THIRD PROGRESS REPORT

on

EFFECT OF LONG-TIME CREEP ON STRUCTURAL SHEET MATERIALS

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INTRODUCTION

This program seeks to obtain information on changes in mechanical properties as a result of prolonged exposure under stress at 550°F. The experimental program was developed to furnish types of data now deemed most useful in evaluating materials for the construction of a Mach 3 transport airplane. The exposure stress of 67,000 psi was selected as representative of the most probable design stress for that type of airplane. The program provides for exposure time periods of 2000, 5000, and 12,000 hours at 550°F, as well as 30,000 hours, to show the effect of time of exposure. It also includes a minimum number of tests designed to study the possibility of using results from shorter-duration exposures to predict changes in properties to be expected during a service life of 30,000 hours.

The following sections are repeated from the Second Progress Report to make the present report a self-contained survey of the research.

EXPERIMENTAL PROGRAM

Table 1 gives the exposure conditions and planned subsequent tensile tests, along with the present status of the tests. Testing is being done at 550°F as well as room temperature because data now available for alloys being considered for the Mach 3 airplane suggest that the properties at 550°F are the more critical. For this reason, as much testing at 550°F as possible has been included in the program.

Duplicate tests are planned at room temperature after exposure of unnotched and $K_t = 3$ specimens for 30,000 hours; but only single tests at 550°F. A fourth specimen is being left uncommitted, with the testing

conditions to be determined after the other three specimens have been tested. For all other exposures, only single tensile tests after exposure are now planned. The omission of replicate specimens is recognized not to be desirable but seemed acceptable to obtain data for more different conditions. Deviations from general trends should be no more troublesome to interpret than deviations from the average of replicate tests.

The following sections indicate reasons for the choices of the actual exposure tests detailed in Table 1.

Effect of Exposure at 550°F for 30,000 Hours Under 67,000 psi

This will be measured by:

(a) the change in short time tensile properties at room temperature and 550°F for unnotched strip specimens.

(b) the change in short time tensile strength of edge notched (K_t = 3) specimens at room temperature and 550°F after exposure with the notch present. This notch is intended to simulate the effect of a stress concentration present from design considerations.

(c) the change in ability to withstand a very sharp notch introduced during exposure. Unnotched specimens are being exposed. After exposure, ASTM sharp notches are machined into the specimens, and tensile tests conducted at room temperature and at 550°F. This procedure was selected on the basis that sharp notches and cracks should not be present originally in the airplane. It should be a severe test of changes during exposure in the important ability of the material to withstand sharp notches or cracks. A sharp notch present during exposure should undergo creep relaxation and thus provide a less severe test of changes in notch

sensitivity than a notch introduced after exposure. The procedure adopted does not, however, test the possibility that a sharp notch might cause cracking during exposure.

Effect of Time at Exposure

In addition to the exposure for 30,000 hours, exposure of specimens for shorter times before tensile testing is providing data for study of possible methods of extrapolating from short time exposures, and also provides interim factual data without need to wait 30,000 hours for an indication of the effect of exposure.

Exposure times of 2000, 5000, and 12,000 hours are being used. Unnotched and notched (K_t = 3) specimens are being exposed for 12,000 hours and are then to be tensile tested at room temperature and 550°F. The 5000 and 2000 hour exposures included similar tests, plus two specimens in which sharp notches were machined after exposure, prior to tensile testing at room temperature and 550°F.

Effect of Stress During Exposure

A very limited study of the effect of stress during exposure was made possible by including a few specimens in the exposure furnaces with no stress applied. Exposure times of 30,000, 12,000, and 5000 hours are being covered, with subsequent tensile tests at room temperature and 550°F.

"Accelerated" Exposures

Table 1 lists some tensile tests to be carried out after prior creep under 67,000 psi stress, but at 600-700°F. Results are to be analyzed to determine if effects of prolonged exposure can be predicted from shorter exposures at higher temperatures. Emphasis is on changes in properties of unnotched specimens, but a few specimens are included in

which sharp edge notches will be added after the creep exposure.

Times of 2000 hours at 600°, 200 hours at 650°, and 20 hours at 700°F were selected to produce changes in subsequent tensile properties roughly the same as would 30,000 hours at 550°F under the 67,000 psi stress. The mechanisms by which exposure to creep should cause any changes in mechanical properties were reasoned to involve reactions of the type obeying the Arrhenius rate equation. Then the rate of property change ($\dot{p}$) at constant stress may be expressed in terms of the gas control R, and a constant A and an energy E which are independent of temperature:

$$\dot{p} = A\, e^{-(E/RT)}$$

Defined, in terms of the inverse of $\dot{p}$, the time t at absolute temperature T for a given degree of property change becomes:

$$t = \frac{C}{\dot{p}} = \left(\frac{C}{A}\right) e^{E/RT} = A'\, e^{E/RT}$$

Converting to common logarithms and rearranging,

$$T\,(-\log A' + \log t) = E/2.3R = \text{Constant at constant stress.}$$

For creep rupture of many alloys, $-\log A'$ is about 20. If this value and the above reasoning apply, times at 600°, 650°, and 700°F corresponding to 30,000 hours at 550°F are, respectively, about 2090, 190, and 20 hours. The 200 hour exposures at 700°F were included to allow for an actual value of $-\log A'$ of 15 or less.

Other Tests

Besides these tests, the following data will be obtained:

1) Creep measurements during exposure will be made on unnotched specimens except for two cases. When two unnotched specimens are exposed in tandem, creep will be measured only on one of the two. Creep measurements will not be made on wide specimens to be notched after exposure.
2) Hardness will be measured on the shoulder section of specimens before exposure, and of specimens after unstressed exposure. Measurements after stressed exposure will be limited to the wide specimens that are to receive sharp edge notches after creep exposure.
3) Selected specimens will be examined microscopically after exposure.

TEST MATERIAL AND PROCEDURES

All test specimens were sampled with their length in the direction of rolling of AM350 sheet from consumable-electrode melted Heat No. 23327, which had the following reported chemical composition:

C	Si	Mn	Cr	Ni	Mo	N	P	S
.084	.21	.65	16.50	4.29	2.94	.10	.009	.007

Specially-designed long furnaces were made to uniformly heat two specimens in tandem. The specimens being used are shown in Figure 1. The SCT material panels are too small to make the double gage length

wide specimen shown at the bottom of Figure 1 and is, therefore, to be exposed as single specimens. During exposure, the specimens are loaded by pins inserted through the holes at the ends of the specimens. Creep readings are made on the unnotched part of the specimens shown at the top of Figure 1. No creep readings are being taken on the wide specimens shown at the bottom of Figure 1.

After exposure, a tensile test is conducted at room temperature on one of the test sections of the double specimen exposed to creep. The remaining section can then be used for tests at either room temperature or 550°F as the need may be. Special adapters pull against the shoulder fillets to avoid stressing the second gage section of the double specimen during tensile testing of the first.

Rockwell "45N" superficial hardness measurements were taken for most specimens prior to the start of exposures. Hardness values after exposure are to be reported only for the two conditions where readings after the exposure can be taken in the region of uniform exposure stress without affecting subsequent tensile tests: (a) wide unnotched specimens, with hardness readings in the gage section, but not at the location to be notched, and (b) unstressed exposure for which hardness readings may be taken in the specimen shoulders.

PRESENT STATUS OF THE PROGRAM

As Table 1 shows, all planned exposures at 550°F have been started, and tensile tests completed for most of the specimens with 2000- or 5000-hour exposures. Some of the "accelerated" exposures at 600°, 650°, and 700°F have been finished. Additional such exposures now in progress should permit a decision as to whether any resulting

changes in tensile properties are sufficiently large to warrant completion of all the listed tests of this type.

RESULTS TO DATE

Creep strains during exposures so far are not reported because they were all negligibly small. During the first 6000 hours at 550°F under 67,000 psi stress, measured creep remains below 0.01 percent.

Table 2 lists all tensile-test and hardness data obtained to date. Ultimate tensile strengths at 550°F and at room temperature for the three types of specimen, together with elongations for unnotched specimens only, are shown graphically in Figure 2 as a function of exposure time at 550°F.

Study of Figure 2 reveals the following trends:

1) The SCT material is slightly weaker than the CRT at room temperature, but considerably stronger at 550°F.

2) The $K_t = 3$ notches raised net-section strengths at both room temperature and 550°F.

3) Except for a single test of SCT material at 550°F, sharp edge notches had little effect on net-section strength.

4) A consistently lower elongation after 5000 than after 2000 hours of exposure may signify a continuing loss of ductility with prolongation of creep exposure.

Yield strengths and hardness values showed little change as a result of exposures at 550°F, except for an apparent drop in yield strength at room temperature from 179 to 159 ksi for SCT material exposure for 5000 hours without stress.

Exposures carried out to date at 600°, 650°, and 700°F caused no appreciable change except that the CRT specimen exposed for 200 hours at 700°F and subsequently tested at 550°F had an ultimate strength which could be significantly higher than for unexposed material. A repeat test is planned to check this possibility.

Table 1

OUTLINE AND STATUS OF THE TESTING PROGRAM

Outline of Initial Exposures to Creep						Proposed Subsequent Tensile Tests				
						Temperature				
[a] Spec. Type	Stress (ksi)	Temp (°F)	Duration (hrs)	Date Started CRT	Date Started SCT	Room	550°F	[b] Either	Date Completed CRT	Date Completed SCT
U	67	550	30,000	Jan.-Feb. 1962		X			(Est: July 1965)	
U	67	550	30,000	Jan.-Feb. 1962		X			(Est: July 1965)	
U	67	550	30,000	Jan.-Feb. 1962			X		(Est: July 1965)	
U	67	550	30,000	Jan.-Feb. 1962				X	(Est: July 1965)	
N	67	550	30,000	Jan.-Feb. 1962		X			(Est: July 1965)	
N	67	550	30,000	Jan.-Feb. 1962		X			(Est: July 1965)	
N	67	550	30,000	Jan.-Feb. 1962			X		(Est: July 1965)	
N	67	550	30,000	Jan.-Feb. 1962				X	(Est: July 1965)	
W	67	550	30,000	Jan.-Feb. 1962		X			(Est: July 1965)	
W	67	550	30,000	Jan.-Feb. 1962			X		(Est: July 1965)	
U	None	550	30,000	Jan.-Feb. 1962		X			(Est: July 1965)	
U	None	550	30,000	Jan.-Feb. 1962		X			(Est: July 1965)	
U	None	550	30,000	Jan.-Feb. 1962			X		(Est: July 1965)	
U	67	550	12,000	Aug.-Sept. 1962		X			(Est: March 1964)	
U	67	550	12,000	Aug.-Sept. 1962			X		(Est: March 1964)	
N	67	550	12,000	Aug.-Sept. 1962		X			(Est: March 1964)	
N	67	550	12,000	Aug.-Sept. 1962			X		(Est: March 1964)	
U	None	550	12,000	Aug.-Sept. 1962		X			(Est: March 1964)	
U	None	550	12,000	Aug.-Sept. 1962			X		(Est: March 1964)	
N	None	550	12,000	Aug.-Sept. 1962				X	(Est: March 1964)	
U	67	550	5,000	Feb. 1962	Jan. 1962	X			Oct. 1962	Oct. 1962
U	67	550	5,000	Feb. 1962	Jan. 1962		X		Oct. 1962	Oct. 1962
N	67	550	5,000	Feb. 1962	Jan. 1962	X			Oct. 1962	Oct. 1962
N	67	550	5,000	Feb. 1962	Jan. 1962		X		Oct. 1962	Oct. 1962
W	67	550	5,000	Feb. 1962	May 1962	X			Oct. 1962	(Feb. 1963)
W	67	550	5,000	Feb. 1962	May 1962		X		Oct. 1962	(Feb. 1963)
U	None	550	5,000	Feb. 1962	Jan. 1962			X	Oct. 1962	Oct. 1962
U	67	550	2,000	Feb.-June 1962	Feb.-Mar. 1962	X			Oct. 1962	May 1962
U	67	550	2,000				X		June 1962	June 1962
N	67	550	2,000	Feb.-June 1962	Feb.-Mar. 1962	X			June 1962	June 1962
N	67	550	2,000				X		Oct. 1962	May 1962
W	67	550	2,000	Feb.-June 1962	Sept. 1962	X			May 1962	(Jan. 1963)
W	67	550	2,000		June 1962		X		May 1962	Oct. 1962
U	67	600	2,000	Sept. 1962	--	X			(Jan. 1963)	--
U	67	600	2,000	Dec. 1961	Dec. 1961		X		Mar. 1962	Mar. 1962
U	67	650	200	--	--	X			--	--
U	67	650	200	Dec. 1961	Dec. 1961		X		Mar. 1962	Mar. 1962
U	67	700	200	Dec. 1961	Dec. 1961	X			--	--
U	67	700	200	Jan. 1962	Jan. 1962		X		Mar. 1962	Mar. 1962
W	67	700	200	Feb. 1962	Feb. 1962	X			Mar. 1962	Mar. 1962
W	67	700	200	Feb. 1962	Feb. 1962		X		May 1962	Mar. 1962
U	67	700	20	--	--	X			--	--
U	67	700	20	Dec. 1961	Dec. 1961		X		Mar. 1962	Mar. 1962

a) U = Unnotched, 0.350-inch gage width; N = Notched, $K_t = 3$; W = Wide unnotched during exposure, sharp edge notches for tensile tests

b) Temperature of these tensile tests is to be selected after other results become available.

Table 2

RESULTS OF TENSILE TESTS FOR AM350 SHEET

Exposure Conditions			Test	Subsequent Tests on Unnotched Specimens							Notched (K_t = 3)	[a]Sharp Edge Notches		
Temp. (°F)	Stress (ksi)	Time (hrs)	Temp (°F)	P.L. (ksi)	Offset Yield Strengths (ksi) 0.02%	0.1%	0.2%	Tensile Strength (ksi)	Elongation (%) Per 2"	Per 0.5"	Tensile Strength (ksi)	Rockwell "45N" Hardness Before Exp.	After Exp.	Tensile Strength (ksi)
CRT Condition														
None			Room	93	122	168	185.5	218.5	28	--	225.5	51	--	214
None			Room	100	126	165	191	217	16.5	--	---	51.5	--	215.1
None			Room	110	137	171.5	182	224.2	23.5	--	---	---	--	---
550	40	2000	Room	89	107	155	[b]178	212.5	21	34	---	---	--	---
550	67	2000	Room	---	---	---	[b](178)	221.8	22	--	220	52	51.5	212
550	90	2000	Room	119	142.5	154.5	186	221.4	16.5	--	---	---	--	---
550	150	2000	Room	(145)	174	198	(208)	221.1	19.5	--	---	---	--	---
550	0	5000	Room	120	140.5	170	178.5	219	20	--	---	---	--	---
550	67	5000	Room	150	174	182	185.5	222.2	19	--	223.8	53.5	51.5	213
700	67	200	Room	---	---	---	---	---	--	--	---	52.5	52	211.4
700	67	200	Room	---	---	---	---	---	--	--	---	52	51	209.8
None			550	95	120	144	153	169	4	--	185	50.5	--	172.1
None			550	96	115	143	153	168.8	4.5	--	---	50.5	--	166.8
550	67	2000	550	85	105	132	141	163.5	2	6	178.2	52	--	160
550	67	5000	550	110	126	144	151	168.6	2	--	181.8	53.5	51.5	170.5
600	67	2000	550	92	113	141	153	172	5	--				
650	67	200	550	85	101	139	154	170.8	4	8	---	---	--	---
700	67	20	550	80	97	130	145	170.7	4	6	---	---	--	---
700	67	200	550	95	104	140	152.5	188	4.5	--	---	52	51	[c](>151)
700	67	200	550	---	---	---	---	---	--	--	---	52.5	52	172
SCT Condition														
None			Room	113	143	170	185.3	214.9	17	32	241.5	---	--	216
None			Room	119	139	165	178	213.1	12	26	---	---	--	208.3
None			Room	105	129	162	176	214	16.5	32	---	---	--	---
550	67	2000	Room	---	---	---	---	---	--	--	238.8	---	--	---
550	67	2236	Room	123	146.8	170	179	212	18	--	237.5	---	--	---
550	0	5000	Room	90	103	136	159	214.5	14	--	---	---	--	---
550	67	5000	Room	120	137	163	176	216	13.3	--	238.5	---	--	---
700	67	200	Room	---	---	---	---	---	--	--	---	53.5	52	208.8
None			550	70	89	119	135	193.6	5	12	210	---	--	159.3
None			550	80	98	126.9	141	194.4	6.5	12	---	---	--	159
550	67	2000	550	95	113.5	138	150	195.9	8.5	16	---	54.5	55	159.2
550	0	2236	550	70	92.3	125.5	142	199.5	7.5	--	---	---	--	---
550	67	2236	550	80	106	132	147.5	199	7.5	--	206.1	---	--	---
550	67	5000	550	110	114	134	145	193.5	4.5	--	208	---	--	---
600	67	2000	550	81	101	132	145.5	198.5	5.5	--	---	---	--	---
650	67	200	550	75	95	122	140	195.8	6	12	---	---	--	---
700	67	20	550	87	101	131	146	200.3	5.5	--	---	53.5	51	163
700	67	200	550	96	118	141	151.5	201.2	6	--	---	---	--	---

a) Exposed unnotched. Sharp edge notches added before tensile test.
b) By "drop of needle"; extensometer erratic
c) Specimen shoulder tore; no fracture at the notch.

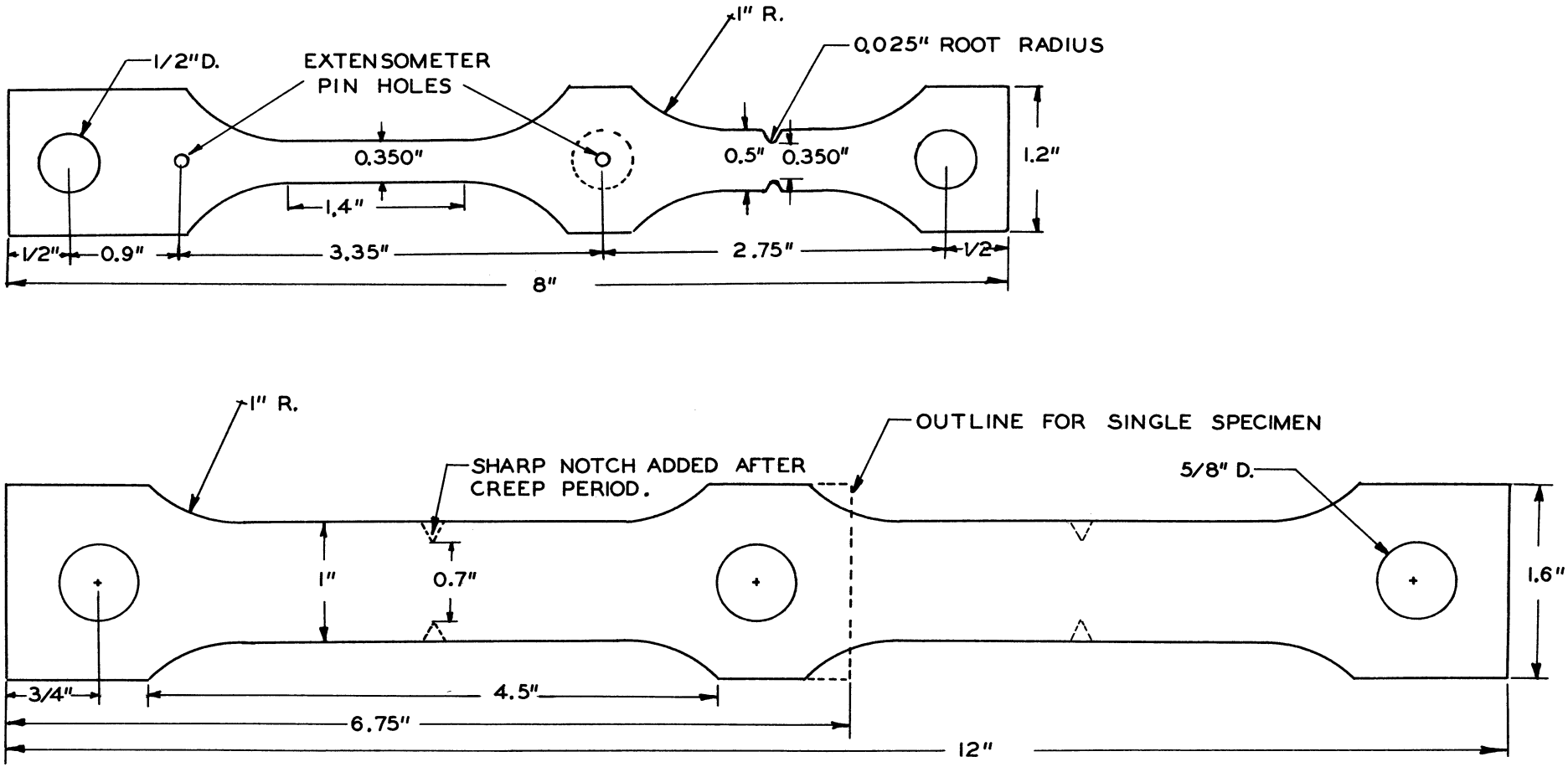

Figure 1 - Specimen for Long-Time Creep and Subsequent Tensile Testing.

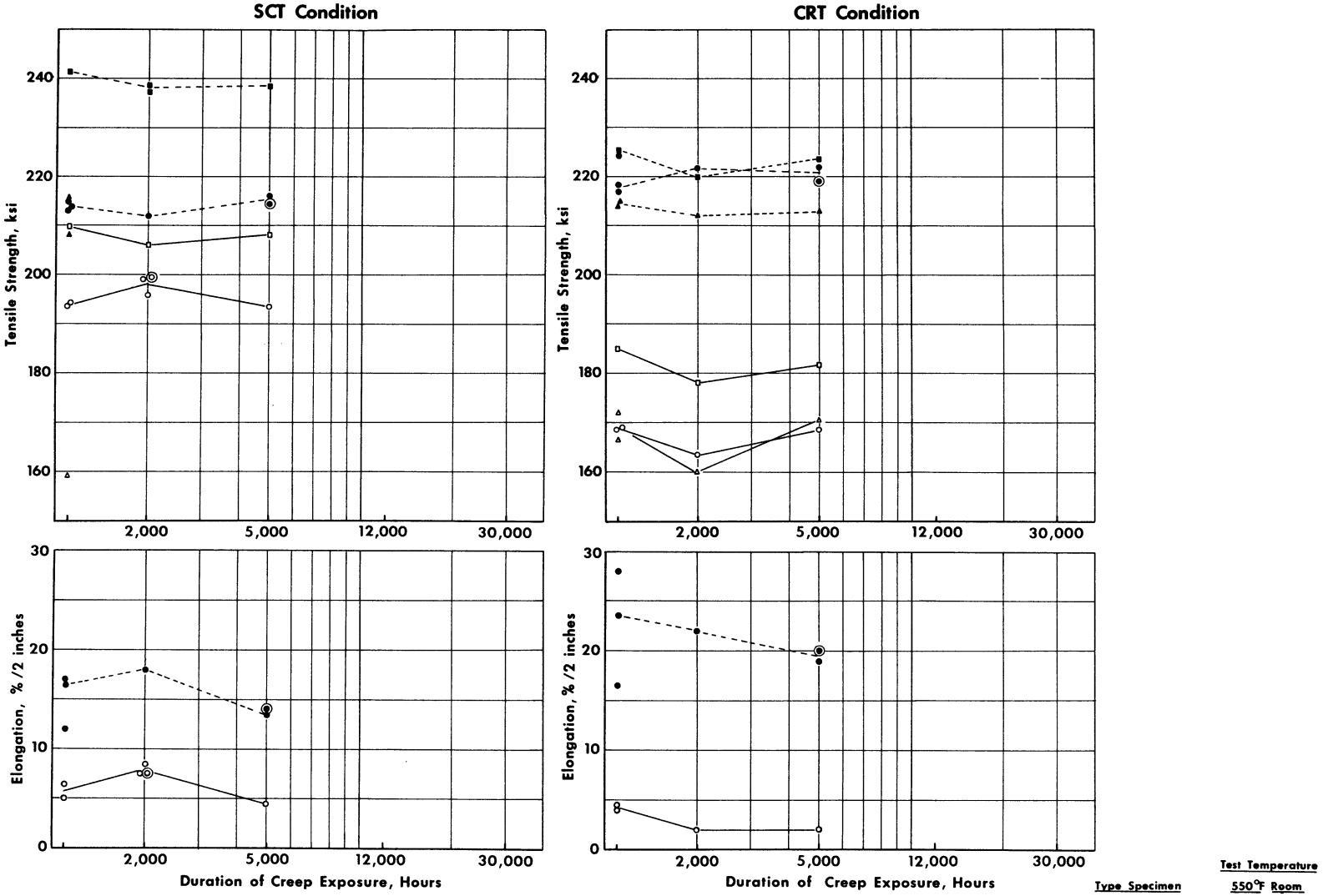

Fig. 2 - Effect of Exposure at 550°F on Tensile Strength and Ductility of Vacuum-Melted AM350 Sheet.