Test Methods for Assessing Long-term Properties of Corrugated HDPE Pipes

Part II – Long-term Tensile Strength

1. INTRODUCTION

The full specification of 100-year corrugated HDPE pipes is pending on three additional tests which are creep rupture of the pipe line (FM 5-575), long-term tensile strength (FM 5-576), and long-term modulus (FM 5-577). Based on the results of the previous project and recently changes in the pipe resins, modifications are required for these three test methods in order to determine the long-term mechanical properties within reasonable testing duration. The test protocol of 100-year modulus was presented in Part I of this report. In this report, the test methods to determine the creep rupture of pipe liner (FM 5-575) and the long-term tensile strength (FM 5-576) are discussed.

2. BACKGROUND

The current design parameters for corrugated HDPE pipe specified by AASHTO Section 17 are shown in Table 1. The short term tensile strength values are taken from the material specification, ASTM D3350, cell classification of 435400C for corrugated pipe resin. Tests are performed on specimens taken from compressive molded plaques; thus, the effects of pipe extrusion are not included. For the long term property values in Table 1, AASHTO Section 17 states that “these values are derived from hydrostatic design bases (HDB) and indicate a minimum 50-year life expectancy under continuous application of tensile stress”. Thus, the long-term values were obtained under a creep mode. Since HDB testing has been removed from the AASHTO Section 18 Bridge specification after 1996, the verification of the long term properties is questionable.

Table 1 – Mechanical Properties for Design HDPE Pipes (NCHRP 631)

Material	Tensile Values (psi)			
	Short-Term	Long-term		
		50-yr	75-yr	100-yr
Corrugated Pipe	3000	900	NA	NA
Profile Pipe	2600	NA	NA	NA

Note: NA = not available

In the recently published NCHRP Report 631, the 75-year and 100-year modulus values of corrugated and profile HDPE pipes were proposed. However, the literature on the long-term tensile strength of HDPE is very sparse, and no values were proposed for design life longer than 50 years.

3. TENSILE STRENGTH

3.1 Short-term tensile strength

The short term tensile strength listed in Table 1 is obtained using specimens taken from compression molded plaques of pure resins; hence, the effects of the pipe manufacturing process and carbon black additives on the tensile properties are not considered. To evaluate the tensile properties of the finished pipe, ASTM D638-Type IV was used to test the pipe. The configuration of the test specimen is same as that of FM 5-572, Procedure B with a junction positioned in the center. A comparison of yield stress between specimens taken from compression molded plaque and pipe junction region can be seen in Table 2, and they are relatively similar. The short-term tensile strength from both materials excesses the AASHTO M294 requirement of 3000 psi.

Table 2 – Comparing Tensile Yield Stress of Molded Plaque and Finished Pipe

Test Material	Specimen	Strain Rate	Yield Strength
Compression molded plaque	ASTM D 638 Type IV	2 in/min	3690 psi
Finished Pipe	FM5-572 Procedure B		3560 psi

3.2 Long-term Tensile Strength

As stated previously, the 50-year long-term tensile strength of 900 psi was obtained using the HDB test (ASTM D2837). ASTM D2837 provides the procedure to linearly extrapolate the creep rupture test data to 50 years. However, the test method to determine HDB value does not reflect the service condition of corrugated pipe used in drainage applications. Therefore an alternative method should be employed to assess the long term tensile strength of corrugated pipe.

An acceleration creep test, the Stepped Isothermal Method (SIM) described in ASTM D6992 can be used to establish creep rupture curve using pipe junction specimens taken from the corrugated HDPE pipe. However, the extrapolation of creep rupture curve can only be validated if the ductile-to-brittle transition occurs beyond 100 years at the temperature of 23^{o}C. To determine the ductile-to-brittle transition point of corrugated HDPE pipes, the stress crack resistance test for pipe junction (FM 5-572, Procedure B) was performed on a corrugated pipe with diameter of 24-in. The test conditions used to establish the transition point are shown in Table 3. The test result is presented in Figure 1 by plotting applied stress versus failure time in a log-log scale. The transition points, which correspond to the onset of the brittle curve, are also shown in Table 3. (The test data are included as Appendix A of this report.)

Table 3 – Test conditions for the junction stress crack resistance test

Pipe	Applied Stress (psi)	Test Temperature (^{o}C)	Transition Stress (psi)	Transition Time (hour)
P-A	950, 850, 750, 650	80	850	79.7
	1000, 900, 800	70	900	472.3

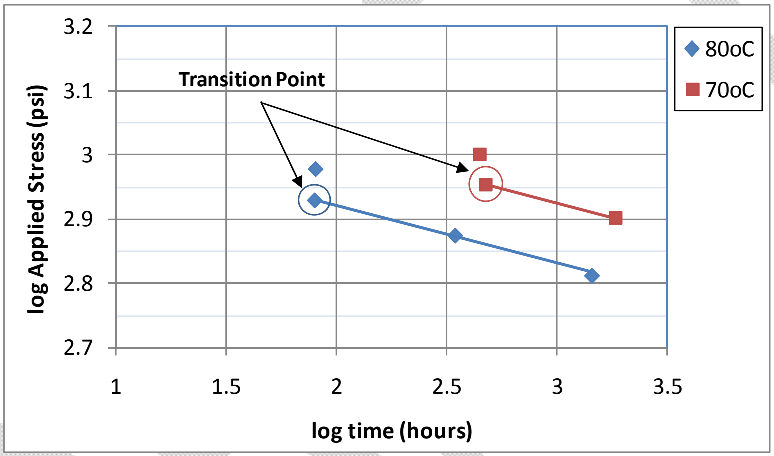


Figure 1 – Stress crack resistance test results of pipe junction

To determine the ductile-to-brittle transition point at 23^{o}C, transition points at 80^{o}C and 70^{o}C are extrapolated using Popelar's shift factors, as expressed in Eq. (1) and (2) (Popelar et al. 1991). The extrapolated transition points at 23^{o}C are shown in Table 4, and the transition will occur at applied stress above 1500 psi and less than 10 years. Therefore, the long-term tensile strength cannot be determined by extrapolating the ductile portion of the creep rupture curve. Instead, it should be evaluated using data from the brittle portion of the curve.

$$a_T = exp[-0.109(T - T_R)] \tag{1}$$

$$b_T = exp[0.0116(T - T_R)] \tag{2}$$

where:

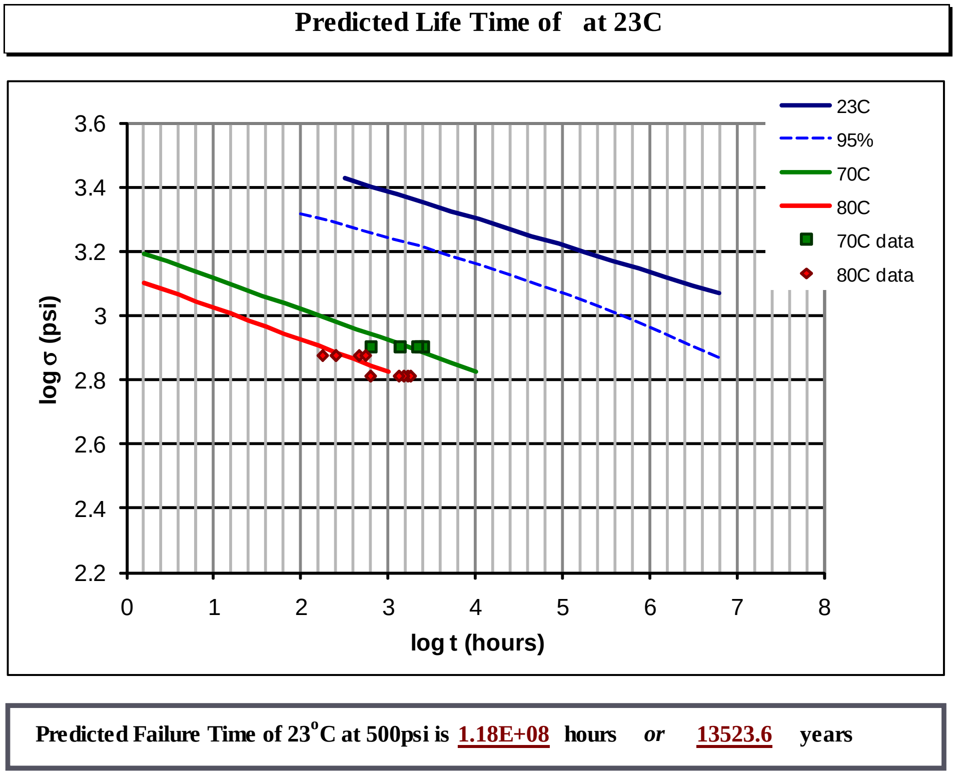
a_T = horizontal shift function (time function)
b_T = vertical shift function (stress function)
T = temperature of the test, in K
T_R = target temperature, in K

Table 4 – Predicted Transition Stress and Time at 23°C

Based on test data at temperature of	Transition Stress (psi)	Transition Time (years)
80°C	1647	4.5
70°C	1552	9.0

Note: The details of the calculation is shown in Appendix B

It should be noted that the predicted failure time of the junction SCR test for P-A at 23°C under the applied stress of 500 psi is well over 100 years, as shown in Figure 2.



Predicted Life Time of at 23C

Predicted Failure Time of 23°C at 500psi is 1.18E+08 hours *or* 13523.6 years

Figure 2 – Predicted stress crack failure time under 500 psi at 23°C

3.2.1 Determine the 100-year Tensile Strength

Using the SCR test data obtained from the pipe junction specimens, the 100-year tensile strength can be predicted. The outline of the method is as follows:

a) Establish the SCR curve using FM 5-572, Procedure B.
b) Perform test at temperatures of 70 and 80^{o}C and applied stresses of 650 and 450 psi, or others.
c) Extrapolate the test data generate the SCR curve at 23^{o}C with 95% confidence.
d) Determine the applied stress corresponding to 100 year from the predicted 23^{o}C curve.

Figures 3 and 4 depict the SCR test result of two pipe junction tests. Curves shown in Figure 3 were obtained from pipe that was **not** certified for the 100 year interim specification. In this case, the predicted tensile stress that would induce stress cracking after 100 years is 550 psi. Contrary, curves shown in Figure 4 were generated from junction specimens taken from P-A pipe, which is a 100-year pipe. The predicted 100-year tensile strength is 930 psi.

Using the minimum required parameters defined in the 100-year specification for junction SCR (at 80^{o}C failure times are 110 hr at 650psi and 430 hr at 450 psi; at 70oC, failure time is 500 hr at 650 psi). The predicted long-term tensile strength is approximately 800 psi, as depicted in Figure 5.

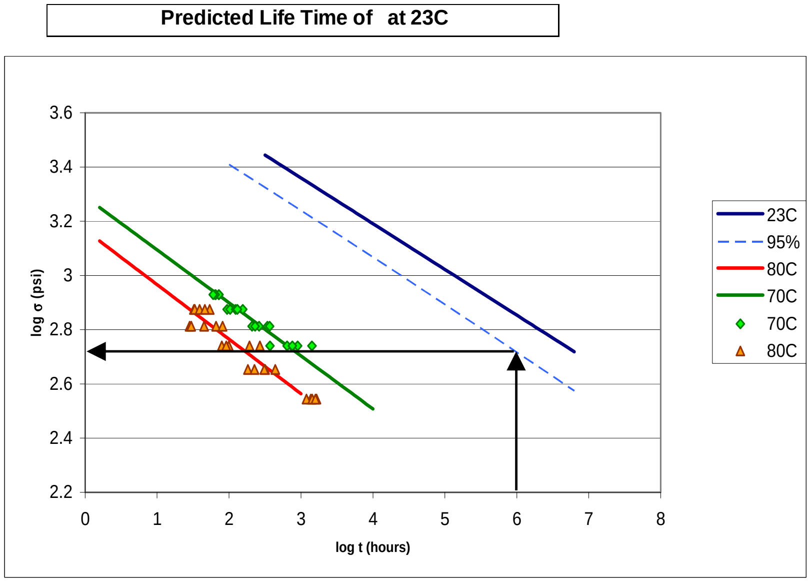


Figure 3 – Determine 100-year tensile stress using predicted 23^{o}C SCR curve from pipe not being certified for 100-year interim specification.

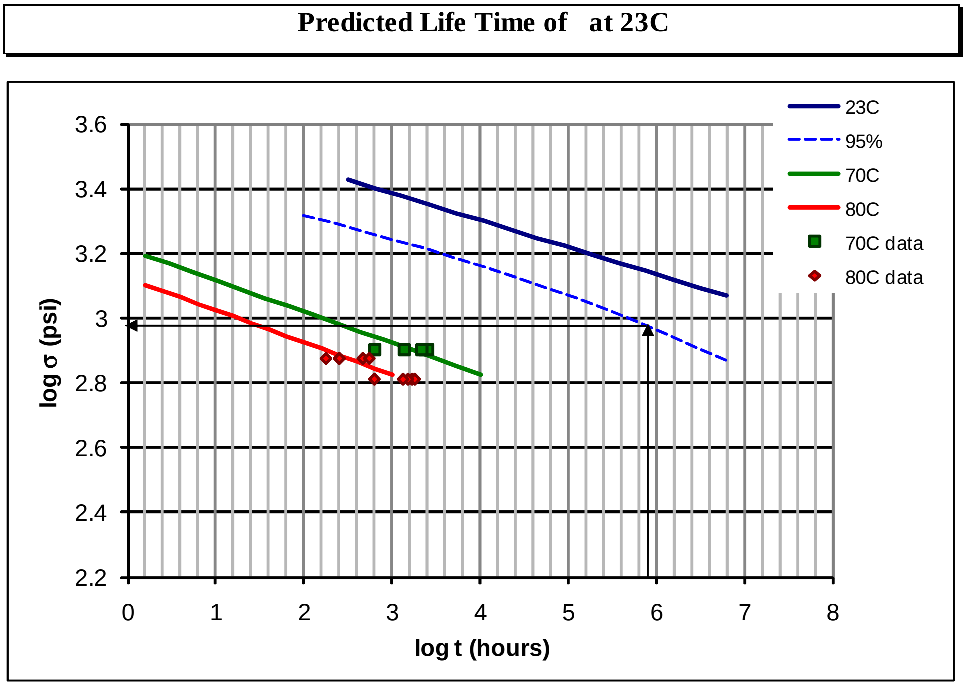


Figure 4 – Determine 100-year tensile stress using predicted 23°C SCR curve from the P-A pipe which has approved for 100-year interim specification.

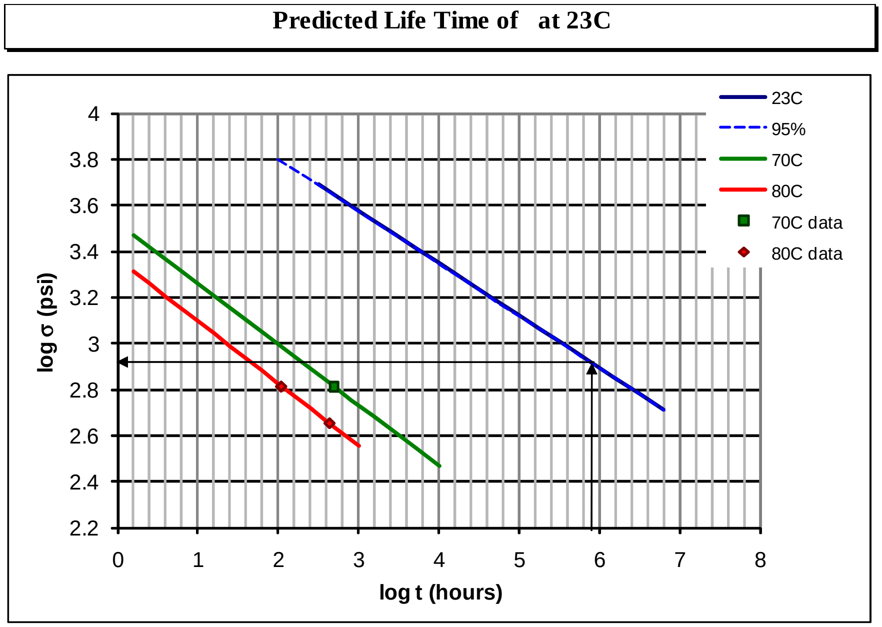


Figure 5 – Determine 100-year tensile stress using predicted 23°C SCR curve obtained from minimum required parameters of the 100-year interim specification.

3.3 Summary

For determination of 100-year tensile strength, tests should be performed on specimens taken from the finished pipes. Two test methods (FM 5-575 and FM 5-576) were developed to assess the long-term tensile strength of corrugated pipe; FM 5-575 describes the test procedure to determine the ductile-to-brittle curve using pipe liner material, and FM 5-576 describes the analytical method to predict the long-term tensile strength. However, the location that is most likely for stress cracking to occur is the pipe junction. Therefore, the creep rupture test should be evaluated using the junction specimens instead of liner specimens. The test shall be performed according to FM 5-572, procedure B. Using the test conditions and required failure time values specified in Section 948, the 100-year tensile strength is predicted to be 800 psi. This strength value is a conservative prediction because the 100-year approval pipes exhibit failure times well exceed the specified minimum failure times at all three test conditions.

4.0 Recommendation

- The long-term tensile strength shall be determined by the junction stress crack resistance test based on FM 5-572, procedure B.
- Based on the Section 948 specification, the 100-year tensile strength for corrugated HDPE pipe is predicted to be 800 psi.
- If industry would like to increase the 100-year tensile strength value, an interlaboratory test program can be carried out using slightly higher applied stresses defined in Section 948. All tests must be carried out until failure.
- The two test methods, FM 5-575 and FM 5-576, are no longer relevant to the determination of 100-year tensile strength, and should be removed from the listing.

References

Popelar, C.H., Kenner, V.H. and Wooster, J.P. (1991) “An Accelerated Method for Establishing the Long Term Performance of Polyethylene Gas Pipe Materials”, Polymer Engineering and Science, Vol. 31, No. 24, pp. 1693-1700.

Appendix – Stress Crack Resistance Test Data using Junction Specimens from Pipe P-A

SCR Test - Plastic/Test Device-2							
Sample =P-A							
Specimen = Junction							
App. Stress (psi) =	950		Temperature = 80°C				
Test Specimens	Specimen Thickness (in)	Specimen Width (in)	Calculated Load (grams)	Arm Weight (grams)	Holder Weight (grams)	Applied Load (grams)	Failure Time (hours)
1	0.116	0.238	11896.8	448.3	47.26	1916.0	77.5
2	0.098	0.237	10008.5	448.3	47.69	1601.3	72.5
3	0.099	0.236	10068.0	448.3	46.96	1611.1	77.5
4	0.101	0.234	10184.4	448.3	48.00	1630.7	94.5
5	0.114	0.238	11691.7	448.3	46.66	1881.7	80.5
				Average Failure Time			80.5

SCR Test - Plastic/Test Device-4							
Sample = P-A							
Specimen = Junction							
App. Stress (psi) =	850		Temperature = 80°C				
Test Specimens	Specimen Thickness (in)	Specimen Width (in)	Calculated Load (grams)	Arm Weight (grams)	Holder Weight (grams)	Applied Load (grams)	Failure Time (hours)
1	0.115	0.236	11695.2	448.3	46.10	1882.2	76.3
2	0.101	0.236	10271.4	448.3	47.20	1645.1	114.1
3	0.111	0.236	11288.4	448.3	48.01	1814.7	61.2
4	0.113	0.236	11491.8	448.3	46.40	1848.3	69.0
5	0.100	0.238	10255.9	448.3	47.47	1642.5	78
				Average Failure Time			79.7

SCR Test - Plastic/Test Device-2							
Sample = P-A							
Specimen = Junction							
App. Stress (psi) =	750		Temperature = 80°C				
Test Specimens	Specimen Thickness (in)	Specimen Width (in)	Calculated Load (grams)	Arm Weight (grams)	Holder Weight (grams)	Applied Load (grams)	Failure Time (hours)
1	0.097	0.238	7853.9	448.3	47.26	1242.1	253.1
2	0.115	0.238	9311.3	448.3	47.69	1485.1	178.9
3	0.096	0.237	7740.2	448.3	46.96	1223.1	471.4
4	0.098	0.237	7901.5	448.3	48.00	1250.2	560.6
5	0.098	0.236	7868.1	448.3	46.66	1244.4	255.2
				Average Failure Time			343.8

SCR Test - Plastic/Test Device-4							
Sample = P-A							
Specimen = Junction							
App. Stress (psi) =	650		Temperature = 80°C				
Test Specimens	Specimen Thickness (in)	Specimen Width (in)	Calculated Load (grams)	Arm Weight (grams)	Holder Weight (grams)	Applied Load (grams)	Failure Time (hours)
1	0.112	0.236	7793.2	448.3	46.10	1231.8	1723.5
2	0.096	0.237	6708.2	448.3	47.20	1051.2	1851.3
3	0.112	0.237	7826.2	448.3	48.01	1237.7	639.7
4	0.112	0.236	7793.2	448.3	46.40	1231.9	1548.2
5	0.112	0.240	7925.3	448.3	47.47	1254.1	1358.3
				Average Failure Time			1424.2

SCR Test - Plastic/Test Device-1							
Sample = P-A							
Specimen = Junction			Temperature = 70°C				
App. Stress (psi) =	1000	Temperature = 70°C					
Test Specimens	Specimen Width (inches)	Specimen Thickness (inches)	Calculated Load (grams)	Arm Weight (grams)	Holder Weight (grams)	Applied Load (grams)	Failure Time (hours)
1	0.23	0.118	12310.7	448.3	47.0	1984.9	394.5
2	0.23	0.097	10119.8	448.3	47.6	1619.9	394.5
3	0.23	0.099	10328.5	448.3	46.8	1654.5	511.0
4	0.23	0.101	10537.1	448.3	48.5	1689.6	457.1
5	0.23	0.101	10537.1	448.3	46.5	1689.2	455.9
				Average Failure Time			442.6

SCR Test - Plastic/Test Device-2							
Sample = P-A							
Specimen = Junction							
App. Stress (psi) =	900		Temperature = 70°C				
Test Specimens	Specimen Width (inches)	Specimen Thickness (inches)	Calculated Load (grams)	Arm Weight (grams)	Holder Weight (grams)	Applied Load (grams)	Failure Time (hours)
1	0.236	0.113	10886.9	448.3	46.42	1747.5	421.6
2	0.246	0.090	9038.4	448.3	46.60	1439.5	483.8
3	0.237	0.114	11029.8	448.3	46.70	1771.4	550.5
4	0.243	0.093	9225.8	448.3	47.33	1470.8	433.4
5	0.240	0.092	8965.0	448.3	46.60	1427.2	433.4
				Average Failure Time			464.5

SCR Test - Plastic/Test Device-4							
Sample = P-A							
Specimen = Junction							
App. Stress (psi) =	800		Temperature = 70°C				
Test Specimens	Specimen Width (inches)	Specimen Thickness (inches)	Calculated Load (grams)	Arm Weight (grams)	Holder Weight (grams)	Applied Load (grams)	Failure Time (hours)
11	0.23	0.117	9765.1	448.3	46.1	1560.5	2330.9
12	0.23	0.097	8095.9	448.3	47.2	1282.5	637.6
13	0.230	0.097	8095.9	448.3	48.0	1282.6	2612.0
14	0.23	0.113	9431.3	448.3	46.4	1504.9	1386.1
15	0.23	0.119	9932.0	448.3	47.5	1588.5	2166.7
				Average Failure Time			1826.7

Appendix B – Calculation of Popelar's Shift Factors

The Popelar’s shift factors used to predict the transition point at 23°C based on test data at 70 and 80°C are illustrated in this appendix. The equation to determine the shift factors for stress and failure time are expressed in Eq. (1) and (2).

$$a_T = exp[-0.109(T - T_R)] \tag{1}$$

$$b_T = exp[0.0116(T - T_R)] \tag{2}$$

where:

a_T = horizontal shift function (time function)
b_T = vertical shift function (stress function)
T = temperature of the test, in K
T_R = target temperature, in K

Procedure to predict the transition time and transition stress at 23°C:

a. Calculate a_T and b_T values based on T = 80°C and 70°C and T_R = 23°C:

At 80°C, a_T = exp[-0.109((80+273) - (23+2730))] = 0.00200
b_T = exp[0.0116((80+273) - (23+2730))] = 1.937

At 70°C, a_T = exp[-0.109((70+273) - (23+2730))] = 0.00596
b_T = exp[0.0116((70+273) - (23+2730))] = 1.725

b. Determine the transition time and transition stress at 23°C:

Using 80°C data (from Table 3):

$t_{23^{o}C}$ = 79.7 hr / 0.002 = 39850 hr = <u>4.5 years</u>

$\sigma_{23^{o}C}$ = 850 psi *1.937 = <u>1647 psi</u>

Using 70°C data (from Table 3):

$t_{23^{o}C}$ = 472.3 hr / 0.00596 = 79245 hr = <u>9 years</u>

$\sigma_{23^{o}C}$ = 900 psi *1.725 = <u>1553 psi</u>