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In Situ and Laboratory Geotechnical Test Results from Borehole GD-1 in Southeast Utah

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In Situ and Laboratory Geotechnical Test Results from Borehole GD-1 in Southeast Utah

Technical Report

November 1982

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Madeline R. Schnapp

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The content of this report is effective as of September 1982. This report was prepared by Woodward-Clyde Consultants under Subcontract E512-01800 with Battelle Project Management Division, Office of Nuclear Waste Isolation under Contract No. DE-AC06-RL1830-ONWI with the U.S. Department of Energy. This contract was administered by the Battelle Office of Nuclear Waste Isolation.
The National Waste Terminal Storage (NWTS) program was established in 1976 by the Department of Energy's (DOE) predecessor agency, the Energy Research and Development Administration (ERDA), to develop the technology and provide the facilities for the safe, environmentally acceptable, permanent disposal of high-level nuclear waste (HLW).

DOE's responsibility for the long-term management of highly radioactive nuclear wastes is defined by federal laws, which specify that DOE must provide facilities for the successful isolation of HLW from the environment in federally licensed and federally owned repositories for as long as the wastes represent a significant hazard.

Highly radioactive nuclear wastes include wastes from both commercial and defense sources, such as spent (used) fuel from nuclear power reactors, accumulations of wastes remaining from production of nuclear weapons, and solidified wastes from fuel reprocessing.

To meet its major objective of isolating HLW, DOE is developing a technical program that will meet all relevant radiological protection criteria as well as other applicable regulatory requirements.

NWTS activities include providing the technology and facilities for other terminal isolation of these wastes. DOE's program emphasizes disposal in mined repositories deep underground in stable geologic formations. Several types of rock are being studied in several states. Rock types include bedded salt deposits, salt domes, basalt (solidified lava), tuff (compacted volcanic ash), and "crystalline" rocks.*

Steps leading to the permanent disposal of HLW are:
- Studying, characterizing, and recommending potential sites for repositories
- Designing, licensing, and operating commercial repositories

*"Crystalline" rock is a general term for igneous and metamorphic rocks, as opposed to sedimentary rocks. Granite is one type of crystalline rock.
• Providing waste packaging facilities
• Developing transportation requirements
• Developing the technology to support these steps
• Studying alternative disposal methods as long-range options to the geologic disposal program.

Four separate but coordinated projects are involved in the HLW disposal program: the Office of Nuclear Waste Isolation (ONWI), the Basalt Waste Isolation Project (BWIP) at DOE's Hanford Reservation in Washington state, the Nevada Nuclear Waste Storage Investigations (NNWSI) at the federal Nevada Test Site, and the Subseabed Disposal Project. ONWI, BWIP, and NNWSI focus on different rock types and conduct studies in site evaluation, technology development, facility design, and field testing. They share data and information of general benefit. ONWI coordinates site exploration studies on non-DOE land. The Subseabed Disposal Project is assessing the technical, environmental, engineering, and institutional feasibility of disposing of processed highly radioactive nuclear waste and/or repackaged spent fuel in geologic formations beneath the sediments of the oceans.

Identifying possible sites for geologic repositories and evaluating their potential involve the collection and analysis of detailed geologic and environmental data and comparison of the data against predetermined site performance criteria (i.e., geologic characteristics, environmental protection, and socioeconomic impacts). The site selection process consists of a series of increasingly detailed steps to obtain environmental and geologic information. The steps are: national survey of one or more rock types with potential for waste containment; identification of regions containing potentially suitable rock types; recommendation of study areas and locations. At the conclusion of each screening step, the focus narrows to smaller land areas, while the amount of data collected increases. Screening steps will identify potential sites at several locations, leading to the next phase, site characterization. The purpose of site characterization is to assess a site's suitability for a repository. The process culminates in DOE's application to the U.S. Nuclear Regulatory Commission (NRC) for authorization to construct and operate the first repository.

The first federal repository for the isolation of high-level nuclear wastes is expected to be in operation between 1998 and 2006, following the site selection process outlined, field testing and technology development programs, and fulfillment of licensing requirements. DOE expects to choose one site from among several qualified sites and apply to NRC in 1988 for a license to construct the first repository. Several repositories are planned.

Throughout the repository siting and construction process, opportunities are provided for public and peer review and comment. DOE maintains an open information program for nuclear waste management activities and is committed to a policy of consultation with state and local officials. Information is provided to both technical and nontechnical groups and to governmental officials through review of major reports, briefings, conferences, public meetings, and printed material. Additional opportunities for public input will occur at public hearings and reviews that are part of the licensing process.

Several documents and statements provide policy and technical guidance in the definition and planning of the NWTS program:

(1) President's Nuclear Policy Statement, October 8, 1981
(2) DOE Record of Decision (to adopt the mined geologic disposal strategy and develop repositories), May 14, 1981
(3) National Plan for Site and Environmental Assessment (Draft), February, 1982
(4) Final Generic Environmental Impact Statement (FEIS) (U.S. DOE, 1980)
(7) Report to the President by the Interagency Review Group on Nuclear Waste Management, March, 1979 (IRG, 1979)
Both the IRG Report and the FEIS evaluate alternative waste disposal processes and conclude that mined geologic disposal will be the earliest one available. The IRG report recommends that near-term program activities should be predicated on the tentative assumption that the first disposal facilities will be geologic repositories. The FEIS provides a detailed evaluation of 10 methods for waste disposal and concludes that the technology for emplacement of radioactive wastes in geologic formations can probably be developed and applied with minimal environmental consequences. The ESTP, which is the product of a cooperative effort by DOE and the U.S. Geological Survey (USGS), furnishes detailed programmatic guidance for implementing research addressing specific earth science issues associated with geologic waste disposal.
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INTRODUCTION

Nuclear Waste Terminal Storage geologic studies provide the information needed to evaluate the selected geologic formation for potential repositories from the standpoint of engineering feasibility, safety, public health, and resource conflicts. The geologic information gathered in the Paradox Basin during the regional studies phase is reported in "Overview of the Regional Geology of the Paradox Basin Study Region" (Woodward-Clyde Consultants, 1980: ONWI-92).

On the basis of information in Paradox Basin regional geologic and environmental reports, four study areas (Gibson Dome, Salt Valley, Elk Ridge, Lisbon Valley) were selected for additional study (Bechtel and Woodward-Clyde Consultants, 1980: ONWI-36). The results of area-level studies at Gibson Dome, Elk Ridge, and Lisbon Valley are presented in a geologic area characterization report (ACR) for the Paradox Basin (Woodward-Clyde Consultants, 1982: ONWI-290).

This report presents preliminary in situ and laboratory geotechnical data of salt strata in the Gibson Dome study area. In situ testing was done in the Gibson Dome No. 1 (GD-1) borehole at depths ranging from 954 to 1,507 m* (3,130 to 4,945 feet). These tests were made in a number of salt strata (primarily sodium chloride) to measure: (1) stress-strain behavior of the borehole (hole "squeeze") as the pressure in an isolated test zone was varied from hydrostatic drilling fluid pressure; (2) short-term borehole creep as the pressure in the test zone was maintained at a minimum pressure for a period of about one day; and (3) in situ stresses in salt strata using hydraulic fracture techniques. These data will be used to assist in estimating the maximum feasible depth for a repository in the Gibson Dome Area, to validate computer codes that predict the thermomechanical response of an underground structure in this Area, and to provide data for engineering characterization of the Area.

*Note: All depths in the GD-1 borehole are referenced to the drill rig Kelly Bushing datum, which is at 4,949 feet above mean sea level.
Laboratory triaxial strength tests and creep tests were conducted to provide engineering data under a variety of test conditions (stress state, strain rate, and temperature). The combination of in situ and laboratory measurements provide an unusual opportunity to predict behavior (borehole deformation) using laboratory strength and creep data as input to thermo-mechanical computer codes and then to compare the predictions with the actual in situ measurements. This report presents data with which to make such comparisons. Actual computations of predicted versus measured behavior are being done by other ONWI subcontractors and are not discussed in this report.

This report is divided into three major sections. Section 2 is a discussion of the in situ test program, detailing objectives and methodology and reviewing results and their implications. The unloading and loading/hydraulic fracture programs are discussed in separate subsections of Section 2. Typical plots of individual test data and summary plots of interpreted data from several tests are included. Complete individual test data plots and tabulations and test apparatus compliance measurements are presented in Appendix A.

Section 3 documents laboratory triaxial strength and creep testing. Triaxial strength testing is discussed separately from creep testing because test procedures and purposes for the two tests are different. Detailed plots of laboratory results for this phase are presented in Appendix B.

The final major section of the report includes a listing of conclusions or summary statements that highlight in situ and laboratory results (Section 4) and references (Section 5).

English measurements were used in all GD-1 field and laboratory work. Metric conversions have been made for this report; however, the English measurement should be considered most accurate if rounding discrepancies occur.

**IN SITU TEST PROGRAM**

2.1 OVERVIEW

2.1.1 Objectives

During previous drilling and hydrogeologic drill-stem testing in the Salt Valley area of the Paradox Basin of southeast Utah, it was noted that oilfield drill-stem test (DST) equipment was potentially useful in making deformation measurements in deep salt strata to assess the behavior of underground openings. These earlier measurements indicated that substantial hole closure might be occurring at a depth of approximately 1,150 m (3,800 feet). Following these observations, a program was developed and implemented to measure geotechnical properties of salt strata in borehole GD-1, located in the Gibson Dome Area, 80 km (50 miles) south of Salt Valley.

The in situ test program in GD-1 had several objectives: (1) to evaluate whether oilfield DST equipment and ancillary services could be used to measure in situ geotechnical properties of salt; (2) to collect stress-strain data for the first unloading and loading of deep salt strata; (3) to measure short-term (approximately one-day) creep of salt strata when subjected to a constant (minimum) unloading stress; and (4) to estimate the in situ state of stress by loading salt strata to the point of hydraulic fracture. These objectives were achieved by special DST operational sequences and utilization of stable and accurate downhole quartz-crystal pressure transducers (QCT).

Deep in situ tests were predicated on two characteristics of salt: its moderate deformability and its negligible permeability. The former property permits borehole deformation resulting from pressure changes in a downhole test zone to be large enough to monitor with relative ease. The latter factor, the near impermeability of salt, yields borehole walls within a salt stratum that are a natural barrier to flow of fluid, except in the case where fluid pressure increases to the point of hydraulic fracture. It is therefore possible to isolate a deep test zone with rubber packers at the top and bottom of the zone without sealing the borehole walls within the zone. Deep in situ geotechnical tests in salt monitor borehole closure or expansion in response
to pressure decrease or increase. This geotechnical testing is in marked contrast to hydrogeologic testing, where a test zone is also isolated by rubber packers, but test zone pressures and volume changes are caused primarily by fluid flow into or out of the surrounding formations.

In situ geotechnical tests were conducted to monitor the response of deep test zones within the salt strata of the Paradox Formation when pressure in a test zone varied from normal drilling-fluid pressure. Two types of tests were conducted: (1) unloading tests, in which the test zone pressure was reduced below drilling-fluid pressure in a gradual, controlled manner; and (2) loading/hydraulic fracture tests, in which the test zone pressure was increased above drilling-fluid pressure until the formation hydrologically fractured.

2.1.2 Stratigraphy at GD-1

Logging of the GD-1 borehole indicated rock strata of Pennsian age immediately underlying the surface. These subsurface strata are characterized by essentially horizontally bedded sedimentary deposits of sandstone, siltstone, limestone, and dolomite. Below these strata, the Paradox Formation, of Pennsian age, is encountered at a depth of 798 m (2,618 feet). This 881-m (2,890-foot) thick formation consists of salt (primarily sodium chloride) deposited in distinct cycles separated by interbed sequences of anhydrite, black shale carbonate, and other clastic rocks. Salt within the Paradox Formation constitutes approximately 68 percent of the whole formation; individual salt beds are often more than 30 m (100 feet) thick. The salt often includes thin bands of anhydrite in two forms: (1) laminar anhydrite, approximately 0.15 cm (1/16 inch) thick, having a rhythmic spacing of 2.5 to 7.5 cm (1 to 3 inches); and, (2) more commonly, bands of diffuse anhydrite sand, about 2.5 cm (1 inch) thick, in salt. Additional details about GD-1 stratigraphy can be found in Woodward-Clyde Consultants (1982, Vol. II).

2.2 UNLOADING GEOTECHNICAL DRILL-STEM TESTS

2.2.1 Methodology

The geotechnical drill-stem test (GSDT) procedure began with isolating the test zone in the 25.4- to 30.5-cm (10- to 12-inch) diameter borehole with inflatable rubber packers (Figure 2-1). The test zone was 21 to 49 m (70 to 160 feet) long to maximize measurement sensitivity and minimize test zone end effects. Borehole drilling fluid completely filled the test zone below a closed shut-in valve; 7.39-cm (2-7/8-inch) diameter tubing above the valve was filled to a level of a few hundred meters above the zone with a brine fluid (specific gravity of both drilling fluid and brine fluid was 1.4), leaving the remaining 900 to 1,200 m (3,000 to 4,000) feet of tubing empty. The tubing was then pressurized with compressed nitrogen to a value equal to full borehole hydrostatic drilling-fluid pressure to start the test. When the shut-in valve was opened and nitrogen pressure was gradually reduced, the change of fluid level in the tubing, and thus the change of test zone volume, was monitored.

The concept of gradually reducing test zone pressure from drilling-fluid pressure differs from the procedure in a conventional flow-in hydrogeologic DST, in which the pressure is suddenly reduced from fluid pressure to atmospheric pressure as soon as the shut-in valve is opened. With the gradual reduction of pressure in an unloading GOST, the test zone volume change is measured during the first unloading of the test zone below fluid pressure. (The GD-1 borehole was unloaded from lithostatic to drilling-fluid pressure, about 52 percent of lithostatic, during drilling.)

Downhole pressures were monitored in real time using three precise and stable quartz crystal transducers (QCTs). This triple QCT (TQCT) configuration was installed to monitor pressures below, within, and above the test zone (Figure 2-1), so leakage past the packers could be detected while the test was in progress. Signals from the TQCT were transmitted through an electric cable strapped to the outside of the tubing and were displayed on plotters and printers at the surface. Signals from an electrical thermometer temperature sensor located near each QCT were also relayed up the cable to the real-time...
monitoring system. Two different remote pressure sensors, a digital memory type and a mechanical scratch type, were used on GDSs as backups to the real-time TQCT.

The test zone was unloaded by venting nitrogen pressure in a series of approximately 3.4-MPa (500-psi) steps. At the beginning of the test and after each 3.4-MPa (500-psi) pressure bleedoff, the pressure was maintained at a constant value and a probe was raised or lowered in the tubing to determine the depth to fluid. Because the salt stratum would neither contribute to nor accept appreciable fluid from the test zone, measurement of fluid level was a direct measure of test zone volume change. After all nitrogen pressure was bled from the tubing, the test zone was at the minimum unloading pressure (gage pressure 1.4 MPa [200 psi] to 2.8 MPa [400 psi]). This pressure was maintained for about one day, during which time the borehole walls slowly squeezed inward and the fluid level rose slowly in the tubing. After this creep monitoring period, the test zone was reloaded by pressurizing with nitrogen, again in 3.4-MPa (500-psi) increments, and the depth to fluid was again measured at each sequential step. This test zone pressure sequence is illustrated on Figure 2-2.

Fluid level can be monitored easily when the tubing is at atmospheric pressure by recording test zone pressure and calculating the fluid height required to produce this pressure. When nitrogen gas pressure is superimposed on fluid head, however, measurement of fluid level depends on accurate measurement of gas pressure at the fluid/gas interface to determine the precise contribution of nitrogen pressure to the total downhole pressure. Nitrogen pressure at the surface can be accurately measured by a bourdon-type pressure gage and a sensitive, digital-readout QCT of the same type as the downhole TQCT. Because nitrogen gas pressure at a depth of approximately 1,000 meters is influenced by nitrogen density and downhole temperature that the GDS configuration was not designed to monitor, gas pressure at the fluid/gas interface could not be extrapolated from a surface measurement with the precision required to detect small changes, less than a meter, in fluid level. It was therefore necessary to measure deep nitrogen pressure by lowering probes into the tubing on an electric cable wireline.
NOTES:
1. PARADOX FORMATION: SALT CYCLE 19
2. DEPTH = 4785 TO 4945 FT BELOW RIG DATUM
A dual-transducer probe was the design fluid level measurement method. One pressure transducer hanging below the fluid level would record pressure of both the small fluid column and the nitrogen gas. Another transducer hanging just above fluid level (approximately 30 m [100 feet] above the first transducer) would measure nitrogen pressure alone, and that direct measurement subtracted from pressure below the fluid would yield the height of fluid above the lower transducer. However, because the dual-transducer system malfunctioned during testing (both transducers would not operate simultaneously), a single transducer was used to sense the fluid surface by alternately lowering it into or raising it out of the fluid. When the transducer sensed fluid pressures, the pressure gradient increased more rapidly than the normal increase caused only by nitrogen at increasing depths; the elevation at which this change occurred was taken as the depth to the fluid surface. The dunking method was cumbersome because it was difficult to repeatedly detect the precise depth at which the fluid gradient commenced when surface nitrogen pressure varied by as much as 7 kPa (1 psi). Later in the test program, that method was replaced by an electrical shorting sensor lowered into the tubing on a wireline. This sensor completed an electrical circuit when it touched fluid surface, allowing the fluid elevation to be determined with relative ease and repeatability.

Before any unloading tests were made, the DST tool was tested in the upper, cased portion of the hole for compliance, determining how much the fluid level moved as test zone pressures changed. The 13-5/8 inch casing in this section of the borehole was cemented in sandstone and siltstone strata. The steel casing (11-mm [0.43-inch] thickness)–cement–rock system is relatively rigid in comparison to the rubber packer DST tool, so most volumetric change during compliance testing was attributed to deformation of the test zone fluid and rubber packers. For example, the rubber packers could be deformed into the test zone by higher pressures outside the zone, giving erroneously high measurements of test zone volume change. The compliance tests provided tool deformation data that were subtracted from total volume change measurements; details of compliance testing are presented in Appendix A.

The accuracy of measurements recorded during testing varied with the type of data acquired. The most accurate data were those from the TQCT downhole pressure sensors, which recorded data on a real-time basis. These transducers were calibrated and were accurate to ± 14 kPa (2 psi). However, when they were used to record relative pressure changes over a range less than about 350 kPa (50 psi), they performed with an apparent relative drift of about ± 1 kPa (0.2 psi). The pressures recorded by the downhole TQCT sensors were within about 76 kPa (10 psi) of the absolute values recorded from the less precise digital memory recorders. Fluid level measurements were repeatable to within ± 0.6 m (2 feet); the most important aspect of the fluid level measurements is not their absolute elevation, but their relative change during a test. Volumetric strain values based on the fluid level change measurements have a potential error of about ± 0.1 percent strain; strain values corrected for system compliance have an error of about ± 0.15 percent strain at maximum unloading pressure. Downhole temperature probes, with an accuracy specified as ± 1°C (2°F), were used to correct the temperature-dependent TQCT sensors.

2.2.2 Unloading Stress–Strain Results

Unloading tests were attempted in five zones in the GDST-1 borehole (Table 2-1 and Figure 2-2). GDSTs-1, -2, and -4 were successful, although the fluid level sensor was inoperable during the first half of GDST-2. All test results and plots for the three successful tests are presented in Appendix A. Figure 2-2, showing GDST-1, is a typical summary plot of pressure data obtained during an unloading test. Although it is not noticeable on this graph, pressure data are recorded to 0.07 kPa (0.01 psi) and can be displayed at much larger scales to analyze a subtle pressure rise, such as that during the minimum pressure interval from about 33 to 60 hours on this figure.

Pressure and fluid level data from each unloading GDST were translated into unloading pressure versus volumetric strain values. During each test, the fluid level measurement taken about one hour after the shut-in valve was first opened was taken as zero strain. Fluid level depths were then measured approximately one hour after the nitrogen pressure was stabilized at each unloading or reloading step. From these measurements, uncorrected volumetric strain was calculated as follows:
TABLE 2-1
SUMMARY OF UNLOADING GDSTs

<table>
<thead>
<tr>
<th>GDST No.</th>
<th>Depth (ft)</th>
<th>Test Zone</th>
<th>Test Zone</th>
<th>Max. V/V₀ (%) (Uncorrected/Corrected)</th>
<th>Comments</th>
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<tr>
<td>1</td>
<td>4785-4945</td>
<td>160</td>
<td>106</td>
<td>8.76 / 8.33</td>
<td>Successful test</td>
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<tr>
<td>2</td>
<td>3160-3320</td>
<td>160</td>
<td>95</td>
<td>0.42 / 0.12</td>
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<tr>
<td>3</td>
<td>3928-4028</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>Unsuccessful; leakage past packers in 4 attempts</td>
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<tr>
<td>4</td>
<td>3575-3675</td>
<td>100</td>
<td>97</td>
<td>1.80 / 1.46</td>
<td>Successful test</td>
</tr>
<tr>
<td>5</td>
<td>4245-4315</td>
<td>70</td>
<td>-</td>
<td>-</td>
<td>Unsuccessful; leakage past packers</td>
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Metric Conversions:
1 ft = 0.3048 m
Temp °F = 1.8 x Temp°C + 32

<table>
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<tr>
<th>Depth (ft)</th>
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<th>Unloading GDST Test Number</th>
<th>Loading (Hydraulic Fracture) GDST Test Number</th>
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IN SITU TEST LOCATIONS
BOREHOLE GD-1
LOG 1036
REV.0-4/5/82
Project No 16000
Woodward-Clyde Consultants
Figure 2-3
volumetric strain = \Delta V/V_o \tag{2-1}

where \( V_o \) is the initial volume in liters (gallons) of the test zone, or the average cross-sectional area taken from caliper logs of the hole diameter multiplied by the length of the test zone; and \( \Delta V \) is the cumulative change in test zone volume, which is reflected by the change in height of fluid in the tubing from its initial value. It can be shown using simple geometric relationships that radial strain for small strain values can be expressed as:

\[
\frac{\Delta r}{r_0} = 0.5 \frac{\Delta V}{V_o} \tag{2-2}
\]

To estimate corrected volumetric strain data, compliance test results were utilized. Correction factors in units of volumetric strain per unit pressure were multiplied by the average pressure difference across the packers and subtracted from uncorrected volumetric strain values.*

Unload pressure was determined as test zone pressure during the test minus initial pressure (approximately equal to drilling-fluid pressure). The initial pressure is the measurement taken after the shut-in valve is opened at the beginning of a test, at the time when the zero strain fluid level measurement was taken. Unloading pressures were calculated for the fluid level measurement at each unloading step and at the beginning and end of the minimum test zone pressure interval.

Graphs of unloading stress versus uncorrected volumetric strain and versus corrected volumetric strain for the three successful unloading tests are presented on Figures 2-4 and 2-5, respectively. The uncorrected curves are taken directly from fluid level measurements. Arrows indicate unpath (decreasing test zone pressure) and reload path (increasing test zone pressure). The volumetric strain does not approach zero during the reload cycle (particularly GOST-1 and -4) because of irreversible strain (permanent deformation) of the salt into the borehole.

\*Procedures and data from compliance testing of the packer test tool in an upper, cased portion of the borehole are included in Appendix A.

The maximum magnitude of the compliance correction for each test is noted by comparing maximum corrected and uncorrected \( \Delta V/V_o \) values in Table 2-1. This correction value, although small, has significant bearing on the interpretation of data from GOST-2, where the compliance correction is nearly equal to uncorrected volumetric strain values, bringing corrected stress-volumetric strain to the y-axis (zero strain) on Figure 2-5 and even, implausibly, to negative values. Equipment malfunctions during this test could have yielded anomalous measurements; however, the results could also be attributed to the fact that the instruments were monitoring changes that were within the tolerance of the measurement accuracy.

2.2.3 Short-Term Creep Results

Short-term creep was evaluated during the minimum unloading pressure interval when nitrogen pressure was zero. Volumetric strain values were obtained from direct measurements of fluid level and from precise measurements of test zone pressure. Because repeatability of direct fluid level readings was only \( \pm 0.6 \) m (2 feet), these data were adequate only when relatively large fluid level changes (more than 6 m (20 feet)) occurred. Such large changes were evident only in GOST-1 (the steepest test), where total fluid level change during creep was approximately 17 m (55 feet); in the other successful tests (GOSTs-2 and -4), total fluid level change only from 0.3 to 1.2 m (1 to 4 feet).

Test zone pressure measurements from the TQCT pressure sensor within the test zone were the most accurate creep movement sensors because of the inherent stability of the QCTs. Because all nitrogen pressure had been bled from the tubing prior to commencing creep measurements, the transducer within the test zone measured only the head from the small fluid column extending up from the test zone. In contrast to the \( \pm 0.6 \) m (2-foot) repeatability of the direct fluid level sensing device lowered down the tubing on a wireline, the TQCT pressure sensor, with drift of \( \pm 1 \) kPa (0.2 psi), was able to record fluid level changes as small as \( \pm 0.09 \) m (0.3 foot).
LEGEND

- GDST No. 1 4785-4945 ft.
- GDST No. 2 3160-3320 ft.
- GDST No. 4 3975-3975 ft.

NOTES:
1. RADIAL STRAIN, $\Delta r/r_0$, % in $\Delta V/V_0$
2. VOLUMETRIC STRAIN VALUES ARE NOT CORRECTED FOR SYSTEM COMPLIANCE

LEGEND

- GDST No. 1 4785 to 4945 ft.
- GDST No. 2 3160 to 3320 ft.
- GDST No. 4 3975 to 3975 ft.

NOTES:
1. RADIAL STRAIN, $\Delta r/r_0$, % in $\Delta V/V_0$
2. VOLUMETRIC STRAIN IS CORRECTED FOR COMPLIANCE OF THE TESTING SYSTEM
Figure 2-6 shows direct fluid level measurements and Figure 2-7 presents test zone pressure values, both plotted versus linear time, for GDST-1. A similar shape appears for both curves. Converting maximum pressure change into fluid level change gives 15.9 m (52 feet), a value close to the directly measured value. The three successful short-term creep tests displayed generally similar pressure versus time behavior.

Slopes of pressure versus time plots for the three tests were converted to volumetric and radial logarithmic strain rates. Expression of creep rate with radial strain units (one-half of volumetric strain) facilitates comparisons with other data. Radial strain rates for the three GDST creep intervals are listed in Table 2-2.

Short-term creep data are considered to be more accurate than data from the unloading and reloading portions of the GDSTs for two reasons. First, small fluid level changes during the creep period, typical of the two shallowest tests, were accurately monitored by precise downhole TQCT sensors after all nitrogen pressure had been vented from the tubing. Second, compliance corrections of the downhole test tool are not a factor during the creep period; the compliance correction is constant because the average pressure across the packers remained nearly constant throughout this period.

Creep rates shown in Table 2-2 are conservative (highest) values because any leakage past the packers would flow into the test zone, and volumetric strain calculations would include any such leakage. There was no evidence of leakage past the packers in the successful tests.

2.2.4 Discussion

Unloading stress-strain results are displayed versus depth on Figure 2-8. This figure shows total volumetric strain at the beginning and end of the minimum pressure (short-term creep) interval. Figure 2-9 displays short-term creep rate (radial strain per second) plotted against depth. Comparison of strain behavior versus depth plots indicates that creep rates did not show the same general increase with depth as did total unloading volumetric strain. While three data points do not permit definitive conclusions about creep rate and strain as functions of increasing depth, there is some indication that creep behavior differs from unloading stress-strain behavior.

Young's modulus can be computed for the reloading portion of GDST-4 using the relationship (Hall and others, 1974):

$$ E = (1 + v) \frac{\Delta \sigma}{\Delta e} = (1 + v) \frac{\Delta \sigma}{\Delta e_v} $$  (2-3)

where \( v \) is Poisson's ratio, taken from geophysical log measurements to be 0.3; \( \Delta \sigma \) is the change in unloading stress over which the modulus is determined; \( e \) is radial strain of the cylindrical chamber, and \( e_v \) is volumetric strain of the cylindrical chamber. A secant modulus value of 6.6 GPa (0.96 x \( 10^6 \) psi) was computed between the maximum and minimum stresses on the reload portion of GDST-4 (shown on Figure 2-5). This value is in general agreement with other findings for salt's modulus (Isherwood, 1981; Dames and Moore, 1978), although there is a wide scatter in reported results. Geophysical compression and shear wave velocities logged in the borehole indicated a Young's modulus of 37 GPa (5.3 x \( 10^6 \) psi); this value is believed to be much higher than those from unloading tests because of the extremely small stress and strain levels of the geophysical testing (Hall and others, 1974). Laboratory triaxial strength results from borehole GD-1 (Section 3.2) gave a Young's modulus of 29 GPa (4.2 x \( 10^6 \) psi) for an unload/reload cycle.

The short-term creep data can be compared with direct measurements of borehole squeeze in a dry borehole drilled from within the Asse salt mine in the Federal Republic of Germany (Kuhn and Verkerk, 1980; Wallner, 1981). These data were for a much longer duration (190 days) than the GDST short-term results and showed a gradually decreasing rate with increasing time. Values for creep rates were calculated from the Asse data near the beginning of the measurements (4 days elapsed time) and at the end of the measurements (190 days) (Table 2-2). The Asse creep rates are close to values for the two shallowest tests in GD-1. These Asse data are also plotted on Figure 2-9.

Short-term creep rates can also be estimated from the rate of pressure increase of the closed hydraulic system below the bottom packer during unloading GDSTs (e.g., the upper curve of Figure 2-2 between 36 and 83 hours). An average radial strain rate was calculated using the compressibility of the brine borehole fluid, the proportion of salt in the closed system, and the...
\[ \frac{\Delta V}{V_0} = 81 \times 10^{-9} \text{ sec}^{-1} \]

\[ \frac{\Delta r}{r_0} = 41 \times 10^{-9} \text{ sec}^{-1} \]

ELAPSED TIME DURING MINIMUM PRESSURE INCREMENT, MINUTES

FLUID RISE IN TUBING, FEET

DEPTH 4785 to 4945 ft.
\[ \Delta V/V_o = 83 \times 10^{-9} \text{ sec}^{-1} \]
\[ \Delta r/r_o = 42 \times 10^{-9} \text{ sec}^{-1} \]

Pressure spikes from dunking wireline transducer to sense fluid level.

All nitrogen pressure vented from tubing.

Notes:
1. Paradox Formation: Salt Cycle 19
2. Depth = 4785 to 4945 FT below rig datum
3. Zero elapsed time in creep interval = 32.33 elapsed hours in entire test
TABLE 2-2
CREEP RATE COMPARISONS

<table>
<thead>
<tr>
<th>Test Number / Data Source</th>
<th>Test Zone Depth (ft)</th>
<th>Creep Interval (days)</th>
<th>Creep Radial Strain Interpretation</th>
<th>Time When Creep Rate Interpreted (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDST-1</td>
<td>4865</td>
<td>0 - 1.1</td>
<td>42 x 10^-9</td>
<td>1.1</td>
</tr>
<tr>
<td>GDST-2</td>
<td>3240</td>
<td>0 - 0.7</td>
<td>4.4 x 10^-9</td>
<td>0.7</td>
</tr>
<tr>
<td>GDST-4</td>
<td>3625</td>
<td>0 - 0.5</td>
<td>1.6 x 10^-9</td>
<td>0.6</td>
</tr>
<tr>
<td>Asse^a</td>
<td>3420</td>
<td>4 - 190.0</td>
<td>4.4 x 10^-9</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0 x 10^-9</td>
<td>57</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.9 x 10^-9</td>
<td>190</td>
</tr>
</tbody>
</table>

^aSources: Kuhn and Verkerk, 1980; Wallner, 1981

Metric Conversion:

1 foot = 0.3048 m
slope of the pressure-time curve (Appendix A). Apparent radial strain creep rates calculated from these data ranged from $2.1 \times 10^{-9}$ to $4.1 \times 10^{-9}$ sec$^{-1}$. Total unloading stress (below lithostatic) for the closed system beneath the bottom packer is less than that of the unloading GDSTs, but the calculated radial strains are similar. These creep rates are approximate because fluid flow into or out of interbed formations of the borehole below the bottom packer may affect the pressure-time response.

Creep rates measured in GD-1 appear reasonable, even though they have not necessarily reached a steady-state value. If anything, the longer-term values for GD-1 would be lower than the 0.7-day values listed on Table 2-2. Moreover, these GD-1 rates are conservatively high because they include possible undetected leakage into the test zone from the borehole walls or past the packers. The creep comparisons, finally, indicate that creep behavior of salt may be site-specific and thus vary from location to location.

2.3 LOADING/HYDRAULIC FRACTURE GEOTECHNICAL DRILL-STEM TESTS

The hydraulic fracture technique was used for in situ stress measurements because it enables measurements in deep boreholes. The technique, first described by Hubbert and Willis (1957) and further refined by Haimson and Fairhurst (1967), involves raising the fluid pressure in a sealed segment of a borehole until a tensile fracture is induced. Continued pumping opens the fracture and extends it away from the borehole. When pumping ceases, the pressure in the borehole comes to an equilibrium level as the horizontal stress closes the fracture. Subsequent analyses of pressure-time histories from the tests yield the magnitudes of in-situ principal stresses.

The following assumptions are implicit in the technique: (1) one of the principal stress axes is vertical; (2) the fracture propagates parallel to the maximum horizontal stress and perpendicular to the minimum horizontal stress; (3) the rock strata are homogeneous and isotropic; and (4) the rock strata deform elastically.
Haimson and Fairhurst (1967) demonstrated that a fracture would form when the breakdown pressure, $P_b$, is:

$$P_b = 3S_h - S_H - P_p + T$$  \hfill (2-4)$$

where $S_h$ is the minimum horizontal stress perpendicular to the fracture, $S_H$ is the maximum horizontal stress parallel to the fracture, $P_p$ is the pore pressure, and $T$ is the tensile strength.

Bredehoeft and others (1976) showed that the fracture opening pressure, $P_F$, can also be used to calculate $S_H$ in cases where the tensile strength is not known. The fracture will propagate when the fracture opening pressure, $P_F$, is:

$$P_F = 3S_h - S_H - P_p$$  \hfill (2-5)$$

Zoback and others (1980) successfully utilized this technique in several tests conducted in California.

The azimuth of the maximum horizontal stress corresponds to the direction of fracture propagation and can be determined from the orientation of the hydraulic fracture at the borehole wall. Impression packers and/or seismic televiwers are commonly used for this determination.

2.3.1 Methodology

The test arrangement for loading/hydraulic fracture GDSTs was similar to that used for unloading tests, with the following exceptions: (1) the tubing was completely filled with fluid during the test, rather than containing only the short fluid column of the unloading GDSTs; (2) test zones were generally shorter than for the unloading tests (4.1 m [13.5 feet] versus 21 to 49 m [70 to 160 feet]); (3) the rubber packers were typically inflated with a downhole pump (rather than being inflated by a surface pressure source); and (4) the tool did not contain downhole real-time TQCT pressure sensors. The test schematic diagram (Figure 2-10) depicts aspects of the loading tests that are slightly different from those of the unloading tests.
Care was taken to choose test zones that were totally within a single cycle of salt and unfractured. To choose an unfractured interval within the salt cycle, the core was carefully examined for pre-existing fractures. None were observed within any salt strata. Five of the test zones were 4.1 m (13.5 feet) long; one of the test zones was 30 m (100 feet) long. In all tests, borehole drilling fluid (brine with a specific gravity of 1.4) completely filled the borehole, including the test zone. Table 2-3 lists the test intervals, depths, and data gathered; Figure 2-3 shows the locations of the test zones.

The test sequence began with lowering a straddle packer test tool ("drillstem test tool" in oilfield terminology) to the desired elevation and inflating the packers. A downhole pump powered by rotating the tubing string was used to inflate the packers approximately 8.3 MPa (1,200 psi) above hydrostatic for the 4.1-m (13.5-foot) zones; surface nitrogen pressure inflated them for the 30-m (100-foot) zone. The shut-in valve was then opened and pressure inside the test zone was increased at a slow, constant volumetric injection rate of between 2 and 20 liters (0.5 and 5 gallons) per minute until a fracture was induced or until a maximum pressure plateau was achieved. Surface wellhead pressure and the quantity of fluid injected at the wellhead were measured. Immediately after the test zone was fractured, the system was shut in with a surface valve and pressure was monitored for a period of time. Fluid was then let out or added to the system in a series of bleed, shut-in, pump-in, shut-in cycles. The system was pressurized again at a higher flow rate until a maximum pressure plateau was encountered. The system was shut in again and a final bleed, shut-in, pump-in, shut-in cycle was conducted. The test was terminated by reducing surface pressure to atmospheric pressure.

The tests utilized a high-pressure/low-flow hydraulic "triplex" piston pump capable of delivering between 2 and 40 liters (0.5 and 10 gallons) per minute at pressures to 70 MPa (10,000 psi). The low injection volume of this pump arrangement was utilized to obtain an accurate record of peak breakdown pressure. Fluid volume was measured by observing the fluid level in a 167-liter (44-gallon) fluid supply tank equipped with a graduated sight glass.

Surface injection pressure was monitored by a bourdon-type pressure gage and a sensitive digital QCT. Downhole pressure was measured by lowering a pressure transducer on a wireline to a depth of 30 m (100 feet) above the test zone. Pressure was not monitored below the bottom packer except in the 30-m (100-foot) long test zone. Backup pressure measurements were made within the test zone with a digital memory recorder and a mechanical scratch-type recorder.

An impression packer was used for loading/hydraulic fracture GDSTs to record the extent and orientation of any fractures formed at peak injection pressure. This device is a conventional inflatable packer wrapped by a soft rubber compound that is forced into a fracture as the packer is pressurized. An impression of the fracture is left on the soft rubber and can be examined and related to true north after the packer is deflated and hoisted from the hole. Orientation of the inflated packer is recorded by a downhole camera photographing a compass.

Downhole wireline sensors indicated that downhole pressure was within ± 0.5 percent of the sum of the surface injection pressure and hydrostatic pressure of the fluid filling the tubing. The accuracy of the surface pressure measurements was approximately ± 14 kPa (2 psi). Volume measurements were accurate to ± 6.8 liters (0.2 gallons), or within ± 0.5 percent of a typical injection test volume of 140 liters (37 gallons).

Because the tubing was completely filled with fluid for loading/hydraulic fracture GDSTs, compliance of the test tool included two components:

1. Compliance of the tool within the test zone below the shut-in valve; and
2. Compliance of tubing, wellhead piping, and hydraulic pressure connections above the shut-in valve. The tubing above the valve constituted the major volume of the total test system, ranging from 68 percent to more than 97 percent of the total volume for the 30-m (100-foot) and 4.1-m (13.5-foot) test zones, respectively. Compliance results from unloading tests were used to estimate compliance of the tool below the shut-in valve. Compliance above the valve was measured before testing in the single 30-m (100-foot) zone.
### 2.3.2 Hydraulic Fracture Results

Six hydraulic fracture tests were attempted. Five of the tests (GDST-6, -6A, -7, -8, and -9) were conducted in 4.1-m (13.5-foot) intervals; GDST-6 was not successful. GDST-4A was conducted in a 30-m (100-foot) interval and was successful. The pressure versus time histories of GDSTs-4A, -6A, -7, -8, and -9 are shown on Figures A-16 through A-20 in Appendix A; pressure versus injection volume data are presented on Figures A-11 through A-15 in Appendix A. A typical example of a pressure-time curve with a distinct breakdown pressure is shown on Figure 2-11. The deepest tests did not show a breakdown pressure, as illustrated by Figure 2-12.

An idealized pressure-time history is shown on Figure 2-13 indicating breakdown and fracture-opening pressures. The instantaneous shut-in pressure, ISIP, is defined as the minimum horizontal stress, \( S_h \), Breakdown pressure, \( P_b \), is the maximum pressure during the first pump-in. The ISIP and the fracture-opening pressure, \( P_f \), are determined where the pressure versus time curve begins to depart from linearity after shut-in of the first pressurization cycle and pump-in during the second pressurization cycle. \( P_b, P_f, \) and ISIP are shown on Figure 2-13.

The fracture-opening pressure and the ISIP used to calculate the maximum and minimum horizontal stresses were generally taken from the second or third pressurization cycles. To determine the fracture-opening pressure, a straight line was drawn through the data points of a pressurization cycle. The point at which the data deviated from the line was defined as the fracture-opening pressure. A similar technique was used to determine the ISIP. The pressure-time history of GDST-8 is enlarged on Figure 2-14 to illustrate the determination of fracture-opening pressure and ISIP.

At 956 m (3,137 feet), test GDST-9, a breakdown pressure was observed at 30.4 MPa (4,410 psi), indicating that a fracture had been initiated. An impression packer inflated in the test zone confirmed this observation. The magnitudes of the ISIP, measured during the first, second and third pressurization cycles, were approximately the same. The magnitudes of the fracture-opening pressures of the second and third pressurization cycles are reproducible, providing confidence in the values chosen.
At 1,106 m (3,630 feet), test GDST-4A, an attempt was made to fracture a 30-m (100-foot) interval. Although the breakdown pressure of the first pressurization cycle was not followed by decreasing pressure as pumping continued, it was greater than subsequent pressure maximums of the second and third pressurization cycles. The low volumetric strain rate (only about 14 percent of the rate for shorter zone tests) might create a condition favorable for slow crack propagation. The shape of the pressure-time curve, particularly the first and second pressurization cycles, favors this interpretation. The breakdown pressure and ISIP were 35.2 and 34.2 MPa (5,100 and 4,960 psi), respectively.

At 1,273 m (4,177 feet), test GDST-8, breakdown was observed at 39.6 MPa (5,740 psi). The ISIP is 36.1 MPa (5,230 psi). As in GDST-9, the fracture-opening pressures of the second and third pressurization cycles are of nearly equal magnitude and are reproducible.

At 1,395 m (4,577 feet), test GDST-7, a breakdown pressure was not observed. The magnitude of the maximum pressure of the first pressurization cycle was nearly equal to the ISIP. The pressure maximum of the second and third pressurization cycles was slightly greater than the ISIP. The typical explanation of this type of pressure-time history is that a pre-existing fracture was encountered; however, a careful examination of the core showed no fractures. An alternative explanation is that the hole was plastically deforming.

A breakdown pressure was also not observed at 1,477 m (4,847 feet), during test GDST-6A. Little difference was observed in the pressure maximums and ISIP of the first, second, and third pressurization cycles. As in the previous test, it is assumed that this type of pressure-time history is caused by plastic deformation. Pressure response during various shut-in periods in both GDSTs -6A and -7 indicated that test zone fluid was not leaking past the packers; for example, shut-in periods beginning at 67, 138, and 141 minutes (Figure 2-12) all show pressure increases after shut-in, indicating tight packer seals.

Table 2-3 is a summary of in situ stresses and test pressures interpreted from the pressure-time curves. The magnitudes of \( P_B \) and ISIP are plotted versus depth on Figure 2-15a. The magnitudes of the inferred in situ
SURFACE INJECTION PRESSURE, PSI

PUMP-IN
0.8 gpm

SHUT-IN

BLEED

PUMP-IN
2.4 gpm

SHUT-IN

BLEED

ELAPSED TIME, MINUTES

DEPTH 3130 to 3153.5 ft.
DEPTH 4570 to 4583.6 ft.

SURFACE INJECTION PRESSURE, PSI

SHUT-IN  BLEED  SHUT-IN  BLEED  SHUT-IN  BLEED

PUMP-IN  0.6 gpm  PUMP-IN  1.4 gpm

ELAPSED TIME, MINUTES

PUMP-IN  0.8 gpm

END OF TEST

BEST DOCUMENT AVAILABLE
LEGEND

- $P_B =$ Breakdown Pressure
- $P_F =$ Fracture Opening Pressure
- ISIP = Instantaneous Shut-in Pressure
- $S_h =$ Minimum Horizontal Stress

IDEALIZED PRESSURE vs. TIME HISTORY

IN SITU HYDRAULIC FRACTURE TESTS
BOREHOLE GD-1

LOG 945
REV. 1-4/6/82

LOG 949
REV. 1-4/6/82

WOODWARD-CLYDE CONSULTANTS

Figure 2–13

WOODWARD-CLYDE CONSULTANTS

Figure 2–14
2.3.2 Discussion

In Situ State of Stress. The maximum horizontal stress in borehole GD-1 is generally about 1.5 times the minimum horizontal stress, a high value considering the plastic nature of salt. Several potential sources of error exist in the determination of the maximum horizontal stress: (1) uncertainty in the determination of pore pressure; (2) uncertainty of the magnitude of the tensile strength of salt; and (3) the possibility that the assumption of elastic response may not be strictly valid for the salt strata encountered in GD-1.

In borehole GD-1, the assumptions used for the pore pressure determinations may be a source of error. If pore pressure in salt is assumed to be equal to the lithostatic stress (vertical stress), the values for the maximum horizontal stress are nearly equal to the vertical and minimum horizontal stresses and thus indicate hydrostatic stress conditions. An additional determination of $S_h$ was calculated assuming that the pore pressure gradient is equal to the lithostatic pressure gradient. Results of these calculations are presented in Table 2-4. In this case, $S_h$ ranges from 28.8 MPa (4,180 psi) at 956 m (3,137 feet) to 39.9 MPa (5,780 psi) at 1,273 m (4,177 feet). The shear and tensile strength values also change slightly.

To assess the potential influence of the non-elastic properties of salt, the hydraulic fracture test results of GD-1 were compared with the results of
tests in other rock types. The pressure-time histories of the shallower tests (depths less than 1,219 m [4,000 feet]) showed a breakdown pressure characteristic of hydraulic fractures induced in brittle elastic rocks.

Other in situ stress measurements have been made in hard rock (non-salt) within the Colorado Plateau in the Piceance Basin, Colorado (Bredehoeft and others, 1976) and Rangely, Colorado (Raleigh and others, 1972). The results of hydraulic fracture tests in the Piceance Basin indicate near hydrostatic stress conditions at a depth of 488 m (1,600 feet) with the maximum horizontal stress oriented approximately 70 to 80 degrees northwest. At Rangely, Colorado, stress measurements made at depths of approximately 1,798 m (5,900 feet) indicate that the magnitude of the maximum horizontal stress is approximately twice the vertical stress and 1.5 times the minimum horizontal stress, with the maximum horizontal stress axis oriented 70 degrees northeast. The unusually high stress difference is thought to be influenced by the oilfield activities and is not caused by the regional stress field (Raleigh and others, 1972). The direction of the maximum horizontal stress axis measured at GD-1 is consistent with the results at Rangely, Colorado; however, more direction data need to be gathered in the Gibson Dome Area.

Pure salt normally displays plastic behavior when subjected to small stress differences. Results of the hydraulic fracture tests in GD-1 tentatively suggest that salt behaves in a relatively brittle manner at depths less than 1,219 m (4,000 feet) and in a more plastic manner at depths greater than 1,219 m (4,000 feet). Volumetric strain measurements from the unloading GDSTs (Figure 2-5) support this observation.

Hydraulic fracture data were compared with stress orientations inferred from earthquake focal mechanism data in the Paradox Basin (Wong and Simon, 1981). Microearthquake activity has been observed in the proximity of the confluence of the Green and Colorado Rivers, southeastern Utah. The earthquake activity is located in the Precambrian basement (at depths greater than 2,012 m [6,600 feet]) below the salt in the Paradox Basin. The focal mechanisms indicate strike-slip faulting with predominantly east-west compression; the intermediate stress axis is near vertical. The earthquake activity suggests a stress state other than lithostatic. The non-lithostatic stress
TABLE 2-4
RECALCULATED STRESS VALUES ASSUMING PORE PRESSURE EQUAL TO LITHOSTATIC GRADIENT

<table>
<thead>
<tr>
<th>Test</th>
<th>$P_o$ (psi)</th>
<th>$P_f$ (psi)</th>
<th>$S_h$ (psi)</th>
<th>$S_h$ (psi)</th>
<th>$S_v$ (psi)</th>
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</thead>
<tbody>
<tr>
<td>GDST-9</td>
<td>3,610</td>
<td>3,820</td>
<td>4,180</td>
<td>3,870</td>
<td>3,610</td>
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<tr>
<td>GDST-4A</td>
<td>4,170</td>
<td>4,960</td>
<td>5,750</td>
<td>4,960</td>
<td>4,170</td>
</tr>
<tr>
<td>GDST-8</td>
<td>4,800</td>
<td>5,110</td>
<td>5,780</td>
<td>5,230</td>
<td>4,800</td>
</tr>
<tr>
<td>GDST-7</td>
<td>5,260</td>
<td>5,240</td>
<td>5,310</td>
<td>5,270</td>
<td>5,260</td>
</tr>
<tr>
<td>GDST-6A</td>
<td>5,570</td>
<td>5,290</td>
<td>5,490</td>
<td>5,450</td>
<td>5,570</td>
</tr>
</tbody>
</table>

$P_o$ = Pore Pressure  
$P_f$ = Fracture-Opening Pressure  
$S_h$ = Maximum Horizontal Stress  
$S_h$ = Minimum Horizontal Stress  
$S_v$ = Vertical Stress

Metric Conversion:  
1,000 psi = 6.89 MPa
path below drilling fluid pressure, while curve B represents reloading of the zone from the minimum pressure back to drilling fluid pressure.

After the unloading test, the tubing was filled with brine drilling fluid for the loading test. The test tool was lowered 1.5 m (5 feet) to achieve new, tight packer seats. The loading test was then done by increasing test zone pressure above drilling fluid pressure. Curve C shows corrected volumetric strain versus pressure for the loading test.

Reloading data from unloading GDST-4 (curve B on Figure 2-16) markedly resemble the loading GDST-4A results (curve C) at stresses within 14 MPa (2,000 psi) of drilling-fluid pressure. The loading/hydraulic fracture test (GDST-4A) was the first pressurization cycle above fluid pressure, just as the reload segment ending unloading test GDST-4 was the first pressurization cycle above minimum test zone pressure. Both sets of data are for increasing stress paths and both represent the first reloading of a test zone, even though they are at different magnitudes of test zone pressure (GDST-4 test zone pressure increases from 1.1 to 14.5 MPa [16 to 2,101 psi]; GDST-4A test zone pressure increases from 14.3 to about 34.5 MPa [2,070 to about 5,000 psi]). During drilling, the salt was unloaded from a lithostatic stress of approximately 26 kPa (1.15 psi) per foot of depth to the stress imposed by drilling fluid pressure of 13.6 kPa (0.6 psi) per foot of depth. This close correspondence of two sources of reloading strain values suggests that the data are reasonable, even though different volumetric strain measurement systems with unlike system compliances were employed.
3 LABORATORY STRENGTH AND CREEP TESTING

3.1 OVERVIEW

Core samples of halite from salt cycle 6 recovered during drilling of Borehole GD-1 were tested in the laboratory for strength and creep properties. The test program, summarized on Table 3-1, is a systematic preliminary evaluation of a number of test variables potentially affecting the strength and creep behavior of salt in the Gibson Dome Area. The triaxial strength test program addressed the following factors: (1) stress state during test: extension versus compression; (2) mean stress direction: loading versus unloading; (3) specimen temperature; (4) strain rate; and (5) apparent percentage and strength of anhydrite laminae in sample. The creep test program provided data to evaluate the effect of stress difference and specimen temperature on creep parameters with a single stress state/mean stress direction—triaxial extension unloading.

Equipment used for the test program included identical pressure vessels for both phases, but loading systems and frames for creep testing differed slightly from equipment used for strength testing. Sample preparation, stress and strain measurement methods, and data acquisition systems were similar for the two test programs. Results of the testing are presented in the form of stress versus strain graphs for strength testing and strain versus time graphs for the creep tests. Interpretations of strength results include graphic stress-strain comparisons of results from test variables, referenced to a standard base case, and plots of failure stresses on Mohr or octahedral stress diagrams. Creep results were analyzed using exponential-time creep laws.

3.2 STRENGTH TESTING

3.2.1 Methodology

3.2.1.1 Sample Selection

Most halite test samples for the strength testing were selected from a 60-foot interval within salt cycle 6 between 998 and 1,017 m (3,275 and 3,335 feet) below the drill rig datum. Salt cycle 6 is a favorable stratum for a repository in the Gibson Dome Area, and the particular interval was chosen for testing because it appeared to be relatively uniform throughout and contained only minor amounts of potassium or other high solubility mineral salts. Three samples were tested for each assessment (Table 3-1); in most cases groups of three samples were selected from a single 0.6- to 0.9-m (2- to 3-foot) interval in an attempt to reduce effects on test results caused by sample variation.

At the Paradox Basin Project Core Storage Facility in Denver, 0.9-m (3-foot) core lengths were cut with a diamond saw to rough sample lengths of approximately 19 cm (7.5 inches). The core samples were packed inside rigid plastic pipe and shipped to WCC's Oakland laboratory facilities.

3.2.1.2 Sample Preparation

The Oakland laboratory staff prepared the rough samples for use as laboratory test specimens. First, the 10.2 cm (4-inch) diameter core was undercored to a nominal 7.6-cm (3-inch) diameter using a drill press to turn a carbide-toothed core barrel. After some adjustments to the drill press/core barrel assembly, this undercoring procedure produced a sample with circumferential smoothness of 0.5 mm (0.020 inches) without further machining. After undercoring, the samples were taken to a machine shop where they were milled while held in a special clamping jig so that the final sample was a right circular cylinder within ± 0.05 mm (0.002 inches) of sample length measured at four points. The sample length sample was 2 to 2.5 times the sample diameter.
The final step in sample preparation was affixing electrical resistance, foil-type strain gages manufactured by Micro-Measurements, Inc. to the sample. The gages were of the post-yield type with a gage length of 5 cm (2 inches) and according to the manufacturer, were capable of measuring strains as high as 20 percent. Two axial gages were affixed with glue recommended by the manufacturer on opposite sides at the center of the sample length; two circumferential gages were glued in a similar manner opposite each other on the diameter perpendicular to that of the axial gages. Lead wires were soldered to the gage tabs and loosely looped and taped to the sample to avoid tension during testing.

3.2.1.3 Loading System and Data Collection Instrumentation

The strain-gaged test specimen was assembled with the platens and piston of the pressure vessel (Figure 3-1). The sample was covered with overlapping strips of teflon sheet to protect the gages and lead wires. The lead wires passed through grooves in the top platen and up through an axial hole in the loading piston. The entire platen-sample-piston assembly was enveloped by heat-shrinkable tubing and was heated so that the tubing contracted tightly around the assembly. The entire assembly was coated with silicone grease and covered by a final neoprene or silicone rubber membrane clamped to the bottom positioning bushing and to the piston. The encapsulated sample assembly was then placed on the bottom plate of the pressure vessel and the cylindrical wall of the vessel was positioned around it on the bottom plate. The top plate was finally lowered over the piston, and the entire vessel was bolted together.

Several aspects of the pressure vessel are noteworthy. The piston and sample were of like diameter, thus permitting extensional loading of samples without tensile stress in the piston. The large diameter piston necessitated special linear motion ball bushings and a controlled oil leakage viscous seal (where the piston passed through the top plate) to reduce piston friction, but its size also allowed routing of strain gage wires from the sample to the cell exterior through a small hole bored along the piston axis.
The cell was filled with hydraulic oil and connected to an air-operated hydraulic pump for application of stress to the sides of the sample (termed "confining stress"). The pumps used could generate confining pressures up to 69 MPa (10,000 psi). Confining pressure was constantly monitored and pump controls were adjusted during strength testing to maintain a pressure within ± 140 kPa (20 psi).

Axial stress was applied by a 44 kN (100,000-lb) capacity loading press. The press could be programmed to apply a variety of stress- or strain-controlled loading paths using an integral servo controller. It incorporated a force transducer (load cell) to measure axial force and an electrical linear-variable-displacement transducer (LVDT) to monitor displacement of the movable loading ram of the press.

One group of tests was conducted at elevated temperatures (50° to 150°C [122° to 302°F]). The pressure vessel in these tests was placed in a small oven with a 0.5°C (1.0°F) sensitivity temperature controller. The closely-controlled oven, in combination with the large thermal mass of the pressure vessel including sample and oil produced a maximum temperature variation during a test of ± 0.5°C (1.0°F). A thermocouple temperature probe was inserted through the axial piston hole to monitor temperatures of the top cap of the sample.

The two axial gages were wired into two opposite arms of a Wheatstone bridge so that strains are averaged and the voltage output is doubled; the two circumferential gages were wired in a similar manner. These electrical strain gage signals and the signals from the loading press LVDT and load cell, the confining pressure transducer, and the temperature sensor were routed to a signal conditioning unit for conversion to digital form in engineering units of strain, length, force, pressure, and temperature. The digital engineering readings were in turn displayed and recorded on cassette magnetic tapes of a desktop microcomputer.

Accuracy and resolution of the test measurements varied among the various measurement devices. Each group of five strain gages included a manufacturer engineering data sheet describing the gage factor and apparent strain variation; typically, the resultant accuracy of strains is ± 0.5 percent of the
The recorded value for temperatures from 22° to 50°C (72° to 122°F) and ± 1 percent for 50° to 150°C (122° to 302°F), with a resolution to 40 microstrain. The remaining transducers and sensors had the following accuracy/resolution:

- Loading press LVDT: accuracy ± 0.5 percent of 2.5 cm (1.0 inch) full scale; resolution to 0.0025 mm (0.0001 inches);
- Loading press force transducer: accuracy ± 0.25 percent of 445 kN (100,000 lb) full scale; resolution to 44 N (10 lb);
- Confining pressure transducer: accuracy ± 0.3 percent of 69 MPa (10,000 psi) full scale; resolution to 7 kPa (1 psi);
- Temperature sensor: accuracy ± 1°C (± 2°F); resolution to 0.1°C (0.2°F).

### 3.2.2 Strength Testing Results

Strength testing results from the laboratory test program are included in Appendix B. Figures B-1 through B-9 are results of uniaxial compression tests on salt core samples; Figures B-10 through B-32 show triaxial strength data on salt samples; and Figures B-33 through B-42 are results of uniaxial and triaxial tests on anhydrite core samples. The plots in Appendix B represent all data available for each sample tested in the laboratory in terms of stress difference versus strain. Details about the computational methods used to calculate stress and strain are presented in the appendix.

Table 3-2 is a summary of triaxial/uniaxial strength results and sample physical properties. Stress and strain values are those recorded immediately before the sample failed (ruptured) or are the maximum applied during the test.

### 3.2.3 Discussion

Triaxial strength results were compared in several combinations in the form of stress-strain behavior and principal stress diagrams. These various summary plots illustrate quantitative differences in the behavior of salt cycle 6 according to the various test variables outlined in Table 3-1. The only other salt test results presently available for the Gibson Dome Area, RE/SPEC (1981), have been included in the stress diagram plots in order to compare data between two investigators.

The base case for the triaxial test program is a series of three triaxial extension tests shown on Figure 3-2. These plots, as well as the other comparative stress-strain graphs presented later in this section, display total strain (calculated as LVDT displacement divided by initial sample height) versus stress difference. Because the axial and circumferential strain gages exhibited abnormal behavior at higher strain levels, only total LVDT strain was recorded throughout the entire strain range of all tests.

The base case tests began at isotropic stress levels of 24, 48, and 69 MPa (3,500, 7,000, and 10,000 psi). During the two tests with lower initial isotropic stresses, confining stress was raised in stages to 69 MPa (10,000 psi), as indicated by the stress difference loops shown on Figure 3-2. These base case plots illustrate close similarity among the three tests, even where the confining stress was raised during the test. The data plot for Sample GD-19, typical of the three tests, was selected as the base case graph to which results from the various test configurations (Table 3-1) would be compared. Tests were terminated when the sample failed, or if total strain reached 20 percent, or if stress difference in extension approached 69 MPa (10,000 psi).

Samples with relatively low percentage of anhydrite bonding are compared on Figure 3-3. Scatter among the plots is somewhat more than that of the base case plot, possibly because of the stress increment loading used in these tests. These low-percentage anhydrite samples were the initial samples of the triaxial test program, and constant strain rate tests had not yet been started.
The stress-strain curves and ultimate strength values do not show any systematic influence of the lower-than-average anhydrite content. In salt cycle 6, the insoluble material (primarily anhydrite) content averaged 5 percent by weight. Therefore, samples with a low proportion of anhydrite had only about 2 to 4 percent by weight less anhydrite than the average sample, a proportion variation apparently too small to have a noticeable effect on strength.

Extension loading test results are summarized on Figure 3-4. The three tests display similar stress-strain behavior, but at higher stresses the strains are more than for the base case extension loading. Also, ultimate rupture stresses are less than those for the base case.

The two compression test series have results plotted on Figures 3-5 and 3-6 for loading and unloading paths, respectively. As with the extension loading series, both compression test series showed greater strain than the extension unloading base case. (Compression test strains are opposite in sign from extension test results; strain values plotted on all stress-strain diagrams are absolute magnitudes of strain with zero at the initial isotropic compression state.) The higher strains in compression may be explained by the elastic strain equation for axial strain of a cylindrical sample under imposed triaxial stresses:

\[ \varepsilon_{\text{axial}} = \frac{1}{E} (\sigma_{\text{axial}} - \nu (2 \times \sigma_{\text{conf}})) \]  

(3-1)

where \( E \) = Young's modulus, \( \nu \) = Poisson's ratio, \( \varepsilon_{\text{axial}} \) = axial strain, \( \sigma_{\text{axial}} \) = axial stress, and \( \sigma_{\text{conf}} \) = confining stress.

For compression tests where \( \sigma_{\text{axial}} > \sigma_{\text{conf}} \) and \( \nu = 1/3 \), the absolute value of strain for a given stress difference should be about twice that for an extension test where \( \sigma_{\text{conf}} > \sigma_{\text{axial}} \). Such a strain difference is apparent on only two compression loading tests (Figure 3-5). With the relatively small number of tests performed for a single loading condition, sample variation may be masking more fundamental sample behavior.

Young's modulus was calculated from the rebound stress loops of two triaxial tests, an extension unloading test, and a compression loading test. Details of the stress-strain behavior from axial strain gage data are
presented in Appendix B, Figures B-19 and B-26. The calculated moduli for the two types of tests were 30 GPa (4,300,000 psi) and 28 GPa (4,100,000 psi), respectively. These results are similar to those reported by Pfeifle and others, 1981.

Uniaxial compression tests are also a form of compression loading test. The five tests that were performed are summarized on Figure 3-7. These tests were the first using the computer-based data acquisition system, and some tests included two or three load cycles during data system shakedown. This test series also addressed strain distribution along the sample axes by measuring axial strain at the three quarter points along the sample axes. As shown on the complete test data plots in Appendix B (Figures 8-1 through B-9), the strain is generally uniform along the length of the sample at higher stress levels.

The rupture stress or maximum stress difference achieved in the various room temperature, constant strain rate triaxial and uniaxial tests described above are plotted on principal stress diagrams on Figures 3-8 and 3-9. The first diagram, a plot of one-half stress difference versus mean stress was calculated using major and minor principal stresses; this diagram is related to a Mohr diagram in that the plotted points are the peak points of the Mohr circles for maximum stress difference. As shown on this plot, there is little difference in the results among the various loading paths. An envelope through the points exhibits flattening under increasing mean stress, characteristic of ductile rock materials at high mean stresses.

The second principal stress diagram is a plot of octahedral stresses, including effects of intermediate principal stress, \( \sigma_2 \). Extension and compression tests differ substantially in that \( \sigma_2 = \sigma_3 \) in compression tests, while \( \sigma_2 = \sigma_1 \) in extension tests. Because \( \sigma_2 = \sigma_1 \) in extension tests is much higher than \( \sigma_2 = \sigma_3 \) in compression tests, mean stress (octahedral normal stress) \( \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) \), is greater for extension tests than for compression tests at similar shear stress levels.

The data from all room temperature tests are plotted on an octahedral normal stress-shear stress diagram on Figure 3-9. The extension test plots clearly fall along a different envelope than do the compression test plots.

This trend is in accordance with experimental data of Handin and others (1967).
NOTES

1. TEST SPECIFICATIONS FOR EACH SAMPLE ARE
   CONTAINED ON PLOTS IN APPENDIX B
2. SAMPLE GD1-39 IS BASE CASE TESTED IN
   EXTENSION UNLOADING
3. SAMPLES GD1-59, -63, AND -61 TESTED IN
   COMPRESSION UNLOADING

LEGEND

--- GD1-39 TOTAL
--- GVD'T STRAIN
--- GD1-59 TOTAL
--- GVD'T STRAIN
--- GD1-61 TOTAL
--- GVD'T STRAIN

BASE CASE vs. COMPRESSION UNLOADING
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1266
REV. 1-8/20/82

Project No. 16000
Woodard-Cycle Consultants
Figure 3-5

BEST DOCUMENT AVAILABLE
**NOTES**

1. TEST SPECIFICATIONS FOR EACH SAMPLE ARE CONTAINED ON PLOTS IN APPENDIX B

2. PLOTS FOR SAMPLES GDI-2 AND GDI-3 REPRESENT FIRST LOADING OF EACH SAMPLE

3. SAMPLE GDI-4 LOADED TO 3298 PSI IN FIRST LOAD CYCLE

4. SAMPLE GDI-5 LOADED TO 3398 PSI IN FIRST LOAD CYCLE

5. SAMPLE GDI-7 LOADED TO 3578 PSI IN FIRST LOAD CYCLE

**LEGEND**

- GDI-2 TOTAL (LVDT) STRAIN
- GDI-3 TOTAL (LVDT) STRAIN
- GDI-4 TOTAL (LVDT) STRAIN
- GDI-5 TOTAL (LVDT) STRAIN
- GDI-7 TOTAL (LVDT) STRAIN

---

**UNIAXIAL COMPRESSION**

LABORATORY STRENGTH TESTS

BOREHOLE GD-1

LOG 1268

Project No. 16000

Woodward-Clyde Consultants

Figure 3-7

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**MOHR DIAGRAM**

LABORATORY STRENGTH TESTS

BOREHOLE GD-1

LOG 1039

Project No. 16000

Woodward-Clyde Consultants

Figure 3-8

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**EXPLANATION**

- WCC COMPRESSION TESTS (LOAD AND UNLOAD) ON SALT CYCLE 6
- WCC EXTENSION TESTS (LOAD AND UNLOAD) ON SALT CYCLE 6
- RESPEC COMPRESSION LOAD TESTS ON SALT CYCLE 7 (PFEIFLE and others, 1981)
from limestone, dolomite, and glass samples. The differences between peak Mohr-circle and octahedral stress data presentations have some implications on the utilization of strength data in numerical analyses of underground works. If the analyses are two-dimensional, it may be sufficient to use a conservative interpretation of the Mohr-type data on Figure 3-8 as strength limits. However, if three-dimensional analyses are made considering the three principal stresses, it may then be necessary to use maximum strength data such as those shown on the octahedral stress diagram (Figure 3-9).

Temperature influence on triaxial extension unloading behavior is illustrated by the series of tests shown on Figure 3-10. As expected, the rupture strength dramatically decreases as temperature increases. A decrease in stress difference at a given strain is apparent as the constant testing strain rate is varied over two orders of magnitude, as shown on Figure 3-11. Laboratory test results on carefully fabricated salt samples were reported by Heard (1972); these tests were done in extension over a wide range of strain and temperature and can be compared with GD-1 temperature and strain rate testing. Although the magnitudes of results at similar test conditions are not exactly the same, relative differences can be used to evaluate steady-state flow phenomena as done by Heard (1972). The flow equation cited by Heard is:

\[ \dot{\varepsilon} = A \exp\left(-\frac{Q}{RT}\right) \sigma^n \]  

(3-2)

where, \( \dot{\varepsilon} \) = strain rate, \( A \) = a constant, \( Q \) = activation energy, \( T \) = test temperature in °K, \( R \) = universal gas constant, \( \sigma \) = stress difference, and \( n \) = stress exponent. This expression was evaluated for the elevated temperature (Figure 3-10) and strain rate variation (Figure 3-11) tests done on GD-1 samples; the evaluation procedure is described in more detail in Section 3.3.2.

The triaxial tests at differing strain rates give a stress exponent, \( n \), in excess of 19. Although this value agrees with Heard’s room temperature data, it is anomalously high, probably because test conditions are out of the range where the flow equation is applicable (strain rate too high and test temperature too low). Tests at various temperatures give a \( Q/R \times 1/n \) value of about 800°K; this value was calculated from the stress differences of the three
high-temperature tests at the constant strain rate of \( 9.3 \times 10^{-6} \) /sec and at 10 percent total strain. The Q/R ratio is divided by the stress exponent, \( n \), because the triaxial data do not give a reliable value for \( n \) as discussed above. Heath's (1972) values for Q/R x 1/n range from 1,200 to 2,200 kN. Further discussion of these flow law relationships is contained in Section 3.3.3.

The final triaxial tests were on anhydrite samples from the interbeds above and below salt cycle 6. Room temperature results are plotted on Figure 3-12; elevated temperature data are plotted on Figure 3-13. As expected, this relatively strong and brittle rock displays relatively linear stress-strain behavior even in response to high stresses and exhibits strains considerably less than the base case on salt for similar stress differences. The apparent modulus from the total strain curves of Figures 3-12 and 3-13 is little changed among the various stress paths and temperatures. As noted on these figures, some of the 7.6-cm (3-inch) diameter anhydrite samples could not be failed with the 445 kN (100,000-lb) capacity loading press.

3.3 CREEP TESTING

3.3.1 Methodology

Creep tests were conducted on right circular cylinders of salt cycle 6 from borehole GD-1. The tests were conducted in extension unloading utilizing the triaxial apparatus described in Section 3.2.1.3. Seven parameters were monitored during testing: axial stress, confining pressure, total axial displacement, axial strain, radial strain, temperature, and time. Data were recorded automatically and stored on magnetic cassette tape for later analysis.

The samples were prepared as described in Section 3.2.1.2. If samples were tested at elevated temperatures, the temperature was increased at a rate of about 0.5°C (1°F) /minute to the desired temperature. The samples were isothermally compressed to the pressure desired and allowed to equilibrate 24 hours. They were then quickly unloaded at rates between 7 kPa/sec (1 psi/sec) and 140 kPa/sec (20 psi/sec). During the unloading portion of the test, data

---

**Figure 3-10**

**NOTES**

1. TEST SPECIFICATIONS FOR EACH SAMPLE ARE CONTAINED ON PLOTS IN APPENDIX B
2. SAMPLE GD1-39 IS BASE CASE TESTED IN EXTENSION UNLOADING AT 22 DEG C
3. SAMPLE GD1-36 TESTED IN EXTENSION UNLOADING AT 58 DEG C
4. SAMPLE GD1-37 TESTED IN EXTENSION UNLOADING AT 100 DEG C
5. SAMPLE GD1-38 TESTED IN EXTENSION UNLOADING AT 150 DEG C

**LEGEND**

- GD1-39 TOTAL (LVDT) STRAIN
- GD1-36 TOTAL (LVDT) STRAIN
- GD1-37 TOTAL (LVDT) STRAIN
- GD1-38 TOTAL (LVDT) STRAIN
NOTES

1. TEST SPECIFICATIONS FOR EACH SAMPLE ARE CONTAINED ON PLOTS IN APPENDIX B
2. SAMPLE GOI-39 IS BASE CASE TESTED IN EXTENSION UNLOADING (STRAIN RATE 8.3 E-6 /SEC)
3. SAMPLE GOI-78 TESTED IN EXTENSION UNLOADING AT FASTEST STRAIN RATE (2.7 E-4 /SEC)
4. SAMPLE GOI-71 TESTED IN EXTENSION UNLOADING AT INTERMEDIATE STRAIN RATE (2.7 E-5 /SEC)
5. SAMPLE GOI-72 TESTED IN EXTENSION UNLOADING AT SLOW STRAIN RATE (2.7 E-6 /SEC)

LEGEND

- - - - GOI-39 TOTAL
  (LVDT) STRAIN
- - - - GOI-78 TOTAL
  (LVDT) STRAIN
- - - - GOI-71 TOTAL
  (LVDT) STRAIN
- - - - GOI-72 TOTAL
  (LVDT) STRAIN

BASE CASE vs. STRAIN RATE VARIATION
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1270  Project No. 16000
REV 1-8/20/82 Woodward-Clyde Consultants  Figure 3-11
were recorded every 30 seconds. After about 15 minutes, the data recording rate was reduced to four data measurements per hour.

Axial stress was held constant for the duration of each stage of the creep tests. Approximately once a day, a small correction was applied to the axial load system to correct for sample deformation. As a sample creeps, the cross-sectional area (in extension unloading tests) decreases. That change in cross-sectional area is expressed as:

$$A' = A_0 \left(1 - \frac{6d}{d_o}\right)^2$$

(3-3)

where $A_0$ is the original sample area, $\Delta d$ is the change in sample diameter, $d_o$ is the original sample diameter, and $A'$ is the new sample area. It has been found from circumferential and axial strain gage measurements that sample volume remained approximately constant during testing. When volume change is small, total axial deformation measured by the LVDT can be used to describe the change in diameter. Equation (3-3) can thus be approximated by

$$A' = A_0 \left(1 + \frac{\Delta LVDT}{H_0}\right)$$

(3-4)

where $\Delta LVDT$ is the change in sample height as measured by the LVDT, and $H_0$ is the original sample height.

### 3.3.2 Results

Six creep tests were conducted. Four of these tests (GD1-32, -34, -35, and -37) were conducted at room temperature, 22°C (72°F). GD1-133 was conducted at 50°C (122°F), and GD1-132 was conducted at 100°C (212°F). A test scheduled at 150°C (302°F) was not performed. A plot of data from a typical creep test is shown on Figure 3-14 (plots of data from all creep tests are included in Appendix B). Each creep test was planned to include three or four unloading stages, each lasting approximately one week. The tests were terminated when the sample failed or after four creep stages had been completed (approximately 700 hours total elapsed time). The test conditions are summarized in Table 3-3. Two samples had particularly early endings: GD1-34 was
terminated after 80 hours because of sample failure, and GD1-132 was terminated after 123 hours because of membrane failure.

An exponential-time creep law can be formed:

\[ \varepsilon = e_a (1 - \exp(-\xi t)) + \dot{\varepsilon}_{ss} t \]  

(3-5)

where \( \varepsilon \) is the total axial strain, \( e_a \) is the asymptotic transient strain, \( \dot{\varepsilon}_{ss} \) is the steady-state strain rate, and \( \xi \) is the relaxation frequency (\( 1/\xi \) is the relaxation time). The parameters of Equation (3-5), \( \dot{\varepsilon}_{ss} \), \( e_a \), and \( \xi \), can best be described by looking at the equation in two parts. The exponential term is characterized by an asymptotic transient strain value, \( e_a \), and a relaxation time, \( 1/\xi \). Strain modeled by the exponential term equals \( 1/e \) of the asymptotic value at a time equal to \( 1/\xi \). In the second term, strain is proportional to time by the constant \( \dot{\varepsilon}_{ss} \); this constant is the slope of the strain-time curve at large values of time. By projecting this slope (steady-state strain rate) back to the zero time axis, the value of \( e_a \) can be approximated.

Total axial strain values as calculated from LVDT measurements versus elapsed time from each stage of the creep tests were fit using the exponential-time creep law described by Equation (3-5). The fit to each creep test was calculated using the IMSL computer code ZXSSQ, a non-linear least-squares fitting algorithm. Typical strain-time creep data and the fit according to Equation (3-5) is shown on Figure 3-15. Regression parameters \( \dot{\varepsilon}_{ss} \), \( e_a \), and \( \xi \) are also shown. Ten creep stages were fit using the above technique; strain-time data and the least-squares fit for all the above stages are included in Appendix B. The parameters of Equation (3-5) for each test are listed on the appendix figures and are summarized in Table 3-4. Samples that failed prematurely or that lacked sufficient data on which to fit the creep law were not used in the least-squares algorithm.

Previous work on salt (Pfeifle and others, 1981; Herrmann and others, 1980; Heard, 1972; and Wawersik, 1980; suggests that \( \dot{\varepsilon}_{ss} \) depends on stress and temperature. This stress and temperature dependence is presented in Equation
TABLE 3-
LABORATORY CREEP TEST MATRIX

<table>
<thead>
<tr>
<th>Test</th>
<th>Stage</th>
<th>Confining Pressure</th>
<th>Differential Stress</th>
<th>Temperature</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GD1-32A</td>
<td>1/3</td>
<td>7,000 psi</td>
<td>3,800 psi</td>
<td>22°C</td>
<td></td>
</tr>
<tr>
<td>GD1-32B</td>
<td>2/3</td>
<td>7,000 psi</td>
<td>4,400 psi</td>
<td>22°C</td>
<td>Confining pressure pumps malfunctioned</td>
</tr>
<tr>
<td>GD1-32C</td>
<td>3/3</td>
<td>7,000 psi</td>
<td>5,250 psi</td>
<td>22°C</td>
<td></td>
</tr>
<tr>
<td>GD1-34A</td>
<td>-</td>
<td>10,000 psi</td>
<td>3,500 psi</td>
<td>22°C</td>
<td>Sample failed after 80 hours</td>
</tr>
<tr>
<td>GD1-35A</td>
<td>1/2</td>
<td>7,000 psi</td>
<td>3,450 psi</td>
<td>22°C</td>
<td></td>
</tr>
<tr>
<td>GD1-35B</td>
<td>2/2</td>
<td>7,000 psi</td>
<td>3,900 psi</td>
<td>22°C</td>
<td></td>
</tr>
<tr>
<td>GD1-73A</td>
<td>1/4</td>
<td>7,000 psi</td>
<td>3,550 psi</td>
<td>22°C</td>
<td></td>
</tr>
<tr>
<td>GD1-73B</td>
<td>2/4</td>
<td>7,000 psi</td>
<td>4,500 psi</td>
<td>22°C</td>
<td></td>
</tr>
<tr>
<td>GD1-73C</td>
<td>3/4</td>
<td>7,000 psi</td>
<td>5,500 psi</td>
<td>22°C</td>
<td></td>
</tr>
<tr>
<td>GD1-73D</td>
<td>4/4</td>
<td>7,000 psi</td>
<td>6,200 psi</td>
<td>22°C</td>
<td></td>
</tr>
<tr>
<td>GD1-132A</td>
<td>-</td>
<td>7,000 psi</td>
<td>2,000 psi</td>
<td>100°C</td>
<td>Membrane failed after 123 hours</td>
</tr>
<tr>
<td>GD1-133A</td>
<td>1/4</td>
<td>7,000 psi</td>
<td>2,500 psi</td>
<td>50°C</td>
<td></td>
</tr>
<tr>
<td>GD1-133B</td>
<td>2/4</td>
<td>7,000 psi</td>
<td>3,250 psi</td>
<td>50°C</td>
<td></td>
</tr>
<tr>
<td>GD1-133C</td>
<td>3/4</td>
<td>7,000 psi</td>
<td>4,100 psi</td>
<td>50°C</td>
<td></td>
</tr>
<tr>
<td>GD1-133D</td>
<td>4/4</td>
<td>7,000 psi</td>
<td>4,800 psi</td>
<td>50°C</td>
<td></td>
</tr>
</tbody>
</table>

Metric Conversion: 1,000 psi = 6.89 MPa

---

**Figure 3-15**

- **GD1-73C**
  - $\varepsilon_{ss} = 2.0 \times 10^{-9} \text{ sec}^{-1}$
  - $\varepsilon = 1.4 \times 10^{-9}$
  - $\ddot{\varepsilon} = 5.6 \times 10^{-9} \text{ sec}^{-1}$

---

**THIRD UNLOAD STAGE GD1-73**

LABORATORY CREEP TESTS
BOREHOLE GD-1

LOG 1028
REV.0.3/31/82
Project No. 16000
Woodward-Clyde Consultants
Figure 3-15

---

**BEST DOCUMENT AVAILABLE**
TABLE 3-4
CREEP-FITTING PARAMETERS FOR TOTAL AXIAL STRAIN VERSUS TIME CURVES

<table>
<thead>
<tr>
<th>Test</th>
<th>ε&lt;sub&gt;ss&lt;/sub&gt; (sec&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>ε&lt;sub&gt;a&lt;/sub&gt;</th>
<th>1/ε</th>
<th>δσ</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>GD1-35A</td>
<td>4.4 x 10&lt;sup&gt;-9&lt;/sup&gt;</td>
<td>2.8 x 10&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>1.7 x 10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>6.0 x 10&lt;sup&gt;3&lt;/sup&gt;</td>
<td>3.450</td>
</tr>
<tr>
<td>GD1-35B</td>
<td>4.4 x 10&lt;sup&gt;-9&lt;/sup&gt;</td>
<td>2.9 x 10&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>6.2 x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>1.6 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>3.900</td>
</tr>
<tr>
<td>GD1-73A</td>
<td>7.1 x 10&lt;sup&gt;-9&lt;/sup&gt;</td>
<td>1.6 x 10&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>3.8 x 10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>2.6 x 10&lt;sup&gt;3&lt;/sup&gt;</td>
<td>3.550</td>
</tr>
<tr>
<td>GD1-73B</td>
<td>5.9 x 10&lt;sup&gt;-9&lt;/sup&gt;</td>
<td>3.9 x 10&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>6.3 x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>1.6 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>4.500</td>
</tr>
<tr>
<td>GD1-73C</td>
<td>2.0 x 10&lt;sup&gt;-8&lt;/sup&gt;</td>
<td>1.4 x 10&lt;sup&gt;-2&lt;/sup&gt;</td>
<td>5.6 x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>1.8 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>5.500</td>
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<tr>
<td>GD1-73D</td>
<td>6.0 x 10&lt;sup&gt;-8&lt;/sup&gt;</td>
<td>1.1 x 10&lt;sup&gt;-2&lt;/sup&gt;</td>
<td>8.6 x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>1.2 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>6.200</td>
</tr>
<tr>
<td>GD1-133A</td>
<td>1.3 x 10&lt;sup&gt;-9&lt;/sup&gt;</td>
<td>1.3 x 10&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>9.6 x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>1.0 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>2.500</td>
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<td>GD1-133B</td>
<td>3.1 x 10&lt;sup&gt;-9&lt;/sup&gt;</td>
<td>2.0 x 10&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>2.8 x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>3.5 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>3.250</td>
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<td>4.100</td>
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<td>1.3 x 10&lt;sup&gt;-8&lt;/sup&gt;</td>
<td>2.0 x 10&lt;sup&gt;-2&lt;/sup&gt;</td>
<td>1.7 x 10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>5.8 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
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<td>4,400</td>
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<td>6.0 x 10&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>5,250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GD1-32C</td>
<td>7.4 x 10&lt;sup&gt;-9&lt;/sup&gt;</td>
<td>3,500</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Steady state strain rates fit by judgment

ε<sub>ss</sub> = steady state strain rate
ε<sub>a</sub> = asymptotic transient strain
ε = relaxation frequency
1/ε = relaxation time
δσ = stress difference

Metric Conversion: 1,000 psi = 6.89 MPa

(3-2). Stress difference and steady state strain rate at each creep stage were used to determine A, n, and Q/R.

A plot of log ε<sub>ss</sub> versus log δσ is shown on Figure 3-16. Equation (3-2) is a straight line in logarithmic space at constant temperature; the slope of the line is n. Parallel straight lines were fit to the data by judgment for the data from 22°C (72°F) and 50°C (122°F) tests. The slope of these lines, which equals the stress exponent, n, was estimated as 5.6. A Q/R of 2,400 K was determined by choosing points from the 22°C (72°F) line and the 50°C (122°F) line at a constant stress difference and solving Equation (3-2) for Q/R.

Computed values of n and Q/R were then used to determine an A of 1.3 x 10<sup>-13</sup>. Values for n, Q/R, and A are summarized in Table 3-5.

It has been suggested (Hermann and others, 1980; Pfeifle and others, 1981) that the stress and temperature dependence of the relaxation frequency, ε, and the asymptotic transient strain, ε<sub>a</sub>, is different between low and high steady-state strain rate regions. The data set presented here did not cover a sufficiently broad range of stress and temperatures to observe the boundary between regions. Previous work (Pfeifle and others, 1981) suggests that a reasonable steady-state strain rate value that divides the above two regions is ε<sub>ss</sub> = 5 x 10<sup>-8</sup> sec<sup>-1</sup>. With the exception of Test GD1-73 Stage D, all steady-state strain rates calculated from the creep data presented here are in the low strain rate region, being less than ε<sub>ss</sub> = 5 x 10<sup>-8</sup> sec<sup>-1</sup>.

In the low strain rate region, the relationship between ε and steady-state strain rate has been found to be a constant (Pfeifle and others, 1981). A plot of ε vs ε<sub>ss</sub> is shown on Figure 3-17. Even with considerable scatter in the data, a constant (average) value of ε = 9.7 x 10<sup>-5</sup> sec<sup>-1</sup> appears to describe the data. This value is shown as a solid line on Figure 3-17. For the low strain rate region, Pfeifle and others (1981) described the average value, ε<sub>ss</sub>, in terms of ε<sub>ss</sub> as ε = B ε<sub>ss</sub>. For comparison with Pfeifle's data, a B value of 1,960 has been calculated using ε<sub>ss</sub> = 5.0 x 10<sup>-8</sup> sec<sup>-1</sup>.

Asymptotic transient strain, ε<sub>a</sub>, has been found to be proportional to ε<sub>ss</sub> in the low steady-state strain rate region (Pfeifle and others, 1981). A plot of ε<sub>a</sub> against ε<sub>ss</sub> for data from this creep test program is presented on Figure 3-18. A linear relationship describing the data gives a slope, ε<sub>a</sub>/ε<sub>ss</sub>, estimated as 4.9 x 10<sup>-3</sup> sec. Pfeifle and others (1981) defined the slope of
this line in terms of $C_E$ as $C_E \times \beta$. A value for $C_E$ of $2.5 \times 10^{-2}$ has been calculated. All of the fitting parameters, $n$, $Q/R$, $A$, $B$, and $C_E$, are summarized in Table 3-5.

3.3.3 Discussion

The exponential-time creep law provides a reasonable fit to the data. This creep law indicates that steady-state creep is a linear function of time. In several instances the steady-state portion of the creep curves for salt cycle 6 is slightly curved even at large values of elapsed time. In these cases the steady-state strain rate, as calculated from the least squares fit overestimates creep strains at long times. A comparison of strain rates estimated for the later portion of the creep curves versus those calculated using the exponential time model suggests that the model sometimes overestimates the steady-state strain rate by about 10 percent.

The plot of $\log o$ versus $\log e_{ss}$ shows a great deal of scatter, making the calculation of $n$ somewhat arbitrary. However, an upper and lower bound estimate of $n$ can be approximated from the data as 6.0 and 4.0, respectively. Previous work on Paradox salt (Pfeifle and others, 1981) suggested a value of 1.4 for $n$. This value seems low compared with the results presented here, with values of $n$ for salt from other locations (Pfeifle and others, 1981) and with values of $n$ for pure halite (Heard, 1972).

This testing gives a value of $C_E = 2.5 \times 10^{-2}$, which agrees well with data published by Pfeifle and others (1981) for salt from Richton Dome, Vacherie Dome, Avery Island and New Mexico salts: $C_E$ differs by an order of magnitude from the Paradox salt data presented by Pfeifle and others (1981).

The value of $Q/R$ of 2,400*K derived from this testing seems low compared to values presented elsewhere (Pfeifle and others, 1981; Heard, 1972). As seen on Figure 3-16, there is little separation between the 22°C (72°F) curve and the 50°C (122°F) curve, a circumstance implying that there is only minimal change in creep behavior at temperature differentials of approximately 28°C (50°F). Additional work is needed at elevated temperatures (100°C to 200°C, 212°F to 392°F) to adequately evaluate $Q/R$ and the stress and temperature dependence of $e_{ss}$. A comparison of the $\log o$ vs $\log e_{ss}$ relationship.
# Summary of Parameters for Creep Equations

\[ \dot{\varepsilon}_{ss} = A \exp \left( -\frac{Q}{RT} \right) \varepsilon^n \]

<table>
<thead>
<tr>
<th>Description of Parameter</th>
<th>Parameter ( n )</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Exponent</td>
<td>( n )</td>
<td>5.6</td>
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<table>
<thead>
<tr>
<th>Description of Parameter</th>
<th>Parameter ( \frac{Q}{R} )</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>Activation Energy Gas Constant</td>
<td>( \frac{Q}{R} )</td>
<td>2400 K</td>
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<table>
<thead>
<tr>
<th>Description of Parameter</th>
<th>Parameter ( A )</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitting Constant</td>
<td>( A )</td>
<td>( 1.3 \times 10^{-13} ) (MPa units)</td>
</tr>
</tbody>
</table>

\[ \dot{\varepsilon} = B \dot{\varepsilon}_{ss} \]

<table>
<thead>
<tr>
<th>Description of Parameter</th>
<th>Parameter ( \dot{\varepsilon}_{\text{avg}} )</th>
<th>Value</th>
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<tr>
<td>Average value of Relaxation Frequency</td>
<td>( \dot{\varepsilon}_{\text{avg}} )</td>
<td>( 9.8 \times 10^{-5} ) sec(^{-1} )</td>
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<th>Description of Parameter</th>
<th>Parameter ( \dot{\varepsilon}_{\text{avg}} )</th>
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<tr>
<td>Average value of Relaxation Time</td>
<td>( \dot{\varepsilon}_{\text{avg}} )</td>
<td>( 1 \times 10^5 ) sec</td>
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<table>
<thead>
<tr>
<th>Description of Parameter</th>
<th>Parameter ( \dot{\varepsilon}_{ss} )</th>
<th>Value</th>
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</thead>
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<tr>
<td>Boundary between high and low steady state strain rate regions</td>
<td>( \dot{\varepsilon}_{ss} )</td>
<td>( 5 \times 10^{-5} ) sec(^{-1} )</td>
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<thead>
<tr>
<th>Description of Parameter</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Fitting Constant</td>
<td>( B )</td>
<td>( 1960 )</td>
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</table>

\[ \varepsilon_a = \frac{\varepsilon}{\dot{\varepsilon}_{\text{avg}}} \]

<table>
<thead>
<tr>
<th>Description of Parameter</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>Slope of ( \varepsilon_a ) vs. ( \dot{\varepsilon}_{ss} )</td>
<td>( \varepsilon_a / \dot{\varepsilon}_{ss} )</td>
<td>( 4.9 \times 10^{-5} )</td>
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<tr>
<th>Description of Parameter</th>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Normalized asymptotic Transient Strain</td>
<td>( \varepsilon_a )</td>
<td>( 2.5 \times 10^{-2} )</td>
</tr>
</tbody>
</table>
133D

O CREEP TESTS, 22°C
△ CREEP TESTS, 50°C

0.0 x 10^3
10.0
5.0

△ 133C

SLOPE = 4.9 x 10^-6 sec

O 73C

133B

△ 73B

35A

△ 35B

133A

O 73A

\( \dot{\epsilon}_s = \frac{\dot{\epsilon}_a \dot{\epsilon}_{ss}}{\dot{\epsilon}_{ss}} \)

\( \dot{\epsilon}_{ss} = 59.57 \times 10^{-9} \)

LABORATORY CREEP TESTS
BOREHOLE GD-1

LOG 1043
REV 0-4/5/82
Woodward-Clyde Consultants

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presented here, and the one developed by Pfeifle and others (1981) from tests at 100° and 200°C (212°F and 392°F) tentatively suggest markedly different creep behavior; part of the difference may be caused by the difference in loading states: compression loading for Pfeifle's work and extension unloading in these results.

Some of the scatter in the data may be attributed to sample variation. Test results from samples adjacent to one another in borehole GD-1 seemed to exhibit more consistent material behavior than results from samples separated by 3 to 15 m (10 to 50 feet). Although tests were grouped such that samples came from the adjacent portions of the borehole, experimental difficulties occasionally required substitution of samples from other locations. One of the advantages of multistage creep tests is that they eliminate variability caused by sample variation. The data presented on Figure 3-16 support this observation; for example, \varepsilon_{\text{ss}} values of GD1-32 are systematically different from those of GD1-73 at the same temperature and stress levels.

4 CONCLUSIONS

The in situ test program established that the equipment and methodology developed for geotechnical drill-stem testing of deep salt strata are workable. Refinements to the equipment will facilitate measurement and improve accuracy of unloading fluid level data taken while the system is pressurized by a compressed gas. Data from the short-term creep phase of the unloading test, because they are unaffected by tool compliances or gas pressure and are measured by precise and stable pressure transducers, display favorable accuracy. Impression packer workability should be improved for hydraulic fracture tests to yield reliable fracture orientation data.

Stress-strain data were obtained from the first unloading of salt strata below drilling-fluid pressure. These data are uncommon because they reflect test zone behavior devoid of previous non-geologic stress influences; prior to the test program, the test zone had experienced no stresses as low as those of the unloading tests. A Young's modulus of 6.6 GPa (0.96 x 10^6 psi) interpreted from one test is consistent with values reported in the literature but is lower than values from geophysical logs and laboratory strength testing (37 GPa [5.3 x 10^6 psi] and 29 GPa [4.2 x 10^6 psi], respectively).

Short-term creep deformations were measured for three depths. Radial strain creep rates of \(1.6 \times 10^{-9}\), \(4.4 \times 10^{-9}\), and \(42 \times 10^{-9}\) sec^{-1} are generally consistent with other laboratory tests and other direct measurements of borehole creep.

The results of hydraulic fracture measurements in the Paradox salt strata indicate that successful fracture tests can be conducted. Results of the tests indicate a non-lithostatic stress state at depths shallower than 1,220 m (4,000 feet). From a single impression packer measurement, the maximum horizontal stress axis appears oriented ENE-WSW, consistent with other hydraulic fracture measurements in the Colorado Plateau and with earthquake focal mechanism data (Wong and Simon, 1980).

Magnitudes of the minimum horizontal stress interpreted from hydraulic fracture testing appear reasonable. The magnitude of the maximum horizontal stress seems high considering the plastic, time-dependent properties of salt. Initial elastic assumptions and pore pressure estimates used in stress
interpretation may not be applicable to hydraulic fracture in salt. At depths above 1,220 m (4,000 feet), salt appears to behave in a relatively brittle, elastic manner, as evidenced by the shape of the pressure-time curve. At depths below 1,220 m (4,000 feet), salt appears to behave in a more plastic manner.

Laboratory triaxial strength tests on salt samples and some anhydrite samples were completed for a number of different loading paths, strain rates, and temperatures. Strength and Young's modulus results are generally consistent with other test data from the GD-1 borehole and display trends similar to those from salt in other locations. As observed in previous studies, the Paradox salt has higher strengths than many other salts at similar test conditions.

Triaxial strength data at failure or at maximum stress difference were plotted on principal stress diagrams for extension and compression loading paths. Data plotted on a Mohr diagram show little effect of loading path. However, results plotted on an octahedral stress diagram display a marked difference between extension versus compression loadings. Principal stress diagrams should be useful in establishing strength criteria for thermomechanical computer models.

A number of creep tests were conducted and the results were analyzed using accepted techniques. An exponential-time creep law adequately described strain-time data. Steady-state creep rates for several tests (developed from the creep law) were studied using a steady-state flow law to determine stress difference and temperature dependence. A stress exponent, n, of 5.6 and activation energy term, Q/R, of 2,400 K were computed from the flow law.

Parameters developed from analyses of the creep data were roughly comparable to other reported data. The n was higher than previously reported for GD-1 samples, but the Q/R was lower than other results from GD-1 and other locations. Some of the difference may be attributed to the extension unload stress path of these tests compared with the conventional compression loading sequence.

REFERENCES

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Hansen, F.D., and Mellegard, K.D., 1980, Further creep behavior of bedded salt from southeastern New Mexico at elevated temperature: Sandia Laboratories SAND 80-7114.


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### APPENDIX A

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<td>Compliance Above Valve: GDST-1</td>
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<td>GDST-6A: Pressure vs. Volume</td>
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Unreduced field measurements from in situ geotechnical testing at Borehole GD-1 are presented in this appendix. The figures and tables presented herein show the data from which stresses and strains were interpreted for both unloading and loading (hydraulic fracture) test sequences. Unloading data are included in Section A.1; loading/hydraulic fracture data are presented in Section A.3. Compliance testing of the downhole test system for both unloading and loading test sequences is discussed in Section A.2.

A.1 UNLOADING GDST DATA

Downhole pressures and fluid level measurements were the primary data recorded during each unloading geotechnical drill-stem test (GDST). Pressures were recorded above drilling-fluid pressure, within and below the test zone at one- to five-minute intervals during each test. These data were displayed in real time during the test on an x-y plotter and printer and were stored on magnetic tape cassettes for subsequent interpretation. Figures A-1 through A-3 are pressure-time graphs of all real-time pressure data recorded during the three successful GDSTs. Critical points identified on Figure A-1 are also typical of the other two tests.

These pressure data are recorded to 0.07 kPa (0.01 psi) and are available in printout form in the project files; these printouts, because of their digital form, were used to calculate unloading pressure (initial test zone pressure minus test zone pressure at time when fluid level reading was taken). Backup pressure data from digital memory recorders and mechanical scratch recorders and measurements of nitrogen pressure applied at the wellhead are also available in the files. Table A-1 indicates the measurement equipment used for the in situ tests and summarizes the types of data available for each test.

Fluid level data were measured by dunking a pressure transducer or a shorting-type electrical sensor on an electric cable wireline. All such fluid level measurements, and the elapsed test time and test zone pressure, are
tabulated in Tables A-2 through A-4. Table A-2 lists the type of fluid sensor used in each unloading test.

For GDST-2, a special interpretation procedure was used to determine approximate fluid level values for the first 41 hours of the test, because the fluid level sensing system was inoperative. Using fluid level data measured during the concluding reloading portion of the test, the proportion of down-hole nitrogen (N₂) gas pressure caused by the weight of N₂ could be estimated. Because the unloading steps at the beginning of the test had almost the same test zone and surface nitrogen pressures as the reloading steps, the N₂ gas weight pressures estimated for the reloading segment were added to the unloading surface pressure measurements to determine the total gas pressure immediately above the fluid. These total N₂ pressures were then subtracted from the test zone pressures to determine the height of fluid during the unloading steps. This procedure was not as accurate as direct measurement of fluid level; however, when it was implemented for GDST-1 and the results were compared with direct fluid level measurements during that test, values calculated were within approximately 5 feet of the measured values.

Pressure-time data for the short-term creep period of the three successful GDSTs are presented on Figures A-4 through A-6. Each figure includes a caption identifying the slope at the end of the creep interval in terms of radial and volumetric strain rates. This slope was calculated as:

\[
\frac{\Delta \varepsilon}{\Delta t} = \frac{\Delta p}{\Delta t} \frac{TC}{FG \times V_o}
\]

where:
- \(\varepsilon_r\) = radial strain rate, sec\(^{-1}\)
- \(\varepsilon_v\) = volumetric strain rate, sec\(^{-1}\)
- \(\Delta p/\Delta t\) = slope of pressure-time curve, psi/sec
- TC = tubing capacity, gallons/ft of tubing
- FG = fluid gradient of test zone fluid, psi/ft of height
- \(V_o\) = initial volume of test zone, gallons.
INFLATE PACKERS TO ISOLATE TEST ZONE

OPEN VALVE TO TEST ZONE

PRESSURE BELOW TEST ZONE

DRILLING FLUID PRESSURE

BEGIN REDUCING PRESSURE (UNLOADING) IN 5 STEPS

PRESSURE IN TEST ZONE

BEGIN TO MEASURE SHORT-TERM CREEP

INCREASE PRESSURE (RELOADING)

NOTES
1. PARADOX FORMATION: SALT CYCLE 19
2. DEPTH = 4785 TO 4945 FT BELOW RIG DATUM
NOTES
1. PARADOX FORMATION: SALT CYCLE 6
2. DEPTH = 3150 TO 3320 FT BELOW RIG DATUM
NOTES
1. PARADOX FORMATION: SALT CYCLE 9
2. DEPTH = 3575 TO 3675 FT BELOW RIG DATUM
| Successful tests | X | X\(^a\) | X | | X | X | X | X | X |
| Length of test zone (feet) | 160 | 160 | 100 | 70 | 100 | 13.5 | 13.5 | 13.5 | 13.5 | 13.5 |
| Packer Inflation\(^c\) | S | S | S | S | S | S | D | D | D | D | D |
| Fluid Depth Sensor\(^d\) | PTA | N/PTB | PTB | PTB/SF | SF | No Downhole Fluid Sensor Used |
| Real-time TQCT pressure sensor in test zone | X | X | X | X | X | X | X |
| Surface pressure data\(^e\) | N\(_2\) | N\(_2\) | N\(_2\) | N\(_2\) | N\(_2\) | W | W | W | W | W |
| Backup DMR data in test zone | X | X | X | X | X | X | X | X | X | X | X |
| Real-time pressure sensor 100 feet above test zone | X | X | X | X | X | X | X | X | X | X | X |
| Impression packers run | X | X | X | X | X | X | X | X | X | X | X |

\(^a\) Partial

\(^b\) Test 3: 100 ft; tests 3A, 3B, 3C: 70 feet

\(^c\) S = Surface; D = Downhole

\(^d\) PTA = Two pressure transducers 100 feet apart on wireline
PTB = Single pressure transducer on wireline
SF = Shorting-type fluid sensor
N = No fluid depth sensor until late in test

\(^e\) TR N\(_2\) = Nitrogen; W = Fluid injection pressure
### Table A-2

**Fluid Level Measurements: GDST-1**

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  - 2858.6
  - 2858.0
  - 2359.4
  - 2358.3
  - 1879.1
  - 1879.6
  - 1879.8
- Fluid:
  - 4156.5
  - 4159
  - 4159.5
  - 4160
  - 2858.0
  - 2858.6
  - 2358.6
  - 2359.1
  - 2358.3
  - 2359.4
  - 2360.1
  - 1879.1
  - 1879.6
  - 1879.8

**Change in Fluid Level (ft):**
- 4075
- 4072
- 4067
- 4066
- 3975
- 3960
- 3958
- 3954
- 3947
- 3945
- 3942
- 3942
- 3940
- 3942
- 3935
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- 4080.0
Table A-3
Fluid Level Measurements: GSDT-2

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*Change in fluid level is not applicable to this test because no fluid level readings were taken at the beginning of the test.

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Fluid Level Measurements: GSDT-4

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*Change in fluid level is not applicable to this test because no fluid level readings were taken at the beginning of the test.
NOTES
1. PARADOX FORMATION: SALT CYCLE 19
2. DEPTH = 4785 TO 4945 FT BELOW RIG DATUM
3. ZERO ELAPSED TIME IN CREEP INTERVAL = 32.33 ELAPSED HOURS IN ENTIRE TEST
NOTES
1. PARADOX FORMATION: SALT CYCLE 6
2. DEPTH = 3160 TO 3320 FT BELOW RIG DATUM
3. ZERO ELAPSED TIME IN CREEP
   INTERVAL = 22.72 ELAPSED HOURS IN ENTIRE TEST
PRESSURE FLUCTUATIONS CAUSED BY DUNKING PRESSURE TRANSDUCER TO SENSE FLUID LEVEL

\[ \Delta V/V_0 = 3.3 \times 10^{-9} \text{ sec}^{-1} \]
\[ \Delta r/r_0 = 1.6 \times 10^{-9} \text{ sec}^{-1} \]

NOTES
1. PARADOX FORMATION SALT CYCLE 9
2. DEPTH = 3575 TO 3675 FT BELOW RIG DATUM
3. ZERO ELAPSED TIME IN CREEP
   INTERVAL = 17.25 HOURS IN ENTIRE TEST
These data were the bases for short-term creep rates. The direct measurements of fluid level were sensitive to short-term creep movements only in the deepest test (GDST-1); these direct fluid level measurements are included in the main text as Figure 2-6. For GDST-1, short-term creep strain rates from the pressure-time curves (Figure A-4) correspond closely with rates calculated from direct fluid level measurements.

Borehole deformation below the bottom packer was measured indirectly using the rate of pressure rise in this closed system during unloading GDSTs. A typical graph of pressure rise versus time is shown on Figure A-1 as the uppermost curve from 10 to 83 hours. An average radial strain rate, \( \dot{\varepsilon}_r \), can be approximated as:

\[
\dot{\varepsilon}_r = 0.5 \frac{\Delta V}{V_0} \frac{1}{n} = 0.5 \frac{k}{n} \frac{\Delta P}{P_0} \frac{1}{\Delta t}
\]

where \( \dot{\varepsilon}_r \) is volumetric strain rate; \( n \) = fraction of borehole below bottom packer that is salt (typically \( n = 2/3 \)); \( k \) = compressibility of brine fluid in borehole = 2.0 \( \times 10^{-6} \) volumetric strain per psi (Section A.2.2); and \( \Delta P/\Delta t \) is the rate of pressure rise in the closed system below the bottom packer. These results are approximate because they do not account for fluid flow into the numerous non-halite interbeds. \( \dot{\varepsilon}_r \) values ranged from \( 2.1 \times 10^{-9} \) to \( 4.1 \times 10^{-9} \) sec\(^{-1}\).

A.2 COMPLIANCE TESTS OF IN SITU TEST APPARATUS

Measurements made during both unloading and loading GDSTs include some volumetric strain that can be attributed to deformation of the test apparatus in response to test zone pressure changes. For instance, in an unloading test, pressure differences across the inflated rubber packers of as much as 20.7 MPa (3,000 psi) tend to force the packers into the test zone, adding to the apparent volumetric strain (hole squeeze) in the test zone. Pressure differences of a reverse nature in a loading/hydraulic fracture test tend to force the packers away from the test zone and to compress all fluid in the test system, overstating hole expansion upon pressurization. Test system compliance for both unloading and loading GDSTs is discussed in the following subsections.

A.2.1 Compliance of Unloading GDST Test Apparatus

Prior to commencing the unloading GDSTs, a compliance test on the drill-stem test tool was conducted in the cased portion of the hole by pressurizing the tool and reading fluid levels at given pressures (Figure A-7). The fluid level readings were then plotted against average pressure difference across the packers to determine a compliance correction (Figure A-8). The total pressure range of the compliance test was not as great as that of the GDSTs because pressures higher than those shown on Figure A-7 could break the cement bond on the outside of the casing.

Two different slopes shown on Figure A-8 correspond to increasing and decreasing test zone pressure. These slopes were used to express compliance corrections as volumetric strain per psi of pressure difference across the packers. These compliance corrections were subtracted from the total unloading or reloading volumetric strain measured during the GDST testing to compute corrected volumetric strain. For the unloading portion of each test (reducing test zone pressure), a correction of \( 3.0 \times 10^{-6} \) \( \Delta V/V_0/\text{psi} \) was used, corresponding to the reducing pressure load path (Figure A-8, points A and B). This correction factor was multiplied by the average pressure difference across the packers and subtracted from the uncorrected volumetric strain value. For the reloading steps, after the minimum pressure interval, a correction factor of \( 3.0 \times 10^{-6} \) \( \Delta V/V_0/\text{psi} \) was used to correct the volumetric strain values.

A.2.2 Compliance of Loading/Hydraulic Fracture GDST Test Apparatus

Compliance of the loading apparatus includes two components: deformation of the test tool below the downhole shut-in valve and compressibility of the fluid, tubing, and surface connections above the shut-in valve. Compliance below the shut-in valve was set as the reloading value of \( 3.0 \times 10^{-6} \) \( \Delta V/V_0/\text{psi} \). Two compliance tests above the shut-in valve were made; one preceded GDST-1 and the other was made before GDST-4A. The compliance test before GDST-1 gave a correction of \( 2.0 \times 10^{-6} \) (Figure A-9); the test before GDST-4A gave a compliance of \( 3.0 \times 10^{-6} \) (Figure A-10). The difference in these values was attributed to the fact that the
NOTES
1. COMPLIANCE TEST CONDUCTED BEFORE GOST-1
   IN UPPER, CASED PORTION OF BOREHOLE
2. DEPTH = 768 TO 928 FT BELOW RIG DATUM
DEPTH 760 to 920 ft.

LOADING SLOPE = 0.013 ft/psi
= 3.1 x 10^-4 gal/psi
= 3.0 x 10^-4 ft³/psi

UNLOADING SLOPE = 1.73 x 10^-4 ft³/psi

AVERAGE PRESSURE DIFFERENCE ACROSS PACKERS

BLEEDING PRESSURE FROM TUBING
INCREASING PRESSURE IN TUBING

SLOPE = 3.5 x 10^-4 gal/psi
= 3.0 x 10^-4 ft³/psi

GALLONS INJECTED AT WELLHEAD

SURFACE INJECTION PRESSURE

COMPLIANCE ABOVE VALVE: GDST-1
IN SITU TEST PROGRAM
BOREHOLE GD-1
Project No. 18000
LOG 141
REV. 06/15/81
Woodward-Clyde Consultants
Figure A-9
tubing string in GDST-1 was accidently filled with water rather than brine, resulting in a higher compressibility.*

A summary of the measured compliance values for loading GDSTs is presented in Table A-5. The contribution to compliance of tubing expansion and the compressibility values of the initial pump-in interval of loading/hydraulic fracture tests are also listed in this table. Test compressibility values for the five loading tests were taken from the initial pump-in portion of the injection pressure versus volume curves (Figures A-11 through A-15). The volumetric strain per psi from each of these curves was taken as the slope of the pressure-volume curve in gallons per psi; that value was then divided by the total gallons in the test system, including the volume of the fluid in the tubing.

Several observations can be made by comparing various sets of results shown in Table A-5. First, the values for the two compliance tests above the shut-in valve conducted before GDST-1 and GDST-4A were substantially different, probably because of the fluid differences discussed previously. Second, values for total test compressibility of the short-zone loading GDSTs (GDST-6A through -9) were only slightly less than the compliance value measured before GDST-4A. Finally, elastic, internal-pressure expansion of the tubing above the shut-in valve accounts for only about 20 percent of test system compliance, implying that most test system deformation above the shut-in valve was caused by fluid and some air bubble compressibility.

Even if careful compliance calibration tests are conducted before each loading GDST, it will be difficult to accurately determine corrected volumetric strain for short-zone hydraulic fracture tests. The volume of compressible air in the tubing above the shut-in valve differs each time the tubing is filled with fluid and the wellhead is connected to the hydraulic pump. In the loading tests, varying amounts of air apparently were entrained in the tubing fluid even though the tubing was filled consistently by application of a vacuum of 26 inches of mercury on the empty portion of the tubing.

*Earlougher (1977) gave the compressibility of distilled water at 90 degrees F and 2,845 psi as 2.49 x 10⁻⁶ psi⁻¹ and of brine fluid with 3000,000 ppm NaCl as 1.83 x 10⁻⁶ psi⁻¹ at the same temperature and pressure.
The small test zone volume is also a factor in short-zone loading where the test zone is less than 5 percent of the total volume. A slight error (even 1 percent) made in determining compliance above the shut-in valve could possibly yield an error of as much as 50 percent in corrected test zone volumetric strain. The interpolation of a straight-line compliance correction to the measured compliance test data points in short test zones could easily be subject to at least a 1 percent error (Figures A-9 and A-10). Therefore, it does not appear promising to attempt measurement of volumetric strain for small test zones.

Loading GDST-4A was the only viable candidate for stress versus corrected volumetric strain computations because a compliance calibration test was conducted immediately before the actual test and because the test zone was a substantial portion (32 percent) of the total volume. Two compliance correction volumes were subtracted from the total volume injected at the wellhead (Figure A-15): (1) deformation of the test system above the shut-in valve caused by injection pressures; and (2) deformation of the test tool below the shut-in valve caused by differential pressures between the test zone and the borehole drilling-fluid pressure outside of the packers. Test system deformation above the shut-in valve was calculated by multiplying $\frac{\Delta V}{V_o}/psi = 2.04 \times 10^{-6}$ (Figure A-10) by the initial test zone volume and injection pressure corresponding to each cumulative volume measurement. Test tool deformation below the shut-in valve was calculated by multiplying $\frac{\Delta V}{V_o}/psi = 3.0 \times 10^{-6}$ (slope corresponding to increasing test zone pressure on Figure A-7) by initial volume and average pressure difference across the packers.

A.3 LOADING/HYDRAULIC FRACTURE GDST DATA

Primary data collected during loading/hydraulic fracture GDSTs were surface injection pressure and injection volume measured at 30-second to 1-minute intervals during each test. Surface pressure versus time curves for the successful short-zone tests, GDST-6A, -7, -8, and -9, are presented on Figures A-16 through A-19, respectively. Surface pressure versus time for the one long-term test is shown on Figure A-20. The pressures for this test were
### Table A-5
**Compliance Measurements**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Type of Compliance Measurement</th>
<th>Test Zone Volume as % of Total Volume</th>
<th>Compliance Value (V/Vo/psi for Initial Pump-in Interval)</th>
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<tr>
<td>Before GDST-1</td>
<td>Test system above shut-in valve (increasing pressure)</td>
<td>--</td>
<td>3.0 x 10^{-6}</td>
</tr>
<tr>
<td>Before GDST-1</td>
<td>Test system below shut-in valve (increasing pressure)</td>
<td>--</td>
<td>3.0 x 10^{-6}</td>
</tr>
<tr>
<td>Before GDST-4A</td>
<td>Test system above shut-in valve</td>
<td>--</td>
<td>2.04 x 10^{-6}</td>
</tr>
<tr>
<td></td>
<td>Theoretical internal pressure expansion of 2-7/8-inch tubing</td>
<td>--</td>
<td>4.22 x 10^{-7}</td>
</tr>
<tr>
<td></td>
<td>Theoretical internal pressure expansion of 4-1/2-inch drill pipe</td>
<td>--</td>
<td>4.5 x 10^{-7}</td>
</tr>
<tr>
<td>GDST-4A</td>
<td>Total test compliance including borehole deformation</td>
<td>32.0%</td>
<td>3.39 x 10^{-6}</td>
</tr>
<tr>
<td>GDST-6A</td>
<td>Total including borehole deformation</td>
<td>1.9%</td>
<td>1.84 x 10^{-6}</td>
</tr>
<tr>
<td>GDST-7</td>
<td>Total including borehole deformation</td>
<td>2.0%</td>
<td>2.00 x 10^{-6}</td>
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<td>GDST-8</td>
<td>Total including borehole deformation</td>
<td>2.2%</td>
<td>1.79 x 10^{-6}</td>
</tr>
<tr>
<td>GDST-9</td>
<td>Total including borehole deformation</td>
<td>2.9%</td>
<td>1.95 x 10^{-6}</td>
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</table>

Average of short-zone tests = 1.90 x 10^{-6}
SHUT-IN
BLEED
PUMP-IN 0.5 gpm

SHUT-IN
BLEED
PUMP-IN 2.5 gpm

PUMP-IN 4.0 gpm

SURFACE INJECTION PRESSURE, PSI

CUMULATIVE GALLONS IN/OUT DURING TEST

0 40 80 120 160 200 240
0 400 800 1200 1600 2000 2400
DEPTH 4840 to 4853.5 ft.

SURFACE INJECTION PRESSURE, PSI

SHUT-IN

BLEED

PUMP-IN

SHUT-IN

BLEED

PUMP-IN

SHUT-IN

BLEED

SHUT-IN

BLEED

PUMP-IN

SHUT-IN

BLEED

END OF TEST

ELAPSED TIME, MINUTES
NOTES:
1. PARADOX FORMATION : SALT CYCLE 9
2. DEPTH = 3590 TO 3680 FT BELOW RIG DATUM
3. SURFACE INJECTION PRESSURE = TEST ZONE PRESSURE
   MINUS PRESSURE FROM FLUID COLUMN IN TUBING
taken from a transducer in the test zone with the static pressure of the brine fluid column subtracted from the downhole pressure to yield surface pressure.

Pressure versus volume curves for the five loading tests are presented on Figures A-11 through A-15.
APPENDIX B
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B.1 LABORATORY STRENGTH TESTING

B.2 LABORATORY CREEP DATA

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<td>Fourth Unload Stage GD1-133</td>
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</table>
This appendix presents laboratory stress-strain measurements taken during uniaxial and triaxial strength testing and creep testing of samples from salt cycle 6 and from the adjacent anhydrite interbeds in Borehole GD-1.

### B.1 LABORATORY STRENGTH TESTING

Stress-strain results of all uniaxial and triaxial tests are presented on Figures B-1 through B-42 and are summarized in Table B-1. Most figures contain all strain gauge and total (LVDT)* strain data plotted versus stress difference. Figures B-19 and B-26 present enlarged detail of strain gauge data for calculation of Young's modulus in a rebound-reload stress-strain loop. All tests with sample number less than GD1-75 were made on core samples from salt cycle 6; sample numbers greater than GD1-75 correspond to anhydrite samples.

Each graph includes test specifications: the loading path (extension or compression, loading or unloading) is indicated in the figure title; the stress maintained at a single value during testing is identified in the test notes, which also indicate the stress that was gradually varied during testing and the axial strain rate at which the stress was varied. The test notes also include the test temperature, sample depth, and any unusual occurrences such as equipment malfunction or erratic strain gauge behavior.

Strain values from the axial and circumferential gauges were calculated as:

\[
\epsilon = 0.5 \text{ abs } (S_e - S_o) \tag{1}
\]

where:
- \( \epsilon \) = axial or circumferential strain
- \( S_e \) = Wheatstone bridge measurement during the test
- \( S_o \) = the bridge measurement at the beginning of the test after application of any initial isotropic stresses.

The 0.5 factor accounts for doubled Wheatstone bridge output when two active gauges were wired into opposite arms of the bridge.

Axial and circumferential strain are reported as absolute values for ease of plotting. In extension tests axial strain is tensile and circumferential strain is compressive (that is, the sample elongates and decreases in cross-sectional area). Conversely, in compression tests axial strain is compressive and circumferential strain is tensile (sample shortening and increase in cross-sectional area).

Total strain measured by the LVDT is calculated as:

\[
\epsilon_t = \frac{(LVDT_e - LVDT_o)/H_o}{2} \tag{2}
\]

where:
- \( \epsilon_t \) = total (LVDT) strain
- \( LVDT_e \) = LVDT measurement during the test
- \( LVDT_o \) = the initial LVDT measurement
- \( H_o \) = the initial height of the sample (after isotropic stressing).

The computation of stress difference uses the total (LVDT) strain to correct the sample area during testing for sample deformation assuming constant volume. This assumption is most nearly achieved in extension tests, where circumferential strain was approximately one-half axial strain, the condition for constant volume. This method also allows for area corrections throughout the entire test beyond the point when most strain gauges failed.

Axial stress on the sample was computed as:

\[
\sigma_{ax} = \frac{L - (A_p - A_t) P}{A_t} \tag{3}
\]

where:
- \( \sigma_{ax} \) = actual axial stress on the corrected average cross-sectional area of the sample
- \( L \) = total load applied by loading press
- \( A_p \) = area of loading piston
- \( A_t \) = corrected area of sample defined as \( A_o/1 + \epsilon \) for extension or \( A_o/1 - \epsilon \) for compression
- \( A_o \) = initial area of sample after isotropic stressing
- \( P \) = confining stress (cell pressure).
NOTES
1. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 8&-6 /SEC
2. STRESS DIFFERENCE = AXIAL STRESS
3. TEST TEMPERATURE = 72 DEG F = 22 DEG C
4. SAMPLE TOP DEPTH = 3322.3 FT BELOW RIG DATUM
5. STRAIN GAUGES EXCEEDED RANGE OF DATA ACQUISITION SYSTEM AT 8.358 STRAIN
6. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 M

LEGEND
- CIRCUMFERENTIAL STRAIN GAUGES
- TOP AXIAL STRAIN GAUGES
- BOTTOM AXIAL STRAIN GAUGES
- MIDDLE AXIAL STRAIN GAUGES
- TOTAL (LVDT) STRAIN

UNIAXIAL COMPRESSION: SAMPLE GD1-2
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1136
REV.1-8/31/82
Project No. 16000
Woodward-Clyde Consultants
Figure B-1

BEST DOCUMENT AVAILABLE
NOTES

1. FIRST LOADING OF SAMPLE
2. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 6x9 /SEC
3. STRESS DIFFERENCE = AXIAL STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3387.8 FT BELOW RIG DATUM
6. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 M

LEGEND

- CIRCUMFERENTIAL STRAIN GAUGES
- TOP AXIAL STRAIN GAUGES
- BOTTOM AXIAL STRAIN GAUGES
- MIDDLE AXIAL STRAIN GAUGES
- TOTAL (LVDT) STRAIN

RESULTS

1. SECOND LOADING OF SAMPLE FROM ZERO STRESS
2. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 6x9 /SEC
3. STRESS DIFFERENCE = AXIAL STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3387.8 FT BELOW RIG DATUM
6. TOP AND BOTTOM AXIAL GAUGES WERE NOT RECORDED ON SECOND LOADING
7. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 M

UNIAXIAL COMPRESSION: SAMPLE GD1-4
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1137
REV.1-8/31/82
Project No. 16000
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BEST DOCUMENT AVAILABLE
NOTES
1. FIRST LOADING OF SAMPLE
2. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 6x10^{-6} /SEC
3. STRESS DIFFERENCE = AXIAL STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3281.9 FT BELOW RIG DATUM
6. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa,
   1 FT = 0.305 M

LEGEND
CIRCUMFERENTIAL STRAIN GAUGES
MIDDLE AXIAL STRAIN GAUGES
TOTAL (GLVD) STRAIN

UNIAXIAL COMPRESSION: SAMPLE GD1-5
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1139
Project No. 16000
Woodward-Clyde Consultants
Figure 8–5

UNIAXIAL COMPRESSION: SAMPLE GD1-5
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1140
Project No. 16000
Woodward-Clyde Consultants
Figure 8–6
NOTES
1. THIRD LOADING OF SAMPLE FROM ZERO STRESS
2. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 6x10^-6 /SEC
3. STRESS DIFFERENCE = AXIAL STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 328 8 9 FT BELOW RIG DATUM
6. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 m

LEGEND
--- CIRCUMFERENTIAL STRAIN GAUGES
--- MIDDLE AXIAL STRAIN GAUGES
--- TOTAL (LVDT) STRAIN

UNIAXIAL COMPRESSION: SAMPLE GD1-5
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1141
REV.1-8/31/82
Project No. 16000
Woodward-Clyde Consultants
Figure B-7
NOTES

1. SECOND LOADING OF SAMPLE FROM ZERO STRESS
2. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 6 x 10^-6 /SEC
3. STRESS DIFFERENCE = AXIAL STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 329.3 FT BELOW RIG DATUM
6. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 M

LEGEND

--- CIRCUMFERENTIAL STRAIN GAUGES
----- TOP AXIAL STRAIN GAUGES
------ BOTTOM AXIAL STRAIN GAUGES
--------- MIDDLE AXIAL STRAIN GAUGES
---------- TOTAL (LVDT) STRAIN

UNIAXIAL COMPRESSION: SAMPLE GD1-7 LABORATORY STRENGTH TESTS BOREHOLE GD-1

LOG 1143 Project No. 16000 Woodward-Clyde Consultants Figure 8-9
NOTES

1. AXIAL STRESS GRADUALLY REDUCED IN APPROX.
   200 PSI STEPS

2. INITIAL CONFINING STRESS = 2500 PSI; REDUCED
   TO ZERO THEN INCREASED TO 200 PSI; REDUCED
   TO ZERO THEN INCREASED TO 7000 PSI

3. STRESS DIFFERENCE = CONFINING STRESS MINUS
   AXIAL STRESS

4. TEST TEMPERATURE = 72 DEG F = 22 DEG C

5. SAMPLE TOP DEPTH = 3208.3 FT BELOW RIG DATUM

6. METRIC CONVERSION: 1000 PSI = 6.9 MPA
   1 FT = 0.305 M

LEGEND

1. AXIAL STRESS GRADUALLY REDUCED IN APPROX.
   200 PSI STEPS

2. CONFINING STRESS = 7000 PSI

3. STRESS DIFFERENCE = CONFINING STRESS MINUS
   AXIAL STRESS

4. TEST TEMPERATURE = 72 DEG F = 22 DEG C

5. SAMPLE TOP DEPTH = 3208.3 FT BELOW RIG DATUM

6. AXIAL AND RADIAL GAUGES GAVE ERRATIC READINGS
   DURING TEST

7. METRIC CONVERSION: 1000 PSI = 6.9 MPA
   1 FT = 0.305 M

EXTENSION UNLOADING: SAMPLE GD1-15
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1145
REV.1-8/31/82
Woodward-Clyde Consultants

Figure B-11
NOTES
1. AXIAL STRESS GRADUALLY REDUCED AT AXIAL STRESS RATE APPROX. 8 x 10^{-5} /SEC
2. CONFINING STRESS = 10,000 PSI
3. STRESS DIFFERENCE = CONFINING STRESS MINUS AXIAL STRESS
4. TEST TEMPERATURE = 122 DEG F = 50 DEG C
5. SAMPLE TOP DEPTH = 3330.8 FT BELOW RIG DATUM
6. AXIAL STRAIN GAUGES GAVE ERRATIC READINGS DURING TEST
7. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 M

LEGEND
--- CIRCUMFERENTIAL STRAIN GAUGES
----- TOTAL (LVDT) STRAIN

EXTENSION UNLOADING: SAMPLE GD-1-36 LABORATORY STRENGTH TESTS BOREHOLE GD-1
LOG1147 Project No. 16000 REV.1-8/31/82 Woodward-Clyde Consultants Figure B-13
BEST DOCUMENT AVAILABLE

NOTES
1. AXIAL STRESS GRADUALLY REDUCED AT AXIAL STRESS RATE APPROX. 8 x 10^{-5} /SEC
2. CONFINING STRESS = 10,000 PSI UNTIL 5.35X STRAIN, WHEN 'O'-RING LEAK REQUIRED REDUCTION TO 6000 PSI
3. STRESS DIFFERENCE = CONFINING STRESS MINUS AXIAL STRESS
4. TEST TEMPERATURE = 212 DEG F = 100 DEG C
5. SAMPLE TOP DEPTH = 3331.2 FT BELOW RIG DATUM
6. AXIAL AND RADIAL GAUGES GAVE ERRATIC READINGS DURING TEST
7. HYDRAULIC FITTING BROKE AT 1.1X STRAIN
8. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 M

LEGEND
----- TOTAL (LVDT) STRAIN

EXTENSION UNLOADING: SAMPLE GD-1-37 LABORATORY STRENGTH TESTS BOREHOLE GD-1
LOG1148 Project No. 16000 REV.1-8/31/82 Woodward-Clyde Consultants Figure B-14
BEST DOCUMENT AVAILABLE
NOTES
1. AXIAL STRESS GRADUALLY REDUCED AT AXIAL STRAIN RATE APPROX. 8x10^-6 /SEC
2. CONFINING STRESS = 7800 PSI
3. STRESS DIFFERENCE = CONFINING STRESS MINUS AXIAL STRESS
4. TEST TEMPERATURE = 382 DEG F = 150 DEG C
5. SAMPLE TOP DEPTH = 3331.0 FT BELOW RIG DATUM
6. AXIAL AND RADIAL WHEATSTONE BRIDGES INCLUDED ONLY ONE ACTIVE ARM
7. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 M

LEGEND
--- CIRCUMFERENTIAL STRAIN GAUGES
--- AXIAL STRAIN GAUGES
--- TOTAL (LVDT) STRAIN

EXTENSION UNLOADING: SAMPLE GD1-39
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1149
Project No. 16000
Woodward-Clyde Consultants
Figure B-15
NOTES

1. AXIAL STRESS GRADUALLY REDUCED AT AXIAL STRAIN RATE APPROX. 6x10^-6 /SEC
2. INITIAL CONFINING STRESS = 7000 PSI; INCREASED IN STAGES TO 8000, 10000, AND 18,000 PSI
3. STRESS DIFFERENCE = CONFINING STRESS MINUS AXIAL STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3275.5 FT BELOW RIG DATUM
6. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa

LEGEND

- CIRCUMFERENTIAL STRAIN GAUGES
- AXIAL STRAIN GAUGES
- TOTAL (LVDT) STRAIN

EXTENSION UNLOADING: SAMPLE GD1-40
LABORATORY STRENGTH TESTS
BOREHOLE GD-1
LOG 1151
REV.1-8/31/82
Project No. 16000
Woodward-Clyde Consultants
Figure 8-17

BEST DOCUMENT AVAILABLE
NOTES
1. DETAIL OF AXIAL STRAIN FOR MODULUS COMPUTATION
2. TEST NOTES ON PREVIOUS PAGE
3. LOOP AT LEFT: INCREASED AXIAL STRESS FROM 2000 TO 3000 PSI THEN DECREASED TO 2000 PSI
4. LOOP AT RIGHT: INCREASED AXIAL STRESS FROM 2000 TO 3000 PSI THEN INCREASED CONFINING STRESS FROM 9500 TO 5000 PSI
5. METRIC CONVERSION: 1000 PSI = 6.9 MPa

E = 4,300,000 PSI = 30 GPa

LEGEND
----- AXIAL STRAIN GAUGES

NOTES
1. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 6X10^5 /SEC
2. CONFINING STRESS = 2000 PSI
3. STRESS DIFFERENCE = AXIAL STRESS MINUS CONFINING STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3290.5 FT BELOW RIG DATUM
6. AXIAL STRESS PUMP SURGE AT 0.23 TOTAL STRAIN
7. METRIC CONVERSION: 1000 PSI = 6.9 MPa

COMPRESSION LOADING: SAMPLE GD1-58
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

EXTENSION UNLOADING: SAMPLE GD1-41
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

PROJECT NO. 18000
WOODWARD-CLYDE CONSULTANTS

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REV.1-8/31/82
LOG 1153
Figure B–19

REV.1-8/31/82
LOG 1154
Figure B–20

REV.1-8/31/82
LOG 1154
Figure B–20

BEST DOCUMENT AVAILABLE
NOTES
1. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 6x10^-6 /SEC
2. CONFINING STRESS = 1000 PSI
3. STRESS DIFFERENCE = AXIAL STRESS MINUS CONFINING STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3207.5 FT BELOW RIG DATUM
6. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa;
   1 FT = 0.3048 m

LEGEND
--- CIRCUMFERENTIAL STRAIN GAUGES
--- AXIAL STRAIN GAUGES
--- TOTAL (LVDT) STRAIN

COMPRESSION LOADING: SAMPLE GD1-69
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1156
REV. 1/8/82
Project No. 160000
Woodward-Clyde Consultants
Figure 8-21

BEST DOCUMENT AVAILABLE
NOTES

1. INITIAL CONFINING STRESS = 7,000 PSI, GRADUALLY REDUCED AT AXIAL STRAIN RATE APPROX. 8E-6 /SEC
2. AXIAL STRESS = 10,000 PSI
3. STRESS DIFFERENCE = AXIAL STRESS MINUS CONFINING STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3291.5 FT BELOW RIG DATUM
6. RADIAL GAUGE WHEATSTONE BRIDGE INCLUDED ONLY ONE ACTIVE ARM
7. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 M

LEGEND

CIRCUMFERENTIAL STRAIN GAUGES
AXIAL STRAIN GAUGES
TOTAL (LVDT) STRAIN

COMPRESSION UNLOADING: SAMPLE GD1-62
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1157
Project No. 16000
Woodward-Clyde Consultants
Figure 8-23

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NOTES

1. INITIAL CONFINING STRESS = 3500 PSI; GRADUALLY REDUCED AT AXIAL STRAIN RATE APPROX. 1X - 6 SEC, INCREASED TO 7000 PSI THEN GRADUALLY REDUCED
2. INITIAL AXIAL STRESS = 3500 PSI; INCREASED TO 7000 PSI
3. STRESS DIFFERENCE = AXIAL STRESS MINUS CONFINING STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3200.5 FT BELOW RIG DATUM
6. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
1 FT = 0.305 M

LEGEND

- CIRCUMFERENTIAL STRAIN GAUGES
- AXIAL STRAIN GAUGES
- TOTAL (LVDT) STRAIN

COMPRESSION UNLOADING: SAMPLE GD1-64
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1159
REV. 1-8/31/82

COMPRESSION UNLOADING: SAMPLE GD1-64
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1160
REV. 1-8/31/82

NOTES

1. DETAIL OF AXIAL STRAIN FOR MODULUS COMPUTATION
2. TEST NOTES ON PREVIOUS PAGE
3. INCREASED CONFINING STRESS FROM 10 TO 3500 PSI THEN INCREASED AXIAL STRESS FROM 3500 TO 7000 PSI
4. METRIC CONVERSION: 1000 PSI = 6.9 MPa

LEGEND

- AXIAL STRAIN GAUGES

COMPRESSION UNLOADING: SAMPLE GD1-64
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

PROJECT NO. 16000

WOODWARD-CLYDE CONSULTANTS
1. INITIAL CONFINING STRESS = 5000 PSI
   GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 5x10⁻⁶ /SEC
2. AXIAL STRESS = 500 PSI
3. STRESS DIFFERENCE = CONFINING STRESS MINUS AXIAL STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3294.7 FT BELOW RIG DATUM
6. AXIAL GAUGES GAVE ERRATIC READINGS DURING TEST
7. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 M

NOTES

LEGEND

1. CIRCUMFERENTIAL STRAIN GAUGES
   TOTAL (LVDT) STRAIN

2. AXIAL STRAIN GAUGES
   TOTAL (LVDT) STRAIN

EXTENSION LOADING: SAMPLE GD1-65
LABORATORY STRENGTH TESTS BOREHOLE GD-1

LOG 1161
REV.1-8/31/82
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EXTENSION LOADING: SAMPLE GD1-67
LABORATORY STRENGTH TESTS BOREHOLE GD-1

LOG 1162
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1. Initial confining stress = 250 psi
   Gradually increased at axial strain rate approx. 6x10^-6 /sec
2. Axial stress = 250 psi
3. Stress difference = confining stress minus axial stress
4. Test temperature = 72 deg F = 22 deg C
5. Sample top depth = 3297.4 ft below rig datum
6. Metric conversion: 1000 psi = 6.9 MPa, 1 ft = 0.305 m
NOTES
1. AXIAL STRESS GRADUALLY REDUCED AT AXIAL
   STRAIN RATE APPROX. 2.7e-6 /SEC
2. CONFINING STRESS = 10,000 PSI
3. STRESS DIFFERENCE = CONFINING STRESS MINUS
   AXIAL STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3304.1 FT BELOW RIG DATUM
6. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa;
   1 FT = 0.305 M

LEGEND
1. CIRCUMFERENTIAL
   STRAIN GAUGES
2. AXIAL STRAIN
   GAUGES
3. TOTAL (LVDT)
   STRAIN

EXTENSION UNLOADING: SAMPLE GD1-71
LABORATORY STRENGTH TESTS
BOREHOLE GD-1
LOG 1166
Project No. 16000
Woodward-Clyde Consultants
Figure B–31

EXTENSION UNLOADING: SAMPLE GD1-72
LABORATORY STRENGTH TESTS
BOREHOLE GD-1
LOG 1166
Project No. 16000
Woodward-Clyde Consultants
Figure B–32
NOTES
1. ANHYDRITE SAMPLE
2. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 8x10^-6 /SEC
3. STRESS DIFFERENCE = AXIAL STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3115.8 FT BELOW RIG DATUM
6. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
1 FT = 0.305 M

LEGEND
-------------------
- CIRCUMFERENTIAL STRAIN GAUGES
- AXIAL STRAIN GAUGES
- TOTAL (LVDT) STRAIN

EXTENSION UNLOADING: SAMPLE GD1-79
LABORATORY STRENGTH TESTS
BOREHOLE GD-1
LOG 1167
Project No. 16000
Woodward-Clyde Consultants
Figure 8-33

BEST DOCUMENT AVAILABLE
NOTES
1. ANHYDRITE SAMPLE
2. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 8.6E-6 /SEC
3. CONFINING STRESS = 1000 PSI
4. STRESS DIFFERENCE = AXIAL STRESS MINUS CONFINING STRESS
5. TEST TEMPERATURE = 72 DEG F = 22 DEG C
6. SAMPLE TOP DEPTH = 3368.8 FT BELOW RIG DATUM
7. AXIAL AND RADIAL GAUGES GAVE ERRATIC READINGS DURING TEST
8. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
   1 FT = 0.305 M

LEGEND
TOTAL (LVDT) STRAIN

COMPRESSION LOADING: SAMPLE GD1-81
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1169
REV.1-1/9/92
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Figure B-35

BEST DOCUMENT AVAILABLE
NOTES

1. THIRD LOADING OF ANHYDRITE SAMPLE
2. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 8X10^-6 /SEC
3. STRESS DIFFERENCE = AXIAL STRESS
4. TEST TEMPERATURE = 72 DEG F = 22 DEG C
5. SAMPLE TOP DEPTH = 3380.8 FT BELOW RIG DATUM
6. AXIAL GAUGE GAVE ERRATIC READINGS, AXIAL GAUGE WHEATSTONE BRIDGE INCLUDED ONLY ONE ACTIVE ARM
7. METRIC CONVERSIONS

- 1000 PSI = 6.9 MPa
- 1 FT = 0.305 M

---

LEGEND

- AXIAL STRAIN GAUGES
- TOTAL (LVDT) STRAIN

---

NOTES

1. ANHYDRITE SAMPLE
2. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 8X10^-6 /SEC
3. STRESS DIFFERENCE = AXIAL STRESS
4. TEST TEMPERATURE = 122 DEG F = 50 DEG C
5. SAMPLE TOP DEPTH = 3381.5 FT BELOW RIG DATUM
6. RADIAL GAUGE GAVE ERRATIC READINGS, RADIAL GAUGE WHEATSTONE BRIDGE INCLUDED ONLY ONE ACTIVE ARM
7. METRIC CONVERSIONS

- 1000 PSI = 6.9 MPa
- 1 FT = 0.305 M

---

LEGEND

- CIRCUMFERENTIAL STRAIN GAUGES
- TOTAL (LVDT) STRAIN

---

BEST DOCUMENT AVAILABLE
1. SECOND LOADING OF ANHYDRITE SAMPLE
2. AXIAL STRESS GRADUALLY INCREASED AT AXIAL STRAIN RATE APPROX. 10E-6 /SEC
3. STRESS DIFFERENCE = AXIAL STRESS
4. TEST TEMPERATURE = 122 DEG F = 50 DEG C
5. SAMPLE TOP DEPTH = 3081.5 FT BELOW RIG DATUM
6. AXIAL GAUGE GAVE ERRATIC READINGS. RADIAL GAUGE WHEATSTONE BRIDGE INCLUDED ONLY ONE ACTIVE ARM
7. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa
1 FT = 0.3048 M

UNIAXIAL COMPRESSION: SAMPLE GD1-B2
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1173
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12000
10000
8000
6000
4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- CIRCUMFERENTIAL STRAIN GAUGES
TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1174
REV.1-9/1/82
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10000
8000
6000
4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1174
REV.1-9/1/82
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10000
8000
6000
4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1174
REV.1-9/1/82
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10000
8000
6000
4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1174
REV.1-9/1/82
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10000
8000
6000
4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1174
REV.1-9/1/82
Woodward-Clyde Consultants

10000
8000
6000
4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1174
REV.1-9/1/82
Woodward-Clyde Consultants

10000
8000
6000
4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1174
REV.1-9/1/82
Woodward-Clyde Consultants

10000
8000
6000
4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1174
REV.1-9/1/82
Woodward-Clyde Consultants

10000
8000
6000
4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

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4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

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8000
6000
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0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %

EXTENSION UNLOADING: SAMPLE GD1-B3
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1174
REV.1-9/1/82
Woodward-Clyde Consultants

10000
8000
6000
4000
2000
0.0
0.4
0.8
1.2
1.6
2.0
STRESS DIFFERENCE, PSI

NOTES

LEGEND

--- TOTAL (LVDT) STRAIN

STRAIN, %
UNIAXIAL COMPRESSION: SAMPLE GD1-83
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1175
REV. 1-9/82
Woodward-Clyde Consultants
Figure 8-41

EXTENSION UNLOADING: SAMPLE GD1-116
LABORATORY STRENGTH TESTS
BOREHOLE GD-1

LOG 1176
REV. 1-9/82
Woodward-Clyde Consultants
Figure 8-42
Stress difference is the absolute value of the difference of axial stress and confining stress.

All measurement devices were calibrated at least to the manufacturers' specified accuracy. In addition, two tests were made to verify the overall performance of the strain measurement and temperature control systems. An aluminum cylinder of the same dimension as most samples was instrumented with the same strain gauges used for the strength and creep testing. The sample was tested in uniaxial compression in both the strength loading frame and the creep frame; the modulus of elasticity for aluminum measured by the axial strain gauges ranged from 10.1 to 10.3 x 10^6 psi, which is in accordance with published values for aluminum.

A salt sample with a small hole drilled along its axis to the mid-height was assembled in the triaxial cell and placed in the oven to check temperature gradients in the sample. Thermocouples were placed (1) at the center of the sample inside the hole; (2) at the top center of the sample; and (3) at the bottom outside circumference. Thermocouples were placed (1) at the center of the sample inside the hole, (2) at the top center of the sample, and (3) at the bottom outside circumference. Temperatures measured by these sensors were within ±2 degrees C of each other while the sample was stabilized at 150 degrees C. Temperature variation during a test was generally ±2 degrees C at these elevated temperatures: 50, 100, and 150 degrees Celsius.

B.2 LABORATORY CREEP DATA

This section presents plots of the basic laboratory measurements for creep tests GD1-32, -34, -35, -73, -132, and -133. Exponential-time model fits are also included for those tests where the calculations could be made. Whenever possible, total (LVDT) strain measurements were used as the data to which the exponential-time fits were made. In some tests, however, the LVDT did not function properly; axial strain gauge data were then used. In creep tests where both total and axial strain data were available, the ratio of axial to total strain was a relatively constant value of 1.2. That relation, then, was used to approximate total strain when the LVDT instrumentation yielded erratic data.

Creep test GD1-32. GD1-32 (Figure B-43) was the first test in the series of creep tests. Circumferential, axial, and total strain in percent versus elapsed time in hours are plotted on one set of axes; confining stress and

\[
\text{Stress difference} = |\text{Axial stress} - \text{Confining stress}|.
\]
stress difference in psi versus elapsed time are plotted on the second set of axes. As with the triaxial tests, circumferential and axial strain were measured with electric resistance strain gauges, while total strain was measured with an LVDT monitoring piston displacement. The test lasted approximately 760 hours and was terminated when the piston movement out of the pressure vessel activated the automatic pump shut-down. The sample did not rupture.

Malfunction of the pumps controlling confining stress and axial stress in GD1-32 caused fluctuations in stress levels, which in turn affected strain levels. As a result, the exponential-time model fit was not made. An approximate steady-state creep rate was estimated by fitting straight lines through the axial strain data by judgement from 90 to 170 hours, 240 to 390 hours, and 490 to 750 hours, calculating the slopes for these intervals, then dividing by 1.2 to approximate total strain.

**Creep test GD1-34.** The data for this test are shown on Figure B-44. The duration of the test was approximately 80 hours. The test was terminated prematurely at a low stress difference, possibly because of a pump malfunction. However, when the sample was disassembled it was ruptured, suggesting that premature sample failure may have terminated the test.

The LVDT readings were erratic throughout the duration of the test. As a result, creep parameters were not calculated using the exponential-time fit.

Steady-state strain rates were calculated by fitting a straight line through the axial strain data from 30 to 75 hours and calculating the slope. The total (LVDT) steady-state strain rate was approximated by dividing this value by 1.2.

**Creep test GD1-35.** The data for this test are shown on Figure B-45. The duration of the test was approximately 330 hours. The test was terminated prematurely either because of failure in a weak area of the sample or because of a pump malfunction.

The LVDT did not function properly during much of the test, so total strain data were simulated by dividing axial strain measurements by 1.2. These simulated LVDT data were used as input data for the creep modeling program. The first two unloading stages of test GD1-35, denoted GD1-35A and GD1-35B, were used to model the creep data. The creep data and the model fit
NOTES
1. TEST TEMPERATURE = 72 DEG F = 22 DEG C
2. SAMPLE TOP DEPTH = 3325.5 FT BELOW RIG DATUM
3. SWITCHED AXIAL AND CELL PRESSURE PUMPS AT 272 HRS
4. METRIC CONVERSIONS: 1000 PSI = 6.9 MPA; 1 FT = 0.305 M
CONFINING STRESS (CELL PRESSURE)

AXIAL STRAIN GAUGES

TOTAL (LVDT) STRAIN

STRESS DIFFERENCE

CIRCUMFERENTIAL STRAIN GAUGES

ELAPSED TEST TIME, HOURS

STRAIN, %

0.0

0.5

1.0

1.5

2.0

0

25

50

75

100

NOTES

1. TEST TEMPERATURE = 72 DEG F = 22 DEG C
2. SAMPLE TOP DEPTH = 3327.5 FT BELOW RIG DATUM
3. TOTAL (LVDT) STRAIN ERRATIC DURING TEST
4. METRIC CONVERSIONS: 1000 PSI = 6.9 MPA; 1 FT = 0.305 M
NOTES
1. TEST TEMPERATURE = 72 DEG F = 22 DEG C
2. SAMPLE TOP DEPTH = 3328.8 FT BELOW RIG DATUM
3. TOTAL (LVDT) STRAIN ERRATIC FROM 130 TO 310 HOURS
4. METRIC CONVERSIONS: 1000 PSI = 6.9 MPA; 1 FT = 0.305 M
for stages GD1-35A and GD1-35B are shown on Figures B-46 and B-47. Zero strain and zero time were taken when the stress level for the unloading stage was reached, removing the unloading portion of each creep stage.

Creep test GD1-73. The data for this test, which had a duration of approximately 555 hours, are shown on Figure B-48. This test consisted of four unloading stages: GD1-73A, -73B, -73C, and -73D. Total strain for each unloading stage was used as the input data for the creep modeling program. As in test GD1-35, the unloading portion of the data was removed and the strain and elapsed time were corrected to zero strain and zero time. The creep data and the model fit for GD1-73A, -73B, -73C, and -73D are shown on Figures B-49 through B-52.

Creep test GD1-132. The data for this test are shown on Figure B-53. GD1-132 was an elevated temperature test conducted at 100 degrees C. The test lasted approximately 122 hours and was terminated prematurely because of a membrane leak. The data were plotted using an expanded strain scale because the maximum axial strain achieved on this test was only 0.5 percent. An exponential-time model fit to the data was not attempted because the data were erratic at low stress levels prior to termination.

Creep test GD1-133. The data for this test, conducted at 50 degrees C, are shown on Figure B-54. The test lasted approximately 1,445 hours and was terminated when total strain exceeded 10 percent. The deviations in stress difference and confining pressure were somewhat greater than in some of the other tests. The last stage of this test was much longer than in the previous tests because a new pump system had been developed and was being tested.

Test GD1-133 consisted of four unloading stages: GD1-133A, -133B, -133C, and -133D. Total strain for each unloading stage was used as input data for the exponential-time modeling program. As in test GD1-35, the unloading portion of the test was removed. Starting values of strain and elapsed time were corrected to zero strain and zero time. The creep data and the model fit for GD1-133A, -133B, -133C, and -133D are shown on Figures B-55 through B-58.
LABORATORY CREEP TESTS
BOREHOLE GD-1
SECOND UNLOAD STAGE GD1-35

GD1-35B

\[ \dot{\varepsilon}_s = 4.4 \times 10^9 \text{sec}^{-1} \]
\[ \varepsilon_a = 2.9 \times 10^{-3} \]
\[ \dot{\xi} = 6.2 \times 10^{-6} \text{sec}^{-1} \]
NOTES
1. TEST TEMPERATURE = 72 DEG F = 22 DEG C
2. SAMPLE TOP DEPTH = 3309.8 FT BELOW RIG DATUM
3. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa; 1 FT = 0.305 M
FIRST UNLOAD STAGE GD1-73
LABORATORY CREEP TESTS
BOREHOLE GD-1

LOG 1026
REV 0-4/2/82
Project No. 16000
Woodward-Clyde Consultants
Figure 8-49

SECOND UNLOAD STAGE GD1-73
LABORATORY CREEP TESTS
BOREHOLE GD-1

LOG 1027
REV 0-4/2/82
Project No. 16000
Woodward-Clyde Consultants
Figure 8-50
THIRD UNLOAD STAGE GD1-73
LABORATORY CREEP TESTS
BOREHOLE GD-1

FOURTH UNLOAD STAGE GD1-73
LABORATORY CREEP TESTS
BOREHOLE GD-1
NOTES:
1. TEST TEMPERATURE = 212 DEG F = 100 DEG C
2. SAMPLE TOP DEPTH = 3313.5 FT BELOW RIG DATUM
3. STRAIN GAUGES ERRATIC; MEMBRANE LEAK AT 122 HRS
4. METRIC CONVERSIONS: 1000 PSI = 6.9 MPA; 1 FT = 0.305 M
NOTES

1. TEST TEMPERATURE = 122 DEG F = 50 DEG C
2. SAMPLE TOP DEPTH = 3314.2 FT BELOW RIG DATUM
3. CIRCUMFERENTIAL STRAIN APPEARS LOW
4. METRIC CONVERSIONS: 1000 PSI = 6.9 MPa; 1 FT = 0.305 M
FIRST UNLOAD STAGE GD1–133
LABORATORY CREEP TESTS
BOREHOLE GD–1

LOG 1030
REV 0–4/2/82
Woodward-Clyde Consultants
Figure 8–56

SECOND UNLOAD STAGE GD1–133
LABORATORY CREEP TESTS
BOREHOLE GD–1

LOG 1031
REV 0–4/2/82
Woodward-Clyde Consultants
Figure 8–56