SNO-STR-92-055

TENSILE CREEP TESTING OF ABS PLASTIC
FINAL REPORT

by
Harold Leung
Student Assistant
Lawrence Berkeley Laboratory
Berkeley, California
5 June 1992

TENSILE CREEP TESTING OF ABS PLASTIC
FINAL REPORT

by
Harold Leung

ABSTRACT

In order to ensure proper design specifications for the ABS plastic components in the construction of the Sudbury Neutrino Observatory, the ABS resins must be tested for time dependent deformation, or creep. Since the components will be submerged in deionized water for at least ten years, creep properties need to be analyzed in a water environment. The data obtained from the material tests will help characterize the creep strain and rupture times at various stress levels. In addition, extrapolating the data will determine the creep properties during and at the end of the Sudbury Neutrino Observatory (SNO) experiment. In conclusion, the results of these creep tests will give one confidence that the ABS plastic is designed not to creep rupture during the SNO experiment.

CONTENTS

FIGURES

1.0 Introduction

1.1 Objective

This report documents the information necessary to ensure that the General Electric Cycolac (GPM5600) ABS plastic components are designed to exceed the ten year life of the experiment at the Sudbury Neutrino Observatory. The ABS plastic is tested for time dependent deformation, or creep, in a deionized water environment. In particular, the ABS plastic is tested using constant stresses ranging between 2400 and 4000 psi resulting in rupture times between 20 and 1600 hours. Although the tests performed in this experiment do not exceed 1600 hours, the rupture data is extrapolated to the ten year (87600 hours) life of the SNO experiment. From these material tests, the creep strain and the rupture times at various stresses are used to characterize the specific properties of the GE ABS plastic. In addition to studying creep in deionized water, some other conclusions are made comparing the deionized water tests to those in air and tap water. The results of these tests will ensure that creep rupture will not occur during the SNO experiment.

1.2 Motivation

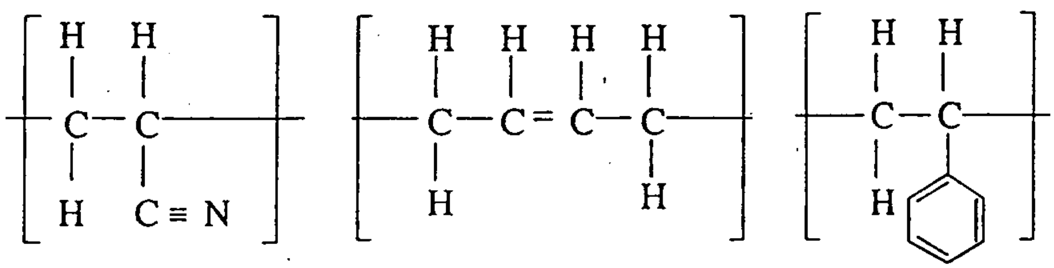
Many of the components that house the photomultiplier tubes such as the hex cells and back baffles are made of ABS plastic. Over the ten year duration of the SNO experiment, the plastic components will be submerged in deionized water and subjected to applied stresses. Since the stresses will be applied over a period of ten years, time dependent deformation is the primary process that must be investigated. Therefore, several material tests need to be performed that will allow us to determine the creep properties of ABS plastic when immersed in deionized water.

1.3 Theoretical Background

Creep is the time dependent plastic deformation of a material when subjected to a constant stress. In addition to time, some other variables that influence creep are the temperature and environment. For example, as the temperature rises, the plastic will tend to soften, and the time to creep-rupture significantly decreases. Similarly, the environment may react with the properties of the material to cause overall rupture time to decrease. Thus, to study creep also means to analyze the variables that influence it, which, in turn, motivates the need for short term testing in order to predict long term effects.

Acrylonitrile-Butadiene-Styrene (ABS) is a name given to a family of thermoplastics. ABS plastics are generally known for their overall engineering properties such as good mechanical and impact strength as well as ease in manufacturing. Most importantly though, ABS plastics are relatively inexpensive. Some of the existing applications for ABS plastic includes pipes, fittings, automobile parts, liners as well as computer housings and shieldings.

The chemical structure units for ABS plastic are shown in Figure 1.



A: polyacrylonitrile B: polybutadiene S: polystyrene

Figure 1 - The general chemical structure of ABS plastic[1].

where acrylonitrile provides heat and chemical resistance, butadiene contributes impact strength, and styrene adds rigidity. To vary the characteristic creep properties when manufacturing, the amount of butadiene rubber content can be changed. See Figure 2 for details.

[1]W.F. Smith, Principles of Materials Science and Engineering

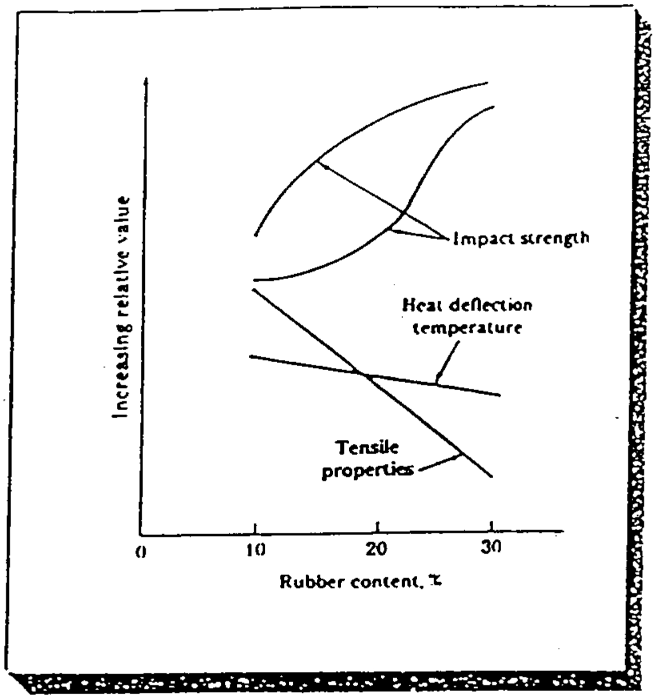


Figure 2 - Variations in the Rubber Content to Change the Properties of ABS Plastic. (After G.E. Teer, ABS and Related Multipolymers, in "Modern Plastics Encyclopedia," McGraw-Hill, 1981-1982)

As a result of a change in rubber content, the ABS plastic can be designed to meet almost any need.

The ABS plastic pipe industry has done extensive research that will help study creep rupture in water. Several experiments on over 1200 sets of data, obtained with thermoplastic pipe and piping assemblies tested with water, natural gas, and compressed air, have been performed, and none of the recommended compounds have exhibited knee-type plots. In other words, for each experiment, all of the stress versus time to rupture data points have been fitted with a straight line on an equiscalar log-log plot. In fact, data have been obtained for test periods over 120,000 hours (13.7 years).[2] Thus, it gives one confidence that the short-term data can be extrapolated to determine long-term failure.

[2]ASTM D2837-90, pg 324

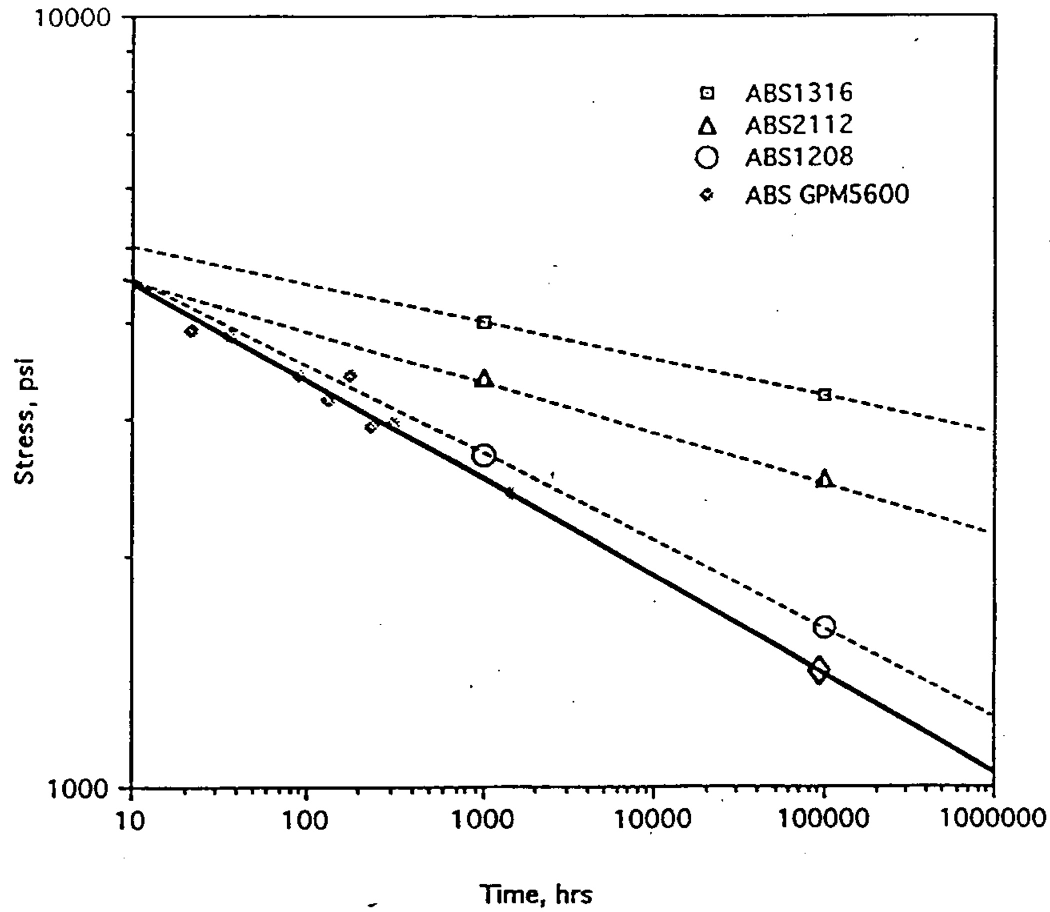


Figure 3 - The straight line plots for ABS plastic in the piping industry compared with the ABS plastic that will be used for the SNO experiment.

Standard specifications for ABS plastic pipes are shown in Figure 3, The hoop stress with respect to the rupture time was plotted for three types of piping: ABS1316, ABS2112, and ABS1208. In addition, the solid line represents the data obtained from the tests being performed on the GE GPM5600 ABS plastic. The completed tests have remained consistent with the straight-line characteristics of the ABS piping material.

To study the creep strain for each tensile stress, the Percent Creep Strain versus time for each specimen was plotted on a log-log scale, and a second order polynomial was best fit to the data points. The polynomial is in the form given by Equation 1.

$$A(\log t)^2 + B(\log t) + C = \log \varepsilon \qquad (1)$$

where A, B, and C are constants determined by the fit, t is time, and ε is strain.

2.0 EXPERIMENTAL SYSTEM

2.1 Procedure

For the SNO experiment, the ABS plastic chosen was Cycolac GPM5600 manufactured by GE Plastics. Some typical properties of this general purpose resin are specified in Appendix A.

The stainless steel test apparatus is shown in Figure 4. All of the tests conformed with standard ASTM methods of testing. Applicable documents are referenced.

In a sealed glass jar, each specimen (Type V) was preconditioned by immersion in deionized water for approximately 48 hours prior to testing. Also, since the deionized water loses its resistivity due to reionization, the water was changed daily.

After the specimen was properly conditioned, the cross-sectional area within the gage length was measured. Without crushing the specimen, the grips were tightened to prevent slippage. Next, the lever rod with the top lid was screwed into one of the grip ends and then, the lid was bolted down onto the stainless steel chamber. The center screw connecting the base plate to the other grip was attached, but not tightened because the screw acted as pivot for multiaxial movement. With the remaining components being attached, the test apparatus was filled with the deionized water, and the flow was adjusted accordingly. The deionized water was maintained at 22 $\pm$ 1 degree C. Also, the displacement gages were adjusted to operate within their range limits. Once the computer program was ready to record data, a known amount of weight was applied rapidly and smoothly (< 5 seconds).

While the specimens were subjected to this constant stress, the flow of deionized water (resistivity of 18 MΩ-cm) entered the top of the cylindrical chamber and exited at the bottom, which kept the deionized water at a high resistivity throughout the experiment. Also, the flow was slow enough such that pressure effects were negligible.

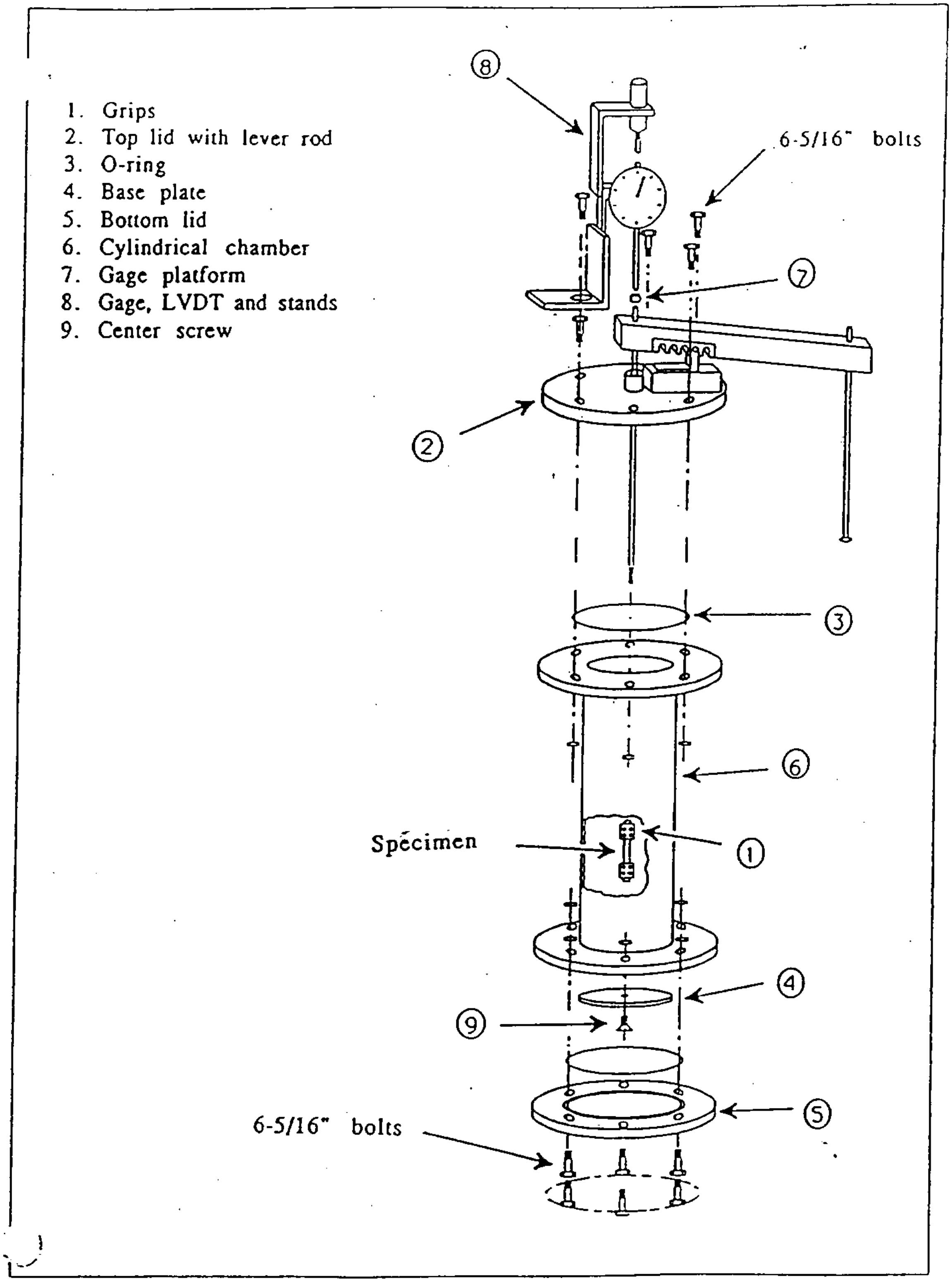


Figure 4 - Schematic of the Stainless Steel Chamber for Tensile Creep Testing.

2.2 Data Acquisition

Two of the major components for data recording are the Linear Variable Differential Transducer (LVDT) and a Hewlett-Packard computer with a HP-IB interface program. Figure 5 is a schematic of the data recording system. The LVDT is an electromagnetic device that produces an electrical voltage proportional to the displacement. When placed in the null position, the LVDT will output a proportional positive voltage in either direction of movement. The specifications for the LVDT used for the recording system is shown in Appendix B.

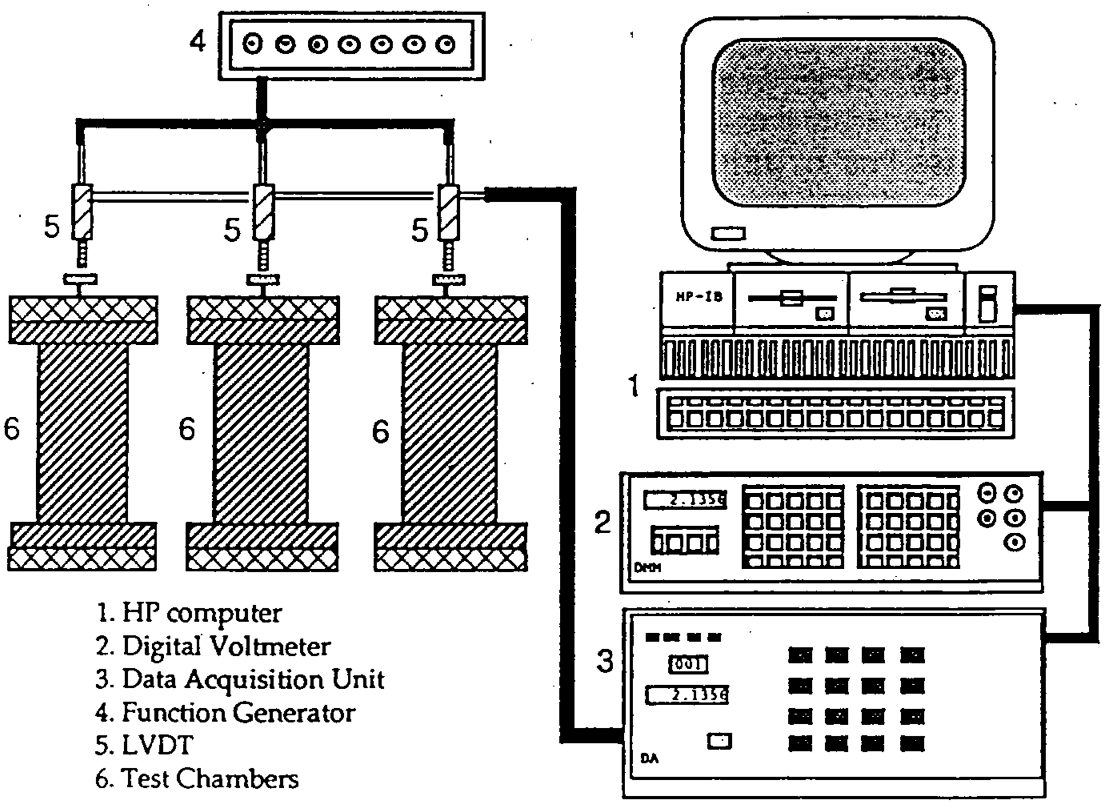


Figure 5 - A detailed schematic of the data recording system.

Providing the ease in automatic data recording, the HP-IB computer interface will sample data from the LVDT's. Not only will data be recorded according to ASTM standards (1, 6, 12, 30 min.; 1, 2, 5, 10, 20, 50, 100, 200, 500, and 1000 hrs.), but also in intervals of two hours where discontinuities in creep strain versus time are encountered. This will reduce the rupture time uncertainties to ± 1 hour. Furthermore, the HP-IB has the capabilities to record three tests simultaneously and independently. In fact, if one of the tests completes, a new test can be started without disturbing the other two.

For the tests performed in this experiment, the linear extension was hand-recorded for the ASTM intervals using the dial gages.

3.0 RESULTS AND DISCUSSION

3.1 Creep Strain and Rupture

The observed extension for each test had to be adjusted due to the "gaps" or slack in the test apparatus and specimen. In order to determine this adjustment factor, the known stress and elastic modulus were used to calculate the theoretical extension. To obtain the extension in the specimen alone, the difference between the observed and theoretical extension had to be subtracted from each observed displacement. Equation 2 was used as an approximation to the actual strain.

$$\varepsilon_{ot} - (\varepsilon_{o1} - \frac{\sigma}{E}) \approx \varepsilon_{at} \qquad (2)$$

where ε_{ot} is the observed strain at time t, ε_{o1} is the observed strain at 1 minute, σ is the tensile stress, E is the modulus of elasticity, and ε_{at} is the actual strain at time t. See Appendix C for a sample calculation. Since there was no significant dimensional change due to the environment alone, no additional corrections were made to the creep strain.

The first tests performed were to study the differences in creep strain and rupture between specimens in air and water. The preliminary tests revealed significant changes in the time to rupture. In fact, the tests done in air lasted over ten times longer than those performed in water. Thus, future tests in air will not aid in characterizing the creep properties in water.

The second set of tests were performed in 18 MΩ-cm, 22 degree C deionized water in order to obtain the creep strain and rupture times of the GPM5600 plastic. For each test, the instantaneous creep at the interval times was plotted, and the second order polynomial was fitted to the data (equation 1). The plots for three tests are found in Figure 6.

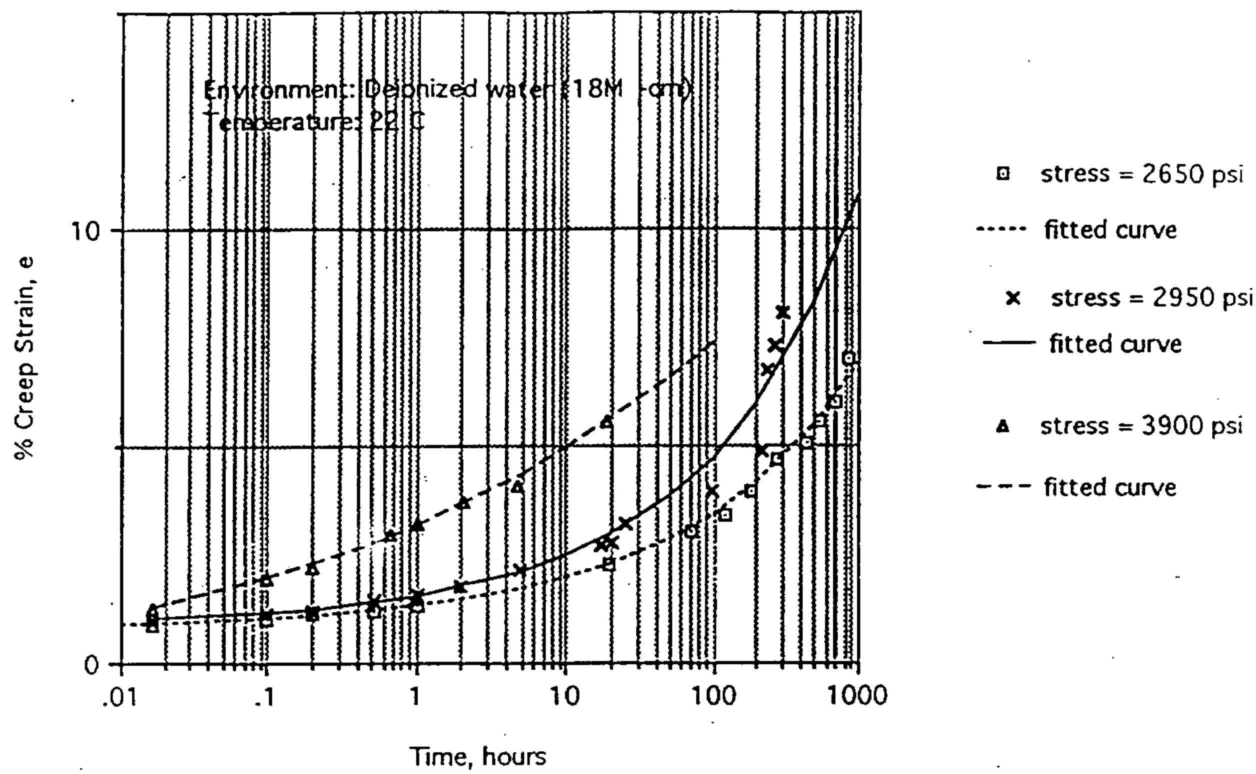
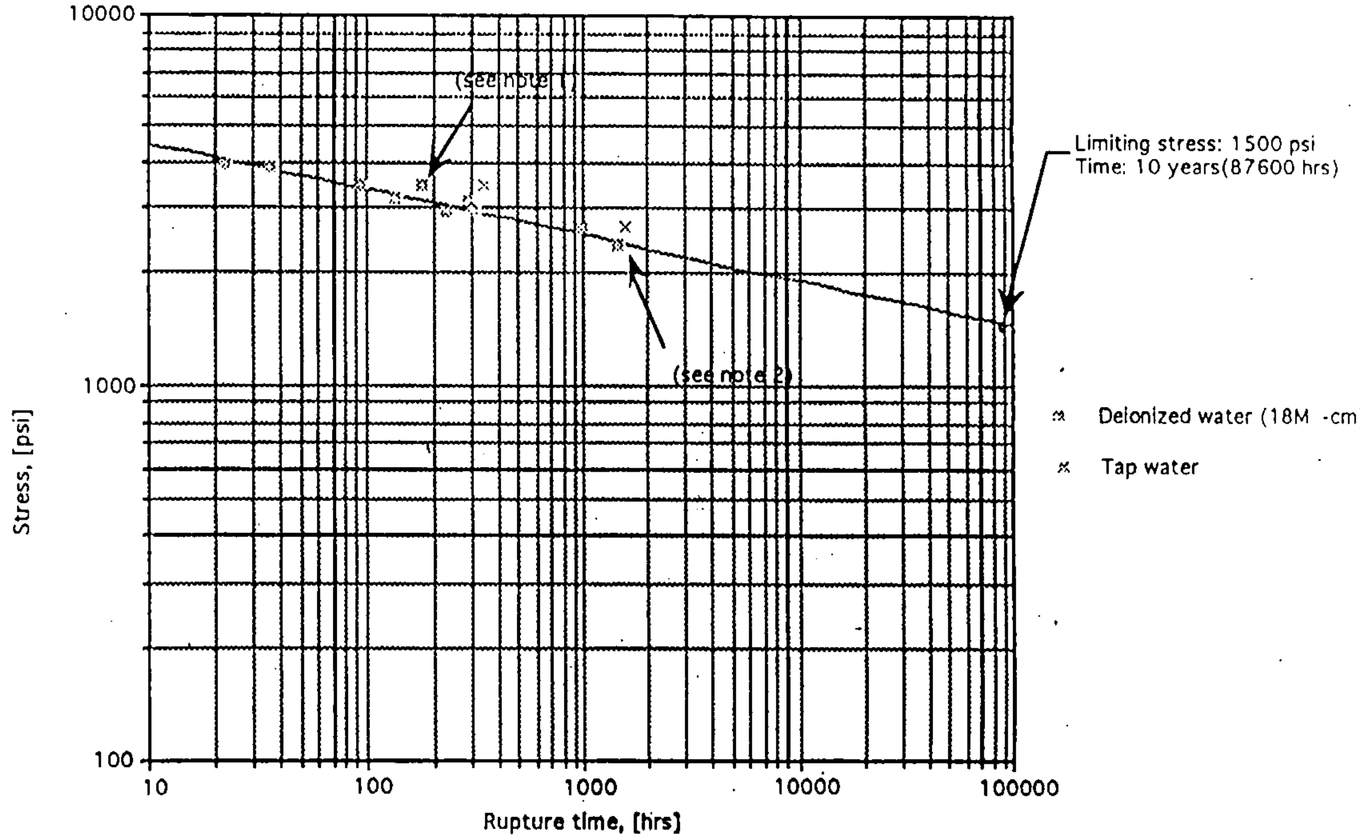


Figure 6 - The percent creep strain for three different tensile stresses.

The creep strain for all stress levels followed the same pattern. Initially, each specimen had gradual creep, and then increased as the specimens approached rupture. As expected for the higher stresses, the creep strain advanced much faster. The plots also revealed that the ABS plastic would rupture within the first 10% of creep strain. However, predicting an exact percentage would depend on the microstructure characteristics of each individual specimen. Creep strain plots for other tests are in Appendix D.

Additional tests were performed in a tap water environment. Appendix E is an evaluation of the water used. For the tests completed, the specimen in tap water lasted longer than the tests in DI water as shown in Figure 7. This suggests that the DI water promotes creep in ABS plastic. However, additional tests need to be performed to confirm this result.

Figure 7 - The Creep Rupture for ABS Plastic Under Various Tensile Stresses.



This graph shows the rupture times for the creep tests at different stresses. Extrapolated to 10 years, the best fit line revealed the relationship between creep-rupture and stress. All tests performed at 22 C.

Note 1: Due to deionized water shutdown, the specimen was exposed to air (less than 18 hours).

Note 2: The 2450 & 2400 psi creep tests were only valid up to 1435 hours due to a deionized water shutdown. Most importantly, these tests did not rupture in 1435 hours, and if the water had not been shutdown, the specimens would have continued to creep.

Figure 7 - The creep rupture for ABS plastic under various tensile stresses.

Tables 1 & 2 in Appendix F summarize the stresses and rupture times for all of the tests that have been completed. The tensile stress of each specimen was calculated from the known load, cross-sectional area and apparatus dimensions. Sample calculations are shown in the Lab-Log book.

Most of the experimental uncertainty observed in the time variable was due to either overnight or weekend ruptures, when personnel were not available to document the ruptures. Unfortunately, the tests with large uncertainties were completed before the HP-IB implementation. For the tests with the HP-IB, the uncertainties in rupture times were due to the limitations in the program.

By plotting Table 1 on a log stress as a function of log rupture time, a best fit line was extrapolated in determining long term creep-rupture as shown in figure 7. As seen from the Table 1 and figure 7, the 2920 psi test specimen broke before the 2950 psi test. The discrepancies were in comparing specimens at relatively close stresses because the experimental ruptures were expected to be scattered within a time interval. Although the scatter was large for low stresses, the rupture time remained near or above the extrapolated line.

By extrapolating the best fit line to the 10 year (87600 hour) life of the SNO experiment, Figure 7 revealed the limiting stress to be 1500 psi. The stresses on the plastic components for the SNO experiment have been calculated to be less than 500 psi. Since the expected limiting stress is 1500 psi, using an allowable design stress of 500 psi will give a safety factor of three to the plastic components. Since the calculated stress is less than the allowable design stress, it gives one confidence that the ABS plastic is designed not to creep-rupture in the SNO experiment.

3.2 Water Absorption

The back baffle of the hex cell was submerged in a slow flow of deionized water. To investigate the water absorption, the weight and dimensional changes were monitored until saturation was reached. Appendix H shows the raw data and the locations of these measurements. After immersing the ABS plastic in deionized water for thirty-one days (saturation), the amount of weight gain experienced in the plastic component was 0.57 %. This verifies the estimates in the Modern Plastics Encyclopedia, which had given an absorption range between 0.2 and 0.6 %.

While the dimensional changes in the height, thickness, and inside diameter were negligible, the outside diameter changed between 0.1 and 0.2 %.

4.0 SUMMARY AND CONCLUSIONS

4.1 Summary

In this experiment, the GE Cycolac (GPM5600) ABS plastic was tested for time dependant deformation, or creep, in an 18MΩ-cm.deionized water environment. At a water temperature of 22 degree C, plastic specimens were subjected to tensile stresses ranging between 2400 and 3900 psi. This range of stresses also resulted in a range of rupture times varying from 20 to 1600 hours.

From the data obtained from the various tests, the creep strain data was used to study the characteristics of ABS plastic in deionized water over time. To determine the life of the ABS plastic components, the rupture times for various stresses was plotted. Similar to the methods used in the Plastic Pipes Industry, a straight line was extrapolated to 10 years on an equiscalar log-log plot of the stress versus rupture time data. As a result, the extrapolation revealed the limiting stress, which, in turn, gave the design stress of the plastic components.

4.2 Conclusions

From the results of these experiments, we conclude that the ABS plastic components are designed not to creep rupture during the 10 year life of the SNO experiment. The allowable design stress was selected to give a safety factor of three against failure.

REFERENCES

1. Smith, W. F., Principles of Materials Science and Engineering, McGraw Hill Book, Inc., 1986, pp 336-337

2. Annual Book of ASTM Standards:

D618-61	Methods of Conditioning Plastics and Electrical Insulating Materials for Testing
D638-84	Test Method for Tensile Properties of Plastics
D1598-86	Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure
D2282-89	Standard Specifications for Acrylonitrile-Butadiene-Styrene (ABS) Plastic Pipe (SDR-PR)
D2837-90	Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials
D2990-77	Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

LIST OF APPENDICES

Appendix A

Typical Properties of ABS Plastic

CYCOLAC® resin General Purpose Grades

The main line of the CYCOLAC® ABS resin family is the general purpose class. Each general purpose grade offers a unique combination of properties designed to meet almost any need. Led by the new G-Series technology, CYCOLAC resins are available with enhanced flow for easier and more economical processing. The world leader in ABS polymers, CYCOLAC general purpose materials provide a cost-effective product representing the industry standard for quality and performance.

Typical Property Values

English Units (SI Units)

PROPERTY	ENG(SI) UNITS	TEST METHOD	CYCOLAC GPM4700 resin	CYCOLAC GPM5500 resin	CYCOLAC GPM5600 resin	CYCOLAC GPM6300 resin	CYCOLAC DSK resin
PHYSICAL							
Specific Gravity, solid	—	ASTM D 792	1.04	1.05	1.05	1.05	1.06
Mold Shrinkage, flow, 0.125" (3.2 mm)	in/in E-3	ASTM D 955	7-9	6-8	7-9	6-8	6-8
MECHANICAL							
Tensile Strength, yield, Type I, 0.125" (3.2 mm)	psi(MPa)	ASTM D 638	6,400(45)	6,900(50)	6,300(45)	6,900(50)	6,700(45)
Tensile Modulus, Type I, 0.125" (3.2 mm)	psi(MPa)	ASTM D 638	320,000(2,200)	360,000(2,500)	310,000(2,100)	360,000(2,500)	350,000(2,400)
Flexural Strength, yield, 0.125" (3.2 mm)	psi(MPa)	ASTM D 790	10,700(75)	12,300(85)	10,500(70)	12,300(85)	12,000(85)
Flexural Modulus, 0.125" (3.2 mm)	psi(MPa)	ASTM D 790	340,000(2,300)	380,000(2,600)	330,000(2,300)	380,000(2,600)	370,000(2,500)
Hardness, Rockwell R	—	ASTM D 785	105	110	105	110	111
IMPACT							
Izod Impact, notched, 0.125" (3.2 mm), 73F (23C)	ft-lb/in(J/m)	ASTM D 256	7.5(400)	5.0(270)	6.5(350)	3.5(190)	3.1(170)
Izod Impact, notched, -40F (-40C)	ft-lb/in(J/m)	ASTM D 256	—	—	—	—	—
THERMAL							
DTUL, 66 psi (0.45 MPa), 0.500" (12.7 mm), annealed	deg F(deg C)	ASTM D 648	—	—	—	—	—
DTUL, 66 psi (0.45 MPa), 0.500" (12.7 mm), unannealed	deg F(deg C)	ASTM D 648	—	—	—	—	—
DTUL, 264 psi (1.82 MPa), 0.500" (12.7 mm), annealed	deg F(deg C)	ASTM D 648	212(100)	200(93)	212(100)	205(96)	210(99)
DTUL, 264 psi (1.82 MPa), 0.500" (12.7 mm), unannealed	deg F(deg C)	ASTM D 648	198(92)	195(91)	198(92)	195(91)	195(91)
Thermal Index, Elec Prop	deg C	UL746B	60	60	60	60	—
Thermal Index, Mech Prop with impact	deg C	UL746B	60	60	60	60	—
Thermal Index, Mech Prop without impact	deg C	UL746B	60	60	60	60	—
ELECTRICAL							
Arc Resistance, Tungsten	ASTM D 495	UL746A	5	6	6	6	—
Hot Wire Ignition	PLC Code	UL746A	4	3	3	3	—
High Voltage Arc Track Rate	PLC Code	UL746A	3	2	3	2	—
High Ampere Arc Ignition, surface	PLC Code	UL746A	0	0	0	0	—
Comparative Track Index UL	PLC Code	UL746A	0	0	0	0	—
FLAME CLASS RATING*							
94HB Flame Class Rating	in(mm)	UL 94	—	0.0620(1.58)	0.0620(1.58)	0.0620(1.58)	0.0630(1.60)

* This rating is not intended to reflect hazards presented by this or any other material under actual fire conditions.

Appendix B

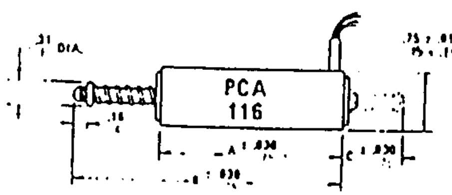
Specifications for the LVDT

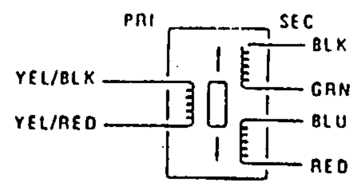
GENERAL SPECIFICATIONS *For Performance Specifications, See Chart Below*

Input Voltage . . . . . 3 V rms (nominal)
Frequency Range . . . 50 Hz to 10 kHz
Temperature Range . . -65°F to +300°F (-55°C to +150°C)
Null Voltage . . . . . . Less than 0.5% full scale output
Housing Material . . . AISI 400 series stainless steel
Lead Wires . . . . 28 AWG stranded copper, Teflon-insulated, 12 inches (300 mm) long (nominal)
Repeatability . . . . . . 0.000050 inch

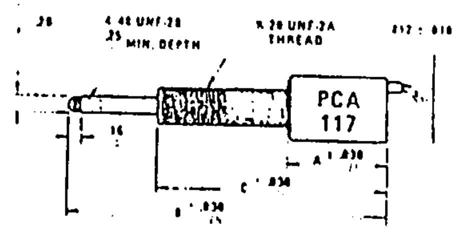
PERFORMANCE SPECIFICATIONS AND DIMENSIONS (2.5 kHz) *METRIC DIMENSIONS IN BLUE*

MODEL NUMBER	NOMINAL LINEAR RANGE Inches	NOMINAL LINEAR RANGE mm	LINEARITY ±PERCENT FULL RANGE	SENSITIVITY mV Per Volt Input Per .001 In.	SENSITIVITY mm	IMPEDANCE Ohms Pri.	IMPEDANCE Ohms Sec.	PHASE SHIFT Degrees	WEIGHT Grams	DIMENSIONS A Inches	A mm	B Inches	B mm	C Inches	C mm	Pretravel Inches	Pretravel mm	Overtravel Inches	Overtravel mm
PCA-116-100	±0.10	±2.5	0.5	2.4	[illegible]	650	920	+1	43	1.75	[illegible]	2.54	64.5	0.44	[illegible]	0.10	2.5	0.03	0.8
PCA-116-200	±0.20	±5	0.5	2.1	[illegible]	1100	120	−3	50	2.25	57.1	3.30	[illegible]	0.69	[illegible]	0.09	[illegible]	0.11	2.8
PCA-116-300	±0.30	±7.5	0.5	1.2	[illegible]	1350	1460	−8	57	2.75	[illegible]	4.10	[illegible]	0.88	[illegible]	0.07	1.8	0.10	2.5
PCA-117-050	±0.050	±1.25	0.25	6.3	[illegible]	430	4000	−1	64	1.19	[illegible]	3.84	[illegible]	2.75	69.2	0.06	1.5	0.60	15.2
PCA-117-100	±0.100	±2.5	0.25	4.5	[illegible]	1070	5000	−5	85	1.87	[illegible]	4.53	[illegible]	3.43	87.1	0.20	5.1	0.40	[illegible]
PCA-117-200	±0.200	±5	0.25	2.5	[illegible]	1150	4000	−4	100	2.56	[illegible]	5.23	[illegible]	4.12	105	0.15	[illegible]	0.28	[illegible]
PCA-117-300	±0.300	±7.5	0.25	1.4	[illegible]	1100	2700	−11	114	3.28	[illegible]	5.94	[illegible]	4.84	123	0.09	[illegible]	0.18	[illegible]
PCA-117-500	±0.500	±12.5	0.25	0.7	[illegible]	460	375	−1	177	5.56	[illegible]	11.20	[illegible]	8.75	222	0.29	[illegible]	0.83	[illegible]
PCA-117-1000	±1.000	±25	0.25	0.4	[illegible]	460	320	−3	199	6.69	[illegible]	12.28	[illegible]	9.88	251	0.03	[illegible]	0.09	[illegible]





CONNECT GRN TO BLU FOR DIFFERENTIAL OUTPUT



Appendix C

Sample Calculation of Strain

C1-A2670-GPM5600-Tap
Gage length = 0.30 in.
Tensile Stress = 2670 psi, E = 310000 psi

time, hours	Observed Extension, in	Actual Extension, in	% Creep Strain
0.016666667	0.1128	0.0026	0.86
0.1	0.1131	0.0029	0.96
0.2	0.1132	0.0030	0.99
0.58333	0.1136	0.0034	1.13
1.15	0.1141	0.0039	1.29
18.75	0.1167	0.0065	2.16
70.48333	0.1188	0.0086	2.86
119.95	0.1202	0.0100	3.33
184.45	0.1222	0.0120	3.99
279.45	0.1249	0.0147	4.89
430.58333	0.1265	0.0163	5.43
533.86667	0.1276	0.0174	5.79
689.95	0.1297	0.0195	6.49
857.7	0.1322	0.0220	7.33
1102.95	0.1369	0.0267	8.89
1530.95	0.1473	0.0371	12.36

$$\varepsilon_{at} = \varepsilon_{ot} - \left(\varepsilon_{o1} - \frac{\sigma}{E}\right)$$

$$\varepsilon_{o1} = \frac{0.1128}{0.30} = 0.3760$$

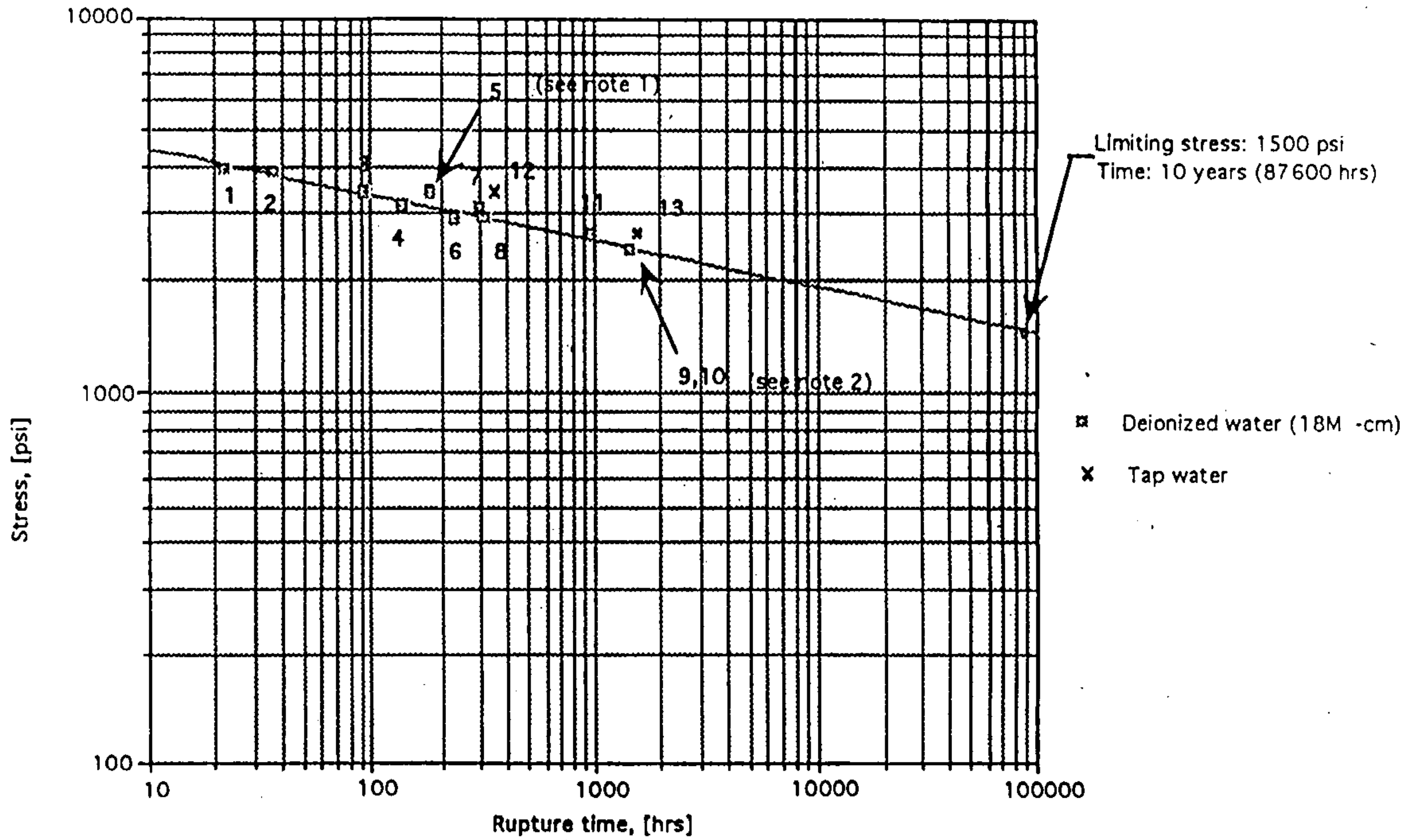
$$\varepsilon_{at} = \frac{0.1131}{0.30} - \left(0.3760 - \frac{2670}{310000}\right)$$

$$\varepsilon_{at} = 0.961$$

Appendix D

Creep Strain and Rupture Plots

The Creep Rupture for ABS Plastic Under Various Tensile Stresses.



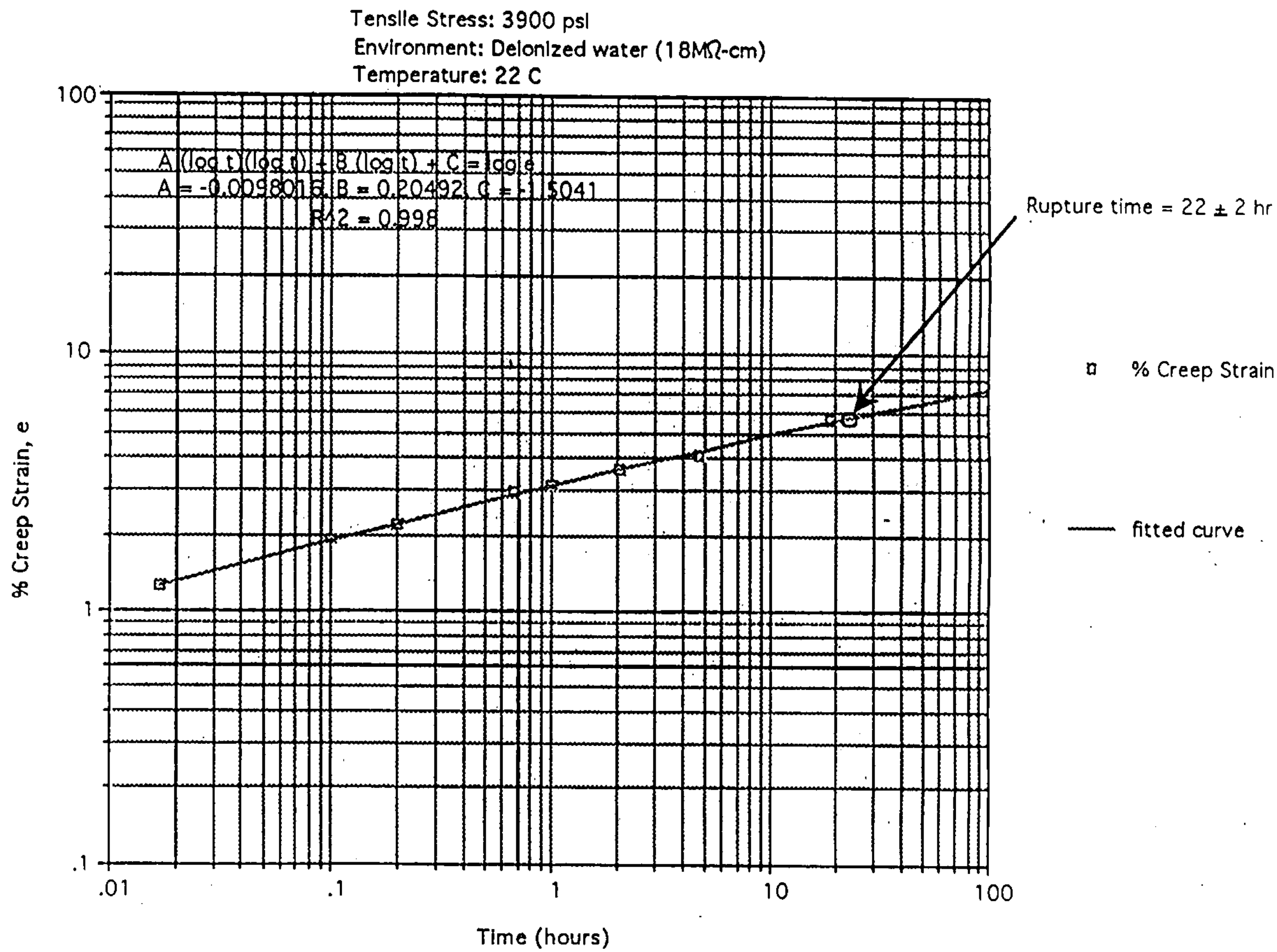
Plot D1

This graph shows the rupture times for the creep tests at different stresses. Extrapolated to 10 years, the best fit line revealed the relationship between creep-rupture and stress. All tests performed at 22 C.

Note 1: Due to deionized water shutdown, the specimen was exposed to air (less than 18 hours).

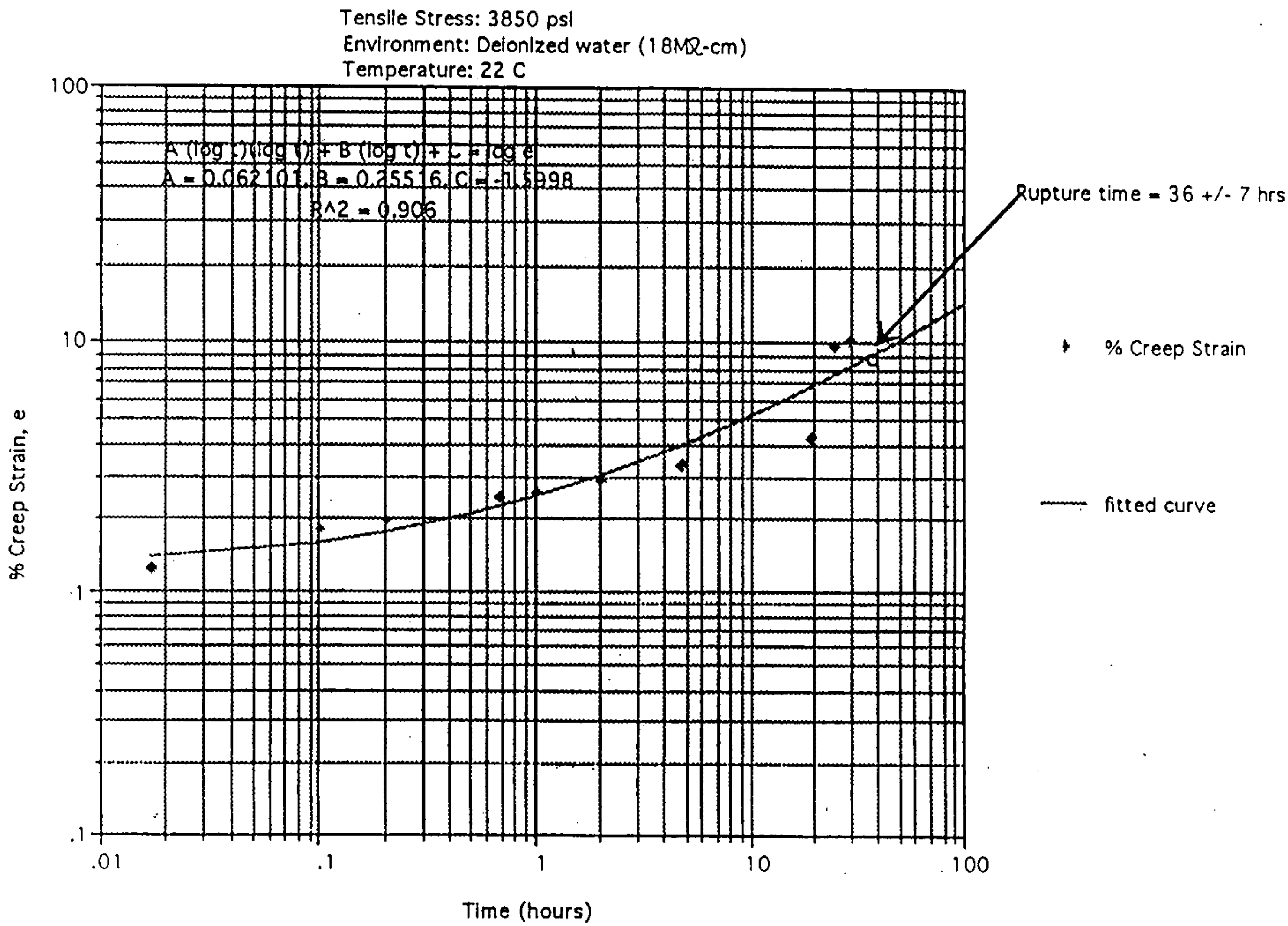
Note 2: The 2450 & 2400 psi creep tests were only valid up to 1435 hours due to a deionized water shutdown. Most importantly, these tests did not rupture in 1435 hours, and if the water had not been shutdown, the specimens would have continued to creep.

The % Creep strain as a function of time for Test # C2-A3900-GPM5600-DI



Plot D2

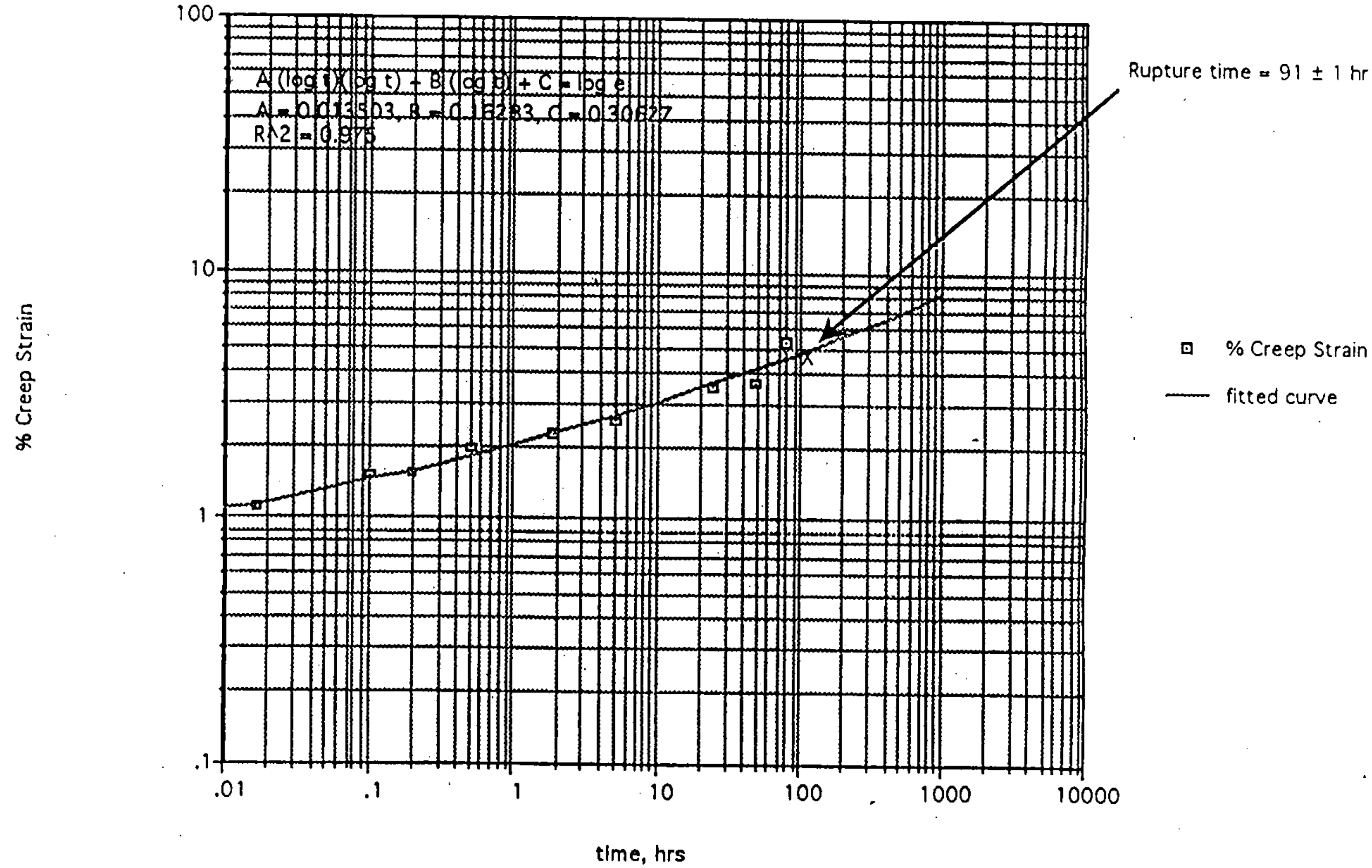
The % Creep strain as a function of time for Test # C3-A3850-GPM5600-DI



Plot D3

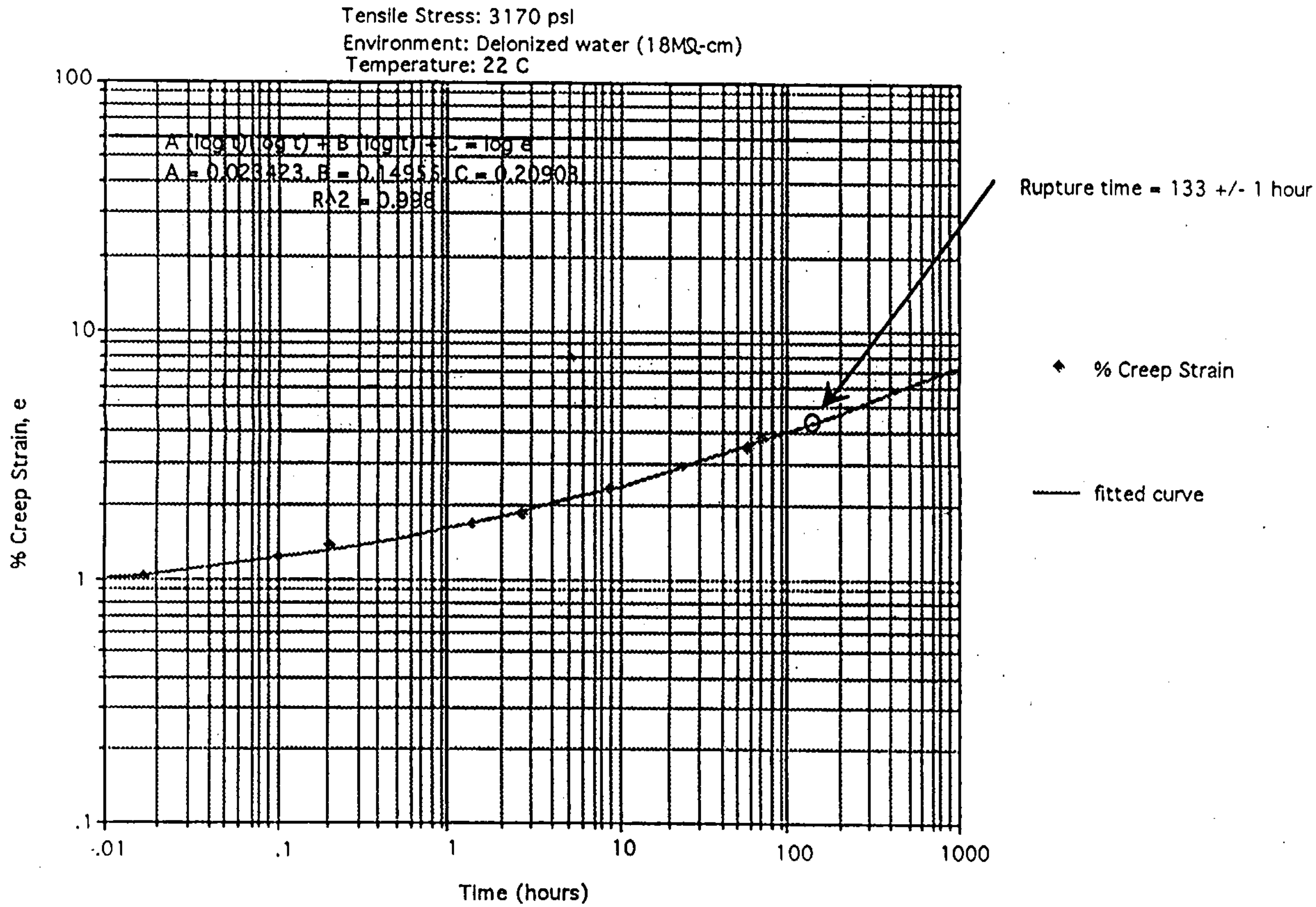
The % Creep strain as a function of time for Test # "Data-C2-A3420-GPM5600-DI"

Tensile Stress: 3420 psi
Environment: Deionized water (18MΩ-cm)
Temperature: 22C



Plot D4

The % Creep strain as a function of time for Test # C3-A3170-GPM5600-DI



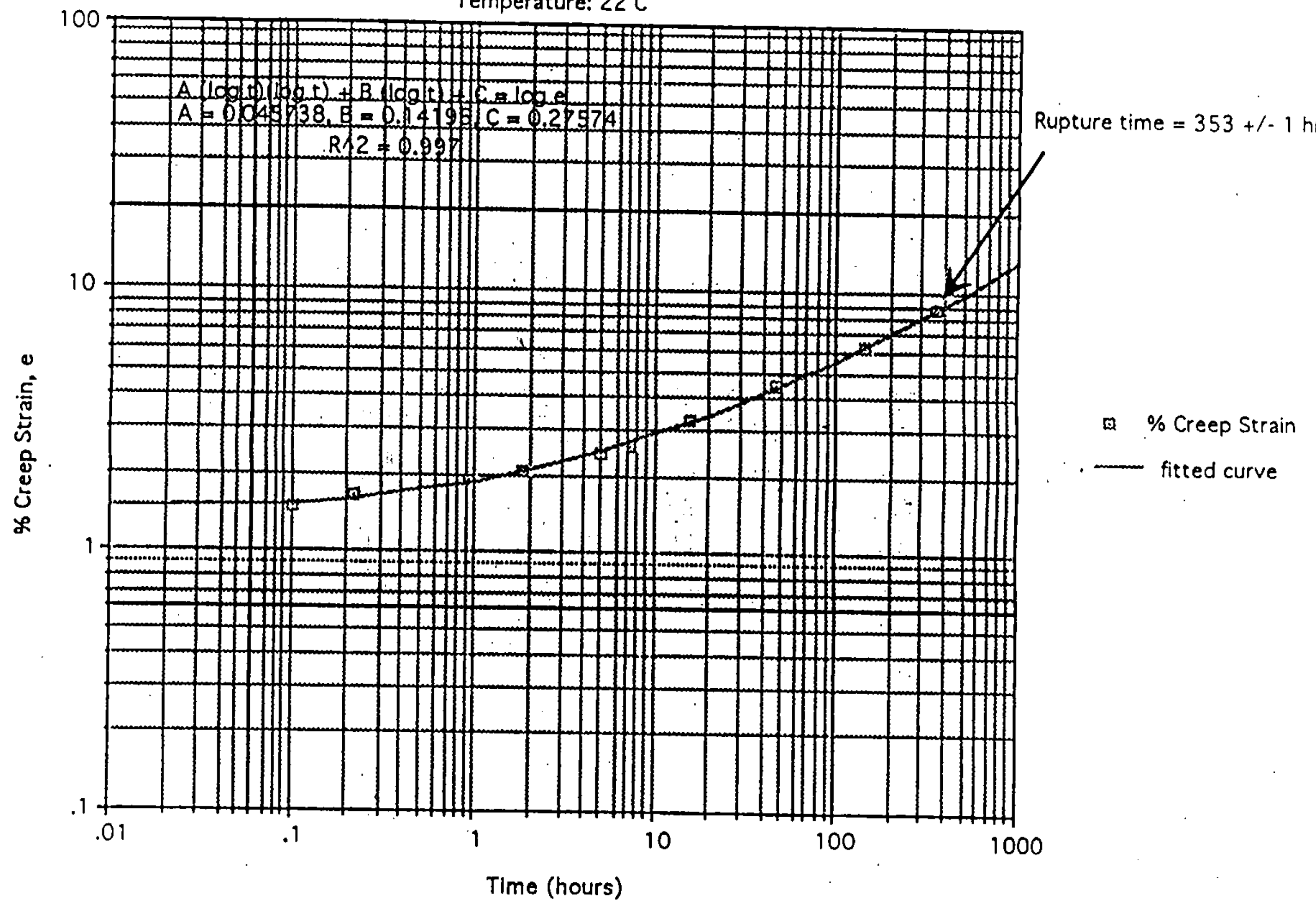
Plot D5

The % Creep strain as a function of time for Test # C1-A3410-GPM5600-tap

Tensile Stress: 3410 psi

Environment: Tap water

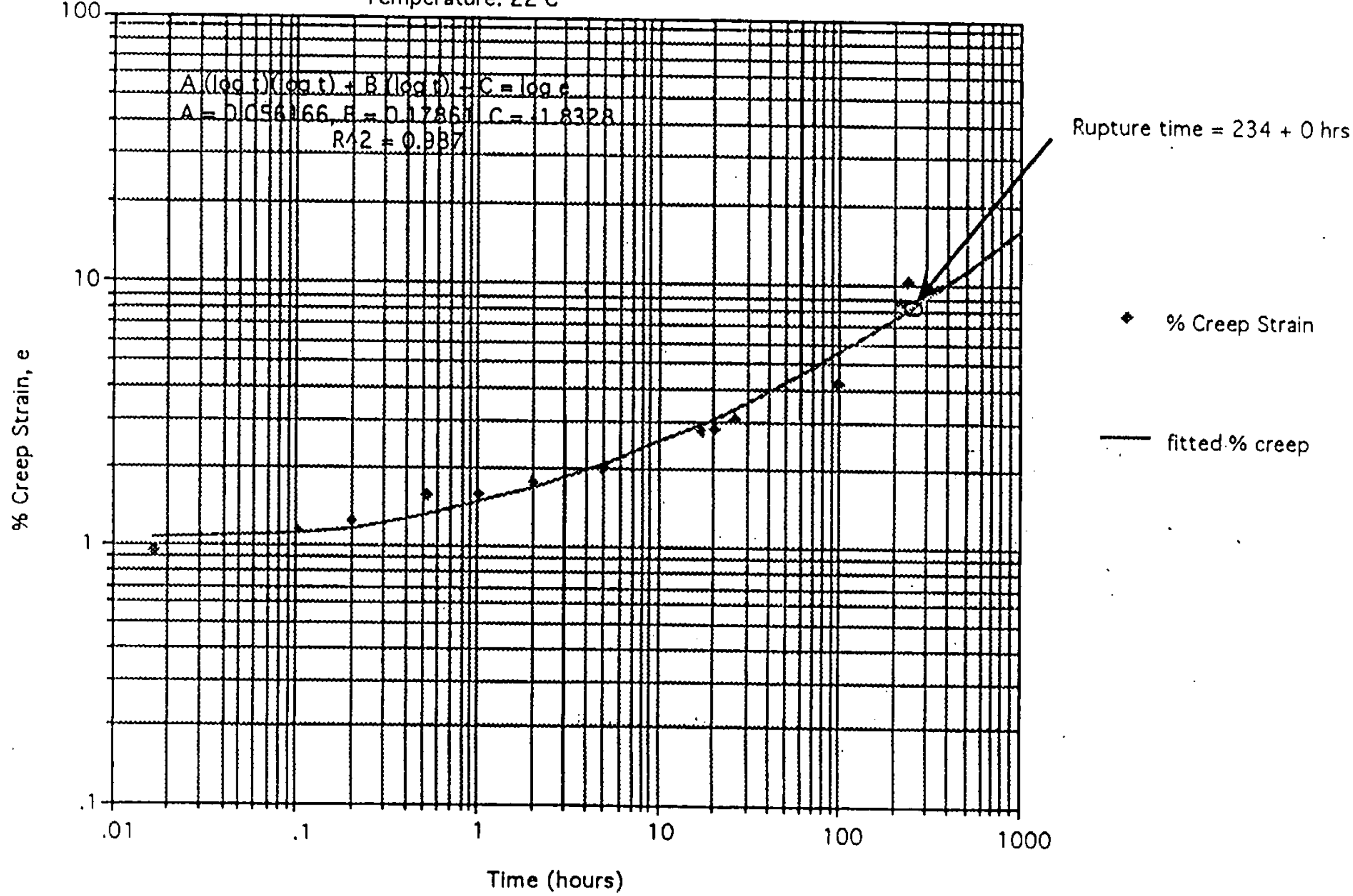
Temperature: 22 C



Plot D6

The % Creep strain as a function of time for Test # C2-A2920-GPM5600-DI

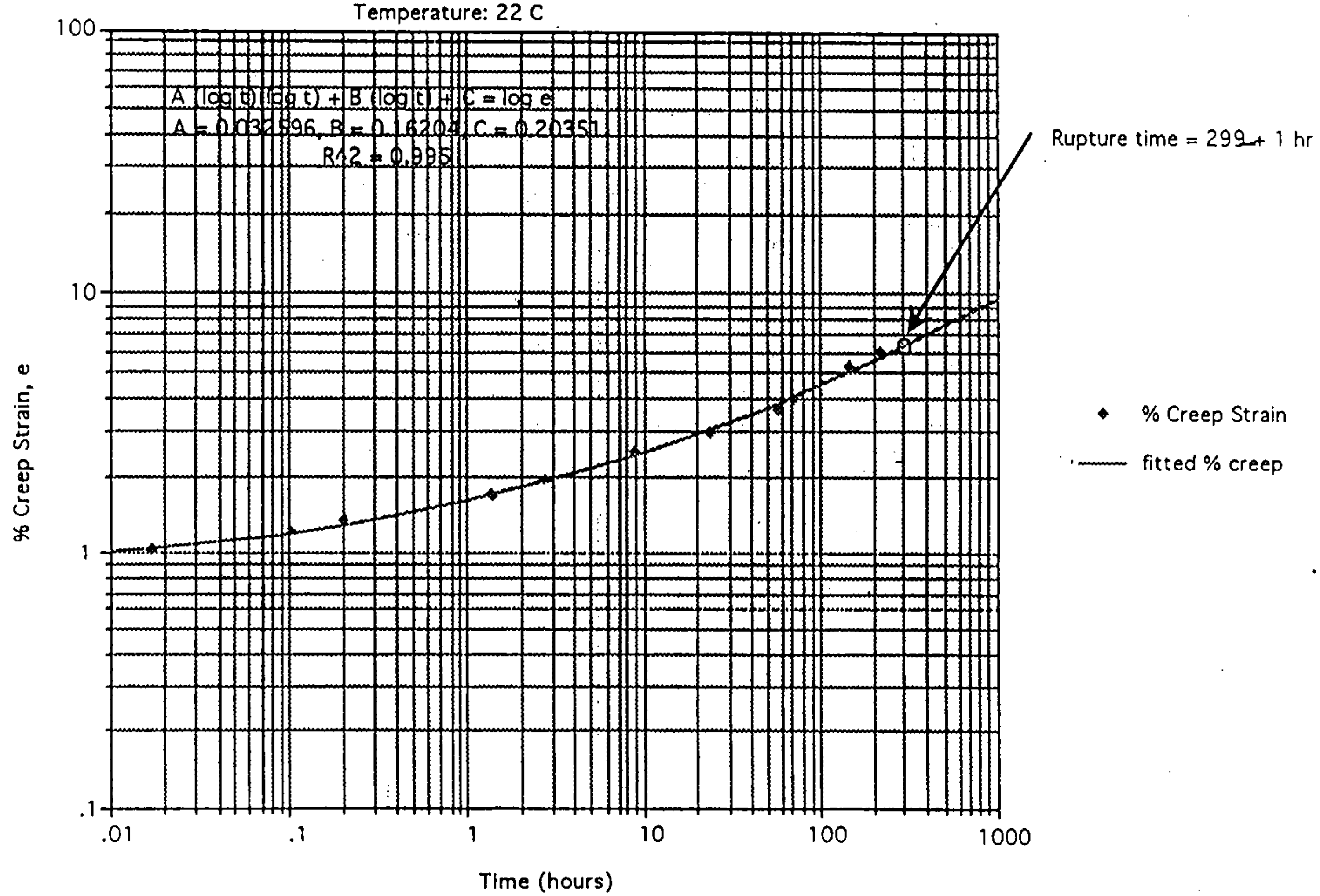
Tensile Stress: 2920 psi
Environment: Deionized water (18MΩ-cm)
Temperature: 22 C



Plot D7

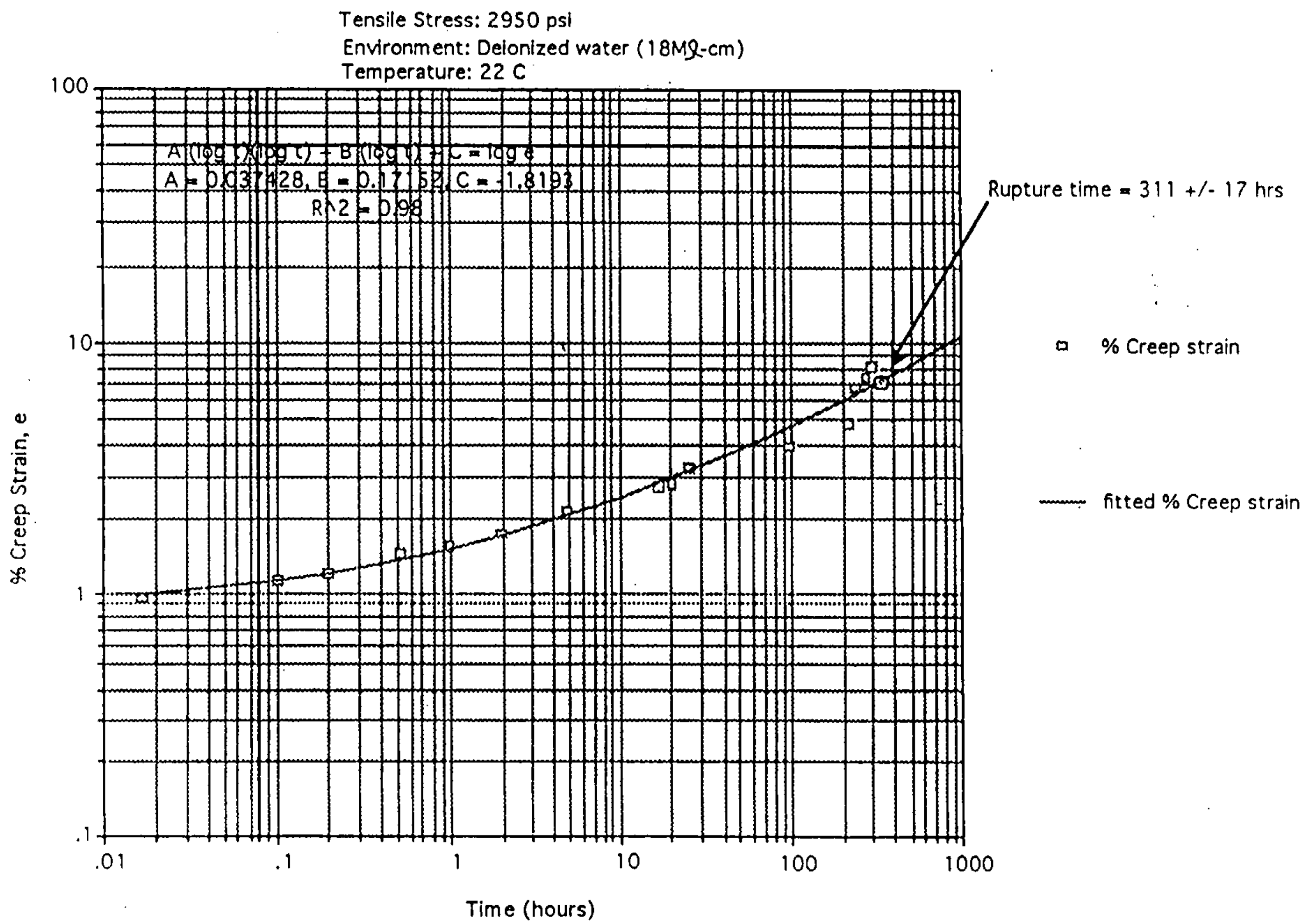
The % Creep strain as a function of time for Test # C2-A3120-GPM5600-DI

Tensile Stress: 3120 psi
Environment: DeIonized water (18MΩ-cm)
Temperature: 22 C



Plot D8

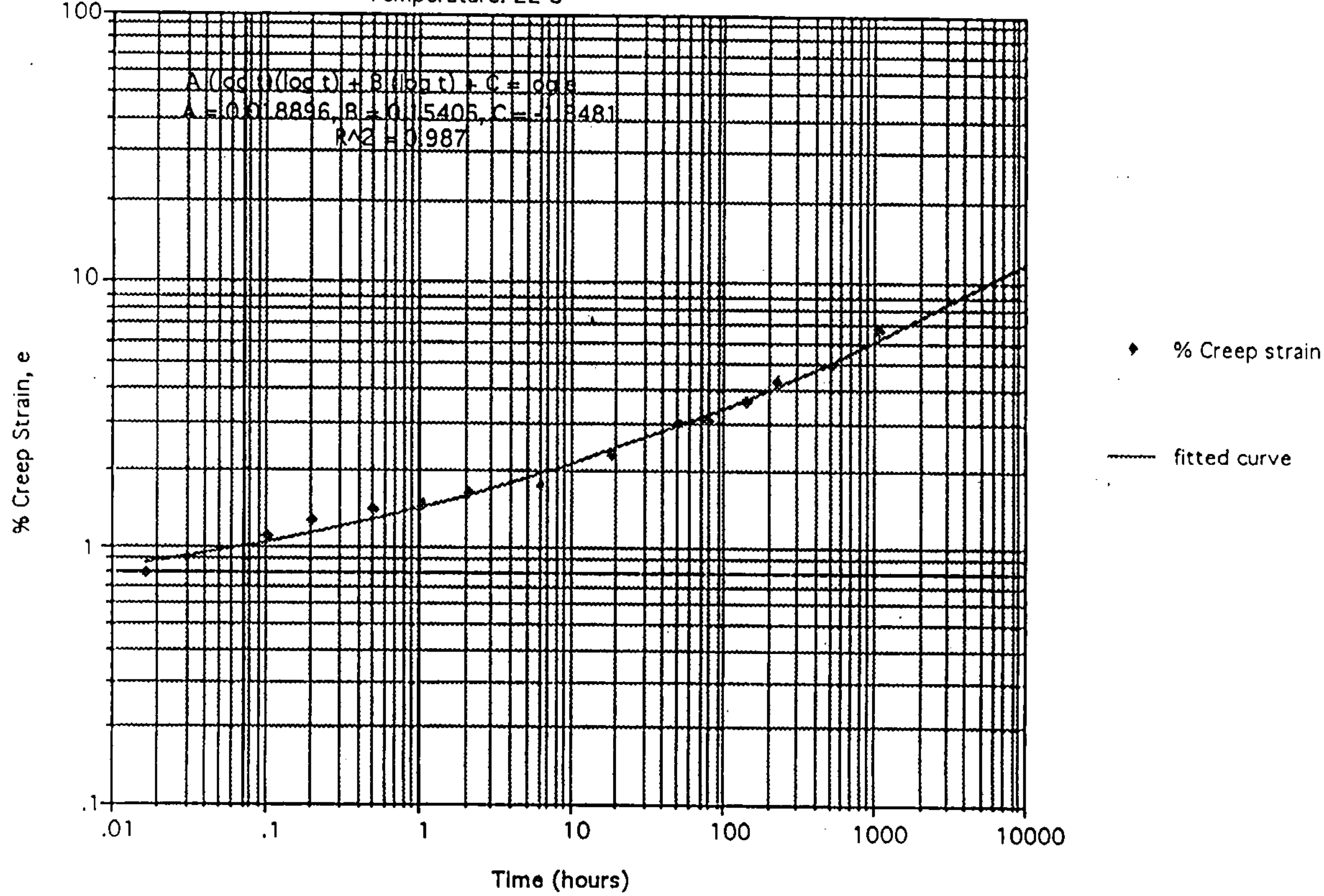
The % Creep strain as a function of time for Test # C3-A2950-GPM5600-DI



Plot D9

The % Creep strain as a function of time for Test # C2-A2400-GPM5600-DI

Tensile Stress: 2400 psi
Environment: Deionized water (18MΩ-cm)
Temperature: 22 C

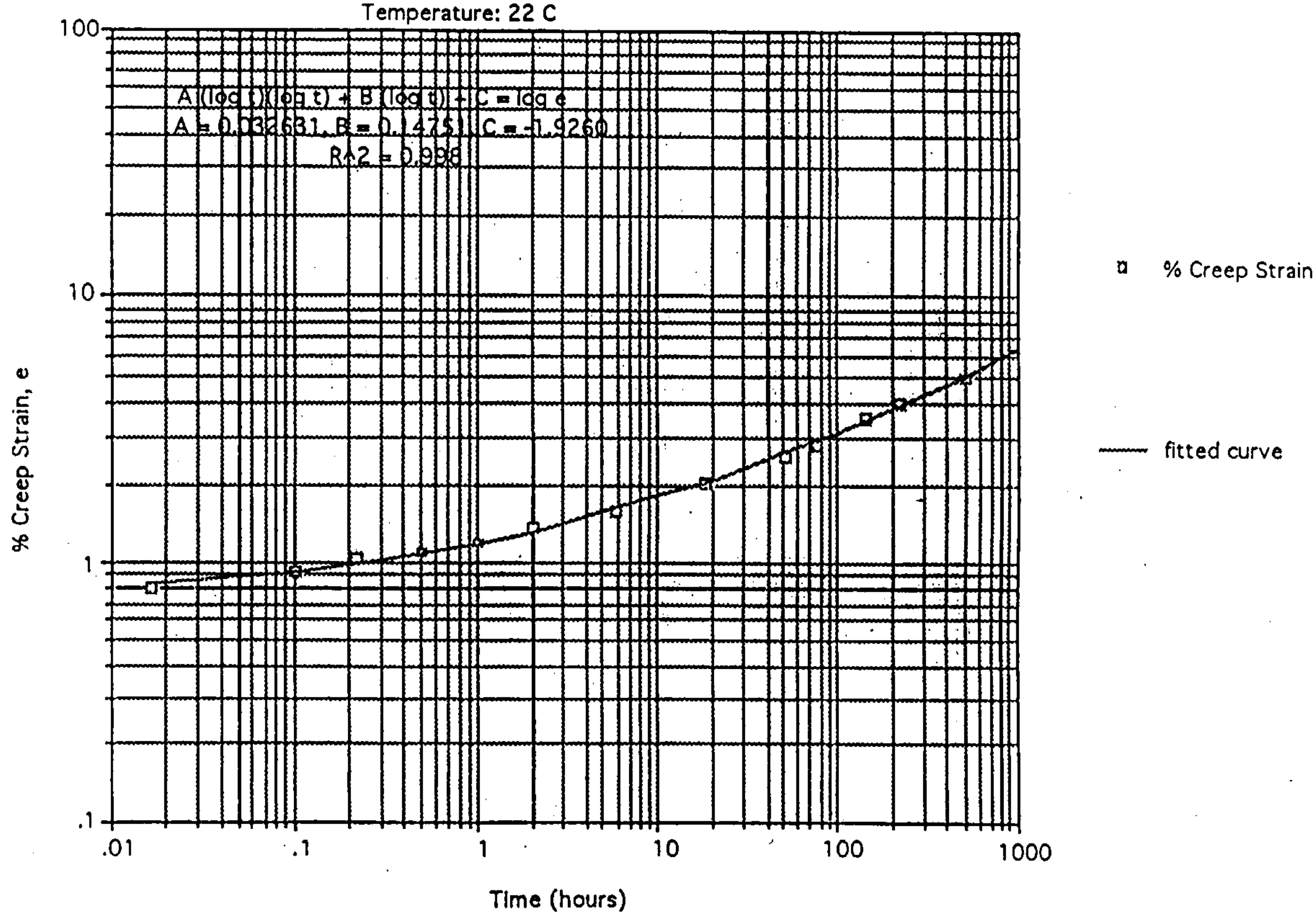


Plot D10

Note: Due to deionized water shutdown, this test was discontinued.

The % Creep strain as a function of time for Test # C3-A2450-GPM5600-DI

Tensile Stress: 2450 psi
Environment: Deionized water (18MΩ-cm)
Temperature: 22 C



Note: Due to deionized water shutdown, this test was discontinued.

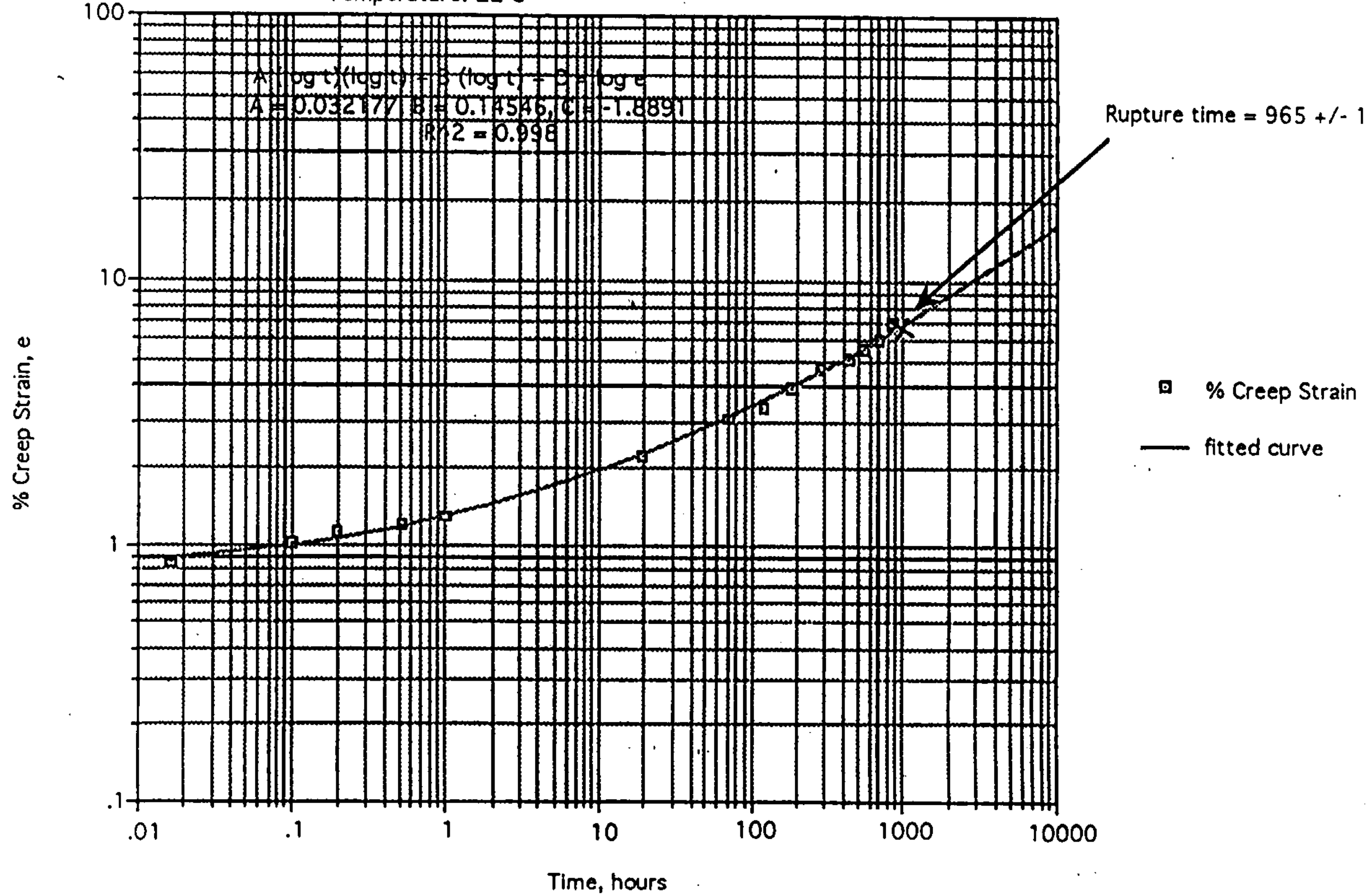
Plot D11

The % Creep strain as a function of time for Test# C2-A2650-GPM5600-DI

Tensile Stress: 2650 psi

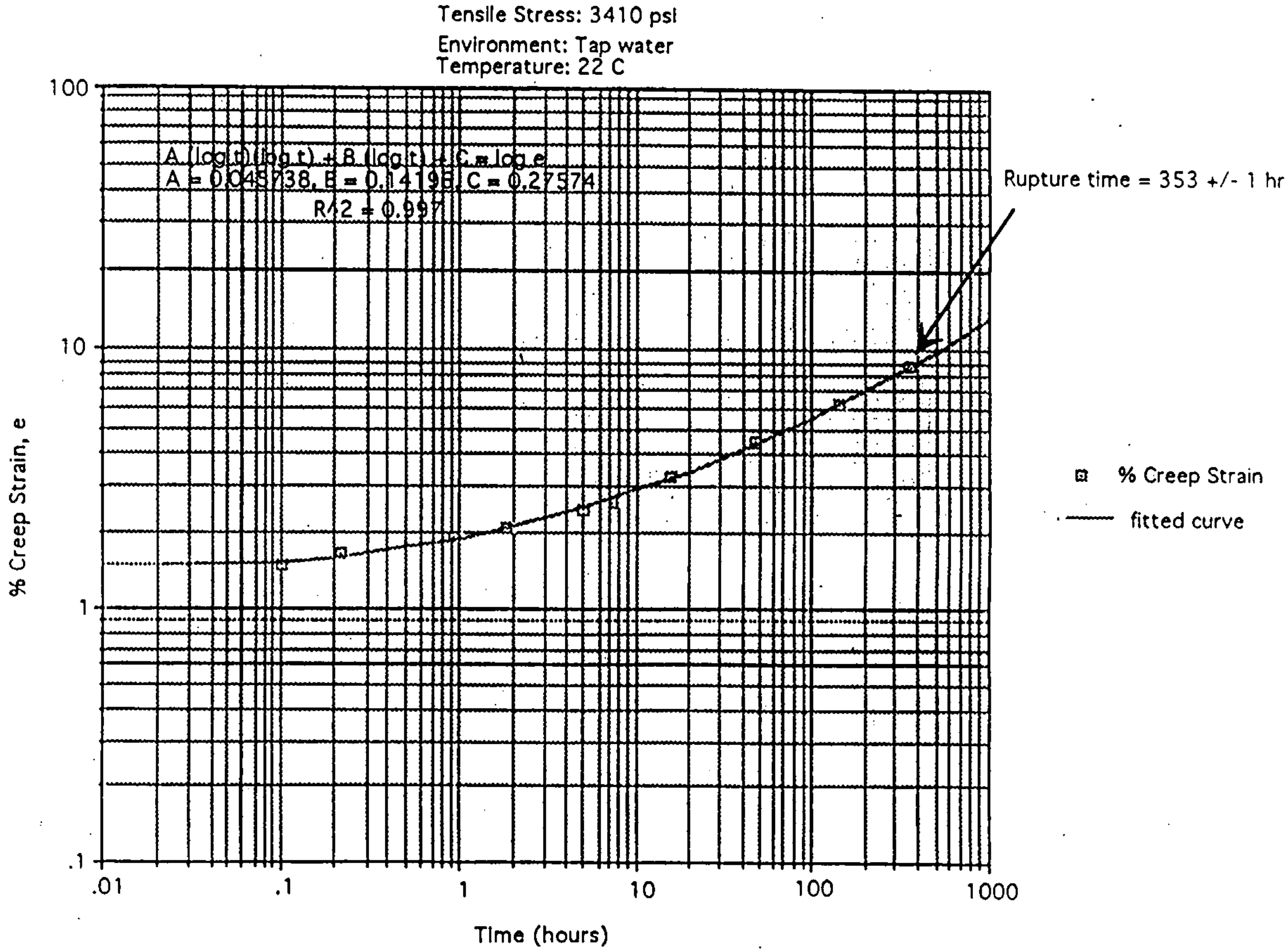
Environment: Deionized water (18MΩ-cm)

Temperature: 22 C



Plot D12

The % Creep strain as a function of time for Test # C1-A3410-GPM5600-tap



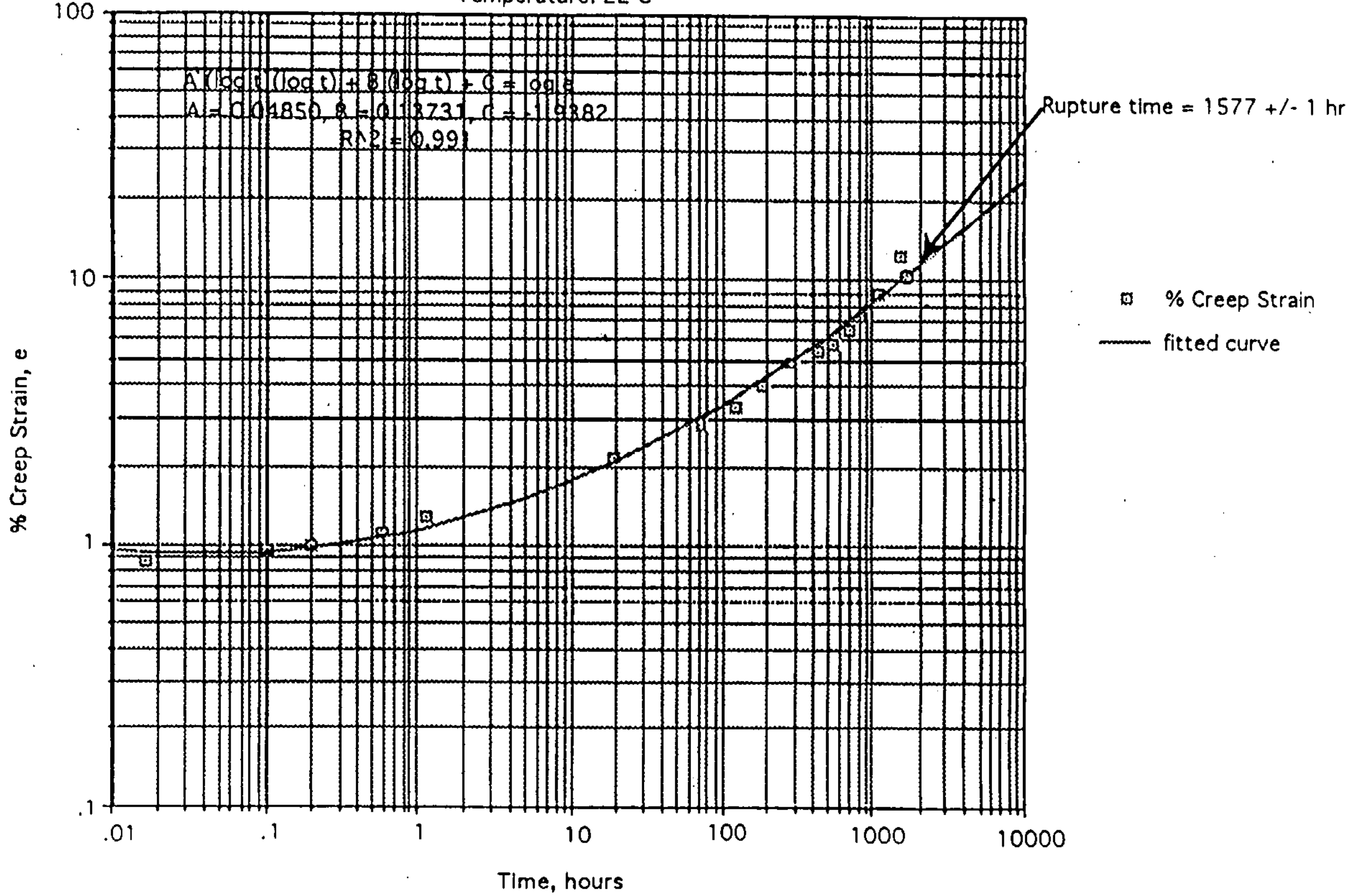
Plot D13

The % Creep strain as a function of time for Test # C1-A2670-GPM5600-tap

Tensile Stress: 2670 psi

Environment: Tap water

Temperature: 22 C



Plot D14

Appendix E

Tap Water Evaluation

'EST RESULTS

Barnstead Water Analysis Service

Sample Number 209732

Date September 9, 1991

Tap

Feedwater sample submitted was: X Raw ☐ Pretreated

If your sample was taken from a pretreated water source (distilled, deionized or reverse osmosis quality) we tested for:

Specific Resistance—This measurement relates directly to the total ionized solids content of the intended feedwater supply. It enables us to determine if pretreatment of feedwater is indicated based on your daily volume and purity level requirements. Specific resistance is measured using a Barnstead Model E3300 PC4 Plus.

Total Ionized Solids—This parameter is an expression of the total concentration of ionizable materials in the intended feedwater supply. Since deionization performance depends upon the level of ionized impurities in the feedwater, this parameter is used to estimate cartridge life and operating cost.

It is calculated from specific resistance and is expressed in concentration units as NaCl.

Total Organic Carbon—This measurement indicates the level of organic contamination in the feedwater supply and is used to determine if organic removal should be used as part of the purification process. Total organic carbon is measured using a Dohrmann Total Organic Carbon Analyzer.

Test Results	Reference
Specific Resistance: 10,680 (ohm-cm @ 25°C)	Distilled Water (500,000 ohm-cm) [1] Deionized Water (Mixed Bed—1,000,000 ohm-cm) Deionized Water (Two Bed—175,000 ohm-cm) Reverse Osmosis Water (25,000 ohm-cm) Reverse Osmosis Water (50,000 ohm-cm)
Total Ionized Solids: 52.89 (ppm as NaCl)	Raw water (Good) 51.3 ppm as NaCl Raw water (Average) 171 ppm as NaCl Raw water (Poor) 342 ppm as NaCl
Total Organic Carbon: 1.50 (ppm as C)	

If your sample was taken from a raw water source (city supplied or a well), the following additional tests were performed to determine suitability of your feedwater for the specified pretreatment method:

pH—This test is used to determine feedwater suitability for reverse osmosis pretreatment. Highly acidic water (below 3) and highly basic water (above 8) may require pH adjustment to prevent membrane damage. pH measurements are per APHA Standard Methods for the Examination of Water and Wastewater.

Alkalinity—The alkalinity test provides an indication of the level of carbonates, bicarbonates and hydroxides in the feedwater supply. Used to determine the scale-forming characteristics of the feedwater, the measurement is per APHA Standard Methods for the Examination of Water and Wastewater.

Calcium—Calcium impurities contribute to the hardness of water. A high level of calcium indicates the need for additional pretreatment since feedwater may cause scaling on a reverse osmosis membrane or in a still evaporator. Calcium measurement is by ASTM procedure D2576.

CO_2—Since CO_2 ionizes in water it is easily removed by an ion exchange cartridge and will therefore use up ion exchange capacity. CO_2 calculations are made to determine the increased load on the mixed-bed ion exchange cartridges.

Test	Result
pH	7.3
Alkalinity	35.00 (ppm)
Calcium	27.75 (ppm as $CaCO_3$)
CO_2	4.06 (ppm as $CaCO_3$)

Comments:

Barnstead | Thermolyne Corp.

[illegible] per Blvd. • Dubuque, Iowa 52001
[illegible] 84767 Thermux (RCA) • FAX: 319-556-0695
Phone: 319-556-2241 • 1-800-553-0039

[1] High purity water readily absorbs CO_2 when exposed to the atmosphere. Readings taken at Barnstead are likely to be considerably less due to this exposure during transport and sampling procedures.
The most accurate method for determining the quality of high purity water is an in-line measurement.

*BDL = Below detection limit

**NES = Not enough sample

Appendix F

Table Summary of Tests

APPENDIX F

Table 1 - The Creep Tests Performed in Deionized Water.

Tensile Stress (± 20), psi	Rupture time, hours
3900	22 ± 2
3850	36 ± 7
3420	91 ± 1
3410	179 ± 1 *
3170	133 ± 1
3120	299 ± 1
2950	311 ± 17
2920	234 ± 0
2700	In progress
2650	965 ± 1
2400 & 2450	**

Table 2 - The Creep Tests Performed in Tap Water.

Tensile Stress (± 20), psi	Rupture time, hours
3410	353 ± 1
2670	In progress

* Due to deionized water shutdown, the specimen was exposed to air (< 18 hours)

** The 2450 & 2400 psi creep tests were only valid up to 1435 hours due to a deionized water shutdown. Most importantly, these tests did not rupture in 1435 hours, and if the water had not been turned off, the specimens would have continued to creep.

Appendix G

Raw Data for Creep Tests

Table G1

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
			C2-A3900-GPM5600-DI				
C2-A3900-GPM5600-DI	0.017	0.047	0.004	1.258	310000	0.017	1.260
	0.100	0.049	0.006	1.925	202626	0.100	1.911
	0.200	0.049	0.007	2.191	177969	0.200	2.228
	0.667	0.052	0.009	2.925	133346	0.500	2.712
	1.000	0.052	0.009	3.158	123493	1.000	3.133
	2.017	0.054	0.011	3.658	106614	2.000	3.603
	4.700	0.055	0.012	4.091	95322	5.000	4.309
	18.883	0.060	0.017	5.591	69750	10.000	4.909
Rupture = 22 ± 2 hrs						50.000	6.543
						100.000	7.354

Table G2

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
			C3-A3850-GPM5600-DI				
C3-A3850-GPM5600-DI	0.017	0.053	0.004	1.242	310000	0.017	1.389
	0.100	0.055	0.005	1.809	212872	0.100	1.611
	0.200	0.056	0.006	1.975	194910	0.200	1.787
	0.667	0.057	0.007	2.442	157662	0.500	2.133
	1.000	0.057	0.008	2.542	151459	1.000	2.513
	2.000	0.058	0.009	2.875	133901	2.000	3.038
	4.683	0.060	0.010	3.309	116363	5.000	4.063
	18.867	0.063	0.013	4.309	89356	10.000	5.217
	23.917	0.079	0.029	9.642	39930	20.000	6.875
	28.783	0.080	0.030	10.142	37961	50.000	10.303
Rupture = 36 ± 7 hrs						100.000	14.419

Table G3

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
			C2-A3420-GPM5600-DI				
C2-A3420-GPM5600-DI	0.017	0.099	0.003	1.103	310000	0.010	1.083
	0.100	0.100	0.005	1.503	227511	0.017	1.147
	0.200	0.100	0.005	1.537	222575	0.100	1.435
	0.500	0.101	0.006	1.970	173614	0.200	1.581
	1.900	0.102	0.007	2.270	150668	0.500	1.813
	5.083	0.103	0.008	2.537	134828	1.000	2.024
	23.933	0.106	0.010	3.470	98562	2.000	2.273
	47.433	0.106	0.011	3.670	93191	5.000	2.671
	79.933	0.111	0.016	5.337	64086	10.000	3.038
Rupture = 91 ± 1 hr						20.000	3.475
						50.000	4.187
						100.000	4.852
						200.000	5.655
						500.000	6.984
						1000.000	8.247

Table G4

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
			C3-A3170-GPM5600-DI				
C3-A3170-GPM5600-DI	0.017	0.162	0.003	1.023	310000	0.010	1.008
	0.100	0.163	0.004	1.223	259288	0.017	1.040
	0.200	0.163	0.004	1.356	233791	0.100	1.210
	1.333	0.164	0.005	1.656	191435	0.200	1.306
	2.683	0.165	0.006	1.856	170805	0.500	1.466
	8.600	0.166	0.007	2.356	134555	1.000	1.618
	23.433	0.168	0.009	2.856	110998	2.000	1.804
	56.017	0.170	0.010	3.456	91727	5.000	2.114
	69.100	0.170	0.011	3.723	85156	10.000	2.410
Rupture = 133 ± 1 hr						20.000	2.775
						50.000	3.394
						100.000	3.998
						200.000	4.755
						500.000	6.071
						1000.000	7.387

Table G5

C3-A3410-GPM5600-DI							
Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
C3-A3410-GPM5600-DI	0.017	0.055	0.003	1.100	310000	0.010	1.158
	0.100	0.055	0.004	1.300	262308	0.017	1.155
	0.200	0.055	0.004	1.267	269211	0.100	1.233
	0.517	0.056	0.005	1.600	213125	0.200	1.306
	1.867	0.057	0.006	1.833	186000	0.500	1.447
	5.050	0.057	0.006	1.967	173390	1.000	1.596
	22.883	0.060	0.009	2.967	114944	2.000	1.791
	47.400	0.062	0.011	3.567	95607	5.000	2.145
	79.883	0.064	0.013	4.300	79302	10.000	2.509
	101.133	0.067	0.016	5.200	65577	20.000	2.987
	145.967	0.068	0.017	5.700	59825	50.000	3.864
Rupture = 179 ± 1 hr						100.000	4.792
DI water shutdown for 18 hrs						200.000	6.050
						500.000	8.458
						1000.000	11.123

Table G6

C2-A2920-GPM5600-DI							
Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
C2-A2920-GPM5600-DI	0.017	0.043	0.003	0.942	310000	0.017	1.065
	0.100	0.044	0.003	1.142	255706	0.100	1.109
	0.200	0.044	0.004	1.242	235117	0.200	1.174
	0.517	0.045	0.005	1.542	189372	0.500	1.314
	1.000	0.045	0.005	1.575	185365	1.000	1.470
	1.967	0.046	0.005	1.742	167630	2.000	1.683
	4.800	0.046	0.006	2.009	145375	5.000	2.087
	16.783	0.049	0.008	2.775	105215	10.000	2.523
	19.967	0.049	0.008	2.809	103966	20.000	3.124
	24.967	0.050	0.009	3.075	94951	50.000	4.293
	96.850	0.053	0.013	4.209	69382	100.000	5.612
	214.917	0.066	0.026	8.509	34318	200.000	7.509
	234.617	0.071	0.031	10.242	28510	500.000	11.439
Rupture = 234 ± 1 hrs						1000.000	16.163
						1000.000	11.123

Table G7

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
			C2-A3120-GPM5600-DI				
C2-A3120-	0.017	0.052	0.003	1.006	310000	0.010	1.023
GPM5600-DI	0.100	0.053	0.004	1.206	258610	0.017	1.043
	0.200	0.053	0.004	1.340	232873	0.100	1.186
	1.333	0.054	0.005	1.673	186478	0.200	1.277
	2.683	0.055	0.006	1.906	163655	0.500	1.438
	8.600	0.057	0.007	2.473	126157	1.000	1.598
	23.433	0.058	0.009	2.940	106130	2.000	1.800
	56.017	0.060	0.011	3.606	86512	5.000	2.151
	69.100	0.061	0.012	3.940	79192	10.000	2.501
	139.517	0.065	0.016	5.306	58796	20.000	2.948
	211.600	0.067	0.018	5.940	52527	50.000	3.740
Rupture = 299 ± 1 hr						100.000	4.550
						200.000	5.610
						500.000	7.556
						1000.000	9.616

Table G8

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
			C3-A2950-GPM5600-DI				
C3-A2950-	0.017	0.040	0.003	0.952	310000	0.017	0.986
GPM5600-DI	0.100	0.040	0.003	1.118	263798	0.100	1.113
	0.200	0.040	0.004	1.185	248956	0.200	1.200
	0.517	0.041	0.004	1.452	203222	0.500	1.357
	1.000	0.041	0.005	1.552	190125	1.000	1.516
	1.967	0.042	0.005	1.752	168416	2.000	1.721
	4.800	0.043	0.006	2.152	137106	5.000	2.084
	16.767	0.045	0.008	2.718	108525	10.000	2.453
	19.967	0.045	0.008	2.752	107210	20.000	2.932
	24.967	0.046	0.010	3.218	91664	50.000	3.803
	96.850	0.049	0.012	3.952	74653	100.000	4.715
	214.917	0.051	0.015	4.852	60805	200.000	5.937
	234.683	0.057	0.020	6.752	43693	500.000	8.246
	269.717	0.059	0.022	7.285	40494	1000.000	10.767
	294.617	0.061	0.024	8.085	36488		
Rupture = 311 ± 17 hrs							

Table G9

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
			C2-A2400-GPM5600-DI				
C2-A2400-GPM5600-DI	0.017	0.034	0.002	0.774	309997	0.017	0.866
	0.100	0.035	0.003	1.074	223422	0.100	1.039
	0.200	0.036	0.004	1.274	188353	0.200	1.131
	0.500	0.036	0.004	1.408	170511	0.500	1.280
	1.017	0.036	0.004	1.441	166566	1.000	1.419
	2.100	0.037	0.005	1.608	149297	2.000	1.585
	6.033	0.037	0.005	1.708	140554	5.000	1.857
	18.417	0.039	0.007	2.274	105532	10.000	2.113
	51.333	0.041	0.009	2.974	80694	20.000	2.423
	75.433	0.041	0.009	3.041	78925	50.000	2.939
	139.533	0.043	0.011	3.608	66527	100.000	3.432
	220.200	0.045	0.013	4.308	55716	200.000	4.041
	500.283	0.047	0.015	4.941	48574	500.00	5.074
	1027.78	0.052	0.020	6.608	36322	1000.00	6.083
No rupture time						10000.00	11.762
DI water							
shutdown							

Table G10

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
			C3-A2450-GPM5600-DI				
C3-A2450-GPM5600-DI	0.017	0.018	0.002	0.790	310000	0.017	0.822
	0.100	0.019	0.003	0.924	265250	0.100	0.910
	0.217	0.019	0.003	1.024	239338	0.200	0.970
	0.500	0.019	0.003	1.090	224704	0.500	1.078
	1.017	0.019	0.004	1.190	205827	1.000	1.186
	2.033	0.020	0.004	1.357	180547	2.000	1.322
	5.967	0.021	0.005	1.557	157355	5.000	1.560
	18.350	0.022	0.006	2.057	119106	10.000	1.795
	51.267	0.024	0.008	2.557	95816	20.000	2.095
	75.367	0.024	0.008	2.790	87803	50.000	2.623
	139.467	0.027	0.011	3.557	68878	100.000	3.159
	220.133	0.028	0.012	4.057	60390	200.000	3.857
	500.217	0.031	0.015	4.990	49095	500.00	5.127
	1027.72	0.036	0.020	6.757	36259	1000.00	6.460
No rupture time						2000.00	8.251
DI water						5000.00	11.644
shutdown						10000.00	15.351

Table G11

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
			C2-A2650-GPM5600-DI				
C2-A2650-	0.017	0.095	0.003	0.855	310000	0.010	0.889
GPM5600-DI	0.100	0.095	0.003	1.022	259421	0.017	0.899
	0.200	0.095	0.003	1.122	236290	0.100	0.995
	0.517	0.096	0.004	1.188	223032	0.200	1.059
	1.000	0.096	0.004	1.288	205718	0.500	1.175
	18.967	0.099	0.007	2.222	119288	1.000	1.291
	70.733	0.101	0.009	3.022	87705	2.000	1.437
	119.167	0.102	0.010	3.388	78213	5.000	1.692
	184.667	0.104	0.012	3.955	67007	10.000	1.943
	279.667	0.106	0.014	4.688	56525	20.000	2.263
	430.750	0.107	0.015	5.088	52082	50.000	2.824
	534.083	0.109	0.017	5.555	47706	100.00	3.393
Submerged but no flow:	690.17	0.110	0.018	6.022	44009	200.00	4.130
4/24/92 11:00am to 4/27/92						500.00	5.469
	857.917	0.113	0.021	7.022	37741	1000.00	6.869
Rupture = 965 ± 1 hours						10000.00	16.128

Table G12

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
			C1-A3410-GPM5600-TAP				
C1-A3410-	0.100	0.141	0.004	1.467	232500	0.010	1.495
GPM5600-TAP	0.217	0.142	0.005	1.633	208776	0.017	1.472
	0.950	0.143	0.006	1.933	176379	0.100	1.512
	1.833	0.143	0.006	2.100	162381	0.200	1.581
	4.933	0.144	0.007	2.433	140137	0.500	1.726
	7.200	0.145	0.008	2.600	131154	1.000	1.887
	15.933	0.147	0.010	3.267	104388	2.000	2.102
	47.433	0.150	0.013	4.433	76917	5.000	2.496
	143.850	0.156	0.019	6.267	54415	10.000	2.907
						20.000	3.450
Rupture = 353 ± 1 hr						50.000	4.456
						100.00	5.529
						200.00	6.991
						500.00	9.819
						1000.00	12.980

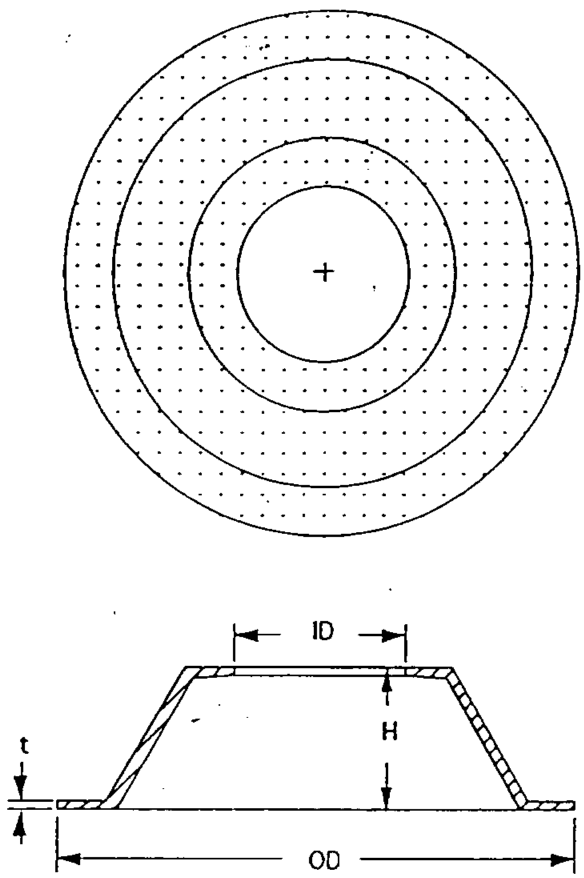
Table G13

Comments	Time, hours	Observed ext, inch	Real ext, inch	% Creep Strain	Creep Modulus, psi	fitted time, hrs	fitted curve
C1-A2670-GPM5600-Tap							
C1-A2670-GPM5600-Tap	0.017	0.113	0.003	0.861	310000	0.010	0.958
	0.100	0.113	0.003	0.961	277752	0.017	0.935
	0.200	0.113	0.003	0.995	268443	0.100	0.940
	0.583	0.114	0.003	1.128	236711	0.200	0.976
	1.150	0.114	0.004	1.295	206238	0.500	1.059
	18.750	0.117	0.006	2.161	123537	1.000	1.153
	70.483	0.119	0.009	2.861	93315	2.000	1.281
	119.950	0.120	0.010	3.328	80229	5.000	1.519
	184.450	0.122	0.012	3.995	66840	10.000	1.769
	279.450	0.125	0.015	4.895	54550	20.000	2.102
	430.583	0.127	0.016	5.428	49190	50.000	2.723
	533.867	0.128	0.017	5.795	46077	100.00	3.392
	689.95	0.130	0.019	6.495	41111	200.00	4.311
	857.700	0.132	0.022	7.328	36436	500.00	6.105
	1102.95	0.137	0.027	8.895	30018	1000.00	8.133
	1530.95	0.147	0.037	12.361	21600	10000.00	2.44E+01
Rupture at 1577 hours							

Appendix H

Absorption Test Schematic and Raw Data

Absorption Measurement Schematic



t = thickness, in
H = height, in
ID = inside diameter, in
OD = outside diameter, in

Initial Measurements - 4/10/1992				
Weight = 262.1± 0.1 g				
Marked Position #	H ± 0.001	t ± 0.002	ID ± 0.002	OD ± 0.002
1	2.938	0.163	4.005	10.857
2	2.938	0.161	4.003	10.863
3	2.938	0.166	4.006	10.855
4	2.938	0.163		
5	2.938	0.160		
6	2.938	0.162		
Measurement #1 - 4/20/1992				
Weight = 263.2 ± 0.1 g				
Marked Position #	H ± 0.001	t ± 0.002	ID ± 0.002	OD ± 0.002
1	2.939	0.164	4.006	10.864
2	2.939	0.166	4.005	10.870
3	2.939	0.164	4.005	10.864
4	2.939	0.162		
5	2.940	0.160		
6	2.940	0.162		
Measurement #2 - 4/27/1992				
Weight = 263.5 ± 0.1 g				
Marked Position #	H ± 0.001	t ± 0.002	ID ± 0.002	OD ± 0.002
1	2.939	0.164	4.005	10.871
2	2.939	0.166	4.003	10.875
3	2.939	0.164	4.005	10.874
4	2.939	0.162		
5	2.940	0.160		
6	2.939	0.162		
Measurement #3 - 5/4/1992				
Weight = 263.5 ± 0.1 g				
Marked Position #	H ± 0.001	t ± 0.002	ID ± 0.002	OD ± 0.002
1	2.939	0.162	4.005	10.871
2	2.939	0.165	4.005	10.876
3	2.939	0.164	4.006	10.875
4	2.939	0.163		
5	2.940	0.160		
6	2.939	0.161		
Measurement #4 - 5/11/1992		Weight =	263.6 ± 0.1 g	
Marked Position #	H ± 0.001	t ± 0.002	ID ± 0.002	OD ± 0.002
1	2.939	0.163	4.005	10.868
2	2.939	0.165	4.005	10.876
3	2.939	0.164	4.006	10.872
4	2.940	0.163		
5	2.940	0.160		
6	2.940	0.162		

LAST PAGE