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Mechanical and Physical Properties of TZM Molybdenum Alloy Sheet and of Tungsten Sheet

September 30, 1964

Prepared under Bureau of Naval Weapons Contract No. N600(19)59530

Seventh Quarterly Progress Report

SOUTHERN RESEARCH INSTITUTE

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Seventh Quarterly Progress Report
(May 1 through August 31, 1964)

Southern Research Institute
Birmingham 5, Alabama
September 30, 1964
6985-1479-VII

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INTRODUCTION AND SUMMARY

This is the seventh progress report on a program to determine preliminary design information for tungsten and TZM molybdenum sheet produced in Phase I of the Refractory Metal Sheet Rolling Program. The work described in this report was performed between May 1 through August 31, 1964.

The original scope of the program, which was defined in our proposal to BuWeps and in the first progress report, included many different types of evaluations on a limited number of sheets of the two materials. Appendix A lists the different types of evaluations in the original scope. For the tungsten, 0.060 in. and 0.100 in. sheets were selected for evaluation; for the TZM, 0.020 in., 0.040 in. and 0.060 in. sheets were selected There have been a number of revisions in the scheduled evaluations as shown in Appendix A, which have been discussed in previous progress reports. Besides these relatively minor revisions, the scope of the program was extended to obtain sufficient data on the tensile and notched-tensile properties of the TZM sheet in the warm-rolled-and-stress-relieved (optimum condition) and the recrystallized conditions to permit an analysis of the probable variation of these properties at different temperatures for different locations within sheets, different sheets, different material lots and different sheet thicknesses. The sampling plan and scheduled evaluations for the extension were summarized in the Sixth Progress Report.

The tungsten sheet was produced by Fansteel Metallurgical Corporation under BuWeps Contract No. NOw-60-0621c. The TZM sheet was produced by the Refractomet Division of Universal-Cyclops Steel Corporation under BuWeps Contract NOas-59-6142c.

In previous progress reports we reviewed the scope and purpose of the program, described the experimental procedures and equipment that would be used in the program, and presented data that had been obtained on the tungsten and TZM sheet. For the tungsten sheet, data have been reported for the recrystallization temperature, bend transition temperature and compression strength in the optimum and recrystallized conditions, and for the tensile properties up to 3500° F for tungsten sheet in the optimum condition. In earlier progress reports we presented data for the TZM sheet on the recrystallization temperature and on the bend-transition temperature of the sheet in the optimum condition.

During the period that this report covers, tensile tests were conducted on recrystallized 0.060 in. and 0.100 in. tungsten sheet from room temperature up to 3500° F. Notched- and unnotched-tensile tests were conducted on the 0.060 in. tungsten sheet in the optimum and recrystallized conditions at moderately elevated temperatures (900° F and below) to determine the notched-tensile, brittle-ductile transition temperature. Tensile tests were completed on the 0.020 in., 0.040 in. and 0.060 in. TZM sheet in both the optimum and recrystallized conditions. The evaluation temperatures for these tests ranged from room temperature to 3000° F. The preparation of specimens for future evaluations was continued during the report period. TZM specimens for determination of the bend-transition temperature and the tensile properties in the optimum-coated condition at different temperatures were prepared and submitted to the University of Dayton, which is coordinating the application of coatings to be evaluated in this contract with related work that the University of Dayton is conducting under an Air Force contract. Preparation was begun in this report period of the 672 notched and unnotched TZM tensile specimens for evaluation of the property variability, which was discussed in detail in the Sixth Progress Report, under the extended scope of the contract.

In general the experimental work is proceeding satisfactorily. Most of the experimental work that was planned for the report period, as given in the Sixth Progress Report, was completed.

One additional modification was made in the evaluation program for the tungsten sheet since the previous progress report. The evaluation of spot-welded tungsten sheet has been dropped from the program and several compression tests at elevated temperatures have been substituted into the program. Data from the compression tests are needed by Solar in the performance of Contract No. NOw 63-0786d on the formability of the tungsten sheet. The table below shows the sheet thicknesses and temperatures at which compression data on sheet in the optimum condition will be obtained.

Thickness, In.	Temperature, ° F
0.020	600
0.060	900
0.100	1050 and 1700

MATERIALS AND SPECIMENS

A. Tungsten Sheet

The description and processing of the tungsten sheets and the location of the required specimen blanks for all of the scheduled evaluations was discussed in the Third and Fourth Progress Reports. The recrystallization, at 2550° F, has been completed on all of the tungsten specimens that will be needed in the program. The machining and grinding of all of the tungsten specimens is now complete except for those specimens that will be needed for the thermal-property evaluations and for the fusion-welded tensile evaluations. The shoulders on a few tungsten specimens are also being modified to obtain additional notched-tensile data, as will be discussed later in the report.

B. TZM Sheet

The description and processing of the TZM sheet and the location of specimens within specific sheets was given in the Fifth Progress Report for the original program scope. The identification of the TZM sheets for evaluation of the property variability, in the extended scope of the program, was given in the Sixth Progress Report.

Most of the TZM specimens that will be used in the original program scope have been prepared. The only exceptions are the specimens for the thermal-property and spot- and fusion-welded property evaluations. Recrystallization, at 2475° F, has been completed on all of the TZM specimens. We have been advised recently by the University of Dayton that the application of the PFR-6 and W-3 coatings, by Pfaudler and Chromalloy respectively, has been completed on the 80 bend-transition and 48 tensile specimens that were submitted about July 1, 1964.

The extended program scope on the TZM sheet to evaluate the property variation at different temperatures for different locations within sheets, different sheets, different material lots, and different sheet thicknesses requires a total of 672 specimens. The preparation of the 504 unnotched tensile specimens was completed during the report period and the preparation of the 168 notched tensile specimens was started. One-hundred-sixty-eight of the unnotched specimens and 72 of the notched specimens will be recrystallized for one hour at 2475° F in vacuum before evaluation at selected temperatures.

EXPERIMENTAL PROCEDURES AND RESULTS

A. Tungsten Sheet

Tensile tests have been completed on the 0.060 in. tungsten sheet up to 3500° F and on the 0.100 in. tungsten sheet up to 3000° F in the recrystallized condition for determination of the conventional tensile properties. Additional tensile tests have been completed at temperatures between 75 and 900° F on notched and unnotched specimens of the 0.060 in. tungsten sheet in the optimum and recrystallized conditions to determine the brittle-ductile transition temperature. The specimens and procedures that were used for the room- and elevated-temperature tensile tests to determine the conventional tensile properties of the tungsten sheet are the same as those discussed in earlier progress reports for similar tests. Briefly, the specimens evaluated at elevated temperatures were heated to temperature in approximately 30 minutes in a vacuum lower than 5×10^{-4} torr by radiation from tantalum elements, held 15 minutes at temperature, and then strained to fracture at controlled rates. At room temperature and 1200° F the strain rates were 0.005 min^{-1} to 0.6% offset and 0.05 min^{-1} to fracture. For the evaluations at 2000° F and higher, the strain rate was 0.05 min^{-1} throughout the tests. The notched-tensile specimen used in the moderately-elevated tensile tests to determine the brittle-ductile transition temperature is shown in Figure 1. The stress concentration factor, K_t, for this specimen is 4.2. The unnotched specimens that were evaluated at moderately elevated temperatures for determinations of the brittle-ductile transition temperature were identical to other unnotched specimens used to determine the conventional tensile properties at other temperatures. A split-muffle type radiation furnace was used to heat the notched-tensile specimens. The temperature of the furnace was manually adjusted by a variac to the desired temperature, which was indicated by the signal from a chromel-alumel thermocouple that contacted the specimen at the notch. A conventional null-balance potentiometer was used to measure the temperature. The unnotched tensile specimens for the determination of the brittle-ductile transition temperature were heated in a vacuum chamber as discussed earlier for the other unnotched specimens. A cross-head rate of approximately 0.005 in. min^{-1} was used for the notched-tensile tests. For the unnotched tensile tests the strain rates were the same as for the tests at room temperature and 1200° F discussed above, i.e., 0.005 to the 0.6% offset and 0.05 from the 0.6% offset to fracture. In general all of the procedures used for the tensile evaluations were in agreement with the procedures recommended in MAB-192-M.

Results of the tensile tests on the 0.060 in. and 0.100 in. tungsten sheet in the recrystallized condition to determine the conventional tensile properties are summarized in Tables I and II respectively. The tensile data for the recrystallized sheet are plotted as functions of temperature with similar data for the sheet in the optimum condition in Figures 2 and 3 for the 0.060 in. sheet and in Figures 4 and 5 for the 0.100 in. sheet. Data from the evaluations of unnotched specimens in the optimum and recrystallized conditions which were obtained primarily to determine the brittle-ductile transition temperature were included in plots of data shown in Figures 2 and 3 to better define the property trends at lower temperatures. As these figures show, the strength properties of both sheet thicknesses are much lower in the recrystallized condition than in the optimum condition at all temperatures up to 3000° F. At 3000° F and at 3500° F the specimens representing the optimum conditions were recrystallized in heating to the evaluation temperature and have comparable strength properties to the specimens which were recrystallized before heating. As Figure 2 shows, the strength properties, particularly the 0.2% offset yield strength, of the 0.060 in. tungsten sheet in the recrystallized condition decreased considerably between 700 and 1200° F; above 1200° F the flow stress of the recrystallized 0.060 in. sheet decreased only slightly with temperature between 1200 and 3500° F. As Figure 3 shows, the ductility of the recrystallized 0.060 in. sheet was generally higher at intermediate temperatures, 800 to 3000° F, than for sheet in the optimum condition. The 0.060 in. sheet in the optimum condition, however, had measurable ductility at 600° F while the recrystallized 0.060 in. sheet was brittle at the same temperature. Above the recrystallization temperature, the ductility of the tungsten sheet is comparable for both original structures. The correction factor to be used in the computation of the moduli of elasticity for the tungsten sheet at elevated temperatures has not been determined. These data will be given for the tungsten sheet in a subsequent report.

Tables III and IV and Figures 6 and 7 show, for the 0.060 in. tungsten sheet in the optimum and recrystallized conditions respectively, data from notched and unnotched tensile specimens that were evaluated to determine the brittle-ductile transition temperature. In the performance of these tests a number of specimens fractured across the shoulders at the loading-pin hole rather than in the gage section or in the notch and, of course, no useful data were obtained from the specimens. The shoulders of a number of these specimens are now being modified, and these specimens will be used to obtain additional data from notched and unnotched specimens to further establish the notched-tensile brittle-ductile transition temperature. The data given in Tables III and IV and plotted in Figures 6 and 7 are, therefore, tentative and will be supplemented with additional data in the next progress report. Figure 6 shows that the unnotched tensile strength of the 0.060 in. sheet in the optimum condition decreased from about 200 ksi at room temperature to about 160 ksi at

600° F. The notched tensile strength increased significantly, from 105 to 145 ksi, between 200 and 300° F and remained at approximately 145 ksi up to 600° F, at which temperature it decreased to about 120 ksi. Although additional data at 200° F and below are needed for confirmation, it appears that the notched-tensile brittle-ductile transition temperature of the 0.060 in. tungsten sheet in the optimum condition will probably be between 200 and 300° F. The notched-unnotched strength ratio for the 0.060 in. sheet in the optimum condition is given in the lower part of Figure 6. For the 0.060 in. sheet in the recrystallized condition, as shown in Figure 7, the transition in the notched tensile strength occurs between 400 and 600° F. Since most of the unnotched specimens fractured across the shoulders at the loading-pin hole, only maximum notched/unnotched-strength-ratio data, as shown in the lower part of Figure 7, are available until additional tests are successfully completed. Additional discussion of the notched-tensile brittle-ductile transition temperature will be presented in the next progress report, which will include more data.

B. TZM Sheet

All of the scheduled tensile tests have been completed on the 0.020 in., 0.040 in., and 0.060 in. TZM sheet in both the optimum and recrystallized conditions. The temperatures for these tests ranged between 75 and 3000° F. The procedures and apparatus used for the evaluations are the same as those used for the tensile tests on the tungsten sheet as discussed in the previous section of the report.

Data for the tensile tests on the TZM sheet are summarized in tables and figures as shown below:

Sheet	Condition	Table No.	Figure No.
0.020	Optimum	V	8, 9, 14
	Recrystallized	VI	8, 9, 14
0.040	Optimum	VII	10, 11, 14
	Recrystallized	VIII	10, 11, 14
0.060	Optimum	IX	12, 13, 14
	Recrystallized	X	12, 13, 14

The tabulated and plotted data listed above show that the room-temperature ultimate tensile strength of the three sheet thicknesses of TZM in the optimum condition was approximately 130 to 140 ksi and at 3000° F it was about 15 ksi. At 75° F the transverse tensile strength was generally about 8 ksi higher than the longitudinal tensile strength. For the optimum condition, the 0.2% offset yield was generally about 85% of the ultimate tensile strength at most temperature levels. For the recrystallized condition the ultimate tensile strength was approximately 100 ksi at 75° F and about 30 ksi at 2200° F for the three sheet thicknesses. Although tensile tests on the 0.020 in. and 0.060 in. sheet in the recrystallized condition were not obtained at 2500 and 3000° F, the data for the 0.040 in. sheet in the optimum and recrystallized conditions, shown in Figure 10, suggests that the TZM sheet in the optimum condition retains a strength advantage over the recrystallized sheet up to 3000° F even though recrystallization occurs below 2400° F. The ductility data shown in Figures 9, 11 and 13 for the three sheet thicknesses indicate that in the optimum condition a ductility minimum probably exists at approximately 2000° F for both the elongation and reduction of area. Modulus-of-elasticity data, shown for the three sheet thicknesses in Figure 14, indicate that the modulus of elasticity decreased from approximately 47 x 10^6 psi at 75° F to approximately 15 x 10^6 psi at 3000° F with no consistent difference in the moduli of the sheet in different thickness and structural conditions being apparent.

Although insufficient time has elapsed since the tensile data given in this report was obtained for a complete analysis of the data, Table XI provides a basis for a comparison of some of the data developed at SRI with similar averaged data obtained by Universal Cyclops[1] on the TZM sheet. In general the data reported by SRI and Universal Cyclops are in good agreement, although the strength properties obtained from sheet evaluated by SRI seem to be slightly higher than average data reported by Universal Cyclops.

FUTURE WORK

During the next reporting period we expect to complete the additional notched and unnotched tensile evaluations for determination of the notched-tensile brittle-ductile transition temperature on the 0.060 in. tungsten sheet. Also on the tungsten sheet, we expect to complete the added compression determinations at elevated temperatures and the bearing and shear determinations, which will be performed slightly above the brittle-ductile transition temperature.

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[1] Molybdenum Sheet Rolling Program, Progress Report [illegible] July 26, 1963, to October 25, 1963, on Contract No. NOas 59-[illegible]-c, Universal Cyclops Steel Corp., Refractromet Division [illegible]ridgeville, Pennsylvania

On the TZM sheet we expect to determine the bend transition temperature for sheet in the recrystallized condition, determine the notched-tensile brittle-ductile temperature, and begin the tensile tests on the extended scope of the evaluation of the TZM sheet to determine the variation of properties within sheets, different sheets, different material lots and different sheet thicknesses.

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APPENDIX A

Summary of Property Evaluations Scheduled for Original Program

Property	Alloy	Conditions[1]	Exposure Time, Hr[2]	Temperatures, °F
Tensile	Mo	O., R., C.	0.5	RT[3], 1200, 2000, 2200, 2500, 3000
	W	O., R., C.	0.5	RT[3], 1200, 2000, 2500, 3000, 3500, 4000, 4500
Compression	Mo	O., R.		RT[3]
	W	O., R.		RT[3]
Tensile Notch Sensitivity	Mo	O., R.		RT and to above the transition temp.
	W	O., R.		RT and to above the transition temp.
Shear Strength	Mo	O.		RT
	W	O.		RT
Bearing Strength	Mo	O.		RT
	W	O.		RT
Tensile Creep	Mo	O.	To 100	2000, 2500
	W	O.	To 100	2500, 3000
Thermal Stability	Mo	O.		RT
	W	O.		RT
Bend Transition	Mo	O., R., C.	0.5	50° F increments to 50° F above transition temp.[3]
	W	O., R., C.	0.5	50° F increments to 50° F above transition temp.[3]
Minimum Bend Radius	Mo	O., R		RT
	W	O., R.		RT
Fusion Weld Joint Efficiency	Mo	A.W., H.T.	0.5	RT, 2500° F
	W	A.W., H.T.	0.5	RT, 3000° F
Spot Weld Joint Efficiency	Mo	A.W., H.T.	0.5	RT, 2500° F
	W	A.W., H.T.	0.5	RT, 3000° F
Density	Mo	O.		RT
	W	O.		RT
Thermal Expansion	Mo	O.		Obtain curve RT to 2500° F
	W	O.		Obtain curve RT to 2500° F
Thermal Conductivity	Mo	O.		500, 1200, 1800, 2500
	W	O.		500, 1200, 1800, 2500, 3000
Specific Heat	Mo	O.		500, 1200, 1800, 2500
	W	O.		500, 1200, 1800, 2500, 3000
Recrystallization	Mo	O.		To be determined
	W	O.		To be determined
Hot Formability	Mo	O.		Above transition temp.
	W	O.		Above transition temp.
Oxidation	Mo	C.	0.5, 10, 100	2500, 2800
	W	C.	0.5, 10, 100	2500, 2800

[1] O. - optimum, R. - recrystallized, C. - coated, A.W. - as-welded, H.T. - heat treated.
[2] Applies only to elevated-temperature determinations.
[3] Evaluations to be made in both transverse and longitudinal orientations; all others in longitudinal orientation only.

Table I

Tensile Properties of 0.060 in. Tungsten Sheet in the Recrystallized Condition[1] at Different Temperatures[2]

Specimen Number	Orien-tation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
15-12	L	75	-[3]	56.8	56	0	0
17-294	L	75	-[3]	55.8	68	0	0
Average			-	56.3	62	0	0
15-137	T	75	-[3]	47.8	68	0	0
17-439	T	75	-[3]	67.7	64	0	0
6-269	T	75	-	44.3	66	0	0
Average				53.3	66	0	0
6-156	L	1200	11.1	44.1	-[4]	53	74
6-151	L	1200	9.0	41.0	-[4]	52	75
17-296	L	1200	13.8	55.0	-[4]	55	72
Average			11.3	46.7	-	53	74
15-13	L	2000	10.0	34.4	-[4]	31	>95
17-297	L	2000	12.1	40.0	-[4]	47	>95
Average			11.0	37.2	-	39	>95
6-152	L	2500	7.3	27.5	-[4]	51	>95
17-298	L	2500	8.6	26.7	-[4]	52	>95
Average			8.0	27.1	-	52	>95
6-153	L	3000	8.6	19.3	-[4]	71	86
15-14	L	3000	8.0	18.7	-[4]	44	>95
Average			8.3	19.0	-	58	>90
15-15	L	3500	6.1	11.8	-[4]	50	60
17-299	L	3500	5.8	11.1	-[4]	48	50
Average			6.0	11.5	-	49	55

1 Specimens were recrystallized at 2550° F in 1 hour.

2 Specimens were heated by radiation in a vacuum of approximately 10^{-4} and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

3 Specimen fractured before yielding.

4 Correction factor not established, will be given in subsequent report.

Table II

Tensile Properties of 0.100 in. Tungsten Sheet in the Recrystallized Condition[1] at Different Temperatures[2]

Specimen Number	Orien- tation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
112-22	L	75	-[3]	>77.0[4]	59	0	0
112-23	L	75	-[3]	>52.6[4]	70	0	0
Average			-	>64.8	65	0	0
112-32	T	75	-[3]	>46.4[4]	61	0	0
112-33	T	75	-[3]	>59.2[4]	71	0	0
Average			-	52.8	66	0	0
112-24	L	2500	6.8	29.2	-[5]	50	>95
112-25	L	2500	8.7	30.4	-[5]	53	>95
Average			7.8	29.8	-	52	>95
112-28	L	3000	6.6	18.6	-[5]	57	>95
112-29	L	3000	5.8	18.0	-[5]	56	>95
Average			6.2	18.3	-	56	>95

[1] Specimens were recrystallized at 2550° F in 1 hour.

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

[3] Specimen fractured before yielding.

[4] Specimen broke at radius of shoulder.

[5] Correction factor not established, will be given in subsequent report.

Table III

Notched and Unnotched Tensile Data for 0.060 in. Tungsten Sheet in the Optimum Condition[1] at Moderately-Elevated Temperatures[2]

Temp. °F	Unnotched Specimens: Specimen No.	Unnotched Specimens: 0.2% Offset Yld. Str. ksi	Unnotched Specimens: Ult. Tens. Strength ksi	Unnotched Specimens: Elong. in 1 in. %	Unnotched Specimens: Red. of Area %	Notched Specimens: Specimen No.	Notched Specimens: Ult. Tens. Strength ksi	Unnotched / Notched Strength Ratio
200	15-9	-[3]	188.0	0	0	15-25	106.0	0.565
300	17-288	-[3]	165.0	0	0	15-20	137.0	
300						15-26	154.5	
300						15-19	143.0	
						Average	144.8	0.873
400	6-147	165.0	175.0	0	0	15-27	142.8	
400						17-312	137.0	
						Average	139.5	0.795
500	17-290	166.0	173.0	0	0	15-28	138.9	
500						17-311	145.5	
						Average	142.2	0.820
600	17-291	158.8	162.5	4	5	15-18	119.5	0.732

[1] Warm-rolled and stress-relieved for 10 min at 2100° F.
[2] Specimens were held approximately 15 min at temperature before straining to fracture at a strain rate of 0.005 min.
[3] Fractured before 0.2% offset.

Table IV

Notched and Unnotched Tensile Data for 0.060 in. Tungsten Sheet in the Recrystallized Condition[1] at Moderately-Elevated Temperatures[2]

	Unnotched Specimens					Notched Specimens		
Temp. °F	Specimen No.	0.2% Offset Yld. Str. ksi	Ult. Tens. Strength ksi	Elong. in 1 in. %	Red. of Area %	Specimen No.	Ult. Tens. Strength ksi	Unnotched/Notched Strength Ratio
200	6-185	-[3]	60.5	0	0	17-319	30.0	
200	-	-	-	-	-	17-308	26.0	
Average							28.0	<0.475
300	17-325	-[3]	>37.8[4]	0	0	17-314	25.3	
300	-	-	-	-	-	17-320	26.0	
Average							25.6	<0.677
400	6-180	-[3]	>50.5[4]	0	0	15-36	27.5	<0.545
500	6-184	-[3]	>70.4[4]	0	0	6-172	34.7	
500	-	-	-	-	-	15-32	43.2	
Average							38.9	<0.552
600	15-10	-[3]	>74.0	0	0	15-33	54.7	<0.740
700	15-11	64.8	79.0	7	7	15-34	56.4	0.723
800	17-326	43.5	79.8	24	15	-	-	-
900	17-332	42.0	72.4	12	14	-	-	-

[1] Specimens were recrystallized at 2550° F in 1 hour.
[2] Specimens were held approximately 15 min at temperature before straining to fracture at a strain rate of 0.005 min.
[3] Fractured before 0.2% offset.
[4] Fractured in shoulder across pin hole.

Table V

Tensile Properties of 0.020 in. TZM Sheet in the Optimum Condition[1] at Different Temperatures[2]

Specimen Number	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
74-3	L	75	115.5	133.5	48	9	25
74-16	L	75	120.0	133.0	43	13	22
Average			117.8	133.3	46	11	24
74-22	T	75	136.8	141.0	51	9	22
74-24	T	75	139.0	141.0	46	8	18
Average			137.9	141.0	48	8	20
74-5	L	2000	70.0	80.8	40	4	8
74-6	L	2000	70.3	77.5	37	3	11
Average			70.2	79.2	38	4	10
74-8	L	2200	61.7	72.7	36	6	25
74-9	L	2200	59.2	71.8	40	5	13
Average			60.5	72.3	38	6	19
74-11	L	2500	36.1	42.4	26	9	20
74-12	L	2500	42.2	50.0	30	8	23
74-17	L	2500	52.2	63.2	40	5	28
Average			42.6	51.9	32	7	24
74-13	L	3000	8.2	13.7	14	53	>95
74-15	L	3000	8.4	14.4	17	40	>95
Average			8.3	14.1	16	46	>95

[1] Sheet was hot-warm rolled and annealed for 1 hour at 2300° F

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6 % offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

Table VI

Tensile Properties of 0.020 In. TZM Sheet at Different Temperatures[1] in the Recrystallized Condition[2]

Specimen Number	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
74-1	L	75	80.3	105.5	48	14	23
74-4	L	75	80.8	107.0	53	18	22
Average			80.6	106.3	50	16	22
74-21	T	75	85.5	108.5	53	18	19
74-23	T	75	83.5	108.3	53	16	19
Average			84.5	108.4	53	17	19
74-7	L	2200	27.3	32.0	29	6	25
74-10	L	2200	24.8	32.3	29	3	30
Average			26.1	32.2	29	4	28

[1] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75° F the strain rate was 0.005 min^{-1} to 0.6% offset and 0.05 min^{-1} from 0.6% offset to fracture. At 2200° F the strain rate was 0.05 min^{-1} to fracture.

[2] Specimens were recrystallized at 2475° F in one hour in a vacuum of approximately 10^{-4} torr.

Table VII

Tensile Properties of 0.040 in. TZM Sheet in the Optimum Condition[1] at Different Temperatures[2]

Specimen Number	Orien-tation	Temp ° F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
55-27	L	75	109.0	129.0	46	28	46
55-3	L	75	105.8	129.7	49	16	34
56-27	L	75	119.2	129.0	54	24	38
56-3	L	75	116.0	140.1	46	18	34
Average			112.5	132.0	49	21	38
55-92	T	75	134.0	140.0	48	13	38
56-92	T	75	130.0	137.0	51	16	38
Average			132.0	138.5	49	14	38
55-7	L	1200	66.6	92.6	48	7	38
56-7	L	1200	80.6	92.0	28	10	33
Average			73.6	92.3	38	8	36
55-11	L	2000	72.0	78.5	29	6	36
56-11	L	2000	69.0	78.0	30	5	26
Average			70.5	78.3	30	6	31
55-15	L	2200	58.7	71.8	31	9	36
56-15	L	2200	61.2	72.5	31	7	18
Average			60.0	72.2	31	8	27
55-19	L	2500	31.8	38.8	20	12	>95
56-19	L	2500	39.1	44.7	23	8	73
Average			35.5	41.7	22	10	>84
55-23	L	3000	7.7	13.4	14	54	>95
56-23	L	3000	8.7	14.5	12	58	>95
Average			8.2	14.0	13	56	>95

[1] Sheet was hot-warm rolled and annealed for 1 hour at 2300° F.

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

Table VIII

Tensile Properties of 0.040 in. TZM Sheet in the Recrystallized Condition[1] at Different Temperatures[2]

Specimen Number	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
55-4	L	75	71.2	93.8	54	21	23
56-4	L	75	73.7	97.3	45	12	12
Average			72.5	95.6	49	16	18
55-89	T	75	75.5	96.3	44	15	12
56-89	T	75	75.5	93.0	46	10	17
Average			75.5	94.7	45	12	14
55-31	L	1200	21.5	48.8	29	16	51
56-8	L	1200	23.7	55.3	38	18	52
Average			22.6	52.1	34	17	52
55-13	L	2000	20.3	40.2	29	14	47
56-13	L	2000	22.2	37.1	30	14	58
Average			21.3	38.7	30	14	52
55-17	L	2200	18.2	28.3	36	24	45
56-17	L	2200	20.5	32.3	35	19	47
Average			19.4	30.3	36	22	46
55-22	L	2500	15.4	23.5	24	27	60
55-22	L	2500	14.8	22.4	23	27	51
Average			15.1	23.0	24	27	56
55-26	L	3000	11.7	14.1	15	42	63
56-26	L	3000	11.2	15.4	18	50	64
Average			11.5	14.8	16	46	64

[1] Specimens were recrystallized at 2475° F in one hour in a vacuum of approximately 10^{-4} torr.

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

Table IX

Tensile Properties of 0.060 in. TZM Sheet in the Optimum Condition[1] at Different Temperatures[2]

Specimen Number	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
23-17	L	75	117.0	134.0	46	20	40
23-2	L	75	98.0	132.5	47	-[3]	-[3]
23-3	L	75	109.5	134.0	42	22	44
Average			108.2	133.5	44	21	42
23-22	T	75	128.0	141.5	46	6	44
23-24	T	75	131.0	140.5	47	4	4
Average			129.5	141.0	46	5	24
23-5	L	2000	81.8	85.5	29	5	24
23-6	L	2000	85.5	90.7	30	7	19
Average			83.7	88.1	30	6	22
23-8	L	2200	67.5	74.2	29	10	25
23-9	L	2200	62.5	74.5	27	8	37
Average			65.0	74.4	28	9	31
23-11	L	2500	31.7	37.6	23	16	>95
23-12	L	2500	38.4	42.7	23	14	>95
Average			35.1	40.2	23	15	>95
23-13	L	3000	9.8	15.4	15	58	>95
23-15	L	3000	8.7	13.2	15	45	>95
Average			9.3	14.3	15	52	>95

[1] Sheet was hot-warm rolled and annealed for 1 hour at 2300° F.

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

[3] Replacement specimen to be tested later because this specimen fractured outside the gage length.

Table X

Tensile Properties of 0.060 in. TZM Sheet in the Recrystallized Condition[1] at Different Temperatures[2]

Specimen Number	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
23-1	L	75	81.7	100.2	49	20	20
23-4	L	75	79.8	99.5	47	18	14
Average			80.8	99.9	48	19	17
23-21	T	75	76.4	96.0	-[3]	26	24
23-23	T	75	77.8	96.0	47	23	28
Average			77.1	96.0	47	24	26
23-7	L	2200	21.4	29.7	27	26	56
23-10	L	2200	21.1	31.9	28	22	57
Average			21.2	30.8	28	24	56

[1] Specimens were recrystallized at 2475° F in one hour in a vacuum of approximately 10^{-4} torr.

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

[3] Value calculated from stress-strain curve was abnormally high and was omitted from the table.

Table XI

Comparison of Tensile Data for TZM Sheet in the Optimum Condition from Universal Cyclops and Southern Research Institute

Sheet Thickness In.	Property[1]	Universal Cyclops 75° F Long.	Universal Cyclops 75° F Trans.	Universal Cyclops 2000° F Trans.	Southern Research Institute 75° F Long.	Southern Research Institute 75° F Trans.	Southern Research Institute 2000° F Long.
0.020	UTS	129	137	82	133	141	79
	0.2% Y.S.	112	128	76	118	138	70
	%E	12	9	4	11	8	4
0.040	UTS	129	134	82	132	138	78
	0.2%Y.S.	109	128	78	112	132	70
	%E	15	9	5	21	14	6
0.060	UTS	129	135	83	133	141	88
	0.2%Y.S.	112	128	80	108	129	84
	%E	17	13	7	21	5	6

[1] Strength properties are in units of 1000 psi.

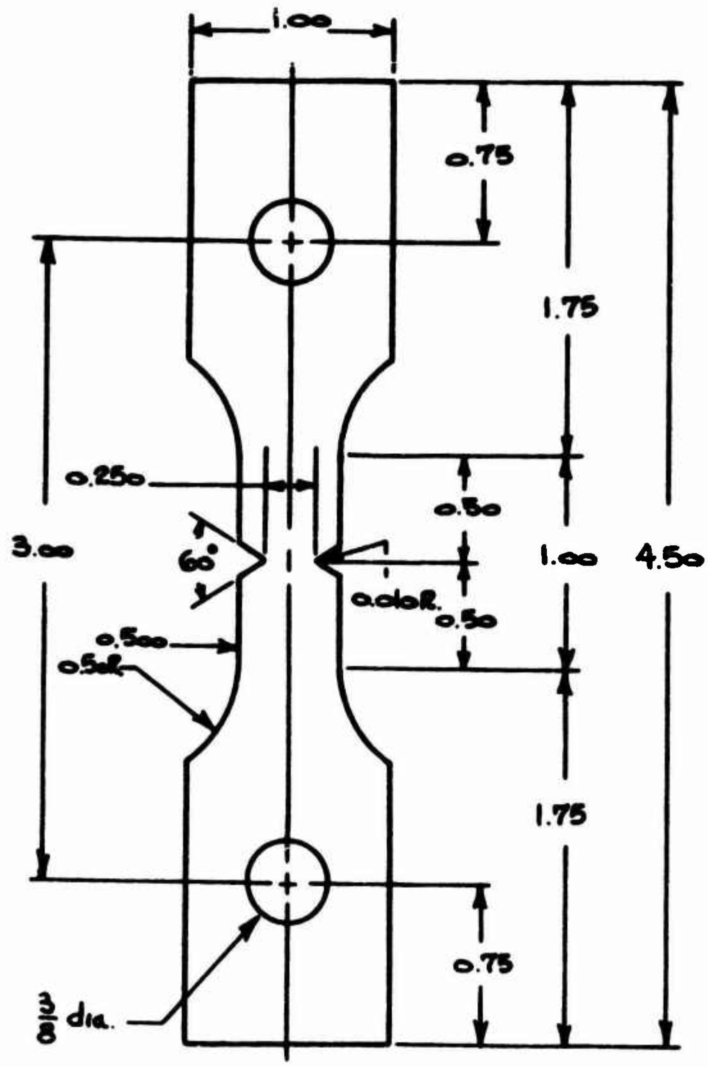
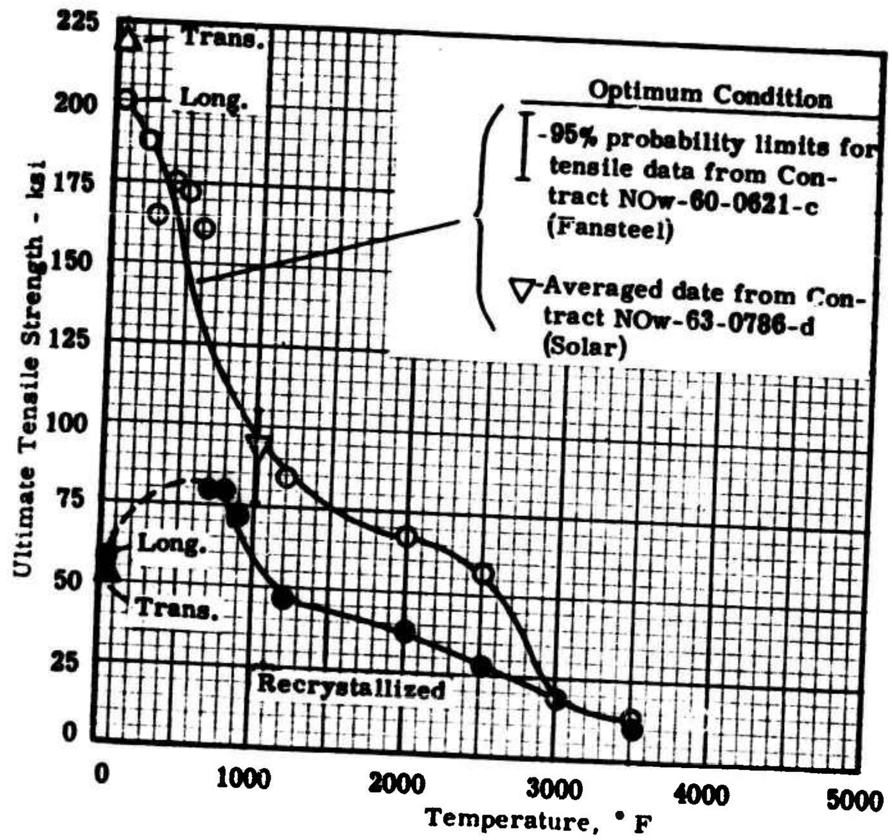


Figure 1 Notched tensile specimen with a stress concentration factor, K_t, of 4.2.



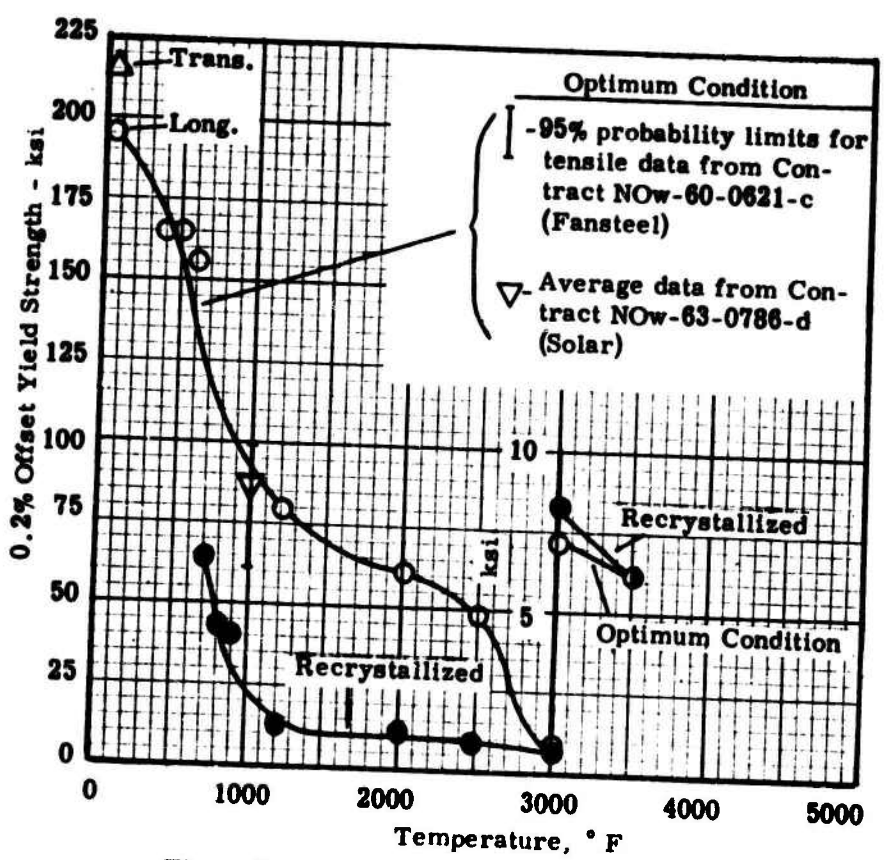


Figure 2 The ultimate-tensile(above) and 0.2%-offset-yield (below) strengths at different temperatures of 0.060 in. tungsten sheet in the optimum and recrystallized conditions.

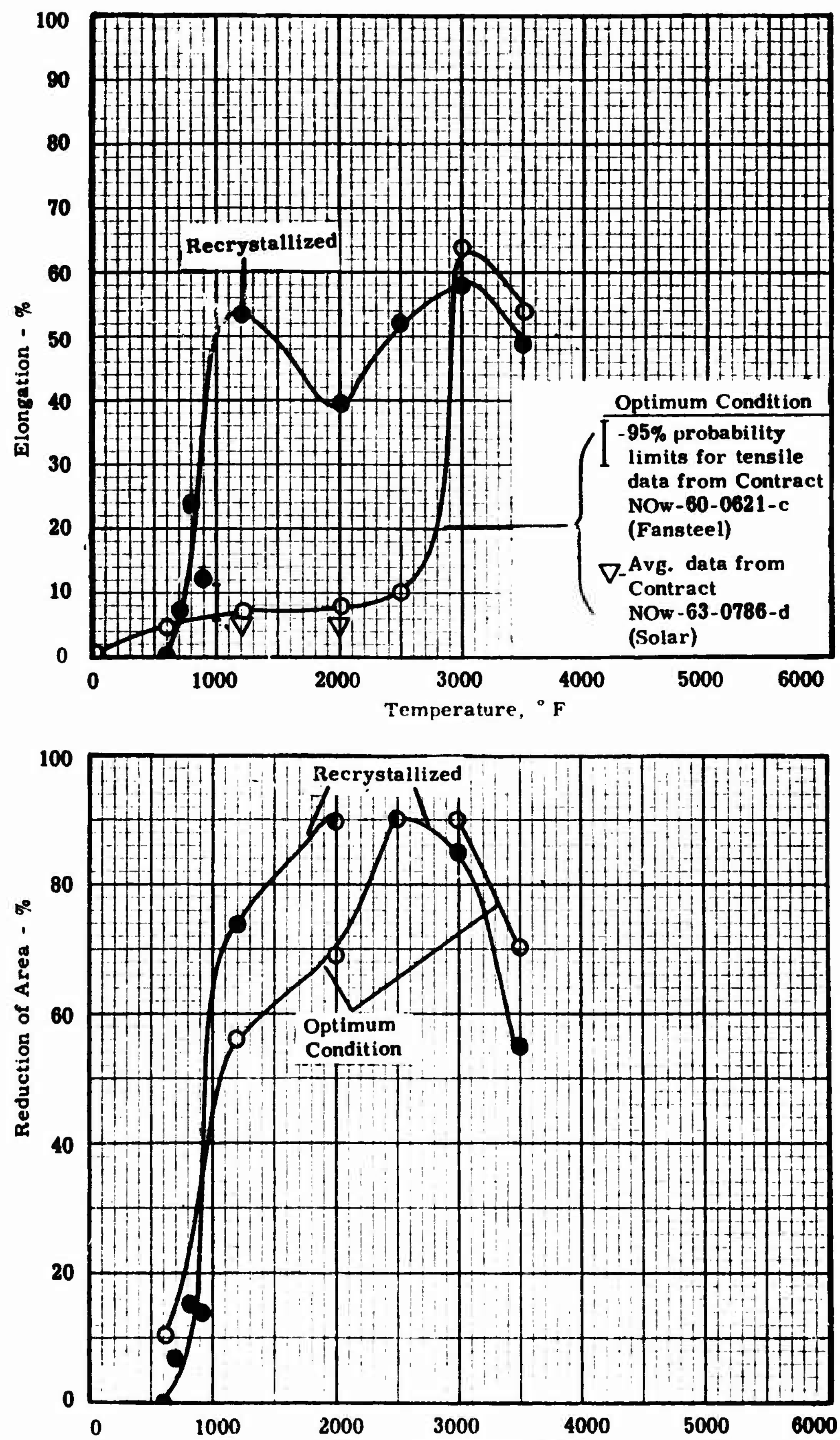
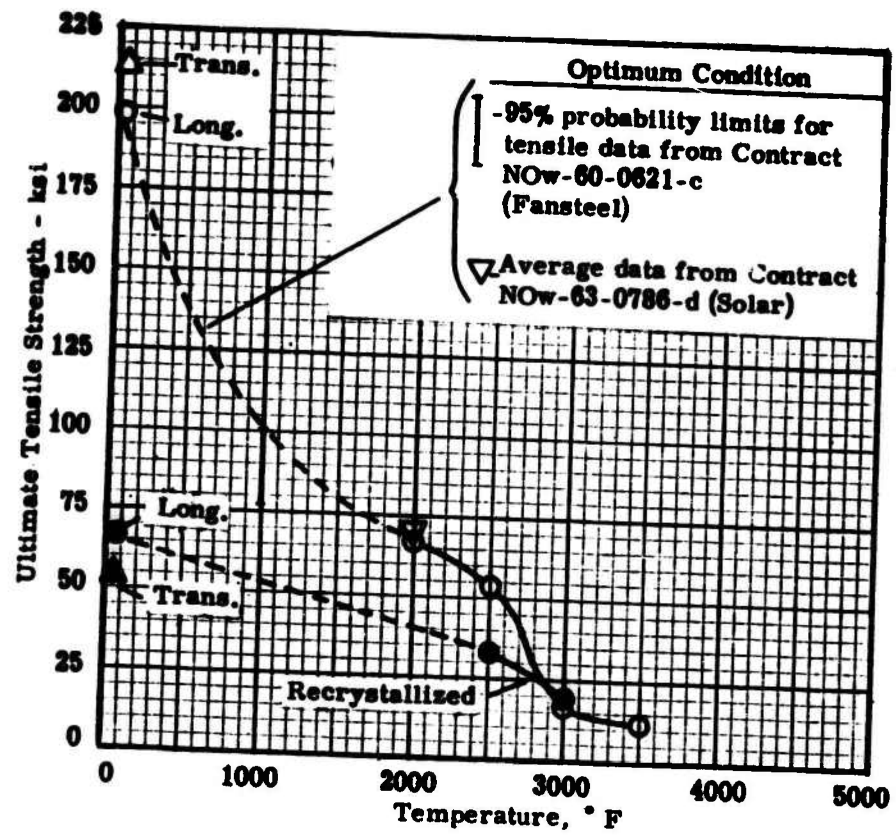


Figure 3 The elongation (above) and reduction of area (below) of 0.060 in. tungsten sheet in the optimum and recrystallized conditions at different temperatures



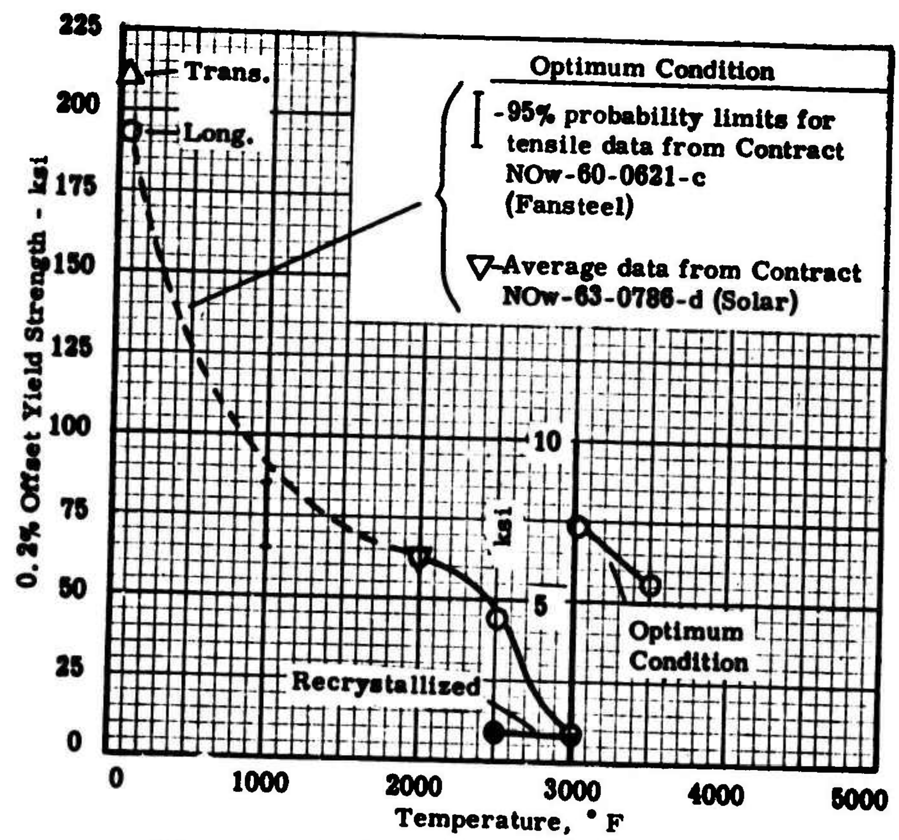


Figure 4 The ultimate-tensile (above) and 0.2%-offset-yield (below) strengths at different temperatures of 0.10 in. tungsten sheet in the optimum and recrystallized conditions

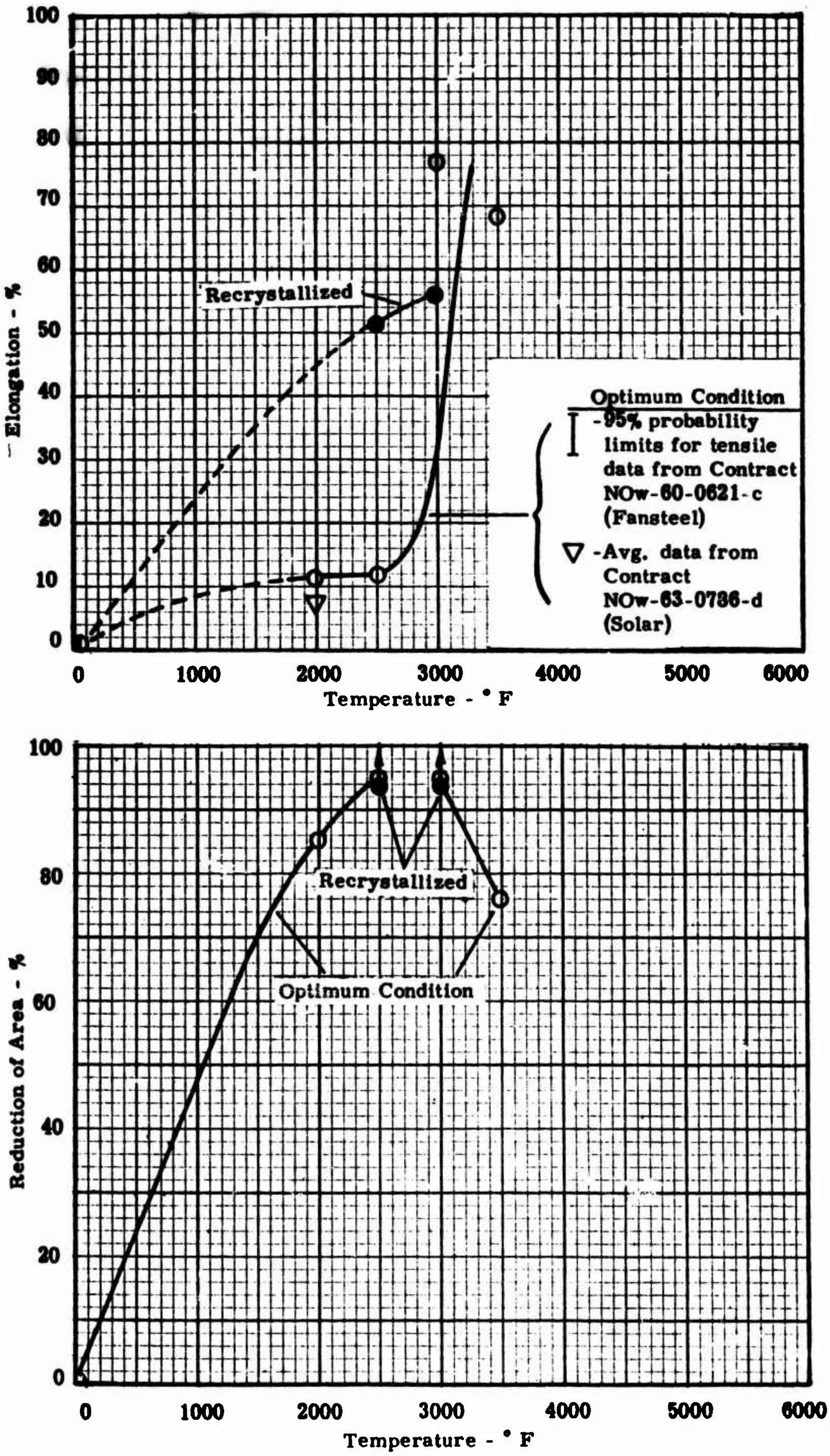


Figure 5 The elongation (above) and reduction of area (below) of 0.100 in. tungsten sheet in the optimum and recrystallized conditions at different temperatures.

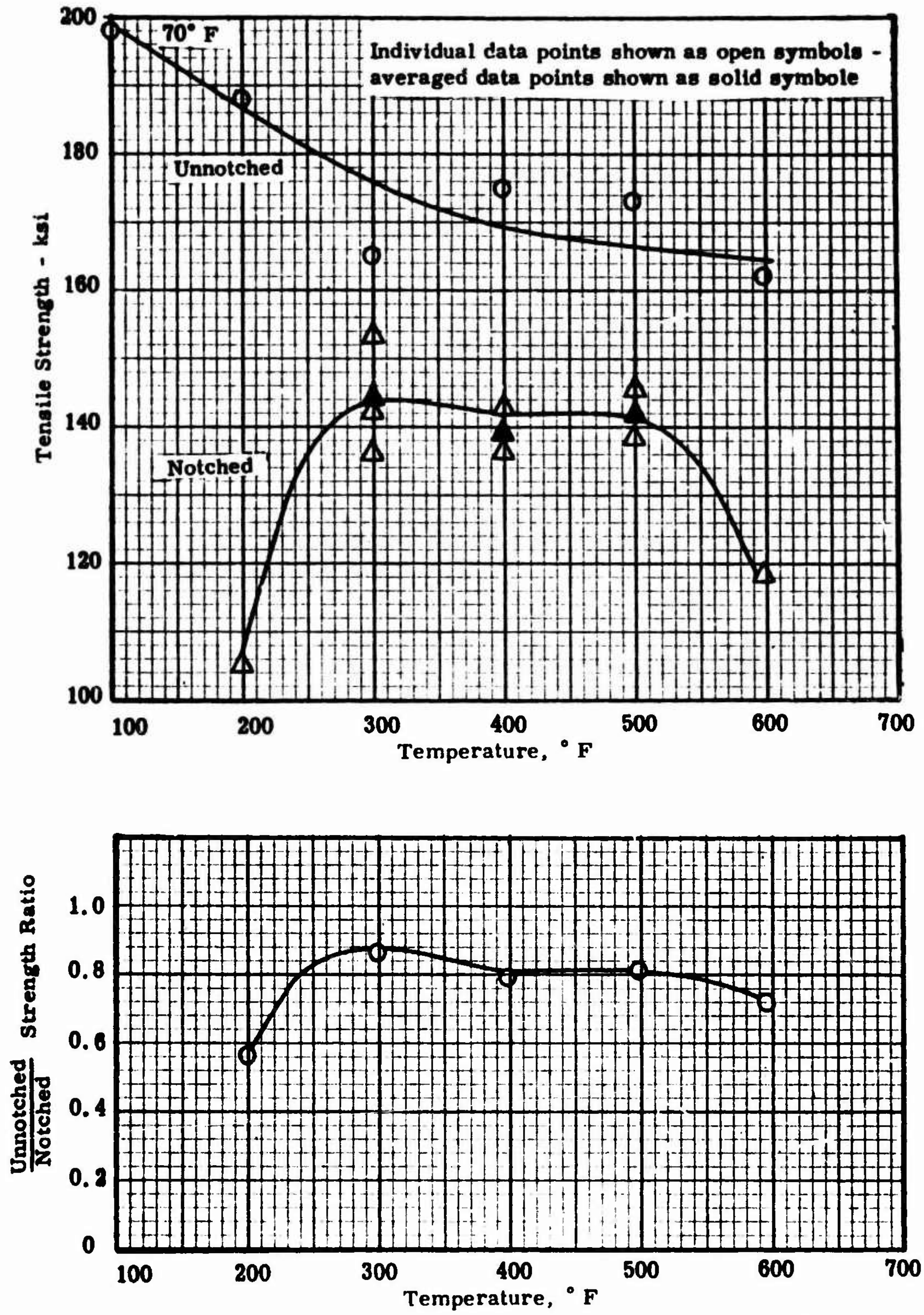


Figure 6 Notched- and unnotched-tensile strength (above) and notched-unnotched tensile strength ratio (below) at different temperatures for 0.060 in. tungsten sheet in the optimum condition

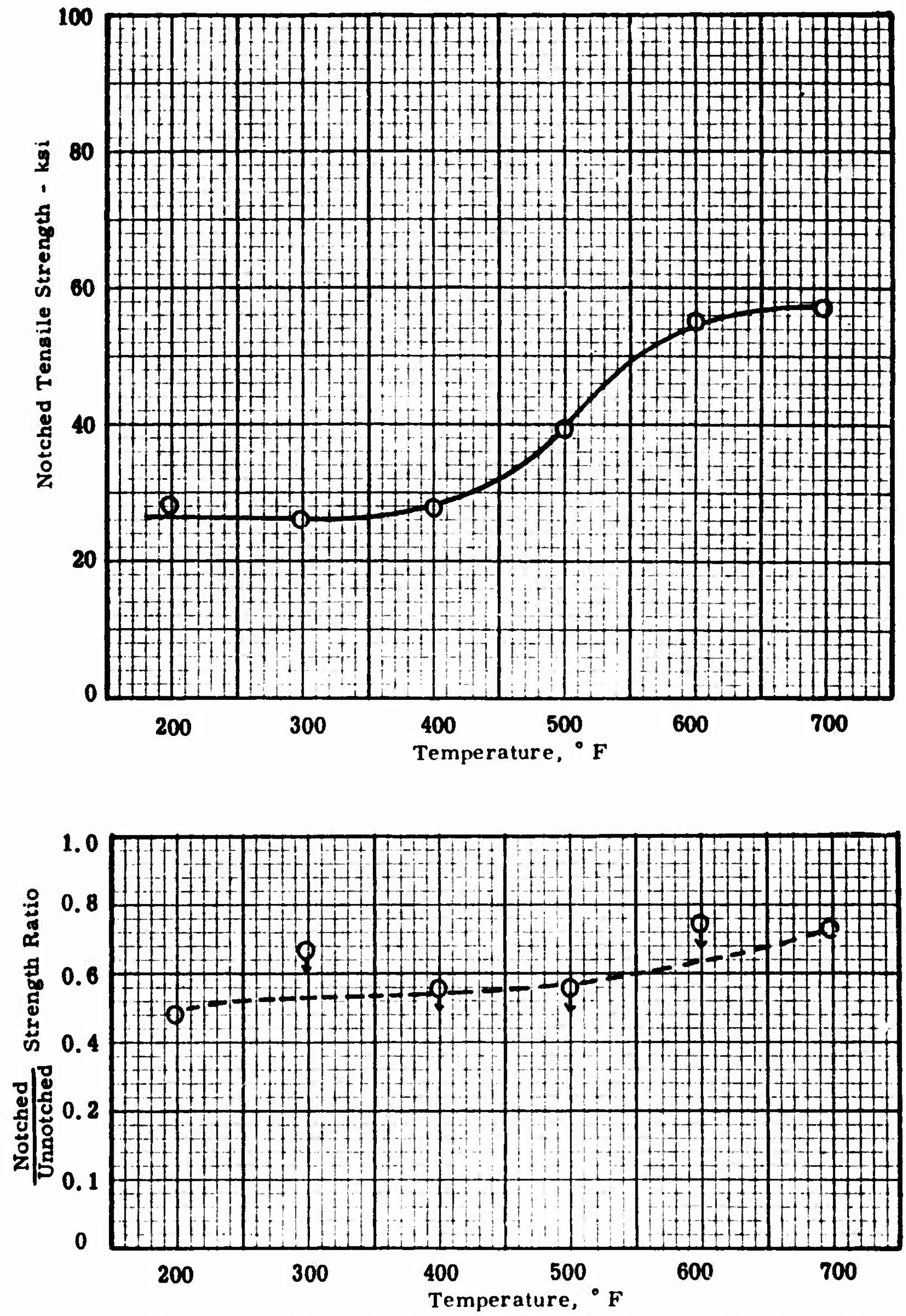


Figure 7 Notched tensile strength (above) and notched-unnotched tensile strength ratio (below) at different temperatures for 0.060 in. tungsten sheet in the recrystallized condition.

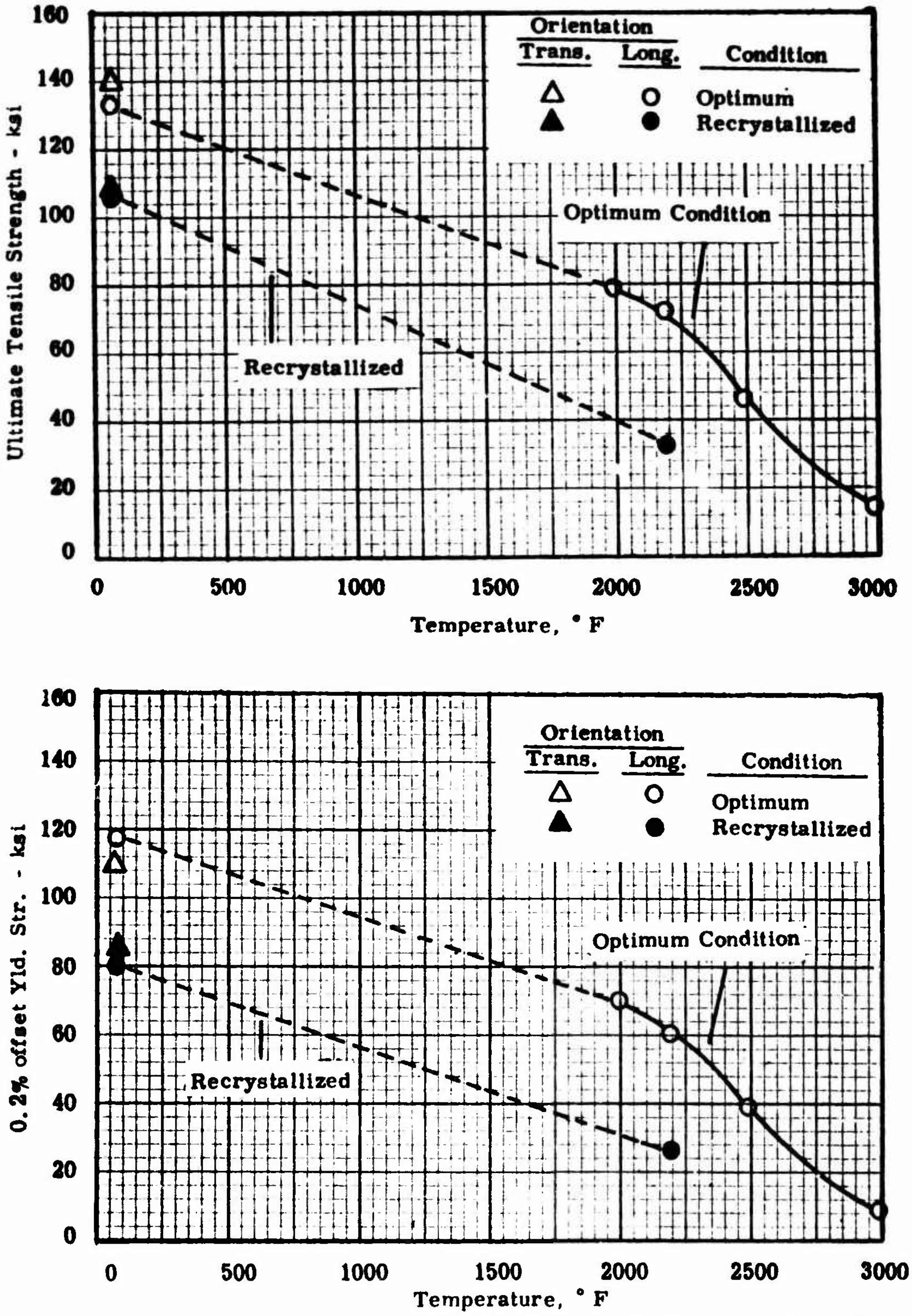
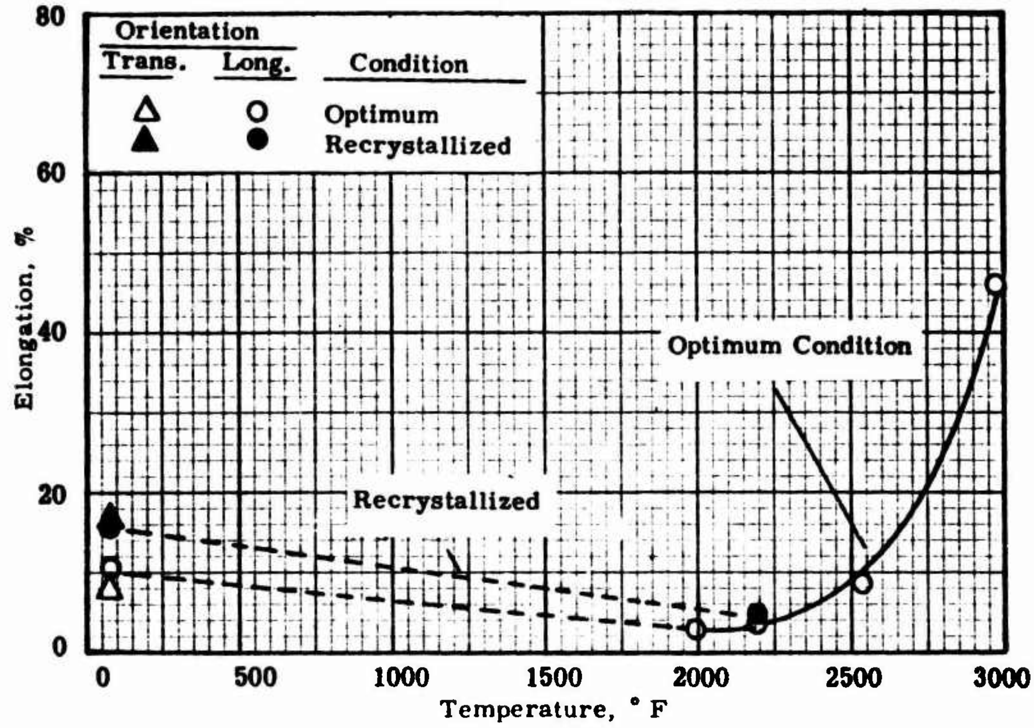


Figure 8 The ultimate-tensile (above) and 0.2% offset-yield (below) strengths of 0.020 in. TZM sheet in the optimum and recrystallized conditions at different temperatures.



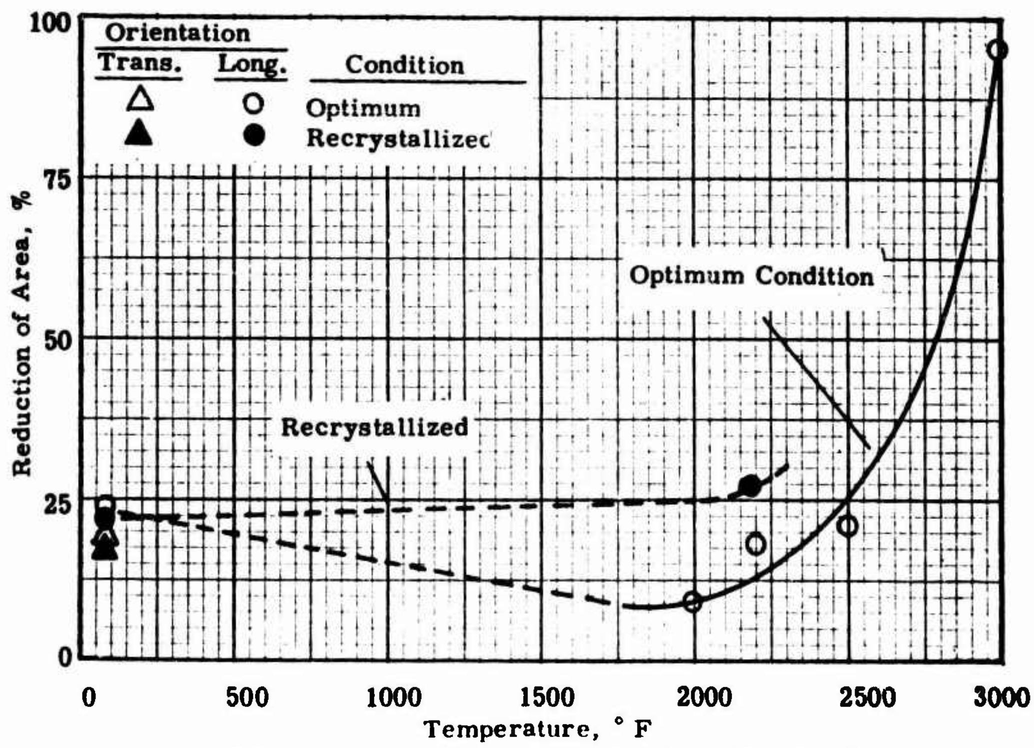


Figure 9 The percent elongation (above) and reduction of area (below) of 0.020 in. TZM sheet in the optimum and recrystallized conditions at different temperatures

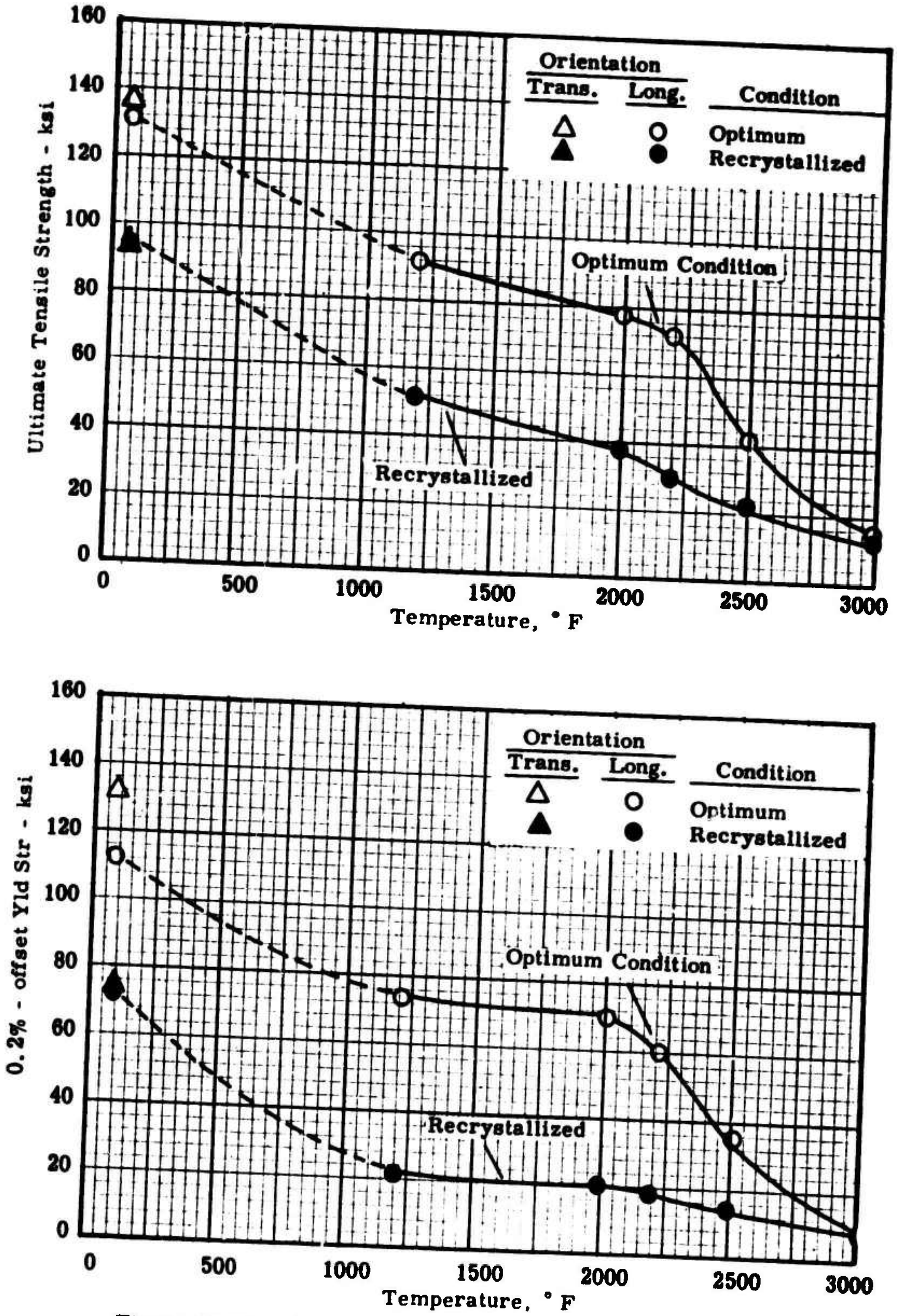


Figure 10 The ultimate-tensile (above) and 0.2%-offset-yield (below) strengths of 0.040 in. TZM Sheet in the optimum and recrystallized conditions at different temperatures.

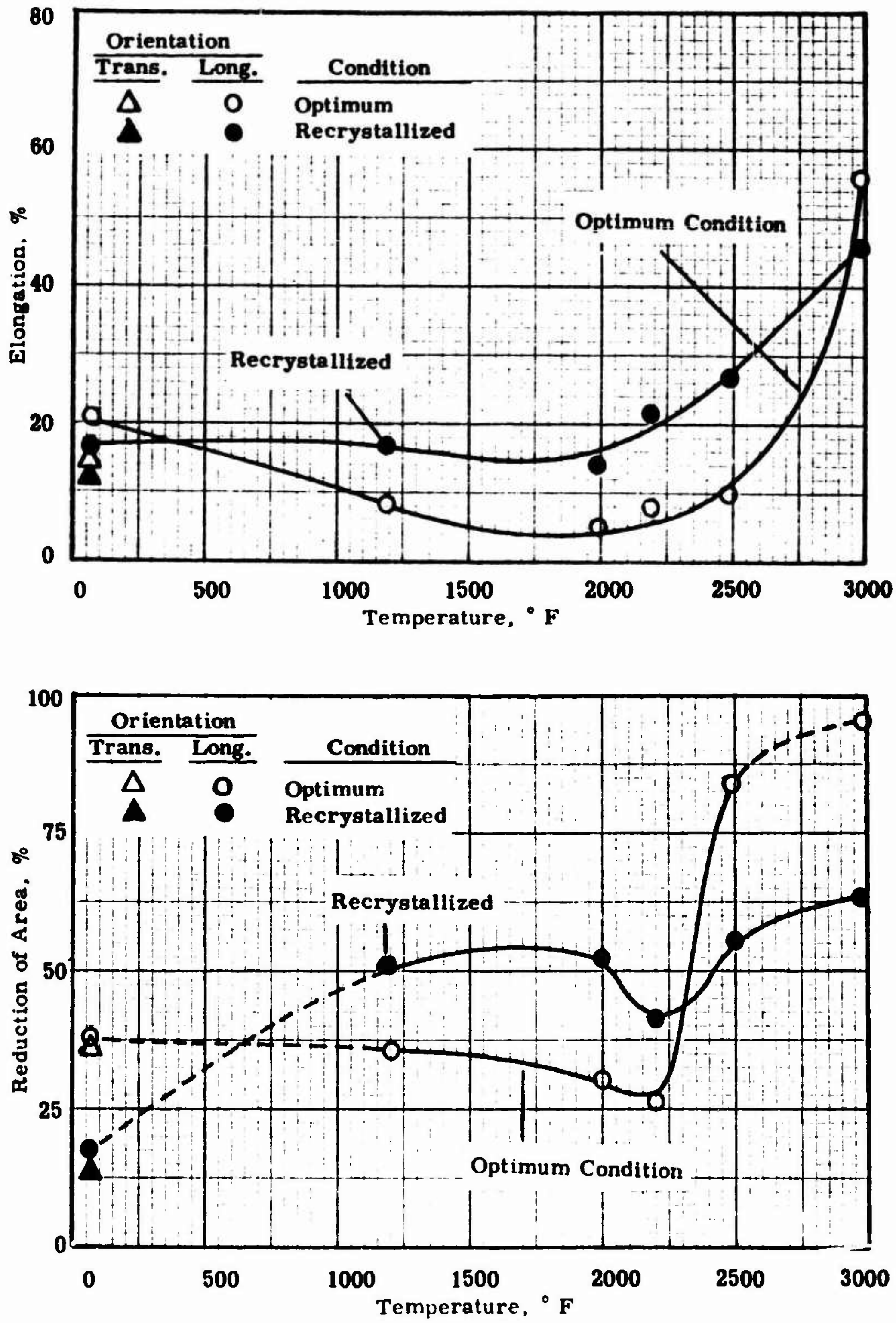


Figure 11 The percent elongation (above) and reduction of area (below) of 0.040 in. TZM sheet in the optimum and recrystallized conditions at different temperatures.

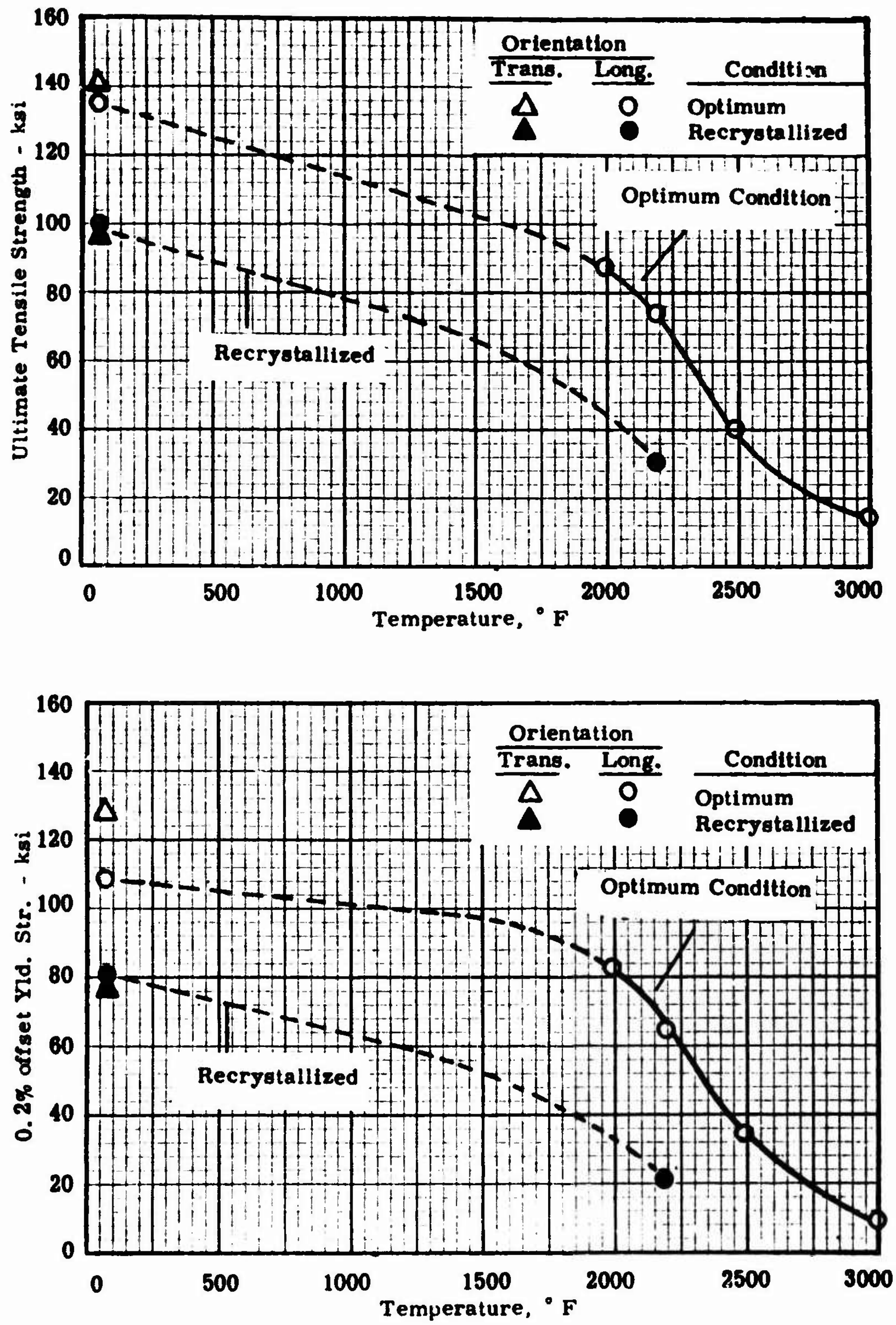


Figure 12 The ultimate tensile (above) and 0.2% offset-yield (below) strengths of 0.060 in. TZM sheet in the optimum and recrystallized conditions at different temperatures.

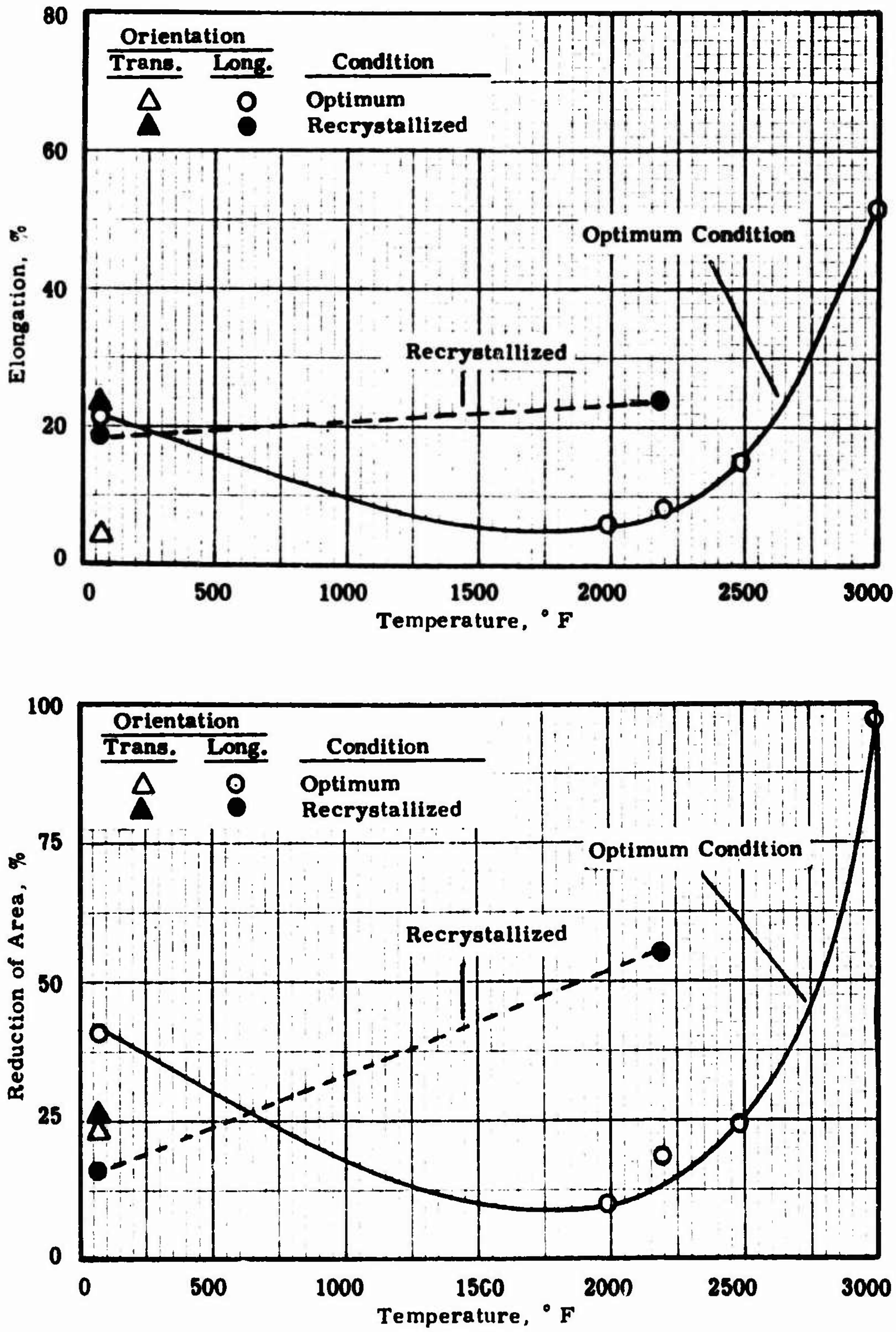


Figure 13 Percent elongation (above) and reduction of area (below) of 0.060 in. TZM sheet in the optimum and recrystallized conditions at different temperatures.

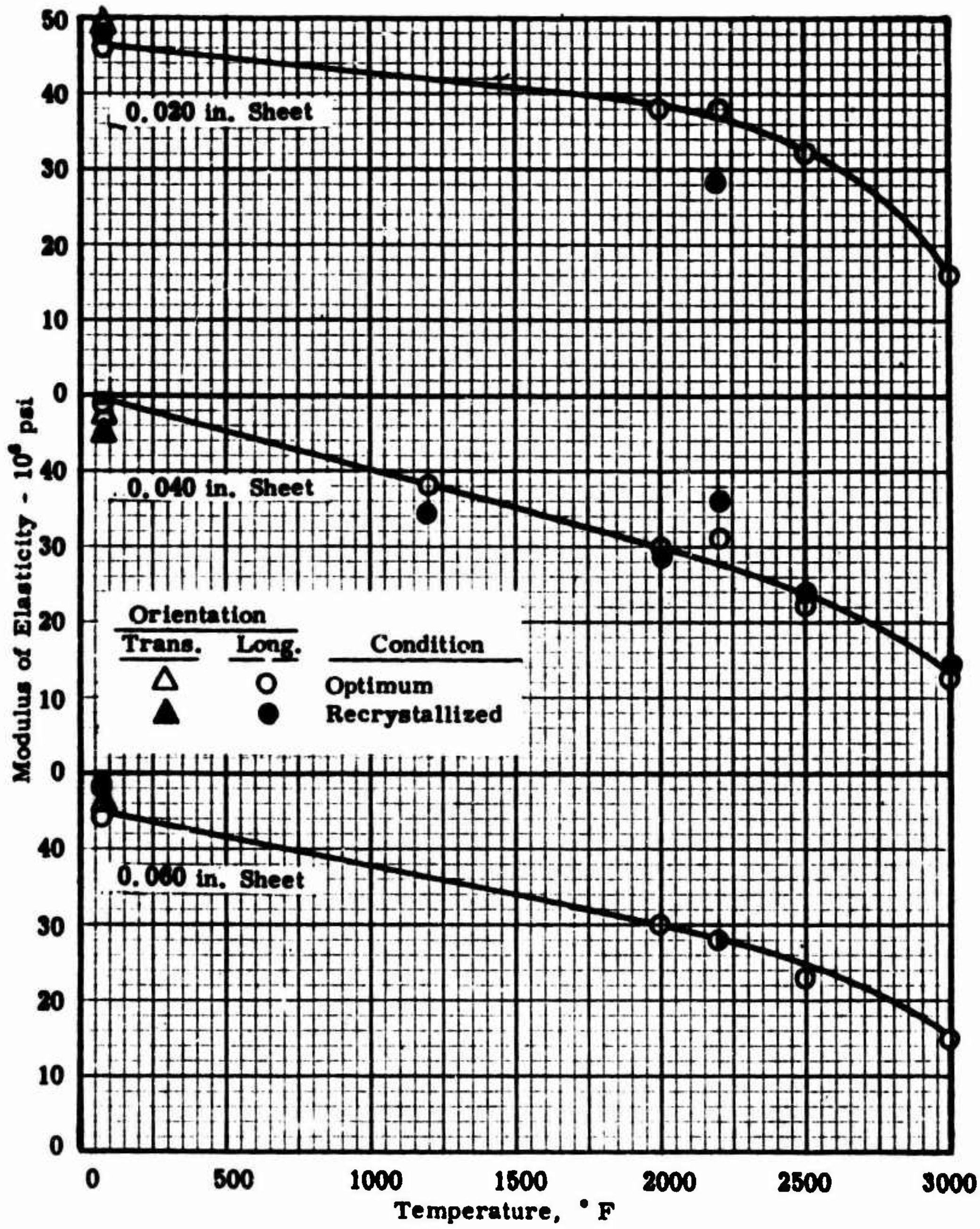


Figure 14 Modulus of elasticity of TZM Sheet in the optimum and recrystallized conditions at different temperatures.

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