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RELATION BETWEEN "FAILURE AND DAMAGE"

SANL 712-002

A. L. Wilson

April, May, June 1970

ATOMIC ENERGY COMMISSION ★ UNITED STATES OF AMERICA ★

DEVELOPMENT DIVISION

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RELATION BETWEEN "FAILURE" AND "DAMAGE"

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The purpose of this project is to establish whether or not the "damage point" obtained from interrupted tensile tests corresponds to the "failure point" obtained from creep tests.

ABSTRACT

Results of this investigation show that the "damage point" derived from an interrupted tensile test does not correspond to the "failure point" obtained from a creep test. It may correspond to the first transition point in constant-stress creep tests. The "damage point" is obtained from repeated tensile stress cycles of ever-increasing intensity; when the stress-strain curve no longer follows parallel paths, the "damage point" has been reached.

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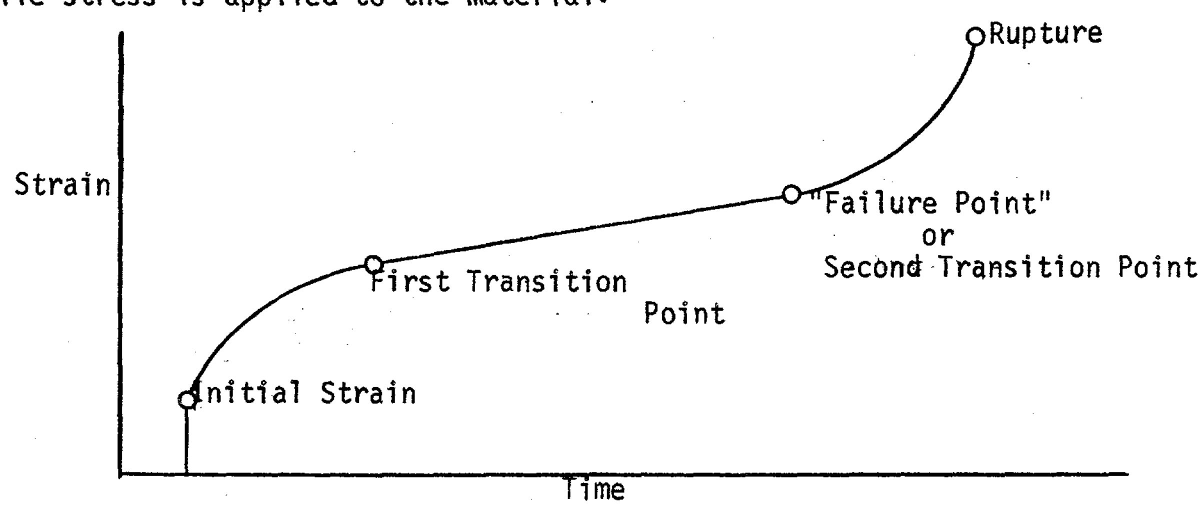
INTRODUCTION

When a regular tensile test (conducted at constant temperature and crosshead speed) is interrupted at successively higher stresses, a "damage point" can be observed where the stress-strain curves no longer follow parallel paths. It is the purpose of this experiment to determine if this "damage point" corresponds to the "failure point" which is found from creep tests. An explanation of general response of HE to stress, and use of the creep test to find the "failure point" will be given.

Plastic bonded high explosive has been described as a "viscoelastic material" because it is both viscous like a fluid and elastic like a solid. When stress is applied to HE it deforms; and this initial strain is due to elasticity as in a solid. If a constant stress is applied, the strain continues to increase with time, as in a viscous fluid. The combination of viscous and elastic effects create an s-shaped curve of strain plotted against time when a constant tensile stress is applied to the material.[1]



[1] *The temperature is also held constant.*

An initial strain is experienced as soon as stress is applied, and then creep commences and continues as long as stress is maintained. After some time has passed, a first transition point is reached and the curve commences to trace a straight line. Later, a second transition point is reached and then the material begins to strain more rapidly, until rupture occurs.

The second transition point has been defined as tensile failure. It is a more conservative value of failure than the rupture point, and certainly the material has undergone irrecoverable damage by this time. The second transition is also easier to locate than the rupture point, and exhibits lower deviation, probably because it is not influenced by the manner in which the specimen breaks.

Thus, failure point has been determined with tensile creep tests conducted at constant temperature. If this second transition-failure point be truly a material property, then it should also be observed in other types of tension tests. Indeed, it would be desirable to have an independent means of determining the failure point. Unfortunately, the standard tensile test conducted at constant crosshead velocity does not reveal the second transition point (at least it is not readily apparent from inspection of the stress-strain diagram).

Recently, a variation of the standard tensile test was devised which had the possibility of showing the second transition point; if so, the test would provide an independent means of establishing the location of the failure point. This test, called the "Interrupted Tensile Test," is done by using a standard dumbbell type tensile specimen prepared in the usual manner of gluing plastic end caps to it while held in an alignment fixture, then drying it with desiccant for 24 hours. The specimen is placed in a test machine equipped with an environmental chamber and stabilized at the temperature of test for at least 30 minutes. An extensometer is calibrated and then clipped onto the test specimen in the central cylindrical portion. A load cell has similarly been calibrated. All instruments are set to zero, then the test is commenced by moving the crosshead at constant speed of 0.005 inches per minute so that the specimen is stretched in uniaxial tension. Load, deflection, temperature and time are recorded.

When the stress has reached a predetermined level, such as 120 psi, the crosshead is stopped, then reversed quickly at 0.05 inches per minute so that the stress is promptly released. The specimen is allowed to recover for a given time, such as thirty minutes, then the crosshead is restarted at 0.005 inches per minute so that tensile stress is again applied to the specimen. When the stress reaches a higher level than previously, the crosshead is reversed as before to release the stress rather quickly and the specimen is allowed to recover for thirty minutes. This procedure of interrupting the tensile test at ever higher stress levels is continued until the specimen ruptures.

The stress levels at which testing is interrupted is a matter of choice and the practice has been to select regular intervals such as 120, 160, 200, 240, ... psi. This choice is a compromise to obtain as many cycles as possible in a practical time, such as one work shift.

DISCUSSION

The stress-strain curves which were generated by each succeeding cycle were offset from each other due to permanent and unrecovered strain in the viscoelastic specimen. It was observed that each curve traced parallel paths for several successive cycles, each cycle reaching a higher stress than the preceding cycle. After several cycles, however, this behavior pattern changes abruptly and the curves no longer follow parallel paths, but "fan out," that is, strain at a faster rate and show a diverging pattern.

Some type of change in the material has occurred when this diverging behavior commences: it is defined as the "damage point." The "damage point" has been consistently observed in PBX-9404 and LX-04-1 at temperatures ranging from 70°F to 165°F. The question to be resolved by this experiment was to determine whether or not the "damage point" corresponds to the "failure point."

An HE was to be selected that would be suitable for comparing "failure point" with "damage point." The particular lot of HE should be one that is now being used, be typical and consistent in physical properties, and have sufficient information available about it. LX-04-1 lot SR-92-13 was selected for this experiment because it met all of these requirements, particularly in regard to the amount of information available about its physical behavior.

Thirty-two tensile specimens having mean density of 1.864 gm/cc were made from a single large billet, then two types of tests were made to find out if the material was representative of LX-04-1 lot SR-92-13. The first type consisted of tension tests at -65°F at constant crosshead speed of 0.005 inches per minute.

	Rupture Stress psi	Stress Std. Dev. psi	Rupture Strain µin/in	Strain Std. Dev. µin/in	No. of Tests
This billet	1268	48	954	97	4
Previous tests	1398	3	940	22	2

(Tension tests at -65°F at constant crosshead speed of 0.005 inches per minute.)

And the second type was tension creep at 200 psi.

	Failure Strain µin/in	Strain Std. Dev. µin/in	Temperature °F	No. of Tests
This billet	4920	787	70	4
Previous tests	4680	679	85	2

(Tension creep tests at 200 psi.)
(Varying the temperature merely changes the time to failure.)

The student's t test was applied to these data.[2]

Null hypothesis: The two groups come from the same population so that

$$M_1 = M_2 \text{ and } \rho_1 = \rho_2$$

	Rupture Stress	Rupture Strain	Failure Strain
Computed t	3.608	0.191	0.364

[2]*Spiegel, M. R., "Theory and Problems of Statistics," McGraw-Hill Book Co., Inc., NY (1961), p 190.*

If a significance level of 99% is chosen so that (with four degrees of freedom) $t_{.99} = 3.75$, then the null hypothesis is accepted because none of the computed t values exceed the critical value.

Now that the present material can be assumed to be substantially equivalent to previous material from the same lot, the original data gathered for this material will be used to establish the "failure point" location over an extensive range of stress and strain. Original creep test data are plotted in Fig. 1 to establish the failure envelope, a curve which denotes where 50% of the test specimens will fail. The right-hand curve is the mean failure envelope for lot SR-92-13, and the other curve represents mean failure for all lots of LX-04-1 (from SR-27B-64 through SR-92-15). The four creep tests made with present material at 200 psi is also displayed in Fig. 1 and these tests group about the failure envelope for SR-92-13 quite well. (Only data from lot SR-92-13 is actually plotted in Fig. 1, whereas the left-hand curve is derived from 164 creep tests.)

The next item to consider is determination of the time to allow specimens to rest between loading cycles. It would be desirable to allow as much recovery as possible within practical time limitations. The next group of tests were made to determine extent of strain recovery for various rest intervals. Four creep recovery tests were conducted at 200 psi at 70°F; the specimens were held at 200 psi for 10, 20, 30, and 40 minutes respectively, then stress was removed and recovery of strain was observed. The strain-time curve for these tests are shown in Fig. 2.

Fig. 1

Creep Test Results for LX-04-1 Showing Location of the Failure Envelope

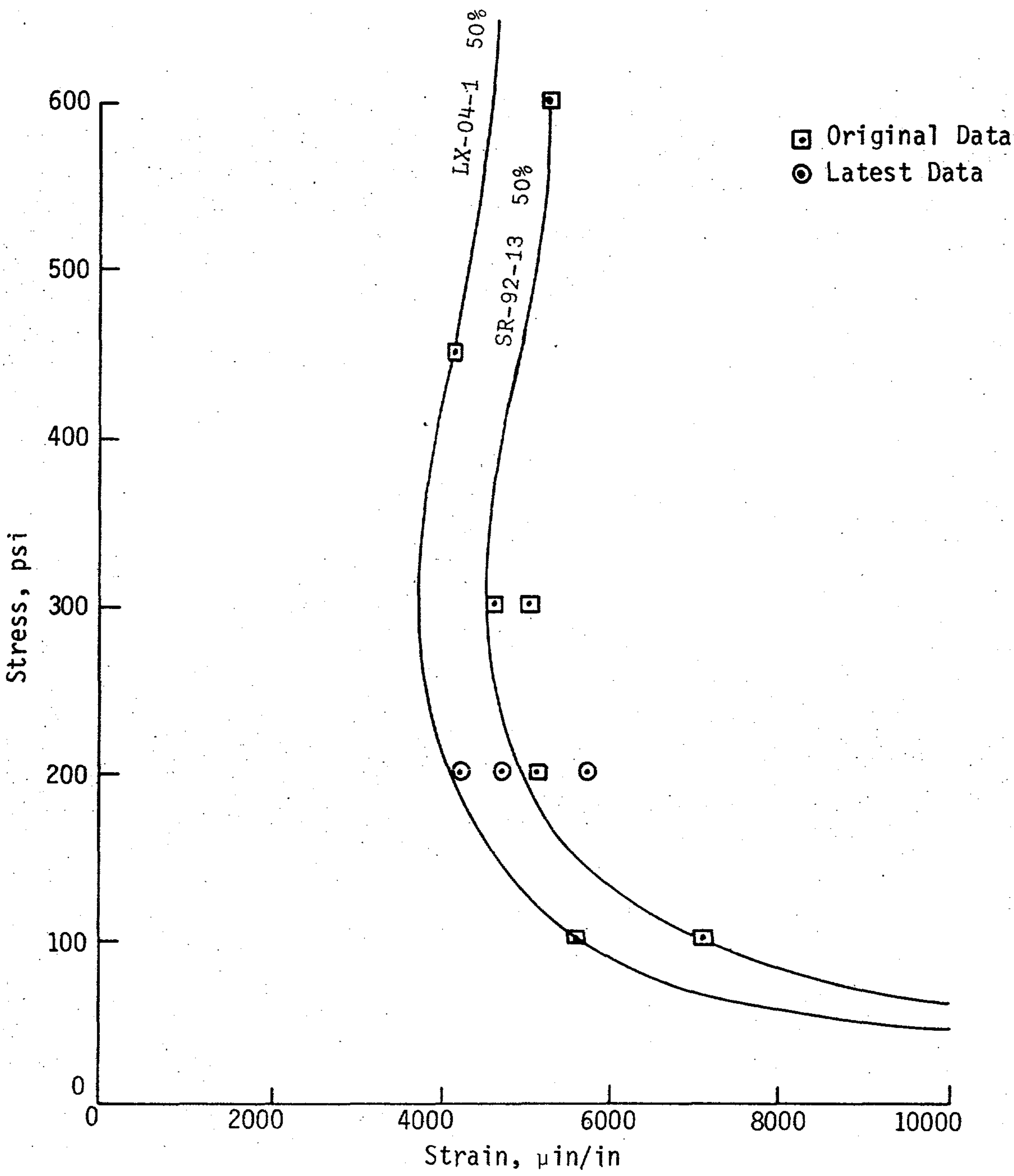
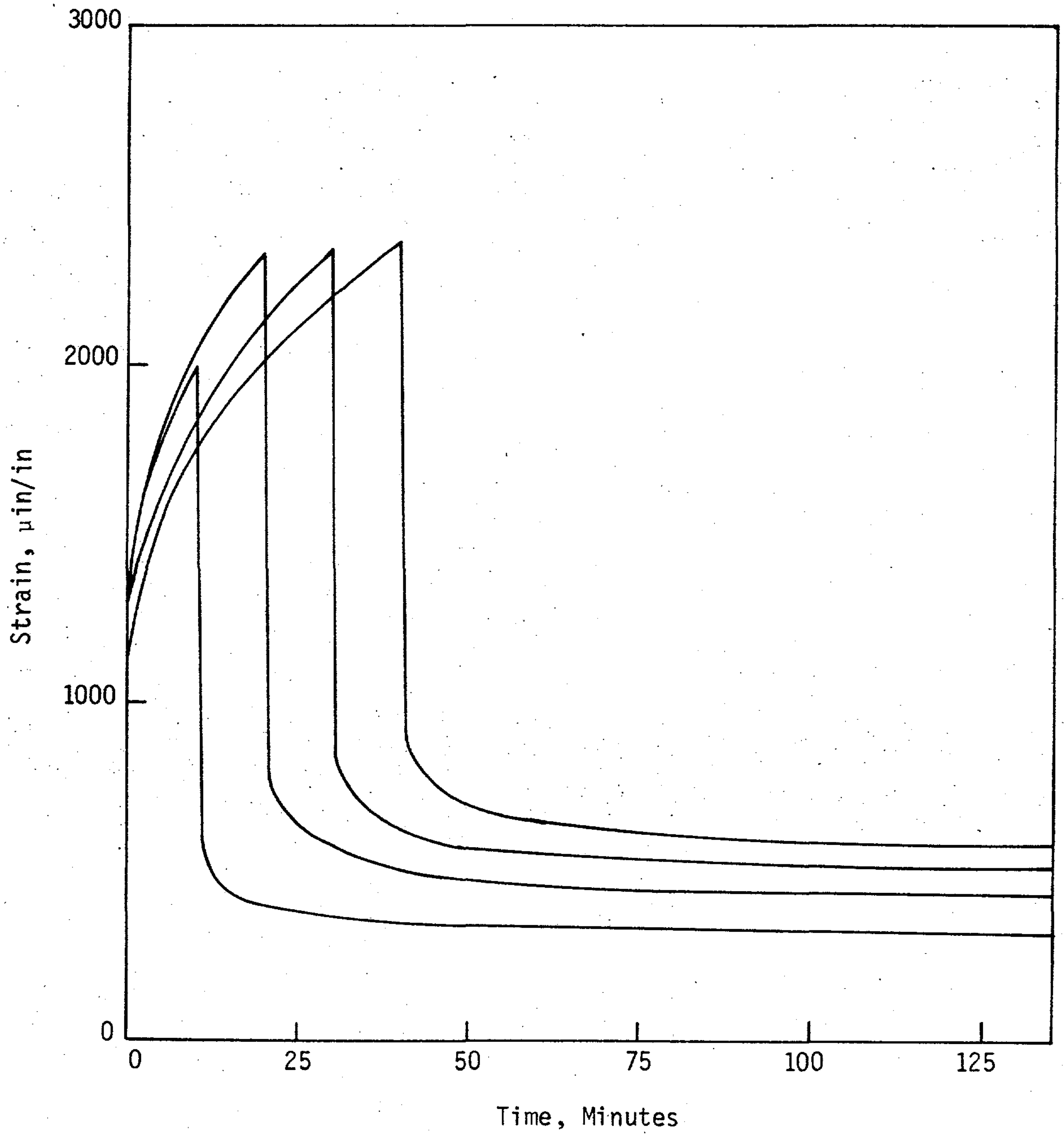


Fig. 2

Creep Recovery Tests at 200 psi at 70°F for LX-04-1 Lot SR-92-13



Recovery portion of the tests are plotted in greater detail in Fig. 3 with recovery time (or time since release of stress) plotted along the abscissa for greater convenience in calculating percent recovery. It is well known that it takes many hours, perhaps days, for the material to reach complete recovery of all strain; in this instance a time of 100 minutes was chosen to be the maximum time that could be allowed for practical reasons in conducting subsequent tests. The strain at 100 minutes of rest was defined as complete recovery, and percent recovery was computed from the equation

$$PR = (A-S)(100)/(A-B) \quad (1)$$

A = maximum strain

B = complete recovery strain

PR = percent recovery of strain

S = strain at given time since recovery commenced

using data from Figs. 2 and 3. The percent recovery results are compiled in Table I and plotted in Fig. 4.

Fig. 4 was used in deciding how much time was to be allowed for recovery during the interrupted tensile tests yet to be made. There seems to be sufficient variation in individual response to completely mask any effect from the length of time that stress was applied. In other words, the relative position of the curves in Fig. 4 bears no relation to the time of stress application. This minor problem was not pursued any further, and the most conservative or minimum curve, was selected for use. Accordingly, if 30 minutes rest were allowed, then at least 97.5% of total recovery will have been achieved. Since about 6 hours of test time will be available per shift after allowing for temperature

Fig. 3

Creep Recovery at 70°F from a Stress of 200 psi Held for Various Times

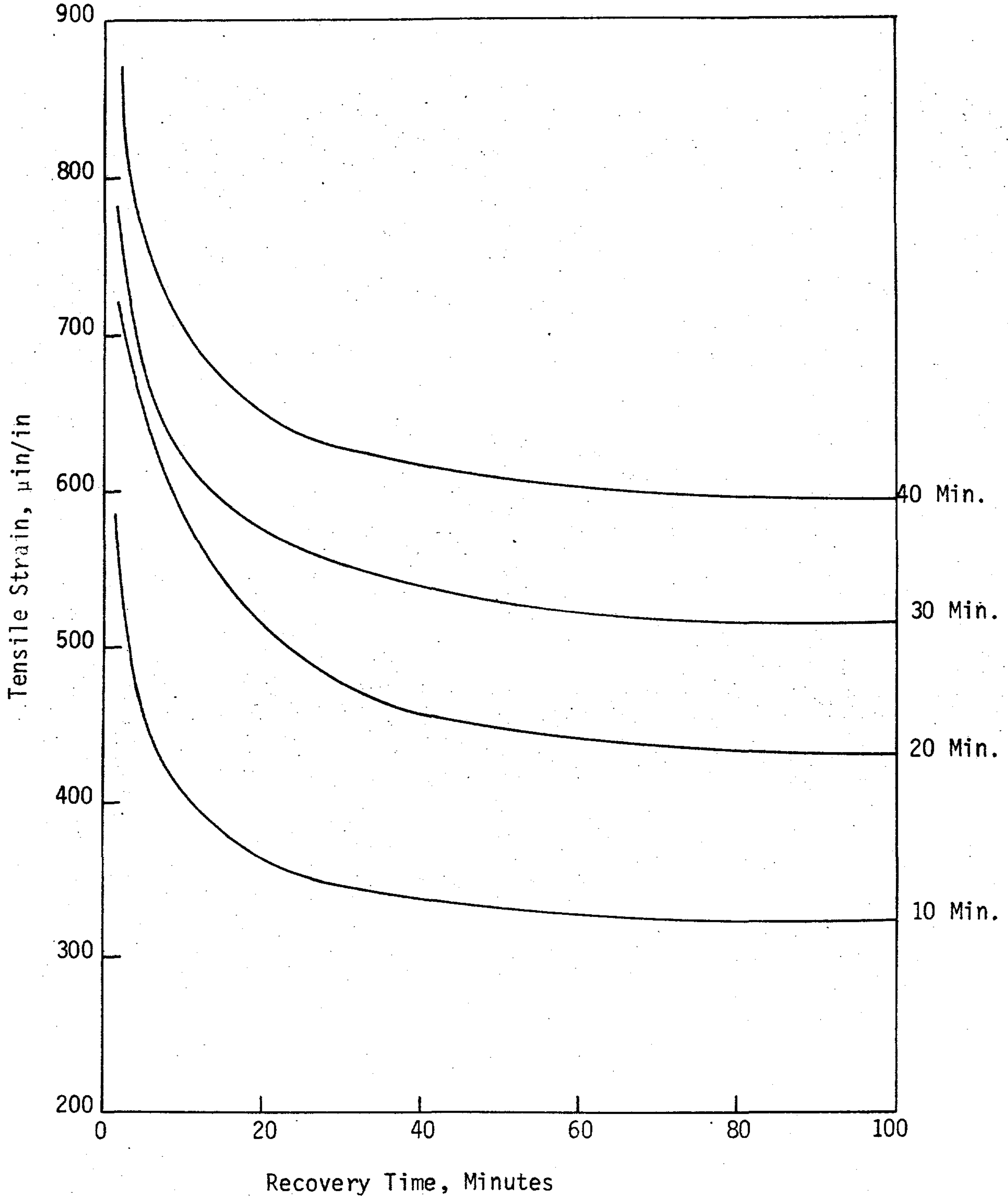
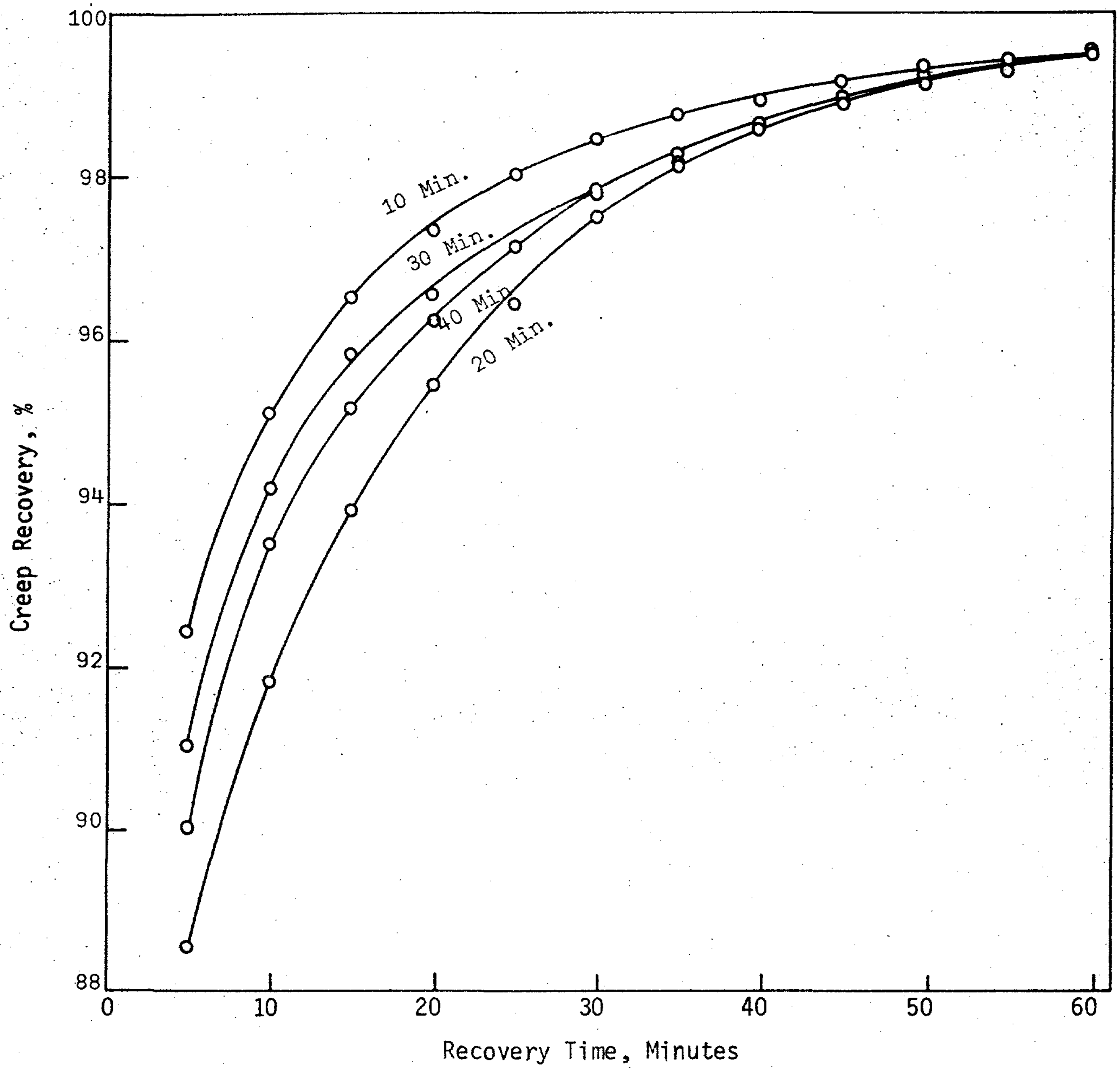


Fig. 4

Percent Recovery from 200 psi Creep for Various Stress Times @ 70°F



conditioning of the specimen and work conditions, a rest interval of 30 minutes would allow approximately 11 to 12 cycles of interrupted tensile testing. From these considerations, it was decided that a rest interval of 30 minutes would be satisfactory. Having established the rest interval to be 30 minutes, and having determined that the material being used is typical for LX-04-1 lot SR-92-13, four interrupted tensile tests were made at 70°F at constant cross-head speed of 0.005 inches per minute. The interruption occurred at a stress of 120 psi for the first cycle and increments of 40 psi thereafter. Stress-strain curves from the four tests are plotted in Figs. 5 through 8, and superimposed on these plots is the mean failure envelope for this lot, and also the general failure envelope for LX-04-1. (Recovery portion of each cycle is not shown in order to improve clarity.) It can be seen that the first few are generally parallel and could be superimposed by sliding along the X-axis to form a single curve. Later cycles, however, could not be made to coincide by translation along the X-axis because they "sag"; that is they strain more at a given stress. Obviously the responses in these later curves are larger than the earlier curves and the "damage point" has been passed. Location of the "damage point" can be determined by superimposing tracings of these curves, and this method was used in earlier experiments. A more exact method is to locate the damage point by means of differences.

To use the method of differences, two stress levels are selected, 50 and 100 psi. Fifty psi was chosen as the low level because lower stresses may have involved irregularities often occurring at the beginning of tests, and 100 psi was selected because it was conveniently near the top of the first cycle. Difference in strain between two consecutive cycles are compared at the two stress levels, and when the cross-difference (difference between the two differences) changes abruptly, the damage point has been reached.

Fig. 5

Interrupted Tensile Test at 70°F at 0.005 Inch/Minute for LX-04-1 Lot SR-92-13 Piece 12

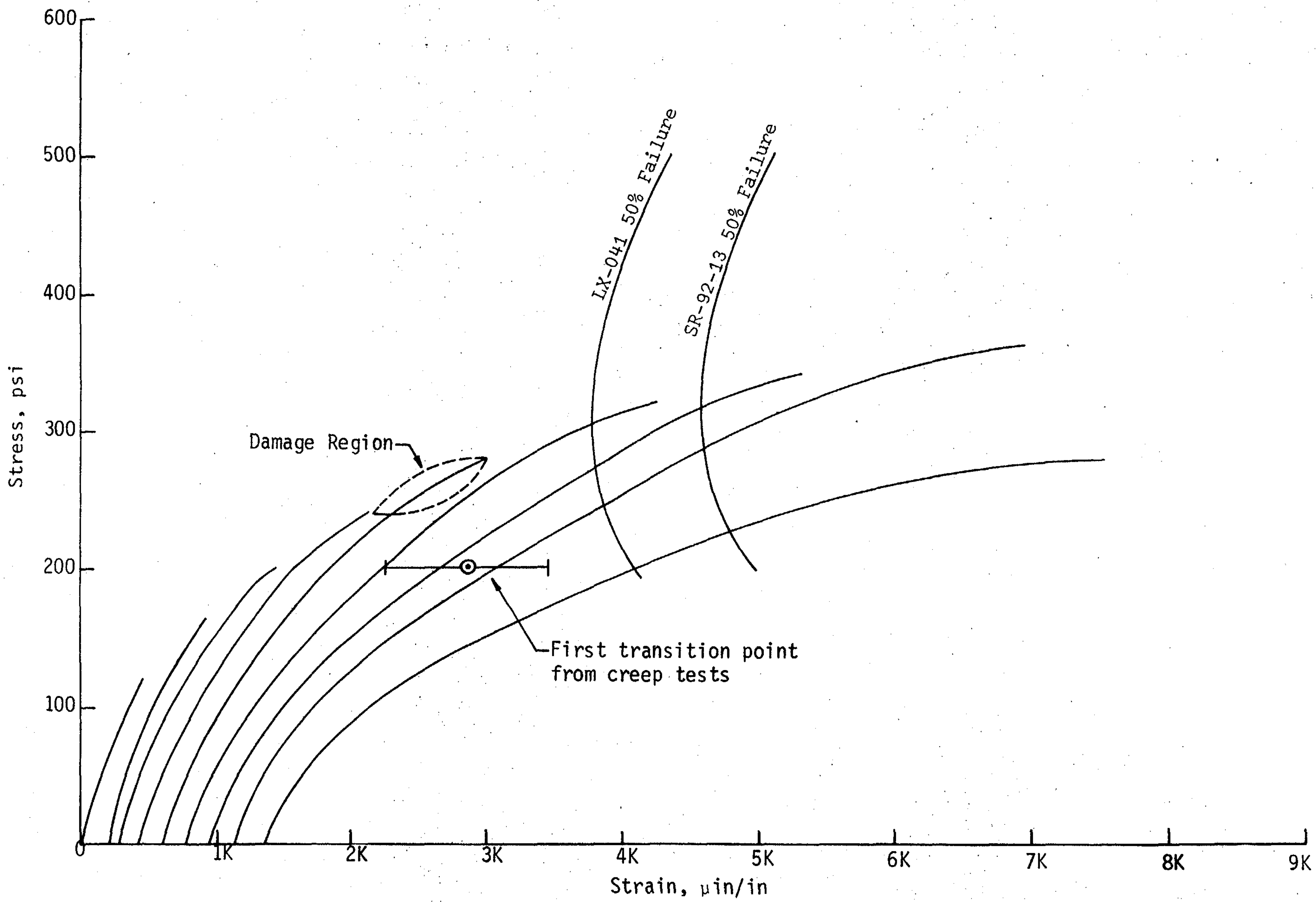


Fig. 6

Interrupted Tensile Test at 70°F at 0.005 Inch/Minute for LX-04-1 Lot SR-92-13 Piece 13

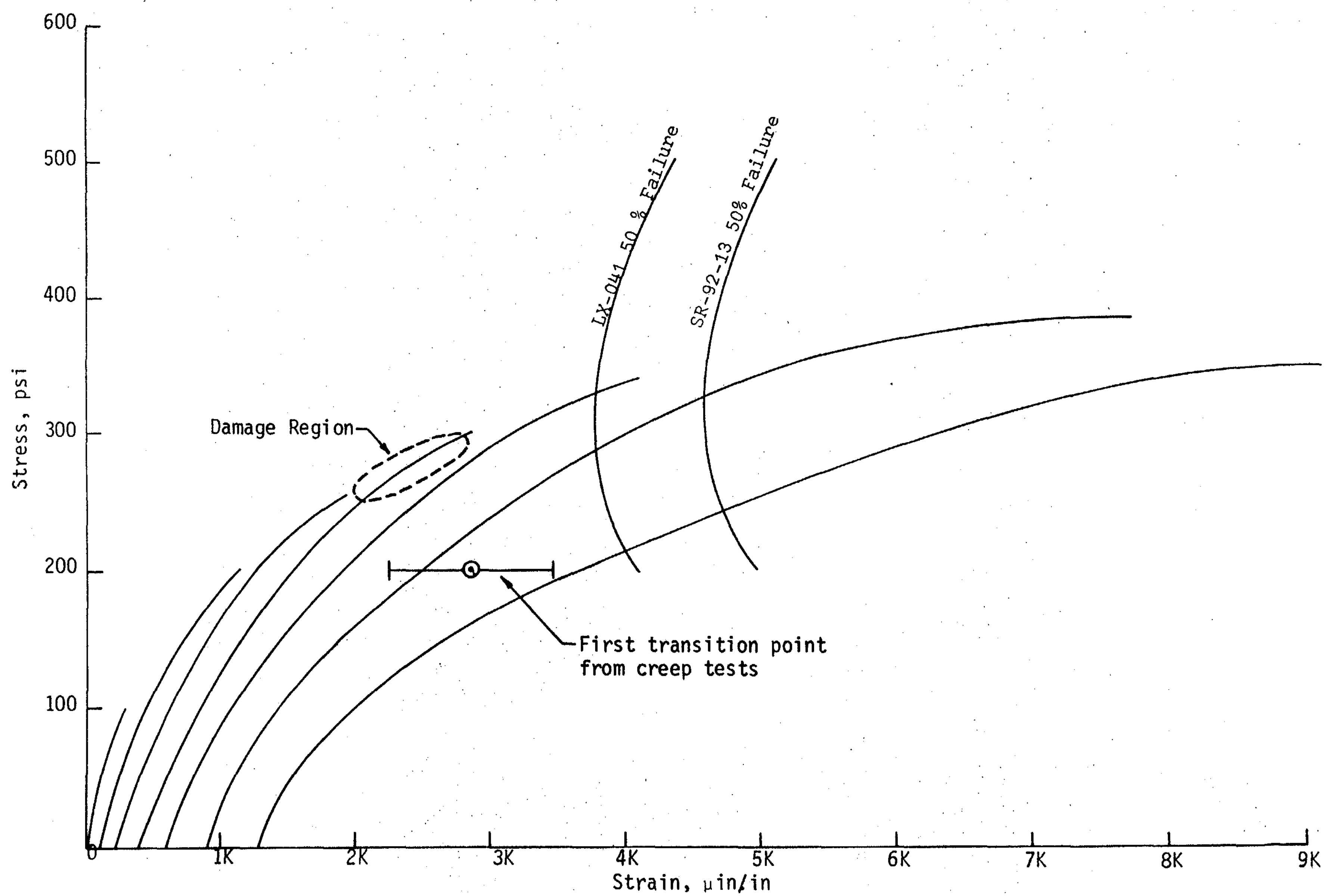


Fig. 7

Interrupted Tensile Test at 70°F at 0.005 Inch/Minute for LX-04-1 Lot SR-92-13 Piece 14

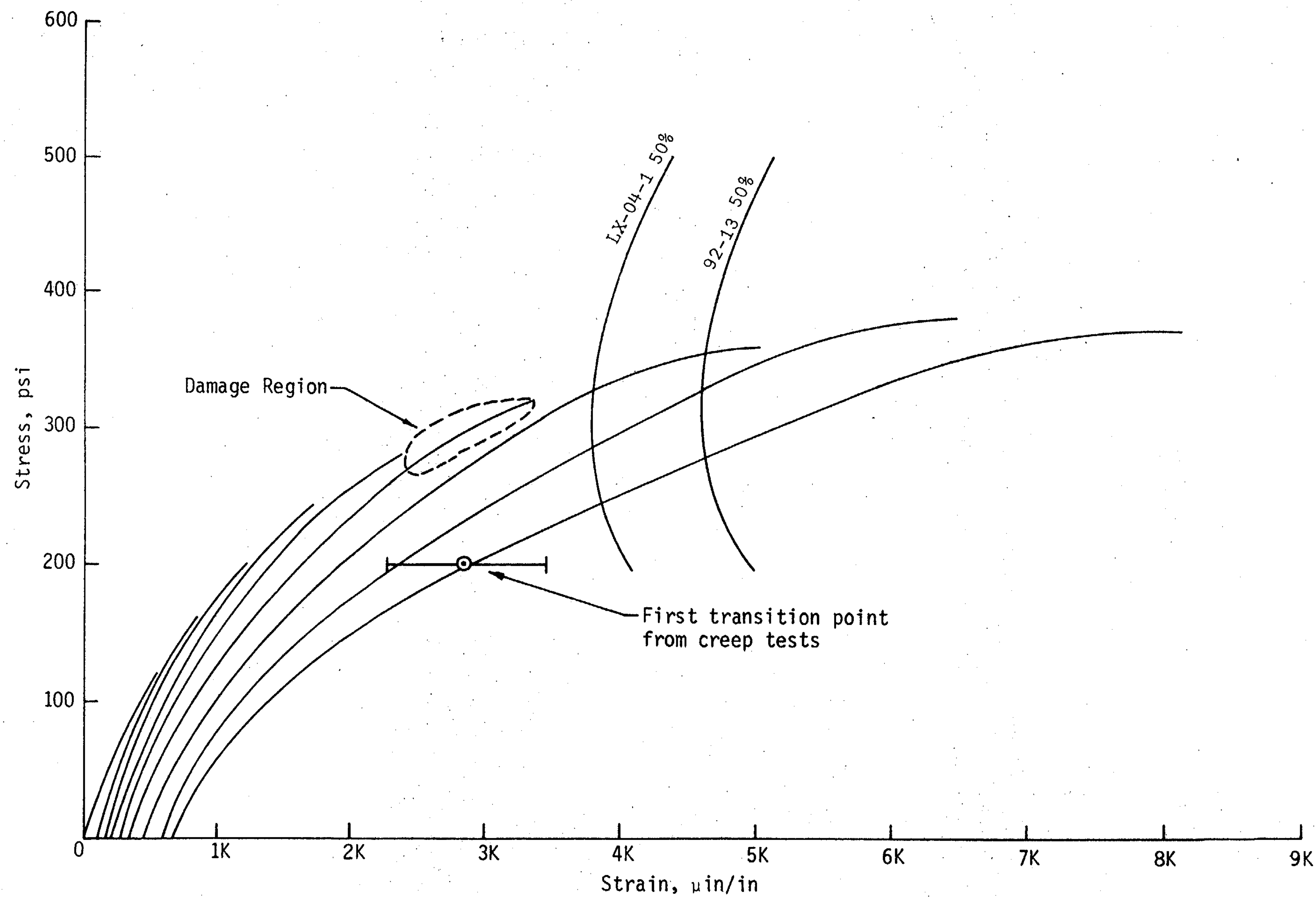
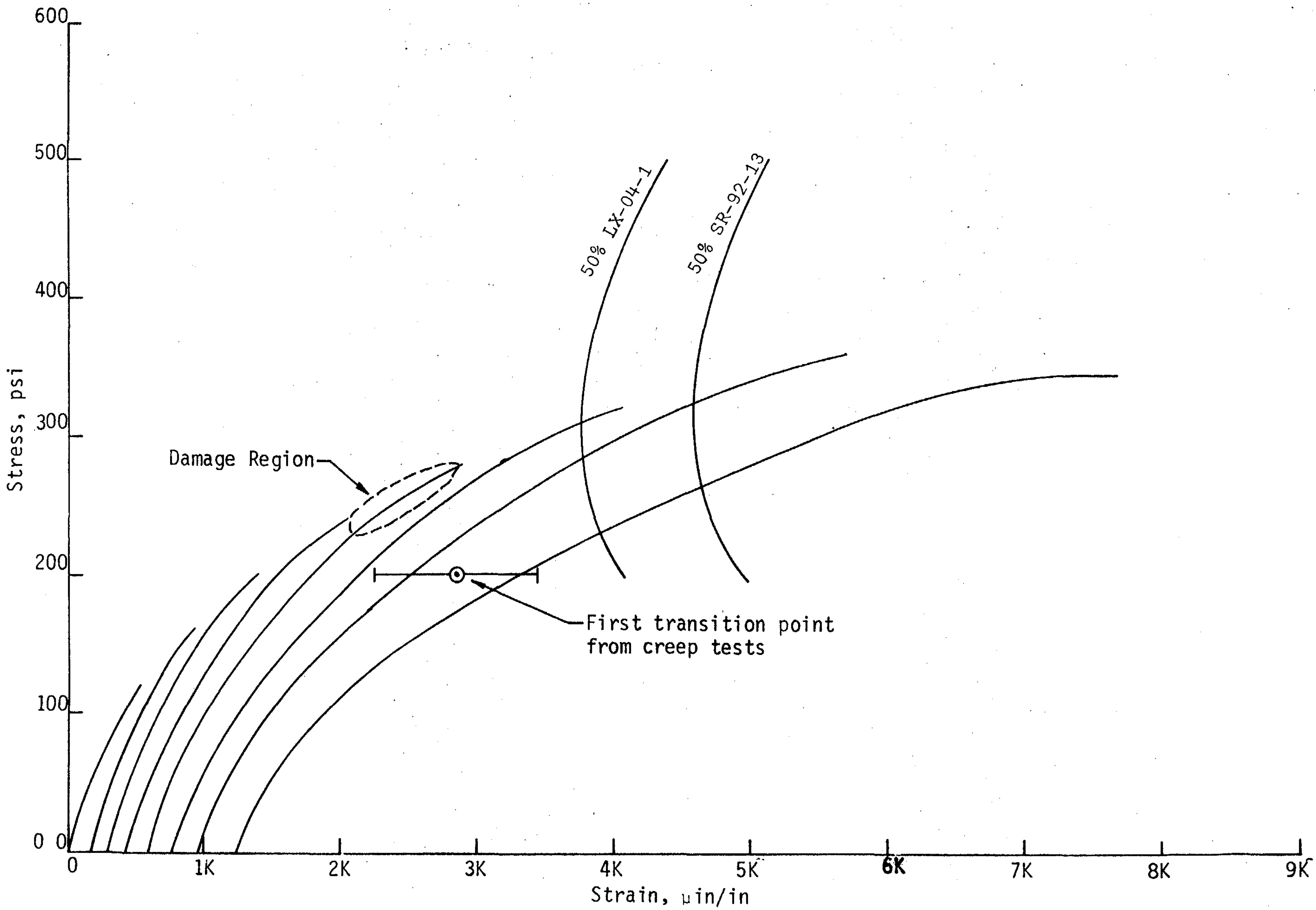


Fig. 8

Interrupted Tensile Test at 70°F at 0.005 Inch/Minute for LX-04-1 Lot SR-92-13 Piece 17



These differences are tabulated in Tables II through V for each of the four tests. Taking Fig. 5 and Table II as an illustration, the difference between cycles 2 and 3* at 50 psi is 120, while at 100 psi the difference is 140. The cross difference amounts to 20.

The "damage point" is determined from the column of cross deltas; whenever the values change abruptly, the "damage point" has been reached. In Table II, the value changes abruptly between cycles 5 and 6; this means that the "damage point" was reached in cycle 5. Moreover, the "damage point" occurred in the upper portion of cycle 5 that lies beyond the stress and strain limit reached in cycle 4. Dashed lines enclose this region in Fig. 5.

It is quite obvious that the "damage point" does not coincide with the "failure point" which is denoted by the failure envelope for LX-04-1. All four interrupted tensile tests give the same results. The "damage point" is so far below the "failure point" that there can be no doubt that the two phenomena are in fact different. The most likely possibility is that the "damage point" corresponds to the first transition point of the creep curve (shown in Fig. 1) rather than the second transition, or "failure point."

The first transition point was located from the four creep tests made at the beginning of this project and the average failure at 200 psi is plotted in each figure to show that it is indeed close to the damage point, much closer than the "failure point." If the first transition point were to be extended parallel to the failure envelope, the extension would intersect that region containing the "damage point."

**Cycle 1 is never used because, for some unknown reason, it is never parallel to any of the remaining cycles.*

Table I

Calculation of Percent Recovery from 200 psi Creep Tests at 70°F Held for Various Times

10 Minute Creep

Recovery Time (Minutes)	Strain (μin/in)	Creep Recovery (%)
5	445	92.43
10	400	95.11
15	376	96.54
20	362	97.38
25	351	98.03
30	344	98.45
35	339	98.75
40	336	98.93
45	332	99.17
50	329	99.35
55	328	99.41
60	327	99.46

20 Minute Creep

Recovery Time (Minutes)	Strain (μin/in)	Creep Recovery (%)
5	641	88.57
10	579	91.82
15	539	93.92
20	510	95.44
25	487	96.64
30	471	97.48
35	459	98.11
40	450	98.59
45	444	98.90
50	440	99.11
55	437	99.27
60	433	99.48

30 Minute Creep

Recovery Time (Minutes)	Strain (μin/in)	Creep Recovery (%)
5	672	91.05
10	615	94.20
15	589	95.64
20	572	96.58
25	559	97.29
30	550	97.79
35	541	98.29
40	534	98.68
45	529	98.95
50	524	99.23
55	520	99.45
60	518	99.56

40 Minute Creep

Recovery Time (Minutes)	Strain (μin/in)	Creep Recovery (%)
5	762	90.01
10	701	93.51
15	669	95.35
20	649	96.50
25	636	97.25
30	626	97.82
35	618	98.28
40	611	98.68
45	607	98.91
50	601	99.25
55	598	99.43
60	596	99.54

Table II

Cross-differences for Fig. 5 Values in the Table are Strain in μin/in

Cycle #	50 psi	Δ	Cross Δ	Δ	100 psi
2	315				540
		120	20	140	
3	435				680
		160	10	170	
4	595				850
		175	20	195	
5	770				1045
		185	45	230	
6	995				1275
		205	30	235	
7	1160				1510
		190	45	235	
8	1350				1745
		280	130	410	
9	1630				2155

Table III

Cross-differences for Fig. 6 Values in the Table are Strain in μin/in

Cycle #	50 psi	Δ	Cross Δ	Δ	100 psi
2	240				450
		160	15	175	
3	400				625
		180	10	190	
4	580				815
		205	55	260	
5	785				1075
		315	55	360	
6	1100				1435
		415	50	565	
7	1515				2000

Table IV

Cross-differences for Fig. 7 Values in the Table are Strain in μin/in

Cycle #	50 psi	Δ	Cross Δ	Δ	100 psi
2	245				475
		65	5	70	
3	310				525
		70	15	85	
4	380				610
		50	20	70	
5	430				680
		95	30	125	
6	525				805
		135	40	175	
7	660				980
		115	60	175	
8	785				1155
		150	80	230	
9	935				1385

Table V

Cross-differences for Fig. 8 Values in the Table are Strain in μin/in

Cycle #	50 psi	Δ	Cross Δ	Δ	100 psi
2	315				530
		135	15	150	
3	450				680
		150	10	160	
4	600				840
		170	10	180	
5	770				1020
		190	50	240	
6	960				1260
		200	40	240	
7	1160				1500
		310	80	390	
8	1470				1890

FUTURE WORK; COMMENTS; CONCLUSIONS

Test results show conclusively that the "damage point" obtained from an interrupted tensile test does not correspond with the "failure point" obtained from a creep test. The evidence suggests that the "damage point" corresponds to the first transition of a creep curve rather than the second transition, or "failure point."

It would have been useful if the interrupted tensile test gave an independent means of locating the "failure point," but such is not the case. No further work is contemplated at this time toward finding an independent means of determining the "failure point."