25 mm) over the length of the sample.[1]

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in.[(2)] (0.25 mm over 51 mm).

4.1.5 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in.[(2)] (0.05 mm).

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in.[1,2] (0.025 mm).

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally, water is used for hard rock, but other fluids may be necessary, such as saturated brine for salt or glycerin for expansive shales.

4.1.8 Measurements. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of measuring to 0.001 in. (0.025 mm). The diameter of the specimen shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measurements shall be recorded as shown on Form L-B.2-1.

4.2 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platens and sample are aligned with the loading axis to within 0.05 in. (1.3 mm).

4.2.2 Heating rate. The sample shall be heated to the test temperature at a rate not to exceed 3.6°F (2°C) per minute, to prevent thermal fracturing.

4.2.3 Thermal equilibrium. The test sample shall be maintained at the test temperature for at least 2 hours prior to testing.

4.2.4 Axial loading. The axial load shall be applied smoothly and continuously at either a constant strain or constant stress rate. For hard rock, the loading rate should produce failure within

[1] ISRM, 1979 (see Ref 1.4.2)

[2] ASTM, 1978 (see Ref. 1.4.1)

5 to 15 minutes;[1] a typical constant stress rate is 25 psi (0.17 MPa) per second while constant strain rates are on the order of 1 to 100με per second. For rocks which exhibit significant non-elastic behavior, such as salt and some shales, constant stress loading rates are generally slower, for example in the range of 0.5 to 4 psi (0.003 to 0.03 MPa) per second; constant strain rates will depend on the material type. The same loading rate shall be used for all samples in a particular suite of tests.

4.2.5 Sample failure. Failure is recognized when the load on the sample becomes constant or decreases. The maximum load sustained by the sample before this occurs is the failure load.

4.2.6 Data recording requirements. The data shown on Form L-B.2-1 shall be recorded as a minimum for this test.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types or at various test temperatures, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program, and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

[1] ISRM, 1979 (see Ref 1.4.2)

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece should be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary table. A summary table including as a minimum rock types, test temperatures, average strengths, ranges and uncertainties shall be presented.

5.4.2 Individual results. A table of results for individual tests including, as a minimum, sample numbers, rock types, test temperatures, and strengths shall be presented.

5.4.3 Other. Other types of analyses and presentations may be included as appropriate.

5.4.3.1 Histograms of results.

5.4.3.2 Relation between strength and temperature.

5.4.3.3 Correlation of results with other rock properties such as modulus of deformation or specific gravity.

5.4.3.4 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the value of the mean compressive strength, range, standard deviation and 95% confidence limits for the mean should be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

Each completed test Form L-B.2-1 should be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in section 2.1.

6.2 Test Inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-B.2-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-B.2-1.

6.3.3 Test sign offs. Quality Assurance shall maintain signed-off copies of Form L-B.2-1.

Uniaxial Compressive Strength of Rock Core -
Elevated Temperature

Test Data Sheet - Form L-B.2-1

Project_____ Sample No._____

Date_____ Rock Type_____

Tested By_____ Test Temperature_____

Equipment Description	Serial No.	Date of Next Calibration

Sample Height_____ Sample Diameter_____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____ Sketch of Sample After Failure

Time Required for Failure_____

Loading Rate_____

Failure Load_____

Strength_____

Remarks:

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Engineer_____ Date_____

Procedure L-B.3

Triaxial Compressive Strength of Rock Core -

Ambient Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines the maximum compressive strength of a cylindrical rock specimen at ambient temperature under triaxial loading. The results obtained give the relationship of shear and compressive strength to confining pressure and the angle of internal friction of the rock.

1.1.2 Limitations.

1.1.2.1 This procedure tests rock core in an undrained state. No provision is made for pore pressure measurements. The pore pressure is assumed to be zero in the calculations.

1.1.2.2 Only the peak compressive strength is evaluated. No information on residual strength or deformation prior to failure is obtained. This test procedure may be combined with Procedure L-C.3, "Triaxial Compressive Modulus of Deformation of Rock Core - Ambient Temperature", to obtain detailed deformation data.

1.2 General description of the test.

A rock core sample is cut to length and the ends are machined flat. The sample is enclosed in a flexible impermeable membrane and is placed in a confining chamber. The sample is loaded axially and the confining chamber is pressurized to provide lateral load. When the desired lateral load is achieved, it is held constant. Axial loading continues to increase until the sample fails. The strength is then calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Load - the total axial force acting on the sample.

1.3.1.2 Pressure, stress - force per unit area.

1.3.1.3 Failure - the inability of the sample to sustain increased load without rapidly increasing deformation or destructive fracturing.

1.3.1.4 Strength - the stress in the rock at which failure occurs.

1.3.2 Equations.

1.3.2.1 The compressive strength, σ_1, is calculated using:

$$\sigma_1 = \frac{P}{A} \qquad (1)$$

where:

P = load at failure

A = cross-sectional area of sample.

1.3.2.2 The angle of internal friction of the rock, ϕ, is obtained from the Mohr envelope shown on Figure 1.1. The terms used on this figure are:

σ_1 = compressive strength

σ_3 = lateral (confining) pressure

τ = shear stress.

The Mohr's circles are constructed by the standard method. The curve tangent to all circles is the Mohr envelope. On Figure 1.1, the envelope is shown as a straight line, corresponding to the Coulomb failure criterion. Other failure criteria, notably Mohr's and Griffith's, predict a parabolic failure envelope. Because of variability between rock samples, however, the Mohr envelope often does not exhibit a distinct curvature unless relatively high confining pressures are applied. In this case, ϕ is calculated from the slope of the envelope at the desired stress level.

1.3.2.3 The unconfined shear strength, S_o, is the intercept of the failure envelope with the shear stress axis see Figure 1.1).

1.3.2.4 The functional relationship between σ_1 and σ_3 may be defined in its most general form by:

$$\sigma_1 = f(\sigma_3) \qquad (2)$$

The functional formulation depends on the failure criterion assumed in the analysis. As with the Mohr failure envelope, however, scatter in the data generally precludes all functions of higher order than linear, unless tests have been conducted at relatively high confining pressures. Thus, Equation 2 may be rewritten:

$$\sigma_1 = C_o + K\sigma_3 \qquad (3)$$

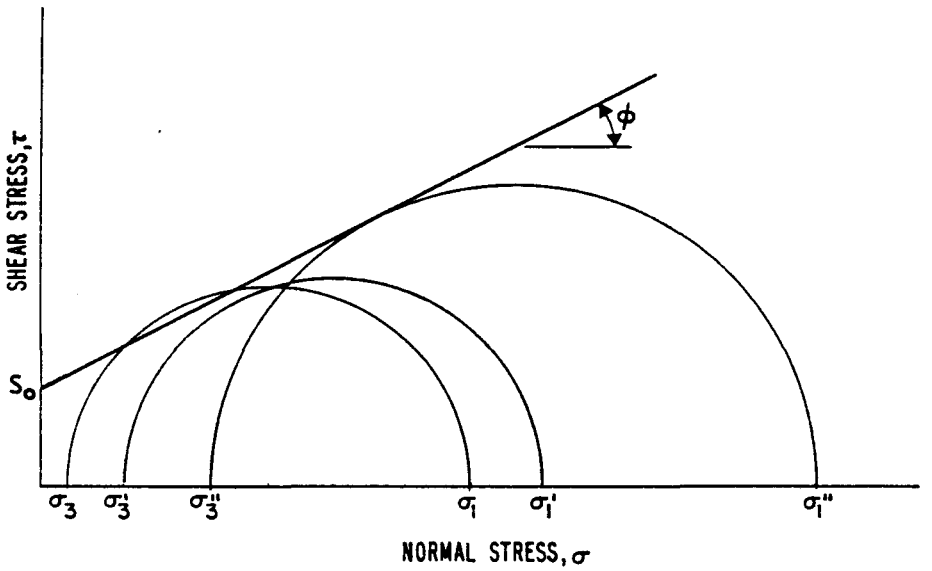

FIGURE I.1 TYPICAL MOHR CIRCLES AND FAILURE ENVELOPE

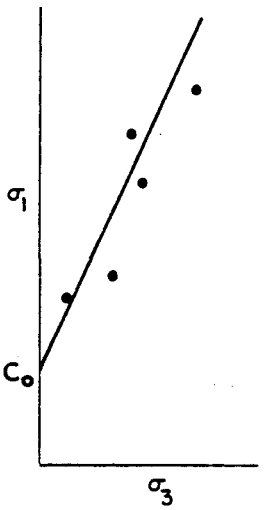

FIGURE I.2 TYPICAL RELATION BETWEEN CONFINING PRESSURE AND STRENGTH.

where:

C_0 = unconfined compressive strength of the rock

K = constant.

A typical plot of the relation between σ_1 and σ_3 is shown on Figure 1.2.

1.3.3 Limits of applicability. The extension of failure criteria into tensile loading situations is complex. Such situations cannot be modeled by this test and, in any case, are of limited value due to the inability of rock masses to sustain appreciable tension. Therefore, the failure envelopes and stress relations, discussed in Sections 1.3.2.2 and 1.3.2.4 respectively, are defined only for confining pressures greater than or equal to zero.

1.4 References.

1.4.1 ASTM, 1978, Test Designation D2664, "Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens Without Pore Pressure Measurements," Annual Book of ASTM Standards, Part 19.

1.4.2 Foundation Sciences, Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI-310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.3 ISRM Commission on Standardization of Laboratory and Field Tests, 1978, "Suggested Methods for Determining the Strength of Rock Materials in Triaxial Compression," Int. J. of Rock Mech. Min. Sci. and Geomech. Abstr., 15, No. 2.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the

site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than a relatively uniform rock, in order to evaluate the results with equal certainty. Triaxial tests using at least three different confining pressures are recommended to determine the failure envelope and the relation between σ_1 and σ_3. At each confining pressure, no fewer than three tests are recommended.

2.3.3 Nonhomogeneities. Discontinuities in the rock mass, such as joints, inclusions, voids, etc., can significantly influence the mass strength of the rock. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy of the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Preservation of moisture condition of samples.

The moisture condition of the rock can influence the measured strength. The moisture content of the rock core shall be preserved between the time of recovery and the time of testing as described in Procedure GT-A.4, "Handling and Storage of Rock Core Samples," see Ref 1.4.2.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanism for applying axial load to the sample, the reaction frame containing the load mechanism and triaxial cell, and the control system for the load mechanism. The loading frame shall be constructed to apply a continuously increasing load to the sample at either a constant strain or constant stress rate.

3.2 Triaxial confining chamber.

The confining chamber consists of a hollow cylinder and end caps to contain the confining fluid, platens to support the sample, and a flexible impermeable membrane to cover the sample during testing.

3.2.1 Cylinder and end caps. The cell design shall be such that changes in confining pressure do not directly cause changes in axial load and vice versa.

3.2.2 Platens. The diameter of the platens shall be equal to or greater than the diameter of the sample. Rock materials subject to large deformations prior to failure, such as salt and some shales, shall be tested using platens sized so that the lateral expansion of the sample does not exceed the platen diameter. The platens shall be at least 0.625 in. (15.9 mm) thick.[1] The surfaces shall be flat to within 0.0002 in. (0.005 mm) and hardened to at least Rockwell HRC 58.[1,2] One of the two platens shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.2.3 Flexible, impermeable membrane. This membrane encloses the rock sample and prevents penetration by the confining fluid. Generally, a sleeve of natural or synthetic rubber or plastic polymer is used. Copper or lead jackets are sometimes used. The membrane shall be inert relative to the confining fluid, and shall cover small pores in the sample without rupturing when confining pressure is applied. Plastic or silicone rubber coatings may be applied directly to the sample, providing these materials do not penetrate and strengthen the sample. The ends of the sample shall not be coated, and care must be taken to form an effective seal where the platen and sample meet. Membranes formed by coatings shall be subject to the same performance requirements as elastic sleeve membranes. Materials requiring a heat cure shall not be used.

3.3 Confining pressure system.

The confining pressure system consists of the pressurizing fluid and the means of applying pressure. The fluid is generally hydraulic oil or water, but inert gas may also be used. The pressurization system shall be capable of maintaining the confining pressure to within $\pm$ 1% throughout the test.

3.4 Transducers.

Transducers are required to determine the axial load on the sample and the confining pressure.

3.4.1 Axial load. An electronic load cell is recommended to measure axial load on the sample. The cell shall have an accuracy of at least $\pm$ 100 lb (45.5 kg), including errors introduced by the excitation and readout system, and a resolution of at least 50 lb (22.7 kg). Alternatively, a pressure gage or

[1] ISRM, 1978 (see Ref. 1.4.3)
[2] ASTM, 1978 (see Ref. 1.4.1)

transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.4.2 Confining pressure. The confining pressure shall be measured with a hydraulic pressure gage or electronic transducer, having an accuracy of ± 1% of the confining pressure, including errors due to readout equipment, and a resolution of at least 0.5% of the confining pressure.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Core size. Rock cores of NX size (2 in. nominal diameter; 51 mm) or larger are recommended. However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.

4.1.2 Length-to-diameter ratio. Cores shall be cut to a length-to-diameter ratio of 2.0 to 3.0.[1,2]

4.1.3 Smoothness. The sides of the core shall be relatively smooth, free of abrupt irregularities and straight to within 0.01 in. (0.25 mm) over the length of the sample.[1]

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in.[(2)] (0.25 mm over 51 mm).

4.1.5 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in.[(2)] (0.05 mm).

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in.[1,2] (0.025 mm).

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally water is used for hard rock, but other materials may require special fluids, such as saturated brine for salt, or glycerin for slaking mudstones.

4.1.8 Voids. Large voids in the sides of the samples, such as vesicles, may be filled with paraffin, plastic or similar material to provide support for the flexible membrane. Such filling material shall not penetrate the rock and shall have

[1]ISRM, 1978 (see Ref. 1.4.3)
[2]ASTM, 1978 (see Ref. 1.4.1)

an elastic modulus no greater than 10% of the intact rock modulus.

4.1.9 Measurements. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of measuring to 0.001 in. (0.025 mm). The diameter of the specimen shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measurements shall be recorded as shown on Form L-B.3-1.

4.2 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platen and sample are aligned with the loading axis to within 0.05 in.

4.2.2 Loading sequence. During the initial stage of the test, the axial load and confining pressure shall be increased concurrently at rates such that the axial stress in the sample is maintained equal to the confining pressure.

4.2.3 Axial loading. The axial load shall be applied smoothly and continuously at either a constant strain or constant stress rate. For hard rock, the loading rate should produce failure within 5 to 15 minutes;[1] a typical constant stress rate is 25 psi (0.17 MPa) per second, while constant strain rates are on the order of 1 to 100 $\mu\varepsilon$ /per second. For rocks which exhibit significant nonelastic behavior, such as salt and some shales, constant stress loading rates are generally slower, for example, in the range of 0.5 to 4 psi (0.003 to 0.03 MPa) per second; constant strain rates will depend on the material properties.

4.2.4 Sample failure. Failure is recognized when the load on the sample becomes constant or decreases. The maximum load sustained by the sample before this occurs is the failure load.

4.2.5 Data recording requirements. The data shown on Form L-B.3-1 shall be recorded as a minimum for this test.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

[1] ISRM, 1978 (see Ref. 1.4.3)

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types or confining pressures, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and type of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure varies from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a nonideal situation shall be fully explained.

5.4 Results.

5.4.1 Basic results. Results shall be presented including sample numbers, confining pressures, and strengths as a minimum. A tabular presentation is recommended for clarity.

5.4.2 Mohr's circles. A Mohr's circle diagram, as discussed in Sections 1.3.2.2 and 1.3.2.3 of this procedure, shall be presented for each suite of samples as appropriate. A summary table of the angle of internal friction and the unconfined shear strength should also be presented.

5.4.3 Strength vs. confinement. A graph of the relationship between σ_1 and σ_3, as discussed in Section 1.3.2.4, shall be presented for each suite of rocks as appropriate. A summary table of unconfined compressive strengths and relational constants as defined in Equation 3 should also be presented.

5.4.4 Other. The following other types of analyses and presentations may be included as appropriate.

5.4.4.1 Histograms of results.

5.4.4.2 Correlation with other rock properties such as specific gravity or modulus of deformation.

5.4.4.3 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean value of the compressive strength, standard deviation and 95% confidence limits for the mean shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

Each completed test Form L-B.3-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-B.3-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-B.3-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-B.3-1.

Triaxial Compressive Strength of Rock Core -
Ambient Temperature

Test Data Sheet - Form L-B.3-1

Project_____ Sample No._____

Date_____ Rock Type_____

Tested By_____ Test Temperature_____

Equipment Description	Serial No.	Date of Next Calibration

Sample Height_____ Sample Diameter_____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____ Sketch of Sample After Failure

Time Required for Failure_____

Loading Rate_____

Failure Load_____

Strength_____

Remarks:

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Engineer_____ Date_____

Procedure L-B.4

Triaxial Compressive Strength of Rock Core -

Elevated Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines the maximum compressive strength of a cylindrical rock specimen at elevated temperature under triaxial loading. The results obtained give the relationship of shear and compressive strength to confining pressure and the angle of internal friction of the rock.

1.1.2 Limitations.

1.1.2.1 This procedure tests rock core in an undrained state. No provision is made for pore pressure measurements. The pore pressure is assumed to be zero in the calculations.

1.1.2.2 Only the peak compressive strength is evaluated. No information on residual strength or deformation prior to failure is obtained. This triaxial test may be combined with Test L-C.4, "Triaxial Compressive Modulus of Deformation of Rock Core - Elevated Temperature", to obtain detailed deformation data.

1.2 General description of the test.

A rock core sample is cut to length and the ends are machined flat. The sample is enclosed in a flexible impermeable membrane and placed in a confining chamber. The sample is slowly heated to the desired temperature. The sample is loaded axially and the confining chamber is pressurized to provide lateral load. When the desired lateral load is achieved, it is held constant. Axial loading continues to increase until the sample fails. The strength is then calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Load - the total axial force acting on the sample.

1.3.1.2 Pressure, stress - force per unit area.

1.3.1.3 Failure - the inability of the sample to sustain increased load without rapidly increasing deformation or destructive fracturing.

1.3.1.4 Strength - the stress in the rock at which failure occurs.

1.3.2 Equations.

1.3.2.1 The compressive strength, σ_1 is calculated by:

$$\sigma_1 = \frac{P}{A} \qquad (1)$$

where:

P = load at failure

A = cross-sectional area of sample

1.3.2.2 The angle of internal friction of the rock, $\emptyset$, is obtained from the Mohr envelope shown on Figure 1.1. The terms used on this figure are:

σ_1 = compressive strength

σ_3 = lateral (confining) pressure

τ = shear stress

The Mohr's circles are constructed by the standard method. The curve tangent to all circles is the Mohr envelope. On Figure 1.1, the envelope is shown as a straight line, corresponding to the Coulomb failure criterion. Other failure criteria, notably Mohr's and Griffith's, predict a parabolic failure envelope. Because of variability between rock samples, however, the Mohr envelope often does not exhibit a distinct curvature unless relatively high confining pressures are applied. In this case, $\emptyset$ is calculated from the slope of the envelope at the desired stress level.

1.3.2.3 The unconfined shear strength, S_o, is the intercept of the failure envelope with the shear stress axis (see Figure 1.1).

1.3.2.4 The functional relationship between σ_1 and σ_3 may be defined in its most general form by:

$$\sigma_1 = f(\sigma_3) \qquad (2)$$

The functional formulation depends on the failure criterion assumed in the analysis. As with the Mohr failure envelope, however, scatter in the data generally precludes all functions higher than linear, unless tests have been conducted at relatively high confining pressures. Thus, Equation 2 may be rewritten:

$$\sigma_1 = C_o + K\sigma_3 \qquad (3)$$

where:

C_o = unconfined compressive strength of the rock

K = constant

A typical plot of the relation between σ_1 and σ_3 is shown on Figure 1.2.

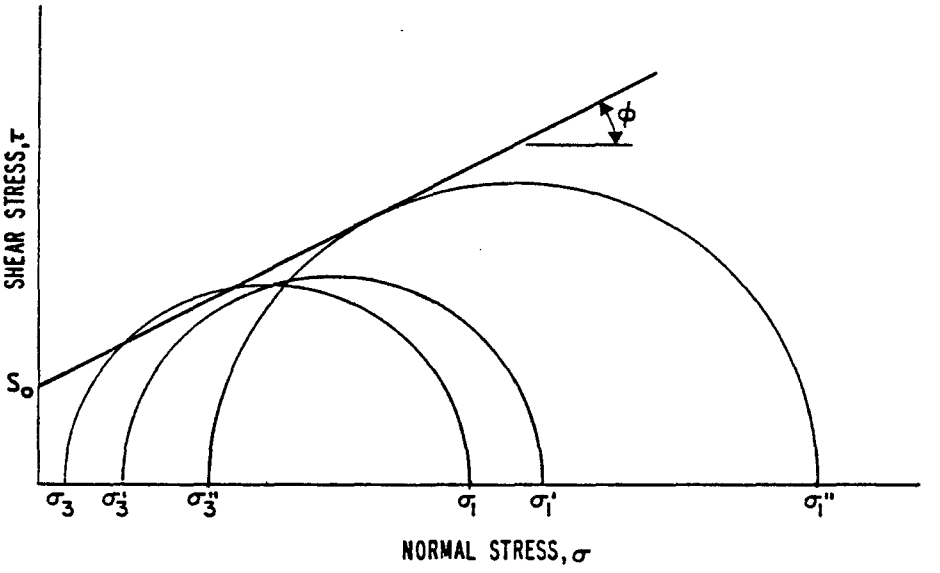

FIGURE 1.1 TYPICAL MOHR CIRCLES AND FAILURE ENVELOPE

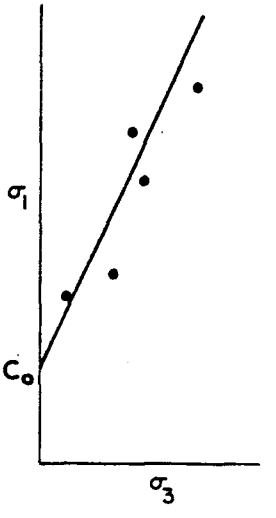

FIGURE 1.2 TYPICAL RELATION BETWEEN CONFINING PRESSURE AND STRENGTH.

1.3.3 Limits of applicability. The extension of failure criteria into tensile loading situations is complex. Such situations cannot be modeled by this test and, in any case, are of limited value due to the inability of rock masses to sustain appreciable tension. Therefore, the failure envelopes and stress relations discussed in Sections 1.3.2.2 and 1.3.2.4, respectively, are defined only for confining pressures greater than, or equal to, zero.

1.4 References.

1.4.1 ASTM, 1978, Test Designation D2664, "Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens without Pore Pressure Measurements," Annual Book of ASTM Standards, Part 19.

1.4.2 Foundation Sciences, Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI-310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.3 ISRM Commission on Standardization of Laboratory and Field Tests on Rock, 1979, "Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials", Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 16, No. 2.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is usually accomplished by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to Standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require

more tests than relatively uniform rocks, in order to evaluate the results with equal certainty. Triaxial tests using at least three different confining pressures are recommended to determine the failure envelope and the relation between σ_1 and σ_3. At each confining pressure and temperature, no fewer than three tests are recommended.

2.3.3 Nonhomogeneities. Discontinuities in the rock mass, such as joints, inclusions, voids, etc., can influence the mass strength of the rock. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Preservation of moisture condition of samples.

The moisture condition of the rock can influence the measured strength. The moisture content of the rock core shall be preserved between the time of recovery and the time of testing as described in Procedure GT-A.4, "Handling and Storage of Rock Core Samples," see Ref. 1.4.2.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanism for applying axial load to the sample, the reaction frame containing the load mechanism and triaxial cell, and the control system for the load mechanism. The loading frame shall be constructed to apply a continuously increasing load to the sample at either a constant strain or constant stress rate.

3.2 Triaxial confining chamber.

The confining chamber consists of a hollow cylinder and end caps to contain the confining fluid, platens to support the sample, and a flexible impermeable membrane to cover the sample during testing.

3.2.1 Cylinder and end caps. The cell design shall be such that changes in confining pressure do not directly cause changes in axial load and vice versa.

3.2.2 Platens. The diameter of the platens shall be equal to or greater than the diameter of the sample. Rock materials which are subject to large deformations prior to failure, such as salt and some shales, shall be tested using platens sized so that the lateral expansion of the sample does not exceed the platen diameter. The platens shall be at least 0.625 in. (15.9 mm) thick.[1] The surfaces shall be flat to within 0.0002 in. (0.005 mm)

[1] ISRM, 1979 (see Ref. 1.4.3)

and hardened to at least Rockwell HRC 58[1,2]. One of the two platens shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.2.3 Flexible, impermeable membrane. This membrane encloses the rock sample and prevents penetration by the confining fluid. Generally, a sleeve of natural or synthetic rubber or other plastic polymer is used. Copper or lead jackets are sometimes used. The membrane shall be inert relative to the confining fluid at the test temperature, and shall cover small pores in the sample without rupturing when confining pressure is applied. Plastic or silicone rubber coatings may be applied directly to the sample, providing these materials do not penetrate and strengthen the sample. The ends of the sample shall not be coated, and care must be taken to form an effective seal where the platen and sample meet. Membranes formed by coatings shall be subject to the same performance requirements as elastic sleeve membranes.

3.3 Confining pressure system.

The confining pressure system consists of the pressurizing fluid and the means of applying pressure. The fluid shall be stable at the expected test temperatures. High temperature hydraulic oil, silicone oil, or inert gas may be used. The pressurization system shall be capable of maintaining the confining pressure to within ± 1% throughout the test.

3.4 Transducers.

Transducers are required to determine the axial load on the sample and the confining pressure.

3.4.1 Axial load. An electronic load cell is recommended to measure axial load on the sample. The cell shall have an accuracy of at least ± 100 lb (± 45.4 kg), including errors introduced by the excitation and readout system, and a resolution of at least 50 lb (22.7 kg). Alternatively, a pressure gage or electronic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.4.2 Confining pressure. The confining pressure shall be measured with a hydraulic pressure gage or transducer having an accuracy of ± 1% of the confining pressure, including errors due to readout equipment, and a resolution of at least 0.5% of the confining pressure.

3.4.3 Temperature. The instrument chosen to monitor temperature depends primarily on the test apparatus and the maximum test temperature. Special Limits of Error thermocouples or platinum

[1] ISRM, 1979 (see Ref. 1.4.3)
[2] ASTM, 1978 (see Ref. 1.4.1)

resistance thermometers (RTD's) are recommended. The temperature transducer shall be accurate to at least ± 0.9°F (± 0.5°C) with a resolution of at least 0.18°F (0.1°C). The temperature shall be measured at three locations, with one sensor near the top, one at mid-height, and one near the bottom of the sample.

3.5 Heating unit.

The heating unit shall be capable of maintaining a uniform temperature throughout the sample to within 7.2°F (4°C). The unit shall incorporate controls so that the sample may be heated at a rate no greater than 3.6°F (2°C) per minute. The mean temperature of the sample shall vary by no more than 3.6°F (2°C) during the test.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Core size. Rock cores of NX size (2 in. nominal diameter; 51 mm) or larger are recommended. However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.

4.1.2 Length-to-diameter ratio. Cores shall be cut to a length-to-diameter ratio of 2.0 to 3.0.[1,2]

4.1.3 Smoothness. The sides of the core shall be relatively smooth, free of abrupt irregularities and straight to within 0.01 in. (0.25 mm) over the length of the sample.[1]

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in.[(2)] (0.25 mm over 51 mm).

4.1.5 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in.[(2)] (0.05 mm).

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in.[1,2] (0.025 mm).

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally, water is used for hard rock, but other materials may require special fluids such as saturated brine for salt or glycerin for slaking mudstones.

4.1.8 Voids. Large voids in the sides of the sample, such as vesicles, may be filled with paraffin, plastic or similar material to provide support for the flexible membrane. Such filling material shall not penetrate the rock, and shall have an elastic

[1] ISRM, 1979 (see Ref. 1.4.3)
[2] ASTM, 1978 (see Ref. 1.4.1)

modulus no greater than 10% of the intact rock modulus.

4.1.9 Measurements. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of measuring to 0.001 in. (0.025 mm). The diameter of the sample shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measurements shall be recorded as shown on Form L-B.4-1.

4.1.10 Membrane application. To avoid membrane disruption caused by moisture escaping from the sample during the test, the sample shall be dried at 221°±4°F (105° ± 2°C) for at least 24 hours prior to membrane application. To prevent thermal fracturing, the heating and cooling rate for drying the sample shall not exceed 3.6°F (2°C) per minute. If thermo-setting or heat-shrink materials are used for the membrane, the heating and cooling rates shall also not exceed 3.6°F (2°C) per minute.

4.2 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platens and sample are aligned with the loading axis to within 0.05 in. (1.27 mm).

4.2.2 Heating rate. The sample will be heated to the test temperature at a rate not to exceed 3.6°F (2°C) per minute, to prevent thermal fracturing.

4.2.3 Thermal equilibrium. The test sample shall be maintained at the test temperature for at least 2 hours prior to testing.

4.2.4 Loading sequence. During the initial stage of the test, the axial load and confining pressure shall be increased concurrently at rates such that the axial stress in the sample is maintained equal to the confining pressure.

4.2.5 Axial loading. The axial load shall be applied smoothly and continuously at either a constant strain or constant stress rate. For hard rock, the loading rate should produce failure within 5 to 15 minutes; a typical constant stress rate is 25 psi (0.17 MPa) per second, while constant strain rates are on the order of 1 to 100με per second. For rocks which exhibit significant nonelastic behavior, such as rock salt and some shales, constant stress loading rates are generally slower, for example, in the range of 0.5 to 4 psi (0.003 to 0.03 MPa) per second; constant strain rates will depend on the material properties. The same loading rate shall be used for all samples in a particular suite of tests.

4.2.6 Sample failure. Failure is recognized when the load on the sample becomes constant or decreases. The maximum load sustained by the sample before this occurs is the failure load.

[1] ISRM, 1979 (see Ref. 1.4.3)

4.2.7 Data recording requirements. The data shown on Form L-B.4-1 shall be recorded as a minimum for this test.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types, confining pressures, or temperatures, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program, and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material, or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each

variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary of results. A table of results including rock suites, temperatures, confining pressure, average strength values, ranges and uncertainties shall be presented.

5.4.2 Individual test results. A table of results including, as as a minimum, individual sample numbers, test temperatures, confining pressures, and strengths shall be presented.

5.4.3 Mohr's circles. A Mohr's circle diagram as discussed in Sections 1.3.2.2 and 1.3.2.3 of this procedure shall be presented for each suite of samples at each temperature as appropriate. A summary table of the angle of internal friction and the unconfined shear strength should also be presented.

5.4.4 Strength vs. confinement. A graph of the relationship between σ_1 and σ_3, as discussed in Section 1.3.2.4, shall be presented for each suite of rocks as appropriate. A summary table of unconfined compressive strengths and relational constants as defined in Equation 3 shall also be presented.

5.4.5 Other. The following other types of analysis or presentation may be included as appropriate.

5.4.5.1 Strength as a function of temperature.

5.4.5.2 Histograms of results.

5.4.5.3 Correlation of strength with other rock properties such as modulus of deformation or specific gravity.

5.4.5.4 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean value of compressive strength, range, standard deviation, and 95% confidence limits for the mean shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

Each completed test Form L-B.4-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing. the completed Form L-B.4-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-B.4-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of L-B.4-1.

Triaxial Compressive Strength of Rock Core -
Elevated Temperature

Test Data Sheet - Form L-B.4-1

Project_____ Sample No._____

Date_____ Rock Type_____

Tested By_____ Test Temperature_____

Equipment Description	Serial No.	Date of Calibration

Sample Height _____ Sample Diameter _____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____

Confining Pressure_____

Time Required for Failure_____

Loading Rate_____

Failure Load_____

Strength_____

Sketch of Sample After Failure

Remarks:

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Engineer_____ Date_____

Procedure L-B.5

Tensile Strength of Rock Core -

Brazilian Tensile Method

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines the splitting tensile strength of a cylindrical rock specimen when subjected to a compressive line load applied across a diameter.

1.1.2 Limitations.

1.1.2.1 The results of the splitting tensile strength test may differ from results of the direct tensile test because of of differences in the loading conditions.

1.1.2.2 The calculations used in this procedure were derived for isotropic, homogeneous materials. The results of this test should be considered approximate for materials which are anisotropic and/or nonhomogeneous.

1.2 General description of the test.

A rock core sample is cut to length. A continuously increasing compressive load is applied across a diameter of the sample to cause tensile failure across the diameter. Splitting tensile strength is determined from the peak load.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Load - the total diametral force acting on the sample.

1.3.1.2 Pressure, stress - force per unit area.

1.3.1.3 Failure - the inability of the sample to sustain increased load without rapidly increasing deformation or destructive fracturing.

1.3.1.4 Strength - the stress in the rock at which failure occurs.

1.3.2 Equations.

The splitting tensile strength, σ_t, is calculated:

$$\sigma_t = \frac{2P}{\pi LD} \qquad (1)$$

where:

P = Maximum load sustained by the sample
L = Length of the sample
D = Diameter of the sample

1.4 Reference.

1.4.1 Foundation Sciences Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI-310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.2 ISRM Commission on Standardization of Laboratory and Field Tests, 1978, "Suggested Methods for Determining Tensile Strength of Rock Materials" Int. J. Rock Mech. Min. Sci. and Geotech. Abstr., 15, No. 3.

1.4.3 U.S. Army Corps of Engineers, 1980, Procedure RTH 113-80, "Standard Method of Test for Determining the Splitting Strength of Rock (Brazilian Method)", Rock Testing Handbook, Geotechnical Laboratory, Waterways Experiment Station, Vicksburg, Miss.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalifed under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are state in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and type of rock cores tested depends partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. A sufficient number of samples should be tested to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than a relatively uniform rock to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Foliation, bedding, joints and fractures, and other features can significantly affect the tensile strength of the rock. Tests of these features should be included to estimate their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Preservation of moisture condition of samples.

The moisture condition of the rock can influence the measured strength. The moisture content of the rock core shall be preserved between the time of recovery and the time of testing, as described in GT-A.4, "Handling and Storage of Rock Core Samples," see Ref. 1.4.1.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus.

3.1 Loading frame.

The loading frame consists of the mechanism for applying load to the sample, the reaction frame containing the load mechanism and the control system for the load mechanism. The loading frame shall be constructed to apply a continuously increasing load to the sample at a constant rate of stress.

3.2 Bearing surfaces.

Flat or curved bearing surfaces may be used. In either case, a spherical seat shall be incorporated in the load train so that the bearing surface can be rotated and tilted through small angles in any direction.

3.2.1 Flat bearing surfaces. Flat bearing surfaces shall have a diameter at least as large as the specimen diameter. The bearing surface shall not depart from a plane by more than 0.0005 in. (0.013 mm) when new and shall be maintained to within 0.001 in. (0.025 mm). The bearing surfaces shall be hardened to at least Rockwell HRC 58.

3.2.2 Curved bearing surfaces. Curved bearing surfaces may be used to reduce the contact stresses. The radius of curvature of these surfaces shall be designed so that the arc of contact with the specimen will in no case exceed 15°. The surfaces shall be smooth to within 0.0005 in. (0.013 mm) when new and maintained to within 0.001 in. (0.025 mm). The curved bearing surfaces shall be hardened to at least Rockwell HRC 58.

3.3 Bearing strips.

Cardboard bearing strips 0.03 to 0.05 in. (0.76 to 1.27 mm) thick shall be placed between the bearing surfaces and the sample during testing to reduce stress concentrations.

3.4 Load transducer.

An electronic load cell is recommended to measure diametral load on the sample. The cell should have an accuracy of at least ± 100 lb (± 45.4 kg), including errors introduced by the excitation and readout system, and a resolution of at least 50 lb (22.7 kg). Alternatively, a pressure gage or electronic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Size. The test sample shall be a circular disk with thickness-to-diameter ratio of 0.5. The diameter of the specimen shall be at least 10 times greater than the largest mineral grain constituent. NX size (2 in. nominal diameter; 51 mm) or larger core is recommended.

4.1.2 Smoothness. The sides of the core shall be smooth to ± 0.005 in. (± 0.13 mm). Smoothness shall be measured along four lines parallel to the axis of the core, at 90° intervals, two of which will be along the diameter to be loaded. The maximum variation shall be recorded as shown on Form L-B.5-1.

4.1.3 Ends. The ends of the sample shall be cut perpendicular to the axis of the core sample to within 0.25. The end roughness shall not exceed 0.01 in. (0.25 mm). The rocks shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally water is used for hard rock, but other types of rock may require different fluids, such as saturated brine for rock salt or glycerin for expansive shales.

4.1.4 Diameter. The diameter of the test sample shall be measured to the nearest 0.001 in. (0.025 mm) by the average of three measurements, one of which shall be across the diameter to be loaded. The measurements shall be recorded as shown on Form L-B.5-1.

4.1.5 Length. The length of the sample shall be measured to the nearest 0.01 in. (0.25 mm) by the average of three measurements, one of which shall be along the diametral plane to be loaded. The measurements shall be recorded as shown on Form L-B.5-1.

4.2 Testing.

4.2.1 Alignment. The desired vertical orientation of the sample shall be indicated by marking a diametral line on each end of the sample. These lines shall be used in centering the sample in the testing machine to ensure proper orientation. The line of thrust of the loading train and the marked sample diameter shall be carefully aligned.

4.2.2 Loading. The load shall be applied smoothly and continuously at a constant stress rate so that failure occurs in 1 to 10 minutes. For NX samples, a rate of approximately 100 to 200 psi (0.69 to 1.38 MPa) tensile stress in the sample per minute is recommended.

4.2.3 Failure. Failure is recognized by the initial tensile crack induced in the sample. The load at which this occurs is the failure load. Care shall be taken to observe this load, as the sample may continue to sustain increasing load for a short time.

4.2.4 Data recording requirements during test. The data shown on Form L-B.5-1 shall be recorded as a minimum for this test.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Application of the test results is beyond the scope of this procedure, but may be an integral part of some testing programs. If so, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of the testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types or orientations, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and type of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum.

Further detail depends on the intended application of the results, but in general is not required. In variable material or not several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations and limitations in their applications shall be noted and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual test situation conforms to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary of results. A table of results including the test suites, average tensile strength values, ranges and uncertainties shall be presented.

5.4.2 Individual test results. A table of individual results including, as a minimum, sample number, rock types or formations, orientations (if appropriate) and tensile strengths shall be presented.

5.4.3 Other. The following types of data analyses may be included if appropriate.

5.4.3.1 Correlation of tensile strength with other rock properties, such as compressive strength or specific gravity.

5.4.3.2 Comparison of tensile strength with other rock type or the results of earlier studies.

5.4.3.3 Histograms of results.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated, including the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean value of the tensile strength, range, standard deviation, and 95% confidence limits for the mean shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement error to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

Each complete test Form L-B.5-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this Section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-B.5-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-B.5-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-B.5-1.

Tensile Strength of Rock Core -
Brazilian Tensile Method

Test Data Sheet - Form L-B.5-1

Project _____ Sample No._____

Date_____ Orientation_____

Tested By_____ Rock Type_____

Equipment Description	Serial No.	Date of Calibration

Sample Diameter _____ Sample Length _____

_____ _____

_____ _____

Average _____ Average _____

Smoothness: Orientation: 0^o 90^o 180^o 270^o

Maximum Deviation: _____ _____ _____ _____

Loading Rate _____

Time for Failure_____

Failure Load _____

Tensile Strength_____

Sketch of sample after failure.

Remarks:

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Engineer_____ Date_____

Procedure L-C.1

Uniaxial Compressive Modulus of Deformation of Rock Core - Ambient Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines deformational properties of a cylindrical rock specimen at ambient temperature under uniaxial compressive loading. Results obtained include the modulus of deformation, Poisson's ratio, and stress-strain curves.

1.1.2 Limitations. The calculations used in this procedure assume a homogeneous, isotropic rock sample. The effects of anisotropy may be estimated by using selectively oriented cores for test specimens.

1.2 General description of the test.

A rock core sample is cut to length and the ends are machined flat. The sample is placed in a loading frame. Load is applied to the sample and the stress and deformation are measured concurrently. Several loading cycles are performed. Modulus of deformation and Poisson's ratio are calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Axial strain - the deformation per unit length of the sample parallel to the long axis of the core.

1.3.1.2 Diametral strain - the deformation per unit length across a diameter of the sample.

1.3.1.3 Load - the total axial force acting on the sample.

1.3.1.4 Stress - force per unit area.

1.3.2 Equations.

1.3.2.1 The axial strain, ε_a, is calculated using:

$$\varepsilon_a = \frac{\Delta l}{l_o} \qquad (1)$$

where:

l_o = original axial length

Δl = change in axial length

1.3.2.2 The diametral strain, ε_d, is calculated using:

$$\varepsilon_d = \frac{\Delta d}{d_o} \qquad (2)$$

where:

l_o = original diameter

Δl = change in diameter.

In the case of measuring the circumferential strain, ε_c, the circumference is $C = \pi d$, and the change in circumference is $\Delta C = \pi d$. Consequently, the circumferential strain is related to diametral strain by:

$$\varepsilon_c = \frac{\Delta C}{C_o} = \frac{\Delta d}{d_o} \tag{3}$$

so that

$$\varepsilon_c = \varepsilon_d \tag{4}$$

where C_o and d_o are original specimen circumference and diameter, respectively.

1.3.2.3 The volumetric strain, ε_v, is calculated using:

$$\varepsilon_v = \varepsilon_a + 2\varepsilon_d \tag{5}$$

1.3.2.4 The axial stress, σ, is calculated using:

$$\sigma = \frac{P}{A} \tag{6}$$

where:

P = load on the sample

A = cross-sectional area of the sample.

1.3.2.5 The modulus of deformation, E, is calculated using:

$$E = \frac{d\sigma}{d\varepsilon_a} \tag{7}$$

where:

$d\sigma$ = change in stress

$d\varepsilon_a$ = change in axial strain.

The modulus is the slope of the stress-axial strain curve.

The change in stress and strain may be evaluated in several ways. The tangent modulus is the instantaneous slope of

the stress-strain curve, as shown on Figure 1.1. The recovery modulus is the tangent modulus during the unloading portion of the pressurization cycle.

The secant modulus is the slope of the curve evaluated between initial conditions and a subsequent state of stress and strain, as shown on Figure 1.2.

The average modulus is similar to the secant modulus, except stress and strain are evaluated over an arbitrary portion of the stress-strain curve as shown on Figure 1.3.

1.3.2.6 Poisson's ratio, ν , is the negative ratio of the diametral strain, ε_d, to the axial strain, ε_a:

$$\nu = -\frac{\varepsilon d}{\varepsilon a} \tag{8}$$

In practice, because of the nonlinearities displayed by rock at low stress levels, Poisson's ratio is calculated at a given stress level from the slopes of the axial and diametral stress-strain curves:

$$\nu = -\frac{\text{slope of axial stress-strain curve}}{\text{slope of diametral stress-strain curve}} \tag{9}$$

1.4 References

1.4.1 ASTM, 1978, Test Designation D 3148, "Standard Test Method for Elastic Moduli of Rock Core Specimens in Uniaxial Compression," Annual Book of ASTM Standards, Part 19.

1.4.2 Foundation Sciences, Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI-310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.3 ISRM Commission on Standardization of Laboratory and Field Tests, 1979, "Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials", Int. J. Mech. Min. Sci. and Geomech. Abstr., 16, No. 2.

1.4.4 U.S. Bureau of Mines, 1974, "Elastic Behavior of Rocks under Uniaxial Compression", Bureau of Mines Test Procedures for Rocks, Information Circular IC 8628.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

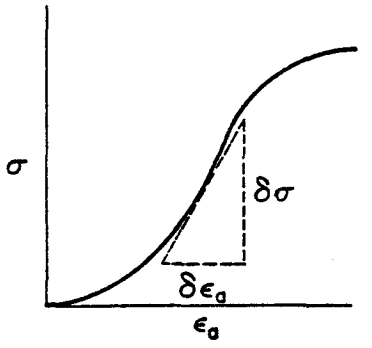

FIG. I.1 STRESS AND STRAIN USED IN CALCULATION OF TANGENT MODULUS.

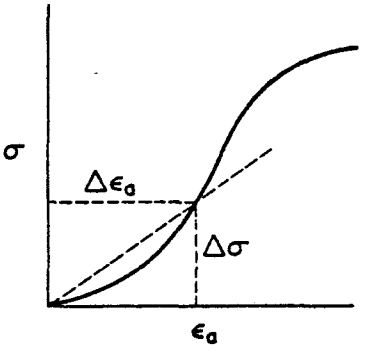

FIG. I.2 STRESS AND STRAIN USED IN CALCULATION OF SECANT MODULUS.

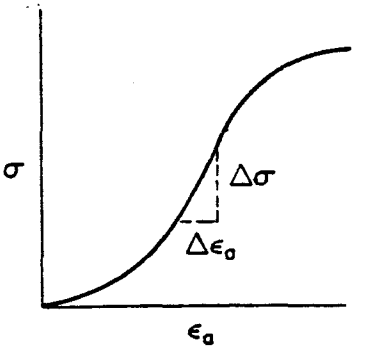

FIG. I.3 STRESS AND STRAIN USED IN CALCULATION OF AVERAGE MODULUS.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to Standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the ultimate application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities in the rock mass, such as joints, inclusions, voids, etc. can affect deformational properties. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Preservation of moisture condition of samples.

The moisture condition of the rock can influence the measured deformational properties. The moisture content of the rock core shall be preserved between the time of recovery and time of testing as described in Procedure GT-A.4, "Handling and Storage of Rock Core Samples," see Ref. 1.4.2.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanism for applying load to the sample, the reaction frame containing the load mechanism, and the control system for the load mechanism. The loading frame shall be constructed to apply load to the sample at either a constant strain or constant stress rate. A stiff testing machine shall be used.

3.2 Platens.

The diameter of the platens shall be equal to or greater than the diameter of the sample. Rock materials which are subject to large deformations prior to failure, such as salt and some shales, shall be tested using platens sized so that the lateral deformation does not exceed the platen diameter. The platens shall be at least 0.625 in. (15.9 mm) thick.[1] The surfaces shall be flat to within 0.0002 in. (0.005 mm) and hardened to at least Rockwell HRC 58.[1,2] One of the two platens shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.3 Transducers.

Transducers are required to determine the axial load and the deformation of the sample.

3.3.1 Axial load. An electronic load cell is recommended to measure axial load on the sample. The cell shall have an accuracy of at least $\pm$100 lb (45.4 kg), including errors introduced by the excitation and readout system, and a resolution of at least 50 lb (22.7 kg). Alternatively, a pressure gage or electronic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.3.2 Deformation. The deformation transducer shall have a resolution of at least 10×10^{-6} strain and an accuracy of at least $\pm 20 \times 10^{-6}$ strain, including errors introduced by excitation and readout equipment. Transducer selection criteria depend primarily on the type of rock and the structure within the sample. Longer gage lengths are recommended for coarse-grained or nonhomogeneous samples. In no case shall the gage length be less than 10 times the diameter of the largest mineral grain.

3.3.2.1 Electrical resistance strain gages shall have a resistance of no less than 350 ohms to avoid the effects of self heating. An axial and a circumferential gage shall be mounted at mid-height of the sample on each end of a diameter. The two axial gages shall be connected in a half Wheatstone bridge configuration to correct for bending. The half Wheatstone bridge configuration shall be completed by connecting two axial strain gages mounted on a similar rock sample, to provide temperature compensation. This sample shall be placed as near the test sample as practical during testing. The two circumferential gages shall be wired in a similar configuration.

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[1] ISRM, 1979, (see Ref. 1.4.3)
[2] ASTM, 1978, (see Ref. 1.4.1)

3.3.2.2 Dial gages shall be graduated to at least 0.0001 in. Two dial gages shall be mounted across a diameter of the sample or platen, or three dial gages shall be mounted at 120° intervals. If they are attached to the sample directly, the points of attachment shall not be within D/2 of the sample end, where D is the sample diameter.

3.3.2.3 Linear variable differential transducers (LVDTs) shall be mounted across a diameter or at 120° intervals on the sample or platens using a non-magnetic attachment. If they are attached to the sample directly, the points of attachment shall not be within D/2 of the sample end.

3.3.2.4 Other types of deformation transducers may be employed provided they satisfy the criteria stated in the above specifications.

3.4 Power supplies.

The type of power supply and voltage level will be determined by the type of deformation transducer used. In all cases, however, the power supply shall be capable of providing accurate and stable voltage to at least ±10mV.

3.5 Signal conditioning and readout.

These devices may be either manual or automatic. Voltmeters shall be capable of reading to 10^{-3} mV. The cumulative error of the readout equipment and transducers shall meet the requirements of Section 3.3 above.[3]

4.0 Procedure

4.1 Sample preparation.

4.1.1 Core size. Rock cores of NX-size (2 in. nominal diameter; 51 mm) or larger are recommended. However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.[1]

4.1.2 Length-to-diameter ratio. The core shall be cut to a length-to-diameter ratio of 2.0 to 3.0.[1,2]

4.1.3 Smoothness. The sides of the core shall be relatively smooth, free of abrupt irregularities and straight to within 0.01 in. (0.25 mm) over the length of the sample.[1]

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in. (0.25 mm over 51 mm).[2]

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[1] ISRM, 1979, (see Ref. 1.4.3)
[2] ASTM, 1978, (see Ref. 1.4.1)

4.1.5 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in.[1] (0.05 mm).

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in.[1,2] (0.025 mm).

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock shall not be degraded during the machining process. Thermal facturing shall be prevented by cooling with an appropriate fluid as required. Generally water is used for hard rock, but other materials may require special fluids, such as saturated brine for salt or glycerin for slaking mudstones.

4.1.8 Measurements. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of measuring to 0.001 in. (0.025 mm). The diameter of the specimen shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measure ments shall be recorded as shown on Form L-C.1-1.

4.2 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platens and sample are aligned with the loading axis to within 0.05 in. (1.27 mm).

4.2.2 Initial readings. Prior to taking initial readings, the electronic transducers shall be allowed sufficient time to warm up, and they shall be powered continuously during the test. Initial readings shall be taken under zero load conditions, except for the weight of the platens and load train.

4.2.3 Loading rate. The axial load shall be applied smoothly and continuously at either a constant strain or constant stress rate. For hard rock, the loading rate should produce failure within 5 to 15 minutes;[2] a typical constant stress rate is 25 psi (0.17 MPa) per second, while constant strain rates are on the order of 1 to 100με per second. For rocks which exhibit significant nonelastic behavior, such as salt and some shales, constant stress loading rates are generally slower, for example in the range of 0.5 to 4 psi (0.003 to 0.03 MPa) per second; constant strain rates will depend on the material type. The same loading rate shall be used for all samples in a particular suite of tests.

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[1] ASTM, 1978, (see Ref. 1.4.1)
[2] ISRM, 1979, (see Ref. 1.4.3)

4.2.4 Pressurization cycles. Three load cycles are recommended for general testing. Maximum stress for each cycle should be approximately 15, 30, and 50% of the estimated unconfined compressive strength of the sample, respectively. The sample may be taken to failure after the cyclic loading.

4.2.5 Measurement intervals. Stress and strain shall be measured at approximately equal stress increments during the loading and unloading portion of each cycle. At least 10 measurements shall be taken over each portion of the load cycle to generate sufficient data points for the stress-strain curve. More frequent readings may be required near and after failure.

4.2.6 Test environment. The temperature of the test environment shall be constant to within ±3.6°F (±2°C) during the test.

4.2.7 Data recording requirements. The exact format of data recording depends on the data acquisition system. As a minimum, however, the information shown on Form L-C.1-1 is required and the general format of Form L-C.1-1 shall be followed as closely as practicable.

4.3 Corrections to data.

4.3.1 Voltage normalization. If electronic transducers are used, output voltages shall be normalized with respect to input voltages at each pressure increment.

4.3.2 Bridge effects. If strain gages are used, corrections shall be made for the effects of Wheatstone bridge non-linear response.

4.3.3 Platen effects. If the deformation transducers are mounted on the loading platens rather than on the sample itself, corrections shall be made for the elastic response of the platens.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In this case, an applications sections compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the nature of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations and limitations in their applications shall be noted and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary. A summary table of results including test suite designations, average modulus of deformation and Poisson's ratio values, ranges, and uncertainties shall be presented.

5.4.2 Individual results. A table of results for individual tests including, as a minimum, sample number, rock type, modulus of deformation, and Poisson's ratio shall be presented.

5.4.3 Other. The following other types of analyses and presentations may be included as appropriate.

5.4.3.1 Modulus and Poisson's ratio as a function of stress, as well as non-linear behavior in general.

5.4.3.2 Volumetric strain vs. stress.

5.4.3.3 Histograms of results.

5.4.3.4 Post-failure behavior.

5.4.3.5 Correlation of results with other rock properties, such as specific gravity or dynamic modulus of deformation.

5.4.3.6 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample Variability. For each suite of rock samples, the mean value of the modulus of deformation and Poisson's ratio, range, standard deviation and 95% confidence limit for the mean shall be calculated as a minimum. The uncertainty of the sample set shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended Data.

The following shall be included as a minimum in an appendix.

5.6.1 Test data. A completed data Form L-C.1-1 shall be included for each test.

5.6.2 Stress-strain curves. A stress-strain curve shall be included for each test.

6.0 Quality Assurance.

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-C.1-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-C.1-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of L-C.1-1.

Uniaxial Compressive Modulus of Deformation of Rock Core - Ambient Temperature

Test Data Sheet - Form L-C.1-1

Project _____ Sample No. _____

Date _____ Test Temperature _____

Tested By _____ Loading Rate _____

Rock Type _____

Equipment Description	Serial No.	Date of Next Calibration

Sample Height _____ Sample Diameter _____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____

Loading Rate _____

Load Reading	Axial Strain Reading	Diametral Strain Reading

Load Reading	Axial Strain Reading	Diametral Strain Reading

Test Supervisor _____ Date _____

Quality Assurance _____ Date _____

Project Engineer _____ Date _____

Procedure L-C.2

Uniaxial Compressive Modulus of Deformation of Rock Core - Elevated Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines deformational characteristics of a cylindrical rock specimen at elevated temperature under uniaxial compressive loading. Results obtained include the modulus of deformation, Poisson's ratio, and stress-strain curves.

1.1.2 Limitations. The calculations used in this procedure assume a homogeneous, isotropic rock sample. The effects of anisotropy may be estimated by using selectively oriented cores for test specimens.

1.2 General description of the test.

A rock core sample is cut to length and the ends are machined flat. The sample is placed in a loading frame, and heated to the specified temperature. Load is applied to the sample, and load and deformation of the sample are measured concurrently. Several loading cycles are performed. Modulus of deformation and Poisson's ratio are calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Axial strain - the deformation per unit length of the sample parallel to the long axis of the core.

1.3.1.2 Diametral strain - the deformation per unit length across a diameter of the sample.

1.3.1.3 Load - the total axial force acting on the sample.

1.3.1.4 Stress - force per unit area.

1.3.2 Equations.

1.3.2.1 The axial strain, ε_a, is calculated using:

$$\varepsilon_a = \frac{\Delta l}{l_o} \qquad (1)$$

where:

l_o = original axial length

Δl = change in axial length.

1.3.2.2 The diametral strain, ε_d, is calculated using:

$$\varepsilon_d = \frac{\Delta d}{d_o} \tag{2}$$

where:

d_o = original diameter

Δd = change in diameter.

In the case of measuring the circumferential strain, ε_c, the circumference is $C = \pi d$, and the change in circumference is $C = \pi \Delta d$. Consequently, the circumferential strain is related to diametral strain by:

$$\varepsilon_c = \frac{\Delta C}{C_o} = \frac{\Delta d}{d_o} \tag{3}$$

so that

$$\varepsilon_c = \varepsilon_d \tag{4}$$

where C_o and d_o are original specimen circumference and diameter, respectively.

1.3.2.3 The volumetric strain, ε_v, is calcualted by using:

$$\varepsilon_v = \varepsilon_a = 2\varepsilon_d \tag{5}$$

1.3.2.4 The axial stress, σ, is calculated as:

$$\sigma = \frac{P}{A} \tag{6}$$

where:

P = load on the sample

A = cross-sectional area of the sample.

1.3.2.5 The modulus of deformation, E, is calculated using:

$$E = \frac{d\sigma}{d\varepsilon_a} \tag{7}$$

where:

$d\sigma$ = change in stress

$d\varepsilon_a$ = change in axial strain.

The modulus is the slope of the stress-strain curve.

The change in stress and strain may be evaluated in several ways. The tangent modulus is the instantaneous slope of the stress-strain curve, as shown on Figure 1.1. The recovery modulus is the tangent modulus during the unloading portion of the pressurization cycle.

The secant modulus is the slope of the curve evaluated between initial conditions and a subsequent state of stress and strain as shown on Figure 1.2.

The average modulus is similar to the secant modulus, except stress and strain are evaluated over an arbitrary portion of the stress-strain curve as shown on Figure 1.3.

1.3.2.6 Poisson's ratio, μ, is the negative ratio of the diametral strain, ε_d, to the axial strain, ε_a:

$$\mu = -\frac{\varepsilon d}{\varepsilon a} \qquad (8)$$

In practice, because of the non-linearities displayed by rock at low stress levels, Poisson's ratio is calculated at a given stress level from the slopes of the axial and diametral stress-strain curves:

$$\mu = \frac{\text{slope of axial stress-strain curve}}{\text{slope of diametral stress-strain curve}} \qquad (9)$$

1.4 References.

1.4.1 ASTM, 1978,, Test Designation D 3148, "Standard Test Method for Elastic Moduli of Rock Core Specimens in Uniaxial Compression." Annual Book of ASTM Standards, Part 19.

1.4.2 ISRM, 1979, Commission on Standardization of Laboratory and Field Tests, "Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials," Int. J. Rock Mech. min. Sci. and Geomech. Abstr., 16, No. 2.

1.4.3 U.S. Bureau of Mines, 1974, "Elastic Behavior Under Uniaxial Compression," Bureau of Mines Test Procedures for Rocks, Information Circular IC 8628.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

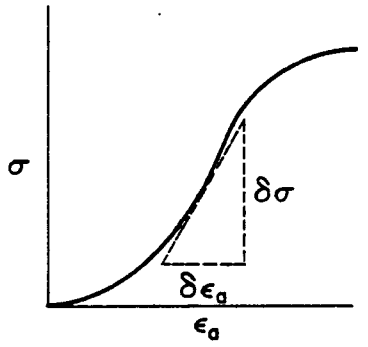

FIG. I.1 STRESS AND STRAIN USED IN CALCULATION OF TANGENT MODULUS.

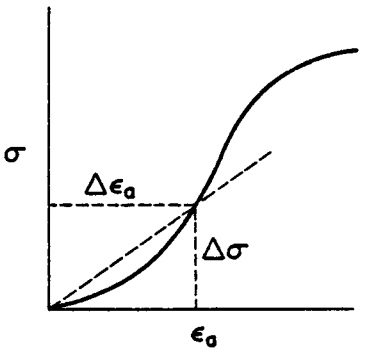

FIG. I.2 STRESS AND STRAIN USED IN CALCULATION OF SECANT MODULUS.

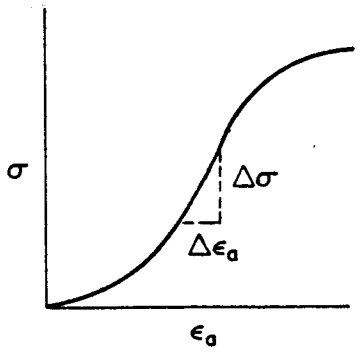

FIG. I.3 STRESS AND STRAIN USED IN CALCULATION OF AVERAGE MODULUS.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the ultimate application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities in the rock mass, such as joints, inclusions, voids, etc. can significantly influence the deformational properties of the rock. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanism for applying load to the sample, the reaction frame containing the load mechanism, and the control system for the load mechanism. The loading frame shall be constructed to apply a continuously increasing load to the sample at either a constant strain or constant stress rate. A stiff testing machine shall be used.

3.2 Platens.

The diameter of the platens shall be equal to or greater than the diameter of the sample. Rock materials which are subject to large deformations prior to failure, such as salt and some shales, shall be tested using platens sized so that the lateral deformation does not exceed the platen diameter. The platens

shall be at least 0.625 in. (15.9 mm) thick.[1] The surfaces shall be flat to within 0.0002 in. (0.005 mm) and hardened to at least Rockwell HRC 58[1,2]. One of the two platens shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.3 Transducers.

Transducers are required to determine the axial load, the deformation, and the temperature of the sample.

3.3.1 Axial load. An electronic load cell is recommended to measure axial load on the sample. The cell shall have an accuracy of at least ± 100 lb (45.4 kg), including errors introduced by the excitation and readout system, and a resolution of at least 50 lb (22.7 kg). Alternatively, a pressure gage or electronic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.3.2 Deformation. The deformation transducers shall have a resolution of at least 10×10^{-6} strain and an accuracy of at least ± 20×10^{-6} strain, including errors introduced by excitation and readout equipment. Transducer selection criteria depend primarily on the type of rock and the structure within the sample. Longer gage lengths are recommended for coarse-grained or nonhomogeneous samples. In no case shall the gage length be less than 10 times the diameter of the largest mineral grain.

3.3.2.1 Electrical resistance strain gages shall have a resistance of no less than 350 ohms to avoid the effects of self heating. An axial and a circumferential gage shall be mounted at mid-height of the sample on each end of a diameter. The two axial gages shall be connected in a half Wheatstone bridge configuration to correct for bending. The two circumferential gages shall be wired in a similar configuration. Each half Wheatstone bridge configuration shall be completed with two precision resistors having a temperature coefficient no greater than 1×10^{-6} ppm/°C.

3.3.2.2 Dial gages shall be graduated to at least 0.0001 in. (0.0025 mm). They shall be mounted on the platens outside of the heater unit. Two dial gages shall be mounted across a diameter, or three dial gages shall be mounted at 120° intervals.

3.3.2.3 Linear variable differential transformers (LVDT s) shall be mounted across a diameter or at 120° intervals on the sample or platens using a non-magnetic attachment.

[1] ISRM, 1979, (See Ref. 1.4.2)
[2] ASTM, 1978, (See Ref. 1.4.1)

If they are attached to the sample directly, the points of attachment shall not be within D/2 of the sample end, where D is the sample diameter.

3.3.2.4 Other types of deformation transducers may be employed provided they satisfy the criteria stated in the above specifications.

3.3.3 Temperature. The instrument chosen to monitor temperature depends primarily on the test apparatus and the maximum test temperature. Special Limits of Error thermocouples or platinum resistance thermometers (RTDs) are recommended. The temperature transducer shall be accurate to at least ± 0.9°F (± 0.5°C) with a resolution of at least 0.18°F (0.1°C). Temperature shall be measured at three locations, with one sensor near the top, one at mid-height, and one near the bottom of the sample.

3.4 Power supplies.

The type of power supply and voltage level will be determined by the type of deformation transducer used. In all cases, however, the power supply shall be capable of providing voltage accurate and stable to at least ± 10mV.

3.5 Signal conditioning and readout.

These devices may be either manual or automatic. Voltmeters shall be capable of reading to 10^{-3}mV. The cumulative error of the readout equipment and transducers shall meet the requirements of Section 3.3 above.

3.6 Heating unit.

The heating unit shall be capable of maintaining a uniform temperature throughout the sample to within 7.2°F (4°C). The unit shall incorporate controls so that the sample may be heated at a rate no greater than 3.6 °F (2°C) per minute. The mean temperature of the sample shall vary by no more than 3.6°F (2°C) during the test.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Core size. Rock cores of NX size (2 in. nominal diameter; 51 mm) or larger are recommended. However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.[1]

4.1.2 Length-to-diameter ratio. The core shall be cut to a length-to-diameter ratio of 2.0 to 3.0.[1,2]

4.1.3 Smoothness. The sides of the core shall be relatively smooth, free of abrupt irregularities and straight to within 0.01 in. over the length of the sample.[1]

[1]ISRM, 1979, (See Ref. 1.4.2)
[2]ASTM, 1978, (See Ref. 1.4.1)

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in.[2] (0.25 mm over 51 mm).

4.1.5 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in.[2] (0.05 mm).

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in.[1,2] (0.025 mm).

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally water is used for hard rock, but other materials may require special fluids, such as saturated brine for salt or glycerin for slaking mudstones.

4.1.8 Measurements. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of reading to 0.001 in. (0.025 mm). The diameter of the specimen shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measurements shall be recorded as shown on Form L-C.2-1.

4.2 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platens and sample are aligned with the loading axis to within 0.05 in.

4.2.2 Heating rate. The sample shall be heated to the test temperature at a rate not to exceed 3.6°F (2°C) per minute to prevent thermal fracturing.

4.2.3 Thermal equilibrium. The test sample shall be considered to have attained thermal equilibrium when the deformation transducer output is stable for at least three readings taken over a period of no less than 30 minutes. Stability is defined as a constant reading showing only the effects of normal instrument and heater unit fluctuations. Prior to taking these readings, the electronic transducers shall be allowed sufficient time to warm up, and they shall be powered continuously during the test.

4.2.4 Initial readings. Initial readings shall be taken under zero load conditions, except for the weight of the platens and load train.

4.2.5 Loading rate. The axial load shall be applied smoothly and continuously at either a constant strain or constant stress rate. For hard rock the loading rate should produce failure within 5 to 15 minutes; a typical constant stress rate is 25 psi (0.17 MPa) per second, while constant strain rates are generally

[1] ISRM, 1979, (See Ref. 1.4.2)
[2] ASTM, 1978, (See Ref. 1.4.1)

on the order of 1 to 100 με per second. For rocks which exhibit significant nonelastic behavior, such as salt and some shales, constant stress loading rates are generally slower, for example in the range of 0.5 to 4 psi (0.003 to 0.03 MPa) per second; constant strain rates will depend on the material type. The same loading rate shall be used for all samples in a particular suite of tests.

4.2.6 Pressurization cycles. Three axial load cycles are recommended for general testing. Maximum stress for each cycle should be approximately 15, 30, and 50%, respectively, of the estimated unconfined compressive strength of the sample. The sample may be taken to failure after the cyclic loading.

4.2.7 Measurement intervals. Stress and strain shall be measured at approximately equal stress increments during the loading and unloading portions of each cycle. At least 10 measurements shall be taken over each portion of the load cycle to generate sufficient data points for the stress-strain curve. More frequent readings may be required near and after failure.

4.2.8 Test environment. The temperature of the test environment external to the heater unit shall be constant to within 3.6°F (2°C) during the test.

4.2.9 Data recording requirements. The exact format of data recording depends on the data acquisition system. As a minimum, however, the information shown on Form L-C.2-1 is required and the general format of Form L-C.2-1 shall be followed as closely as practicable.

4.3 Corrections to data.

4.3.1 Voltage normalization. If electronic transducers are used, output voltages shall be normalized with respect to input voltages at each pressure increment.

4.3.2 Bridge effects. If strain gages are used, corrections shall be made for the effects of Wheatstone bridge nonlinear response.

4.3.3 Platen effects. If the deformation transducers are mounted on the loading platen rather than the sample itself, corrections shall be made for the elastic response of the platens.

5.0 Reporting

The purpose of this section is to establish minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In this case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the nature of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types or at several temperatures, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations and limitations in their applications shall be noted and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary. A summary table of results including test suite designations, temperatures, average modulus of deformation and Poisson's ratio values, ranges, and uncertainties shall be presented.

5.4.2 Individual results. A table of results for individual tests including, as a minimum, sample number, rock type, test temperature, modulus of deformation, and Poisson's ratio shall be presented.

5.4.3 Other. The following types of analyses and presentations may be included as appropriate.

5.4.3.1 The variation of modulus of deformation and Poisson's ratio with temperature.

5.4.3.2 Modulus and Poisson's ratio as a function of stress level. Non-linear behavior may also be discussed.

5.4.3.3 Volumetric strain vs. stress at temperature.

5.4.3.4 Post-failure behavior.

5.4.3.5 Histogram of results.

5.4.3.6 Correlation of results with other rock properties, such as specific gravity, dynamic modulus of deformation, or ambient temperature modulus of deformation.

5.4.3.7 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean value of the modulus of deformation and Poisson's ratio range, standard deviation and 95% confidence limits for the mean shall be calculated as a minimum. The uncertainty of the

sample set shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine if the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

The following shall be included as a minimum in an appendix.

5.6.1 Test data. A completed data Form L-C.2-1 for each test shall be included.

5.6.2 Stress-strain curves. A stress-strain curve for each test shall be included.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-C.2-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-C.2-1.

6.3.3 Test sign offs. Quality Assurance shall maintain signed-off copies of Form L-C.2-1.

Uniaxial Compressive Modulus of Deformation of Rock Core - Elevated Temperature

Test Data Sheet - Form L-C.2-1

Project_____ Sample No._____

Date_____ Test Temperature_____

Tested By_____ Loading Rate_____

Rock Type_____

Equipment Description	Serial No.	Date of Next Calibration

Sample Height _____ Sample Diameter _____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____

Load Reading	Axial Strain Reading	Diametral Strain Reading

Load Reading	Axial Strain Reading	Diametral Strain Reading

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Enginer_____ Date_____

Procedure L-C.3

Triaxial Compressive Modulus of Deformation of Rock Core - Ambient Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines deformational characteristics of a cylindrical rock specimen at ambient temperature under triaxial compressive loading. Results obtained include the modulus of deformation, Poisson's ratio, and stress strain curves.

1.1.2 Limitations. The calculations used in this procedure assume a homogeneous, isotropic rock sample. The effects of anisotropy may be estimated by using selectively oriented cores for test specimens.

1.2 General description of the test.

A rock core sample is cut to length and the ends are machined flat. The sample is enclosed in a flexible impermeable membrane and placed in a confining chamber. The sample is loaded axially and the confining chamber is pressurized to provide lateral load. When the desired lateral load is achieved, it is held constant. Axial load continues to increase, and load and deformation of the sample are measured concurrently. Several loading cycles are performed. Modulus of deformation and Poisson's ratio are calculated.

1.3 Data Reduction.

1.3.1 Terms and definitions.

1.3.1.1 Axial strain - the deformation per unit length of the sample parallel to the long axis of the core.

1.3.1.2 Diametral strain - the deformation per unit length across a diameter of the sample.

1.3.1.3 Load - the total axial force acting on the sample.

1.3.1.4 Stress - force per unit area.

1.3.2 Equations.

1.3.2.1 The axial strain, ε_a, is calculated using:

$$\varepsilon_a = \frac{\Delta l}{l_o} \qquad (1)$$

where:

l_o = original axial length

Δl = change in axial length.

1.3.2.2 The diametral strain, ε_d, is calculated using:

$$\varepsilon_d = \frac{\Delta d}{d_o} \tag{2}$$

where:

d_o = original diameter

Δd = change in diameter.

In the case of measuring the circumferential strain, ε_c, the circumference is $C = \pi d$, and the change in circumference is $\Delta C = \pi \Delta d$. Consequently, the circumferential strain is related to diametral strain by

$$\varepsilon_c = \frac{\Delta C}{C_o} = \frac{\Delta d}{d_o} \tag{3}$$

so that

$$\varepsilon_c = \varepsilon_d \tag{4}$$

where C_o and d_o are original specimen circumference and diameter, respectively.

1.3.2.3 The volumetric strain, ε_v, is calculated using:

$$\varepsilon_v = \varepsilon_a + 2\,\varepsilon_d \tag{5}$$

1.3.2.4 The axial stress, σ, is calculated using:

$$\sigma = \frac{P}{A} \tag{6}$$

where:

P = load on the sample

A = cross-sectional area of the sample.

1.3.2.5 The modulus of deformation, E, is calculated using:

$$E = \frac{d\sigma}{d\varepsilon_a} \tag{7}$$

where:

$d\sigma$ = change in stress

$d\varepsilon_a$ = change in axial strain.

The modulus is the slope of the stress-axial strain curve.

The change in stress and strain may be evaluated in several ways. The tangent modulus is the instantaneous slope of the stress-strain curve, as shown on Figure 1.1. The recovery modulus is the tangent modulus during the unloading portion of the pressurization cycle.

The secant modulus is the slope of the curve evaluated between initial conditions and a subsequent state of stress and strain, as shown on Figure 1.2.

The average modulus is similar to the secant modulus, except stress and strain are evaluated over an arbitrary portion of the stress-strain curve as shown on Figure 1.3.

1.3.2.6 Poisson's ratio, μ, is the negative ratio of the diametral strain, ε_d, to the axial strain, ε_a:

$$\mu = -\frac{\varepsilon d}{\varepsilon a} \qquad (8)$$

In practice, because of the nonlinearities displayed by rock at low stress levels, Poisson's ratio is calculated at a given stress level from the slopes of the axial and diametral stress-strain curves:

$$\mu = -\frac{\text{slope of axial stress-strain curve}}{\text{slope of diametral stress-strain curve}} \qquad (9)$$

1.4 References

1.4.1 ASTM, 1978, Test Designation D2664, "Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens without Pore Pressure Measurements." Annual Book of ASTM Standards, Part 19.

1.4.2 Foundation Sciences, Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI-310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.3 ISRM Commission on Standardization of Laboratory and Field Tests, 1978, "Suggested Method for Determining the Strength of Rock Materials in Triaxial Compression." Int. J. of Rock Mech. Min. Sci. and Geomech. Abstr., 15, No. 2.

1.4.4 ISRM, 1979, "Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials", Int. J. of Rock Mech. Min. Sci. and Geomech. Abstr., 16, No. 2.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified

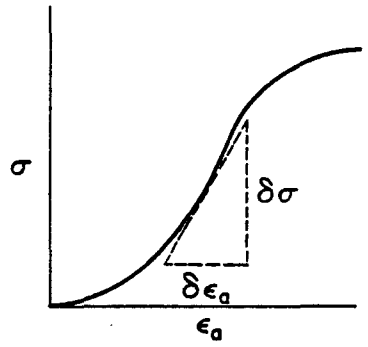

FIG. I.1 STRESS AND STRAIN USED IN CALCULATION OF TANGENT MODULUS.

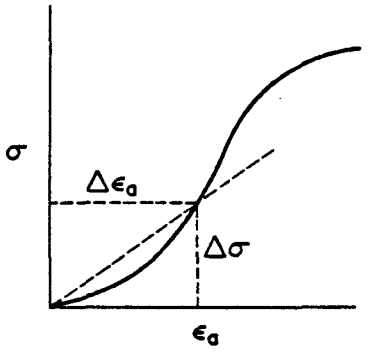

FIG. I.2 STRESS AND STRAIN USED IN CALCULATION OF SECANT MODULUS.

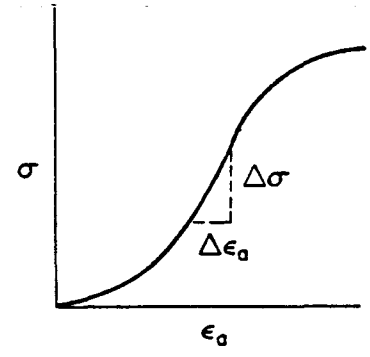

FIG. I.3 STRESS AND STRAIN USED IN CALCULATION OF AVERAGE MODULUS.

under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities in the rock mass, such as joints, inclusions, voids, etc. can significantly influence the deformational properties of the rock. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Preservation of moisture condition of samples.

The moisture condition of the rock can influence the measured deformational properties. The moisture content of the rock core shall be preserved between the time of recovery and testing as described in Procedure GT-A.4, "Handling and Storage of Rock Core Samples," see Ref. 1.4.2.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanism for applying axial load to the sample, the reaction frame containing the load mechanism and triaxial cell, and the control system for the load mechanism. The loading frame shall be constructed to apply a

continuously increasing load to the sample at either a constant strain or constant stress rate. A stiff testing machine shall be used.

3.2 Triaxial confining chamber.

The confining chamber consists of a hollow cylinder and end caps to contain the confining fluid, platens to support the sample, and a flexible impermeable membrane to cover the sample during testing.

3.2.1 Cylinder and end caps. The cell design shall be such that changes in confining pressure do not directly cause changes in axial load and vice versa.

3.2.2 Platens. The diameter of the platens shall be equal to or greater than the diameter of the sample. Rock materials which are subject to large deformations prior to failure, such as salt and some shales, shall be tested using platens sized so that the lateral expansion of the sample does not exceed the platen diameter. The platens shall be at least 0.625 in. (15.9 mm) thick.[1] The surfaces shall be flat to within 0.0002 in. (0.005 mm) and hardened to at least Rockwell HRC 58.[1,2] One of the two platen shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.2.3 Flexible, impermeable membrane. This membrane encloses the rock sample and prevents the confining fluid from penetrating it. Generally, a sleeve of natural or synthetic rubber or plastic polymer is used. Copper or lead jackets are sometimes used. The membrane shall be inert relative to the confining fluid, and shall cover small pores in the sample without rupturing when confining pressure is applied. Plastic or silicone rubber coatings may be applied directly to the sample, providing these materials do not penetrate and strengthen the sample. The ends of the sample shall not be coated, and care must be taken to form an effective seal where the platen and sample meet. Membranes formed by coatings shall be subject to the same performance requirements as elastic sleeve membranes. Materials requiring a heat cure shall not be used.

3.3 Confining pressure system.

The confining pressure system consists of the pressurizing fluid and the means of applying pressure. The fluid is generally hydraulic oil or water, but inert gas may also be used. The pressurization system shall be capable of maintaining the confining pressure constant to within ±1% throughout the test.

3.4 Transducers.

Transducers are required to determine the axial load, the confining pressure, and the deformation of the sample.

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[1] ISRM, 1979 (see Ref. 1.4.4)
[2] ASTM, 1978 (see Ref. 1.4.1)

3.4.1 Axial load. An electronic load cell is recommended to measure axial load on the sample. The cell shall have an accuracy of at least ±100 lb (±45.4 kg), including errors introduced by the excitation and readout system, and a resolution of at least 50 lb (22.7 kg). Alternatively, a pressure gage or electornic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.4.2 Confining pressure. The confining pressure shall be measured with a hydraulic pressure gage or electronic transducer having an accuracy of at least ±1% of the confining pressure, including errors due to readout equipment, and a resolution of at least 0.5% of the confining pressure.

3.4.3 Deformation. The deformation transducers shall have a resolution of at least 10×10^{-6} strain and an accuracy of at least $\pm 20 \times 10^{-6}$ strain, including errors introduced by excitation and readout equipment. Transducer selection criteria depend primarily on the type of rock and the structure within the sample. Longer gage lengths are recommended for coarse-grained or non-homogeneous samples. In no case shall the gage length be less than 10 times the diameter of the largest mineral grain.

3.4.3.1 Electrical resistance strain gages shall have a resistance of no less than 350 ohms to avoid the effects of self heating. An axial and a circumferential gage shall be mounted at mid-height of the sample on each end of a diameter. The two axial gages shall be connected in a half Wheatstone bridge configuration to correct for bending. The two circumferential gages shall be wired in a similar configuration. Each half Wheatstone bridge configuration shall be completed with two precision resistors having a temperature coefficient no greater than 1×10^{-6} ppm/°C.

3.4.3.2 Dial gages shall be graduated to at least 0.0001 in. Dial gages shall be mounted on the platens, using two dial gages mounted across a diameter or three dial gages mounted at 120° intervals.

3.4.3.3 Linear variable differential transducers (LVDTs) shall be mounted across a diameter or at 120° intervals on the sample or platens using a non-magnetic attachment. If they are attached to the sample directly, the points of attachment shall not be within D/2 of the sample end, where D is the sample diameter.

3.4.3.4 Radial deformation may be measured with a volumetric apparatus (dilatometer). This device shall have a resolution of at least 0.002 in.^{3} (32.8 mm^3) and an accuracy of at least 0.5% of the radial strain of the sample.

3.4.3.5 Other types of deformation transducers, such as the Schuler gage, may be employed provided they satisfy the criteria stated in the above specifications.

3.5 Power supplies.

The type of power supply and voltage level will be determined by the type of deformation transducer used. In all cases, however, the power supply shall be capable of providing voltage accurate and stable to at least $\pm$10mV.

3.6 Signal conditioning and readout.

These devices may be either manual or automatic.[3] Voltmeters shall be capable of reading to 10^{-3} mV. The cumulative error of the readout equipment and transducers shall meet the requirements of Section 3.4 above.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Core size. Rock cores of NX size (2 in. nominal diameter; 51 mm) or larger are recommended.[1] However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.[1]

4.1.2 Length-to-diameter ratio. Cores shall be cut to a length-to-diameter ratio of 2.0 to 3.0.[1,2]

4.1.3 Smoothness. The sides of the core shall be relatively smooth, free of abrupt irregularities, and straight to within 0.01 in. (0.25 mm) over the length of the sample.[1]

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in.[2] (0.25 mm over 51 mm).

4.1.5 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in.[2] (0.05 mm).

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in.[1,2] (0.025 mm).

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally water is used for hard rock but other materials may require special fluids, such as saturated brine for salt or glycerin for slaking mudstones.

4.1.8 Voids. Large voids in the sides of the sample, such as vesicles, may be filled with paraffin, plastic or similar material to provide support for the flexible membrane. Such filling material shall not penetrate the rock and shall have an elastic modulus no greater than 10% of the intact rock modulus.

4.1.9 Measurements. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of measuring to 0.001 in. (0.025 mm). The diameter of the specimen

[1] ISRM, 1979, (see Ref. 1.4.4)
[2] ASTM, 1978, (see Ref. 1.4.1)

shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and the base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measurements shall be recorded as shown on Form L-C.3-1.

4.2 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platen and sample are aligned with the loading axis to within 0.05 in. (1.25 mm).

4.2.2 Loading sequence. During the initial stage of the test, the axial load and confining pressure shall be increased concurrently at rates such that the axial stress in the sample is maintained equal to the confining pressure.

4.2.3 Initial readings. Initial reading shall be taken when the axial stress is equal to the specified confining pressure and when transducer output is stable. Prior to taking initial readings, the electronic transducers shall be allowed sufficient time to warm up, and they shall be powered continuously during the test.

4.2.4 Loading rate. The axial load shall be applied smoothly and continuously at either a constant strain or constant stress rate. For hard rock, the loading rate should produce failure within 5 to 15 minutes[1]; a typical constant stress rate is 25 psi (0.17 MPa) per second, while constant strain rates are generally on the order of 1 to 100με per second. For rocks which exhibit significant nonelastic behavior, such as salt and some shales, constant stress loading rates are generally slower, for example in the range of 0.5 to 4 psi (0.003 to 0.03 MPa) per second; constant strain rates will depend on the material type. The same loading rates shall be used for all samples in a particular suite of tests.

4.2.5 Pressurization cycles. Three axial load cycles are recommended for general testing. Maximum stress for each cycle should be approximately 15, 30, and 50% of the estimated unconfined compressive strength of the sample, respectively. The sample may be taken to failure after the cyclic loading.

4.2.6 Measurement intervals. Stress and strain shall be measured at appoximately equal stress increments during the loading and unloading portion of each cycle. At least 10 measurements shall be taken over each portion of the load cycle to generate sufficient data points for the stress-strain curve. More frequent readings may be required near and after failure.

4.2.7 Test environment. The temperature of the test environment external to the triaxial cell shall be constant to within 2°C during the test.

4.2.8 Data recording requirements. The exact format of data recording depends on the data acquisition system. As a minimum,

[1] ISRM, 1979, (see Ref. 1.4.4)

however, the information shown on Form L-C.3-1 is required and the general format of Form L-C.3-1 shall be followed as closely as practicable.

4.3 Corrections to data.

4.3.1 Voltage normalization. If electronic transducers are used, output voltages shall be normalized with respect to input voltages at each pressure increment.

4.3.2 Bridge effects. If strain gages are used, corrections shall be made for the effects of Wheatstone bridge nonlinear response.

4.3.3 Platen effects. If the deformation transducers are mounted on the loading platen rather than on the sample itself, corrections shall be made for the elastic response of the platens.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Numbers of samples tested. In a large report covering the results of tests in several rock types or at various confining pressures, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure fabric, grain size, discontinuities, voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report.

The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary. A summary table of results including test suite designations, confining pressures, average modulus of deformation and Poisson's ratio values, ranges, and uncertainties shall be presented.

5.4.2 Individual results. A table of results for individual tests including, as a minimum, sample number, rock type, confining pressure, modulus of deformation, and Poisson's ratio shall be presented.

5.4.3 Other. The following other types of analyses may be included as appropriate.

5.4.3.1 The variation of modulus of deformation and Poisson's ratio with confining pressure.

5.4.3.2 Modulus and Poisson's ratio as a function of stress level. Nonlinear behavior in general may also be discussed.

5.4.3.3 Volumetric strain vs. stress.

5.4.3.4 Post-failure behavior.

5.4.3.5 Histogram of results.

5.4.3.6 Correlation of results with other rock properties, such as specific gravity, dynamic modulus of deformation, or elevated temperature modulus of deformation.

5.4.3.7 Comparisons of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean value of the modulus of deformation and Poisson's ratio, range, standard deviation and 95% confidence limits for the mean shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

The following shall be included as a minimum in an appendix.

5.6.1 Test data. A completed data Form L-C.3-1 for each test shall be included.

5.6.2 Stress-strain curves. A stress-strain curve for each test shall be included.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing the completed Form L-C.3-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-C.3-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of L-C.3-1.

Triaxial Compressive Modulus of Deformation of Rock Core -
Ambient Temperature

Test Data Sheet - Form L-C.3-1

Project _____ Sample No. _____

Date _____ Test Temperature _____

Tested By _____ Confining Pressure _____

Rock Type _____ Loading Rate _____

Equipment Description	Serial No.	Date of Next Calibration

Sample Height _____ Sample Diameter _____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____

Load Reading	Axial Strain Reading	Diametral Strain Reading

Load Reading	Axial Strain Reading	Diametral Strain Reading

Test Supervisor _____ Date _____

Quality Assurance _____ Date _____

Project Engineer _____ Date _____

Procedure L-C.4

Triaxial Compressive Modulus of Deformation of Rock Core - Elevated Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines deformational characteristics of a cylindrical rock specimen at elevated temperature under triaxial compressive loading. Results obtained include the modulus of deformation, Poisson's ratio and stress-strain curves.

1.1.2 Limitations. The calculations used in this procedure assume a homogeneous, isotropic rock sample. The effects of anisotropy may be estimated by using selectively oriented cores for test specimens.

1.2 General description of the test.

A rock core sample is cut to length and the ends are machined flat. The sample is enclosed in a flexible impermeable membrane and placed in a confining chamber. The sample is heated to the specified temperature. It is loaded axially and the confining chamber is pressurized to provide lateral load. When the desired lateral load is achieved, it is held constant. Axial load continues to increase, and load and deformation of the sample are measured concurrently. Several loading cycles are performed. Modulus of deformation and Poisson's ratio are calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Axial strain - the deformation per unit length of the sample parallel to the long axis of the core.

1.3.1.2 Diametral strain - the deformation per unit length across a diameter of the sample.

1.3.1.3 Load - the total axial force acting on the sample.

1.3.1.4 Stress - force per unit area.

1.3.2 Equations.

1.3.2.1 The axial strain, ε_a, is calculated using:

$$\varepsilon_a = \frac{\Delta l}{l_o} \qquad (1)$$

where:

l_o = original axial length

Δl = change in axial length

1.3.2.2 The diametral strain, ε_d, is calculated using:

$$\varepsilon_d = \frac{\Delta d}{d_o} \tag{2}$$

where:

d_o = original diameter

Δd = change in diameter.

In the case of measuring the circumferential strain, ε_c, the circumference is $C = \pi d$, and the change in circumference is $\Delta C = \pi \Delta d$. Consequently, the circumferential strain is related to diametral strain by

$$\varepsilon_c = \frac{\Delta C}{C_o} = \frac{\Delta d}{d_o} \tag{3}$$

so that

$$\varepsilon_c = \varepsilon_d \tag{4}$$

where C_o and d_o are original specimen circumference and diameter, respectively.

1.3.2.3 The volumetric strain, ε_v, is calculated using:

$$\varepsilon_v = \varepsilon_a + 2\varepsilon_d \tag{5}$$

1.3.2.4 The axial stress, σ, is calculated as:

$$\sigma = \frac{P}{A} \tag{6}$$

where:

P = load on the sample

A = cross-sectional area of the sample.

1.3.2.5 The modulus of deformation, E, is calculated using:

$$E = \frac{d\sigma}{d\varepsilon_a} \tag{7}$$

where:

$d\sigma$ = change in stress

$d\varepsilon_a$ = change in axial strain.

The modulus is the slope of the stress-axial strain curve.

The change in stress and strain may be evaluated in several ways. The tangent modulus is the instantaneous slope of the

stress-strain curve, as shown on Figure 1.1. The recovery modulus is the tangent modulus during the unloading portion of the pressurization cycle.

The secant modulus is the slope of the curve evaluated between initial conditions and a subsequent state of stress and strain, as shown on Figure 1.2.

The average modulus is similar to the secant modulus, except stress and strain are evaluated over an arbitrary portion of the stress-strain curve as shown on Figure 1.3.

1.3.2.6 Poisson's ratio, μ, is the negative ratio of the diametral strain, ε_d, to the axial strain, ε_a:

$$\mu = -\frac{\varepsilon d}{\varepsilon_a} \qquad (8)$$

In practice, because of the nonlinearities displayed by rock at low stress levels, Poisson's ratio is calculated at a given stress level from the slopes of the axial and diametral stress-strain curves:

$$\mu = -\frac{\text{slope of axial stress-strain curve}}{\text{slope of diametral stress-strain curve}} \qquad (9)$$

1.4 References.

1.4.1 ASTM, 1978, Test Designation D2664, "Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens without Pore Pressure Measurements." Annual Book of ASTM Standards, Part 19.

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1.4.3 ISRM, 1979, "Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials," Int. J. of Rock Mech. Min. Sci. and Geomech. Abstr., 16, No. 2.

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All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

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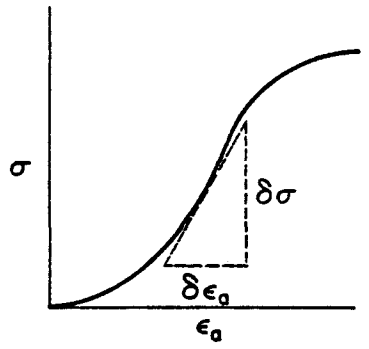

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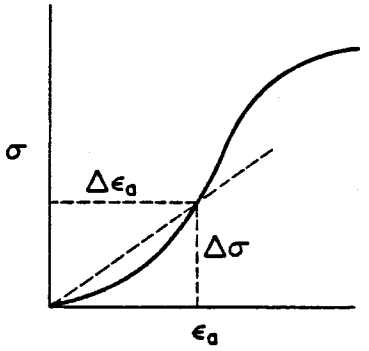

FIG. I.2 STRESS AND STRAIN USED IN CALCULATION OF SECANT MODULUS.

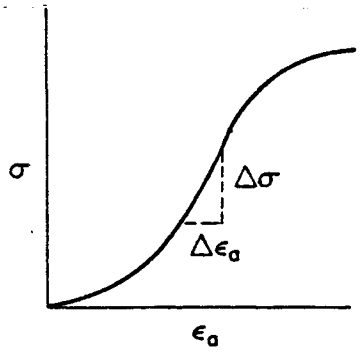

FIG. I.3 STRESS AND STRAIN USED IN CALCULATION OF AVERAGE MODULUS.

performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

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2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanism for applying axial load to the sample, the reaction frame containing the load mechanism and triaxial cell, and the control system for the load mechanism. The loading frame shall be constructed to apply a continuously increasing load to the sample at either a constant strain or constant stress rate. A stiff testing machine shall be used.

3.2 Triaxial confining chamber.

The confining chamber consists of a hollow cylinder and end caps to contain the confining fluid, platens to support the sample, and a flexible impermeable membrane to cover the sample during testing.

3.2.1 Cylinder and end caps. The cell design shall be such that changes in confining pressure do not directly cause changes in axial load and vice versa.

3.2.2 Platens. The diameter of the platens shall be equal to or greater than the diameter of the sample. Rock materials which are subject to large deformations prior to failure, such as salt and some shales, shall be tested using platens sized so that the

lateral expansion of the sample does not exceed the platen diameter. The platens shall be at least 0.625 in. (15.9 mm) thick.[1] The surfaces shall be flat to within 0.0002 in. (0.05 mm) and hardened to at least Rockwell HRC 58.[1,2] One of the two platens shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.2.3 Flexible, impermeable membrane. This membrane encloses the rock sample and prevents the confining fluid from penetrating it. Generally, a sleeve of natural or synthetic rubber or plastic polymer is used. Copper or lead jackets are sometimes used. The membrane shall be inert relative to the confining fluid, and shall cover small pores in the sample without rupturing when confining pressure is applied. Plastic or silicone rubber coatings may be applied directly to the sample, providing these materials do not penetrate and strengthen the sample. The ends of the sample shall not be coated, and care must be taken to form an effective seal where the platen and sample meet. Membranes formed by coatings shall be subject to the same performance requirements as elastic sleeve membranes.

3.3 Confining pressure system.

The confining pressure system consists of the pressurizing fluid and the means of applying pressure. The fluid shall be stable at the expected test temperatures. High temperature hydraulic oil, silicone oil, or inert gas may be used. The pressurization system shall be capable of maintaining the confining pressure constant to within ±1% throughout the test.

3.4 Transducers.

Transducers are required to determine the axial load on the sample, the confining pressure, the deformation, and the temperature.

3.4.1 Axial load. An electronic load cell is recommended to measure axial load on the sample. The cell shall have an accuracy of at least ±100 lb (±45.4 kg), including errors introduced by the excitation and readout system, and a resolution of at least 50 lb (22.7 kg). Alternatively, a pressure gage or electronic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.4.2 Confining pressure. The confining pressure shall be measured with a hydraulic pressure gage or electronic transducer, having an accuracy of at least ±1% of the confining pressure, including errors due to readout equipment and a resolution of at least 0.5% of the confining pressure.

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[1] ISRM, 1979, (see Ref. 1.4.3)
[2] ASTM, 1978, (see Ref. 1.4.1)

3.4.3 Deformation. The deformation transducers shall have a resolution of at least 10×10^{-6} strain and an accuracy of at least $\pm 20 \times 10^{-6}$ strain, including errors introduced by excitation and readout equipment. Transducer selection criteria depend primarily on the type of rock and the structure within the sample. Longer gage lengths are recommended for coarse-grained or nonhomogeneous samples. In no case shall the gage length be less than 10 times the diameter of the largest mineral grain.

3.4.3.1 Electrical resistance strain gages shall have a resistance of no less than 350 ohms to avoid the effects of self heating. An axial and a circumferential gage shall be mounted at mid-height of the sample on each end of a diameter. The two axial gages shall be connected in a half Wheatstone bridge configuration to correct for bending. The two circumferential gages shall be wired in a similar configuration. Each half Wheatstone bridge configuration shall be completed with two precision resistors having a temperature coefficient no greater than 1×10^{-6} ppm/°C.

3.4.3.2 Dial gages shall be graduated to at least 0.0001 in. (0.003 mm). They shall be mounted on the platens outside the heater unit. Two dial gages shall be mounted across a diameter or three dial gages shall be mounted at 120° intervals.

3.4.3.3 Linear variable differential transformers (LVDTs) shall be mounted across a diameter or at 120° intervals on the sample or platens using a non-magnetic attachment. If they are attached to the sample directly, the points of attachment shall not be within D/2 of the sample end, where D is the sample diameter.

3.4.3.4 Radial deformation may be measured with a volumetric apparatus (dilatometer). This device shall have a resolution of at least 0.002 $in.^3$ (32.8 mm^3) and an accuracy of at least 0.5% of the radial strain of the sample.

3.4.3.5 Other types of deformation transducers, such as the Schuler gage, may be employed provided they satisfy the criteria stated in the above specifications.

3.4.4 Temperature. The instrument chosen to monitor temperature depends primarily on the test apparatus and the maximum test temperature. Special Limits of Error thermocouples or platinum resistance thermometers (RTDs) are recommended. The temperature transducers shall be accurate to at least ±0.9°F (±0.5°C) with a resolution of at least 0.18°F (0.1°C). Temperature shall be measured at three locations, with one sensor near the top, one at mid-height, and one near the bottom of the sample.

3.5 Power supplies.

The type of power supply and voltage level will be determined by the type of deformation transducer used. In all cases, however, the power supply shall be capable of providing voltage accurate and stable to at least ±10mV.

3.6 Signal conditioning and readout.

These devices may be either manual or automatic. Voltmeters shall be capable of reading to 10^{-3} mV. The cumulative error of the readout equipment and transducers shall meet the requirements of Section 3.4 above.

3.7 Heating unit.

The heating unit shall be capable of maintaining a uniform temperature throughout the sample to within 4°C. The unit shall incorporate controls so that the sample may be heated at a rate no greater than 3.6°F (2°C) per minute. The mean temperature of the sample shall vary by not more than 3.6°F (2°C) during the test.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Core size. Rock cores of NX size (2 in. nominal diameter) or larger are recommended. However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.[1]

4.1.2 Length-to-diameter ratio. Cores shall be cut to a length-to-diameter ratio of 2.0 to 3.0.[1,2]

4.1.3 Smoothness. The sides of the core shall be relatively smooth, free of abrupt irregularities and straight to within 0.01 in. (0.25 mm) over the length of the sample.

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in.[2] (0.25 mm over 51 mm).

4.1.5 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in.[2] (0.05 mm).

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in.[1,2] (0.025 mm).

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally, water is used for hard rock, but other materials may require special fluids, such as saturated brine for salt or glycerin for slaking mudstones.

[1] ISRM, 1979, (see Ref. 1.4.3)
[2] ASTM, 1978, (see Ref. 1.4.1)

4.1.8 Voids. Large voids in the sides of the sample, such as vesicles, may be filled with paraffin, plastic or similar material to provide support for the flexible membrane. Such filling material shall not penetrate the rock and shall have an elastic modulus no greater than 10% of the intact rock modulus.

4.1.9 Measurements. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of reading to 0.001 in. (0.025 mm). The diameter of the specimen shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measurements shall be recorded as shown on Form L-C.4-1.

4.1.10 Membrane Application. To avoid disruption of the membrane caused by the escape of moisture during the test, the sample shall be dried at 221 ±4°F (105° ±2°C) for at least 24 hours prior to membrane application. To prevent thermal fracturing, the heating and cooling rate for drying the sample shall not exceed 3.6°F (2°C) per minute. If thermo-setting or heat shrink materials are used for the membrane, the heating and cooling rates shall also not exceed 3.6°F (2°C) per minute.

4.2 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platen and sample are aligned with the loading axis to within 0.05 in. (1.25 mm).

4.2.2 Heating rate. The sample will be heated to the test temperature at a rate not to exceed 3.6°F (2°C) per minute to prevent thermal fracturing.

4.2.3 Thermal equilibrium. The test sample shall be considered to have attained thermal equilibrium when the deformation transducer output is stable for at least three readings taken over a period of no less than 30 minutes. Stability is defined as a constant reading showing only the effects of normal instrument and heater unit fluctuations.

4.2.4 Loading sequence. During the initial stage of the test, the axial load and confining pressure shall be increased concurrently at rates such that the axial stress in the sample is maintained equal to the confining pressure.

4.2.5 Initial readings. Initial readings shall be taken when the axial stress is equal to the confining pressure, and the system has reached thermal equilibrium.

4.2.6 Loading rate. The axial load shall be applied smoothly and continuously at either a constant strain or constant stress rate. For hard rock the loading rate should produce failure

within 5 to 15 minutes[1]; a typical constant stress rate is 25 psi (0.17 MPa) per second, while constant strain rates are on the order of 1 to 100 με per second. For rocks which exhibit significant nonelastic behavior, such as salt and some shales, constant stress loading rates are generally slower, for example in the range of 0.5 to 4 psi (0.003 to 0.03 MPa) per second; constant strain rates will depend on the material type. The same loading rate shall be used for all samples in a particular suite of tests.

4.2.7 Pressurization cycles. Three axial load cycles are recommended for general testing. Maximum stress for each cycle should be approximately 15, 30, and 50 %, respectively, of the the estimated unconfined compressive strength of the sample. The sample may be taken to failure after the cyclic loading.

4.2.8 Measurement intervals. Stress and strain shall be measured at approximately equal stress increments during the loading and unloading portion of each cycle. At least 10 measurements shall be taken over each portion of the load cycle to generate sufficient data points for the stress-strain curve. More frequent readings may be required near and after failure.

4.2.9 Test environment. The temperature of the test environment external to the heater unit shall be constant to within 3.6°F (2°C) during the test.

4.2.10 Data recording requirements. The exact format of data recording depends on the data acquisition system. As a minimum, however, the information shown on Form L-C.4-1 is required and the general format of Form L-C.4-1 shall be followed as closely as practicable.

4.3 Corrections to data.

4.3.1 Voltage normalization. If electronic transducers are used, output voltages shall be normalized with respect to input voltages at each pressure increment.

4.3.2 Bridge effects. If strain gages are used, corrections shall be made for the effects of Wheatstone bridge non-linear response.

4.3.3 Platen effects. If the deformation transducers are mounted on the loading platen rather than the sample itself, corrections shall be made for the elastic response of the platens.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

[1] ASTM, 1978 (see Ref. 1.4.1)

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types, at several temperatures, or at various confining pressures, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and type of sample tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material, or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction quations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary. A summary table including test suite designations, temperatures, confining pressures, average modulus of deformation and Poisson's ratio values, ranges, and uncertainties shall be presented.

5.4.2 Individual results. A table of results for individual tests including as a minimum sample number, rock type, test temperature, confining pressure, modulus of deformation, and Poisson's ratio shall be presented.

5.4.3 Other. The following other types of analyses and presentations may be included as appropriate.

5.4.3.1 The variation of modulus of deformation and Poisson's ratio with temperature and confining pressure.

5.4.3.2 Modulus and Poisson's ratio as a function of stress level and confinement. Nonlinear behavior may also be discussed.

5.4.3.3 Volumetric strain vs. stress at temperature, or confinement.

5.4.3.4 Postfailure behavior.

5.4.3.5 Correlation of results with other rock properties, such as specific gravity, dynamic modulus of deformation, on ambient temperature modulus of deformation.

5.4.3.6 Comparison of results to other rock suites or to previous studies.

5.4.3.7 Histogram of results.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean value of the modulus of deformation and Poisson's ratio, the range, standard deviation and 95% confidence limits for the mean shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

The following shall be included as a minimum in an appendix.

5.6.1 Test data. A completed data Form L-C.4-1 for each test shall be included.

5.6.2 Stress-strain curve. A stress-strain curve for each test shall be included.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procdures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-C.4-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-C.4-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-of copies of L-C.4-1.

Triaxial Compressive Modulus of Deformation of Rock Core - Elevated Temperature

Test Data Sheet - Form L-C.4-1

Project _____ Sample No. _____

Date _____ Test Temperature _____

Tested By _____ Confining Pressure _____

Rock Type _____ Loading Rate _____

Equipment Description	Serial No.	Date of Next Calibration

Sample Height _____ Sample Diameter _____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____

Load Reading	Axial Strain Reading	Diametral Strain Reading

Load Reading	Axial Strain Reading	Diametral Strain Reading

Test Supervisor _____ Date _____

Quality Assurance _____ Date _____

Project Engineer _____ Date _____

Procedure L-C.5

Deformation Constants of Rock Core -
Ultrasonic Method

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines the ultrasonic elastic constants of a rock specimen. Results include compressional wave velocity, shear wave velocity, and the elastic properties of deformation modulus, shear modulus, bulk modulus and Poisson's ratio.

1.1.2 Limitations. The equations used in this procedure were derived for homogeneous, isotropic materials. Departure from these conditions will cause progressively greater error in calculated deformation properties. Hence, this test is recommended for isotropic or slightly anisotropic materials only. However, accurate shear and compressive wave velocities may be obtained using this procedure regardless of the degree of anisotropy.

1.2 General description of the test.

A rock sample is cut to length and the ends are machined flat. The sample is positioned between a transmitting transducer and a receiving transducer. If the test is to be conducted in a stress field, the specified load is applied to the sample. Ultrasonic compressional and shear wave pulses are transmitted through the sample. Travel times are measured. The ultrasonic elastic constants are then calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Anisotropic - the condition of having different properties in different directions.

1.3.1.2 Compressional wave - wave motion where the directions of vibration and propagation are the same; P-wave.

1.3.1.3 Shear wave - wave motion where the direction of vibration is transverse to the direction of propagation; S-wave.

1.3.1.4 Stress - force per unit area.

1.3.1.5 Travel time - the time required for a wave to travel a specified distance.

1.3.1.6 Wave velocity - the speed at which a wave travels through the rock.

1.3.2 Equations.

1.3.2.1 The corrected travel time, T_c, is calculated using:

$$T_c = T_m - T_z \quad (1)$$

where:

T_m = measured travel time

T_z = zero length time correction.

1.3.2.2 The P-wave velocity, V_p, is calculated using:

$$V_p = \frac{L_p}{T_{cp}} \quad (2)$$

where:

L_p = distance travelled by the P wave

T_{cp} = corrected travel time for P wave.

1.3.2.3 The S-wave velocity, V_s, is calculated using:

$$V_s = \frac{L_s}{T_{cs}} \quad (3)$$

where:

L_s = distance travelled by the S-wave

T_{cs} = corrected travel time for S-wave.

1.3.2.4 The modulus of deformation, E, is calculated using:

$$E = \frac{\rho V_s^2 (3V_p^2 - 4V_s^2)}{(V_p^2 - V_s^2)} \quad (4)$$

where:

ρ = density of the sample.

1.3.2.5 Poisson's ratio, μ , calculated using:

$$\mu = \frac{(V_p^2 - 2V_s^2)}{2(V_p^2 - V_s^2)} \quad (5)$$

1.3.2.6 The shear modulus, G, is calculated using:

$$G = \rho V_s^2 \quad (6)$$

1.3.2.7 The bulk modulus, K, is calculated using:

$$K = \frac{\rho}{3}(3V_p^2 - 4V_s^2) \quad (7)$$

1.4 References

1.4.1 ASTM, 1978, Test Designation D 2845, "Standard Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock", Annual Book of ASTM Standards, Part 19.

1.4.2 Foundation Sciences, Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI-310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.3 ISRM Commission on Standardization of Laboratory and Field Tests, 1978, "Suggested Methods for Determining Sound Velocity", Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 15.

1.4.4 U.S. Bureau of Mines, 1974, "Elastic Response to Ultrasonic Pulse", Bureau of Mines Test Procedures for Rocks. Information Circular IC 8628.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement system. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while

a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities in the rock mass, such as joints, inclusions, voids, etc. can significantly influence the ultrasonic velocities of the rock. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Preservation of moisture condition of samples.

The moisture condition of the rock can influence the measured velocities. If the rock is to be tested under natural conditions, the moisture content of the rock core shall be preserved between the time of recovery and time of testing as described in Procedure GT-A.4, "Handling and Storage of Rock Core Sample," see Ref. 1.4.2.

2.5 Density determination.

The density of the rock sample shall have been determined as described in Procedure L-A.1, "Bulk Density of Rock Samples".

2.6 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

The schematic layout of the equipment is shown on Fig. 3.1.

3.1 Loading frame.

The loading frame is used to apply a uniaxial stress to the sample only if testing is to be done under stressed conditions. The loading frame consists of the mechanism for applying load to the sample through the transducers, the reaction frame containing the load mechanism, and the control system for the load mechanism. The frame shall be capable of maintaining a constant load to within 1% for the duration of the test.

3.2 Axial load transducer.

The axial load shall be measured if the sample is tested under stress. An electronic load cell is recommended. The cell should have an accuracy of at least $\pm$1% of the stress level, including errors introduced by the excitation and readiout system, and a resolution of 0.5% of the stress level. Alternatively, a pressure

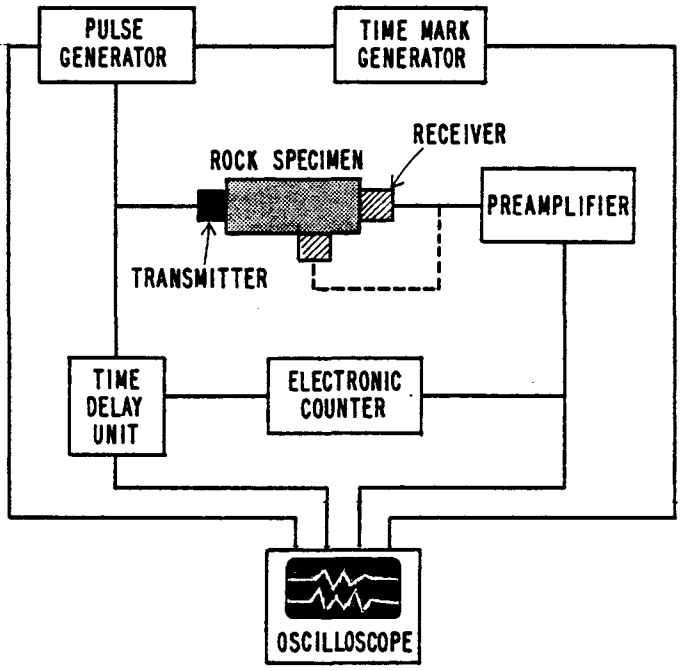

FIG. 3.1 SCHEMATIC OF EQUIPMENT TEST SET-UP(AFTER ISRM,1978)

gage or electronic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.3 Pulse generator.

An electronic pulse generator shall satisfy the following requirements:[1]

pulse form: sine-, square, step-wave pulse;
pulse width: 1-10s;
frequency range: 100 kHz-2MHz;
repetition frequency: 10-10^3 repetitions per second;
pulse voltage: to be compatible to transducer used, as high as transducers allow.

The pulse generator must have a trigger-pulse output to trigger an oscilloscope (trigger-signal).

3.4 Ultrasonic transducers.

The transducers shall consist of a transmitter which converts electrical pulses into mechanical pulses and a receiver which converts mechanical pulses into electrical pulses. Environmental conditions such as ambient temperature, moisture, humidity, and impact should be considered in selecting the transducer element. Piezoelectric ceramics (e.g. barium titanate or lead-zirconate-titanate) in the form of plates, discs, rods, rings or spheres to generate pulses in the frequency range 100kHz-2MHz are recommended.[1] It is usually necessary to use different piezoelectric transducers for compressional or shear-wave transmission and receiving, e.g. cylindrical discs (radius>>thickness) acting in the thickness and radial mode for transmitting and receiving compressional waves; shear plates operating in the shear mode for transmitting and receiving shear waves. In order to eliminate scatter and poor wave arrival, the transmitter should generate wavelengths at least three times the average grain size of the sample.[2] For tests conducted under an axial load, the transducers will serve as platens to transmit the load to the sample.

3.5 Preamplifer.

A voltage preamplifer is required if the voltage output of the receiving transducer is relatively low, or if the display and timing units are relatively insensitive. To preserve fast rise times, the frequency response of the preamplifier shall drop no more than 2 dB over a frequency range from 5 kHz to four times the resonance frequency of the receiver.[2]

[1] ISRM, 1978 (see Ref. 1.4.3)
[2] ASTM, 1978 (see Ref. 1.4.1)

3.6 Time mark generator.

The time mark generator is used to control the pulse generator and send timing marks to the display unit.

3.7 Display unit.

The wave form from the receiving transducer shall be displayed on a cathode ray oscilloscope. A dual beam instrument is recommended. The oscilloscope shall have a flat frequency response from 0 to at least 5 MHz[2] and a maximum sweep rate of 2×10^{-7} second per in. (7.9×10^{-9} second per mm).

3.8 Electronic counter.

An electronic counter with provisions for time interval measurements is recommended.

3.9 Time delay unit.

A time delay unit shall be used to delay the display trigger pulse relative to the transmitter pulse. The delay unit shall be adjustable with a range of at least 0 to 20 μ second.[1]

4.0 Procedure

4.1 Sample preparation.

4.1.1 Dimensions. The shape of the samples tested may be prismatic, cylindrical, or spherical. The ratio of the distance between the transducers to the minimum lateral dimension shall not exceed 5.0. The distance between the transducers shall be at least 10 times the average grain size.[1,2]

4.1.2 Surface preparation. The surfaces to be tested will be flat to within 0.001 in. (0.025 mm). The two opposite surfaces to be tested shall be parallel to within 0.005 in. over 1 in.[1] (0.125 mm over 25.4 mm). For samples with curved surfaces, the width of the flat area shall be the minimum required to achieve adequate transducer coupling.

4.1.3 Measurements. The distance between transducers will be measured at three equally spaced locations to the nearest 0.001 in. (0.025 mm). The average distance between parallel test surfaces shall be the wave travel distance. For the profiling method described in Section 4.2.4, the distance shall be measured from the center of the transmitting transducer to the center of the receiving transducer. The distances shall be recorded as shown on Form L-C.5-1.

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[1] ASTM, 1978(see Ref. 1.4.1)
[2] ISRM, 1978(see Ref. 1.4.3)

4.2 Procedure.

4.2.1 Zero time determination. Zero time is determined by placing the face of the transmitting transducer against the face of the receiving transducer. The travel time for the waves produced during this operation is zero time. The zero times for the P and S-wave transducers shall be recorded as shown on Form L-C.5-1.

4.2.2 Sample/transducer coupling. In order to ensure proper wave transmission across the sample-transducer interface, a thin layer of coupling medium such as water, high-vacuum grease, phenyl salicylate, or other resin shall be applied to the surfaces of the sample to be tested. A small load may be applied to the transducer to seat it against the sample.

4.2.3 Wave measurements. P and S waves shall be generated individually. At least three determinations of travel time for each type of wave shall be made. The average shall be used in the calculations.

4.2.4 Receiver location. Generally the receiver is placed in a fixed position on the opposite side of the sample from the transmitter. For some sample shapes, however, the receiver may be positioned at several points along the side of the sample while the transmitter remains fixed (profiling). This method produces travel time vs. distance curves, from which the wave velocities may be calculated.

4.2.5 Data recording requirements. Test data shall be recorded as shown on Form L-C.5-1. An oscilloscope camera is desirable for recording wave forms.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Numbers of samples tested. In a large report covering the results of tests in several rock types or at various axial loads, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure, fabric, grain size, discontinuities, voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary of Results. Summary tables for each rock property (e.g., modulus of deformation, Poisson's ratio) shall be prepared. The information shall include as a minimum rock suite designation, number of tests, average value, range, and uncertainties.

5.4.2 Individual results. A summary table of individual test results shall be prepared including sample number, wave velocities, and calculated material properties as a minimum.

5.4.3 Other. The following other types of analyses or presentations may be included as appropriate.

5.4.3.1 Photographs of wave forms.

5.4.3.2 Histograms of results.

5.4.3.3 Correlation with other rock properties such as specific gravity or static modulus of deformation.

5.4.3.4 Comparison of results to other rock suites or to previous studies.

5.4.3.5 Relationship of measured properties with moisture content or stress.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean values of the deformational properties, ranges, standard deviations and 95% confidence limits for the means shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

Each completed test Form L-C.5-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-C.5-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-C.5-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of L-C.5-1.

Deformation Constants of Rock Core -
Ultrasonic Method

Test Data Sheet - Form L-C.5-1

Project_____ Sample No._____

Date_____ Rock Type_____

Tested By_____ Density_____

Test Temperature_____ Stress_____

Equipment Description	Serial No.	Date of Next Calibration

Distance _____ P-wave zero time: _____

_____

_____ S-wave zero time: _____

Average:_____

Velocity

P-wave: _____ S-wave: _____

_____ _____

_____ _____

Average:_____ Average: _____

Remarks:

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Engineer_____ Date_____

Procedure L-D.1

Uniaxial Compressive Creep of Rock Core -
Ambient Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. The objective of this test is to evaluate the time-dependent strain (creep) of a rock core sample subjected to a constant uniaxial stress.

1.1.2 Limitations. This procedure does not discuss analysis of creep data.

1.2 General description of the test.

A rock core sample is cut to length and the ends are machined flat. The sample is placed in a loading frame. An axial load is applied to the sample. The load is held constant for the duration of the test. Sample deformation is monitored periodically.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Strain - deformation per unit length of sample.

1.3.1.2 Load - total axial force acting on a sample.

1.3.1.3 Stress - axial force per unit area of the sample.

1.3.1.4 Instantaneous deformation - deformation occurring immediately upon loading sample due to elastic response, as shown on Figure 1.1.

1.3.1.5 Creep - deformation with time under constant load.

1.3.1.6 Transient creep - initial phase of creep during which deformation occurs at a diminishing rate, as shown on Figure 1.1.

1.3.1.7 Steady-state creep - second phase of creep during which deformation occurs at a constant rate, as shown on Figure 1.1.

1.3.2 Equations.

1.3.2.1 The axial strain, ε_a, is calculated using:

$$\varepsilon_a = \frac{\Delta L}{L_o} \qquad (1)$$

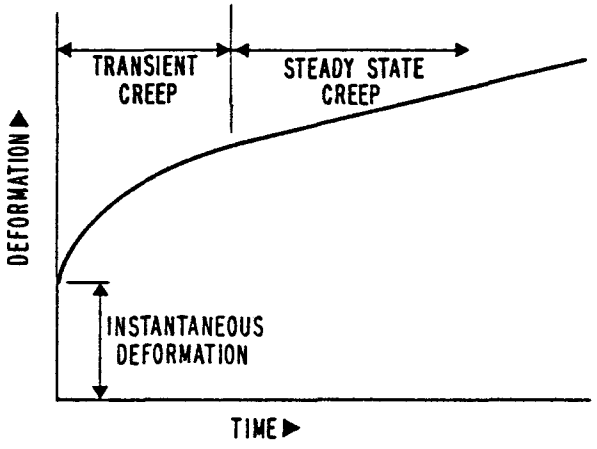

FIG. I.I IDEALIZED CREEP CURVE

where:

ΔL = change in measured axial length

L_o = original measured axial length.

1.3.2.2 The axial stress, σ_1, is calculated using:

$$\sigma_1 = \frac{P}{A} \qquad (2)$$

where:

P = load on the sample

A = cross-sectional area of the sample.

1.3.2.3 The analysis of rock deformation with time is complex and nonstandard. The user is referred to the references in Section 1.4.

1.4 References.

1.4.1 ASTM, 1978, Test Designation D2938, "Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens," Annual Book of ASTM Standards, Part 19.

1.4.2 Carter, N.L., 1976, "Steady State Flow of Rocks," Rev. Geophys. Space Phys., 14.

1.4.3 Carter, N.L. and Kirby, S.H., 1978, "Transient Creep and Semibrittle Behavior of Crystalline Rocks," Pure and Appl. Geophys., 116.

1.4.4 Foundation Sciences, Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI-310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.5 ISRM Commission on Standardization of Laboratory and Field Tests, 1979, "Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials," Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 16, No. 2.

1.4.6 U.S. Army Corps of Engineers, 1980, Test Standard RTH 205-80, "Standard Method of Test for Creep of Rock in Compression," Rock Testing Handbook, Geotechnical Laboratory, Waterways Experiment Station, Vicksburg, Miss.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the re-

quired level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and type of rock cores tested depends partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. A sufficient number of samples should be tested to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rock to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities and nonhomogeneities in the rock mass, such as joints, inclusions, voids, etc., can significantly affect the deformational behavior of the rock. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Preservation of moisture condition of samples.

The moisture condition of the rock can influence the measured deformation. The rock core should be preserved between the time of recovery and testing as described in Procedure GT-A.4, "Handling and Storage of Rock Core Samples," see Ref. 1.4.4.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanism for applying load to the sample, the reaction frame containing the load mechanism, and the control system for the load mechanism. The loading frame shall be constructed to maintain a constant load on the sample throughout the test to $\pm$ 5 psi (0.03 MPa). The loading frame may be constructed so that several samples can be tested in parallel. However, samples shall not be stacked on top of each other for creep testing.

3.2 Platens.

The diameter of the platens shall be equal to or greater than the sample diameter. Rock materials which are subject to large deformations, such as salt and some shales, shall be tested using platens sized so that the lateral expansion of the sample does not exceed the platen diameter. The platens shall be at least 0.625 in. thick[2] (15.9 mm). The surfaces shall be flat to within 0.0002 in. (0.005 mm) and hardened to at least Rockwell HRC 58.[1,2] One of the two platens shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.3 Transducers.

3.3.1 Axial load. An electronic load cell is recommended to measure axial load on the sample. The cell shall be capable of determining sample stress to an accuracy of at least ±20 psi (±0.14 MPa), including errors introduced by the excitation and readout system, and a resolution of at least 10 psi (0.069 MPa). Alternatively, a pressure gage or electronic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.3.2 Deformation. The deformation transducers shall have a resolution of at least 25×10^{-6} strain and an accuracy of at least $\pm 50 \times 10^{-6}$ strain, including errors introduced by excitation and readout equipment. The transducer system shall be free from noncharacterizable long-term instability (drift) greater than 25×10^{-6} strain. Transducer selection criteria depend primarily on the type of rock and the structure within the sample. Longer gage lengths are recommended for coarse-grained or nonhomogeneous samples. In no case shall the gage length be less than 10 times the diameter of the largest mineral grain.

3.3.2.1 Electrical resistance strain gages shall have a resistance of no less than 350 ohms to avoid the effects of self heating. Two strain gages shall be mounted parallel to the long axis of the core at mid-height of the sample at opposite ends of a diameter. These shall be connected in a half Wheatstone bridge configuration to

[1] ASTM, 1978 (see Ref. 1.4.1)
[2] ISRM, 1979 (see Ref. 1.4.5)

correct for bending. The half Wheatstone bridge configuration shall be completed by connecting two strain gages mounted on a similar rock sample, to provide temperature compensation. This sample shall be placed as near the test sample as practicable during testing.

3.3.2.2 Dial gages shall be graduated to at least 0.0001 in. (0.0025 mm) and be accurate to at least ±0.0001 in. (0.0025 mm). Two dial gages shall be mounted across a diameter of the sample or platen, or three at 120° intervals. If they are attached to the sample directly, the points of attachment shall not be within D/2 of the sample end, where D is the sample diameter.

3.3.2.3 Linear variable differential transformers (LVDTs) shall be mounted across a diameter of the sample or platens, or at 120° intervals, using a non-magnetic attachment. If they are attached to the sample directly, the points of attachment shall not be within D/2 of the sample end.

3.3.2.4 Other types of transducers may be employed provided they satisfy the criteria established in the sections above.

3.4 Power supplies.

The type of power supply and voltage level will be determined by the type of deformation transducer used. In all cases, however, the power supply shall be capable of providing voltage accurate and stable to at least ±10 mV.

3.5 Signal conditioning and readout devices.

Signal conditioning and readout devices may be either manual or automatic. Voltmeters shall be capable of reading to 10^{-3} mV. The cumulative error of the readout equipment and transducers shall meet the requirements of Section 3.3 above.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Core size. Rock cores of NX size (2 in. nominal diameter; 51 mm) or larger are recommended. However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.[1]

4.1.2 Length-to-diameter ratio. Cores shall be cut to a length-to-diameter ratio of 2.0 to 3.0.[1,2]

[1] ISRM, 1979 (see Ref. 1.4.5)
[2] ASTM, 1978 (see Ref. 1.4.1)

4.1.3 Smoothness. The sides of the core shall be relatively smooth, free of abrupt irregularities and straight to within 0.01 in. (0.25 mm) over the length of the sample.[1]

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in.[1] (0.25 mm over 51 mm).

4.1.5 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in.[1] (0.05 mm).

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in.[1,2] (0.025 mm).

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock core shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid. Generally, water is used for hard rock, but other materials may require special fluids, such as saturated brine for salt or glycerin for expansive shales.

4.1.8 Measurements. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of measuring to 0.001 in. (0.025 mm). The diameter of the specimen shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measurements shall be recorded as shown on Form L-D.1-1.

4.1.9 Coating. The sample shall be coated to prevent changes in moisture content during the test. The coating shall be flexible, impermeable and shall not penetrate the rock. A silicone rubber such as alcohol-based RTV is recommended. Coatings requiring a heat cure shall not be used. If strain gages are used as deformation transducers, the gages shall be applied directly to the rock prior to coating. The coating shall not degrade the strain gages. Mountings of other types of transducers, if attached to the rock core itself, shall penetrate the coating and be in direct contact with the rock. The ends of the sample shall not be coated.

4.1 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platens and sample are aligned with the loading axis to within 0.05 in. (1.25 mm).

4.2.2 Initial readings. Initial deformation readings shall be taken with the sample in the loading frame with only the weight of the load train above the sample. If electronic transducers

[1] ASTM, 1978 (see Ref. 1.4.1)
[2] ISRM, 1979 (see Ref. 1.4.5)

are used, these shall be allowed to warm up until readings are stable within the limitations of the transducer system.

4.2.3 Power requirements. If electronic transducers are used, they shall be powered continuously over the duration of the test.

4.2.4 Initial loading. Because creep can occur simultaneously with elastic deformation, the sample shall be loaded as rapidly as practicable to evaluate the elastic effects. Full load should be achieved within 30 seconds or less if possible. Impact loading shall be avoided.

4.2.5 Reading intervals. Deformation readings shall be taken immediately upon application of the load. The reading schedule thereafter depends on the applied stress and the type of rock. For evaluating transient creep, deformation readings should be taken every few minutes to few hours until the deformation rate becomes constant. Readings should be taken at least twice daily during the steady-state phase of creep.

4.2.6 Test environment. The temperature of the test environment shall be constant to 3.6°F (±2°C). The humidity shall be constant to ±5% over the duration of the test.

4.2.7 Data recording requirements. The exact format for data recording will depend on the type of readout system employed. However, the information shown on Form L-D.1-1, designed for manual data recording, shall be the minimum required. The format shall follow Form L-D.1-1 as closely as possible.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. The analysis of creep behavior is beyond the scope of this procedure, but if an analysis is included, it should be complete and consistent with the other sections of this procedure.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a larger report covering the results of tests in several rock types or at various stress levels, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for

the number and type of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, description of many samples may be required, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure varies from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations and limitations in their applications shall be noted and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Graphic presentation. A deformation-time curve similar to Figure 1.1 shall be presented for each creep test.

5.4.2 Data. A complete listing of deformation and time data shall be included in the report. This may be attached as an appendix.

5.5 Measurement error.

The error associated with a single test shall be evaluated at the 95% confidence level. This includes the combined effects of all transducers, power supplies, readout devices, etc.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test where Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-D.1-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-D.1-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-D.1-1.

Uniaxial Compressive Creep of Rock Core - Ambient Temperature

Test Data Sheet - Form L-D.1-1

Project _____ Test Temperature _____

Sample No. _____ Load _____

Rock Type _____

Equipment Description	Serial No.	Date of Calibration

Sample Height _____ Sample Diameter _____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____

Date	Time	By	Pressure	Deformation No. 1	Deformation No. 2	Deformation No. 3

Date	Time	By	Pressure	Deformation No. 1	Deformation No. 2	Deformation No. 3

Remarks:

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Engineer_____ Date_____

Procedure L-D.2

Uniaxial Compressive Creep of Rock Core -

Elevated Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. The objective of this test is to evaluate the time-dependent strain (creep) of a rock core sample subjected to a constant uniaxial stress at an elevated temperature.

1.1.2 Limitations. This procedure does not discuss analysis of creep data.

1.2 General description of the test.

A rock core sample is cut to length and the ends are machined flat. The sample is placed in the loading frame and heated to the specified temperature. An axial load is applied to the sample. This load is held constant for the duration of the test. Sample deformation is monitored periodically.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Strain - deformation per unit length of sample.

1.3.1.2 Load - total axial force acting on a sample.

1.3.1.3 Stress - axial force per unit area of the sample.

1.3.1.4 Instantaneous deformation - deformation occurring immediately upon loading a sample due to elastic response, as shown on Figure 1.1.

1.3.1.5 Creep - deformation over time under constant load.

1.3.1.6 Transient creep - initial phase of creep during which deformation occurs at a diminishing rate, shown on Figure 1.1.

1.3.1.7 Steady-state creep - second phase of creep during which deformation occurs at a constant rate.

1.3.2 Equations.

1.3.2.1 The axial strain, ε_a, is calculated using:

$$\varepsilon_a = \frac{\Delta \ell}{\ell_o} \qquad (1)$$

where:

$\Delta \ell$ = change in measured axial length

ℓ_o = original measured axial length

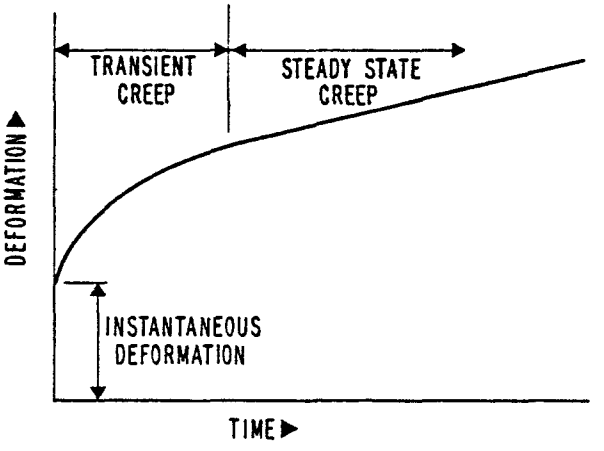

FIG. I.I IDEALIZED CREEP CURVE

1.3.2.2 The axial stress, σ_1, is calculated using:

$$\sigma_1 = \frac{P}{A} \qquad (2)$$

where:

P = load on the sample

A = cross-sectional area of the sample

1.3.2.3 The analysis of rock deformation with time is complex and non-standard. The user is referred to the references in Section 1.4.

1.4 References.

1.4.1 ASTM, 1978, Test Designation D2938, "Standard Test Method For Unconfined Compressive Strength of Intact Rock Core Specimens," Annual Book of ASTM Standards, Part 19.

1.4.2 Carter, N.L., 1976, "Steady State Flow of Rocks," Rev. Geophys. Space Phys., 14.

1.4.3 Carter, N.L. and Kirby, S.H., 1978, "Transient Creep and Semibrittle Behavior of Crystalline Rocks," Pure and Appl. Geophys., 116.

1.4.4 ISRM Commission on Standardization of Laboratory and Field Tests, 1979, "Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials," Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., 16, No. 2.

1.4.5 U.S. Army Corps of Engineers, 1980, Test Standard RTH 205-80, "Standard Method of Test for Creep of Rock in Compression, Rock Testing Handbook, Geotechnical Laboratory, Waterways Experiment Station, Vicksburg, Miss.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. A sufficient number of samples should be tested to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities and nonhomogeneities in the rock mass, such as joints, inclusions, voids, etc., can significantly affect the deformational behavior of the rock. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanisms for applying load to the sample, the reaction frame containing the load mechanism, and the control system for the load mechanism. The loading frame shall be constructed to maintain a constant load on the sample throughout the test to $\pm$ 5 psi (0.03 MPa). The loading frame may be constructed so that several samples can be tested in parallel. However, samples shall not be stacked on each other for creep testing.

3.2 Platens.

The diameter of the platens shall be equal to or greater than the sample diameter. Rock materials which are subject to large deformations, such as rock salt and some shales, shall be tested using platens sized so that the lateral expansion of the sample does not exceed the platen diameter. The platens shall be at least 0.625 in. (15.9 mm) thick. The surfaces shall be flat to within 0.0002 in. (0.005 mm) and hardened to at least Rockwell

HRC 58[1,2]. One of the two platens shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.3 Transducers.

3.3.1 Axial load. An electronic load cell is recommended to measure axial load on the sample. The cell shall be capable of determining sample stress to an accuracy of at least ± 20 psi (0.14 MPa), including errors introduced by the excitation and readout system, and a resolution of at least 10 psi (0.07 MPa). Alternatively, a pressure gage or electronic transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.3.2 Deformation. The deformation transducers shall have a resolution of at least 25×10^{-6} strain and an accuracy of at least $\pm 50 \times 10^{-6}$ strain, including errors introduced by excitation and readout equipment. The transducer system shall be free from noncharacterizable long-term instability (drift) greater than 25×10^{-6} strain. Transducer selection criteria depend primarily on the type of rock and the structure within the sample. Longer gage lengths are recommended for coarse-grained or nonhomogeneous samples. In no case shall the gage length be less than 10 times the diameter of the largest mineral grain.

3.3.2.1 Electrical resistance strain gages shall have a resistance of no less than 350 ohms to avoid the effects of self heating. Two strain gages shall be mounted parallel to the long axis of the core at mid-height of the sample at opposite ends of a diameter. These shall be connected in a half Wheatstone bridge configuration to correct for bending. The half Wheatstone bridge configuration shall be completed with two precision resistors having a temperature coefficient no greater than 0.6×10^{-6} ppm per °F (1×10^{-6} ppm per °C).

3.3.2.2 Dial gages shall be graduated to at least 0.0001 in. (0.0025 mm) and be accurate to ± 0.0001 in. (0.0025 mm). Two dial gages shall be mounted across a diameter of the platen or three at 120° intervals.

3.3.2.3 Linear variable differential transformers (LVDTs) shall be mounted across a diameter of the sample or platens, or at 120° intervals, using a non-magnetic attachment. If they are attached to the sample directly, the points of attachment shall not be within D/2 of the sample end, where D is the sample diameter.

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[1]ASTM, 1978 (see Ref. 1.4.1)
[2]ISRM, 1979 (see Ref. 1.4.4)

3.3.2.4 Other types of transducers may be employed provided they satisfy the criteria established in the sections above.

3.3.3 Temperature. The type of instrument chosen to monitor temperature depends primarily on the test apparatus and the maximum test temperature. Special Limits of Error thermocouples or platinum resistance thermometers (RTD's) are recommended. The temperature transducer shall be accurate to at least ±0.9°F (±0.5°C) with a resolution of 0.18°F (0.1°C). Temperature shall be measured at three locations, with one sensor near the top, one at mid-height, and one near the bottom of the sample.

3.4 Power supplies.

The type of power supply and voltage level will be determined by the type of deformation transducer used. In all cases, however, the power supply shall be capable of providing voltage accurate and stable to at least ± 10mV.

3.5 Signal conditioning and readout devices.

Signal conditioning and readout devices may be either manual or automatic. Voltmeters shall be capable of reading to 10^{-3} mV. The cumulative error of the readout equipment and transducers shall meet the requirements of Section 3.3 above.

3.6 Heating unit.

The heating unit shall be capable of maintaining a uniform temperature throughout the sample to within 7.2°F (4°C). The mean temperature of the sample shall vary by not more than 3.6°F (2°C) during the test. The heating unit shall incorporate controls so that the sample may be heated at a rate no greater than 3.6°F (2°C) per minute.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Core size. Rock cores of NX-size (2 in. nominal diameter; 51 mm) or larger are recommended. However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.[1]

4.1.2 Length-to-diameter ratio. Cores shall be cut to a length-to-diameter ratio of 2.0 to 3.0.[1,2]

4.1.3 Smoothness. The sides of the core shall be relatively smooth, free of abrupt irregularities and straight to within 0.01 in. (0.25 mm) over the length of the sample.[1]

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[1] ISRM, 1979 (see Ref. 1.4.4)
[2] ASTM, 1978 (see Ref. 1.4.1)

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in. (0.25 mm over 51 mm)[1].

4.1.5 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in. (0.005 mm)[1].

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in. (0.025 mm)[1,2].

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock core shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid. Generally, water is used for hard rock, but other materials may require special fluids, such as saturated brine for salt or glycerin for expansive shales.

4.1.8 Measurement. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of measuring to 0.001 in. (0.025 mm). The diameter of the specimen shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measurements shall be recorded as shown on Form L-D.2-1.

4.2 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platens and sample are aligned with the loading axis to within 0.05 in. (1.27 mm).

4.2.2 Heating rate. The sample shall be heated to the test temperature at a rate not to exceed 3.6°F (2°C) per minute to prevent thermal fracturing.

4.2.3 Thermal equilibrium. The test sample shall be considered to have attained thermal equilibrium when the deformation transducer output is stable for at least three readings taken at equal intervals over a period of no less than 30 minutes. Stability is defined as a constant reading showing only the effects of normal instrument and heater unit fluctuations.

4.2.4 Initial readings. Initial deformation readings shall be taken with the sample in the loading frame and only the weight of the load train above the sample. If electronic transducers are used, these shall be allowed to warm up until readings are stable within the limitations of the transducer system.

4.2.5 Power requirements. If electronic transducers are used, they shall be powered continuously over the duration of the test.

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[1] ASTM, 1978 (see Ref. 1.4.1)
[2] ISRM, 1979 (see Ref. 1.4.4)

4.2.6 Initial loading. Because creep can occur simultaneously with elastic deformation, the sample shall be loaded as rapidly as practicable to evaluate the elastic effects. Full load should be achieved in 30 seconds or less if possible. Impact loading shall be avoided.

4.2.7 Reading intervals. Deformation readings shall be taken immediately upon application of the load. The reading schedule thereafter depends on the applied stress and the type of rock. For evaluating transient creep, deformation readings should be taken every few minutes to few hours until the deformation rate becomes constant. Readings should be taken at least twice daily during the steady-state phase of creep.

4.2.8 Test environment. The temperature of the test environment shall be constant to $\pm$ 3.6°F ($\pm$ 2°C).

4.2.9 Data recording requirements. The exact format for data recording will depend on the type of readout system employed. However, the information shown on Form L-D.2-1, designed for manual data recording, shall be the minimum required, and the format shall follow Form L-D.2-1 as closely as possible.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. The analysis of creep behavior is beyond the scope of the procedure, but if an analysis is included, it should be complete and consistent with the other sections of this procedure.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types, or at several stress levels, or temperatures, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering

of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, description of many samples may be necessary and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedures. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be discussed. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations and limitations in their applications shall be noted and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Graphic presentation. A deformation-time curve similar to Figure 1.1 shall be presented for each creep test.

5.4.2 Data. A complete listing of deformation, temperature, and time data shall be included in the report. This may be attached as an appendix.

5.5 Measurement error.

The error associated with a single test shall be evaluated at the 95% confidence level. This includes the combined effects of all transducers, power supplies, readout devices, etc.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of

this section to establish Quality Assurance procedures, but to identify those points during the test where Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-D.2-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-D.2-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of L-D.2-1.

Uniaxial Compressive Creep of Rock Core - Elevated Temperature

Test Data Sheet - Form L-D.2-1

Project _____ Test Temperature _____

Sample No. _____ Load _____

Rock Type _____

Equipment Description	Serial No.	Date of Calibration

Initial Sample Dimensions:

Sample Height _____ Sample Diameter _____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____

Date	Time	By	Pressure	Deformation No. 1	No. 2	No. 3

Date	Time	By	Pressure	Deformation No. 1	No. 2	No. 3

Remarks:

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Engineer_____ Date_____

Procedure L-D.3

Triaxial Compressive Creep of Rock Core -
Elevated Temperature

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. The objective of this test is to evaluate the time-dependent strain (creep) of a rock core sample subjected to a constant triaxial stress.

1.2 General description of the test.

A rock core sample is cut to length, and the ends are machined flat. The sample is placed in a triaxial load cell. A confining pressure and an axial load are applied to the sample, and the sample is heated to the desired test temperature. The load and temperature are held constant for the duration of the test. Sample deformation is monitored periodically. An idealized deformation versus time curve is shown in Figure 1.1.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Strain - deformation per unit length of sample.

1.3.1.2 Load - total axial force acting on a sample.

1.3.1.3 Stress - axial force per unit area of the sample.

1.3.1.4 Confining pressure - pressure applied radially to the core.

1.3.1.5 Instantaneous deformation - deformation occurring immediately upon loading sample due to elastic response, as shown on Figure 1.1.

1.3.1.6 Creep - deformation with time under constant load.

1.3.1.7 Transient creep - initial phase of creep during which deformation occurs at a diminishing rate, as shown on Figure 1.1.

1.3.1.8 Steady-state creep - second phase of creep during which deformation occurs at a constant rate, as shown on Figure 1.1.

1.3.2 Equations.

1.3.2.1 The axial strain, ε_a, is calculated using:

$$\varepsilon_a = \frac{\Delta L}{L_o} \qquad (1)$$

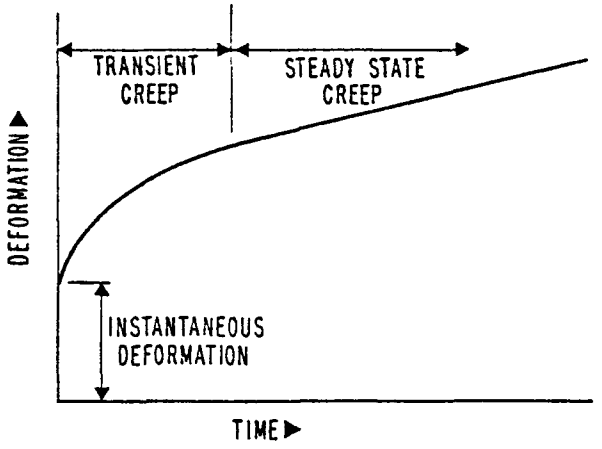

FIG. I.I IDEALIZED CREEP CURVE

where:

ΔL = change in measured axial length

L_o = original measured axial length

1.3.2.2 The axial stress, σ_1, is calculated using:

$$\sigma_1 = \frac{P}{A} \qquad (2)$$

where:

P = load on the sample

A = cross-sectional area of the sample

1.3.2.3 The analysis of rock deformation with time is complex and nonstandard. The user is referred to the references in Section 1.4.

1.4 References.

1.4.1 ASTM, 1978, Test Designation D2664, "Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens without Pore Pressure Measurements." Annual Book of ASTM Standards, Part 19.

1.4.2 Carter, N.L., 1976, "Steady State Flow of Rocks," Rev. Geophys. Space Phys., 14.

1.4.3 Carter, N.L. and Kirby, S.H., 1978, "Transient Creep and Semibrittle Behavior of Crystalline Rocks," Pure and Appl. Geophys., 116.

1.4.4 Foundation Sciences, Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI-310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.5 ISRM Commission on Standardization of Laboratory and Field Tests, 1978, "Suggested Method for Determining the Strength of Rock Materials in Triaxial Compression." Int. J. of Rock Mech. Min. Sci. and Geomech. Abstr., 15, No. 2.

1.4.6 U.S. Army Corps of Engineers, 1980, Test Standard RTH 205-80, "Standard Method of Test for Creep of Rock in Compression," Rock Testing Handbook, Geotechnical Laboratory, Waterways Experiment Station, Vicksburg, MI.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with performance

specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and type of rock cores tested depends partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. A sufficient number of samples should be tested to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rock to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities and nonhomogeneities in the rock mass, such as joints, inclusions, voids, etc., can significantly affect the deformational behavior of the rock. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing cores taken at different orientations.

2.4 Preservation of moisture condition of samples.

The moisture condition of the rock can influence the measured deformation. The rock core should be preserved between the time of recovery and testing as described in Procedure GT-A.4, "Handling and Storage of Rock Core Samples", see Ref. 1.4.4.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Loading frame.

The loading frame consists of the mechanism for applying the axial load to the sample, the reaction frame containing the load mechanism, and the control system for the load mechanism. The loading frame shall be constructed to maintain a constant axial load on the sample throughout the test to ± 5 psi (0.03 MPa). The loading frame may be constructed so that several samples can be tested in parallel. However, samples shall not be stacked on top of each other for creep testing.

3.2 Triaxial confining chamber.

The confining chamber consists of a hollow cylinder and end caps to contain the confining fluid, platens to support the sample, and a flexible impermeable membrane to cover the sample during testing.

3.2.1 Cylinder and end caps. The cell design shall be such that changes in confining pressure do not directly cause changes in axial load and vice versa.

3.2.2 Platens. The diameter of the platens shall be equal to, or greater than, the diameter of the sample. Rock materials which are subject to large deformations prior to failure, such as salt and some shales, shall be tested using platens sized so that the lateral expansion of the sample does not exceed the platen diameter. The platens shall be at least 0.625 in. (15.9 mm) thick.[1] The surfaces shall be flat to within 0.0002 in. (0.05 mm) and hardened to at least Rockwell HRC 58.[1,2] One of the two platens shall incorporate a spherical seat. This platen shall be placed above the sample during testing.

3.2.3 Flexible, impermeable membrane. This membrane encloses the rock sample and prevents penetration by the confining fluid. Generally, a sleeve of natural or synthetic rubber or plastic polymer is used; however, copper or lead jackets are sometimes used. The membrane shall be inert relative to the confining fluid, and shall cover small pores in the sample without rupturing when confining pressure is applied. Plastic or silicone rubber coatings may be applied directly to the sample, providing these materials do not penetrate and strengthen the sample. The ends of the sample shall not be coated, and care must be taken to form an effective seal where the platen and sample meet. Membranes formed by coatings shall be subject to the same performance requirements as elastic sleeve membranes.

3.3 Confining pressure system.

The confining pressure system consists of the pressurizing fluid and the means of applying pressure. The pressurization system shall be capable of maintaining the confining pressure constant to within ±1% throughout the test.

3.4 Transducers.

Transducers are required to determine the axial load on the sample, the confining pressure, the deformation, and the temperature.

3.4.1 Axial load. An electronic load cell is recommended to measure axial load on the sample. The cell shall have an accuracy of at least ±100 lb (±45.4 kg), including errors introduced by the excitation and readout system, and a resolution of at least 50 lb (22.7 kg). Alternatively, a pressure gage or electronic

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[1] ISRM, 1978, (see Ref. 1.4.5)
[2] ASTM, 1978, (see Ref. 1.4.1)

transducer may be used if a hydraulic loading system is employed, provided that the load measurement requirements above are satisfied, including the effects of friction in the hydraulic ram, etc.

3.4.2 Confining pressure. The confining pressure shall be measured with a hydraulic pressure gage or electronic transducer having an accuracy of at least ±1% of the confining pressure, including errors due to readout equipment, and a resolution of at least 0.5% of the confining pressure.

3.4.3 Deformation. The deformation transducers shall have a resolution of at least 25×10^{-6} strain and an accuracy of at least $\pm 50 \times 10^{-6}$ strain, including errors introduced by excitation and readout equipment. The transducer system shall be free from noncharacterizable long-term instability (drift) greater than 25×10^{-6} strain. Transducer selection criteria depend primarily on the type of rock and the structure within the sample. Longer gage lengths are recommended for coarse-grained or nonhomogeneous samples. In no case shall the gage length be less than 10 times the diameter of the largest mineral grain.

3.4.3.1 Electrical resistance strain gages shall have a resistance of no less than 350 ohms to avoid the effects of self heating. An axial and a circumferential gage shall be mounted at mid-height of the sample on each end of a diameter. The two axial gages shall be connected in a half Wheatstone bridge configuration to correct for bending. The two circumferential gages shall be wired in a similar configuration. Each half Wheatstone bridge configuration shall be completed with two precision resistors having a temperature coefficient no greater than 1×10^{-6} ppm/°C.

3.4.3.2 Dial gages shall be graduated to at least 0.0001 in. (0.0025 mm) and be accurate to at least ±0.0001 in. (0.0025 mm). Two dial gages shall be mounted across a diameter of the sample or platen, or three at 120° intervals. If they are attached to the sample directly, the points of attachment shall not be within D/2 of the sample end, where D is the sample diameter.

3.4.3.3 Linear variable differential transformers (LVDTs) shall be mounted across a diameter or at 120° intervals on the sample or platens using a nonmagnetic attachment. If they are attached to the sample directly, the points of attachment shall not be within D/2 of the sample end, where D is the sample diameter.

3.4.3.4 Radial deformation may be measured with a volumetric apparatus (dilatometer). This device shall have a resolution of at least 0.002 in.^{3} (32.8 mm^3) and an accuracy of at least 0.5% of the radial strain of the sample.

3.4.3.5 Other types of deformation transducers, such as the Schuler gage, may be employed provided they satisfy the criteria stated in the above specifications.

3.4.4 Temperature. The type of instrument chosen to monitor temperature depends primarily on the test apparatus and the maximum test temperature. Special limits of error thermocouples or platinum resistance thermometers (RTDs) are recommended.

The temperature transducer shall be accurate to at least ±0.9°F (±0.5°C) with a resolution of 0.18°F (0.1°C). Temperature shall be measured at three locations, with one sensor near the top, one at mid-height, and one near the bottom of the sample.

3.5 Power supply.

The type of power supply and voltage level will be determined by the type of deformation transducer used. In all cases, however, the power supply shall be capable of providing voltage accurate and stable to at least ±10 mV.

3.6 Signal conditioning and readout devices.

Signal conditioning and readout devices may be either manual or automatic. Voltmeters shall be capable of reading to 10^{-3} mV. The cumulative error of the readout equipment and transducers shall meet the requirements of Section 3.4 above.

3.7 Heating unit.

The heating unit shall be capable of maintaining a uniform temperature throughout the sample to within 7.2°F (4°C). The mean temperature of the sample shall vary by not more than 3.6°F (2°C) during the test. The heating unit shall incorporate controls so that the sample may be heated at a rate no greater than 3.6°F (2°C) per minute.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Core size. Rock cores of NX size (2 in. nominal diameter; 51 mm) or larger are recommended. However, in no case shall the core diameter be less than 10 times the size of the largest mineral grain.[1]

4.1.2 Length-to-diameter ratio. Cores shall be cut to a length-to-diameter ratio of 2.0 to 3.0[1,2].

4.1.3 Smoothness. The sides of the core shall be relatively smooth, free of abrupt irregularities and straight to within 0.01 in. (0.25 mm) over the length of the sample.[1]

4.1.4 Perpendicularity. The ends of the sample shall be perpendicular to the long axis to within 0.01 in. over 2 in. (0.25 mm over 51 mm).[1]

4.1.4 Parallelism. The ends of the sample shall be parallel to each other to within 0.002 in. (0.05 mm).[1]

4.1.6 Flatness. The ends of the sample shall be flat to within 0.001 in. (0.025 mm).[1,2]

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[1] ASTM, 1978 (see Ref. 1.4.1)
[2] ISRM, 1978 (see Ref. 1.4.4)

4.1.7 Machining. No capping materials or end surface treatments other than machining shall be applied to the ends of the sample. The rock core shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid, Generally, water is used for hard rock, but other materials may require special fluids, such as saturated brine for salt or glycerin for expansive shales.

4.1.8 Measurements. The height of the sample shall be measured at three equally spaced intervals with a caliper capable of measuring to 0.001 in. (0.025 mm). The diameter of the specimen shall be determined by averaging two diameters measured at right angles to each other at the top, mid-height, and base of the sample, using a caliper capable of measuring to 0.001 in. (0.025 mm). All measurements shall be recorded as shown on Form L-D.3-1.

4.1.9 Voids. Large voids in the sides of the sample, such as vesicles, may be filled with paraffin, plastic or similar material to provide support for the flexible membrane. Such filling material shall not penetrate the rock and shall have an elastic modulus no greater than 10% of the intact rock modulus.

4.1.10 Coating. The sample shall be coated to prevent changes in moisture content during the test and to prevent penetration of the confining pressure fluid. The coating shall be flexible, impermeable and shall not penetrate the rock. A silicone rubber such as alcohol-based RTV is recommended. Coatings requiring a heat cure shall not be used. If strain gages are used as deformation transducers, the gages shall be applied directly to the rock prior to coating. The coating shall not degrade the strain gages. Mountings of other types of transducers, if attached to rock core itself, shall penetrate the coating and be in direct contact with the rock. The ends of the sample shall not be coated.

4.2 Testing.

4.2.1 Alignment. The apparatus shall be assembled so that the platens and sample are aligned with the loading axis to within 0.05 in. (1.25 mm).

4.2.2 Heating rate. The sample shall be heated to the test temperature at a rate not to exceed 3.6°F (2°C) per minute to prevent thermal fracturing.

4.2.3 Thermal equilibrium. The test sample shall be considered to have attained thermal equilibrium when the deformation transducer output is stable for at least three readings taken at equal intervals over a period of no less than 30 minutes. Stability is defined as a constant reading showing only the effects of normal instrument and heater unit fluctuations.

4.2.4 Initial readings. Initial deformation readings shall be taken with the sample in the loading frame with only the weight of the load train above the sample. If electronic transducers are used, these shall be allowed to warm up until readings are stable within the limitations of the transducer system.

4.2.5 Power requirements. If electronic transducers are used, they shall be powered continuously over the duration of the test.

4.2.6 Initial loading. Because creep can occur simultaneously with elastic deformation, the sample shall be loaded to the desired confining pressure and axial load as rapidly as practicable to evaluate the elastic effects. Full load should be achieved within 30 seconds or less if possible. Impact loading shall be avoided.

4.2.7 Reading intervals. Deformation readings shall be taken immediately upon application of the load. The reading schedule thereafter depends on the applied radial and axial stress and the type of rock. For evaluating transient creep, deformation readings should be taken every few minutes to few hours until the deformation rate becomes constant. Readings should be taken at least twice daily during the steady-state phase of creep.

4.2.8 Test environment. The temperature of the test environment shall be constant to $\pm$3.6°F (2°C).

4.2.9 Data recording requirements. The exact format for data recording will depend on the type of readout system employed. However, the information shown on Form L-D.3-1, designed for manual data recording, shall be the minimum required. The format shall follow Form L-D.3-1 as closely as possible.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. The analysis of creep behavior is beyond the scope of this procedure, but if an analysis is included, it should be complete and consistent with the other sections of this procedure.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a larger report covering the results of tests in several rock types or at various stress levels, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and type of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, description of many samples may be required, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure varies from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations and limitations in their applications shall be noted and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a nonideal situation shall be fully explained.

5.4 Results.

5.4.1 Graphic presentation. A deformation-time curve similar to Figure 1.1 shall be presented for each creep test.

5.4.2 Data. A complete listing of deformation and time data shall be included in the report. This may be attached as an appendix.

5.5 Measurement error.

The error associated with a single test shall be evaluated at the 95% confidence level. This includes the combined effects of all transducers, power supplies, readout devices, etc.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test where Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-D.3-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-D.3-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-D.3-1.

Triaxial Compressive Creep of Rock Core - Elevated Temperature

Test Data Sheet - Form L-D.3-1

Project _____ Rock Type _____

Sample No. _____

Equipment Description	Serial No.	Date of Next Calibration

Sample Height _____ Sample Diameter _____ _____

_____ _____ _____

_____ _____ _____

Average _____ Average _____

Date	Time	By	Temp. °C	Confining Pressure	Axial Load	Deformation No. 1	Deformation No. 2	Deformation No. 3

Date	Time	By	Temp. °C	Confining Pressure	Axial Load	Deformation No. 1	Deformation No. 2	Deformation No. 3

Remarks:

Test Supervisor _____ Date _____

Quality Assurance _____ Date _____

Project Engineer _____ Date _____

Procedure L-E.1

Thermal Expansion of Laboratory Rock Samples

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. The test measures the strain in a rock sample caused by changing the temperature of the sample. The coefficient of thermal expansion is calculated from this data.

1.1.2 Methods. This procedure discusses two methods of measuring thermal expansion, using dilatometers and strain gages. The dilatometer method has a longer history and can measure strains at higher temperatures. The strain gage method is simpler to perform and can be easily used to evaluate the anisotropy of thermal properties in a single sample.

1.1.3 Limitations.

1.1.3.1 This procedure measures thermal expansion in unstressed samples only. The strain gage method may be used with suitable pressurization equipment to determine the thermal expansion properties at elevated stress levels.

1.1.3.2 This test procedure measures thermal expansion over the temperature range from cryogenic to approximately 2200°F (1200°C), depending on equipment limitations.

1.2 General description of the test.

1.2.1 Dilatometer method. A rock core sample is cut to length and the ends are machined flat. The sample is placed in a dilatometer and heated or cooled to a specified temperature. Strain is measured and thermal expansion is calculated.

1.2.2 Strain gage method. Strain gages are attached to a rock sample and a standard sample of known thermal properties. The two specimens are placed in an oven/cooler and heated or cooled to the specified temperature. The differential strain between the specimens is measured and the coefficient of thermal expansion of the rock is calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Linear thermal expansion - the change in length per unit length resulting from a change in the temperature of the sample.

1.3.2 Equations - dilatometer method.

1.3.2.1 The linear thermal strain, ε_L, is calculated using:

$$\varepsilon_L = \frac{\Delta L}{L_o} + \varepsilon_d \qquad (1)$$

where:

ΔL = change in sample length

L_o = original sample length

ε_d = thermal strain of dilatometer.

1.3.2.2 The linear thermal strain of the dilatometer, ε_d, is calculated using:

$$\varepsilon_d = \frac{\Delta L_s}{L_{os}} - \varepsilon_s \qquad (2)$$

where:

ΔL_s = change in standard length

L_{os} = original standard length

ε_s = calculated thermal strain of standard.

The details of dilatometer calibration are discussed in Section 4.2.1.

1.3.2.3 The mean coefficient of linear thermal expansion, α_m, is calculated using:

$$\alpha_m = \frac{\Delta \varepsilon_L}{\Delta T} \qquad (3)$$

where:

$\Delta \varepsilon_L$ = change in strain in the sample between temperatures T_1 and T_2

ΔT = difference between temperatures T_1 and T_2.

1.3.2.4 The instantaneous coefficient of linear thermal expansion, α_T, is calculated by:

$$\alpha_T = \frac{\partial \varepsilon_L}{\partial T} \qquad (4)$$

where:

$\frac{\partial \varepsilon L}{\partial T}$ = slope of the strain - temperature curve at any point.

1.3.2.5 If the rock sample is assumed to be homogeneous and isotropic, the coefficient of volumetric thermal expansion, α_v, may be calculated using:

$$\alpha_v = 3\alpha_L \qquad (5)$$

where:

α_L = coefficient of linear thermal expansion calculated from either Equation 3 or 4.

1.3.3 Equations - strain gage method.

1.3.3.1 The mean coefficient of linear thermal expansion, α_m, is calculated using:

$$\alpha_m = \frac{\Delta U}{\Delta T} + \alpha_r \qquad (6)$$

where:

ΔU = change in differential strain between sample and reference material over the temperature range T_1 to T_2

ΔT = difference between temperatures T_1 and T_2

α_r = mean coefficient of linear expansion of the reference material over the temperature range T_1 to T_2.

1.3.3.2 The instantaneous coefficient of linear thermal expansion, α_T, is calculated using:

$$\alpha_T = \frac{\partial U}{\partial T} + \alpha_{rT} \qquad (7)$$

where:

$\frac{\partial U}{\partial T}$ = slope of the differential strain vs. temperature curve at temperature T

α_{rT} = instantaneous coefficient of linear thermal expansion of the reference material at temperature T.

1.3.3.3 The coefficient of volumetric thermal expansion, α_v, is calculated using:

$$\alpha_v = \alpha_{Lx} + \alpha_{Ly} + \alpha_{Lz} \qquad (8)$$

where:

α_{Lx}, α_{Ly}, α_{Lz} = coefficients of linear thermal expansion calculated by Equation 6 or 7 in the x, y, and z directions, respectively.

If the rock sample is homogeneous and isotropic, Equation 8 reduces to Equation 5.

1.4 References.

1.4.1 ASTM, Test Designation E 228, "Standard Method of Tests for Linear Thermal Expansion of Rigid Solids with a Vitreous Silica Dilatometer," Annual Book of ASTM Standards, Part 30.

1.4.2 Foundation Sciences, Inc., 1981, Field and In Situ Rock Mechanics Testing Manual, ONWI-310, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

1.4.3 Micro-Measurements, 1976, "Temperature-Induced Apparent Strain and Gage Factor Variation in Strain Gages," Tech Note TN-128-2, Measurements Group, Raleigh, N.C.

1.4.4 Richter, S., and Simmons, G., 1974, "Thermal Expansion Behavior of Igneous Rocks," Int. J. Rock Mech. Min. Sci and Geomech. Abstr., 11.

1.4.5 U.S. Bureau of Mines, 1974, "Thermal Expansion", Bureau of Mines Test Procedures for Rocks, Information Circular IC 8628.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations,

while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuties in the rock mass, such as joints, inclusions, voids, etc., can influence the thermal expansion of the rock. These should be sampled and tested to provide an estimate of their effect.

2.4 Moisture condition of samples.

The moisture condition of the rock can influence the measured thermal expansion. It is recommended that samples be tested in both natural and dry conditions. For natural conditions, the moisture content of the rock core shall be preserved between the time of recovery and testing as described in Procedure GT-A.4, "Handling and Storage of Rock Core Samples," see Ref. 1.4.2.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Dilatometer method.

3.1.1 Dilatometer. The dilatometer holds the sample in position and transfers thermal expansion to the measurement transducer by means of a rod. The dilatometer may also contain mountings for thermocouples and the tube furnace. A dilatometer constructed of a material with a low coefficient of thermal expansion, such as fused quartz, is recommended. The dilatometer shall be capable of measuring both positive and negative strains.

3.1.2 Displacement transducer. The displacement transducer measures the thermal expansion of the sample. The transducer shall have an accuracy of no less than $\pm$ 50 x 10^{-6} strain, including errors introduced by readout equipment, and a resolution of at least 20 x 10^{-6} strain. Mechanical dial gages, linear variable differential transformers, interferometers, or other types of transducers are satisfactory if they satisfy the above requirements.

3.1.3 Heating unit. The heating unit shall be capable of maintaining a uniform temperature throughout the sample to within 3.6°F (2°C). The unit shall incorporate controls so that the

sample may be heated or cooled at a rate not greater than 3.6°F (2°C) per minute. The heating unit shall be capable of maintaining the mean temperature of the sample to within 3.6°F (2°C).

3.1.4 Temperature transducer. The instrument chosen to monitor temperature depends primarily on the test apparatus and the maximum test temperature. Special Limits of Error thermocouples or platinum resistance thermometers (RTDs) are recommended. The temperature transducer shall be accurate to at least ± 0.9°F (± 0.5°C) with a resolution of at least 0.18°F (0.1°C). Two transducers shall be mounted on the sample, one near each end.

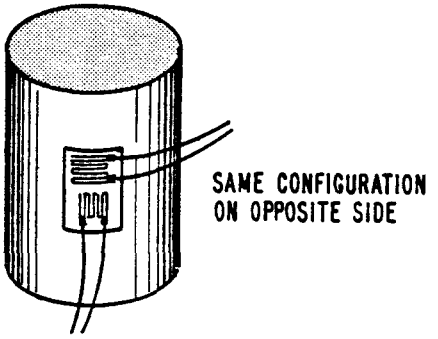
3.1.5 Calibration standard. The length of the calibration standard shall be the same as the length of the test sample to within 10%. The standard may be any material whose thermal expansion characteristics are known, so that thermal strain at any temperature can be calculated to an accuracy of no less than $\pm$ 50 x 10^{-6} strain. Platinum or quartz cut parallel to the A axis is often used.

3.2 Strain gage method.

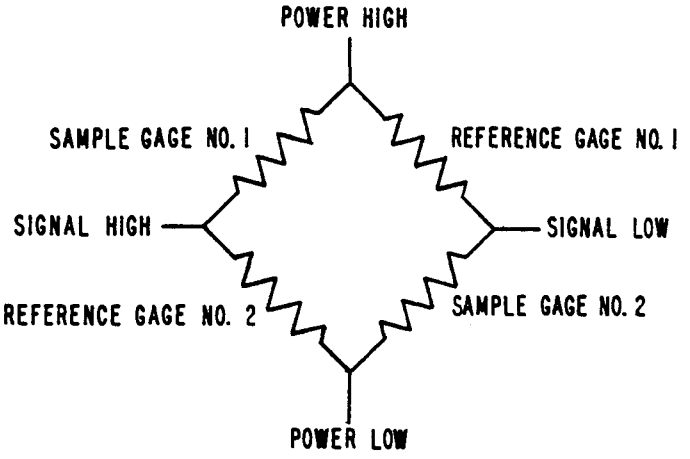
3.2.1 Strain gages. Strain gages shall be foil-resistance type with a resistance of at least 350 ohms. The type of strain gage and the adhesive used for mounting shall be suitable for the temperature range of the test. The size of the strain gage shall be at least 10 times the largest grain diameter in the sample. Gages covering a larger area are recommended to minimize self heating. For core samples, two strain gages shall be mounted with the axes of sensitivity parallel to the long axis of the sample or reference, at mid-height of the sample, on opposite ends of a diameter. Two additional strain gages shall be mounted with the axes of sensitivity normal to the long axis of the sample or reference, also at mid-height, on opposite ends of a diameter. On prismatic samples, a third set of gages shall be mounted in an orientation orthogonal to the other two sets. All strain gages in similar orientation on the sample and reference specimen shall be from the same manufacturing lot. The four gages in similar orientation on the sample and reference shall be wired together in a full Wheatstone bridge configuration as shown on Figure 3.1.

3.2.2 Power supply. The power supply shall be capable of providing AC or DC voltage accurate and stable to at least ± 10mV. The voltage level shall be chosen so as to minimize self-heating effects. In general, 1 to 2 V has been found satisfactory.

3.2.3 Signal conditioning and readout devices. These may be either manual or automatic. Voltmeters shall be capable of reading to 10^{-3} mV. The cumulative error of the readout equipment and strain gages shall meet the requirements of Section 3.1.2 above.



A. LOCATION OF GAGES ON CORE SAMPLE



B. WHEATSTONE BRIDGE CONFIGURATION

FIG. 3.1 STRAIN GAGE METHOD FOR THERMAL EXPANSION

3.2.4 Reference specimen. The dimensions of the reference specimen shall be equal to those of the test sample within 10%, and it shall be composed of a material with a coefficient of thermal expansion which is known to within 0.56×10^{-7}/°F (0.1×10^{-6}/°C) over the temperature range of interest. The coefficient of thermal expansion of the reference shall differ significantly from the estimated coefficient of the rock sample, in order to maximize the output of the differential strain circuit. Stainless steel, with a coefficient generally higher than rock, or titanium silicate,[1] with a coefficient lower than rock, has been used.

3.2.5 Heating unit. The heating unit shall be large enough to contain the test sample and reference specimen. It shall satisfy the performance requirements stated in Section 3.1.3.

3.2.6 Temperature transducers. The temperature transducers shall satisfy the requirements of Section 3.1.4. Two transducers shall be mounted on the sample and two on the reference, one near each end.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Dimensions. Samples shall be right circular cylinders or right prisms. The minimum dimension shall be at least 10 times the size of the largest mineral grain.

4.1.1.1 For the dilatometer method, the longest sample that can be contained by the dilatometer is recommended to increase the measured strain. In no case shall the sample be shorter than 2 in. (51 mm).

4.1.1.2 For the strain gage method, the length of the samples shall be at least as long as the diameter. A length-to-diameter ratio of 2 is recommended.

4.1.2 Surface preparation.

4.1.2.1 For the dilatometer method, the sample ends shall be flat to within 0.001 in. (0.025 mm). The ends shall be parallel to within 0.002 in. (0.05 mm) and perpendicular to the long axis of the sample to within 0.01 in. over 2 in. (0.025 mm over 51 mm).

4.1.2.2 For the strain gage method, the areas on the sample where the gages are to be mounted shall smooth to within 0.001 in. (0.025 mm).

4.1.2.3 The rock shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally, water is used for hard rock, but some materials require special fluids, such as saturated brine for salt or glycerin for expansive shales.

[1] Manufactured by Corning Glass Co., Corning, NY, product code 7971.

4.1.3 Mounting strain gages. For the strain gage method, the gages shall be mounted in accordance with the manufacturer's directions. If the adhesive requires a heat cure, the temperature of the sample shall be raised and lowered at a rate no greater than 3.6°F (2°C) per minute.

4.1.4 Drying. If the sample is tested under dry conditions, it shall be heated to 221° ±4°F (105°C ±2°C) at a rate not greater than 3.6°F (2°C) per minute and maintained at this temperature for at least 24 hours. The sample shall be cooled to ambient temperature at a rate no greater than 3.6°F (2°C) per minute.

4.1.5 Measurement. The dimensions of the sample shall be measured with a micrometer caliper capable of measuring to 0.001 in. (0.025 mm). The measurements shall be recorded as shown on Form L-E.1-1.

4.1.5.1 For cylindrical samples, three length measurements shall be taken at equal intervals. The diameter shall be measured at top, mid-height, and bottom of the sample.

4.1.5.2 For prismatic samples, the length shall be measured across the center of the face adjacent to the ends. The length of the sample shall be measured across two opposite sides in this way, as well as the depth and width.

4.2 Testing.

4.2.1 System calibration. If the dilatometer method is used, the system shall be calibrated by testing the standard specimen. The same heating and cooling cycle shall be used as for the test sample. The system shall be calibrated more often as higher temperatures are used.

4.2.2 Heating and cooling rate. Samples shall be heated and cooled at a rate not greater than 3.6°F (2°C) per minute to minimize thermally induced fractures.

4.2.3 Thermal equilibrium. The sample will be considered to have attained thermal equilibrium when the strain transducer reading is constant for at least three readings over a period of not less than 30 minutes, except for normal fluctuations caused by the limitations of the test system.

4.2.4 Number of points. At least 10 data points shall be recorded at equally spaced temperature intervals for each of the heating and cooling curves. The system shall reach thermal equilibrium for each data point.

4.2.5 Number of cycles. At least two complete heating and cooling cycles shall be performed consecutively on each sample to check for changes induced by heating.

4.2.6 Data recording requirements. The data shown on Form L-E.1-1 shall be recorded as a minimum for the test. The exact format will be determined by the readout system, but the format shown on Form L-E.1-1 shall be followed as closely as practicable.

4.3 Corrections to data - strain gage method.

4.3.1 Voltage normalization. The output voltages shall be normalized with respect to input voltages.

4.3.2 Bridge efects. Corrections shall be made for the effects of Wheatstone bridge nonlinear response.

4.3.3 Gage factor. The correct strain gage factor for the test temperature shall be used. This information is supplied with the gages by the manufacturer.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types or over several temperature ranges, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure and fabric, grain size, discontinuities or voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary. A summary table of results including test suite designations, temperature ranges, average coefficients of thermal expansion, ranges, and uncertainties shall be presented.

5.4.2 Individual results. A table of results for individual samples including, as a minimum, individual sample number, rock type, temperature range, and coefficient of thermal expansion shall be presented.

5.4.3 Other. The following other types of analysis or presentation may be included as appropriate.

5.4.3.1 Histograms of results.

5.4.3.2 Coefficient of thermal expansion as a function of temperature.

5.4.3.3 Correlation with other rock properties such as specific gravity or modulus of deformation.

5.4.3.4 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all transducers, power supplies, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean value of thermal expansion, range, standard deviation, and 95% confidence limits for the mean shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

5.6.1 Data curves. A strain vs. temperature curve for each test sample shall be included in an appendix.

5.6.2 Data forms. A completed data Form L-E.1-1 for each test sample shal be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-E.1-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded Form L-E.1-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-E.1-1.

Thermal Expansion of Laboratory Rock Samples
Test Data Sheet - Form L-E.1-1

Project _____ Sample No. _____

Date _____ Rock Type _____

Tested by _____ Orientation _____

Test Temperature Range _____

Equipment Description	Serial No.	Date of Calibration

Dimensions

Core Samples:

Sample Height _____ Sample Diameter _____

_____ _____

_____ _____

Average _____ Average _____

Prismatic Samples:

Length _____ Width _____ Depth _____

_____ _____ _____

Average _____ Average _____ Average _____

Time	Temperature, °C		Deformation Reading		
	No. 1	No. 2	Axial	Circumferential	Other

Time	Temperature, °C No. 1	Temperature, °C No. 2	Deformation Reading Axial	Deformation Reading Circumferential	Deformation Reading Other

Remarks:

Test Supervisor _____ Date _____

Quality Assurance _____ Date _____

Project Engineer _____ Date _____

Procedure L-E.2

Specific Heat of Laboratory Rock Samples

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test measures the change in enthalpy of a rock sample as its temperature is changed. Specific heat at a particular temperature may be calculated from this data.

1.1.2 Applicability. The sample may be either solid or in powder form. The temperatures at which the specific heat may be investigated with this procedure range from cryogenic to approximately 1200°C. For simplicity, this procedure is written for tests conducted at elevated temperature.

1.2 General description of the test.

A rock sample is heated to a specified temperature. The sample is dropped into a container in a water bath. This system is designed to be abiabatic. The sample and receiving system reach thermal equilibrium. The sample enthalpy is calculated. This procedure is repeated at several temperatures. The relationship of sample enthalpy to temperature is determined, from which the specific heat is calculated.

1.3 Data Reduction.

1.3.1 Terms and definitions.

1.3.1.1 Adiabatic - an adiabatic system is one which is perfectly thermally insulated from its surroundings.

1.3.1.2 Enthalpy - a measure of the energy content of systems under constant pressure. In this procedure, enthalpy is equivalent to heat energy.

1.3.2 Equations.

1.3.2.1 The change of enthalpy, ΔH, is calculated using:

$$\Delta H = C_p M \Delta T \qquad (1)$$

where:

C_p = specific heat (heat capacity) of a substance

M = mass of the substance

ΔT = temperature change of the substance.

1.3.2.2 The change in enthalpy, ΔHr, of an adiabatic system composed of a metal receiver and a water bath is calculated using:

$$\Delta H_r = (C_{pm}M_m + C_{pw}M_w)(T_f - T_i) \qquad (2)$$

where:

C_{pm} = specific heat of metal receiver

M_m = mass of metal receiver

C_{pw} = specific heat of water

M_w = mass of water

T_f = final system temperature

T_i = initial system temperature

1.3.2.3 The loss of enthalpy, ΔH_l, in the system because it is not completely adiabatic is calculated by:

$$\Delta H_l = C_{pr} M_r (T_r - T_f) - \Delta H_r \quad (3)$$

where:

C_{pr} = specific heat of a reference material at T_r

M_r = mass of reference material

T_r = reference material temperature when introduced into adiabatic system

T_f = equilibrium temperature of adiabatic system plus the reference material.

ΔH_r is calculated from Equation 2 for a test using the reference material.

1.3.2.4 The enthalpy of a test sample, ΔH_s, is calculated using.

$$\Delta H_s = \Delta H_r + \Delta H_l \quad (4)$$

where:

ΔH_r = enthalpy change of the system when the sample is tested, calculated from Equation 2

ΔH_l = enthalpy loss of the system, determined by calibration with a reference material, as shown in Equation 3.

1.3.2.5 The specific heat, C_{ps}, of a sample is calculated using:

$$C_{ps} = \frac{d(\Delta H_s)}{dT_s} \quad (5)$$

where:

T_s = sample temperature before entrance into adiabatic system.

The enthalpy change as a function of a temperature for a typical rock is shown in Figure 1.1. It may be noted that enthalpy change is referenced to 0 at a sample temperature of 32°F (0°C).

1.3.3 Factors influencing the data. The specific heat test is very sensitive to enthalpy losses during the test which do not result in raising the temperature of the water bath. These occur primarily during transfer of the sample from the furnace to the receiver and during equilibration. They are corrected for using the calibration given by Equation 3. However, the test procedure must be quite standardized, so that it can be repeated to the finest detail possible. The same technician should perform both the calibration and the test, and environmental factors should be constant as far as possible.

1.4 References.

1.4.1 ASTM, 1973, Test Designation C 351, "Standard Test Method for Mean Specific Heat of Thermal Insulation", Annual Book of ASTM Standards, Part 18.

1.4.2 U.S. Bureau of Mines, 1974, "Thermal Capacity", Bureau of Mines Test Procedures for Rocks, Information Circular IC 8628.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, then manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and type of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

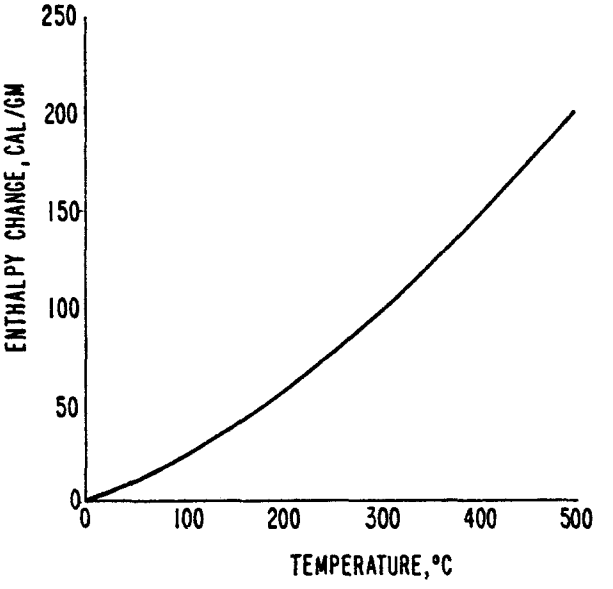


FIG. I.I ENTHALPY CHANGE AS A FUNCTION OF TEMPERATURE FOR A TYPICAL ROCK.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Material differences within the rock mass, such as filled vugs, inclusions, and alteration zones, can significantly influence the specific heat of the rock. These should be sampled and tested to provide an estimate of their effect.

2.4 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Calorimeter.

The calorimeter consists of the receiving vessel, the water bath, the adiabatic container, and the necessary support mechanisms. The receiving container shall be constructed of metal with high thermal conductivity and known specific heat characteristics. Copper is recommended. Distilled water shall be used for the water bath. The adiabatic container shall be a Dewar flask with an insulated lid. When performing the test, it is desirable for the system equilibrium temperature to differ from the initial temperature by only 3.5° to 7.0°F (2° to 4°C) in order to minimize heat losses. As discussed in Section 1.3.2, the mass of the water, receiver and sample, as well as the sample temperature, determine the temperature change during the test. The components of the calorimeter shall be sized to satisfy this requirement. The receiver shall be supported in such a way as to minimize heat loss by conduction. A schematic of the calorimeter and test assembly is shown on Figure 3.1.

3.2 Heater.

The heater shall be a tube furnace open at its lower end. It shall be of sufficient length to accomodate the sample capsule. The furnace shall provide a uniform temperature within 1.8°F (1°C) over the length of the sample capsule and shall be capable of maintaining a temperature constant to within 3.6°F (2°C) over a period of time.

3.3 Sample capsule.

The capsule to contain the rock during the test shall be constructed of metal which will not react with the sample or atmosphere during the test. An alloy of 90% platinum and 10% rhodium has been successfully used. The capsule shall be sealable, for example with a screw cap or by welding.

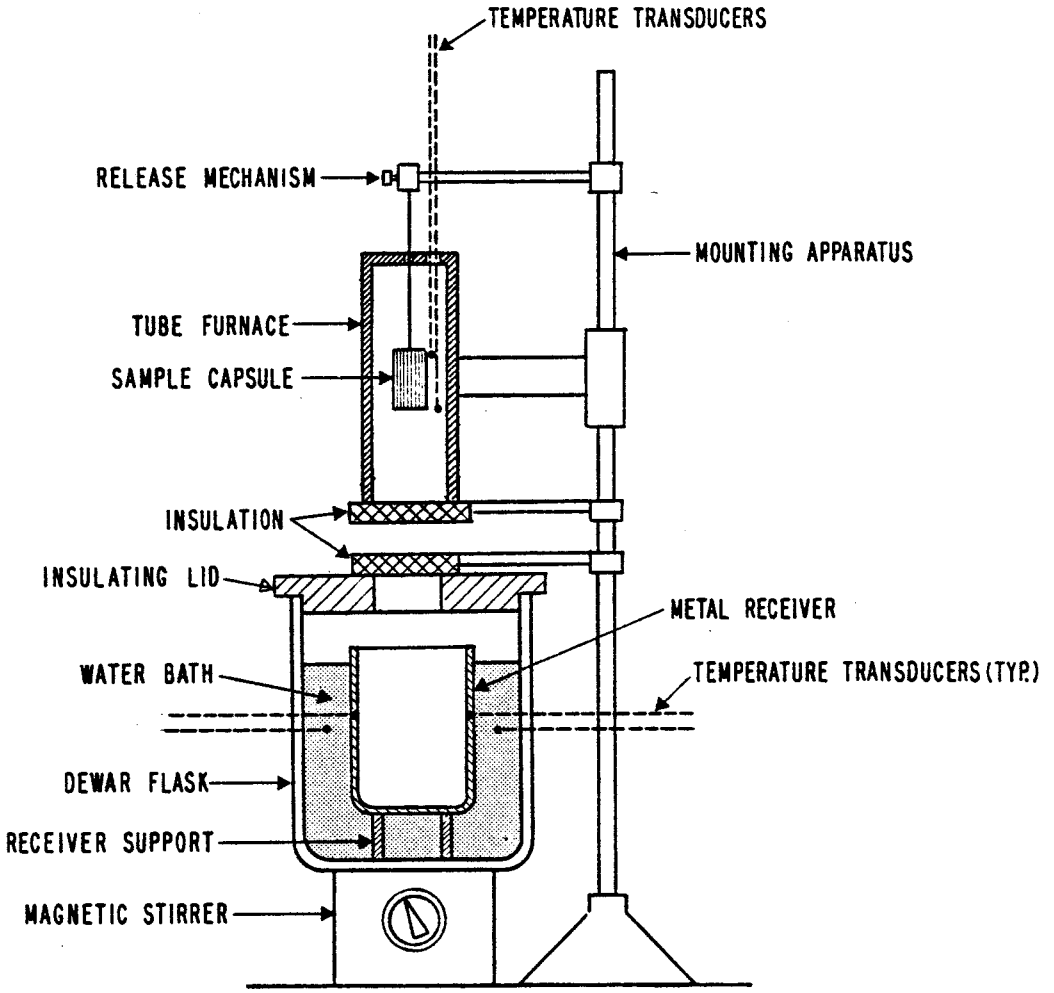


FIG. 3.1 SCHEMATIC OF SPECIFIC HEAT APPARATUS

3.4 Temperature transducers.

The exact type of temperature transducer used depends on the test temperature and the equipment configuration. Special Limits of Error thermocouples or platinum resistance thermometers (RTDs) are recommended. In the furnace, the temperature transducers shall be accurate to at least ±1.8°F (±1°C), including errors introduced by readout equipment, and shall have a resolution of at least 0.18°F (0.1°C). Two transducers shall be mounted in the furnace, one at each end of the sample capsule. In the calorimeter, the temperature transducers shall have an accuracy of at least ±0.2°F (±0.1°C), including errors introduced by readout equipment, and a resolution of at least 0.1°F (0.05°C). Two transducers shall be placed in the water bath and two shall be incorporated in the metal receiver.

3.6 Mounting apparatus.

The furnace shall be mounted over the calorimeter. An insulating medium shall be in place at the base of the furnace and on the top of the Dewar flask at all times except when the sample capsule is being transferred from the furnace to the calorimeter. The mounting shall contain apparatus for suspending the sample capsule at a repeatable location in the furnace. This apparatus shall be capable of releasing the sample capsule in a controlled and repeatable manner. It is recommended that a system which automatically removes the insulation from the bottom of the furnace and top of the calorimeter, releases the sample capsule, and replaces the insulation over a short and fixed time period be incorporated into the mounting apparatus.

3.7 Magnetic stirrer.

The calorimeter shall be placed on a magnetic stirrer with a variable speed control.

3.8 Reference material.

A reference material with known specific heat shall be used to calibrate the system. The reference shall be approximately the same mass as the sample. Copper and fused quartz have been used successfully.

3.9 Weighing apparatus.

Apparatus shall be available for determining the mass of the water bath, metal receiver, and Dewar flask to an accuracy of at least ±0.004 oz (±0.1 g). The mass of the sample capsule and sample shall be determined to an accuracy of at least $\pm 3.5 \times 10^{-4}$ oz (±0.01 g).

4.0 Procedure

4.1 Sample preparation.

4.1.1 Dimensions. Intact rock core, fragments, or powder may be used. At least 3.5 oz (100 g) of sample shall be tested.

4.1.2 Drying. The sample shall be placed in the sample container but not sealed. The sample and container shall be placed in an oven and dried at 221° ±4°F (105° ±2°C) for at least 24 hours.

4.2 Testing.

4.2.1 Sample heating. The sealed capsule containing the sample shall be heated until the average furnace temperature stabilizes within 3.6°F (2°C) of the desired test temperature. The furnace shall be maintained at that temperature for at least 1 hour before the sample is tested. The readings of the two furnace temperature transducers shall not differ by more than 1.8°F (1°C) at the time of the test.

4.2.2 Temperature monitoring. The temperature of the furnace and calorimeter shall be monitored at 30-second intervals for 10 minutes before the test. The calorimeter temperatures shall be monitored at 30-second intervals during the first 10 minutes after the release of the sample capsule, and at 2-minute intervals thereafter until the rate of temperature change becomes constant with time. This generally takes 30 to 60 minutes.

4.2.3 Number of tests. The sample shall be tested at least three times at each test temperature. At least five test temperatures equally spaced over the range of interest shall be used to obtain the enthalpy-temperature curve. The same sample should be used for all tests.

4.2.4 System calibration. The loss of enthalpy shall be determined by testing the reference material in the same manner and at the same temperatures as the rock sample.

4.2.5 Test environment. The temperature of the test room shall be maintained to within ±3.6°F (±2°C). The apparatus shall be protected from drafts during the test.

4.2.6 Stirring. The water bath shall be stirred at the minimum rate necessary to achieve uniform readings of the temperature sensors in the bath, in order to minimize heat introduced into the system by agitation.

4.3 Data handling.

The average calorimeter temperature shall be plotted as a function of time, and the equilibrium temperature shall be determined by extrapolating the constant temperature change rate back to the release time (see Figure 4.1).

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

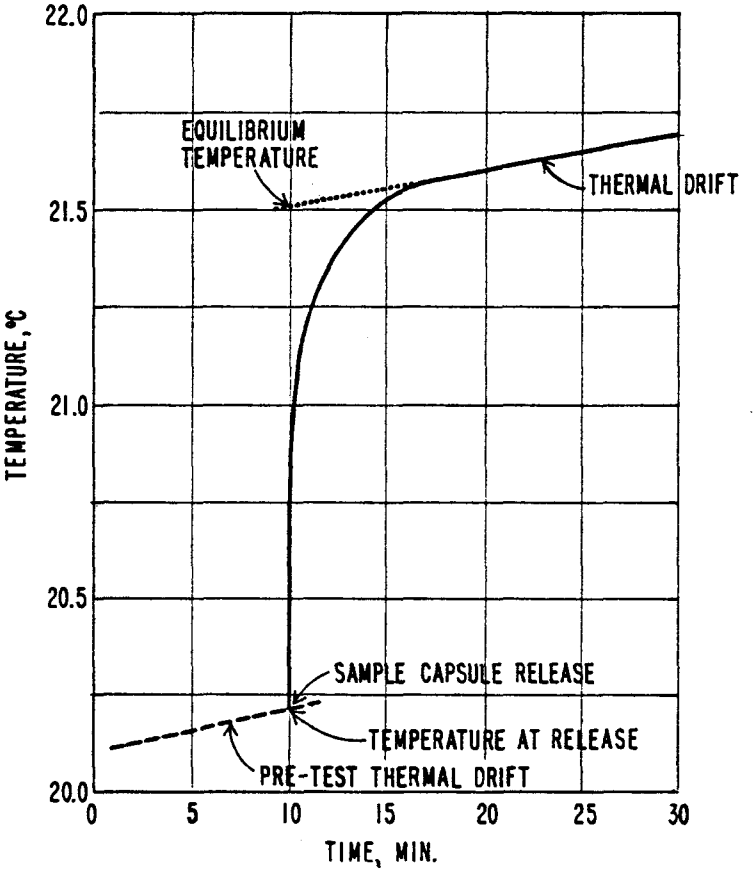


FIG. 4.1 TYPICAL CALORIMETER TEMPERATURE VS TIME CURVE

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests of several rock types, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program, and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure fabric, grain size, discontinuities, voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure varies from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary of results. A summary table containing, as a minimum, rock suite identification, test temperature range, the functional formulation of specific heat over that range, and the uncertainty shall be presented.

5.4.2 Individual results. A table of results including, as a minimum, individual sample numbers, test temperature ranges, and the functional formulations of specific heat over that range shall be presented.

5.4.3 Graphics presentation. A plot of specific heat as a function of temperature shall be included for each rock suite.

5.4.4 Other. The following other types of analyses may be included as appropriate.

5.4.4.1 Correlation with other rock properties such as thermal conductivity or specific gravity.

5.4.4.2 Histograms of results.

5.4.4.3 Comparison of results with other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error in enthalpy change and temperature associated with a single test shall be evaluated. The error in specific heat shall be determined.

5.5.2 Sample variability. For each suite of rock samples,the mean, range, standard deviation and 95% confidence limits for the mean specific heat at individual temperatures shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

5.6.1 Curves. The temperature-time curves and enthalpy-time curves for each sample shall be included in an appendix.

5.6.2 Data forms. A completed data form L-E.2-1 for each sample shall be included in an appendix.

6.0 Quality Assurance.

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-E.2-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-E.2-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of L-E.2-1.

Specific Heat of Laboratory Rock Samples
Test Data Sheet - Form L-E.2-1

Project _____ Sample No. _____

Date _____ Rock Type _____

Tested By _____ Sample Form _____

Room Temperature _____

Equipment Description	Serial No.	Date of Next Calibration

Mass of Capsule _____ Mass of Capsule and sample _____

Mass of Metal receiver and support _____ Mass of Dewar flask _____

Mass of Calorimeter plus water bath _____

Time	Furnace Temp, °C		Receiver Temp, °C		Water Bath Temp, °C	
	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2

Time	Furnace Temp, °C		Receiver Temp, °C		Water bath Temp, °C	
	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2

Remarks:

Test Supervisor ______________________ Date __________

Quality Assurance ______________________ Date __________

Project Manager ______________________ Date __________

Procedure L-E.3

Thermal Conductivity of Laboratory Rock Samples

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test determines the thermal conductivity of a rock core sample under steady-state heat flow conditions. Thermal resistivity may also be calculated.

1.1.2 Limitations. This procedure is applicable to isotropic rock materials only. Selectively sized and oriented samples should be tested if several types of material are present.

1.2 General description of the test.

A thermal stack is assembled consisting, in order, of a heat source, an upper heat flow meter, the test sample, a lower heat flow meter, a cold plate, and a heat sink. The stack is insulated or supplied with guard heaters to minimize heat loss through the sides. A fixed temperature difference is maintained between the heat source and the cold plate while the system comes to thermal equilibrium. The temperature at each material interface in the stack is then measured and the thermal conductivity is calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Guard heater - a controllable cylindrical heater surrounding the thermal stack used to minimize heat losses through the sides of the stack.

1.3.1.2 Heat flow meter - a specimen of material with a known thermal conductivity. If the temperature difference between the ends is known and there is no heat loss through the sides, the heat flow through the specimen may be calculated.

1.3.1.3 Thermal conductivity - an inherent property of every material related to its ability to conduct heat.

1.3.1.4 Thermal stack - the assembly of heat sources and sinks, heat flow meters, sample, and temperature measurement devices placed together in the thermal conductivity test.

1.3.2 Equations.

1.3.2.1 The thermal conductivity, K, of a material is calculated using:

$$K = \frac{QL}{A\Delta T} \qquad (1)$$

where

Q = heat flow through the material

L = thickness of the material

A = cross-sectional area of the material

ΔT = temperature difference between the two sides of the material.

1.3.2.2 The thermal resistivity, r, is calculated using:

$$r = \frac{1}{K} \qquad (2)$$

1.3.2.3 The heat flow through each heat flow meter is calculated by rearranging Equation 1:

$$Q = \frac{KA\Delta T}{L} \qquad (3)$$

1.3.3 Factors influencing the data. The above equations are for steady-state one-dimensional heat flow through a homogeneous material. To maintain the steady-state requirements, it is important that the test system comes to thermal equilibrium. To achieve one-dimensional heat flow, the heat flow through the edges of the thermal stack must be minimized. Finally, to measure the true thermal conductivity of the material, thermal "short circuits," or paths of anomalously high conductivity, must be avoided in the sample.

1.4 References.

1.4.1 ASTM, 1976, Test Designation C-177, "Test for Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate," Annual Book of ASTM Standards, Part 18.

1.4.2 ASTM, 1976, Test Designation C-518, "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter," Annual Book of ASTM Standards, Part 18.

1.4.3 Morgan, M. T., and West, G. A., 1980, "Thermal Conductivity of the Rocks in the Bureau of Mines Standard Rock Suite," Oak Ridge National Laboratory ORNL/TM-7052.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities in the rock mass such as joints, alteration zones, fracture fillings, variable porosity, etc. can significantly influence the thermal conductivity of the rock mass. These should be sampled and tested individually to provide an estimate of their effect.

2.3.4 Anisotropy. Anisotropy in the rock mass should be evaluated by testing samples taken at different orientations.

2.4 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Hot plate.

A hot plate of the same diameter as the test sample shall be used to apply heat to the thermal stack. The hot plate shall be constructed so that the side in contact with the thermal stack is isothermal. This side shall be flat and smooth to within 0.001 in.

3.2 Cold plate.

A cold plate shall be used to control the temperature gradient in the stack. It shall meet the specifications of Section 3.1.

3.3 Heat sink.

A heat sink shall be provided on the side of the cold plate opposite the thermal stack.

3.4 Temperature control unit.

A unit to control the temperatures of the hot and cold plates shall be provided. The temperature at each face of the test sample shall not vary during the test by more than 0.27°F (0.15°C). The control unit shall also be capable of achieving the desired average sample temperature within 1.8°F (1°C). The control unit shall allow the sample to be heated at a rate not greater than 3.6°F (2°C) per minute.

3.5 Heat flow meters.

The heat flow meters shall be constructed of a material of known thermal conductivity which is similar to that of rock. Fused silica is recommended. The heat flow meters shall be the same diameter as the sample and have a length-to-diameter ratio between 1/5 and 1/3. The faces shall be flat and smooth to within 0.001 in. (0.025 mm) and parallel to each other to within 0.002 in. (0.05 mm).

3.6 Insulation/guard heater.

Insulation shall be placed around the thermal stack to minimize heat flow through the sides. The thickness and type of insulation shall satisfy the heat loss requirements of Section 4.2.5. Alternatively, a guard heater consisting of a cylindrical furnace and control units may be placed around the thermal stack. It is recommended that the guard heater have at least three zones with independent temperature controls to provide a thermal gradient similar to that of the stack.

3.7 Temperature measurement.

Temperature shall be measured at several locations in the thermal stack as shown on Figure 3.1. Special Limits of Error 30 AWG thermocouples are recommended. The wire and insulation shall not degrade at the maximum test temperature. The thermocouples shall be positioned at the center of the faces of the samples and heat flow meters. A small slot shall be cut in the face of the sample or heat flow meter to accommodate the bare thermocouple wires, as shown on Figure 3.2.[1] The wires shall be cemented into the slot with a grout suitable for the test temperature. The thermocouples shall be accurate to at least +0.1°F (± 0.05°C) and have a resolution of at least 0.02°F (0.01°C).

3.8 Thermal compound.

To ensure good thermal contact between the sample, heat flow meters, and heaters, a thermally conductive viscous compound may be applied at each interface.

3.9 Holding frame.

A frame for applying axial load to the thermal stack shall be used to ensure good contact between the components of the stack. The frame shall be capable of applying a stress of 10 psi (0.07 MPa) constant to within 1 psi (0.007 MPa) for the duration of the test.

[1] Morgan and West, 1980 (see Ref. 1.4.3).

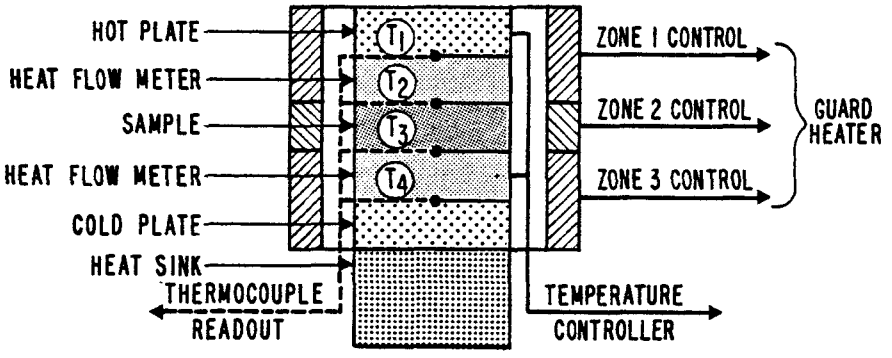


FIG. 3.1 SCHEMATIC OF THERMAL STACK

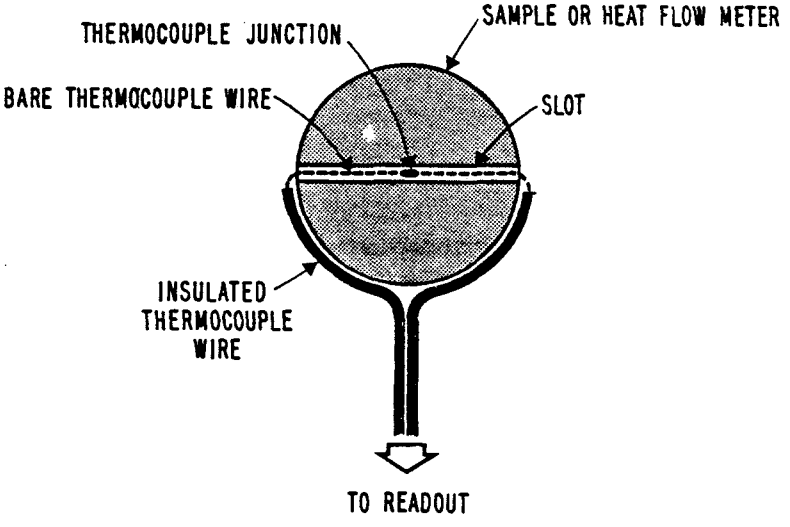


FIG. 3.2 SCHEMATIC OF THERMOCOUPLE INSTALLATION
(AFTER REFERENCE 1.4.3)

4.0 Procedure

4.1 Sample preparation.

4.1.1 Dimensions.

4.1.1.1 The diameter of the sample shall be at least 10 times larger than the largest mineral grain, but in no case less than 1.5 in. (38 mm). NX-size (2 in. nominal diameter; 51 mm) cores are recommended for all except very coarse-grained rocks. The diameter shall be measured across two perpendicular diameters at mid-height of the sample with a dial micrometer capable of measuring to 0.001 in. (0.025 mm). These readings shall be recorded as shown on Form L-E.3-1.

4.1.1.2 The thickness of the sample shall be at least 10 times the diameter of the largest grain, but in no case less than 0.5 in. (12.7 mm). The length-to-diameter ratio of the test sample shall be between 1/5 and 1/3. The length shall be measured at three equally spaced intervals with a dial micrometer capable of measuring to the nearest 0.001 in. (0.025 mm). These readings shall be recorded as shown on Form L-E.3-1.

4.1.2 Faces. The sample faces shall be flat and smooth to within 0.001 in. (0.025 mm) and parallel to within 0.002 in. (0.05 mm). The rock shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally, water is used for hard rock, but other materials may require special fluids, such as saturated brine for salt or glycerin for slaking mudstones.

4.1.3 Structures. Small joints and seams are potentially high-conductivity heat flow routes through the sample. Material which has fractures running axially through the test sample should be avoided.

4.1.4 Drying. Samples shall be dried prior to testing by heating in an oven at 221° ±4°F (105° ± 2°C) for at least 24 hours. The rate of heating and cooling of the sample shall not exceed 3.6°F (2°C) per minute. Rocks which degrade at this temperature may be dried in a vacuum desiccator.

4.2 Testing.

4.2.1 Axial load. An axial load of 10 psi (0.07 MPa) shall be applied to the thermal stack.

4.2.2 Heating rate. The sample shall be heated at a rate not greater than 3.6°F (2°C) per minute.

4.2.3 Temperature differential. A temperature gradient of 46°F per in. (1°C per mm) shall be maintained across the sample.

4.2.4 Thermal equilibrium. Temperature readings of all thermocouples shall be taken at 3-minute intervals during the test. The system shall be considered to have achieved thermal equilibrium

when the temperatures are constant to within 0.27°F (0.15°C) for three consecutive readings.[1]

4.2.5 Heat loss. The heat flow indicated by the upper and lower heat flow meters shall not differ by more than 10%. The insulation, guard heater, or dimensions of the sample may be adjusted to satisfy this requirement. The average value of the two heat flow meters shall be considered the heat flow through the sample.

4.2.6 Data recording. The data shown on Form L-E.3-1 shall be recorded, as a minimum. The exact format will depend on the temperature readout equipment, but shall be as close to that shown on Form L-E.3-1 as practicable.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of sample tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure, fabric, grain size, discontinuities, voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

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[1] Morgan and West, 1980 (See Ref. 1.4.3).

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure varies from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary table. A summary table including, as a minimum, rock suite identification, temperature, average thermal conductivity, range, and uncertainty shall be presented.

5.4.2 Individual results. A tabular presentation of results including, as a minimum, sample numbers, test temperatures, and thermal conductivities shall be presented.

5.4.3 Graphic presentation. A plot of thermal conductivity versus temperature shall be included for each rock suite.

5.4.4 Other analysis. The following other types of analyses and presentations may be included as appropriate.

5.4.4.1 Histogram of results.

5.4.4.2 Correlation with other rock properties such as specific heat and specific gravity.

5.4.4.3 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all thermocouples, heaters, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean thermal conductivity, the range, standard deviation and 95% confidence limits for the mean shall be calculated, as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

Each completed test Form L-E.3-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-E.3-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-E.3-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of Form L-E.3-1.

Thermal Conductivity of Laboratory Rock Samples
Test Data Sheet - Form L-E.3-1

Project _____ Sample No. _____

Date _____ Rock Type _____

Tested By _____ Test Temperature _____

Load _____

Equipment Description	Serial No.	Date of Next Calibration

Sample Thickness _____ Sample Diameter _____

_____ _____

_____

Average _____ Average _____

Heat Flow Meter 1 Thickness _____

Heat Flow Meter 2 Thickness _____

	Thermocouple Temperature, °C			
Time	t_1	t_2	t_3	t_4

	Thermocouple Temperature, °C			
Time	t_1	t_2	t_3	t_4

Remarks:

Test Supervisor_____ Date_____

Quality Assurance_____ Date_____

Project Engineer_____ Date_____

Procedure L-F.1

Fluid Permeability of a Rock Sample

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. The objective of this test is to determine fluid permeability for disk-shaped or cylindrical rock specimens at ambient temperature and confining pressure.

1.1.2 Limitations. Use of this procedure is limited to specimens which have a sufficiently high permeability that the flow of fluid through the specimen can be measured with a flow meter. Commercially available liquid permeameters can be used on rock down to about 3.9×10^{-8} in. (1×10^{-7} cm) per second, and special high-pressure permeameters can measure to about 3.9×10^{-10} in. (1×10^{-9} cm) per second.

Care must be exercised that the rocks tested with the liquid permeameter are not sensitive to the fluid being used. When water is used, it must be freshly distilled or prepared in such a way that the growth of bacteria is prevented. In the micro-permeability range, bacterial growth in the water can block the pores. As a standard procedure, water used for permeability determinations is filtered through a 0.22 m filter.

1.2 General description of the test.

In permeability testing, fluid is forced through a rock specimen under pressure. The pressure is measured at the entrance to, and the exit from, the specimen, the run length is recorded and the quantity of seeping fluid is determined using a flow meter. Either of two specimen configurations are commonly used: disks or cylinders.

For disk-shaped specimens, pressure is applied to each face, establishing a pressure gradient between them. For cylindrical specimens, the testing fluid is either forced from the outside wall of the sample to the inside (compressional stress field), or it is forced from the inside wall to the outside (tensional stress field). Flow through the cylinder wall is monitored and permeability is calculated.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Darcy: Unit of permeability. A porous medium has a permeability of 1 darcy when a fluid of 1 centipoise viscosity [water has 1 centipose viscosity at 68°F (20°C)] flows through it at a rate of 0.06 in.^{3} (1 cm^3) per second per 0.16 in.^{2} (1 cm^2) of cross-sectional area and 0.39 in. (1 cm) of length at a pressure differential of 1 atmosphere [407 in. (1034 cm) of water at the same temperature].

1.3.1.2 Velocity of flow: Through a rock of unit permeability, water of 1 centipoise viscosity moves 0.39 in.(1 cm) per second at 100% gradient. Note that this rate of flow is the same as stated in defining the darcy, although in this case the gradient is 1:1 rather than 1034:1. The term "velocity of flow" is most commonly used in civil engineering geology and soil mechanics (1 cm per second = 1034 darcy).

1.3.2 Equations.

1.3.2.1 For disk-shaped specimens, permeability is calculated using the follwing relationship:

$$k = \eta \frac{QL}{A(P_i - P_o)} \quad (1)$$

where: k = permeability, darcy

η = viscosity of the fluid at the temperature of the experiment, centipoise

Q = rate of flow of the outlet fluid, cm^3 per second

L = thickness of the specimen, cm

A = cross-sectional area of the specimen perpendicular to direction of flow, cm^2

P_i = absolute pressure at the inlet, atmosphere

P_o = absolute pressure at the outlet, atmosphere.

1.3.2.2 For cylindrical specimens, radial permeability is obtained from the following equation:

$$k = \frac{\eta\, q_o \ln \frac{r_o}{r_i}}{\pi L\, p_i^2 - p_o^2} \quad (2)$$

where: k = permeability, darcy

η = viscosity of the fluid at the temperature of the experiment, centipoise

q_o = rate of flow of outlet fluid, cm^3 per second

r_o = outer radius of specimen, cm

r_i = inside radius of specimen, cm

L = axial length of core, cm

p_i = absolute pressure at the inlet, atmosphere

p_o = absolute pressure at the outlet, atmosphere.

$\ln$ = natural logorithm

1.4 References.

1.4.1 Jaeger, C., 1972, Rock Mechanics and Engineering, Cambridge University Press, 417 p.

1.4.2 Lama, R.D., and Vutukuri, V.S., 1978, Handbook on Mechanical Properties of Rocks - Testing Techniques and Results, Vol. IV, pg. 356-380.

1.4.3 U.S. Bureau of Mines, 1974, "Percolation of Gas and Water in Rock", Bureau of Mines Test Procedures for Rocks, Information Circular IC 8628.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished according to Standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks to evaluate the results with equal certainty.

2.3.3 Nonhomogeneities. Discontinuities in the rock mass, such as joints, weathered zones, inclusions, voids, etc. may control rock mass permeability. These should be sampled and tested to provide an estimate of their effect.

2.3.4 Anisotropy. Permeability is a highly directionally dependent property. Therefore, test cores should be taken such that permeability can be measured in several different directions.

2.4 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

The main components of the apparatus used for permeability testing are shown schematically on Figure 3.1.

3.1 Hydraulic power supply.

A pressure pumping system is required which is capable of producing and maintaining the desired inlet pressure. The capacity of the hydraulic power supply will depend upon the desired flow rate and inlet pressure.

3.2 Pressure regulator.

A suitable pressure regulator should be provided to supply the inlet fluid at a constant pressure.

3.3 Fluid separator.

The purpose of the fluid separator is to isolate the test fluid, which is usually water or brine, from the hydraulic system. A fluid separator is required only if the hydraulic power supply fluid is different from the test fluid.

3.4 Pressure gages.

Inlet and outlet pressure must be accurately measured. For low pressure tests, water-, oil- or mercury-filled manometers are usually used. For tests where the inlet pressure exceeds 14.5 psi (100 kPa) a bourdon tube gage or electronic pressure transducer is usually used.

3.5 Specimen holder.

The specimen holder must be designed such that when pressure is applied to one end of the system, all flow is through the specimen. Care must be taken that no fluid bypasses the sample either through an imperfect seal between the core holder and sample or between the sample and the supporting material, if the sample is mounted.

3.6 Flow meter.

A device to measure the flow rate at the outlet is required. In addition, a flow meter at the inlet is recommended to verify that the specimen holder does not leak.

4.0 Procedure

4.1 Sample preparation.

To ensure that the surface pores of the sample do not become obstructed during sample preparation, the specimen should be saturated with the cutting fluid. Longitudinal samples shall not be used to measure permeability of less than 10^{-8} cm per sec.[1]

[1] Lama, R.D., and Vutukuri, V.S., 1978, (see Ref. 1.4.2)

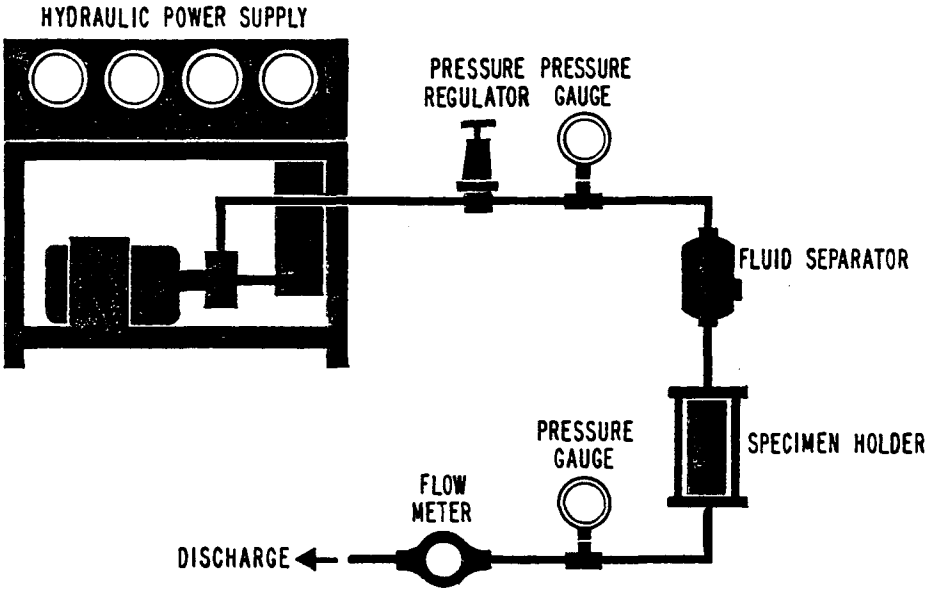

FIG. 3.1 PERMEABILITY TEST SETUP

4.1.1 Dimensions. Pore size varies with different materials. If the pore size is assumed to be approximately the same size as the mineral grains in the sample, the shortest distance for the testing medium to flow through the sample shall be 20 to 30 grain diameters.

4.1.1.1 Length. For longitudinal tests, the sample shall be 20 to 30 grain diameters long. Minimum length will be at least 0.5 in. (12.7 mm). For radial tests the sample shall be approximately 180 grain diameters long. This will allow the usable length of the central hole to be four times the testing medium travel distance (Figure 4.1).

4.1.1.2 Diameter. Longitudinal samples shall have a minimum diameter of 7.8 in. (19.8 cm, EX core). Radial sample diameter shall be such that r_2-r_1 is at least 30 grain diameters (Figure 4.1).

4.1.2 Parallelism. Sample ends shall be parallel to each other to within 0.002 in.[2] (0.05 mm). Sides shall be true to 0.002 in. (0.05 mm) diameter.

4.1.3 Machining. The rock shall not be degraded during the machining process. Thermal fracturing shall be prevented by cooling with an appropriate fluid as required. Generally water is used for hard rock, but other materials require special fluids, such as saturated brine for salt or glycerine for slaking mudstones.

4.2 Procedure.

4.2.1 Saturating the specimen. The specimen must be saturated with the test fluid prior to testing. The specimen is saturated by placing it in a vacuum of at least 0.022 psi (150 Pa) for a minimum of 30 minutes. Then the vacuum chamber is flooded with the test fluid while maintaining the vacuum. After the samples are covered with the test fluid, the vacuum is maintained for at least 15 minutes before allowing the specimen to return to atmospheric pressure.

4.2.2 Installing the specimen. When installing the specimen in the specimen holder, care must be exercised to prevent the specimen from drying. Also, the specimen must be sealed in the fixture so that all the test fluid passes through the specimen during the test.

4.2.3 Bleeding the system. After placing the specimen in the specimen holder, the pressure system must be bled to ensure that no air is present in the pressure line.

4.2.4 Data acquisition. The test is performed by adjusting the pressure regulator to the desired inlet pressure and monitoring the inlet pressure, outlet pressure and flow rate. All data shall be recorded as shown on Form L-F.1-1.

[2] USBM, 1974, (see Ref. 1.4.3)

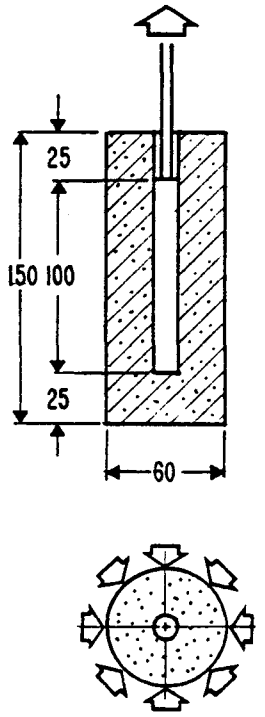

FIG. 4.1 DIMENSIONS OF RADIAL PERMEABILITY SAMPLE (IN MM)

(After Jaeger, 1972)

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types or at various axial loads, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure, fabric, grain size, discontinuities, voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a nonideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary of results. Summary tables for each rock type shall be prepared. The information shall include as a minimum rock suite designation, number of tests, average value, range, and uncertainties.

5.4.2 Individual results. A summary table of individual test results shall be prepared including sample number, sample dimensions, inlet and outlet pressure, flow rate and permeability as a minimum.

5.4.3 Other. The following other types of analyses or presentations may be included as appropriate.

5.4.3.1 Photographs of specimens.

5.4.3.2 Histograms of results.

5.4.3.3 Correlation with other rock properties such as porosity.

5.4.3.4 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated. This includes the combined effects of all pressure gages, flow meters, readout devices, etc.

5.5.2 Sample variability. For each suite of rock samples, the mean values of the permeability, ranges, standard deviations and 95% confidence limits for the means shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

Each completed test Form L-F.1-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-F.1-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-F.1-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of L-F.1-1.

Fluid Permeability of a Rock Sample

Test Data Sheet - Form L-F.1-1

Project _____ Sample No. _____

Date _____ Rock Type _____

Tested by _____

Equipment Description	Serial No.	Date of Next Calibration

Specimen Dimensions:

Length _____

Outside Diameter _____

Inside Diameter _____

Inlet Pressure _____

Outlet Pressure _____

Flow Rate _____

Permeability _____

Test Supervisor _____ Date _____

Quality Assurance _____ Date _____

Project Engineer _____ Date _____

Procedure L-F.2

Water Content of a Rock Sample

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. This test is intended to measure the water contained in a rock sample as a percentage of the oven-dry sample weight.

1.1.2 Limitations. If in situ water content is desired, precautions must be taken to retain the natural water content during sampling and storage.

1.2 General description of the test.

The water content of a rock sample is determined by weighing the sample before and after drying it. The difference in weight before and after drying is the weight of the water in the sample.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Grain weight. The weight of the mineral grains in the sample.

1.3.1.2 Pore water weight. The weight of the water in the specimen prior to drying.

1.3.1.3 Water content. The ratio of pore water weight to grain weight expressed as a percentage of the grain weight.

1.3.2 Equations. Water content is determined using the following equation:

$$w = \frac{B-C}{C-A} \times 100\%$$

where: w = water content, %

A = weight of the sample container, g

B = weight of the sample plus sample container before drying, g

C = weight of the sample plus sample container after drying, g.

1.4 References.

1.4.1 ISRM Commission on Standardization of Laboratory and Field Tests, 1972, "Suggested Method for Determining the Water Content of a Rock Sample.", Suggested Methods for Determining Water Content, Porosity, Density, Absorption and Related Properties and Swelling and Slake-Durability Index Properties, ISRM Committee on Laboratory tests, Document No. 2.

1.4.2 Lama, R.D. and Vutukuri, V.S., 1978, Handbook on Mechanical Properties of Rocks, Vol IV, Trans Tech Publications, pp. 351-352.

1.4.3 U.S. Army Corps of Engineers, 1980, "Method for Determination of the Water Content of a Rock Sample," Rock Testing Handbook, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MI.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement system. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock samples tested depends partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.4 Preservation of moisture condition of the samples.

In order to determine the natural water content, it is important to seal field samples immediately after removal from the sampling location. Sample sealing is commmonly accomplished by coating with melted paraffin.

2.5 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus

3.1 Oven.

The oven must be capable of maintaining a temperature of 221°F (105°C) to within ±5.5°F (±3°C) for a period of at least 24 hours.

3.2 Sample container.

The sample container, including an air-tight lid, must be of non-corrodible material.

3.3 Disiccator.

A disiccator to hold sample containers during cooling is required.

3.4 Balance.

The balance must be of adequate capacity, and capable of weighing to an accuracy of 0.01% of the sample weight.

4.0 Procedure

4.1 Sample preparation.

4.1.1 Dimensions. Any shape sample may be tested. The total sample weight should be at least 17.63 oz (500 g).

4.1.2 Sample selection. If possible, each test sample should be taken from the center portion of a field sample in order to obtain test samples with moisture contents as close as possible to the in situ conditions.

4.2 Procedure.

4.2.1 Container weight. The container and its lid are cleaned, dried, and weighed.

4.2.2 Sample weight. The sample is placed in the container, the lid is replaced and the weight of the sample plus the container is determined.

4.2.3 Drying. The lid is removed and the sample is dried to constant weight at a temperature of 221°F (105°C) for at least 24 hours.

4.2.4 Dry weight. The lid is replaced and the sample is allowed to cool in the desicator for 30 minutes. The weight of the sample plus the container is determined.

4.2.5 Data recording requirements. Test data shall be recorded as shown on Form L-F.2-1.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of the pro-

cedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.2 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure, fabric, grain size, discontinuities, voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary of results. Summary tables for each rock type shall be prepared. The information shall include, as a minimum, rock suite designation, number of tests, average value, range, and uncertainties.

5.4.2 Individual results. A summary table of individual test results shall be prepared including sample number, grain weight, pore water weight, and water content as a minimum.

5.4.3 Other. The following other types of analyses or presentations may be included as appropriate.

5.4.3.1 Histograms of results.

5.4.3.2 Correlation with other rock properties such as bulk density, porosity, or grain density.

5.4.3.3 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated.

5.5.2 Sample variability. For each suite of rock samples, the mean water content values, ranges, standard deviations and 95% confidence limits for the means shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6 Appended data.

Each completed test Form L-F.2-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-F.2-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-F.2-1.

6.3.3 Test sign-offs. Quality Assurance shall maintain signed-off copies of L-F.2-1.

Water Content of a Rock Sample

Test Data Sheet - Form L-F.2-1

Project _____ Sample No. _____

Date _____ Rock Type _____

Tested by _____

Equipment Description	Serial No.	Date of Next Calibration

Container Weight, g _____

Wet Weight, g _____

Dry Weight, g _____

Water Weight, g _____

Grain Weight, g _____

Water Content, % _____

Test Supervisor _____ Date _____

Quality Assurance _____ Date _____

Project Engineer _____ Date _____

Procedure L-F.3

Apparent Porosity of a Rock Sample

1.0 Background

1.1 Scope.

1.1.1 Objective of this test. The test is intended to measure the apparent porosity of a rock sample in the form of lumps or aggregate of irregular geometry. It may also be applied to a sample in the form of specimens of regular geometry.

1.1.2 Limitations. This method should only be used for rocks that do not swell appreciably or disintegrate when oven-dried and immersed in water.

1.2 General description of the test.

The apparent porosity is given by the ratio of the interconnected pore volume to the bulk volume of a test sample. The interconnected pore volume is determined by measuring the amount of water required to saturate a dry sample. The bulk volume is determined by measuring the amount of water which the specimen displaces when submerged.

1.3 Data reduction.

1.3.1 Terms and definitions.

1.3.1.1 Apparent porosity - the porosity of the interconnected pore volume in a rock.

1.3.1.2 Pore volume - the volume of the interconnected pore space.

1.3.1.3 Symbols

W_{sub} = Net weight of submerged specimen

W_{sat} = Weight of saturated, surface dry specimen

W_{ss} = Weight of submerged specimen and basket

W_{sb} = Weight of submerged basket

W_s = Weight of sample container plus saturated specimen

W_c = Weight of dry sample container

W_g = Grain weight of specimen

W_d = Weight of sample container plus dry specimen

V_b = Bulk volume of specimen

V_p = Interconnected pore volume of specimen

ρ_w = Density of water

1.3.2 Equations.

1.3.2.1 The surface dry weight of the specimen is calculated using:

$$W_{sat} = W_s - W_c$$

1.3.2.2 The grain weight is calculated using:

$$W_g = W_d - W_c$$

1.3.2.3 The bulk volume is calculated using:

$$V_b = \frac{W_{sat} - W_{sub}}{\rho w}$$

1.3.2.4 The pore volume is calculated using:

$$V_p = \frac{W_{sat} - W_g}{\rho w}$$

1.3.2.5 The apparent porosity is calculated using:

$$n = \frac{V_p}{V_b} \times 100 \text{ percent}$$

1.4 References.

1.4.1 ISRM Commission on Standardization of Laboratory and Field Tests, 1972, "Suggested Method for Porosity/Density Determination using Saturation and Buoyancy Technique," Suggested Methods for Determining Water Content, Porosity, Density, Absorption and Related Properties, and Swelling and Slake-Durability Index Properties, Committee on Laboratory Tests, Document No. 2.

1.4.2 Vutukuri, V.S. and Lama, R.D., 1978, Handbook on Mechanical Properties of Rocks, Testing Techniques and Results, IV, Trans Tech Publications, Clausthal, Germany.

2.0 Prerequisites

2.1 Personnel prequalification.

All personnel involved in performing the test, including the Technicians and Test Supervisor, shall be formally prequalified under the Quality Assurance procedures established as part of the overall testing program.

2.2 Equipment performance verification.

The compliance of all equipment and apparatus with the performance specifications in Section 3.0 of this procedure shall be verified. If no requirements are stated in Section 3.0, the

manufacturer's specifications for the equipment shall be the required level of performance. Performance verification is generally done by calibrating the equipment and measurement system. Calibration and documentation shall be accomplished according to standard Quality Assurance procedures.

2.3 Criteria for sample selection.

2.3.1 Project scope. The number and types of rock cores tested depend partly on the intended application of the test results. For example, an initial mechanical characterization of the site might require several samples from a variety of formations, while a detailed thermo-mechanical investigation of a candidate repository rock may require many tests from a single formation. The final testing program will depend heavily on the technical judgment and experience of project personnel.

2.3.2 Statistical requirements. The number of samples tested must be sufficient to provide an adequate statistical basis for evaluation of the results. Rock types which are highly variable will require more tests than relatively uniform rocks, in order to evaluate the results with equal certainty.

2.4 Documentation.

Each sample shall be fully documented before testing according to standard Quality Assurance procedures.

3.0 Equipment and apparatus.

3.1 Oven.

The oven must be capable of maintaining a temperature of 221°F (105°C) to within 5.5°F (3°C) for a period of at least 24 hours.

3.2 Sample container.

The sample container, including an air-tight lid, must be of noncorrodible material.

3.3 Desicator

A desicator must be available to hold sample containers during cooling.

3.4 Vacuum pump.

Vacuum saturation equipment is required such that the sample can be immersed in water under a vacuum of less than 6 torr (800 Pa) for a period of at least 1 hour.

3.5 Balance.

A balance of adequate capacity and capable of weighing to an accuracy of 0.01% of the sample weight is required.

3.6 Immersion bath.

An immersion bath and a wire basket or perforated container are required, such that the sample immersed in water can be freely suspended from the stirrup of the balance to determine the

saturated-submerged weight. The basket should be suspended from the balance by a fine wire so that only the wire intersects the water surface in the immersion bath.

4.0 Procedure.

4.1 Sample preparation.

4.1.1 Dimensions. A representative sample is selected, preferably comprising at least 10 rock lumps each weighing at least 1.8 oz (50 g), to give a total sample weight of at least 18 oz (500 g). Aggregate of smaller or larger size may, however, be tested in a similar manner.

4.1.2 Cleaning. All samples should be washed in water to remove dust.

4.2 Procedure.

4.2.1 Saturate sample. The sample is saturated by water immersion in a vacuum of less than 6 torr (800 Pa) for a period of at least 1 hour, with periodic agitation to remove trapped air.

4.2.2 Weigh submerged wire basket. The wire basket is submerged in the immersion bath and weighed.

4.2.3 Weigh saturated-submerged sample. The sample is transferred under water to the wire basket in the immersion bath. Its saturated-submerged weight, W_{sub}, is determined to an accuracy of 0.004 oz (0.1 g) from the difference between the saturated-submerged weight of the basket plus sample and that of the basket alone.

4.2.4 Weigh dry sample container. The sample container with its lid is cleaned and dried, and its weight is determined.

4.2.5 Weigh saturated, surface-dry sample. The sample is removed from the immersion bath and surface-dried with a moist cloth, care being taken to remove only surface water and to ensure that no rock fragments are lost. The sample is transferred to the sample container, the lid is replaced, and the weight of the saturated, surface-dry sample plus container is measured.

4.2.6 Dry sample. The lid is removed and the sample dried to constant weight at a temperature of 221°F (105°C), the lid is replaced and the sample is allowed to cool for 30 minutes in a dessicator.

4.2.7 Weigh dry sample. The weight of the oven-dry sample plus container is determined.

4.2.8 Data recording requirements. Test data shall be recorded as shown on Form L-F.3-1.

5.0 Reporting

The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed if necessary. Applications of the test results are beyond the scope of this procedure, but may be an integral part of some testing programs. In that case, an applications section compatible with the format described below should be included.

5.1 Introductory section of the report.

The introductory section is intended to present the scope and purpose of the testing program, and the characteristics of the material tested.

5.1.1 Scope of testing program.

5.1.1.1 Number of samples tested. In a large report covering the results of tests in several rock types, the test matrix is best presented in a tabular form.

5.1.1.2 Rationale for sample selection. The reasons for the number and types of samples tested shall be clearly stated.

5.1.1.3 Limitations of the testing program. The areas of interest which are not covered by the testing program and the limitations of the data within the areas of application shall be discussed in general terms.

5.1.2 Brief description of the samples. The rock type, structure, fabric, grain size, discontinuities, voids, and weathering of the samples shall be described as a minimum. Further detail depends on the application of the results, but in general is not required. In variable material or for several rock types, many samples may be described, and a tabular presentation is recommended for clarity.

5.2 Test method.

5.2.1 Equipment and apparatus. A detailed listing of the equipment actually used for the test shall be included in the report. The name, model number, and basic specifications of each major piece shall be listed.

5.2.2 Procedure. The procedure actually used for the test shall be listed in detailed steps.

5.2.3 Variations. If the actual equipment or procedure has varied from the requirements contained in this procedure, each variation and the reasons for it shall be noted. The effect of the variation upon the test results shall be discussed.

5.3 Theoretical background.

5.3.1 Data reduction equations. All equations used to reduce the data shall be clearly presented and fully defined. Any assumptions inherent in the equations or limitations in their applications shall be noted, and the effect on the results discussed.

5.3.2 Site-specific influences.

5.3.2.1 Assumptions. The degree to which the actual laboratory test conditions conform to the assumptions contained in the data reduction equations shall be discussed.

5.3.2.2 Correction factors. Any factors or methods applied to the data to correct for a non-ideal situation shall be fully explained.

5.4 Results.

5.4.1 Summary of results. Summary tables for each rock type shall be prepared. The information shall include rock suite designation, number of tests, average value, range, and uncertainties as a minimum.

5.4.2 Individual results. A summary table of individual test results shall be prepared including sample number and porosity as a minimum.

5.4.3 Other. The following other types of analyses or presentations may be included as appropriate.

5.4.3.1 Histograms of results.

5.4.3.2 Correlation with other rock properties such as permeability or total porosity.

5.4.3.3 Comparison of results to other rock suites or to previous studies.

5.5 Error estimate.

The results shall be analyzed using standard statistical methods. All uncertainties shall be calculated using a 95% confidence interval.

5.5.1 Measurement error. The error associated with a single test shall be evaluated.

5.5.2 Sample variablity. For each suite of rock samples, the mean apparent porosity values, ranges, standard deviations and 95% confidence limits for the means shall be calculated as a minimum. The uncertainty of the sample suite shall be compared with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

5.5.3 Group correlation. When appropriate, the means of groups shall be compared to determine whether the observed difference between groups is significant at the 95% confidence level.

5.6. Appended data.

Each completed test Form L-F.3-1 shall be included in an appendix.

6.0 Quality Assurance

The following items are the minimum requirements to ensure that the test results are defendable and traceable. It is not the intent of this section to establish Quality Assurance procedures, but to identify those points during the test at which Quality Assurance action is required.

6.1 Personnel prequalification.

Prior to testing, all personnel shall be prequalified as described in Section 2.1.

6.2 Test inspection.

Quality Assurance personnel shall review the test setup, the procedure, and the equipment performance verification. After testing, the completed Form L-F.3-1 shall be reviewed and signed off only if correct.

6.3 Required documentation.

6.3.1 Equipment performance verification. Quality Assurance shall maintain complete calibration records and certificates.

6.3.2 Equipment serial numbers. Quality Assurance shall verify that serial numbers of all equipment used in the test are recorded on Form L-F.3-1.

6.3.3 Test sign offs. Quality Assurance shall maintain signed-off copies of L-F.3-1.

Apparent Porosity of Rock Samples

Test Data Sheet - Form L-F.3-1

Project _____ Sample No. _____

Data _____ Rock Type _____

Tested by _____

Equipment Description	Serial No.	Date of Next Calibration

Weight of submerged specimen plus basket	W_{ss}	= _____
Weight of submerged basket	W_{sb}	= _____
Net weight of submerged specimen	W_{sub}	= _____
Weight of dry sample container	W_c	= _____
Weight of sample container plus saturated specimen	W_s	= _____
Weight of sample container plus dry specimen	W_d	= _____
Weight of saturated surface dry specimen	W_{sat}	= _____
Specimen grain weight	W_g	= _____
Bulk volume	V_b	= _____
Pore volume	V_p	= _____
Porosity	n	= _____

Test Supervisor _____ Date _____

Quality Assurance _____ Date _____

Project Engineer _____ Date _____

ONWI-311

Public Draft

Laboratory Rock Mechanics Testing Manual

Technical Report

October, 1981

Frank S. Shuri
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ONWI
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