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Laboratory Evaluation of Damage Criteria and Creep Parameters of Tioga Dolomite and Rock Salt from Cavern Well No. 1

Moo Y. Lee and Brian Ehgartner

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Laboratory Evaluation of Damage Criteria and Creep Parameters of Tioga Dolomite and Rock Salt from Cavern Well No. 1.

Moo Y. Lee
Geomechanics Department

and

Brian Ehgartner
Underground Storage Technology Department

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-07310706

ABSTRACT

A suite of laboratory triaxial compression and triaxial steady-state creep tests provide quasi-static elastic constants and damage criteria for bedded rock salt and dolomite extracted from Cavern Well No.1 of the Tioga field in northern Pennsylvania. The elastic constants, quasi-static damage criteria, and creep parameters of host rocks provides information for evaluating a proposed cavern field for gas storage near Tioga, Pennsylvania. The Young's modulus of the dolomite was determined to be 6.4 ($\pm$1.0) $\times 10^6$ psi, with a Poisson's ratio of 0.26 ($\pm$0.04). The elastic Young's modulus was obtained from the slope of the unloading-reloading portion of the stress-strain plots as 7.8 ($\pm$0.9) $\times 10^6$ psi. The damage criterion of the dolomite based on the peak load was determined to be $J_2^{\ 0.5}$ (psi) = 3113 + 0.34 I_1 (psi) where I_1 and J_2 are first and second invariants respectively. Using the dilation limit as a threshold level for damage, the damage criterion was conservatively estimated as $J_2^{\ 0.5}$ (psi) = 2614 + 0.30 I_1 (psi). The Young's modulus of the rock salt, which will host the storage cavern, was determined to be 2.4 ($\pm$0.65) $\times 10^6$ psi, with a Poisson's ratio of 0.24 ($\pm$0.07). The elastic Young's modulus was determined to be 5.0 ($\pm$0.46) $\times 10^6$ psi. Unlike the dolomite specimens under triaxial compression, rock salt specimens did not show shear failure with peak axial load. Instead, most specimens showed distinct dilatancy as an indication of internal damage. Based on dilation limit, the damage criterion for the rock salt was estimated as $J_2^{\ 0.5}$ (psi) = 704 + 0.17 I_1 (psi). In order to determine the time dependent deformation of the rock salt, we conducted five triaxial creep tests. The creep deformation of the Tioga rock salt was modeled based on the following three-parameter power law as $e_s = 1.2 \cdot 10^{-17} \sigma^{4.75} \exp(-6161/T)$, where e_s is the steady state strain rate in s^{-1}, σ is the applied axial stress difference in psi, and T is the temperature in Kelvin.

ACKNOWLEDGEMENTS

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1. Introduction

In the interest of providing safe, reliable, and economical supplies of natural gas to northeastern U.S., Market Hub Partners (MHP) is planning to build a natural gas storage facility in bedded salt near Tioga, Pennsylvania. The cavern field will be located in the Salina Salt Formation, which is overlain by dolomite layers, and the Oriskany sandstone. The Oriskany is a depleted gas reservoir currently being used to store gas.

Twelve triaxial tests for each rock type and six creep tests for the rock salt were conducted to determine the elastic and fracture responses of the dolomite and rock salt and to determine the steady-state creep parameters for the salt. Table 1 shows the test matrix for two different types of laboratory tests outlined in this report. The objectives of the laboratory experiments were to:

1) characterize elastic constants (Young's modulus and Poisson's ratio) which best represent the properties of dolomite and rock salt using triaxial compression tests,
2) describe the damage criteria of dolomite and rock salt represented by the invariant model,
3) estimate the time dependent deformation of the rock salt.

The detailed geological descriptions of the core and sample locations can be found in Appendix A. The grey dolomite appears to be organic rich and locally shaly. Very thin beds of anhydrite are common. The Tioga rock salt (or halite) has well-developed cleavage. The rock salt is generally light gray and coarser grained at the top and progressively gets finer grained and darker with depth. The salt gets darker because of a decrease in grain size and more importantly a change from predominately gray dolomite / anhydrite impurities to a predominantly black shale insoluble content. Although there is some insoluble material within salt grains, the bulk of the insoluble material is attenuated between the grains at or near the grain boundaries (K. Looff, 2001).

The laboratory experimental data provide the quasi-static mechanical properties and creep behavior of the host rocks necessary for the design, construction and operation of the future gas storage caverns.

Table 1. Planned test matrix and sample locations for the laboratory testing of Tioga dolomite and rock salt from Cavern Well No. 1, Pennsylvania.

Test no.	Rock type	Depth (ft)	Sample diameter (inch)	Sample length (inch)	Test type
MHP-DT2	Dolomite	4448	1.871	3.950	TC
MHP-DT3	Dolomite	4466	1.870	4.194	TC
MHP-DT6	Dolomite	4466	1.873	4.180	TC
MHP-DT12	Dolomite	4467	1.874	4.188	TC
MHP-DT1	Dolomite	4468	1.870	3.856	TC
MHP-DT7	Dolomite	4468	1.872	3.857	TC
MHP-DT10	Dolomite	4469	1.877	3.985	UC
MHP-DT11	Dolomite	4469	1.875	3.932	UC
MHP-DT8	Dolomite	4471	1.875	4.063	TC
MHP-DT9	Dolomite	4471	1.875	4.170	TC
MHP-DT4	Dolomite	4472	1.871	4.202	TC
MHP-DT5	Dolomite	4472	1.873	4.296	TC
MHP-ST11	Rock Salt	4568	3.960	8.030	UC
MHP-ST3	Rock Salt	4569	3.962	7.940	TC
MHP-ST10	Rock Salt	4570	3.960	7.730	TC
MHP-ST7	Rock Salt	4572	3.960	7.967	TC
MHP-ST8	Rock Salt	4573	3.965	7.996	TC
MHP-ST9	Rock Salt	4577	3.960	7.890	TC
MHP-ST1	Rock Salt	4578	3.970	8.020	TC
MHP-ST4	Rock Salt	4580	3.968	7.905	TC
MHP-ST5	Rock Salt	4582	3.962	7.858	TC
MHP-ST6	Rock Salt	4584	3.945	8.017	TC
MHP-ST12	Rock Salt	4804	3.970	7.940	UC
MHP-ST2	Rock Salt	4805	3.978	8.015	TC
A3MHP05	Rock Salt	5568	3.980	7.972	C
A1MHP01	Rock Salt	5580	3.983	8.059	C
A1MHP04	Rock Salt	5591	3.876	8.025	C
A3MHP03	Rock Salt	5596	3.925	7.981	C
A2MHP02	Rock Salt	5639	3.981	8.026	C

TC- Triaxial Compression

UC-Uniaxial Compression

C-Creep Test

2. Sample Preparation and Test Methods

2.1 Quasi-static triaxial compression tests

The extracted core (Figure 1) from Cavern Well (CW) No. 1, Tioga site was prepared in the form of right circular cylinders with nominal dimensions of 1.9 inch in diameter and 4 inch in length for dolomite and 4 inch in diameter and 8 inch in length for rock salt. The dimensions fall within the range of length-to-diameter ratio (2 to 2.5) recommended in ASTM D4543 ("Standard Practice for Preparing Rock Core Specimens and Determining Dimensional and Shape Tolerances"). The ends of the specimen were ground flat within 10^{-3} inch tolerance. Samples were visually inspected for significant flaws and general straightness of circumferential surfaces.

Figure 1. Extracted dolomite (left) and rock salt (right) cores from Cavern Well No.1, Tioga site.

Two axial strain gages were mounted on opposite sides of the specimen (180° apart) at mid-height and two circumferential gages were mounted at mid-height around the circumference perpendicular to the longitudinal axis of the specimen. Figure 2 shows the dolomite specimen instrumented with strain gages. The instrumented specimen was placed between upper and lower cylindrical end-caps with the same diameter as the rock specimen.

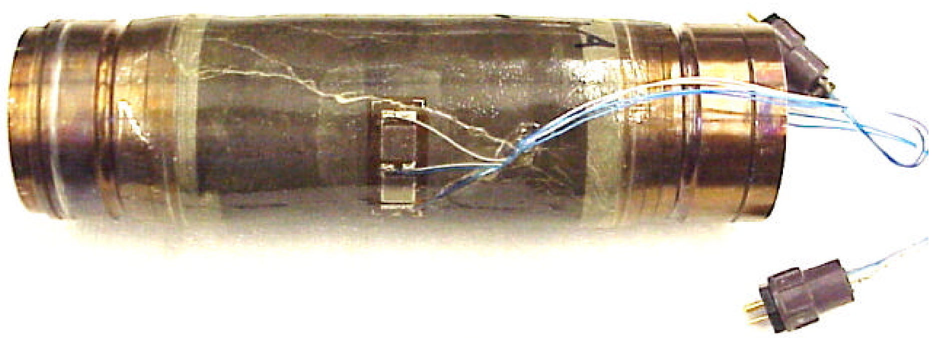


Figure 2. The assembled dolomite specimen MHP-DT1 with strain gages and cylindrical end-caps.

Then, the specimen assembly was coated with approximately 1/16 inch thick impervious polyurethane membrane (see Figure 2). To maintain uniform thickness of the membrane during curing the specimen assembly was turned on a lathe along the axial centerline of the assembly. The flexible membrane allowed the confining pressure to be applied hydrostatically on the specimen and at the same time prevents the confining fluid from infiltrating into the specimen.

After the flexible membrane was cured the instrumented specimen assembly was placed in a triaxial pressure vessel capable of operating at confining pressures up to 70,000 psi. The vessel was also equipped with 12 coaxial feed-throughs for transmitting data from the strain gages to the data acquisition system. Triaxial compression tests were conducted in a 1 million lb. servo-controlled loading machine shown in Figure 3. After the specimen assembly was placed in the pressure vessel, hydraulic pressure was applied to a prescribed level of confining pressure, P. Table 2 shows the prescribed level of confining pressure for each test. The servo-controlled system controlled hydrostatic pressure ($\sigma_1=\sigma_2=\sigma_3=P$ where σ_1,σ_2, and σ_3 are the maximum, intermediate, and minimum principal stresses, respectively). After the confining pressure, P, was stabilized, the specimen was loaded axially at a constant displacement rate of 4×10^{-5} inch/s which corresponds to a strain rate of 10^{-5} /s. During testing, seven channels of data including time, axial load, axial stroke, axial strains from gages, and lateral strains from two gages, were recorded using a DATAVG-event triggered data acquisition program (Hardy, 1993). The experimental apparatus used for the compression tests meets or exceeds the requirements of ASTM2664 for the triaxial compression tests.

For dolomite specimens, the axial load was increased until the peak load, P_p, was reached. The compressive strength of the rocks was calculated from

$$C_o=P_p/\pi r^2$$

where C_o is the compressive strength of the rock in psi; P_p is the peak load in lbs.; and r is the radius of the specimen in inches.

The two fundamental properties to describe the stress-strain behavior of the rock are the Young's modulus, E, and Poisson's ratio, ν. The proportional constant between stress and strain in the elastic portion of compression tests defines the Young's modulus:

$$E = \sigma_a / \varepsilon_a$$

where σ_a is the axial stress and ε_a is the axial strain. The Young's modulus was determined using least square fits of a straight line (or linear regression analysis) to the stress strain data ranging in the interval from 10 to 50% of the peak stress. When approximately 50% of the expected peak load, P_p, was reached, unloading and reloading cycles were carried out. Reversibility of deformation was usually observed during unloading and reloading cycles if the stress level was below the yield stress. Therefore, we may calculate the modulus of elasticity due only to the elastic deformation of the specimen from the slope of the unloading curves. Linear regression analysis was also used to obtain the best-fit straight line to the unloading curve.

The other important elastic constant is the Poisson's ratio defined as the ratio between the axial, ε_a, and lateral, ε_l, strains:

$$\nu = |\varepsilon_l| / |\varepsilon_a|$$

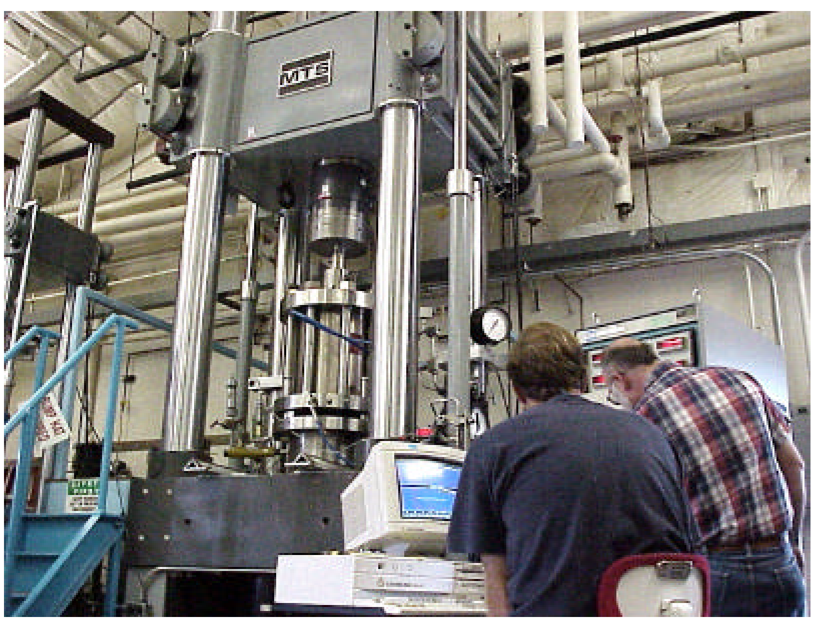


Figure 3. Triaxial compression test set-up with 1 million lb. load frame and 70,000 psi pressure vessel.

When the rock is loaded it initially compresses elastically (plastic strains do not affect the volume of the rock). As deviatoric stress is further incremented, for some stress states, microfracturing becomes prominent and the volumetric strain deviates from elastic compression. In fact, the rock volume will increase under certain stress conditions. The onset of dilatancy can be defined in several ways, however, for consistency with the literature (Mellegard and Pfeifle, 1994), it will be defined as the point at which the rock reaches its minimum volume (or dilation limit). The stress state corresponding to the dilation limit can be described by two stress invariants: I_1, the first invariant of the Cauchy stress tensor, and J_2, the second invariant of the deviatoric stress tensor. In terms of the principal stresses the two invariants are defined as follows:

$$I_1 = \sigma_1+\sigma_2+\sigma_3$$
$$J_2=\{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\} / 6$$

where σ_1, σ_2 and σ_3 are the maximum, intermediate, and minimum principal stresses, respectively.

2.2 *Steady-state triaxial creep tests*

In order to determine the time-dependent deformation of the rock salt from the Tioga field, five creep tests were conducted using the Sandia creep machine shown in Figure 4. As in the triaxial compression test, a right circular cylindrical specimen (4 inch in diameter and 8 inch in length nominally) was prepared according to ASTM D4543. Two strain gages were mounted along the longitudinal axis of the specimen 180° apart. The specimen was placed between the cylindrical end-caps and encapsulated in an impermeable viton jacket. Figure 5 shows the A1MHP01 rock salt specimen before and after the jacket is applied.

First, the specimen assembly was placed in the pressure vessel and was loaded to a hydrostatic pressure equal to the confining pressure. After the confining pressure is stabilized, the specimen was heated in the pressure vessel to a prescribed level. The predetermined levels of confining pressure and the temperature for each specimen are shown in Table 2. Finally, the axial stress was increased to create the stress condition with constant confining pressure and prescribed axial stress difference. Axial strains are measured by two axial strain gages. As a back up, a linear displacement transducer (LVDT) was mounted to measure the axial displacement of the piston as it enters the pressure vessel. The deformation measured by the LVDT consists of displacements from both the specimen and the steel end-caps. The test conditions (confining pressure, axial stress difference, and specimen temperature) were maintained throughout the duration of the test.

The response surface of the strain rate over the space of stress and temperature is based on the following empirical power law (Dorn, 1957):

$$e_s = C\sigma^n \exp(-Q/RT)$$

where $\dot{\varepsilon}_s$ = Steady state strain rate

C = Constant

σ = Applied axial stress difference in psi

n = Stress exponent

Q = Activation energy

R = Gas constant

T = Temperature in Kelvin

To determine the response surface defined by three unknown parameters of this equation, *C*, *n* and Q/R, the steady state strain rate must be determined for each test stage.

Figure 4. Sandia National Laboratories creep machine.

Figure 5. Rock salt specimen A1MHP01 with and without an impermeable viton jacket. Strain gages were used to measure deformation of the rock salt.

3. Laboratory Test Results

3.1 Compressive strengths and elastic constants

Twelve dolomite and twelve rock salt specimens from Cavern Well No. 1, Tioga field were tested to obtain elastic constants, E and ν, and damage criteria. Figure 6 shows the failed dolomite specimens retrieved after reaching a peak load. Dolomite specimens failed under confining pressure showed a well-defined single shear failure surface whereas specimens fractured under uniaxial compression showed multiple splitting fractures parallel to the longitudinal axis of the specimen.

Figure 7 shows rock salt specimens retrieved after uniaxial and triaxial compression tests. Unlike the brittle failure shown in dolomite specimens, the rock salt specimens exhibited strain hardening ductile deformation without reaching the peak load associated with the brittle failure of the specimen even after undergoing more than 3 % strain. Stress vs. strain plots for all triaxial compression tests are given in Appendices B (dolomite) and C (rock salt) and the results are summarized in Table 2.

Unconfined compressive strength of the dolomite is determined to be approximately 15,100 psi and the strength increases as the confining pressure increases. The Young's modulus of dolomite was determined to be 6.4 (±1.0) $\times$ 10^6 psi, with a Poisson's ratio of 0.26 (±0.04). The Young's modulus of rock salt was determined to be 2.4 (±0.65) $\times$ 10^6 psi, with a Poisson's ratio of 0.34 (±0.23). The large standard deviation is a result from two unconfined compression tests shown in Table 2. If we consider these two results as outliers, then the average Poisson's ratio becomes 0.24 (±0.07).

To obtain the elastic Young's modulus, $E_{elastic}$, of the rock, we conducted unloading and reloading cycles during the compression tests. Figures 8 through 10 show examples of unloading and reloading cycles. We calculated the $E_{elastic}$ from the slope of the unloading curve. Table 2 and Figure 9 shows the modulus of elasticity due only to the elastic deformation of the specimen.

The elastic Young's modulus was approximately as 7.8 ($\pm$0.9) $\times 10^6$ psi for dolomite and 5.0 ($\pm$0.5) $\times 10^6$ psi for rock salt, respectively. For the dolomite, $E_{elastic}$ was approximately 20 % higher than E determined from the slope of the virgin loading curve. For the rock salt, $E_{elastic}$ was approximately twice as large as E, suggesting that a large portion of deformation for the rock salt is not reversible.

Figure 6. Dolomite specimens retrieved after reaching a peak load in the uniaxial (MHP-DT11) and triaxial compression (MHP-DT12) tests. The nominal diameter of the specimen was 1.9 inches.

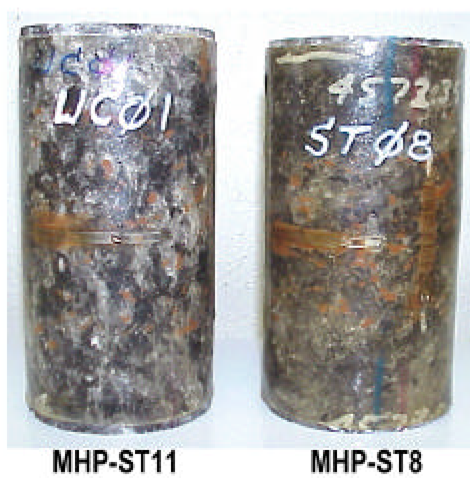


Figure 7. Rock salt specimens retrieved after uniaxial (MHP-ST11) and triaxial compression (MHP-ST8) tests. The specimen did not show failure surfaces after undergoing more than 3% strain. The nominal diameter of the specimen was 4 inches.

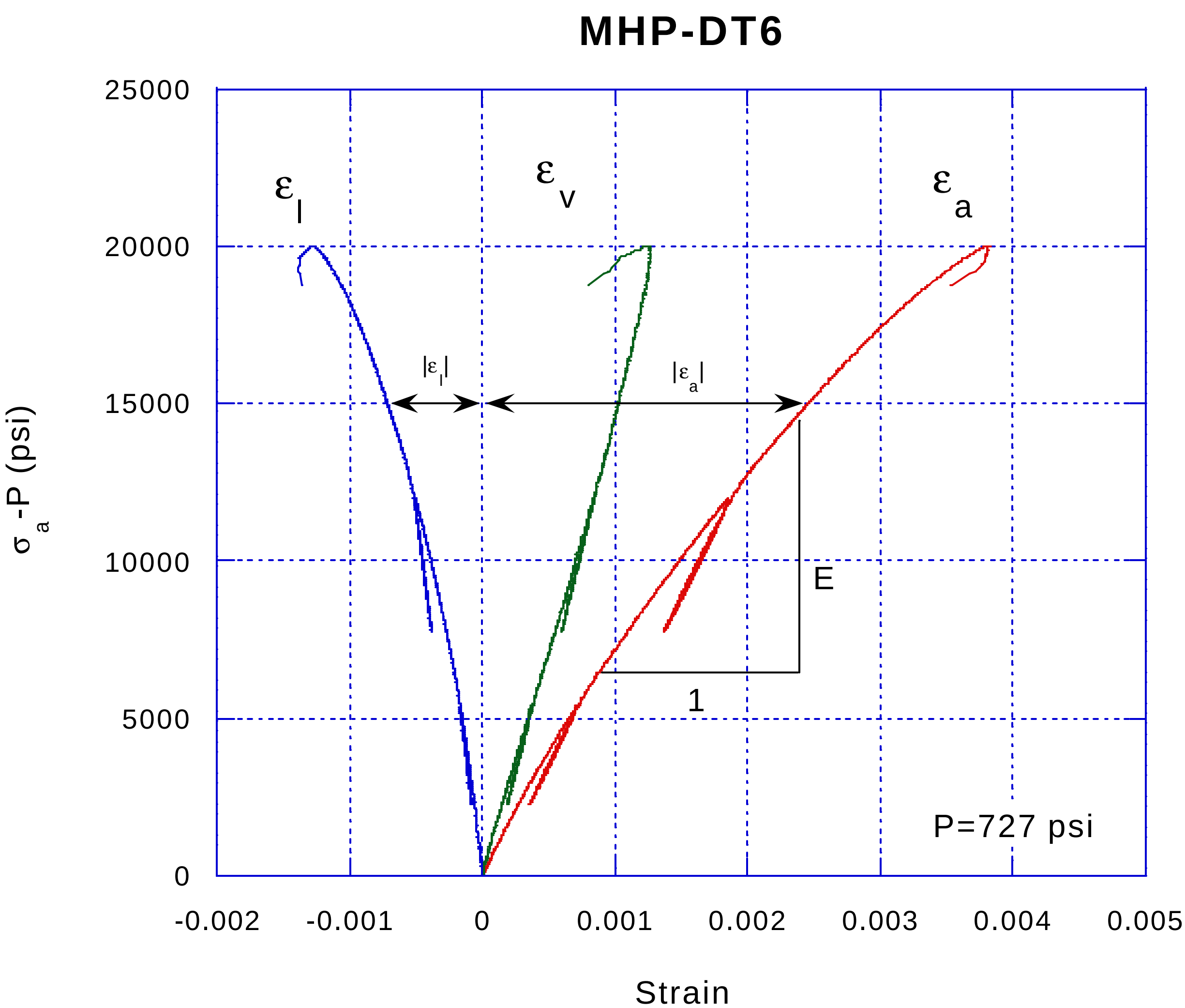


Figure 8. Stress-strain plot obtained during the triaxial compression test for the MHP-DT6 dolomite. The volumetric strain was calculated from the axial and lateral strains. Also shown are the components for elastic constants (Young's modulus E and Poisson's ratio $\nu = |\varepsilon_l| / |\varepsilon_a|$).
See Appendix B for other test records.

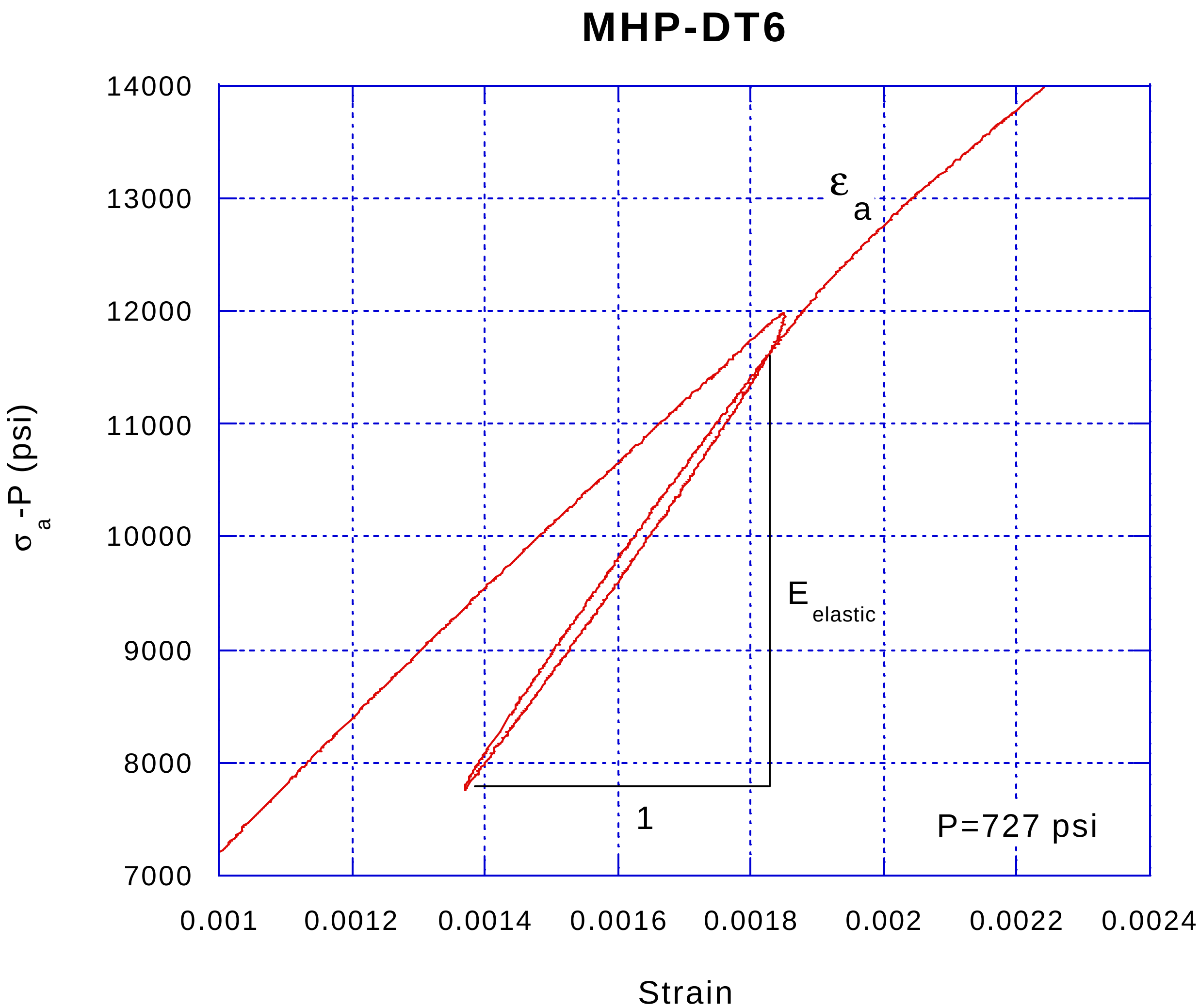


Figure 9. Unloading and reloading portion of the stress-strain plot obtained during the triaxial compression test of the MHP-DT6 dolomite. The elastic portion of the Young's modulus, $E_{elastic}$, was calculated from the slope of the unloading and reloading curves.

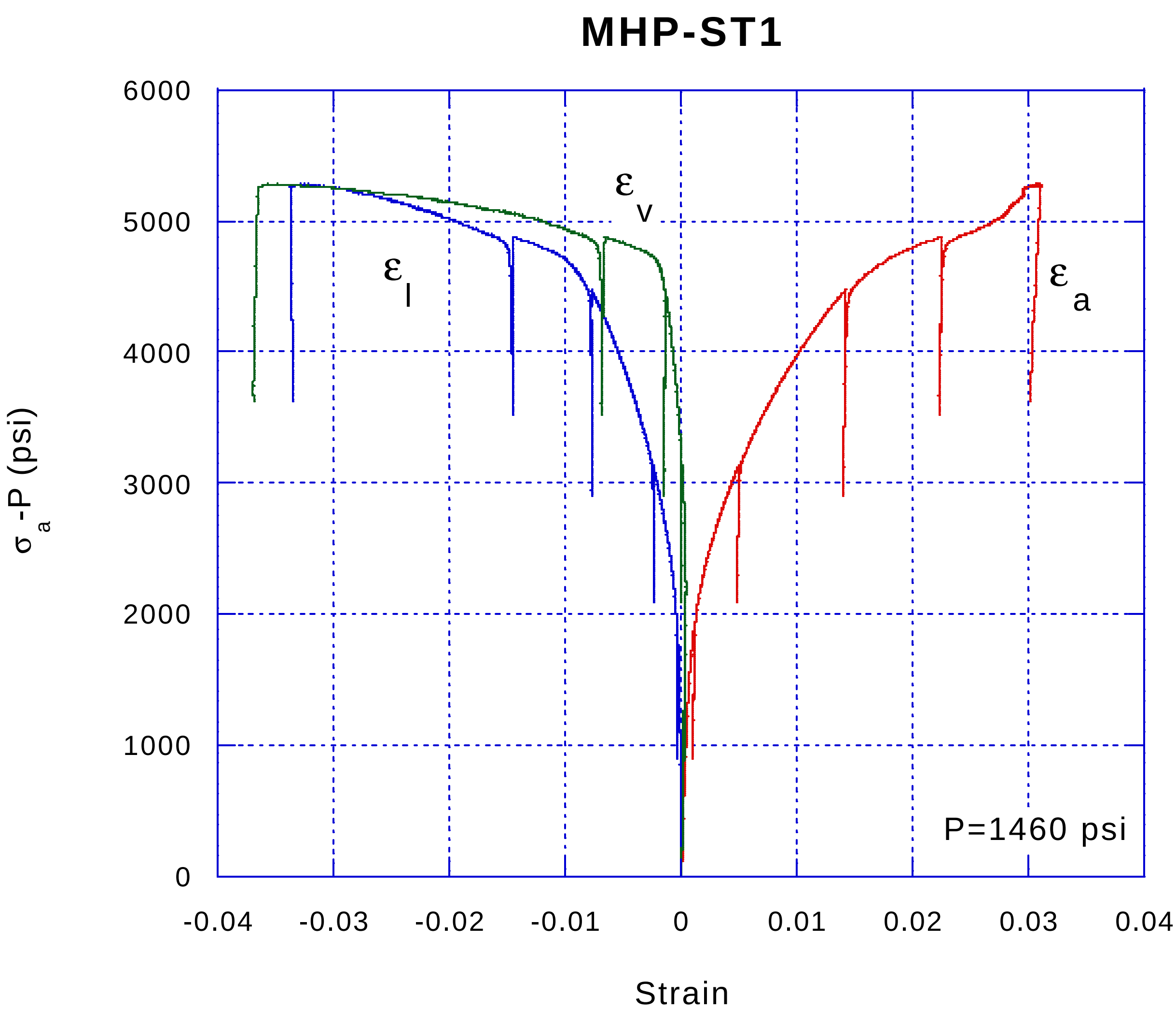


Figure 10. Stress-strain plot obtained during the triaxial compression test of the MHP-ST1 rock salt. The volumetric strain was calculated from the axial and lateral strains. See Appendix C for other test records.

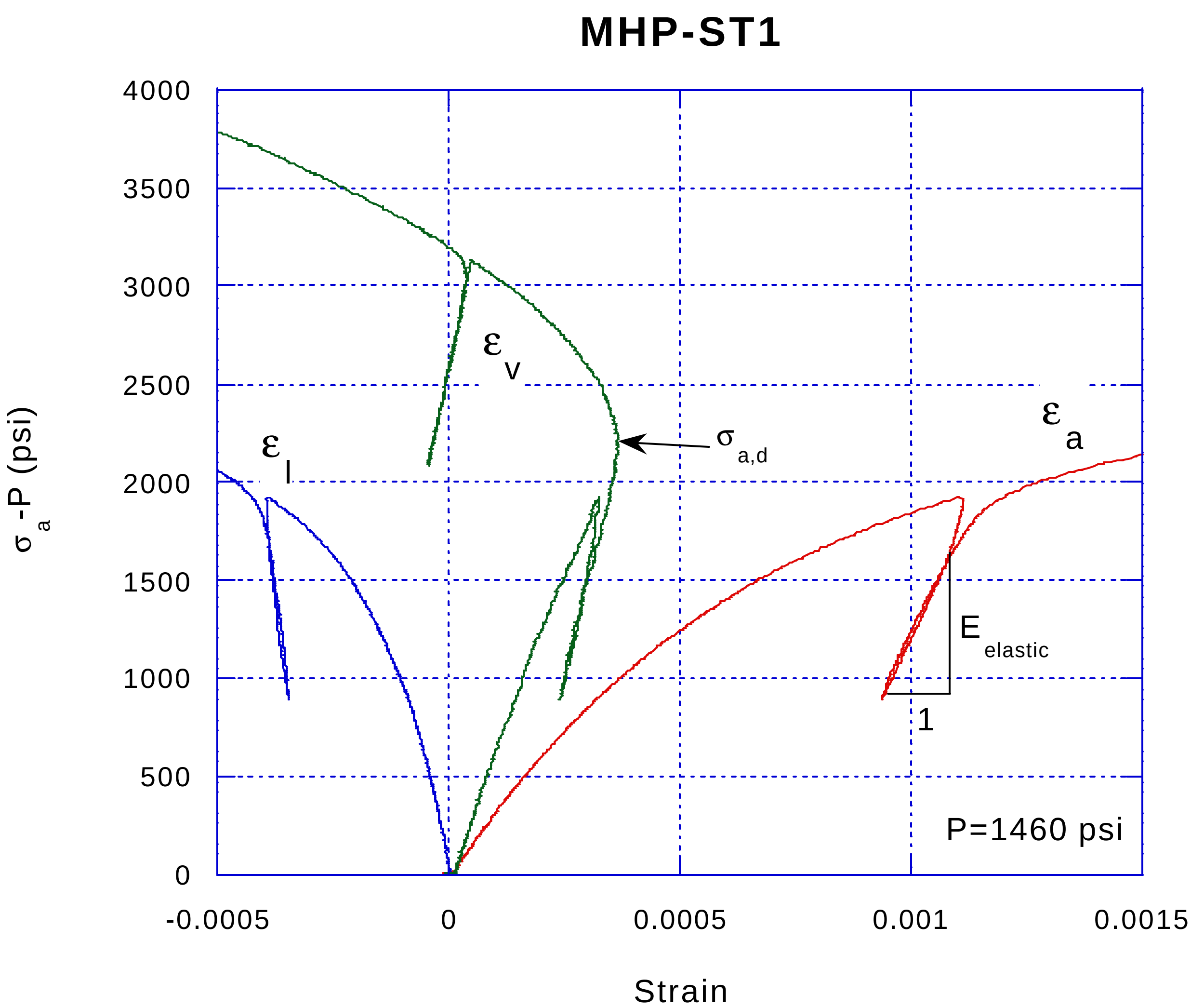


Figure 11. Unloading and reloading portion of the stress-strain plot obtained during triaxial compression test of the MHP-ST1 rock salt. The dilation limit is shown as $\sigma_{a,d}$ in which the volume of the sample reaches the minimum point. The elastic portion of the Young's modulus, $E_{elastic}$, was calculated from the slope of the unloading and reloading curves.

Table 2. Summary of triaxial compression tests of Tioga dolomite and rock salt from Cavern Well No. 1, Pennsylvania.

Specimen no.	Rock type	Sample interval (ft)	Sample diameter (in)	Sample length (in)	P (psi)	$E_{elastic}$ ($\times 10^6$psi)	E ($\times 10^6$psi)	ν	$\sigma_{a,p}$ (psi)	$\sigma_{a,d}$ (psi)	I_1 for $\sigma_{a,p}$ (psi)	$J_2^{0.5}$ for $\sigma_{a,p}$ (psi)	I_1 for $\sigma_{a,d}$ (psi)	$J_2^{0.5}$ for $\sigma_{a,d}$ (psi)
MHP-DT1	Dolomite	4468	1.870	3.856	1450	8.13	6.85	0.31	19929	12500	22829	10669	15400	6380
MHP-DT2	Dolomite	4448	1.871	3.950	1454	7.93	6.43	0.24	25014	NA	27922	13602	NA	NA
MHP-DT3	Dolomite	4466	1.870	4.194	727	6.42	4.79	0.23	14629	NA	16083	8026	NA	NA
MHP-DT4	Dolomite	4472	1.871	4.202	2174	9.44	7.00	0.36	29399	16800	33747	15718	21148	8444
MHP-DT5	Dolomite	4472	1.873	4.296	2180	7.50	5.80	0.27	22043	NA	26403	11468	NA	NA
MHP-DT6	Dolomite	4466	1.873	4.180	727	8.49	6.76	0.26	20749	19800	22203	11560	21254	11012
MHP-DT7	Dolomite	4468	1.872	3.857	2901	7.86	6.27	0.25	25342	NA	31144	12956	NA	NA
MHP-DT8	Dolomite	4471	1.875	4.063	290	7.63	6.61	0.21	13193	11500	13773	7450	12080	6472
MHP-DT9	Dolomite	4471	1.875	4.170	290	8.14	7.24	0.24	15187	NA	15767	8601	NA	NA
MHP-DT10	Dolomite	4469	1.877	3.985	0	7.24	6.38	0.23	15116	NA	15116	8727	NA	NA
MHP-DT11	Dolomite	4469	1.875	3.932	0	8.92	8.20	0.23	15150	NA	15150	8747	NA	NA
MHP-DT12	Dolomite	4467	1.874	4.188	2904	6.17	4.73	0.25	26416	17500	32224	13575	23308	8427
MHP-ST1	Rock Salt	4578	3.970	8.020	1460	5.14	2.25	0.31	NA	3670	NA	NA	6590	1276
MHP-ST2	Rock Salt	4805	3.978	8.015	2160	5.13	2.55	0.15	NA	5110	NA	NA	9430	1703
MHP-ST3	Rock Salt	4569	3.962	7.940	730	5.61	2.11	0.70	NA	NA	NA	NA	NA	NA
MHP-ST4	Rock Salt	4580	3.968	7.905	1450	4.80	2.28	0.15	NA	NA	NA	NA	NA	NA
MHP-ST5	Rock Salt	4582	3.962	7.858	2900	5.28	2.37	0.29	NA	9120	NA	NA	14920	3591
MHP-ST6	Rock Salt	4584	3.945	8.017	730	5.08	2.10	0.21	NA	4450	NA	NA	5910	2148
MHP-ST7	Rock Salt	4572	3.960	7.967	300	4.75	2.29	0.28	NA	2680	NA	NA	3280	1374
MHP-ST8	Rock Salt	4573	3.965	7.996	2190	5.65	2.37	0.26	NA	7260	NA	NA	11640	2927
MHP-ST9	Rock Salt	4577	3.960	7.890	310	4.68	4.17	0.17	NA	2730	NA	NA	3350	1397
MHP-ST10	Rock Salt	4570	3.960	7.730	2900	5.50	2.67	0.28	NA	7400	NA	NA	13200	2598
MHP-ST11	Rock Salt	4568	3.960	8.030	0	4.82	2.38	0.34	NA	1710	NA	NA	1710	987
MHP-ST12	Rock Salt	4804	3.970	7.940	0	4.05	1.28	0.92	NA	NA	NA	NA	NA	NA

$I_1 = \sigma_1 + 2P$; $J_2^{0.5} = [(\sigma_1 - P)^2 / 3]^{0.5}$

$P = \sigma_2 = \sigma_3 =$ confining pressure ; ν (Poisson's ratio) = $| e_l | / | e_a |$

$\sigma_{a,p}$ - peak stress level for failure (psi) ; $\sigma_{a,d}$ – stress for dilation limit (psi)

E (Young's Modulus)= σ_a / ε_a (psi) ; $E_{elastic}$ - elastic Young's modulus obtained from the slope of the unloading curve (psi).

3.2 Damage Criteria in the triaxial compression tests

For purposes of interpreting the results a criterion is needed to evaluate the adequacy of the rock for the storage cavern. In triaxial compression tests, where the axial stress was the major principal stress, σ_1, and the confining pressure P was as σ_2 and σ_3, the mean stress invariant, I_1, and the square root of the deviator invariant, J_2, can be described as,

$$I_1 = \sigma_1 + 2P$$

$$J_2^{\,0.5} = [(\sigma_1 - P)^2 / 3]^{\,0.5}$$

The values of I_1 and $J_2^{\,0.5}$ for different confining pressures are listed in Table 2. During the shear failure of the specimens, the state of stress can be represented as a shear failure envelope represented empirically by the linear equation.

$$J_2^{\,0.5} = A + BI_1$$

where A and B are unknown parameters to be determined for different rock types.

We used a linear regression analysis to determine the unknown parameters that minimized the sum of the squares of errors between the model, predicted values and the observed $J_2^{\,0.5}$ values for different confining pressures. The damage criterion based on the peak stress of the dolomite was represented in terms of invariants:

$$J_2^{\,0.5}\ (\text{psi}) = 3113 + 0.34\ I_1\ (\text{psi})$$

Unlike the brittle failure in dolomite, the rock salt specimens deformed in ductile fashion without the peak stress and significant stress drop immediately following the peak stress. The volumetric strain ($\Delta V/V = \varepsilon_a + 2\varepsilon_l$) was calculated and shown on each plot. Based on the volumetric strain data, dilatancy (volume increase of the specimen due to the creation of new cracks in the specimen) in the triaxial compression tests was observed and considered to be the damage stress for rock salt. As in the dolomite the damage criterion of the rock salt was represented in terms of invariants:

$$J_2^{\,0.5}\ (\text{psi}) = 704 + 0.17\ I_1\ (\text{psi})$$

If we apply the same dilation limit criterion to dolomite, we conservatively estimate the following damage criterion:

$$J_2^{\,0.5}\ (\text{psi}) = 2614 + 0.30\ I_1\ (\text{psi})$$

Figures 12 and 13 summarize the damage criteria obtained for the dolomite and the rock salt.

The figures show that a sufficient number of quasi-static tests have been performed to characterize the damage criteria of Tioga dolomite and rock salt. Also included are previous results from Tioga Well 501 (TW-501).

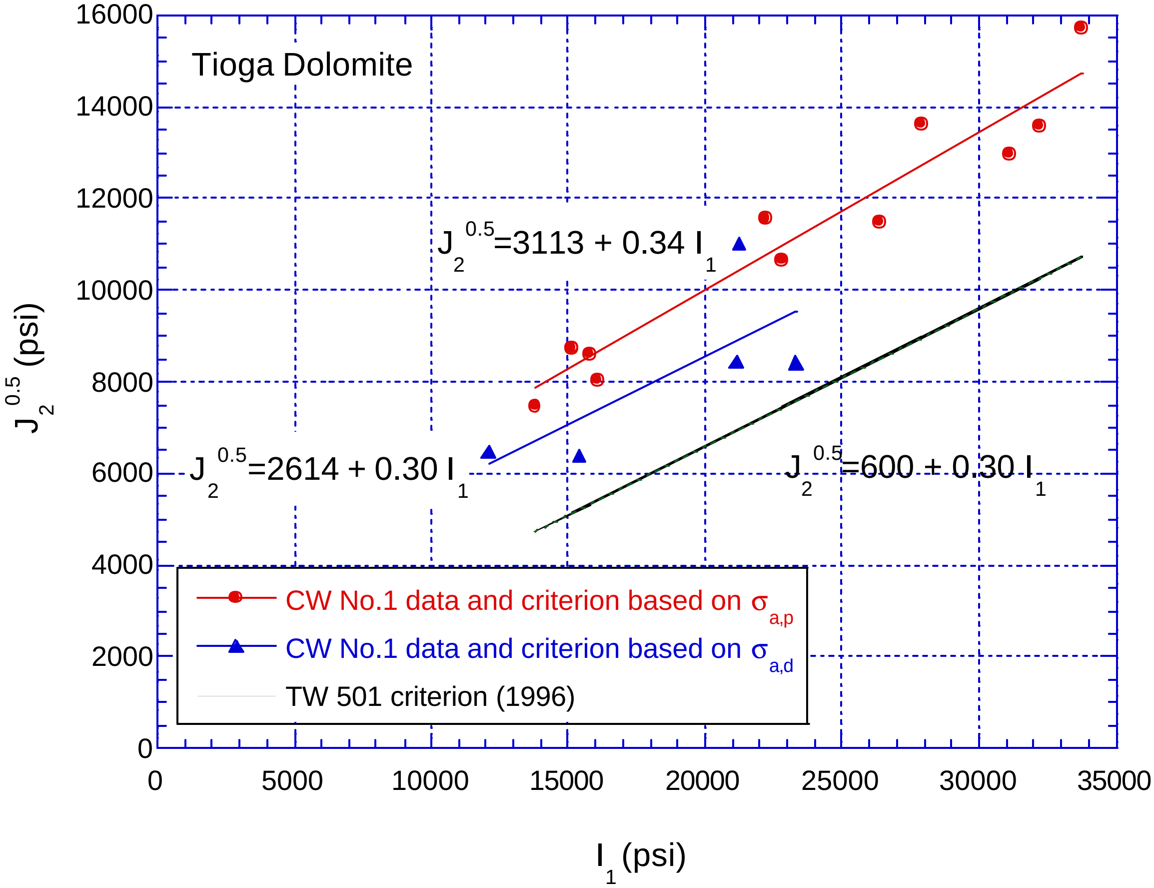


Figure 12. Damage criteria determined by the linear regression analysis of the triaxial compression data for Tioga dolomite (CW-Cavern Well, TW-Tioga Well).

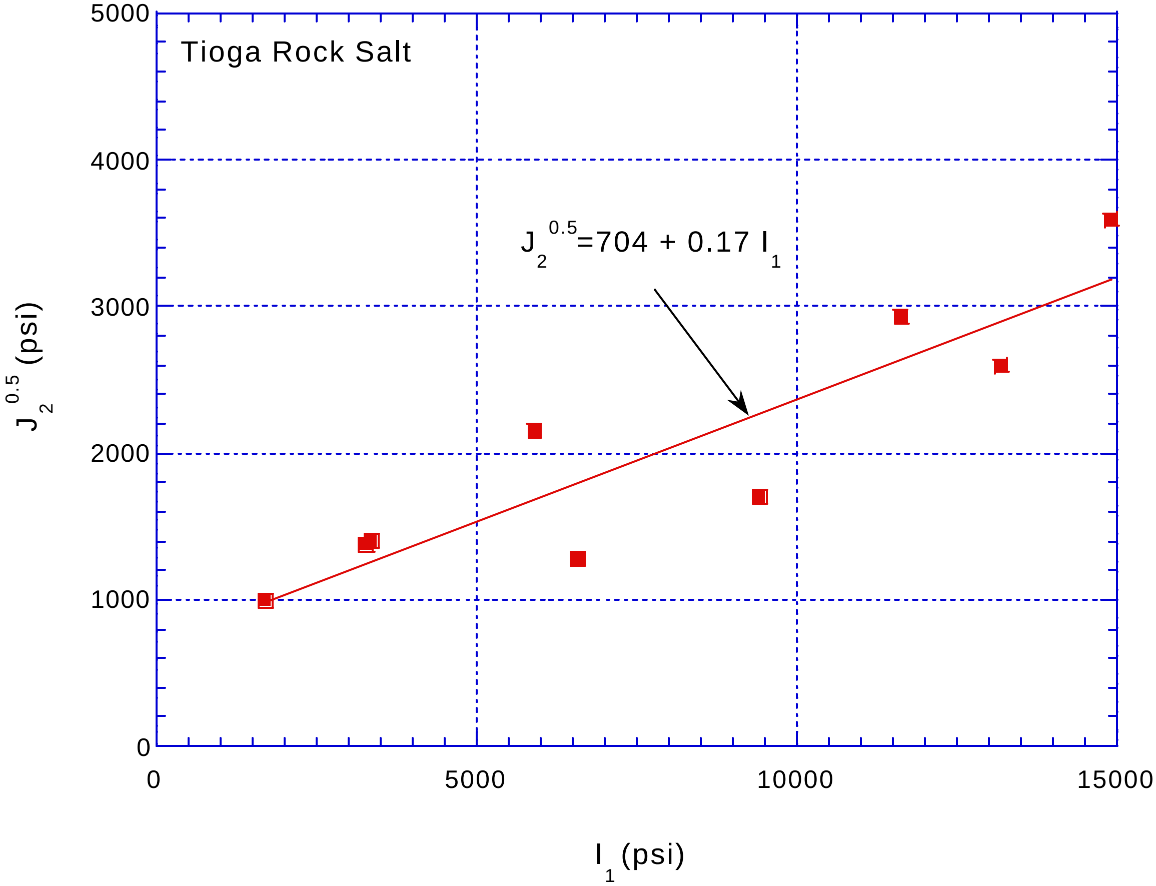


Figure 13. Damage criterion determined by the linear regression analysis of the triaxial compression data for Tioga rock salt.

3.3 Creep Parameters

As shown in Table 3 and Figure 14, the test matrix for steady-state triaxial creep tests was designed to obtain the response surface of strain rate dependency on stress and temperature systematically. As shown in section 2.2 the strain rate was described by three unknown parameters C, n, and Q/R over the space defined by two independent variables of stress difference (σ_1- σ_3) and T. A typical controlled test condition is shown in Figure 15. See Appendix D for other test conditions.

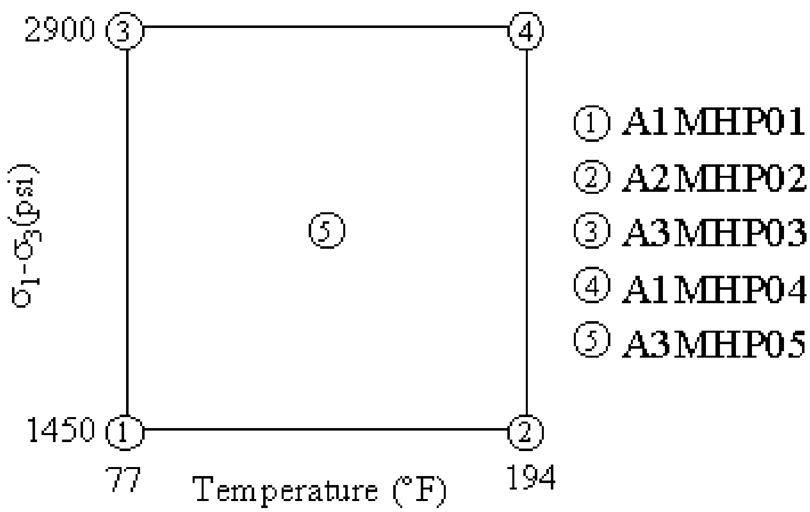


Figure 14. Schematic of an experimental design to obtain the response surface defined by three unknown parameters and two independent variables (σ_1- σ_3 and T) with two levels.

The data obtained from these tests include the steady-state creep rate corresponding to a particular state of stress and a temperature (Figure 16). The test condition was maintained by a feedback system throughout the duration of testing. All tests were performed approximately at 2180 psi confining pressure. Under this test environment we obtained creep data consisting of axial strain vs. time plot. From this plot the strain rate was calculated by differentiating the strains with respect to time (Figure 17). As suggested by the asymptotic trend near the end of the creep test, the steady-state creep rate was reached after approximately 15 days of creep testing. The test results are summarized in Table 3.

In order to determine the creep parameters (C, n, and Q/R) a 'nonlinear regression' technique was used (Appendix E). Nonlinear regression analysis is a technique for fitting an arbitrary function to a given set of data. The procedure determines the best-fit response surface defined by three unknown parameters of the empirical power law. The regression technique considers the entire database at once to solve for the unknown parameters using an iteration procedure to minimize the sum of squares of the error (Draper and Smith, 1981).

The results of the 'nonlinear regression' analysis provide the following relationship for the steady-state strain rate of Tioga rock salt as:

$$e_s = 1.2 \cdot 10^{-17} \sigma^{4.75} \exp(-6161/T)$$

where e_s is steady state strain rate in s^{-1}, σ is applied axial stress difference in psi, and T is temperature in Kelvin.

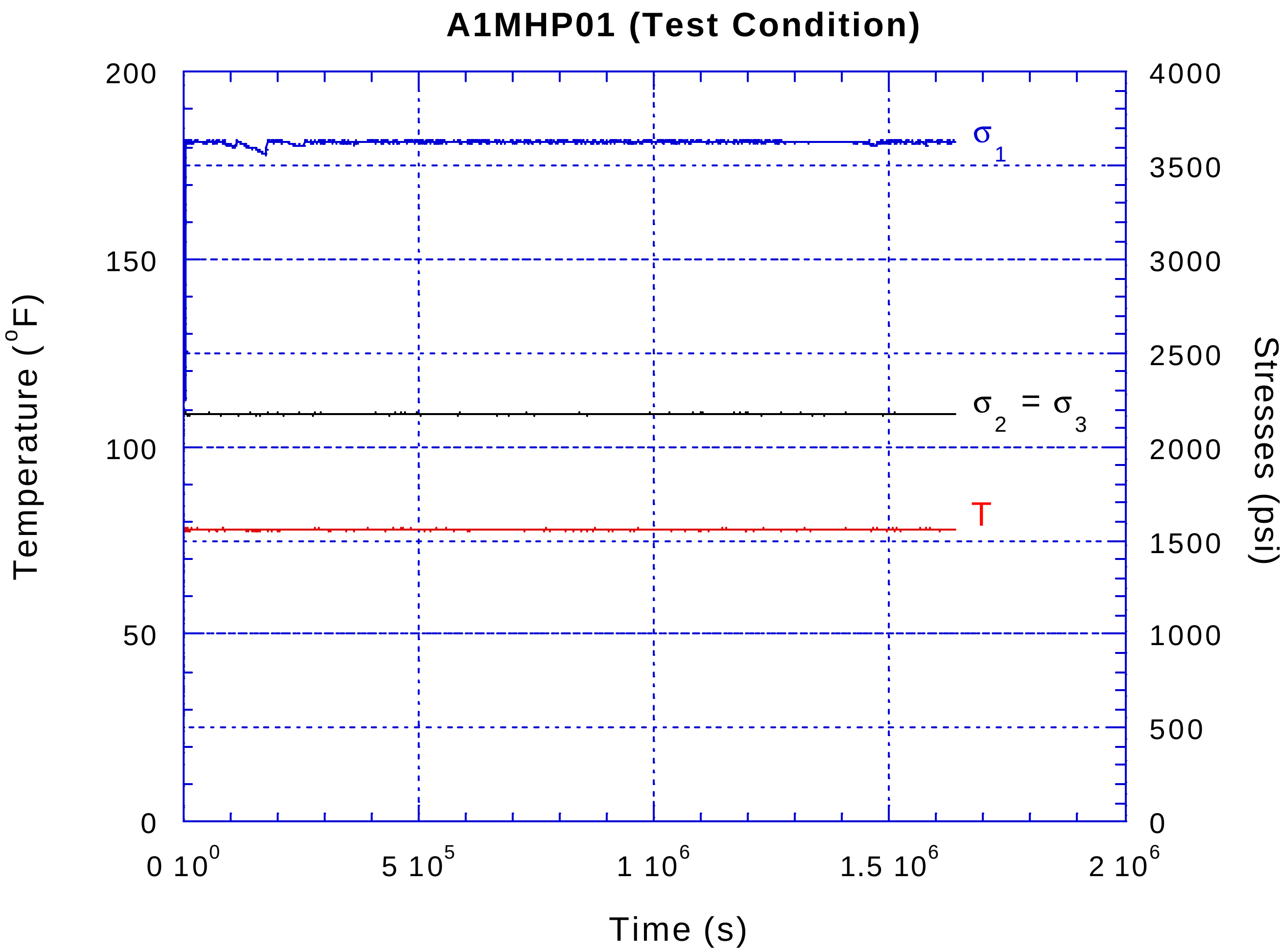


Figure 15. Controlled test condition (temperature T, axial stress σ_1 and confining pressure (σ_2=σ_3) during steady-state creep testing for the A1MHP01 specimen. See Appendix D for other test records

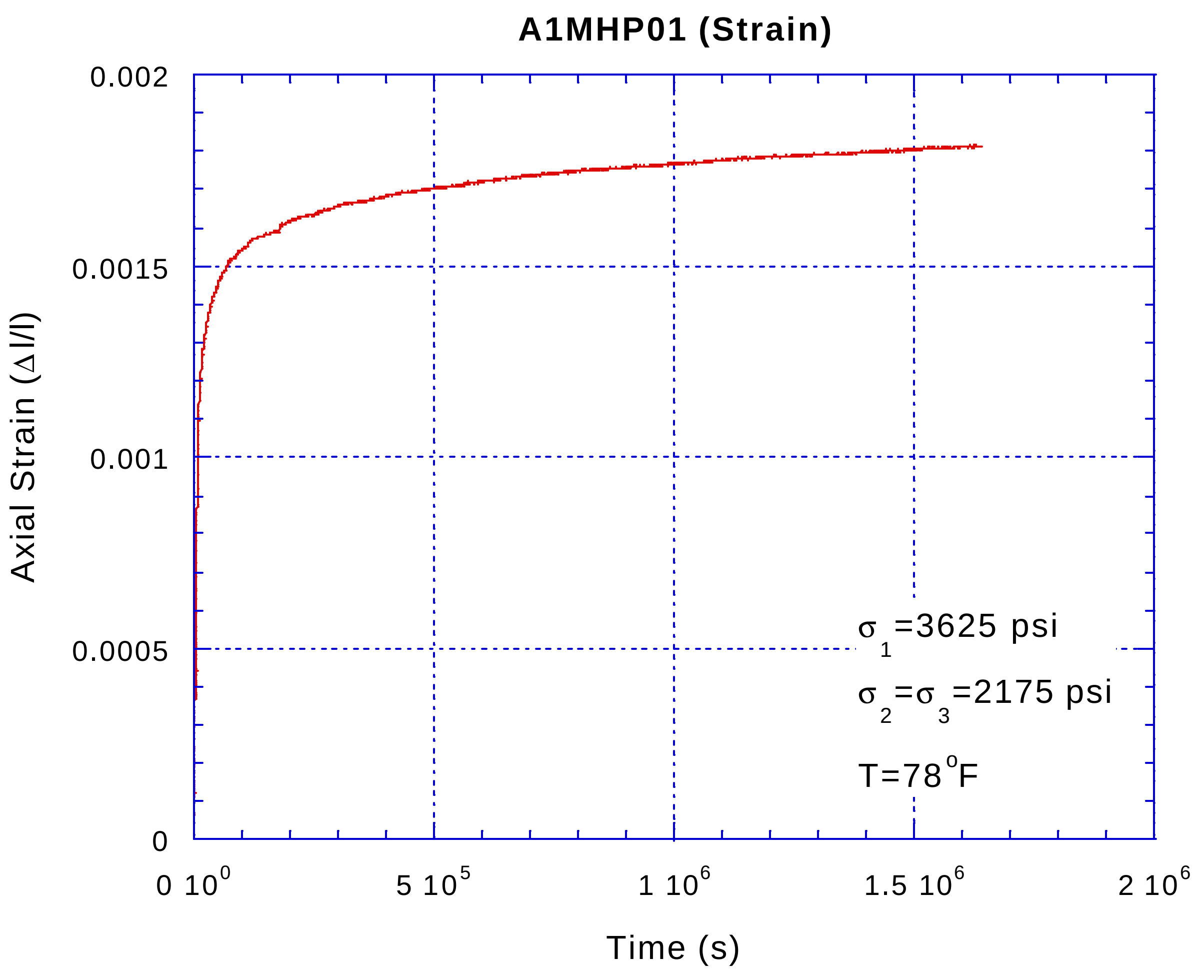


Figure 16. Strain vs. time plot during steady-state creep testing for the A1MHP01 specimen. See Appendix D for other test records

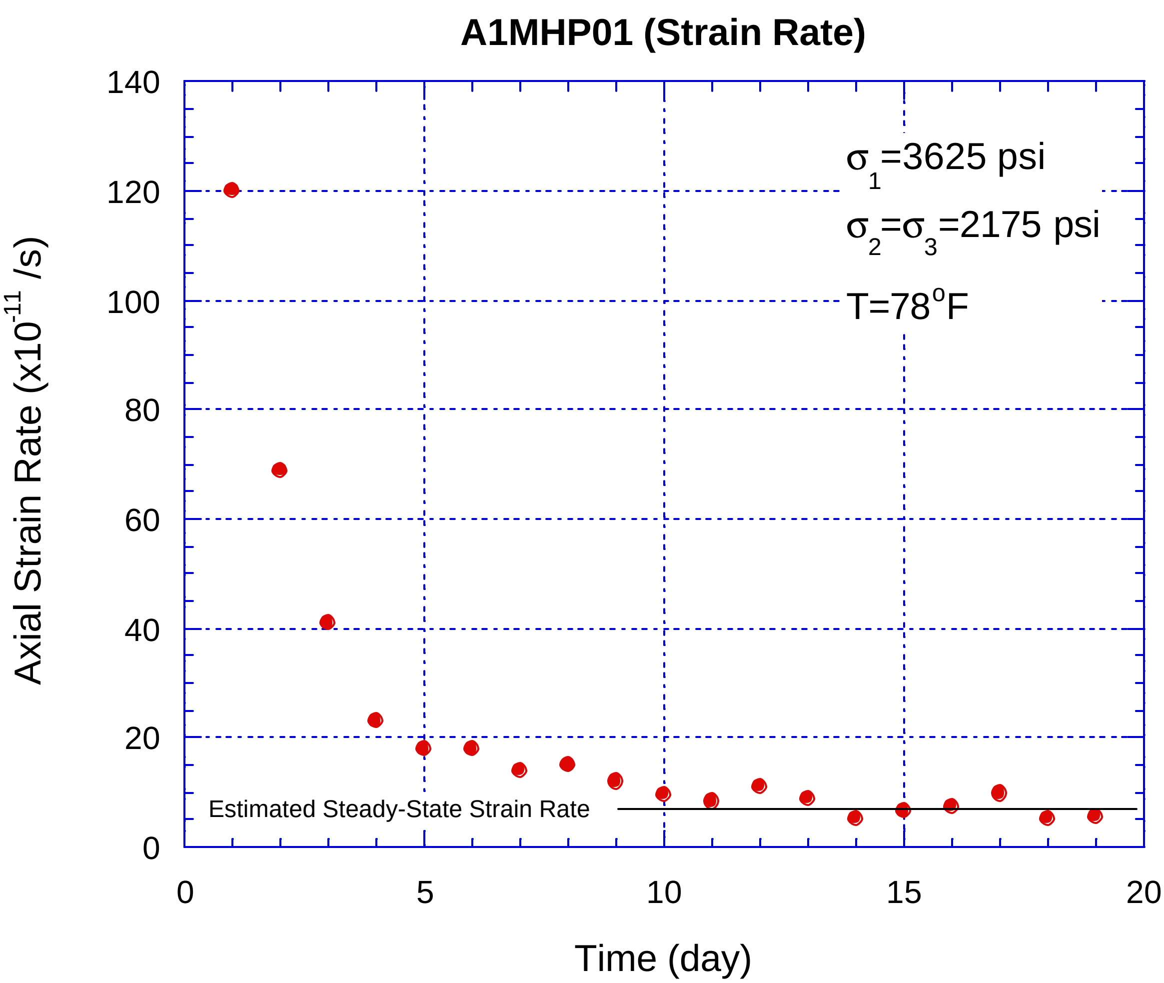


Figure 17. Strain rate vs. time plot to obtain steady-state strain rate for the A1MHP01 specimen. See Appendix D for other test records

Table 3. Summary of creep tests for Tioga rock salt from Cavern Well No. 1, Pennsylvania.

Test I.D.	Depth (ft)	Sample diameter (inch)	Sample length (inch)	Axial stress σ_1 (psi)	Confining pressure $\sigma_2=\sigma_3$ (psi)	Temperature T (^oF)	Test start date	Test end date	Test duration (day)	Estimated steady-state strain rate (10^{-11}/s)
A1MHP01	5580	3.983	8.059	3625	2175	78	7/28/00	8/16/00	19	6.9
A2MHP02	5639	3.981	8.026	3625	2175	194	8/8/00	10/4/00	57	267*
A3MHP03	5596	3.925	7.981	5075	2175	73	8/10/00	9/5/00	26	7.6
A1MHP04	5591	3.876	8.025	5075	2175	196	8/16/00	10/14/00	59	1562**
A3MHP05	5568	3.980	7.972	4350	2175	135	9/6/00	10/4/00	28	43.7

Estimated steady state strain rates were calculated by averaging the last five daily strain rates.

*Steady state strain rate was calculated by fitting a straight line to the axial strain vs. time data from 10^6 to 4×10^6 s range of data. The slope of the best-fit straight line was 267×10^{-11} /s.

** Due to the failure of an axial strain gage after 2.5×10^6 s testing, the steady state strain rate was calculated by fitting a straight line to the axial strain vs. time data from 2×10^6 to 2.35×10^6 s data. The slope of the best-fit straight line was 1562×10^{-11} /s.

3.4 Comparison to Previous Test Results

Prior laboratory testing was performed by Sandia National Laboratories (1995) Ecole Nationale Supérieure des mines de Paris (1995) on core taken from Tioga Well 501 (TW-501), located approximately 1.6 miles ENE of Cavern Well No. 1 (CW No. 1). Dilatancy and failure criteria were derived from the testing and used in numerical analyses to evaluate the design and operation of the cavern field (Ehgartner, 1996). The criteria used to define dilatant damage of the salt in1996 was

$$J_2^{\,0.5}\ (\text{psi}) = 200 + 0.15\ I_1\ (\text{psi})$$

The dilatant damage criteria for salt tested in this report is

$$J_2^{\,0.5}\ (\text{psi}) = 704 + 0.17\ I_1\ (\text{psi})$$

Therefore, the salt tested in this report from CW No.1 results in a criteria that is more resistant to damage. Similarly, the criteria used in 1996 to evaluate damage to the non-salt overburden layers was

$$J_2^{\,0.5}\ (\text{psi}) = 350 + 0.26\ I_1\ (\text{psi})$$

The dilatant damage criteria for non-salt tested in this report is

$$J_2^{\,0.5}\ (\text{psi}) = 2614 + 0.30\ I_1\ (\text{psi})$$

Therefore, the non-salt rock (dolomite) tested in this report from CW No.1 results in a criteria that is more resistant to damage than measured in the previous analyses.

A comparison of failure criteria for the dolomite also show that the core tested from CW No. 1 is considerably stronger than measured in the 1996 analyses.

A comparison of salt creep rates is shown in Figure 18 using creep relationships derived from the previous and recent tests. The stresses span the entire range of conditions tested, and the strain rates are for temperature conditions at cavern depth (110 °F). The creep rate of salt from CW No. 1 is intermediate to the rates derived from previous testing at Sandia and Ecole Nationale Supérieure des mines de Paris.

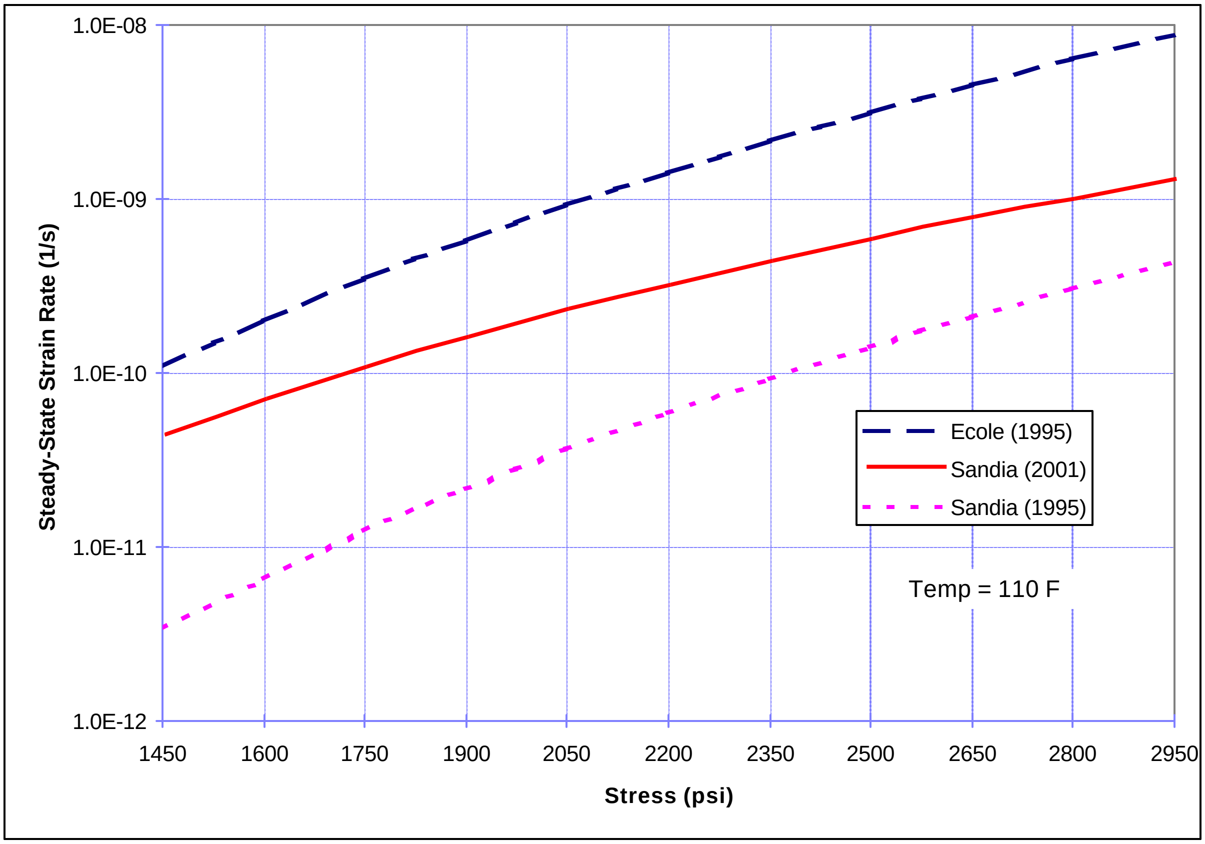


Figure 18. Comparison of creep rates from 1995 testing by Sandia and Ecole (Ecole Nationale Superieure des mines de Paris) with results presented in this report.

4. Conclusions

We conducted twenty four triaxial compression and five creep tests to characterize the quasi-static and creep properties of Tioga dolomite and rock salt for the proposed Tioga storage cavern project in Pennsylvania,. The results from laboratory experiments can be summarized as follows.

- The Young's modulus of the dolomite was 6.4 ($\pm$1.0) $\times 10^6$ psi, with a Poisson's ratio of 0.26 ($\pm$0.04). The elastic Young's modulus obtained from the slope of the unloading and reloading curve was 7.8 ($\pm$0.9) $\times 10^6$ psi.
- The Young's modulus of the rock salt, which will host the storage cavern, was 2.4 ($\pm$0.65) $\times 10^6$ psi, with a Poisson's ratio of 0.24 ($\pm$0.07). The elastic Young's modulus was determined to be 5.0 ($\pm$0.46) $\times 10^6$ psi.
- Based on shear failure, the damage criterion for the dolomite is estimated as $J_2^{\,0.5}$ (psi) = 3113 + 0.34 I_1 (psi). Whereas based on the dilation limit the criterion is conservatively estimated as $J_2^{\,0.5}$ (psi) = 2614 + 0.30 I_1 (psi).
- Based on dilation limit, the damage criterion for the rock salt is estimated as $J_2^{\,0.5}$ (psi) = 704 + 0.17 I_1 (psi).
- The creep deformation of the Tioga rock salt was modeled as $e_s = 1.2{\cdot}10^{-17}\,\sigma^{4.75}\exp(-6161/T)$, where e_s is the steady state strain rate in s^{-1}, σ is the applied axial stress difference in psi, and T is the temperature in Kelvin.

In comparison to previous test results and criteria used to evaluate the performance and impact of the planned cavern field on the overlying stratigraphy, the rock salt tested in this report (from CW No. 1) has creep characteristics intermediate to previous test results on core from a nearby Tioga Well -501. The measurements presented in this report suggest the rock salt and dolomite have a greater resistance to damage than previously measured or inferred from TW-501.

References

ASTM D2664, Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens without Pore Pressure Measurements, American Society for Testing and Materials, 1995.

ASTM D4543, Standard Practice for Preparing Rock Core Specimens and Determining Dimensional and Shape Tolerances, American Society for Testing and Materials, 1995.

Dorn, J., The Spectrum of Activation Energies for Creep, 225-283, Creep and Recovery, American Society for Metals, 1957.

Ehgartner, B.L. Letter Report to X. Allemandou of Market Hub Partners from Sandia National Laboratories, Albuquerque, NM, August 20, 1996.

Hardy, R., Event Triggered Data Acquisition in the Rock Mechanics Laboratory, Sandia Report SAND93-0256, Sandia National Laboratories, Albuquerque NM, 1993.

Looffe, K, Personal Communication, 2001.

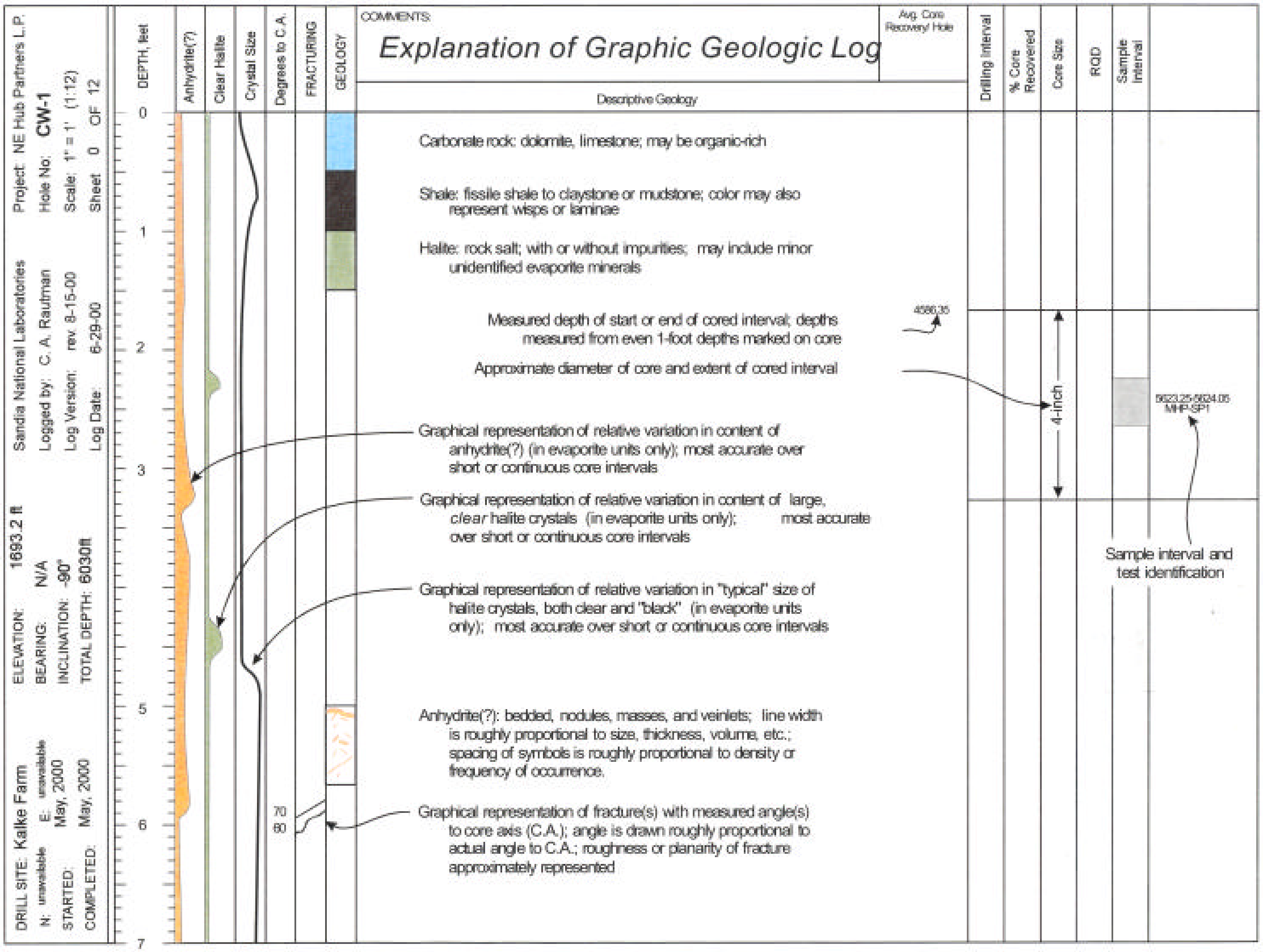
Mellegard and Pfeifle, Laboratory Testing of Dome Salt from Weeks Island, Louisiana, in Support of the Strategic Petroleum Reserve (SPR) Project, RSI-0552, prepared by RE/SPEC Inc, 1994.

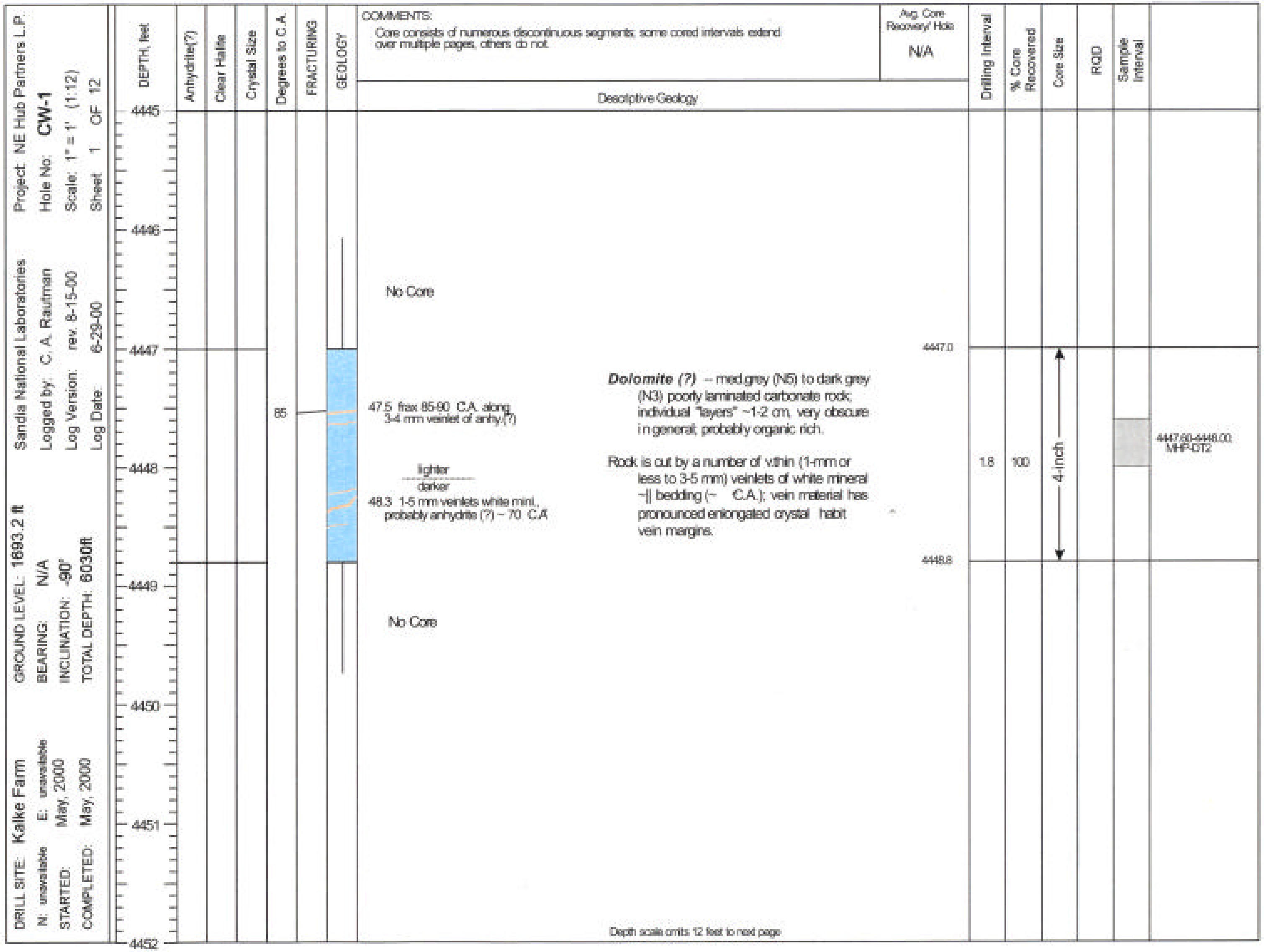
Vouille G. and B. Humbert, Mechanical Behavior of Tioga Rock Samples, Ecole Nationale Superieure des mines de Paris, Paris, 1995.

Wawersik, W.R., Letter Report to H. Heneman of Tejas Power Corporation, Results of Rock Mechanics Tests on Tioga Salt, Sandia National Laboratories, Albuquerque, NM, November 29, 1995.

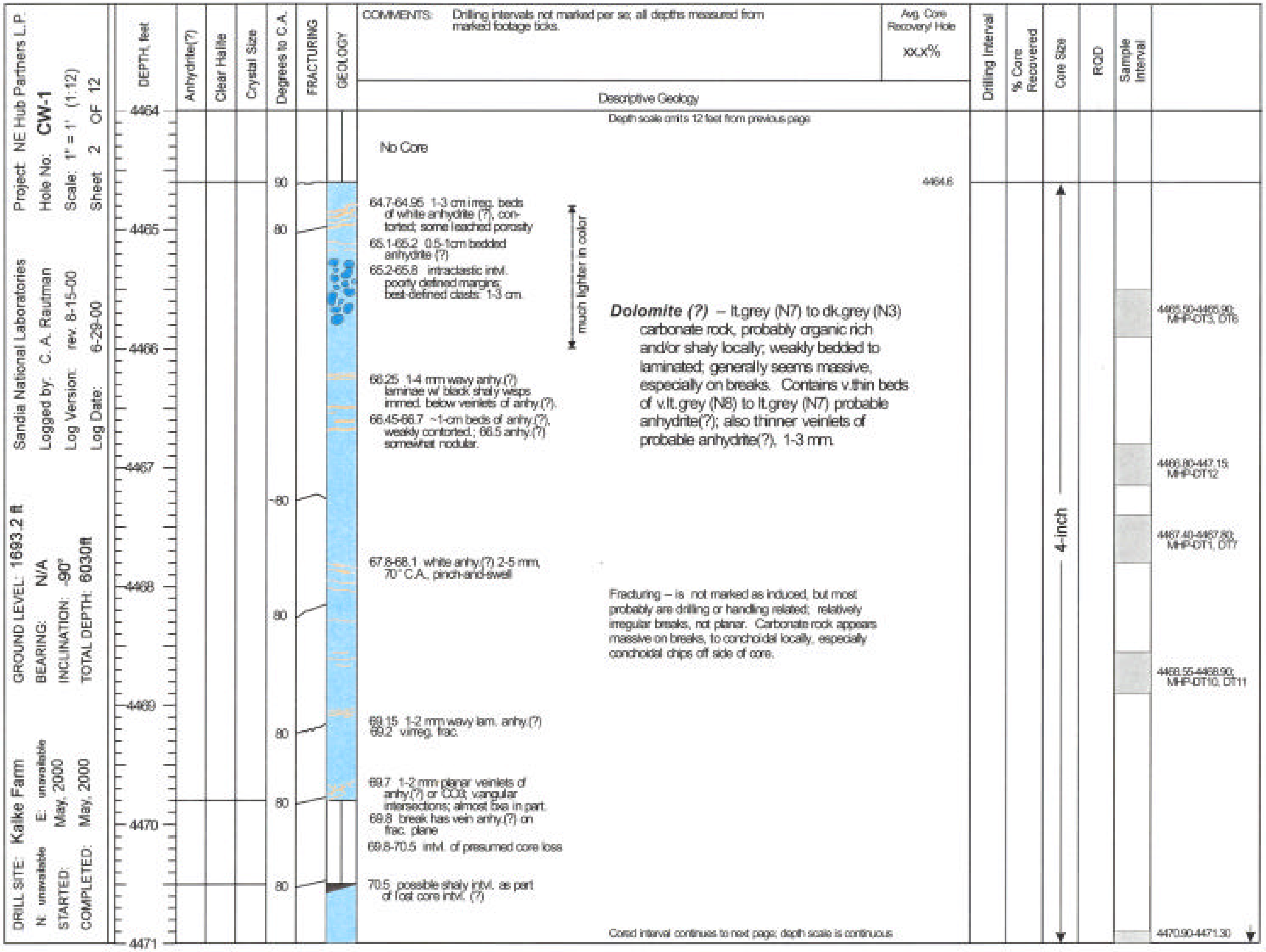
Appendix A

Geologic log of selected sections of CW No. 1 hole used for triaxial compression and steady-state creep tests.

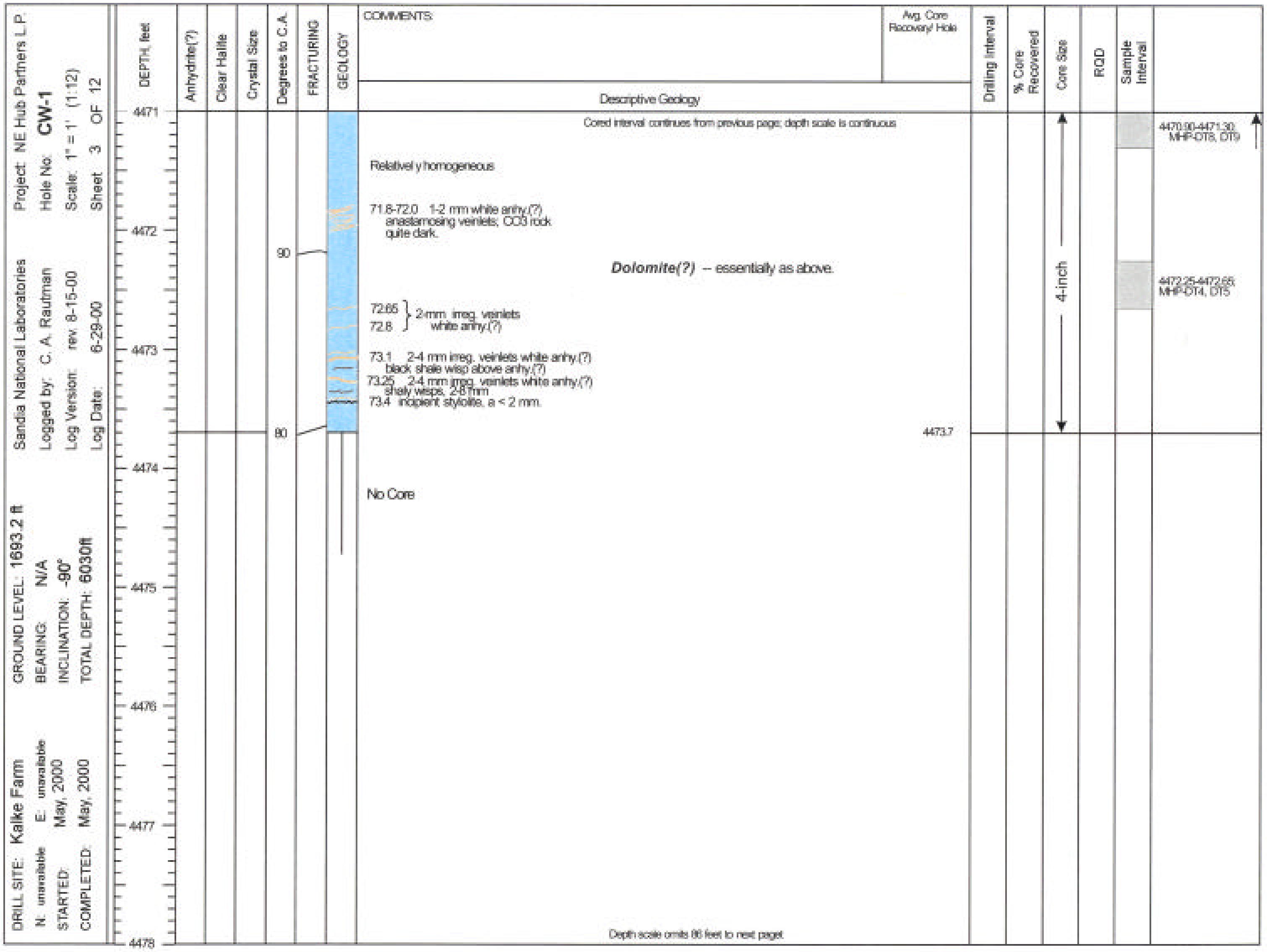

Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 0 OF 12
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
ELEVATION: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030ft
DRILL SITE: Kalke Farm
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
DEPTH, feet
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
COMMENTS:
Explanation of Graphic Geologic Log
Avg. Core Recovery/ Hole
Descriptive Geology
Drilling Interval
% Core Recovered
Core Size
RQD
Sample Interval
Carbonate rock: dolomite, limestone; may be organic-rich
Shale: fissile shale to claystone or mudstone; color may also represent wisps or laminae
Halite: rock salt; with or without impurities; may include minor unidentified evaporite minerals
Measured depth of start or end of cored interval; depths measured from even 1-foot depths marked on core
Approximate diameter of core and extent of cored interval
Graphical representation of relative variation in content of anhydrite(?) (in evaporite units only); most accurate over short or continuous core intervals
Graphical representation of relative variation in content of large, clear halite crystals (in evaporite units only); most accurate over short or continuous core intervals
Graphical representation of relative variation in "typical" size of halite crystals, both clear and "black" (in evaporite units only); most accurate over short or continuous core intervals
Anhydrite(?): bedded, nodules, masses, and veinlets; line width is roughly proportional to size, thickness, volume, etc.; spacing of symbols is roughly proportional to density or frequency of occurrence.
Graphical representation of fracture(s) with measured angle(s) to core axis (C.A.); angle is drawn roughly proportional to actual angle to C.A.; roughness or planarity of fracture approximately represented
4-inch
Sample interval and test identification
70
80
0
1
2
3
5
6
7



DRILL SITE: Kalke Farm
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030ft
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 1 OF 12
DEPTH, feet
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
COMMENTS:
Core consists of numerous discontinuous segments; some cored intervals extend over multiple pages, others do not.
Avg. Core Recovery/ Hole
N/A
Descriptive Geology
Drilling Interval
% Core Recovered
Core Size
RQD
Sample Interval
4445
4446
4447
4448
4449
4450
4451
4452
No Core
85
47.5 frax 85-90 C.A. along 3-4 mm veinlet of anhy.(?)
lighter
darker
48.3 1-5 mm veinlets white minl, probably anhydrite (?) ~ 70 C.A
Dolomite (?) -- med.grey (N5) to dark grey (N3) poorly laminated carbonate rock; individual "layers" ~1-2 cm, very obscure in general; probably organic rich.
Rock is cut by a number of v.thin (1-mm or less to 3-5 mm) veinlets of white mineral ~|| bedding (~ C.A.); vein material has pronounced enlongated crystal habit vein margins.
No Core
4447.0
4448.8
1.8
100
4-inch
4447.60-4448.00; MHP-DT2
Depth scale omits 12 feet to next page



Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 2 OF 12
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030ft
DRILL SITE: Kalke Farm
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
DEPTH, feet
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
COMMENTS: Drilling intervals not marked per se; all depths measured from marked footage ticks.
Avg. Core Recovery/ Hole
xx.x%
Descriptive Geology
Drilling Interval
% Core Recovered
Core Size
RQD
Sample Interval
4464
4465
4466
4467
4468
4469
4470
4471
Depth scale omits 12 feet from previous page
No Core
4464.6
90
80
-80
80
80
80
80
64.7-64.95 1-3 cm irreg. beds of white anhydrite (?), contorted; some leached porosity
65.1-65.2 0.5-1cm bedded anhydrite (?)
65.2-65.8 intraclastic intvl. poorly defined margins; best-defined clasts: 1-3 cm.
much lighter in color
Dolomite (?) – lt.grey (N7) to dk.grey (N3) carbonate rock, probably organic rich and/or shaly locally; weakly bedded to laminated; generally seems massive, especially on breaks. Contains v.thin beds of v.lt.grey (N8) to lt.grey (N7) probable anhydrite(?); also thinner veinlets of probable anhydrite(?), 1-3 mm.
66.25 1-4 mm wavy anhy.(?) laminae w/ black shaly wisps immed. below veinlets of anhy.(?).
66.45-66.7 ~1-cm beds of anhy.(?), weakly contorted.; 66.5 anhy.(?) somewhat nodular.
67.8-68.1 white anhy.(?) 2-5 mm, 70° C.A., pinch-and-swell
Fracturing – is not marked as induced, but most probably are drilling or handling related; relatively irregular breaks, not planar. Carbonate rock appears massive on breaks, to conchoidal locally, especially conchoidal chips off side of core.
69.15 1-2 mm wavy lam. anhy.(?)
69.2 v.irreg. frac.
69.7 1-2 mm planar veinlets of anhy.(?) or CO3; v.angular intersections; almost bx in part.
69.8 break has vein anhy.(?) on frac. plane
69.8-70.5 intvl. of presumed core loss
70.5 possible shaly intvl. as part of lost core intvl. (?)
Cored interval continues to next page; depth scale is continuous
4-inch
4465.50-4465.90; MHP-DT3, DT6
4466.80-447.15; MHP-DT12
4467.40-4467.80; MHP-DT1, DT7
4468.55-4468.90; MHP-DT10, DT11
4470.90-4471.30



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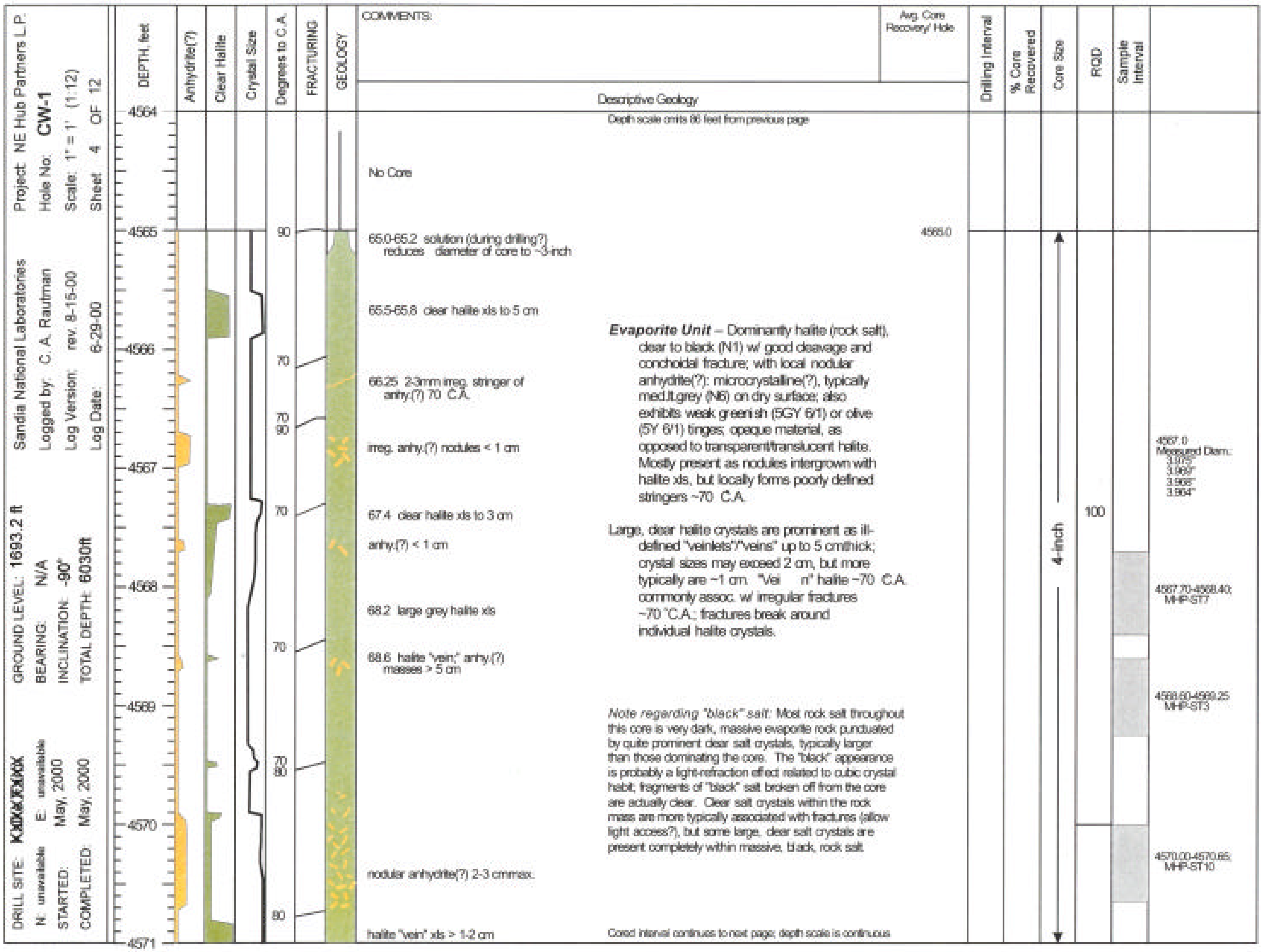
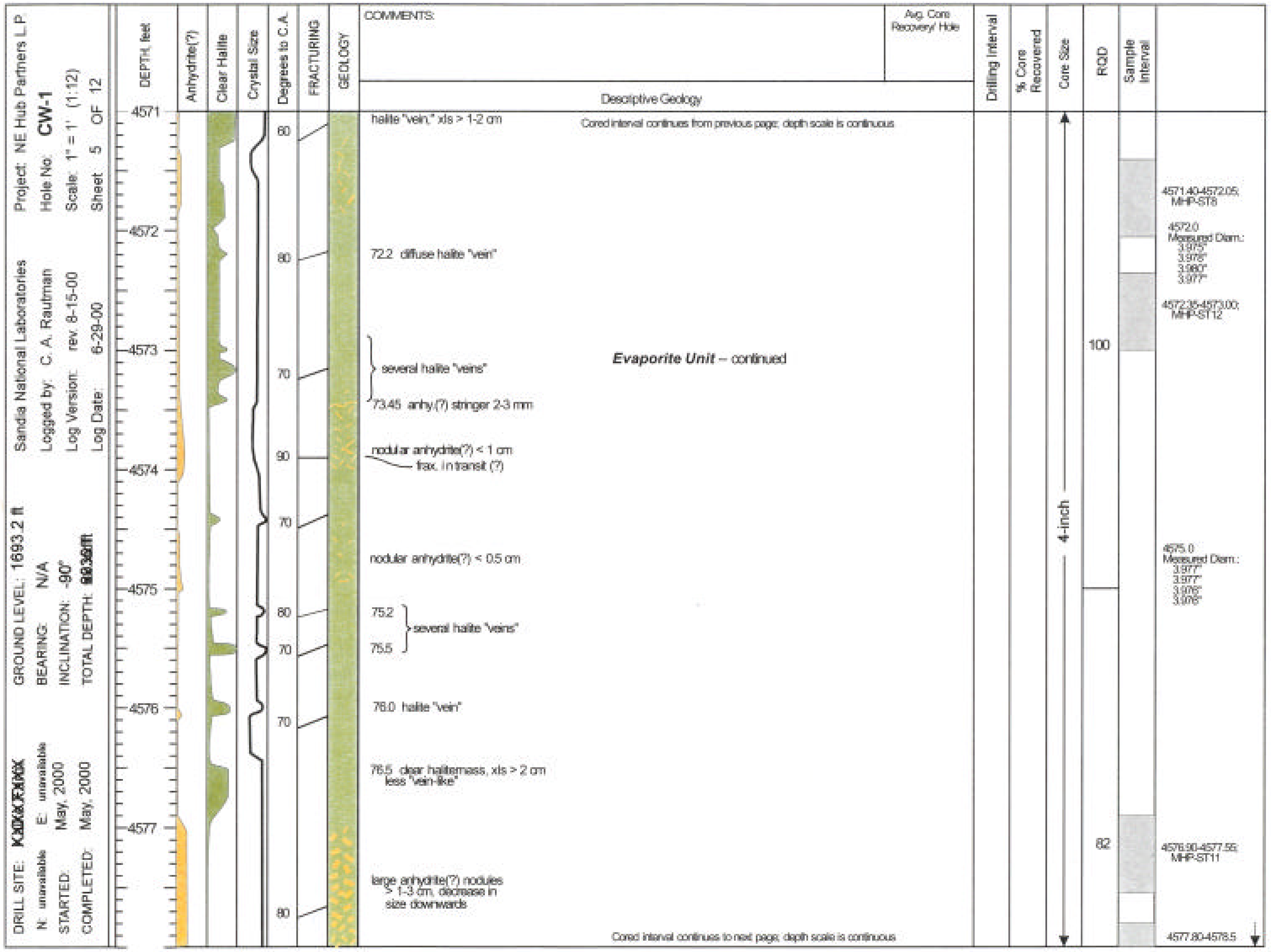
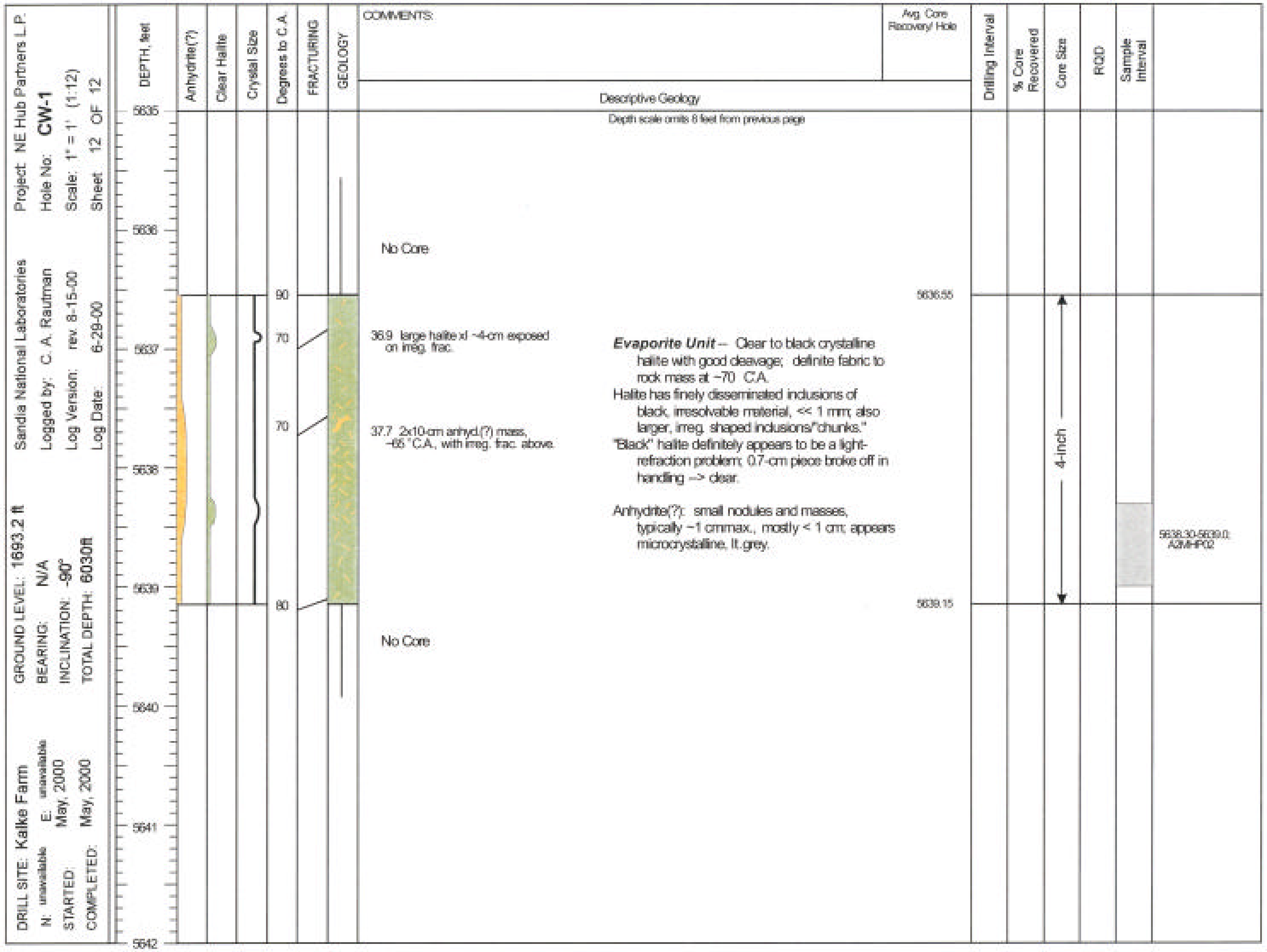
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030ft
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 3 OF 12
DEPTH, feet
4471
4472
4473
4474
4475
4476
4477
4478
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
90
80
COMMENTS:
Avg. Core Recovery/ Hole
Descriptive Geology
Cored interval continues from previous page; depth scale is continuous
Relativel y homogeneous
71.8-72.0 1-2 mm white anhy.(?) anastamosing veinlets; CO3 rock quite dark.
Dolomite(?) -- essentially as above.
72.65
72.8
2-mm irreg. veinlets white anhy.(?)
73.1 2-4 mm irreg. veinlets white anhy.(?) black shale wisp above anhy.(?)
73.25 2-4 mm irreg. veinlets white anhy.(?) shaly wisps, 2-8 mm
73.4 incipient stylolite, a < 2 mm.
4473.7
No Core
Depth scale omits 86 feet to next page!
Drilling Interval
% Core Recovered
Core Size
4-inch
RQD
Sample Interval
4470.90-4471.30; MHP-DT8, DT9
4472.25-4472.65; MHP-DT4, DT5


Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 4 OF 12
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030ft
DRILL SITE:
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
DEPTH, feet
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
COMMENTS:
Avg. Core Recovery/ Hole
Descriptive Geology
Drilling Interval
% Core Recovered
Core Size
RQD
Sample Interval
4564
4565
4566
4567
4568
4569
4570
4571
90
70
70
90
70
70
70
80
80
Depth scale omits 86 feet from previous page
No Core
65.0-65.2 solution (during drilling?) reduces diameter of core to ~3-inch
4565.0
65.5-65.8 clear halite xls to 5 cm
66.25 2-3mm irreg. stringer of anhy.(?) 70 C.A.
irreg. anhy.(?) nodules < 1 cm
67.4 clear halite xls to 3 cm
anhy.(?) < 1 cm
68.2 large grey halite xls
68.6 halite "vein;" anhy.(?) masses > 5 cm
nodular anhydrite(?) 2-3 cmmax.
halite "vein" xls > 1-2 cm
Evaporite Unit – Dominantly halite (rock salt), clear to black (N1) w/ good cleavage and conchoidal fracture; with local nodular anhydrite(?): microcrystalline(?), typically med.lt.grey (N6) on dry surface; also exhibits weak greenish (5GY 6/1) or olive (5Y 6/1) tinges; opaque material, as opposed to transparent/translucent halite. Mostly present as nodules intergrown with halite xls, but locally forms poorly defined stringers ~70 C.A.
Large, clear halite crystals are prominent as ill-defined "veinlets"/"veins" up to 5 cmthick; crystal sizes may exceed 2 cm, but more typically are ~1 cm. "Vei n" halite ~70 C.A. commonly assoc. w/ irregular fractures ~70°C.A.; fractures break around individual halite crystals.
Note regarding "black" salt: Most rock salt throughout this core is very dark, massive evaporite rock punctuated by quite prominent clear salt crystals, typically larger than those dominating the core. The "black" appearance is probably a light-refraction effect related to cubic crystal habit; fragments of "black" salt broken off from the core are actually clear. Clear salt crystals within the rock mass are more typically associated with fractures (allow light access?), but some large, clear salt crystals are present completely within massive, black, rock salt.
Cored interval continues to next page; depth scale is continuous
4-inch
100
4567.0
Measured Diam.:
3.975"
3.969"
3.968"
3.964"
4567.70-4568.40; MHP-ST7
4568.60-4569.25 MHP-ST3
4570.00-4570.65; MHP-ST10



DRILL SITE:
N: unavailable
E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH:
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 5 OF 12
DEPTH, feet
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
COMMENTS:
Avg. Core Recovery/ Hole
Descriptive Geology
Drilling Interval
% Core Recovered
Core Size
RQD
Sample Interval
4571
4572
4573
4574
4575
4576
4577
halite "vein," xls > 1-2 cm
Cored interval continues from previous page; depth scale is continuous
72.2 diffuse halite "vein"
several halite "veins"
73.45 anhy.(?) stringer 2-3 mm
Evaporite Unit – continued
nodular anhydrite(?) < 1 cm
frax. in transit (?)
nodular anhydrite(?) < 0.5 cm
75.2
several halite "veins"
75.5
76.0 halite "vein"
76.5 clear halite mass, xls > 2 cm
less "vein-like"
large anhydrite(?) nodules
> 1-3 cm, decrease in
size downwards
Cored interval continues to next page; depth scale is continuous
60
80
70
90
70
80
70
70
80
4-inch
100
82
4571.40-4572.05;
MHP-ST8
4572.0
Measured Diam.:
3.975"
3.978"
3.980"
3.977"
4572.35-4573.00;
MHP-ST12
4575.0
Measured Diam.:
3.977"
3.977"
3.976"
3.976"
4576.90-4577.55;
MHP-ST11
4577.80-4578.5


DRILL SITE: Kalke Farm
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030ft
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 12 OF 12
DEPTH, feet
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
COMMENTS:
Avg. Core Recovery/ Hole
Descriptive Geology
Depth scale omits 8 feet from previous page
Drilling Interval
% Core Recovered
Core Size
RQD
Sample Interval
5635
5636
5637
5638
5639
5640
5641
5642
90
70
70
80
No Core
5636.55
36.9 large halite xl ~4-cm exposed on irreg. frac.
37.7 2x10-cm anhyd.(?) mass, ~65 °C.A., with irreg. frac. above.
Evaporite Unit -- Clear to black crystalline halite with good cleavage; definite fabric to rock mass at ~70 C.A.
Halite has finely disseminated inclusions of black, irresolvable material, << 1 mm; also larger, irreg. shaped inclusions/"chunks."
"Black" halite definitely appears to be a light-refraction problem; 0.7-cm piece broke off in handling --> clear.
Anhydrite(?): small nodules and masses, typically ~1 cmmax., mostly < 1 cm; appears microcrystalline, lt.grey.
5639.15
No Core
4-inch
5638.30-5639.0; A2MHP02

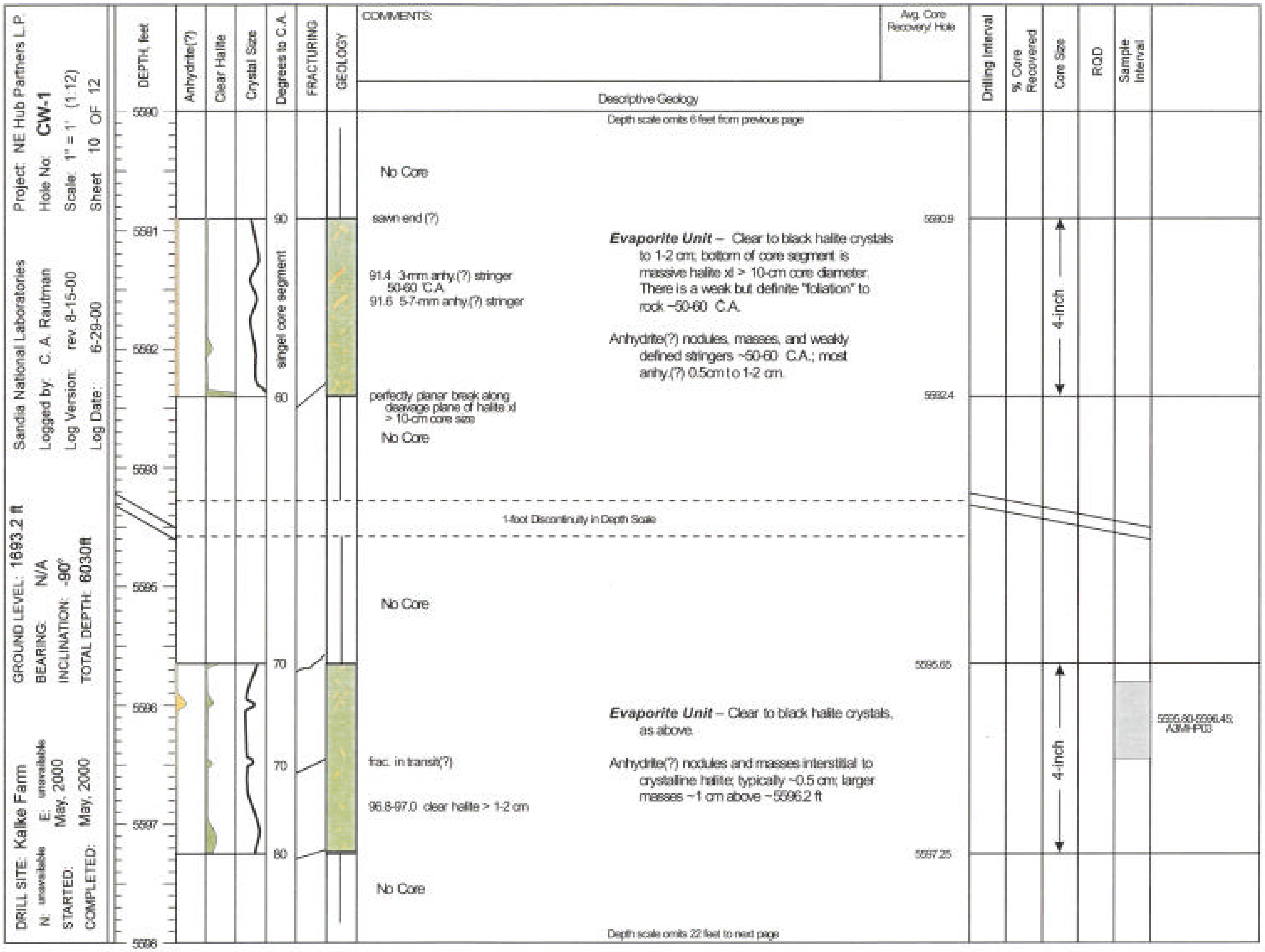
DRILL SITE: Kalke Farm
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000

GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030ft

Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00

Project: NE Hub Partners L.P.
Hole No: **CW-1**
Scale: 1" = 1' (1:12)
Sheet 11 OF 12

DEPTH, feet	Anhydrite(?)	Clear Halite	Crystal Size	Degrees to C.A.	FRACTURING	GEOLOGY	COMMENTS: / Descriptive Geology	Avg. Core Recovery/ Hole	Drilling Interval	% Core Recovered	Core Size	RQD	Sample Interval
5620							Depth scale omits 22 feet from previous page						
5621													
5622							No Core						
				80			frac. irreg. around halite xls	5622.35					
							Evaporite Unit -- Clear to black crystalline halite; typical crystals < 1 cm, but to 1-2 cm locally.				4-inch		
5623				90			frac. in transit(?)						
							23.2 anhy.(?) ~1 cm						
							Anhydrite(?): interstitial and nodular; typically < 1 cm.						
				80			frac. irreg. around halite xls	5623.50					
5624							No Core						
5625													
5626													
5627							Depth scale omits 8 feet to next page						


Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 10 OF 12
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030 ft
DRILL SITE: Kalke Farm
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
DEPTH, feet
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
COMMENTS:
Avg. Core Recovery/ Hole
Descriptive Geology
Drilling Interval
% Core Recovered
Core Size
RQD
Sample Interval
Depth scale omits 6 feet from previous page
5590
5591
5592
5593
5595
5596
5597
5598
No Core
sawn end (?)
90
singel core segment
60
70
70
80
91.4 3-mm anhy.(?) stringer 50-60 C.A.
91.6 5-7-mm anhy.(?) stringer
perfectly planar break along cleavage plane of halite xl > 10-cm core size
No Core
Evaporite Unit – Clear to black halite crystals to 1-2 cm; bottom of core segment is massive halite xl > 10-cm core diameter. There is a weak but definite "foliation" to rock ~50-60 C.A.
Anhydrite(?) nodules, masses, and weakly defined stringers ~50-60 C.A.; most anhy.(?) 0.5cm to 1-2 cm.
5590.9
5592.4
4-inch
1-foot Discontinuity in Depth Scale
No Core
5595.65
Evaporite Unit – Clear to black halite crystals, as above.
Anhydrite(?) nodules and masses interstitial to crystalline halite; typically ~0.5 cm; larger masses ~1 cm above ~5596.2 ft
frac. in transit(?)
96.8-97.0 clear halite > 1-2 cm
5597.25
4-inch
5595.80-5596.45; A3MHP03
No Core
Depth scale omits 22 feet to next page

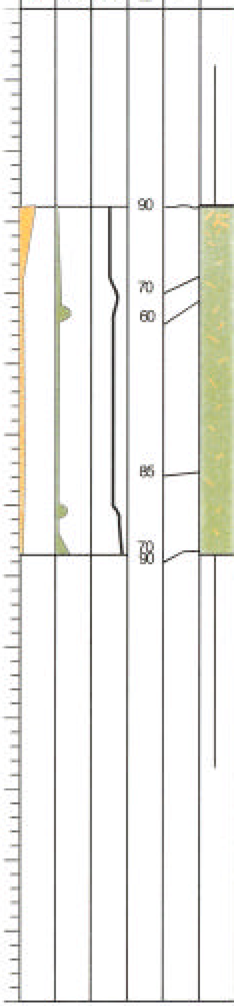
DRILL SITE: Kalke Farm
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000

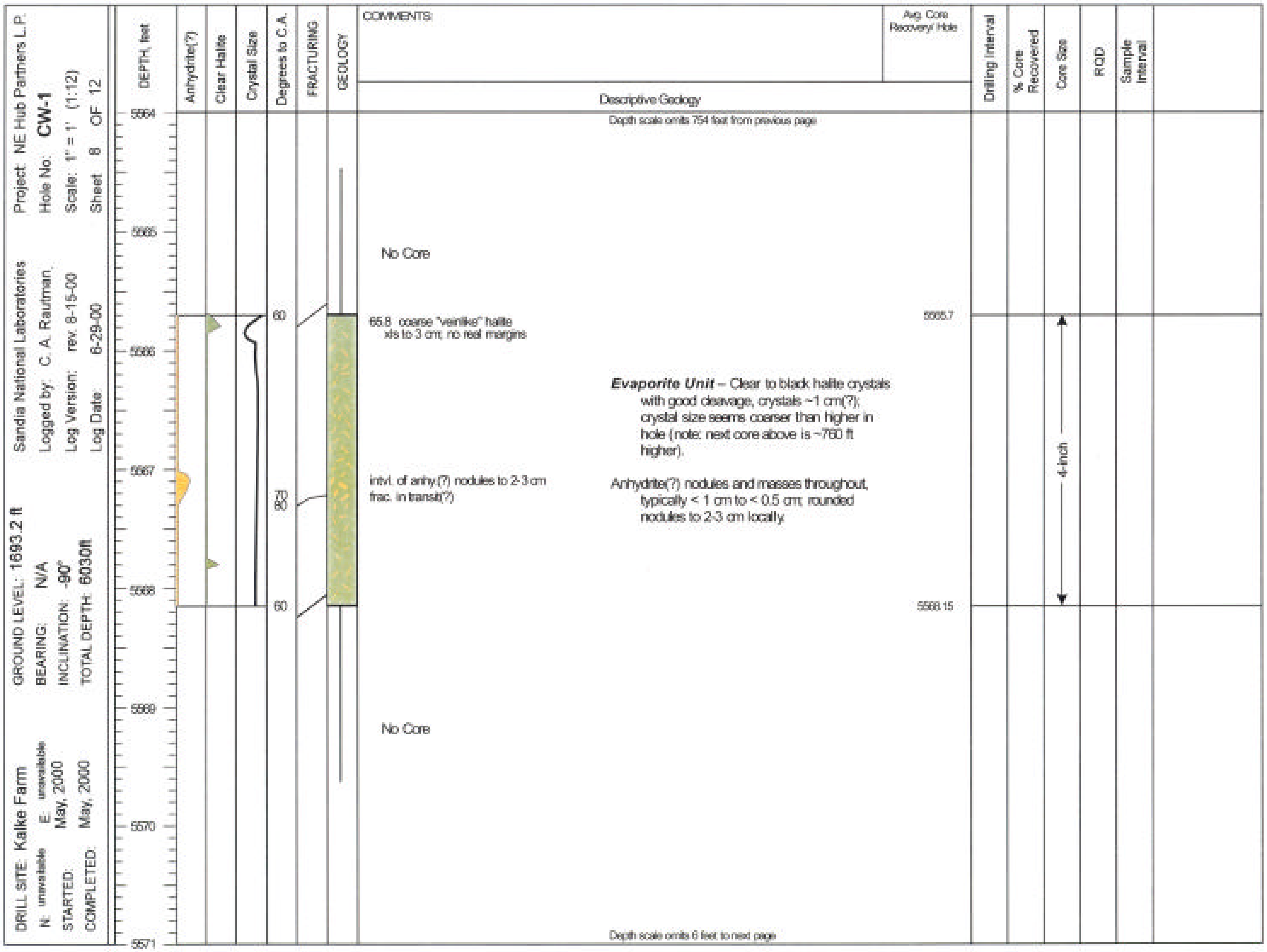
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030ft

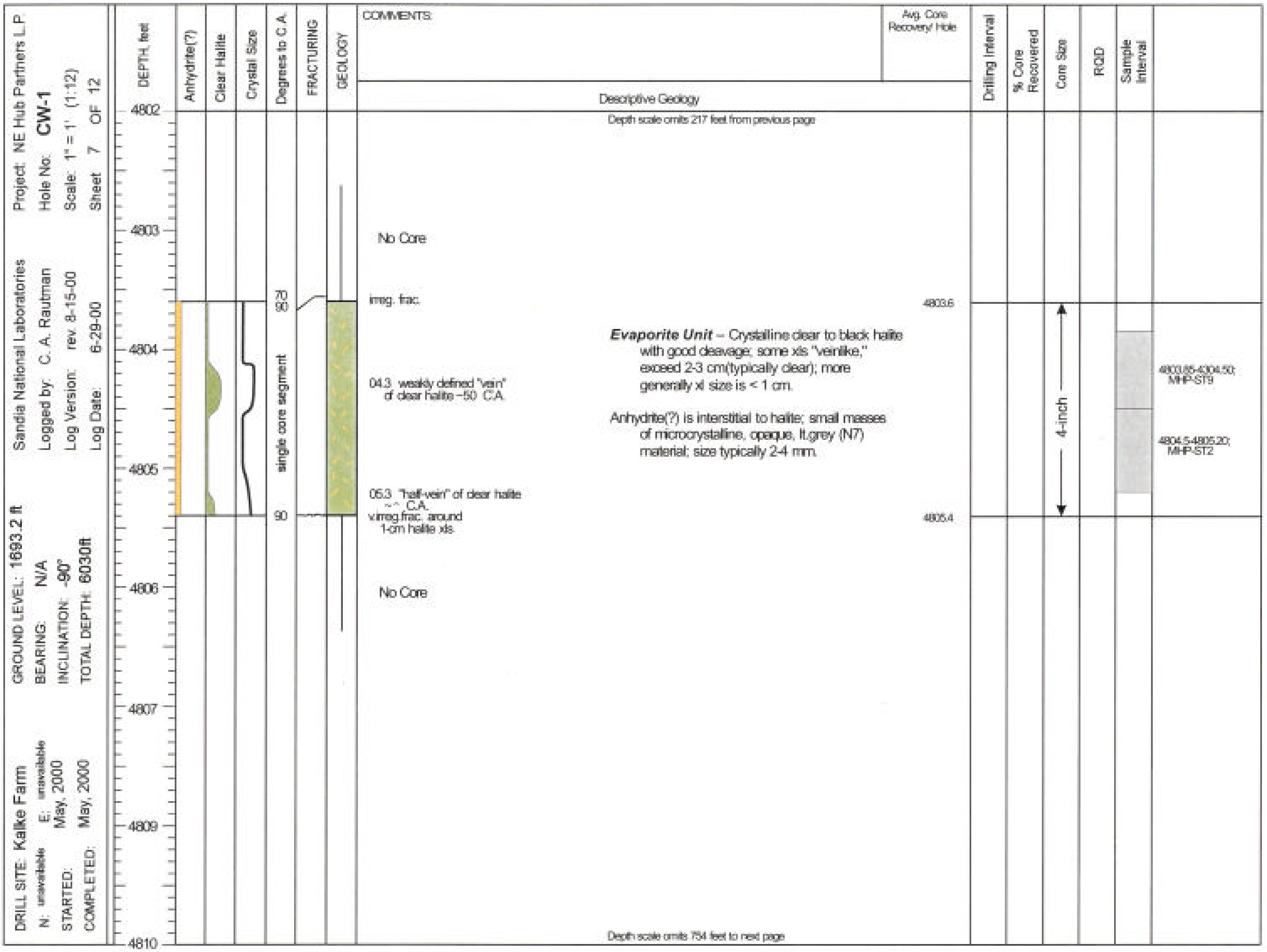
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00

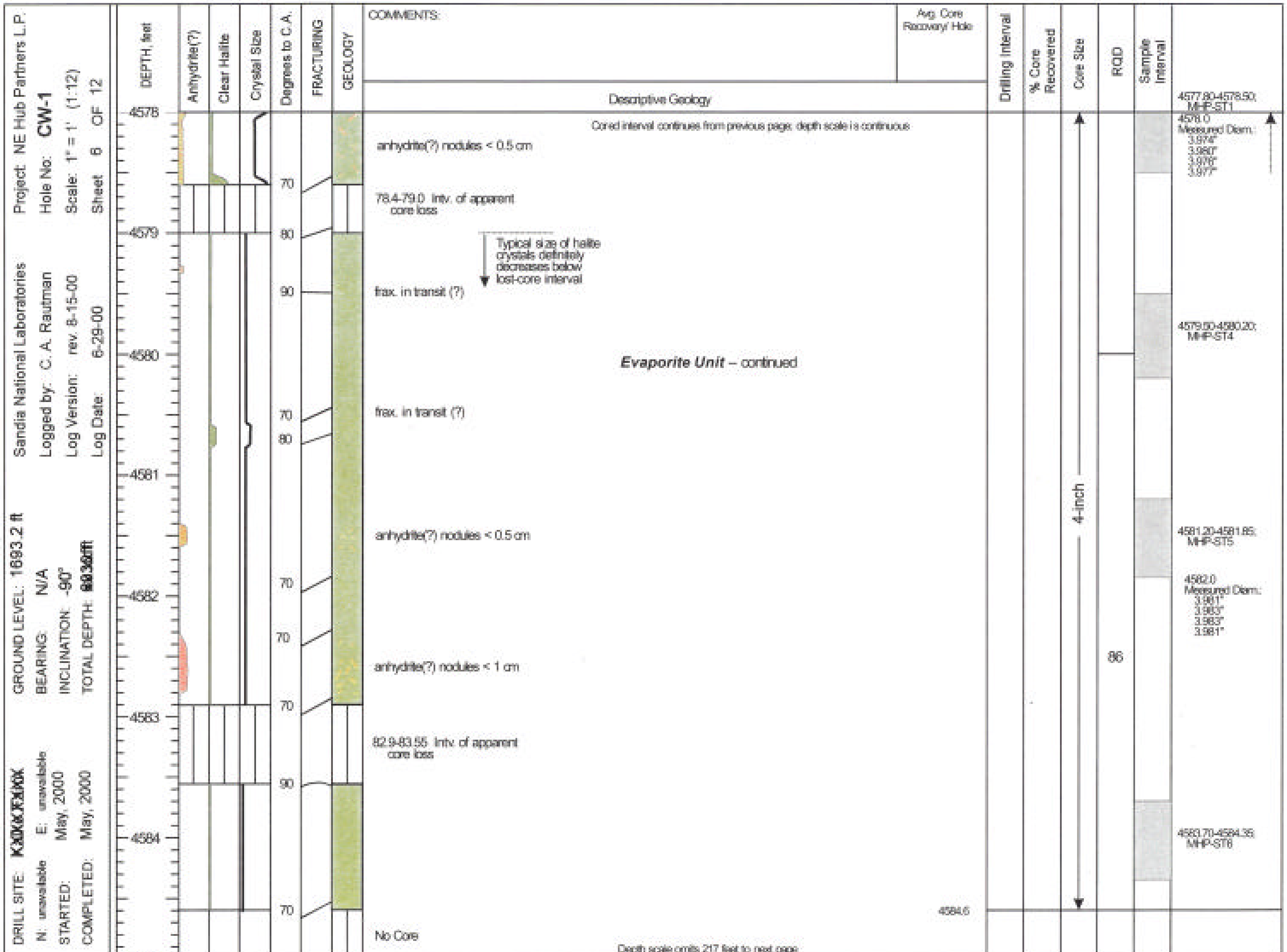
Project: NE Hub Partners L.P.
Hole No: **CW-1**
Scale: 1" = 1' (1:12)
Sheet 9 OF 12

DEPTH, feet	Anhydrite(?)	Clear Halite	Crystal Size	Degrees to C.A.	FRACTURING	GEOLOGY	COMMENTS: / Descriptive Geology	Avg. Core Recovery/ Hole	Drilling Interval	% Core Recovered	Core Size	RQD	Sample Interval	
5577							Depth scale omits 6 feet from previous page							
5578							No Core							
				90			78.4-78.7 small bladed anhy.(?) xls 2x5 mm; also nodular to 1 cm	5578.4						
5579				70							4-inch			
				60			*Evaporite Unit* – Clear to black halite crystals typically to 1 cm; black halite in this core is almost certainly a light-refraction condition. Anhydrite(?): small nodular, interstitial and ? bladed forms; typically < 0.5 cm, but to 1 cm.							5579.35-5580.0: A1MHP01
5580				85										
				70										
				90				5580.85						
5581														
5582							No Core							
5583														
5584							Depth scale omits 6 feet to next page							




DRILL SITE: Kalke Farm
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030ft
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 8 OF 12
DEPTH, feet
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
COMMENTS:
Avg. Core Recovery/ Hole
Descriptive Geology
Drilling Interval
% Core Recovered
Core Size
RQD
Sample Interval
Depth scale omits 754 feet from previous page
5564
5565
5566
5567
5568
5569
5570
5571
No Core
60
65.8 coarse "veinlike" halite xls to 3 cm; no real margins
5565.7
Evaporite Unit – Clear to black halite crystals with good cleavage, crystals ~1 cm(?); crystal size seems coarser than higher in hole (note: next core above is ~760 ft higher).
Anhydrite(?) nodules and masses throughout, typically < 1 cm to < 0.5 cm; rounded nodules to 2-3 cm locally.
70
80
intvl. of anhy.(?) nodules to 2-3 cm
frac. in transit(?)
4-inch
60
5568.15
No Core
Depth scale omits 6 feet to next page


DRILL SITE: Kalke Farm
N: unavailable E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH: 6030ft
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 7 OF 12
DEPTH, feet
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
COMMENTS:
Avg. Core Recovery/ Hole
Descriptive Geology
Drilling Interval
% Core Recovered
Core Size
RQD
Sample Interval
Depth scale omits 217 feet from previous page
4802
4803
4804
4805
4806
4807
4809
4810
No Core
irreg. frac.
70
90
single core segment
90
04.3 weakly defined "vein" of clear halite ~50 C.A.
05.3 "half-vein" of clear halite ~^ C.A.
v.irreg.frac. around 1-cm halite xls.
No Core
4803.6
4805.4
Evaporite Unit – Crystalline clear to black halite with good cleavage; some xls "veinlike," exceed 2-3 cm(typically clear); more generally xl size is < 1 cm.
Anhydrite(?) is interstitial to halite; small masses of microcrystalline, opaque, lt.grey (N7) material; size typically 2-4 mm.
4-inch
4803.85-4304.50; MHP-ST9
4804.5-4805.20; MHP-ST2
Depth scale omits 754 feet to next page



Project: NE Hub Partners L.P.
Hole No: CW-1
Scale: 1" = 1' (1:12)
Sheet 6 OF 12
Sandia National Laboratories
Logged by: C. A. Rautman
Log Version: rev. 8-15-00
Log Date: 6-29-00
GROUND LEVEL: 1693.2 ft
BEARING: N/A
INCLINATION: -90°
TOTAL DEPTH:
DRILL SITE:
N: unavailable
E: unavailable
STARTED: May, 2000
COMPLETED: May, 2000
DEPTH, feet
Anhydrite(?)
Clear Halite
Crystal Size
Degrees to C.A.
FRACTURING
GEOLOGY
COMMENTS:
Avg. Core Recovery/ Hole
Descriptive Geology
Drilling Interval
% Core Recovered
Core Size
RQD
Sample Interval
4578
4579
4580
4581
4582
4583
4584
4585
70
80
90
70
80
70
70
70
90
70
Cored interval continues from previous page; depth scale is continuous
anhydrite(?) nodules < 0.5 cm
78.4-79.0 Intv. of apparent core loss
Typical size of halite crystals definitely decreases below lost-core interval
frax. in transit (?)
Evaporite Unit – continued
frax. in transit (?)
anhydrite(?) nodules < 0.5 cm
anhydrite(?) nodules < 1 cm
82.9-83.55 Intv. of apparent core loss
No Core
4584.6
Depth scale omits 217 feet to next page
4-inch
86
4577.80-4578.50; MHP-ST1
4578.0 Measured Diam.: 3.974" 3.980" 3.976" 3.977"
4579.50-4580.20; MHP-ST4
4581.20-4581.85; MHP-ST5
4582.0 Measured Diam.: 3.981" 3.983" 3.983" 3.981"
4583.70-4584.35; MHP-ST8

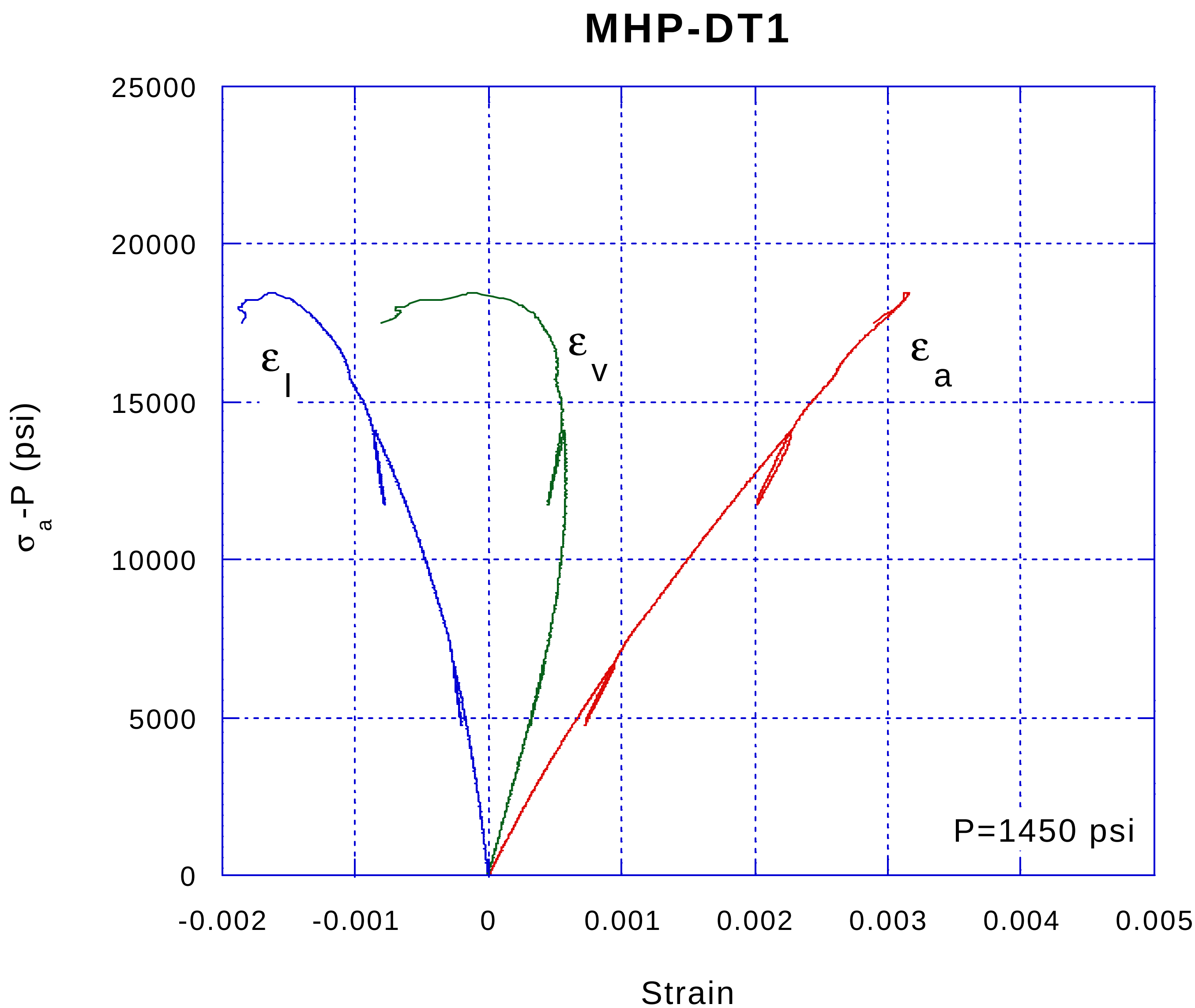
Appendix B

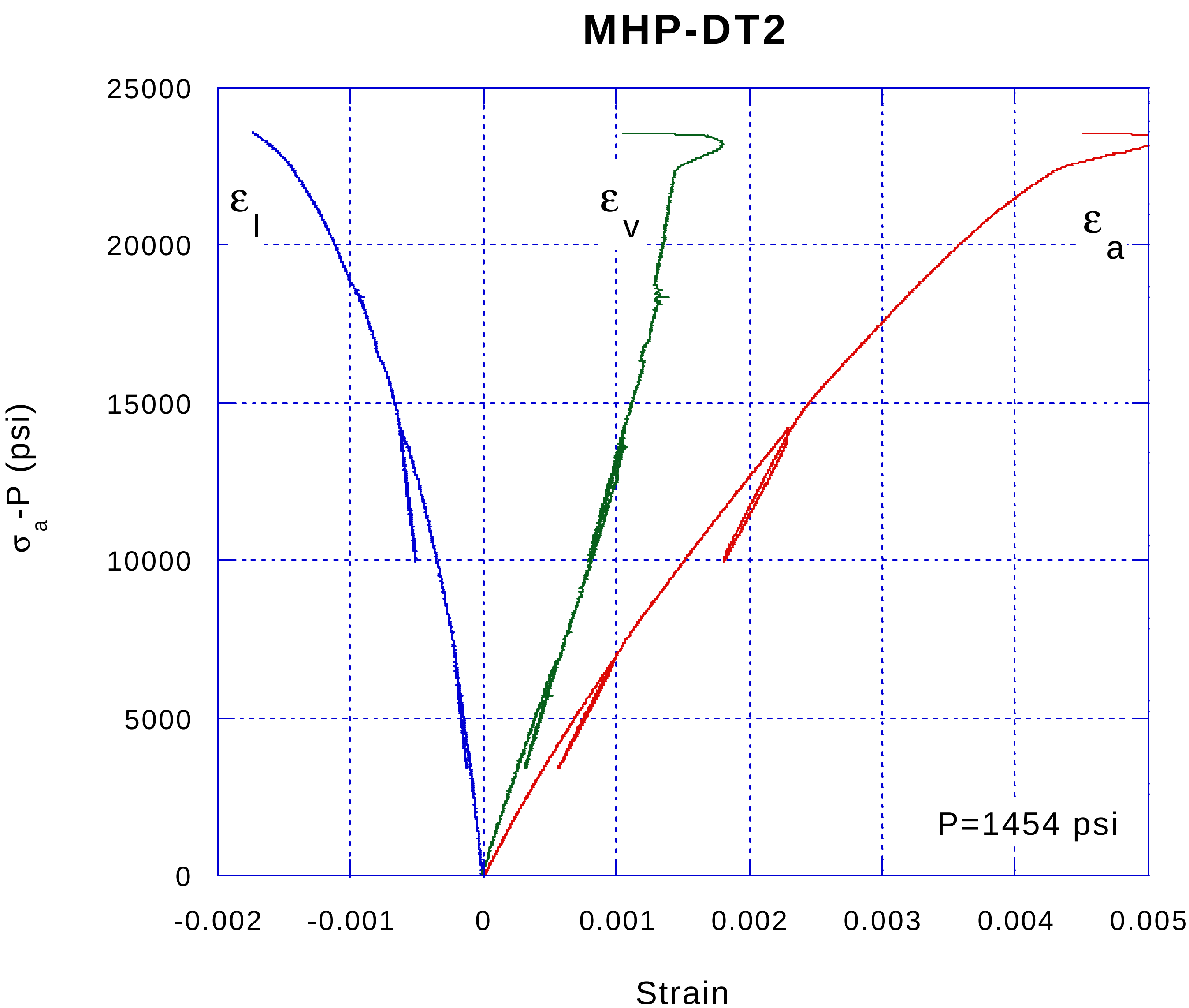
Stress-strain plots for Tioga dolomite obtained during the triaxial compression tests for the MHP project. Shown are the axial, lateral and calculated volumetric strains, respectively.

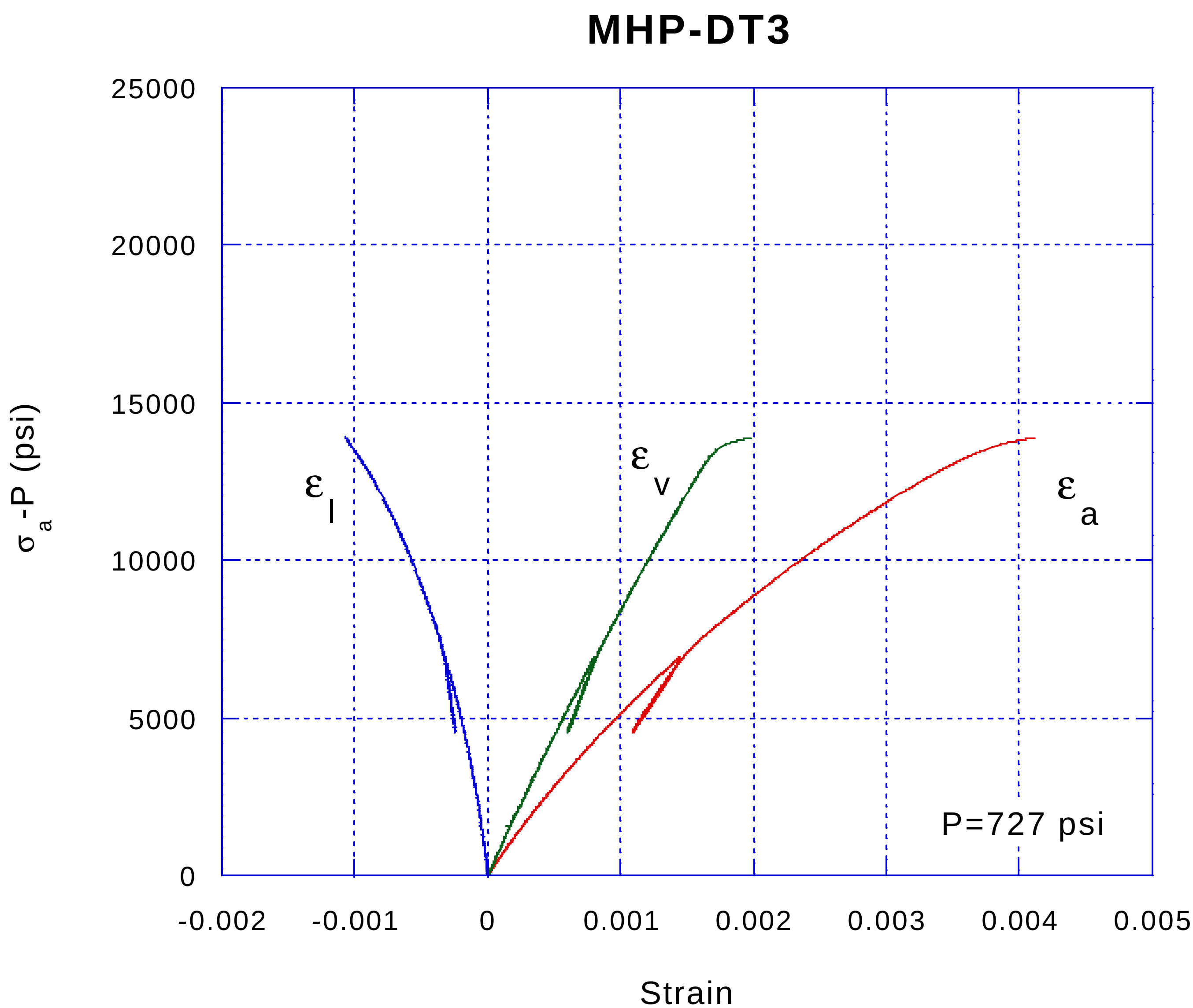
ε_a – axial strain (right or red line)
ε_l –lateral strain (left or blue line)
ε_v – volumetric strain (middle or green line)

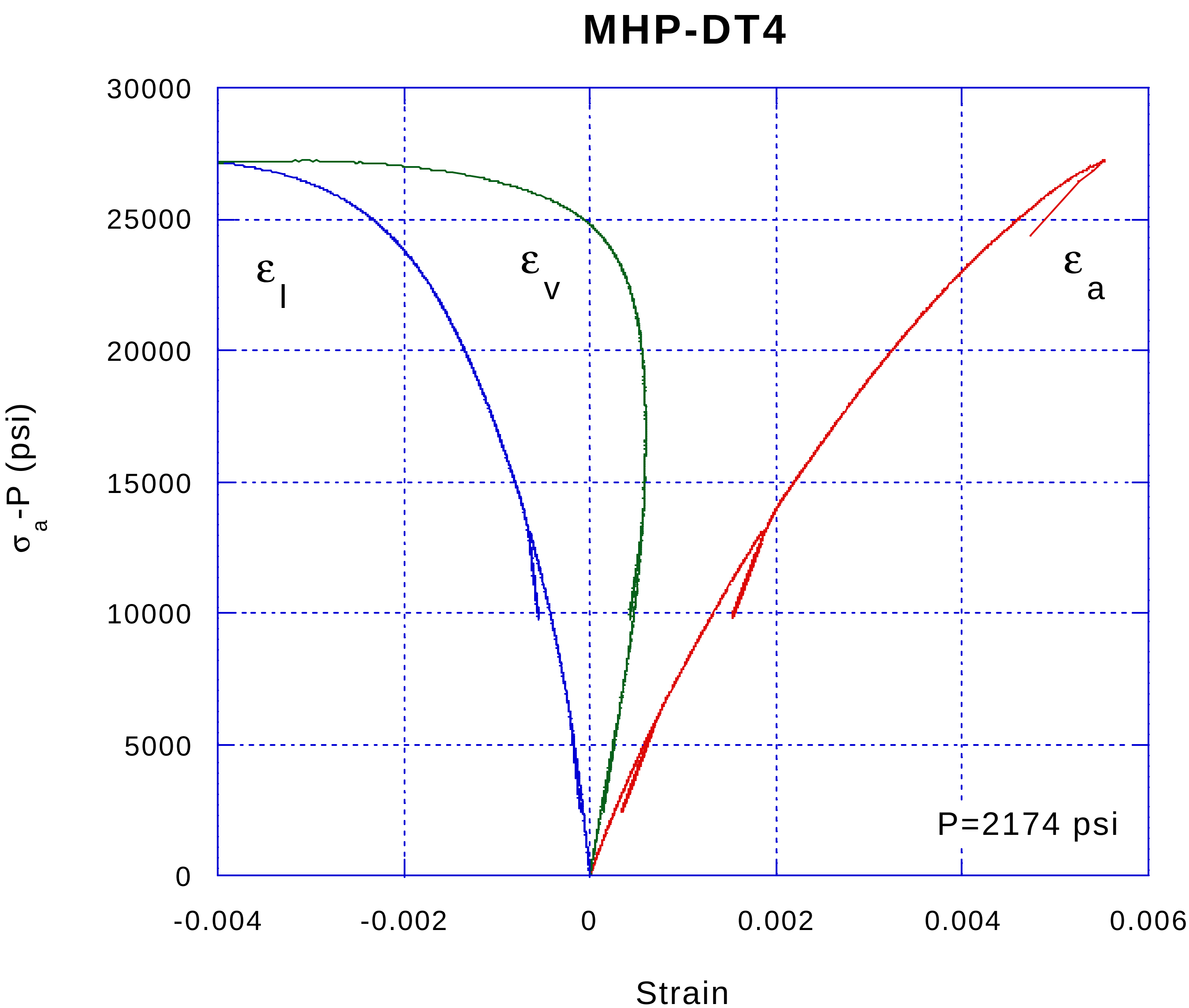
Structure of the file name or the title of the plot

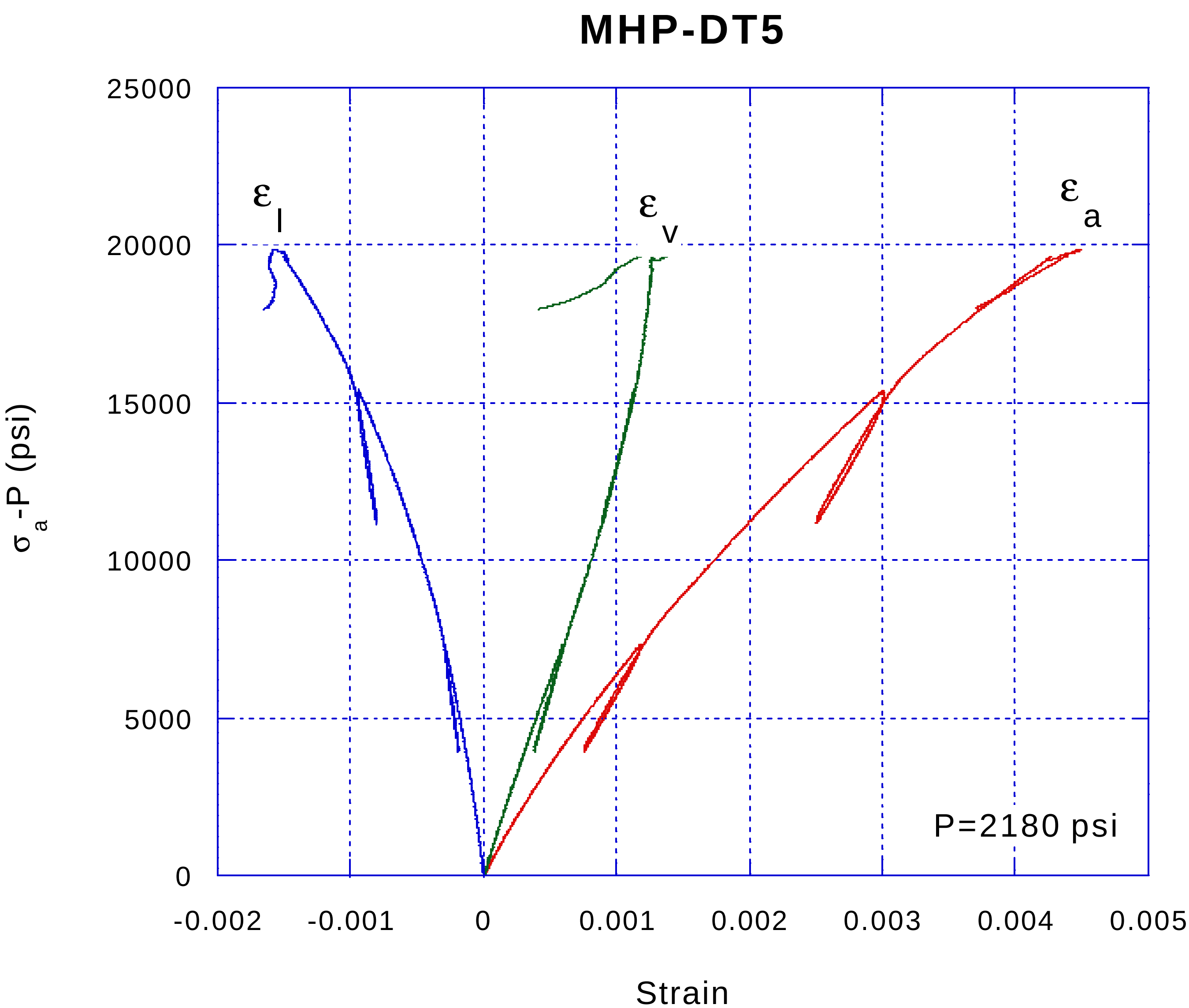
- MHP-DT1 to 12 (**MHP**, Tioga, **D**olomite, **T**riaxial compression #)
- #=sample number

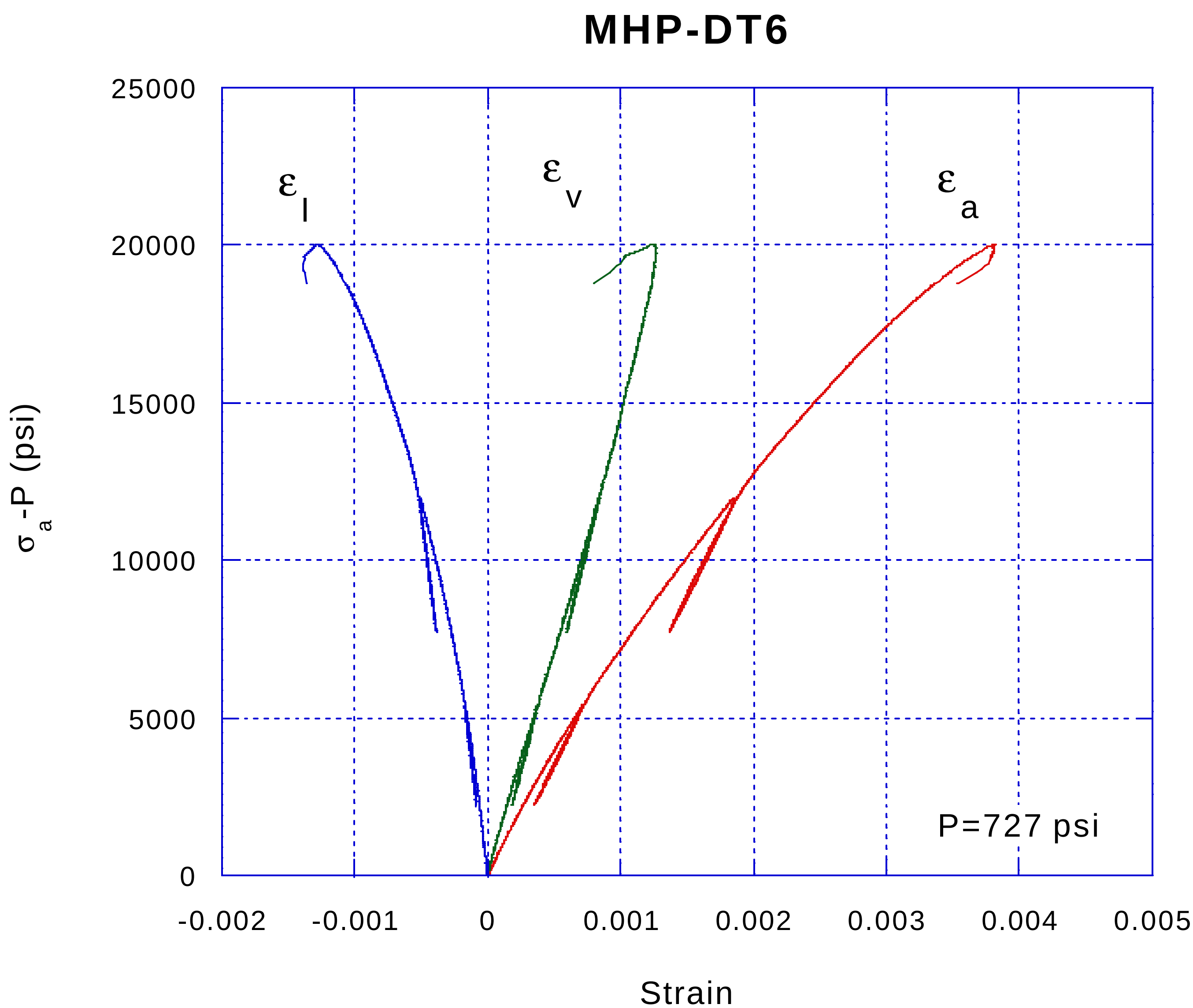

MHP-DT1
25000
20000
15000
10000
5000
0
-0.002
-0.001
0
0.001
0.002
0.003
0.004
0.005
Strain
σ a -P (psi)
ε l
ε v
ε a
P=1450 psi


MHP-DT2
25000
20000
15000
10000
5000
0
-0.002
-0.001
0
0.001
0.002
0.003
0.004
0.005
ε_l
ε_v
ε_a
P=1454 psi
σ_a-P (psi)
Strain

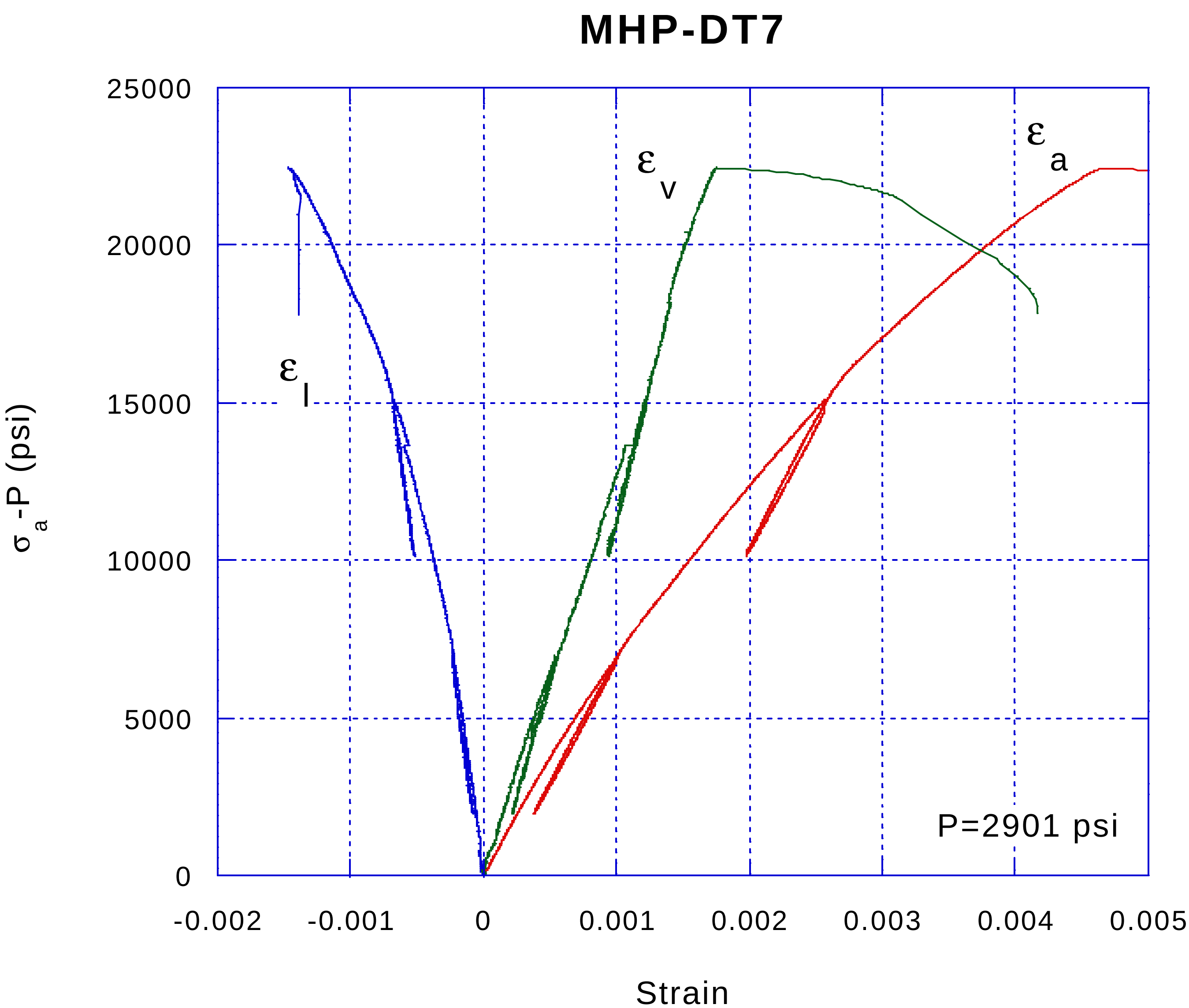

MHP-DT3
σ_a-P (psi)
25000
20000
15000
10000
5000
0
-0.002
-0.001
0
0.001
0.002
0.003
0.004
0.005
Strain
ε_l
ε_v
ε_a
P=727 psi


MHP-DT4
30000
25000
20000
15000
10000
5000
0
ε_l
ε_v
ε_a
P=2174 psi
σ_a-P (psi)
-0.004
-0.002
0
0.002
0.004
0.006
Strain

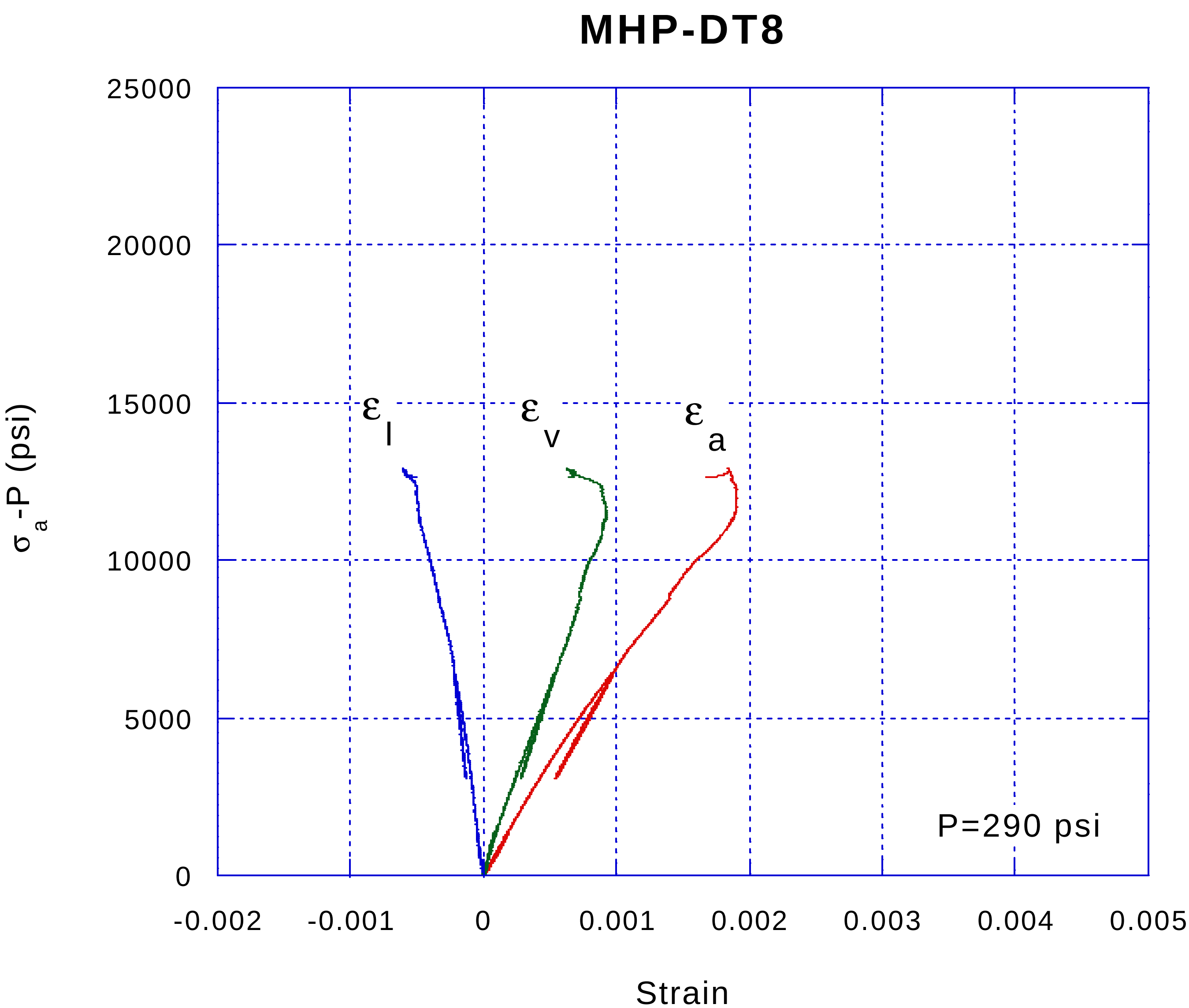

MHP-DT5
25000
20000
15000
10000
5000
0
σ_a-P (psi)
ε_l
ε_v
ε_a
P=2180 psi
-0.002
-0.001
0
0.001
0.002
0.003
0.004
0.005
Strain

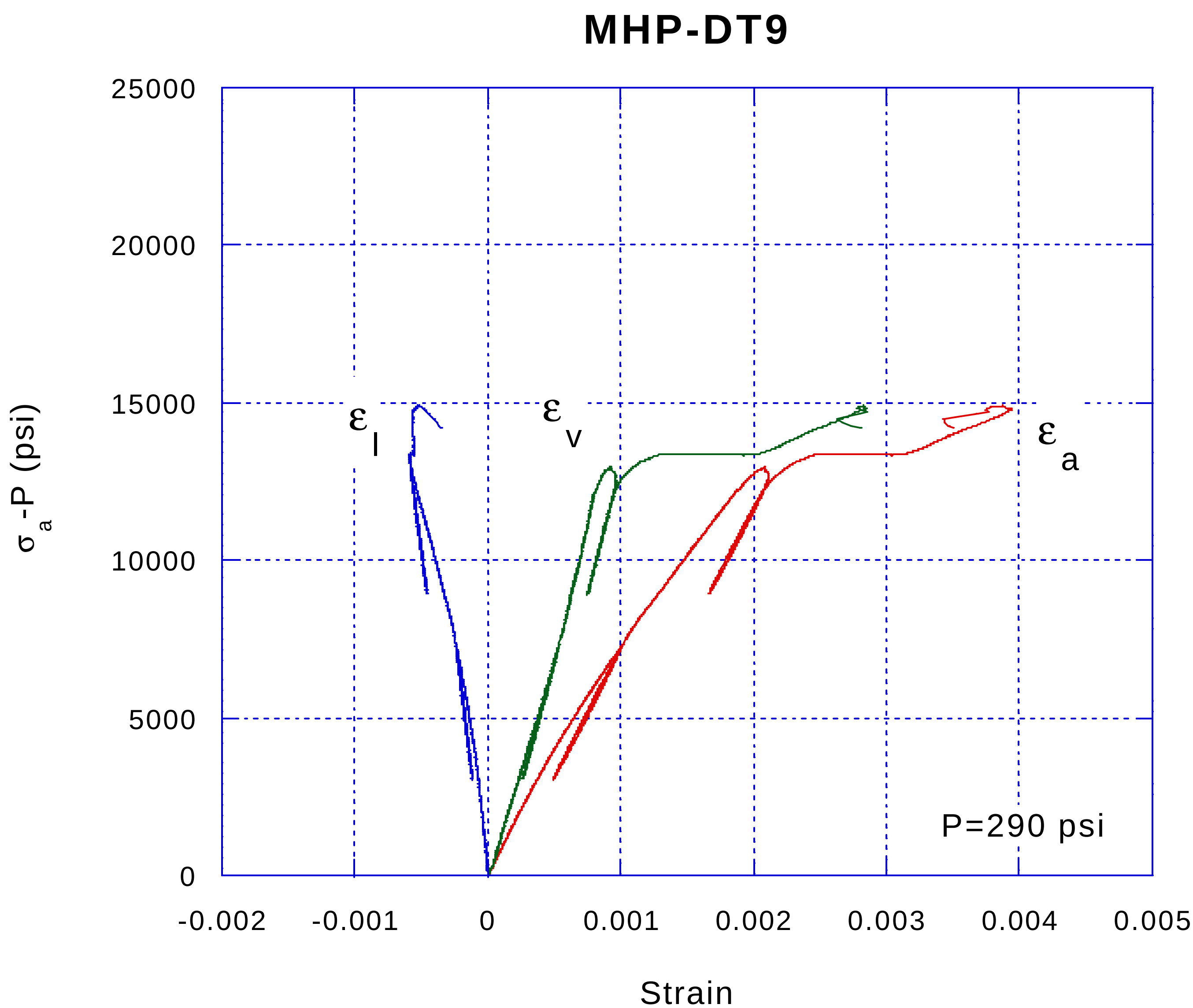

MHP-DT6
25000
20000
15000
10000
5000
0
-0.002
-0.001
0
0.001
0.002
0.003
0.004
0.005
Strain
σ_a-P (psi)
ε_l
ε_v
ε_a
P=727 psi

MHP-DT7

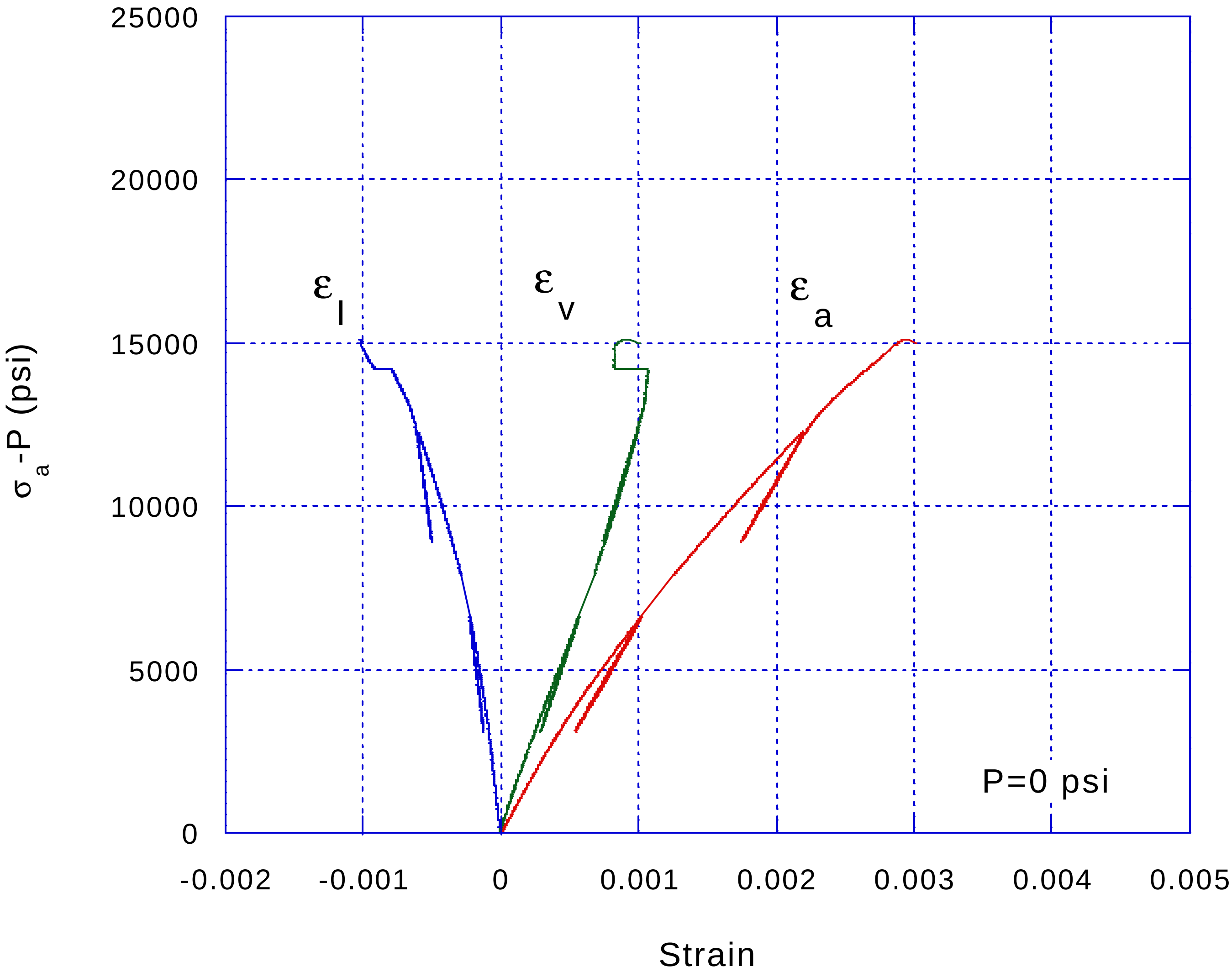


MHP-DT7
25000
20000
15000
10000
5000
0
-0.002
-0.001
0
0.001
0.002
0.003
0.004
0.005
Strain
σ_a-P (psi)
ε_l
ε_v
ε_a
P=2901 psi

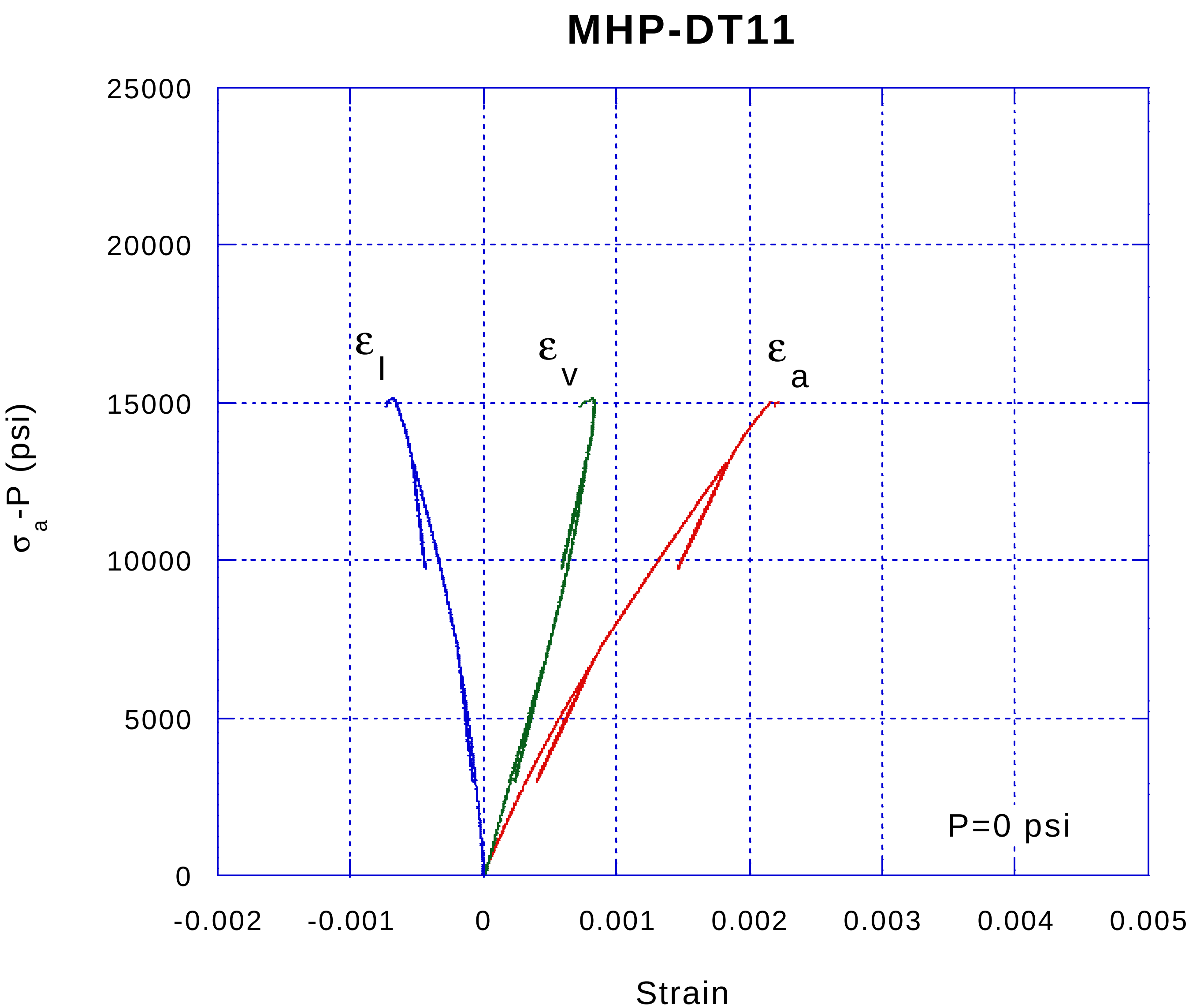

MHP-DT8
25000
20000
15000
10000
5000
0
σa-P (psi)
εl
εv
εa
P=290 psi
-0.002
-0.001
0
0.001
0.002
0.003
0.004
0.005
Strain

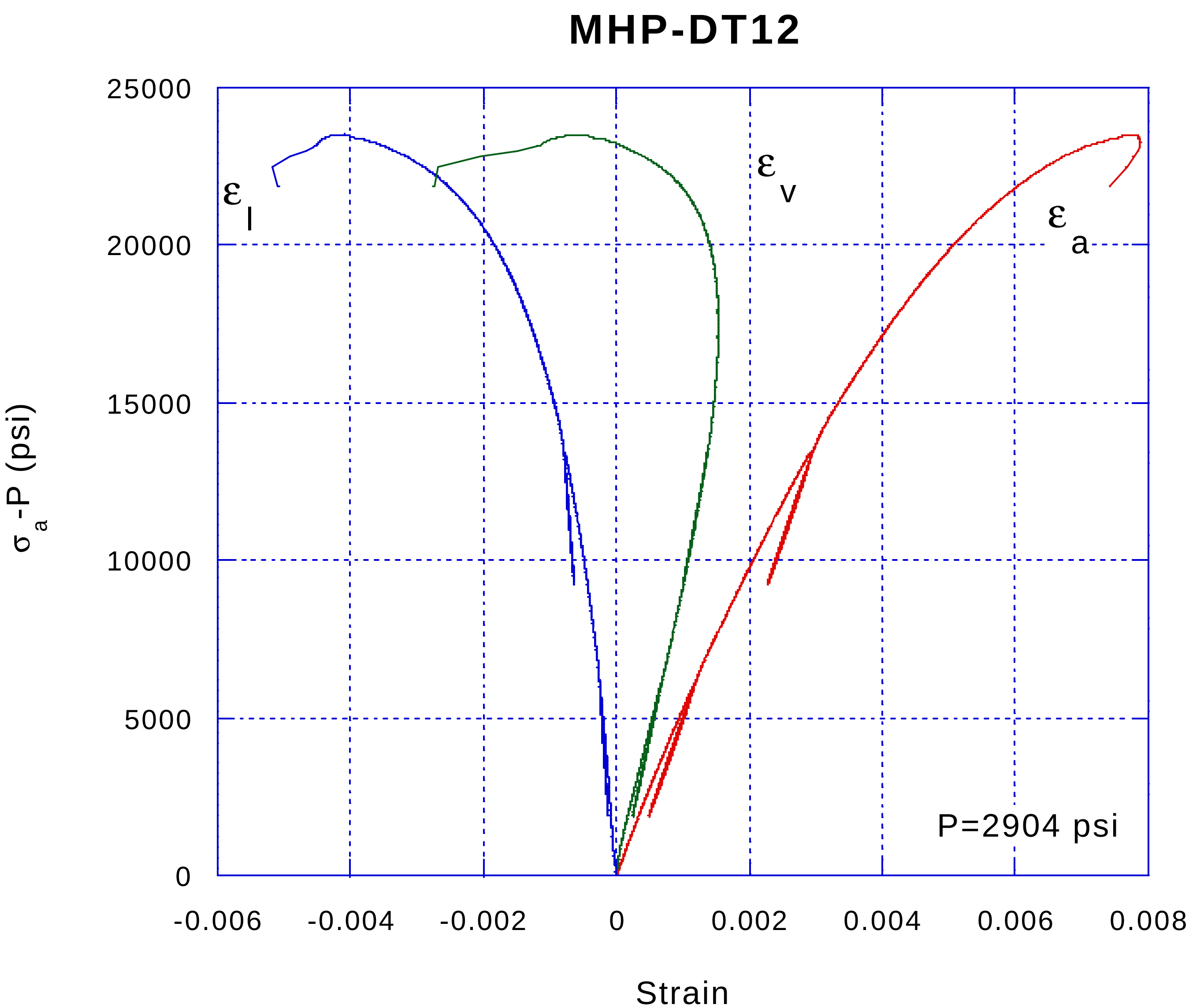

MHP-DT9
25000
20000
15000
10000
5000
0
σa-P (psi)
-0.002
-0.001
0
0.001
0.002
0.003
0.004
0.005
Strain
εl
εv
εa
P=290 psi

MHP-DT10



25000
20000
15000
10000
5000
0
-0.002
-0.001
0
0.001
0.002
0.003
0.004
0.005
σ_a-P (psi)
Strain
ε_l
ε_v
ε_a
P=0 psi


MHP-DT11
25000
20000
15000
10000
5000
0
-0.002
-0.001
0
0.001
0.002
0.003
0.004
0.005
Strain
σ_a-P (psi)
ε_l
ε_v
ε_a
P=0 psi


MHP-DT12
25000
20000
15000
10000
5000
0
-0.006
-0.004
-0.002
0
0.002
0.004
0.006
0.008
Strain
σ_a-P (psi)
ε_l
ε_v
ε_a
P=2904 psi

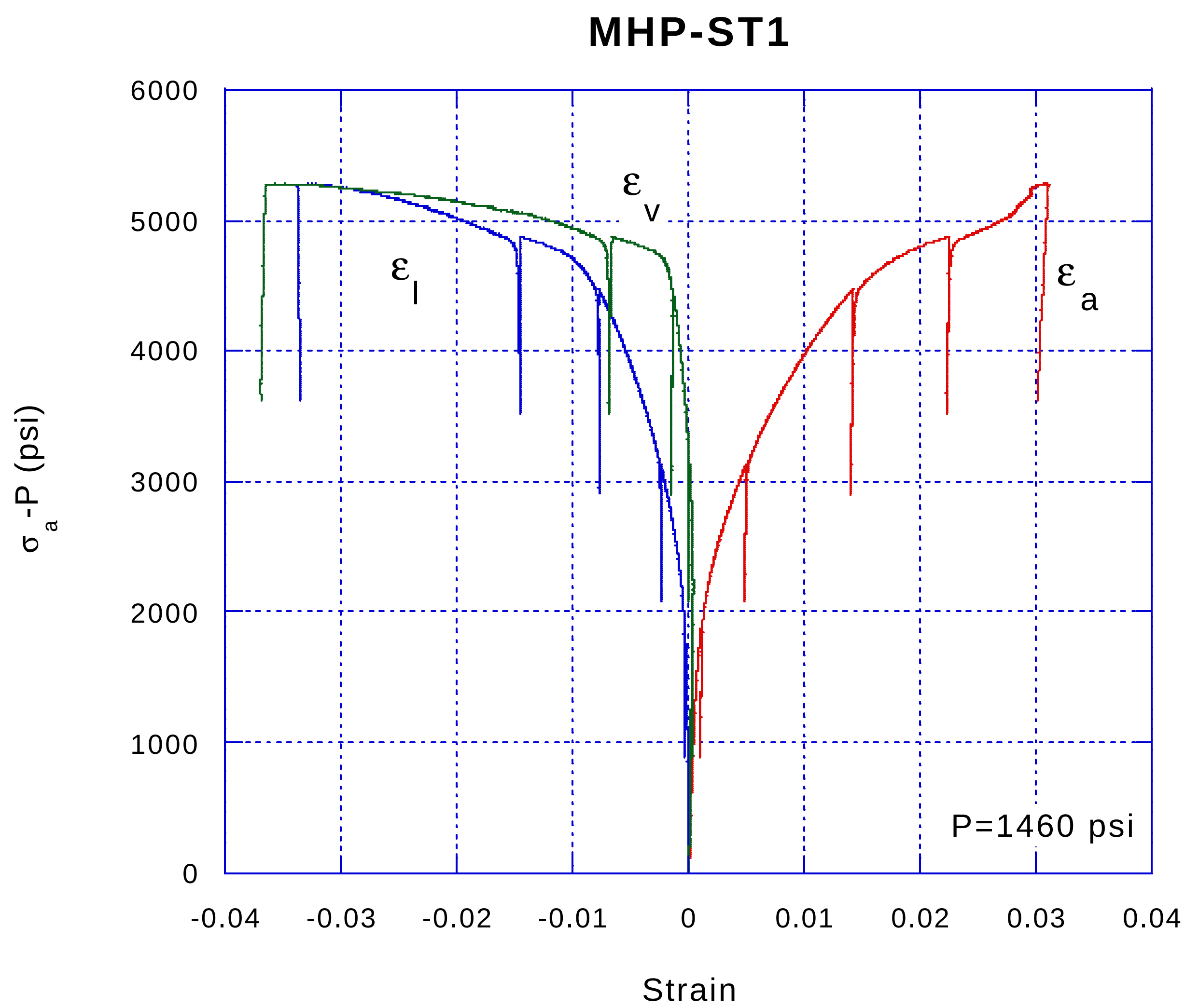
Appendix C

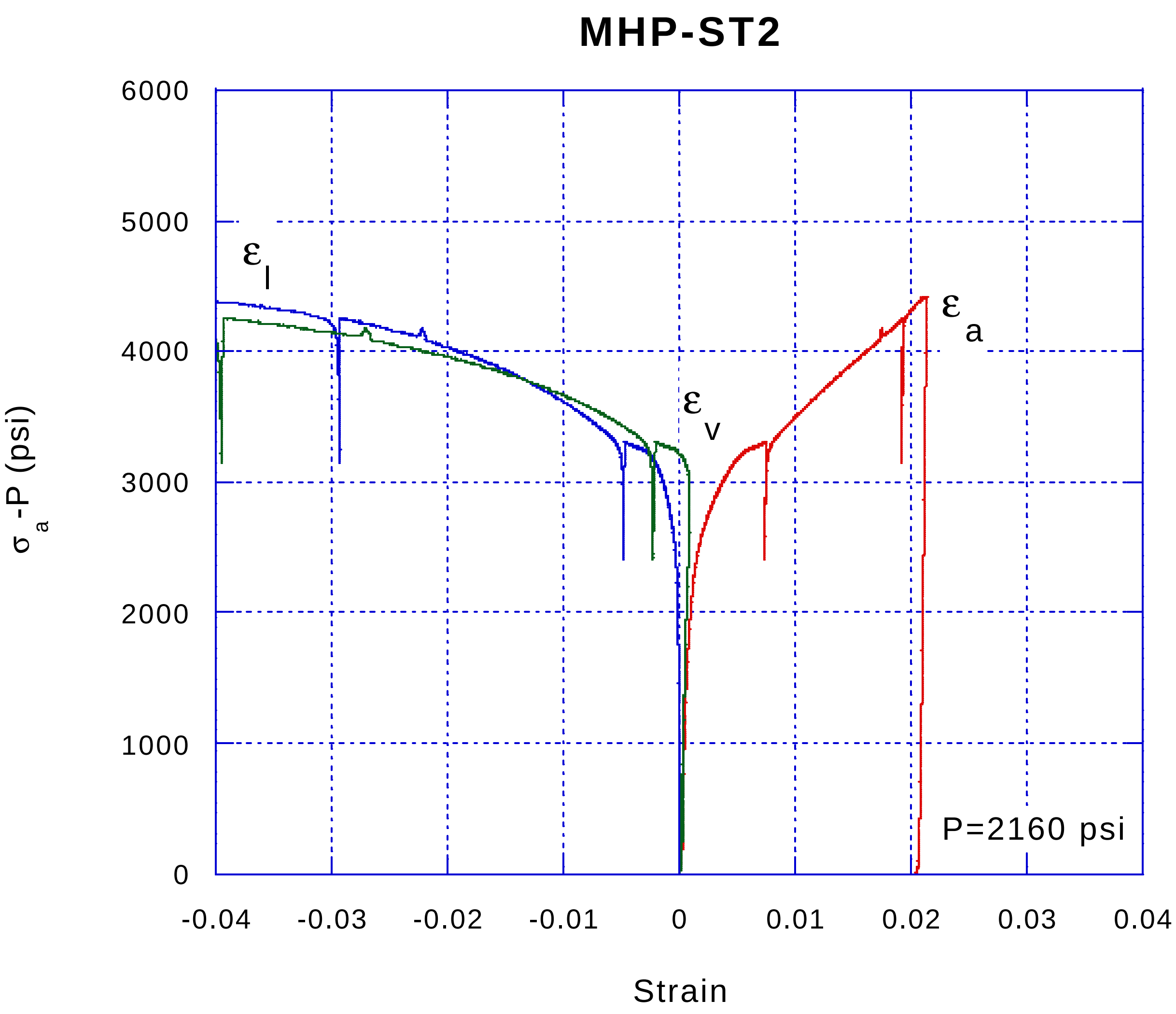
Stress-strain plots for Tioga rock salt obtained during the triaxial compression tests for the MHP project. Shown are the axial, lateral and calculated volumetric strains, respectively.

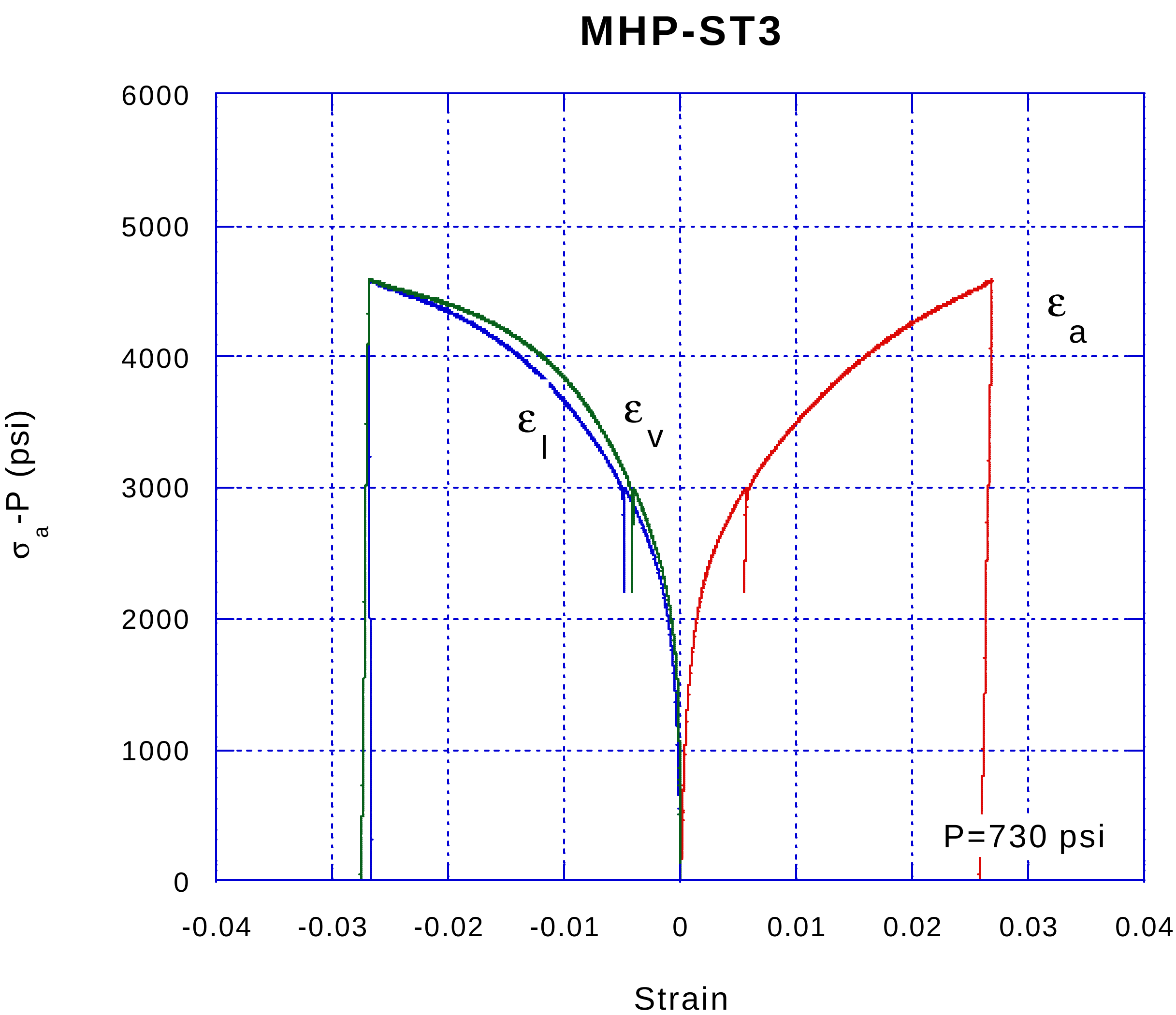
ε_a – axial strain (right or red line)
ε_l –lateral strain (left or blue line)
ε_v – volumetric strain (middle or green line)

Structure of the file name or the title of the plot

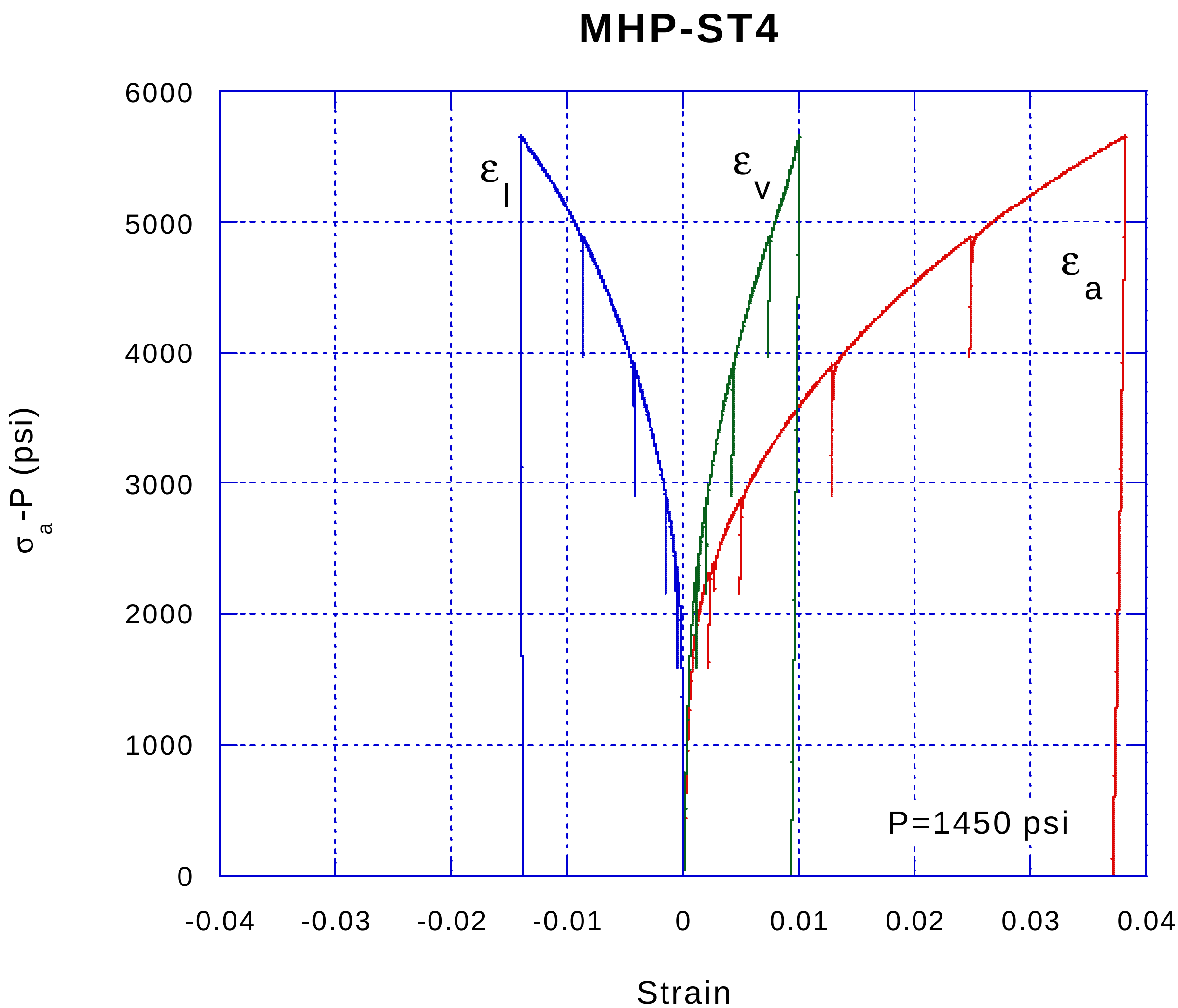
- MHP-ST1 to 12 (**MHP**, Tioga, Rock **S**alt, **T**riaxial compression #)
- #=sample number

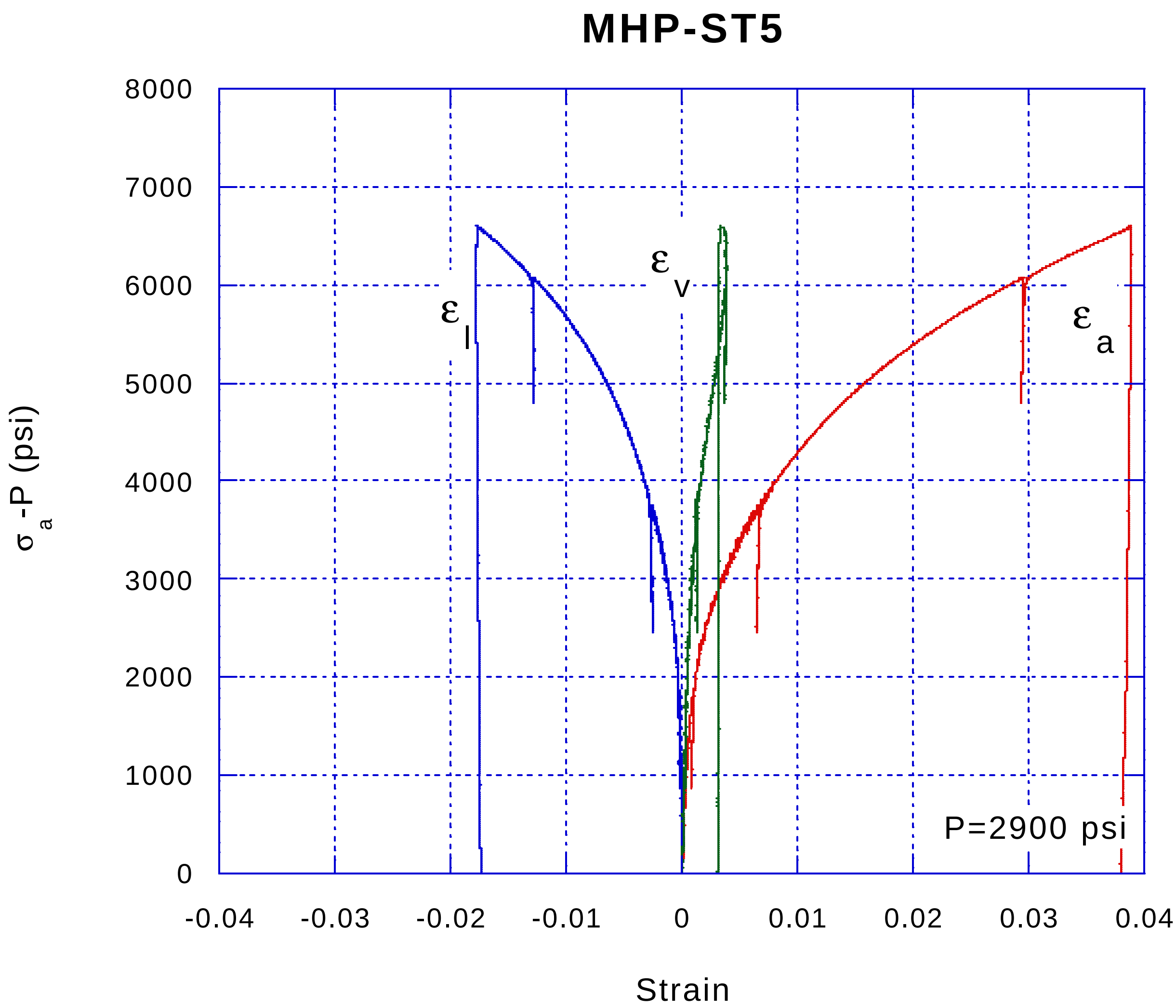

MHP-ST1
6000
5000
4000
3000
2000
1000
0
-0.04
-0.03
-0.02
-0.02
-0.01
0
0.01
0.02
0.03
0.04
Strain
σ_a-P (psi)
ε_v
ε_l
ε_a
P=1460 psi

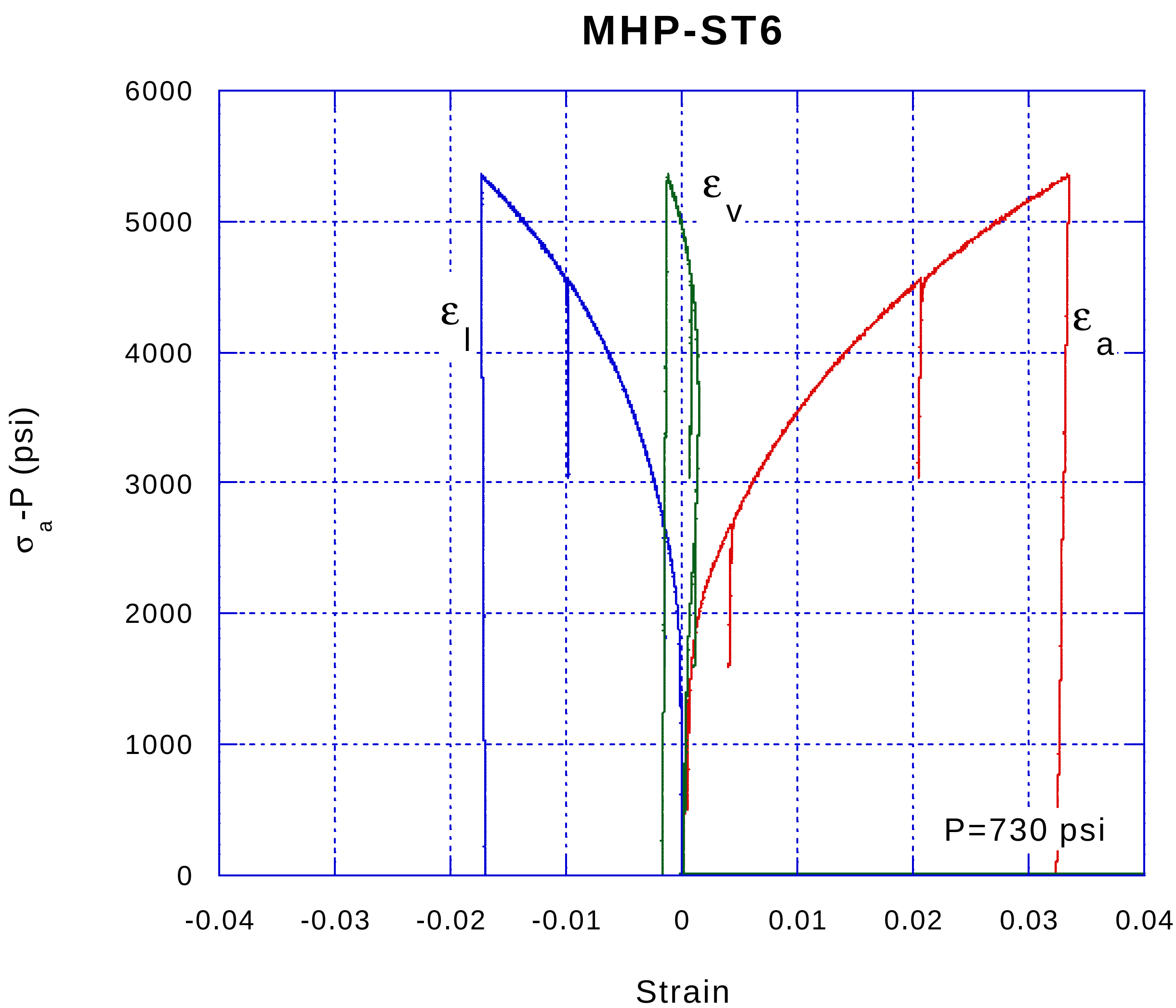

MHP-ST2
6000
5000
4000
3000
2000
1000
0
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
Strain
σ_a-P (psi)
ε_l
ε_v
ε_a
P=2160 psi

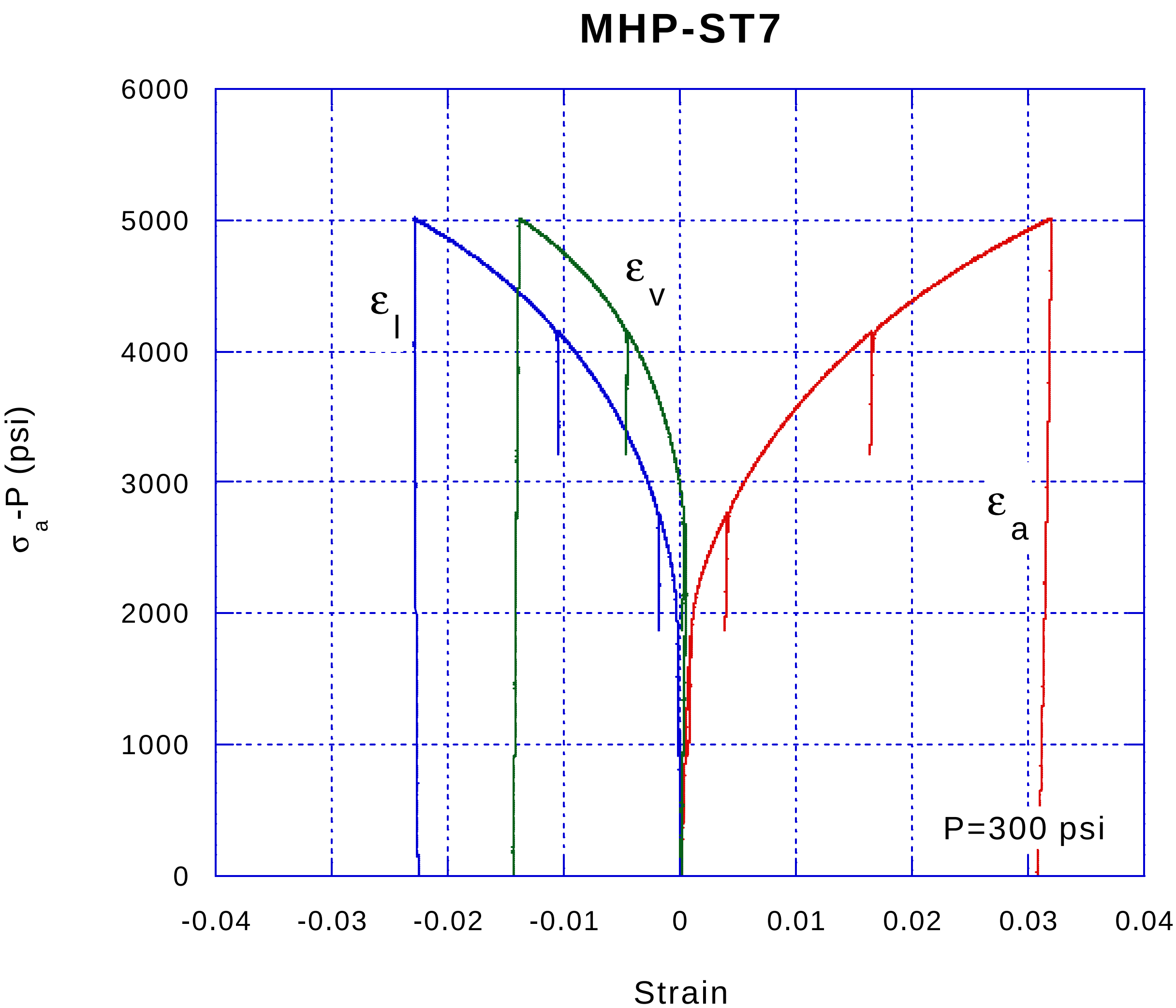


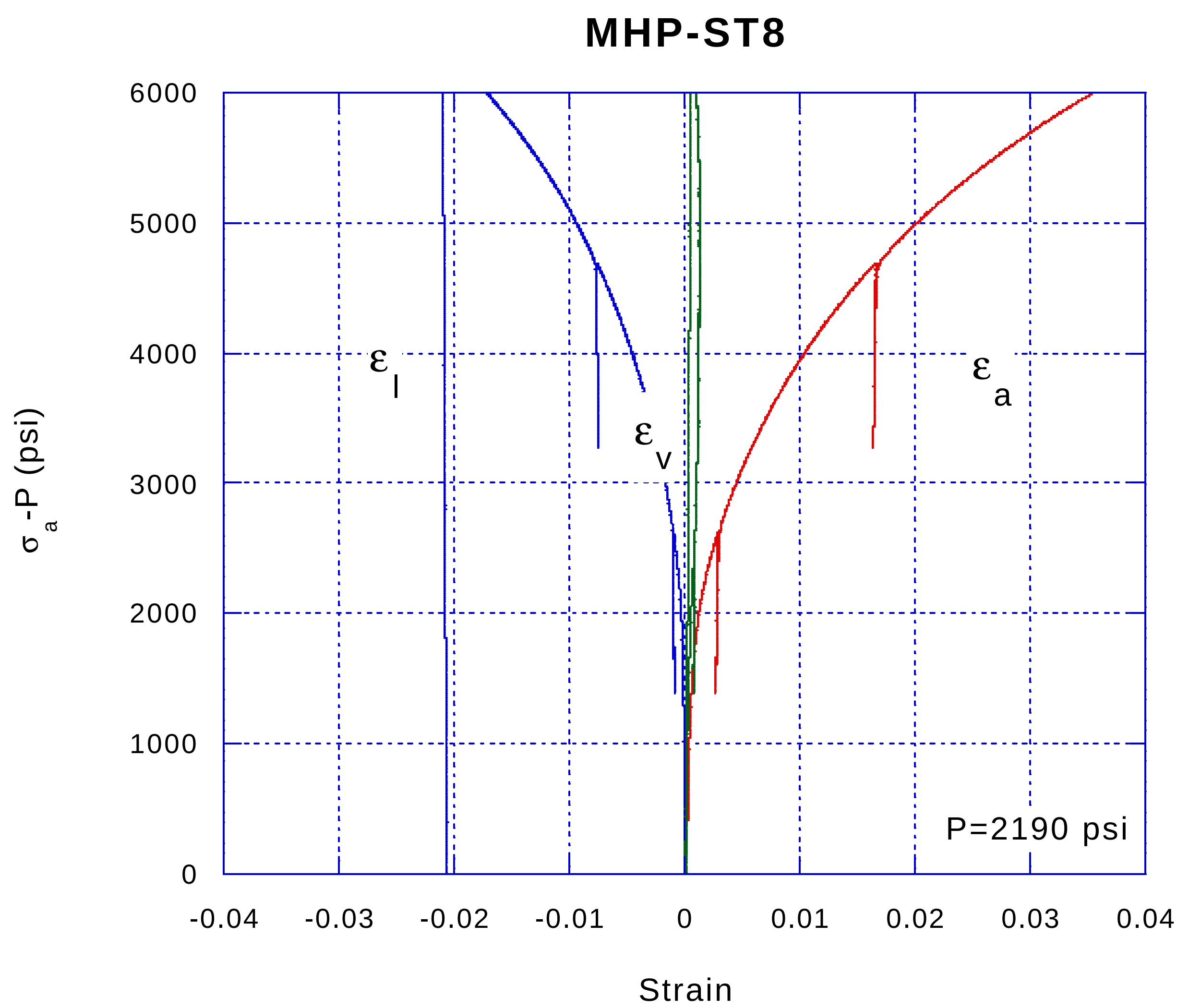
MHP-ST3
6000
5000
4000
3000
2000
1000
0
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
Strain
σ_a-P (psi)
ε_a
ε_l
ε_v
P=730 psi

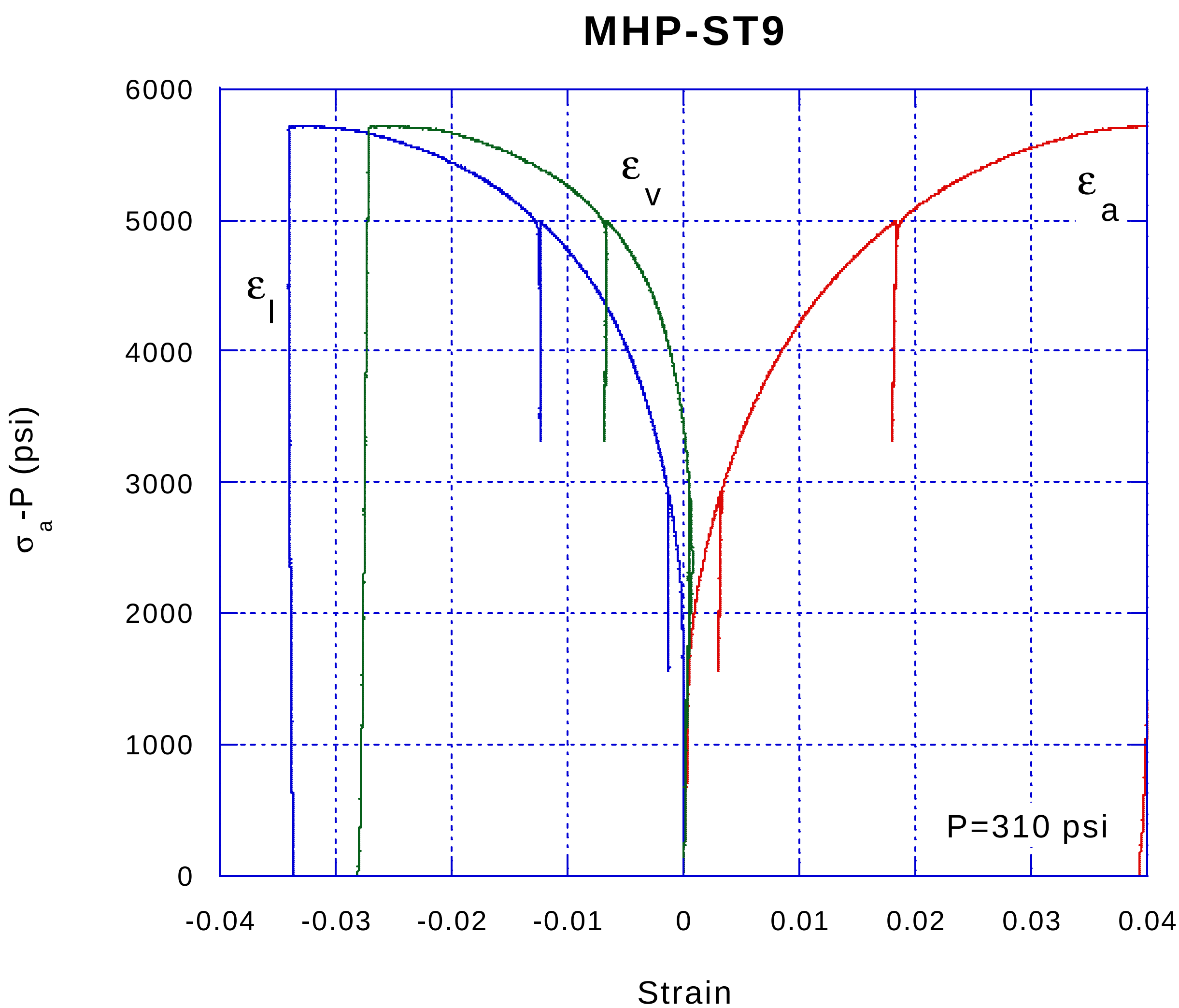

MHP-ST4
6000
5000
4000
3000
2000
1000
0
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
Strain
σ_a -P (psi)
ε_l
ε_v
ε_a
P=1450 psi

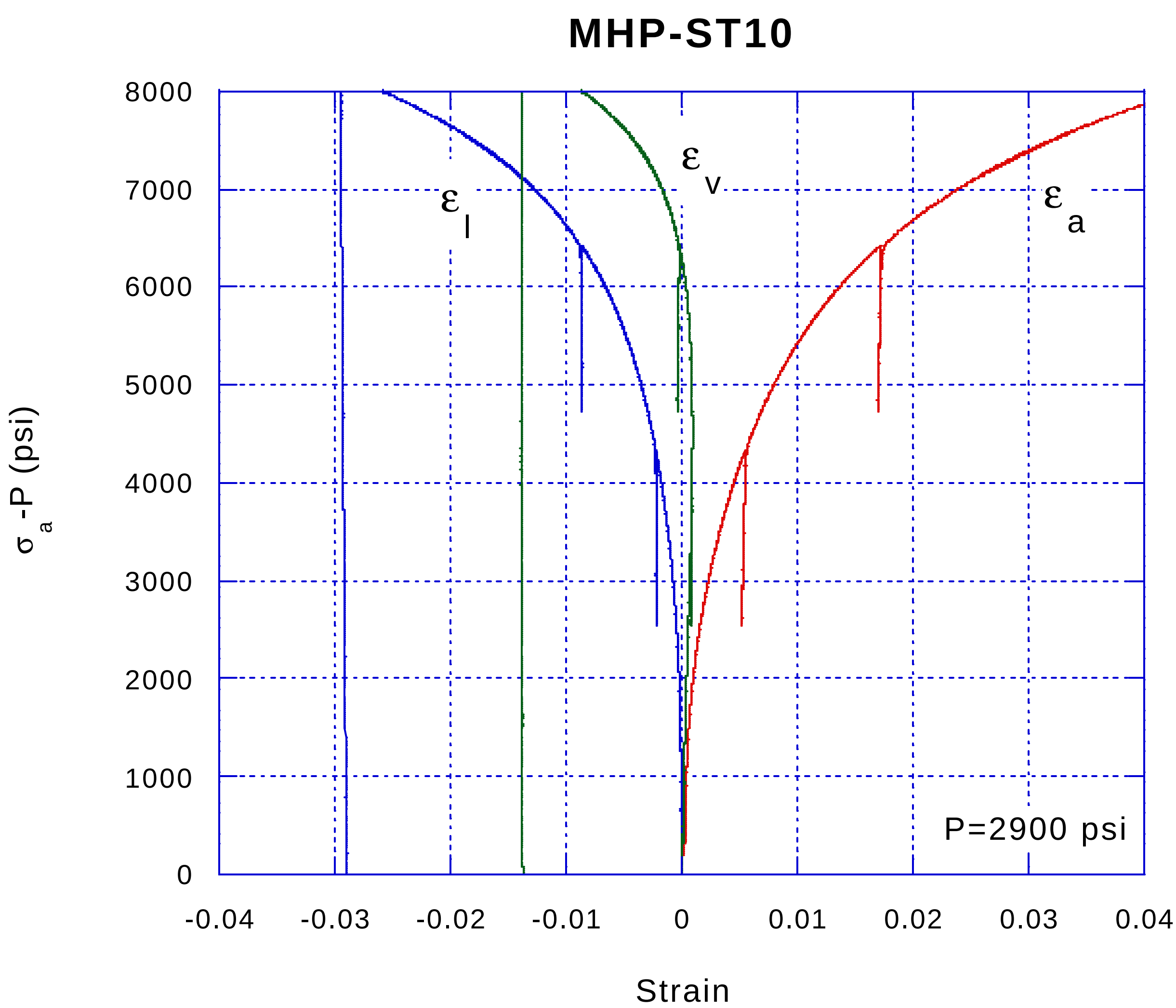

MHP-ST5
8000
7000
6000
5000
4000
3000
2000
1000
0
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
σ_a-P (psi)
Strain
ε_l
ε_v
ε_a
P=2900 psi

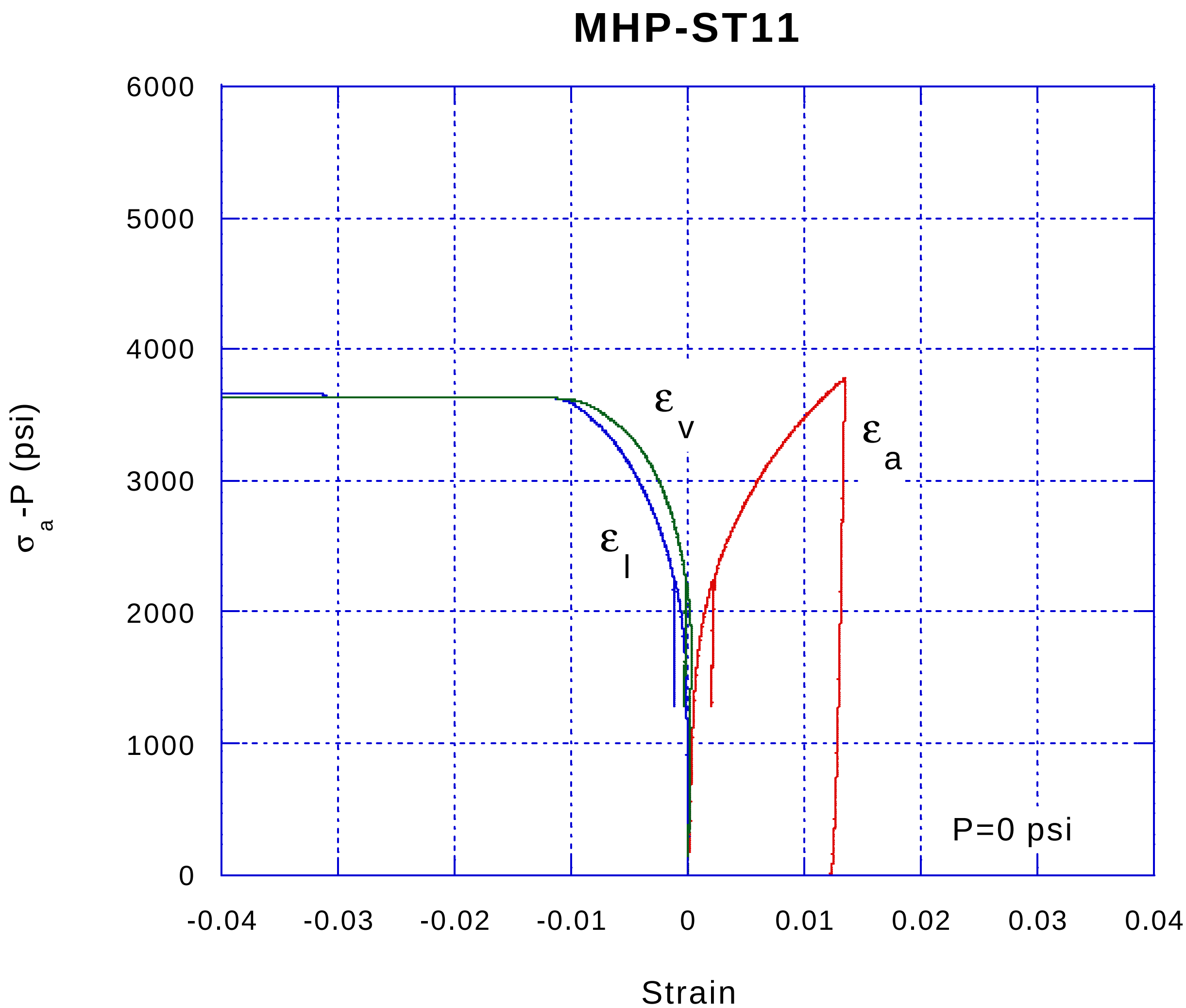

MHP-ST6
6000
5000
4000
3000
2000
1000
0
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
ε_v
ε_l
ε_a
P=730 psi
σ_a-P (psi)
Strain

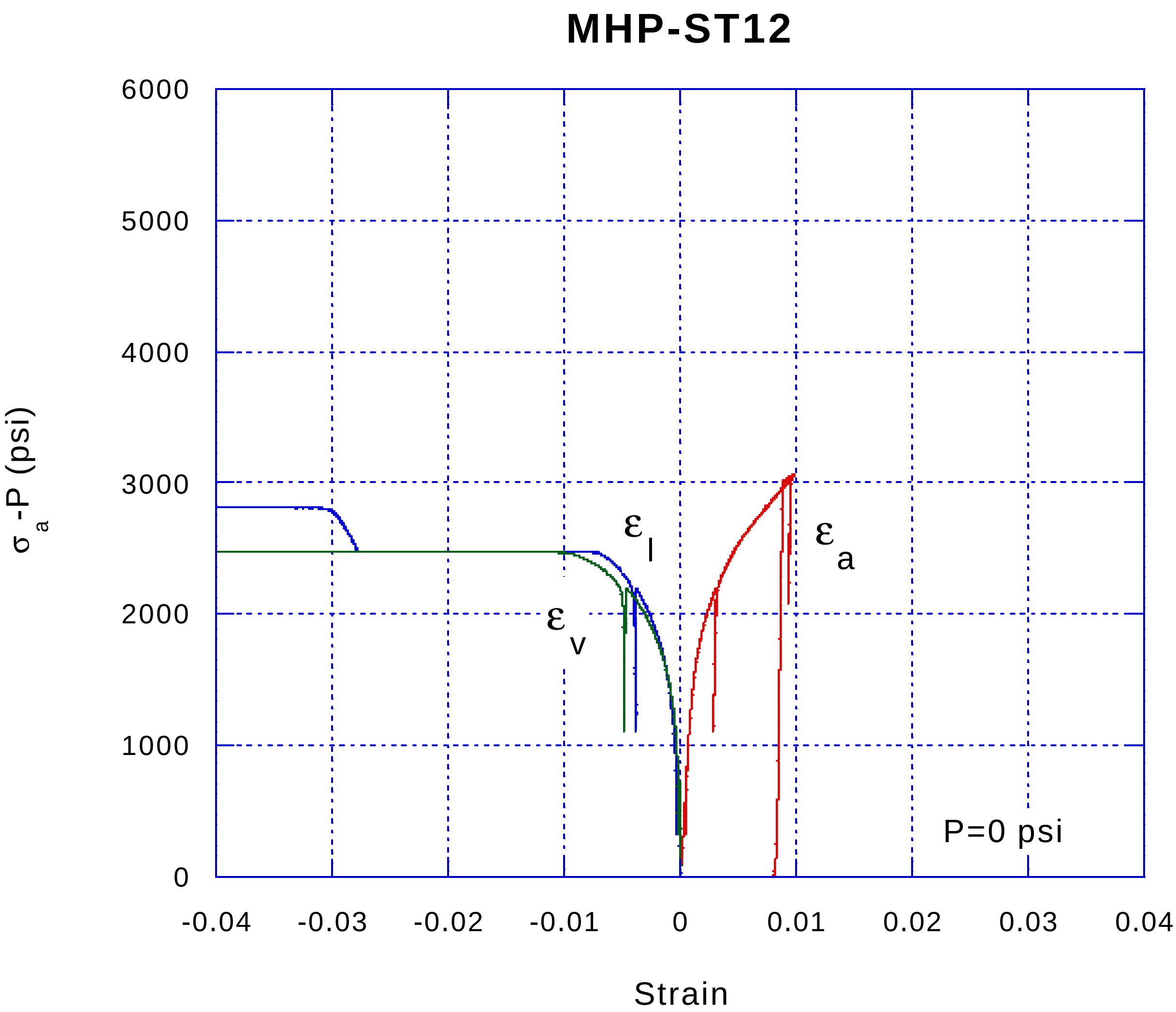

MHP-ST7
6000
5000
4000
3000
2000
1000
0
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
Strain
σ_a -P (psi)
ε_l
ε_v
ε_a
P=300 psi


MHP-ST8
6000
5000
4000
3000
2000
1000
0
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
ε_l
ε_v
ε_a
P=2190 psi
σ_a-P (psi)
Strain


MHP-ST9
6000
5000
4000
3000
2000
1000
0
σ a -P (psi)
ε l
ε v
ε a
P=310 psi
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
Strain


MHP-ST10
8000
7000
6000
5000
4000
3000
2000
1000
0
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
Strain
σ a -P (psi)
ε l
ε v
ε a
P=2900 psi


MHP-ST11
6000
5000
4000
3000
2000
1000
0
σ a -P (psi)
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
Strain
ε v
ε a
ε l
P=0 psi


MHP-ST12
6000
5000
4000
3000
2000
1000
0
σa -P (psi)
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
Strain
εl
εa
εv
P=0 psi

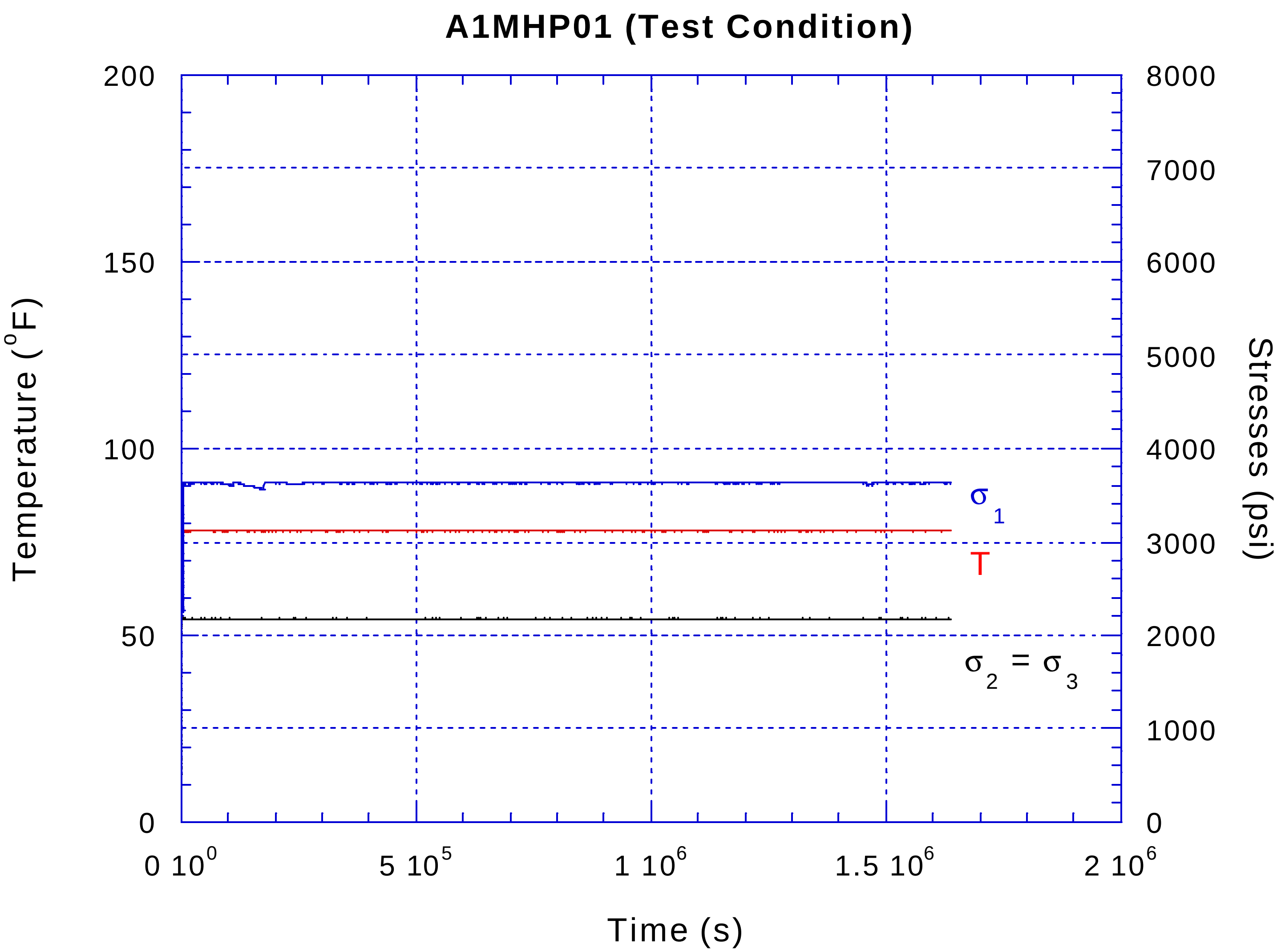
Appendix D

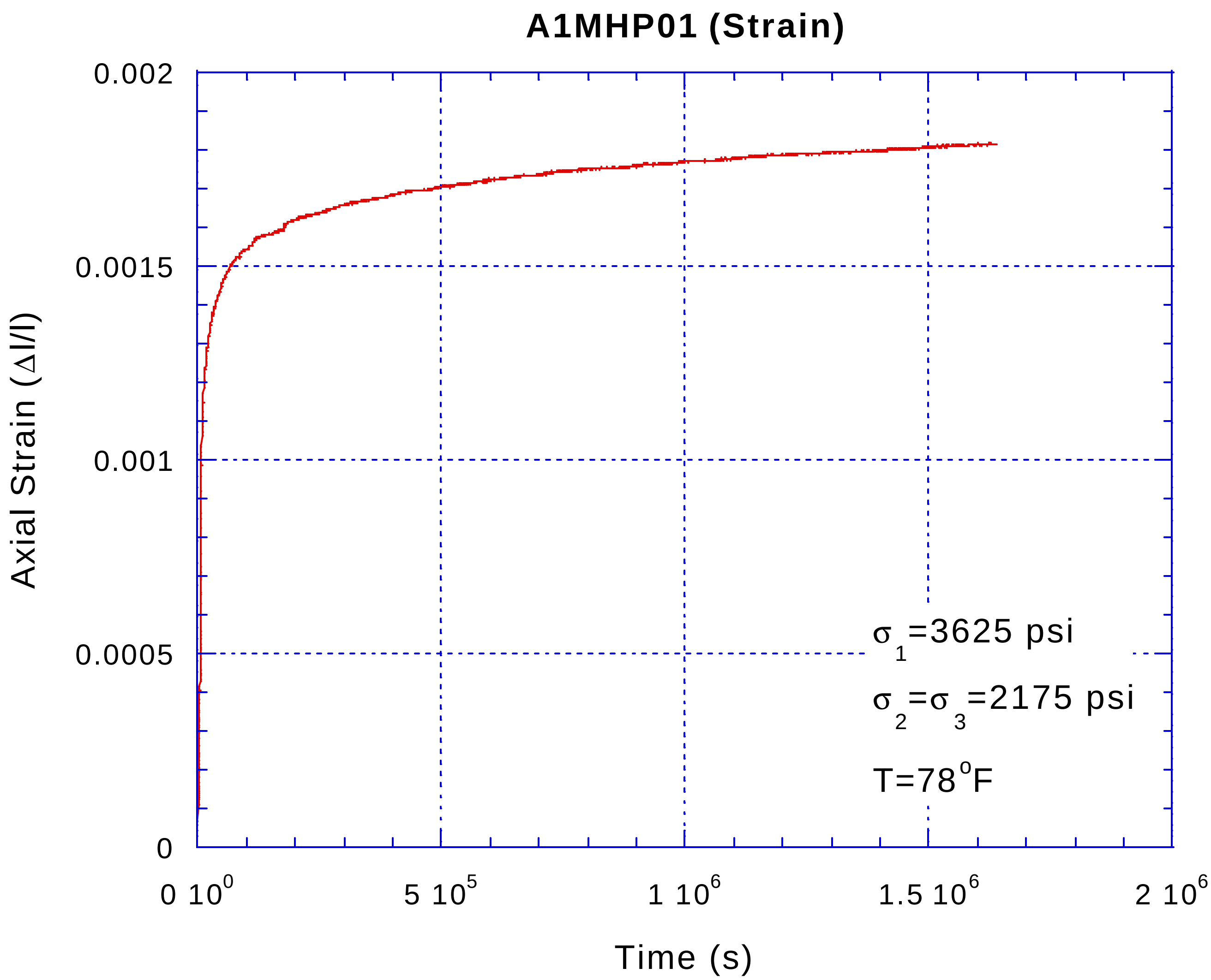
Test conditions, Strain vs. Time, and Strain-rate vs. Time plots for Tioga rock salt obtained during the steady-state triaxial creep tests for the MHP project.

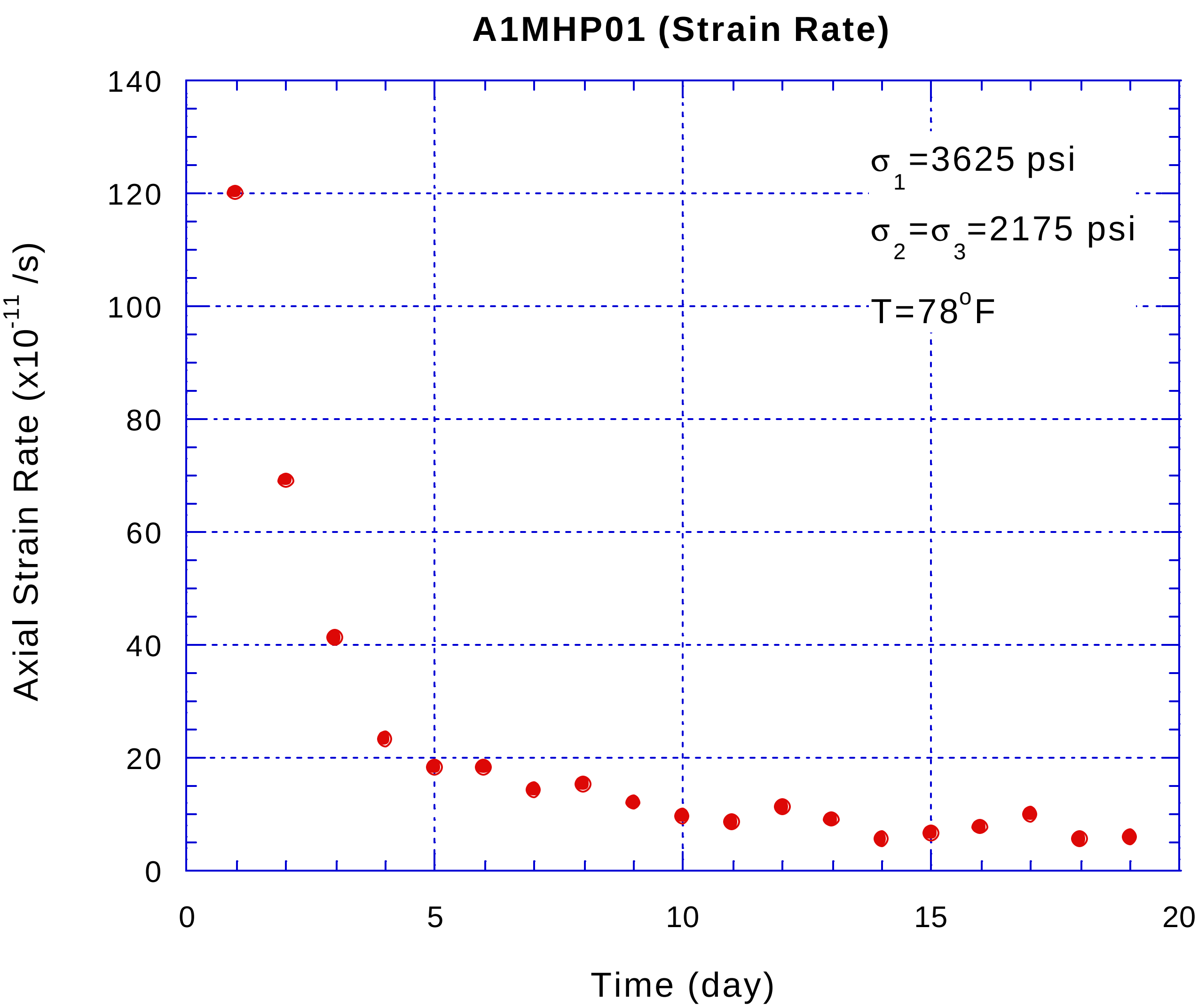
ε_a – axial strain (right or red line)
ε_l –lateral strain (left or blue line)
ε_v – volumetric strain (middle or green line)

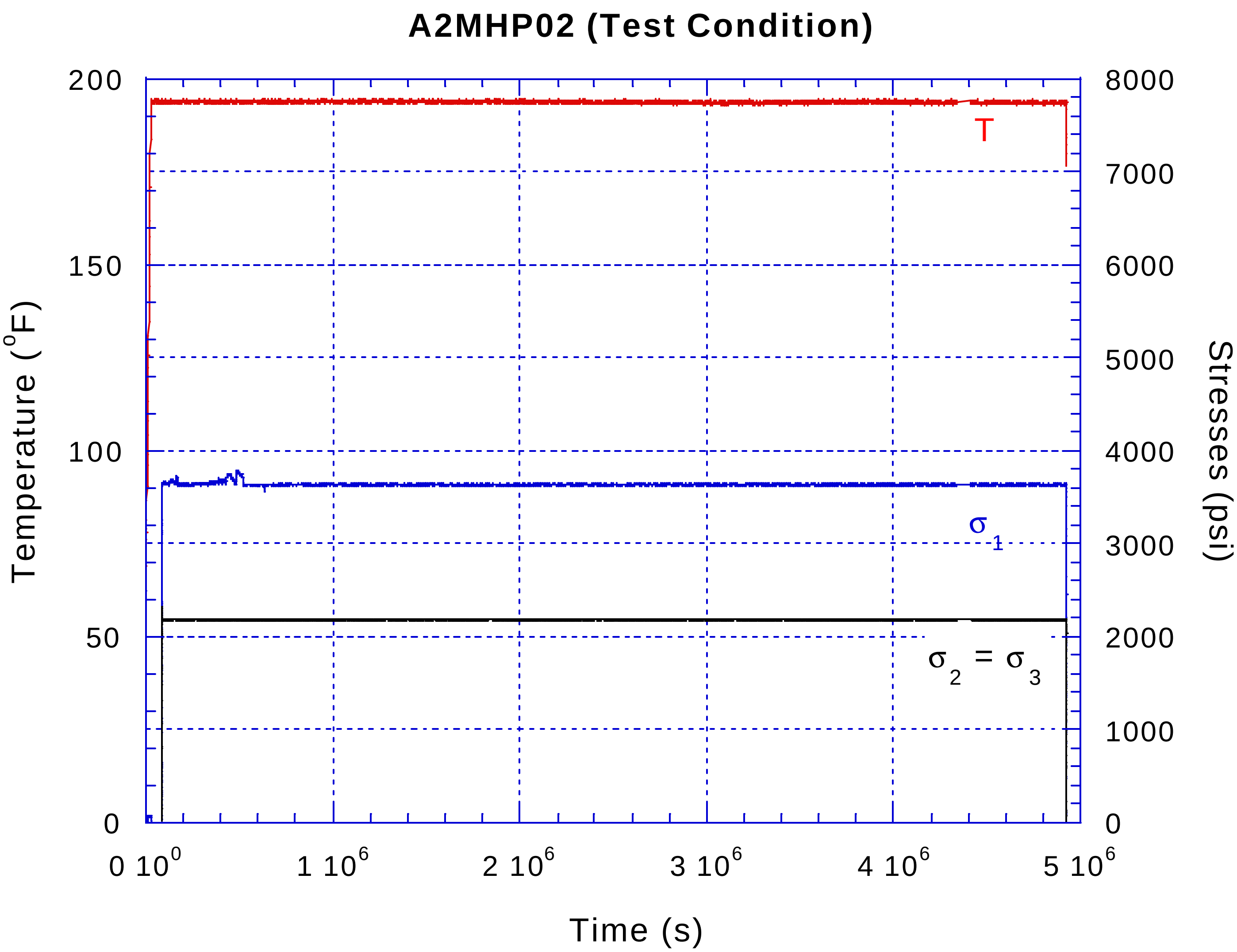
Structure of the file name or the title of the plot

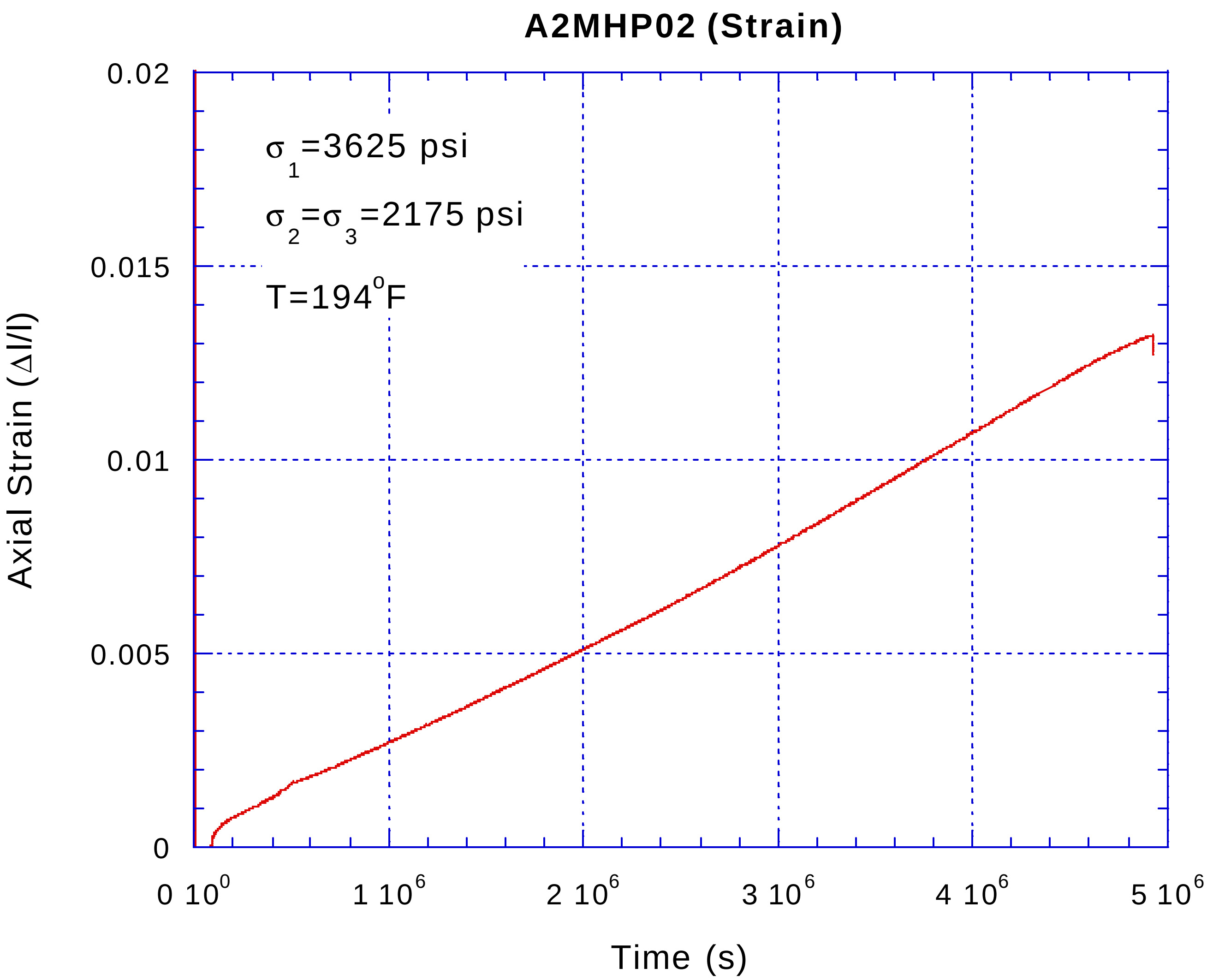
- A*MHP0# (*-creep apparatus I.D, #-sample number)

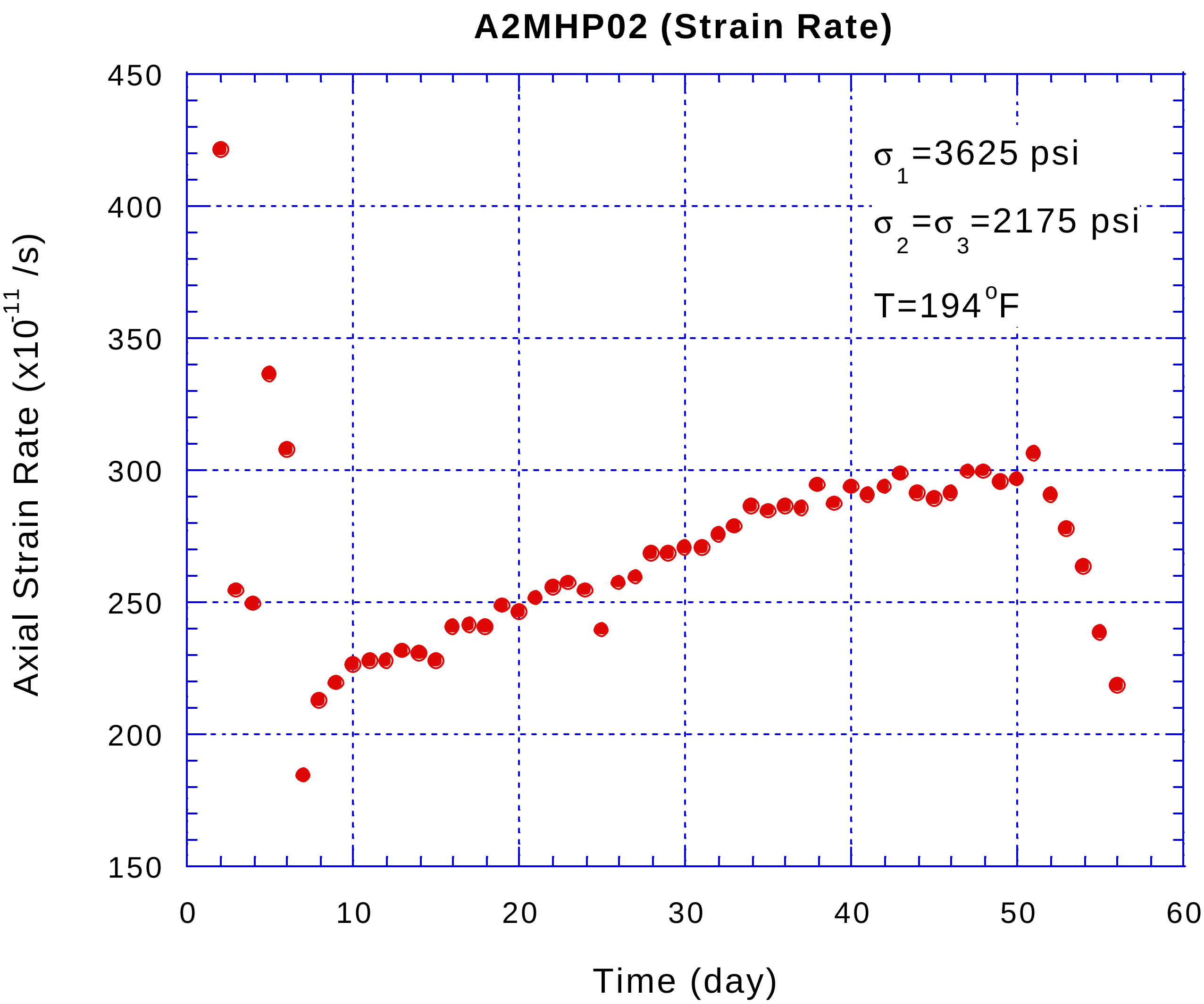

A1MHP01 (Test Condition)
Temperature (°F)
Stresses (psi)
Time (s)
σ1
T
σ2 = σ3
0
50
100
150
200
0
1000
2000
3000
4000
5000
6000
7000
8000
0 10^0
5 10^5
1 10^6
1.5 10^6
2 10^6

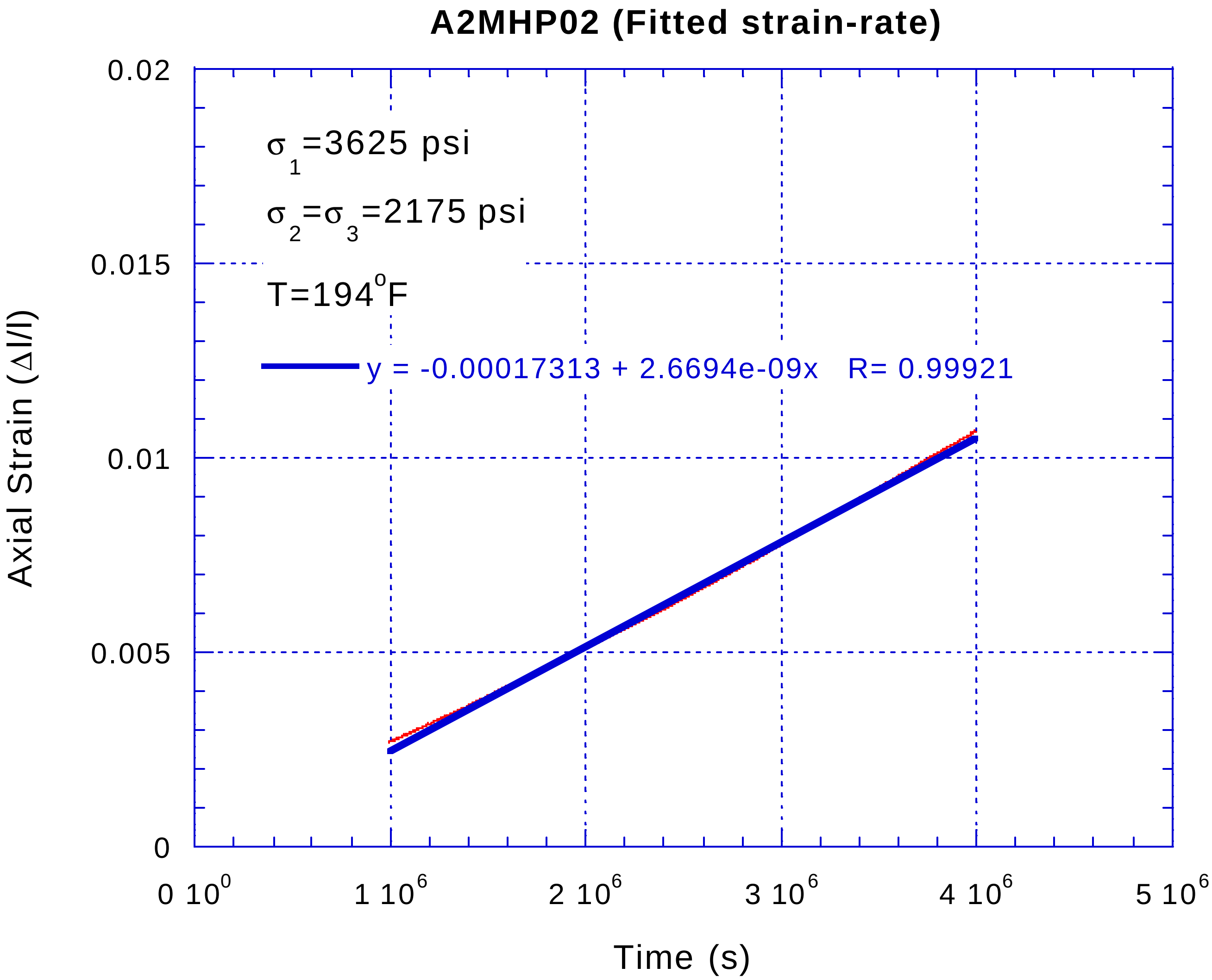

A1MHP01 (Strain)
0.002
0.0015
0.001
0.0005
0
Axial Strain (Δl/l)
σ_1=3625 psi
σ_2=σ_3=2175 psi
T=78°F
0 10^0
5 10^5
1 10^6
1.5 10^6
2 10^6
Time (s)


A1MHP01 (Strain Rate)
σ1=3625 psi
σ2=σ3=2175 psi
T=78oF
Axial Strain Rate (x10-11 /s)
Time (day)
0
20
40
60
80
100
120
140
0
5
10
15
20

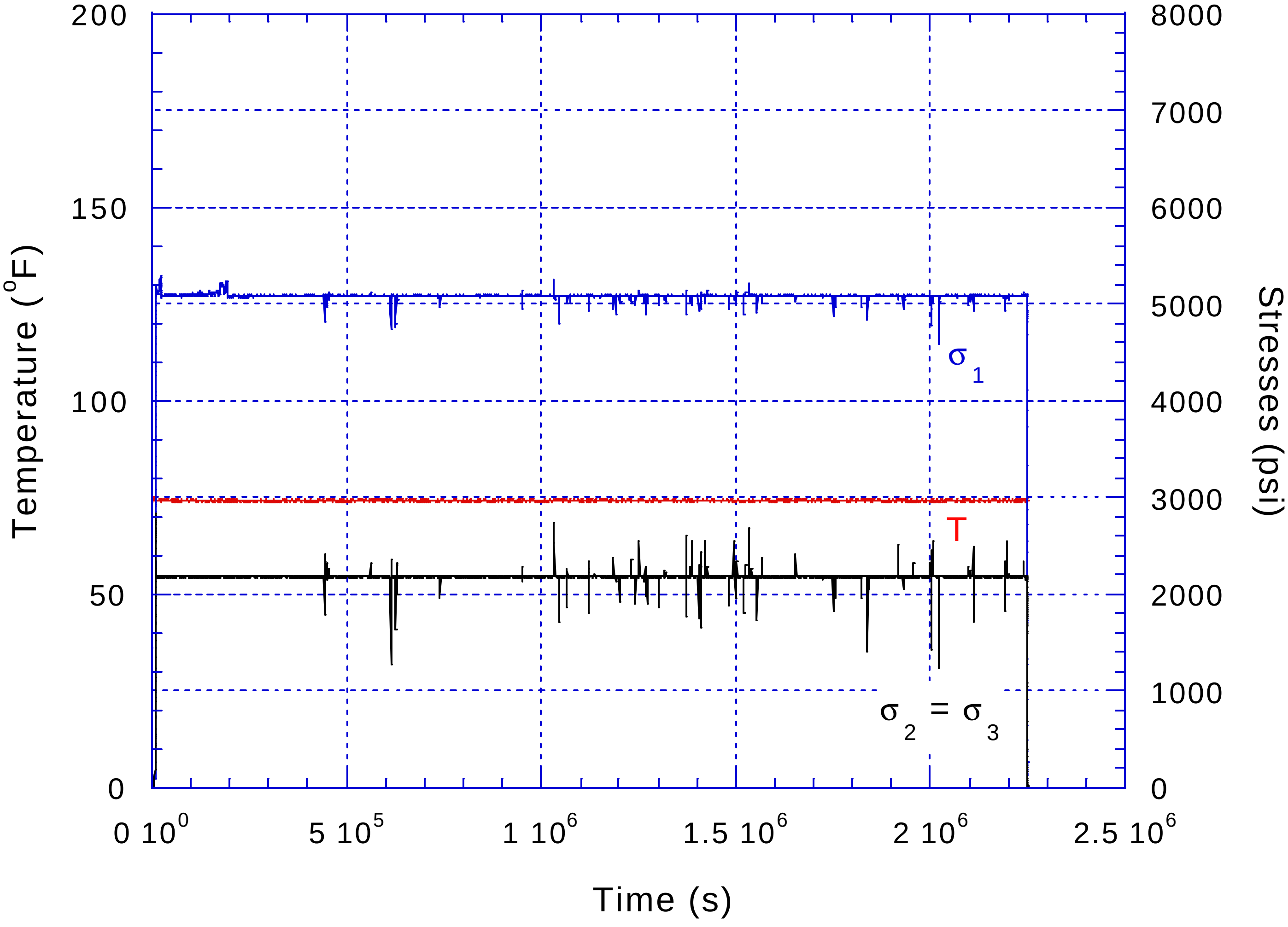

A2MHP02 (Test Condition)
Temperature (°F)
Stresses (psi)
Time (s)
200
150
100
50
0
8000
7000
6000
5000
4000
3000
2000
1000
0
0 10^0
1 10^6
2 10^6
3 10^6
4 10^6
5 10^6
T
σ1
σ2 = σ3

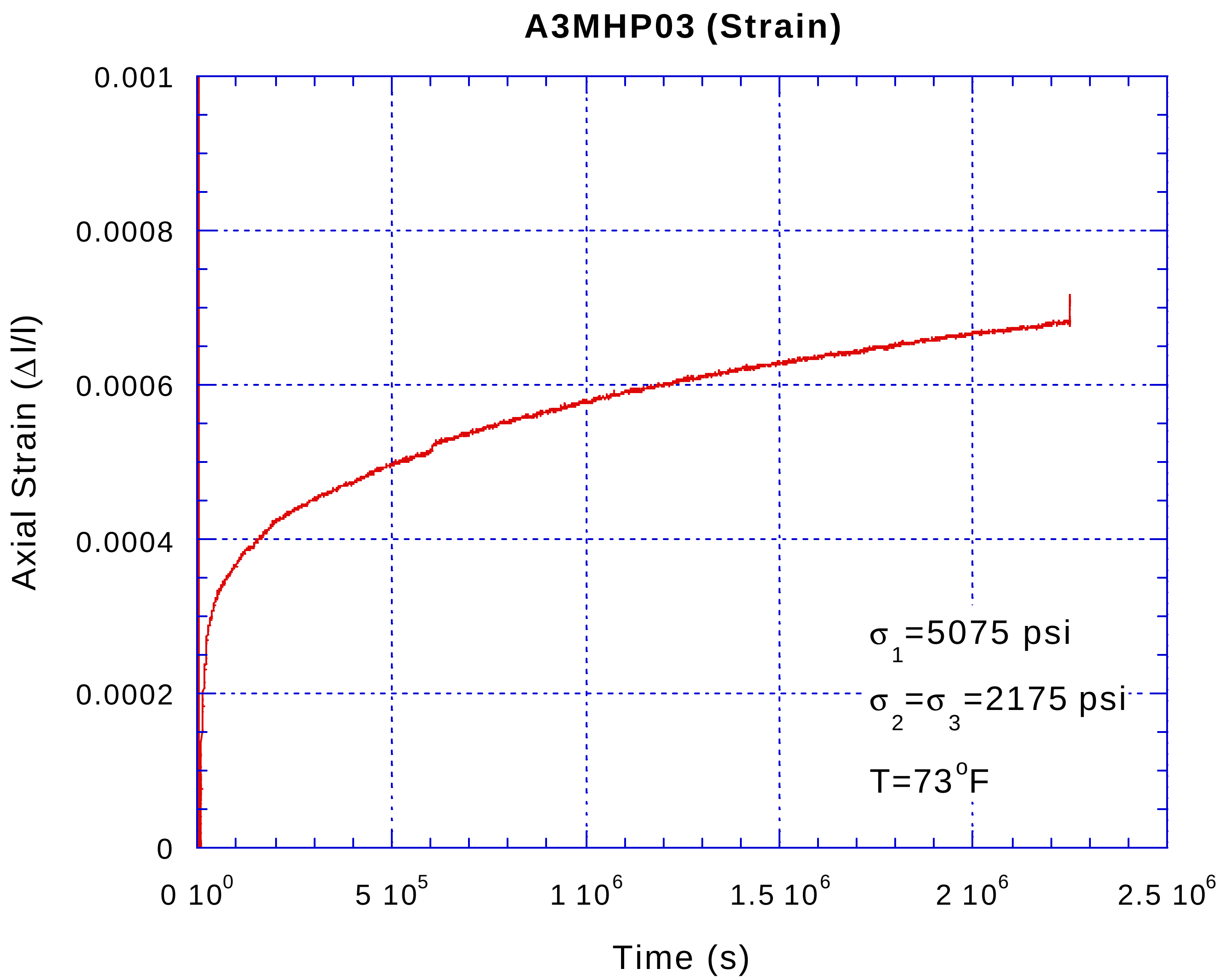

A2MHP02 (Strain)
σ1=3625 psi
σ2=σ3=2175 psi
T=194°F
Axial Strain (Δl/l)
0.02
0.015
0.01
0.005
0
0 10^0
1 10^6
2 10^6
3 10^6
4 10^6
5 10^6
Time (s)


A2MHP02 (Strain Rate)
σ1=3625 psi
σ2=σ3=2175 psi
T=194°F
Axial Strain Rate (x10-11 /s)
Time (day)
450
400
350
300
250
200
150
0
10
20
30
40
50
60

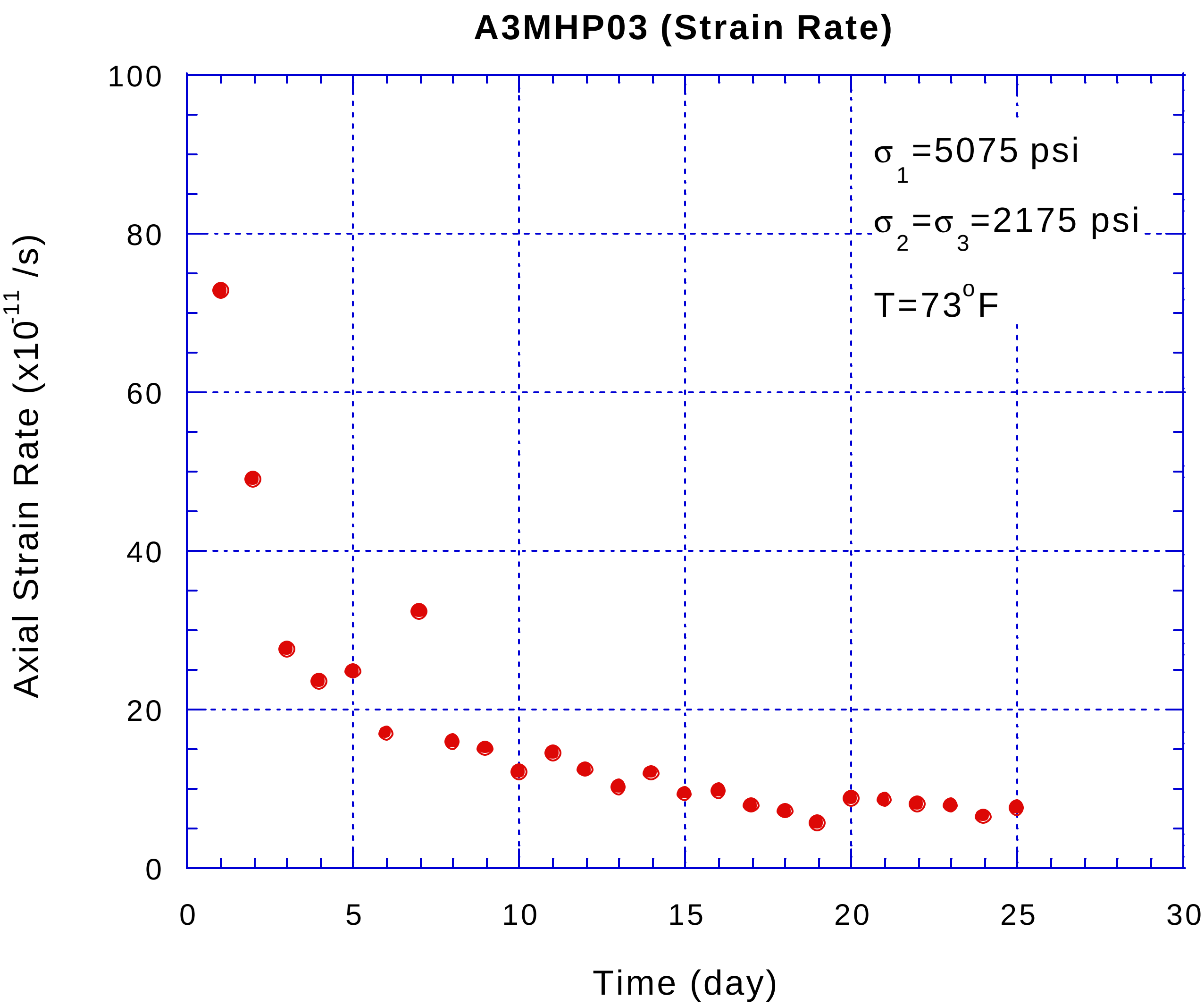

A2MHP02 (Fitted strain-rate)
σ1=3625 psi
σ2=σ3=2175 psi
T=194°F
y = -0.00017313 + 2.6694e-09x R= 0.99921
Axial Strain (Δl/l)
Time (s)
0.02
0.015
0.01
0.005
0
0 10^0
1 10^6
2 10^6
3 10^6
4 10^6
5 10^6

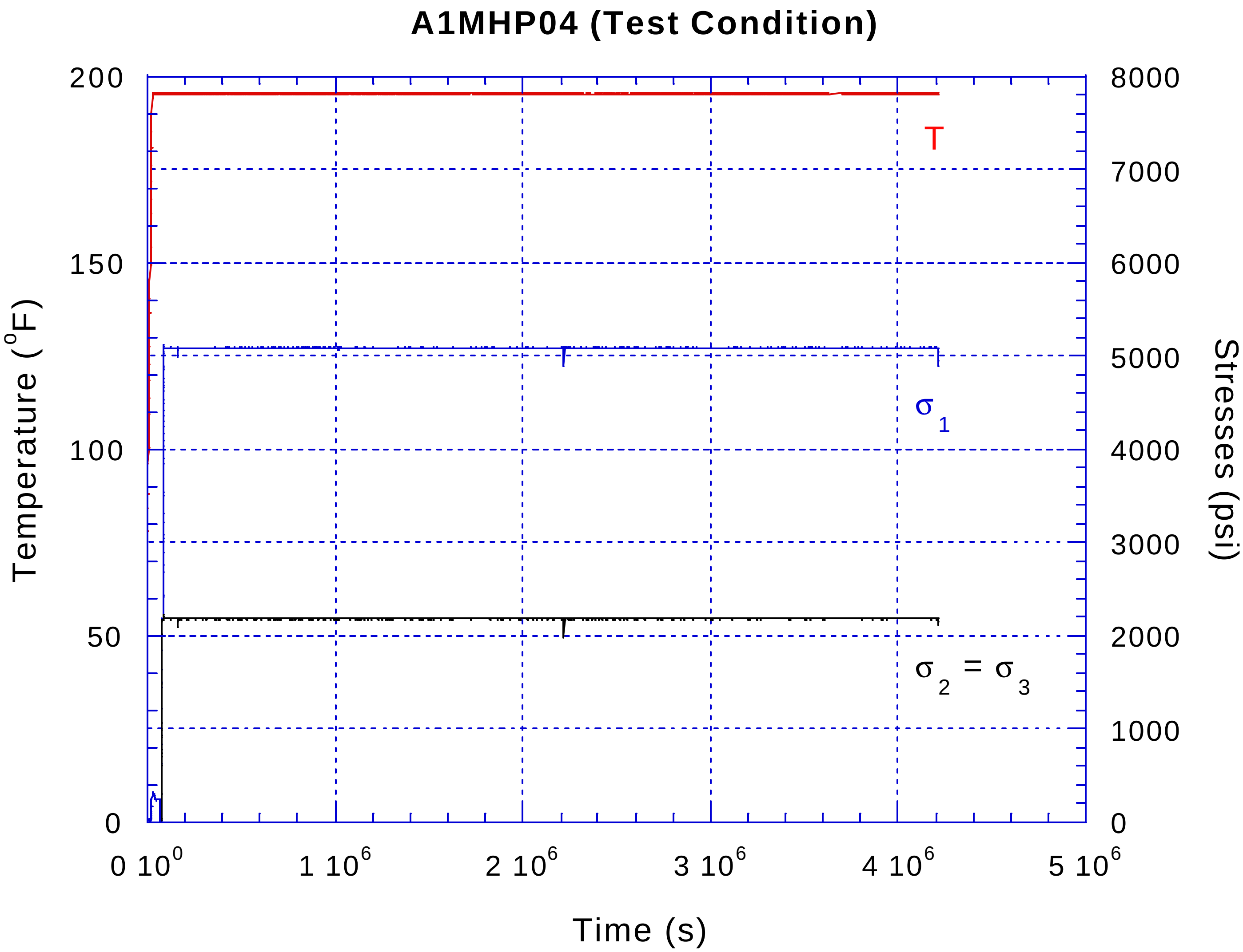
A3MHP03 (Test Condition)

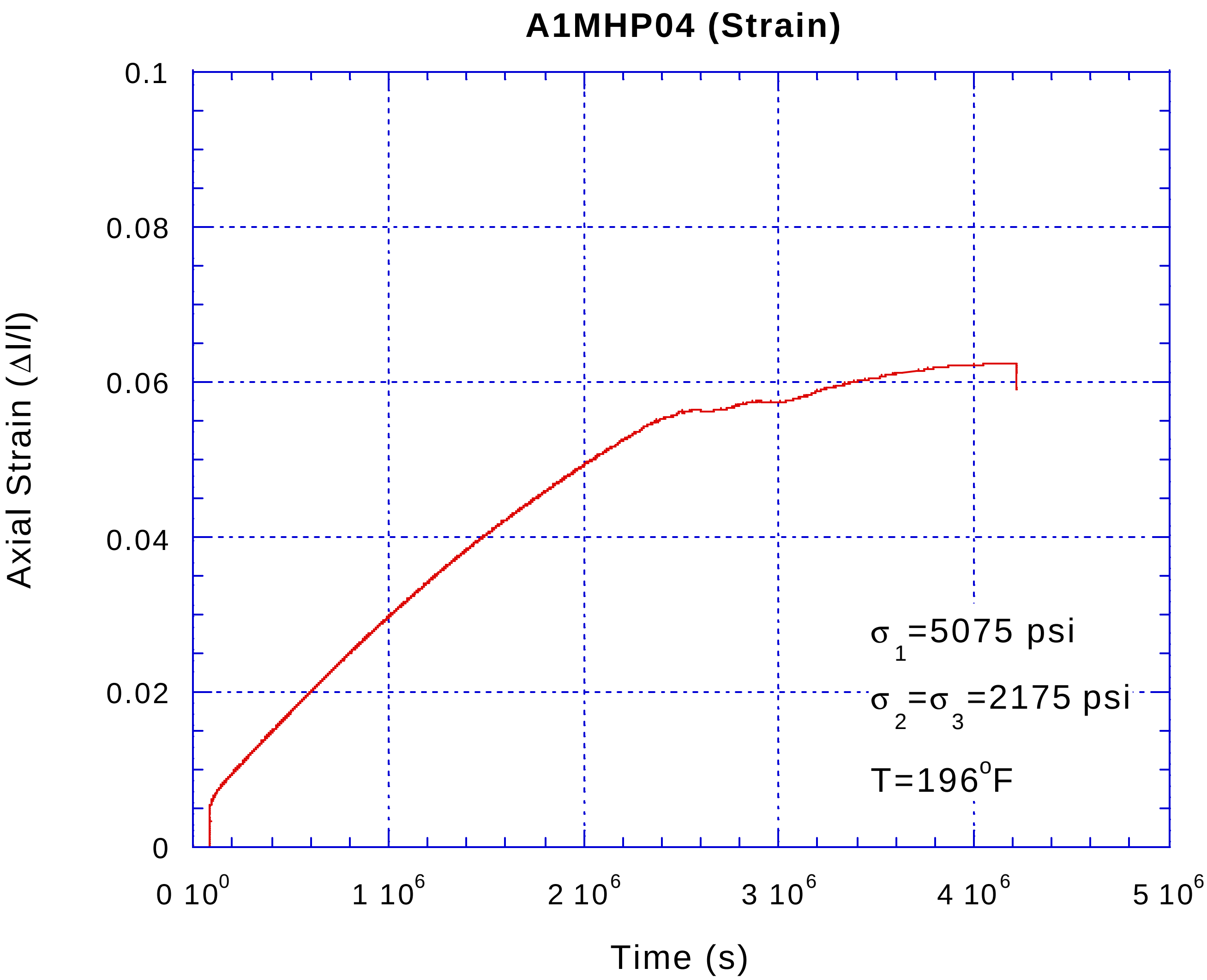


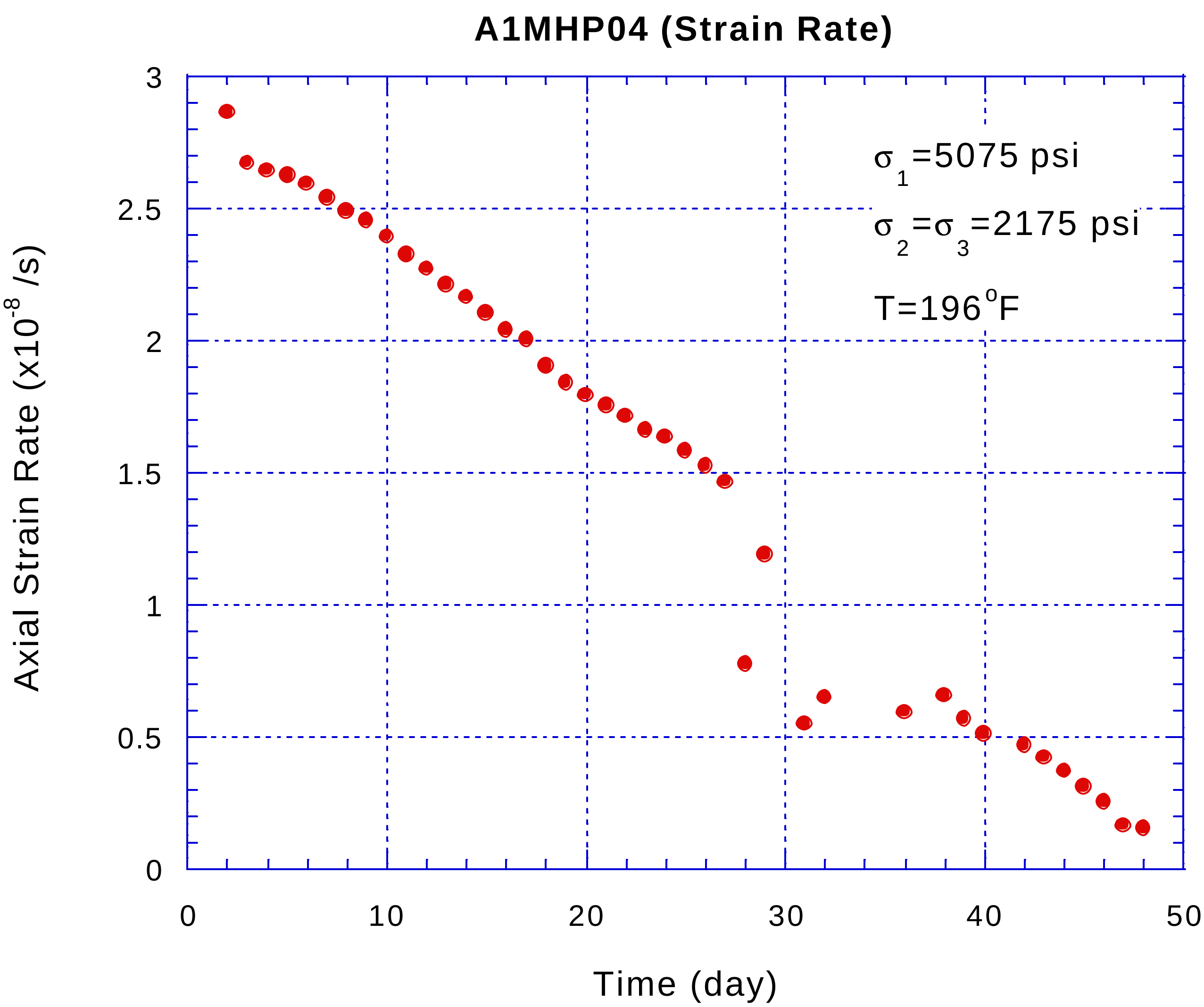


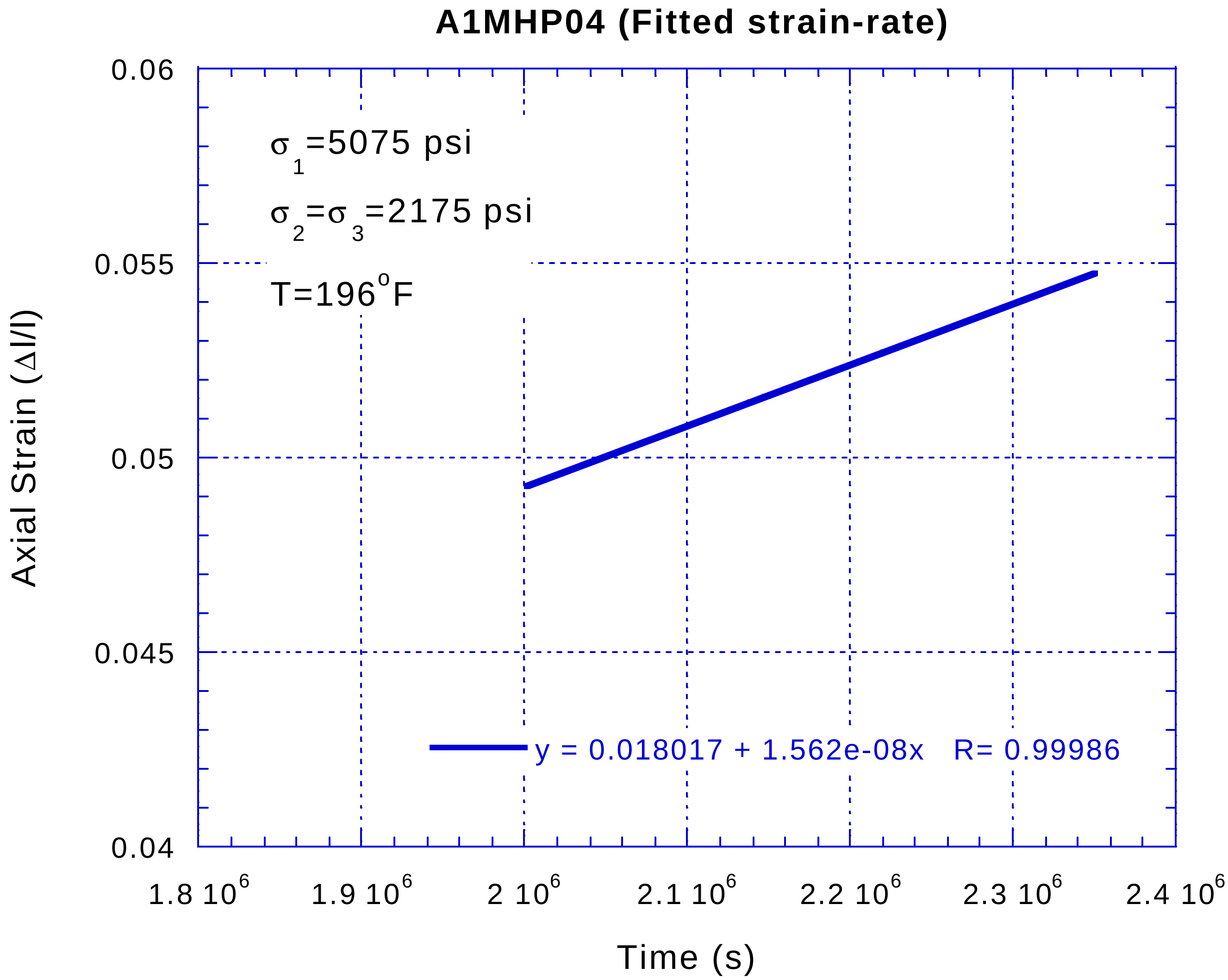
A3MHP03 (Strain)
Axial Strain (Δl/l)
0.001
0.0008
0.0006
0.0004
0.0002
0
0 10^0
5 10^5
1 10^6
1.5 10^6
2 10^6
2.5 10^6
Time (s)
σ1=5075 psi
σ2=σ3=2175 psi
T=73°F


A3MHP03 (Strain Rate)
σ1=5075 psi
σ2=σ3=2175 psi
T=73°F
Axial Strain Rate (x10-11 /s)
Time (day)
0
20
40
60
80
100
0
5
10
15
20
25
30

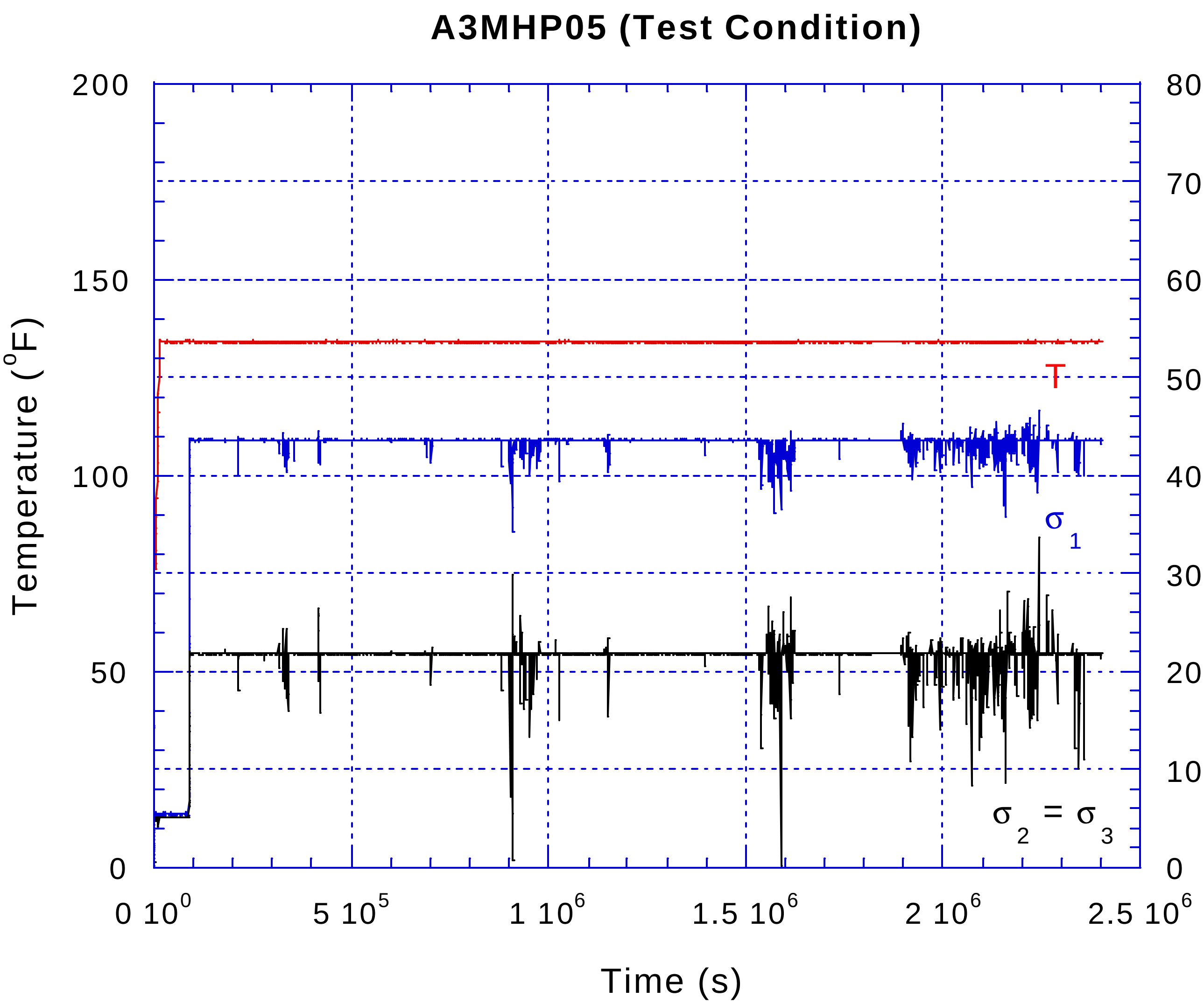

A1MHP04 (Test Condition)
200
150
100
50
0
8000
7000
6000
5000
4000
3000
2000
1000
0
T
σ 1
σ 2 = σ 3
0 10^0
1 10^6
2 10^6
3 10^6
4 10^6
5 10^6
Time (s)
Temperature (oF)
Stresses (psi)

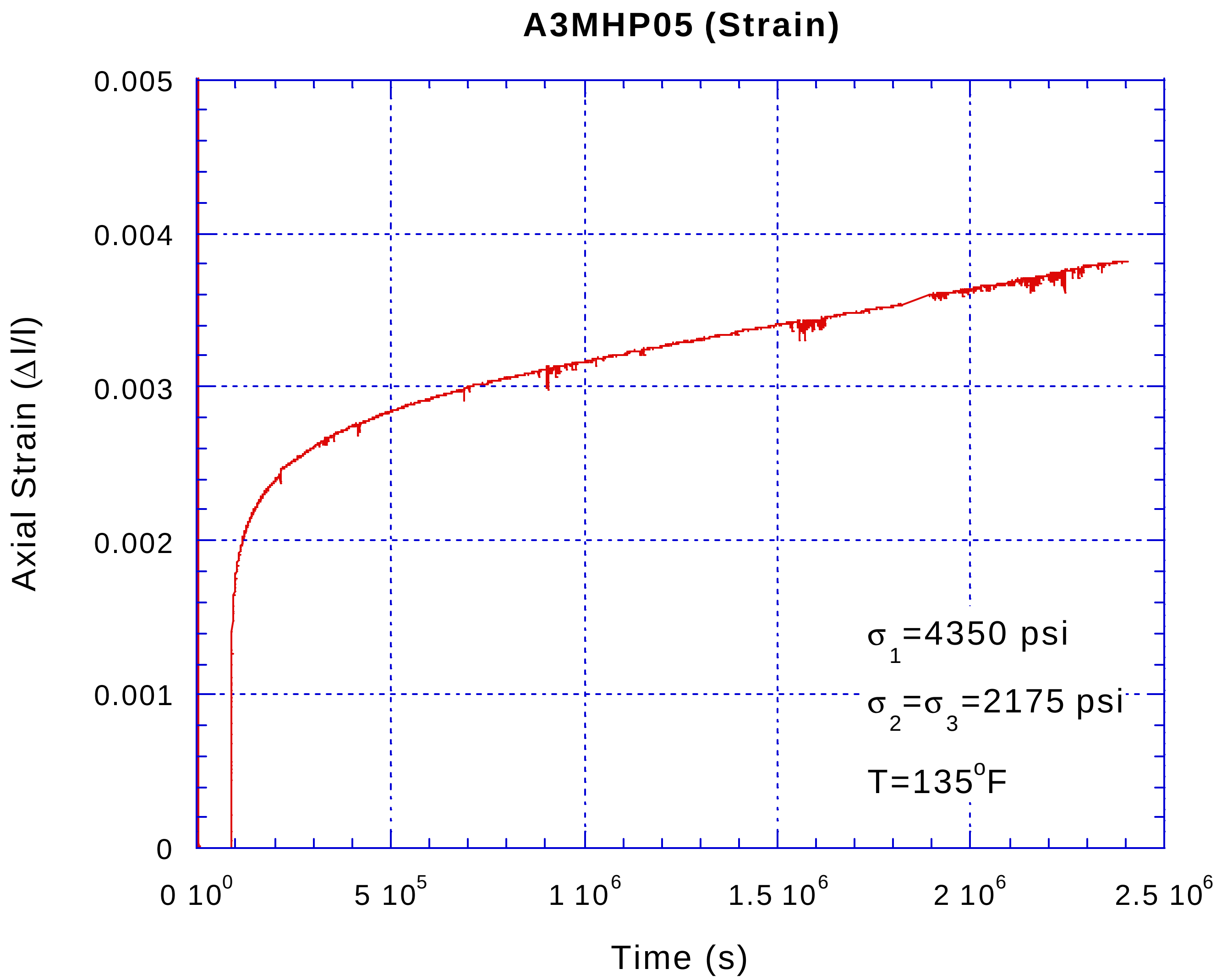

A1MHP04 (Strain)
0.1
0.08
0.06
0.04
0.02
0
Axial Strain (Δl/l)
σ1=5075 psi
σ2=σ3=2175 psi
T=196°F
0 10^0
1 10^6
2 10^6
3 10^6
4 10^6
5 10^6
Time (s)

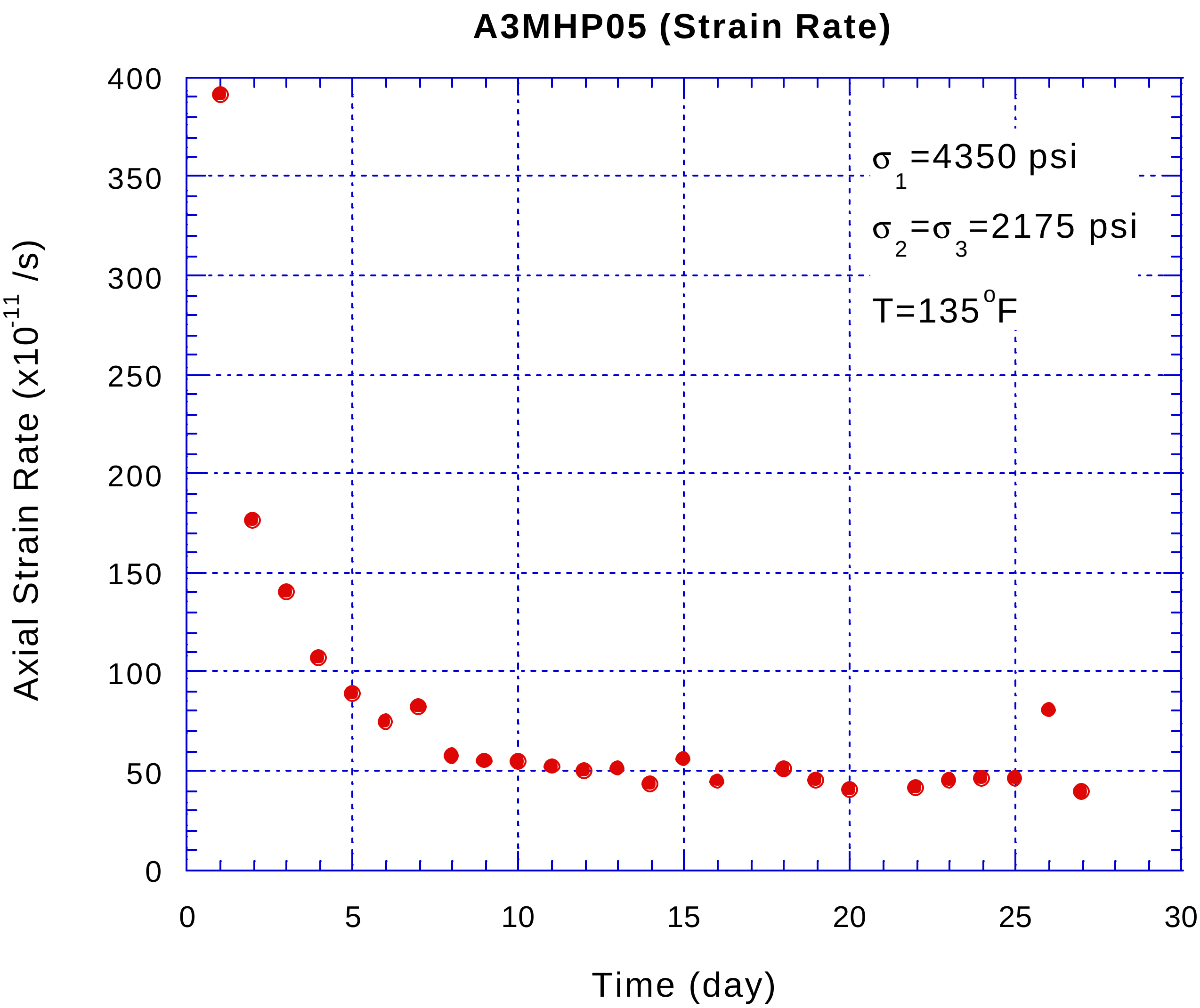

A1MHP04 (Strain Rate)
σ1=5075 psi
σ2=σ3=2175 psi
T=196°F
Axial Strain Rate (x10-8 /s)
Time (day)
0
0.5
1
1.5
2
2.5
3
0
10
20
30
40
50



A1MHP04 (Fitted strain-rate)
σ1=5075 psi
σ2=σ3=2175 psi
T=196°F
Axial Strain (Δl/l)
0.06
0.055
0.05
0.045
0.04
y = 0.018017 + 1.562e-08x   R= 0.99986
1.8 10^6
1.9 10^6
2 10^6
2.1 10^6
2.2 10^6
2.3 10^6
2.4 10^6
Time (s)


A3MHP05 (Test Condition)
Temperature (°F)
Stresses (psi)
Time (s)
T
σ 1
σ 2 = σ 3
200
150
100
50
0
8000
7000
6000
5000
4000
3000
2000
1000
0
0 10^0
5 10^5
1 10^6
1.5 10^6
2 10^6
2.5 10^6


A3MHP05 (Strain)
0.005
0.004
0.003
0.002
0.001
0
Axial Strain (Δl/l)
0 10^0
5 10^5
1 10^6
1.5 10^6
2 10^6
2.5 10^6
Time (s)
σ1=4350 psi
σ2=σ3=2175 psi
T=135°F


A3MHP05 (Strain Rate)
Axial Strain Rate (x10^-11 /s)
Time (day)
σ1=4350 psi
σ2=σ3=2175 psi
T=135°F
0
50
100
150
200
250
300
350
400
0
5
10
15
20
25
30

Appendix E

Nonlinear regression analysis applied to the estimation of creep parameters.

We used a 'nonlinear regression analysis' which determines the best-fit response surface defined by three unknown parameters of the empirical power law. Nonlinear regression analysis is a technique for fitting an arbitrary function to a given set of data point. For the power law creep model, the arbitrary function is expressed as:

$$Y=P1*(X1**P2)*EXP(P3/X2) + \varepsilon$$

where P1, P2,and P3 are the three unknown parameters; X1 and X2 are the two independent variables; Y is the dependent variable (or response); and ε is the random error. Provided that we have m (>3) sets of data points, ($X1_1$, $X2_1$, Y_1), ($X1_2$, $X2_2$, Y_2),..., ($X1_m$, $X2_m$, Y_m), the optimum values of the unknown parameters Pj (j=1 to 3) can be estimated by minimizing the sum of squares of errors.

$$SSE=\varepsilon^2=\Sigma_{i=1 \text{ to } m}\{ Y_i- P1*(X1_i**P2)*EXP(P3/X2_i) \}^2$$

where SSE is the sum of squares of the random errors between the measured response value Y_i (i=1 to m) and their model-predicted values for all of the m data points.
The least squares solutions for Pj are found when SSE is minimum. In order to determine the minimum of SSE the derivative of SSE is taken with respect to each Pj. This yields a set of so called 'normal equations':

DF1=(X1**P2)*EXP(P3/X2)
DF2=P1*(X1**P2)*EXP(P3/X2)*LN(STRESS)
DF3=P1/X2*(X1**P2)*EXP(P3/X2)

In the nonlinear regression model, the partial derivative of the model function with respect to the unknown parameters is also represented as a function of the unknown parameters Pj. Therefore, a closed form solution generally does not exist in the nonlinear case. Thus, an iteration procedure is introduced to solve 'normal equations' until the sum of squares of errors is minimized (Draper and Smith, 1981). The following is the listing of BMDP 3R statistical routine to solve the nonlinear model used for the Tioga rock salt:

```
/PROBLEM        TITLE IS 'NLRA-CREEP'.
/INPUT          VARIABLES ARE 3.
                FORMAT IS FREE.
                FILE IS ‘data’.
/VARIABLE       NAMES ARE SRATE,STRESS,TEMP.
/REGRESS        DEPENDENT IS SRATE.
                PARAMETERS ARE 3.
/PARAMETER      INITIALS ARE 10000,5.0,-6000.0.
/FUNCTION       F=P1*(STRESS**P2)*EXP(P3/TEMP).
                DF1=(STRESS**P2)*EXP(P3/TEMP).
                DF2=P1*(STRESS**P2)*EXP(P3/TEMP)*LN(STRESS).
```

```
                              DF3=P1/TEMP*(STRESS**P2)*EXP(P3/TEMP).
/END
```

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