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THE EFFECT OF NEUTRON IRRADIATION ON THE MECHANICAL PROPERTIES OF INCONEL 'X' AND INCONEL NICKEL-CHROMIUM ALLOYS

CRMet-870

by

C.R. Cupp

(International Nickel Company, Inc.)

Chalk River, Ontario

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ABSTRACT

Tensile specimens of Inconel "X" age-hardenable nickel-chromium alloy, and of Inconel nickel-chromium alloy, in several metallurgical conditions (solution heat treated, mill annealed, cold drawn 35%) were irradiated at 50°, 250°, and 300°C, with integrated fast neutron fluxes of 1.3×10^{20}, 3.1×10^{19} and 7.5×10^{19} n/cm^2 respectively.

Room-temperature tensile tests of specimens irradiated at 50°C showed that the proportional limit and yield strength of annealed structures were considerably increased, while the cold-drawn specimens were much less affected. There was a relatively small (10-20%) increase in the ultimate tensile strength of all specimens, accompanied by a 25-40% decrease in percent total elongation. Property changes in the specimens irradiated at higher temperatures were not as great and results indicate that saturation occurs after about 3.1×10^{19} n/cm^2.

A slight yield point was observed in irradiated annealed (or solution treated) Inconel "X" alloy. This was more marked in the cold-drawn condition and well-developed in cold-drawn Inconel alloy.

Recovery of mechanical property changes in annealed material irradiated at 50°C was not completed in one hour at temperatures below 600°C, at which temperature ageing had already started in unirradiated controls. While many metals show a marked recovery over a narrow temperature

range, recovery here started at 200° and continued gradually to 600°C. There was no evidence of ageing, during the post-irradiation anneals, in the irradiated specimens prior to that in the unirradiated controls.

Considerable recovery during irradiation at the elevated temperatures was suggested by the properties reaching constant values at fairly low flux levels.

There was no evidence to suggest radiation enhanced ageing under any test conditions.

There was no recovery of cold work in Inconel "X" alloy on irradiation at 250°C.

INTRODUCTION

As in other engineering fields there is an increasing demand in reactor technology for materials with higher mechanical properties. These improved properties may be obtained in metallic materials by putting them in a non-equilibrium condition such as, for instance, by heat treating through an allotropic transformation, by cold working, or by optimum precipitation-hardening. It is the latter mechanism with which this study is concerned. In age-hardenable alloys, the structural changes are diffusion controlled and may therefore be affected by neutron irradiation. With radiation-enhanced diffusion, it is possible that ageing would proceed at a lower-than-normal temperature.

For this study, Inconel "X" age-hardenable nickel-chromium alloy was chosen because of a parallel study on its precipitation mechanism by the International Nickel Company's Bayonne Laboratory and because of a possible future practical interest in reactor technology.

Inconel nickel-chromium alloy was used as a non-ageing control to measure the effect of neutron irradiation on the Inconel "X" matrix which has approximately the same composition and structure. The effect of radiation damage on the single-phase alloy could then be related to the measured strength of the age-hardening alloy. By this comparison it might be possible to determine the contribution of the precipitate particles to the strength of the alloy, and the effect of neutron irradiation on the precipitation mechanism.

EXPERIMENTAL PROCEDURE

(a) Material

All the Inconel "X" alloy used in this study was rolled from the same heat. The Inconel nickel-chromium alloy in the annealed and in the cold-drawn (35%) condition was prepared from two separate heats. All materials were provided by the Huntington Division of the International Nickel Company. The analysis of each alloy is shown in Table I.

The Inconel "X" age-hardenable nickel-chromium alloy was provided in three conditions:

(a) Mill annealed temper: Rods hot-rolled and ground, then annealed at 1093°C (2000°F) for 45 minutes and air-cooled.

(b) Solution treated temper: Rods hot-rolled and ground, then held at 1188°C (2100°F) for 2 hours and air-cooled.

(c) Cold-drawn: Rods hot-rolled and ground then cold drawn (approximately 35% reduction in area) and cleaned. These rods were 1/2 in. diameter, while those in (a) and (b) were 5/8 in. diameter.

The difference between "mill annealed temper" and "solution treated temper" requires some explanation although the subject is too complex to discuss adequately in a few paragraphs. Hot working of this alloy is usually carried out at temperatures starting at 1220°C (2225°F) and dropping to 1040°C (1900°F) or sometimes as low as 980°C (1800°F) during working. During ingot solidification there is some formation of massive particles such as nitrides and carbides. As described by Bieber and Raudebaugh[1], subsequent solution treatment for two to four hours at 1150°C (2100°F) dissolves any fine precipitate which has formed, coarsens the grain size of hot-worked Inconel "X" alloy and results in relatively clean boundaries and no visible precipitation within the grains on subsequent air cooling of a 5/8-in.-diameter bar. The massive particles are not taken into solution at 1150°C or even higher and hence do not contribute to age hardening, which results from subsequent treatments.

At temperatures of 2000°F, as used for mill annealing, the γ' phase which is responsible for hardening the Inconel "X" alloy is dissolved. The higher temperature (2100°F) used for solution heat treatment substantially improves the creep and rupture properties of the alloy in service over 1200°F.

Two types of Instron tensile test specimens were prepared as well as a limited number of standard (A.S.T.M. E-8) specimens. The Instron specimens used are shown in Figure 1. The specimens with the smaller diameter shoulder were developed as a means of increasing the number of specimens that could be irradiated within the same length of available irradiation space. It was found that a reduction of shoulder diameter had no significant effect on the test results for comparable unirradiated specimens.

For the sake of brevity, the five different materials used in this part of the work will be referred to hereafter by the following code letters. The code is also given in Appendix I, which may be opened out for reference.

Reference Code to Materials

Material	Code
Inconel "X" Age-Hardenable Nickel-Chromium Alloy	
Annealed Temper	X-A
Solution Treated Temper	X-ST
Cold Drawn	X-CD
Inconel Nickel-Chromium Alloy	
Annealed Temper	I-A
Cold Drawn	I-CD

(b) Irradiation History

The irradiation history of the specimens is shown in Table II. The specimens were irradiated in three types of transformer rod inserts:-

(a) The conventional transformer rod insert (T.R. Mark I) similar to that described by Cook and Cushing(2). The specimen temperature is about 50°C (122°F) and the specimen container is approximately 8 in. long and 0.425 in. diameter.

(b) A modification (T.R. Mark II) of the above rod, in which specimen temperature is 50°C (122°F) and the specimen container effectively 28 in. long with the same diameter as (a).

(c) The high-temperature fast-neutron rod (H.T.F.N.), a further modification, described in an A.E.C.L. report[3] in which irradiation of nickel-chromium specimens at 250°C (482°F) to 325°C (617°F) in air has been accomplished over a working length of 28 in. Unfortunately, it has been found that specimen temperatures in this facility are very difficult to control, due to changes in the reactor flux pattern.

In this work all neutrons above 500 eV are considered to be "fast" neutrons. The calculated fast-neutron flux in the transformer rods included 50% with the fission spectrum from the uranium sleeve surrounding the specimens and the remaining 50% with a normal E^{-1} spectrum from neighbouring rods. The significance of this in terms of defect production is discussed by Piercy[4]. The calculated flux is only accurate to within 30% of the true value.

(c) <u>Tensile Testing</u>

All tensile tests were performed at room temperature with an Instron Tensile Machine. The loading frame of the machine, mounted in a hot cell, was controlled remotely. The specimens were tested either as-irradiated, or after various vacuum-annealing heat treatments to a maximum of 700°C. The purpose of the post-irradiation annealing was to study recovery of irradiation damage, and the effect of irradiation on subsequent ageing. Wherever required, unirradiated control specimens were heat treated with their irradiated counterparts to ensure comparable thermal treatment. In a few cases, unirradiated specimens were annealed and tested outside the cave; however the same Instron machine except for the stressing frame was used throughout.

Elongation measurements were made simply by recording crosshead movement of the Instron machine. As discussed by Howe and Thomas[5], accurate measurements of elastic strain cannot be made by this method, but require the use of an independent extensometer. Using this procedure, the total elongation compares favourably with measured total elongation, but the uniform elongation is slightly in error.

Rockwell hardness tests were made on a standard machine, slightly modified to suit hot-cell manipulation.

Reduction-of-area measurements were made in one instance by using a 7-power binocular microscope to photograph the broken specimens. Later a commercial reduction-of-area gauge was modified for hot-cell use, but the handling of specimens and gauge proved too difficult so the broken specimens were measured on the ground-glass screen of the same binocular previously used for photography. The accuracy of these measurements proved to be so poor that they are not reported.

EXPERIMENTAL RESULTS

(a) Effect of Irradiation on the Room-Temperature Tensile Properties of Inconel "X" and Inconel Nickel-Chromium Alloys

Results of tests on specimens irradiated to approximately 1.3×10^{20} n/cm^2 at 50°C (122°F), and on unirradiated control specimens are summarized in Tables III and IV.

The properties of the irradiated solution-treated specimens are only affected slightly if at all by their position in the same insert.

Specimens irradiated in the Mark II rod at the same time as specimens in a Mark I insert, and in a nominally equal flux, showed slightly lower strength with lower percentage elongation.

Irradiation of the solution-treated material produced large increases (Table IV) in proportional limit and yield strength, with a small increase in the U.T.S. While the elongation decreased by about 40%, there was still 30% uniform elongation remaining. As indicated by the ratio of proportional limit to U.T.S., the rate of work hardening of the irradiated specimens was considerably reduced.

In Figure 2 typical nominal stress-elongation curves are shown for unirradiated and irradiated X-ST specimens as recorded by the Instron machine. The features described above are evident. There is a slightly tendency for a yield point to be developed by irradiation, but this was not marked in any of the tests.

The irradiated yield strength of X-ST (105 kips) was equal to or slightly exceeded that of normal fully-aged material (85 to 105 kips). The irradiated U.T.S. (120 kips) was only 10% above the unirradiated value, and still considerably below the 150-170 kips which would be expected for fully aged specimens. Similarly, the percent elongation (35%) is well above the 15-25% found in aged specimens. It would appear that under these conditions little or no ageing has been induced by irradiation.

Table III shows an anomaly in the X-A test results. Specimens irradiated at different times, but to approximately the same calculated integrated flux (1.2 and 1.3 x 10^{20} n/cm^2 respectively) in equivalent reactor positions, had marked differences in properties. A study of reactor loadings near the transformer rods, and of the output factors gave no explanation for even minor differences in properties.

The lower-strength X-A underwent a greater percentage strength increase than its solution-treated counterpart. However, the decrease of elongation for X-A samples was less than for X-ST. The nominal stress-elongation curves for X-A were similar in form to those shown in Figure 2 for solution-treated specimens.

The X-CD showed relatively little change in strength on irradiation at 50°C. The low uniform elongation after irradiation (Table III) leading to a large percent decrease

(Table IV) is due to the form of the nominal stress-elongation curves shown in Figure 3. While the unirradiated specimen elongates considerably as the load increases to a maximum, the irradiated specimen displayed a type of yield point beyond which there was a period of considerable plastic strain with no change in load. Since the uniform elongation was arbitrarily taken at the point of maximum load, it was quite low in this case. It is probable that true uniform elongation continued beyond the yield point to the point at which the steady load began to drop. In this case it would have been 14% instead of 4%, and the percentage decrease would have been 39% instead of 83%.

While some differences in response to irradiation are shown in Tables III and IV, the greatest difference between the cold-drawn alloys is shown by a comparison of Figures 3 and 4. The latter shows the marked yield phenomenon which developed after irradiation of the Inconel alloy. As with the unirradiated specimens, the elongation was relatively low compared with the X-CD.

Since the Instron machine is not able to record the elastic behaviour of the specimens accurately, the elastic moduli of the unirradiated specimens calculated from Figures 2-4 do not agree with published data. In a qualitative sense however it appears that while the elastic modulus of the solution-heat-treated Inconel "X" alloy was unaffected by irradiation

(Figure 2), the modulus of the I-CD was slightly increased (Figure 4) and that of the X-CD (Figure 3) considerably increased on irradiation. Quantitative measurements of this effect have not been made.

The strain-rate dependence of yield strength in irradiated austenitic stainless steels suggested looking for a similar dependence in solution-treated Inconel "X" alloy. It was found that, by increasing the strain rate of one or two solution-treated specimens from the standard 0.05 in./in./min. to 0.2 in./in./min. a slight rise in proportional limit, yield strength and percent elongation was induced with no effect on the ultimate strength. The hot-cell operation would not allow an even higher strain rate to be used.

(b) Effect of Irradiation at Approximately 300°C (572°F) on the Room-Temperature Tensile Properties of Nickel-Chromium Alloys

Results of tests on specimens irradiated at approximately 300°C (572°F) and unirradiated control specimens are summarized in Tables V and VI. As noted previously, the temperature control in the H.T.F.N. transformer rod allowed rather wide variations. Charts for the shorter irradiation (3.1×10^{19} n/cm^2) showed a range from 235°-275°C (455°-527°F) and for the longer irradiation (7.5×10^{19} n/cm^2) from 275°-315°C (527°-599°F). The median values were taken as 250°C (482°F) and 300°C (572°F) respectively.

The irradiation damage at elevated temperatures appears to be lower than that at 50°C, (cf Tables III and V). This is due both to higher irradiation temperature and to lower integrated flux. Present data are not sufficient to separate these two effects.

Figures 5 and 6 indicate a saturation of radiation damage at elevated temperatures at quite a low integrated flux for both mill-annealed and solution-treated tempers.

The elongation of all specimens was affected relatively little by elevated temperature irradiation. While the increased strength of the solution-treated specimens was accompanied by a decreased elongation, the mill-annealed specimens displayed no change in ductility after 3.1×10^{19} n/cm^2. In both cases, the higher temperature associated with the longer of the two irradiations has reduced the effect of irradiation on the proportional limit and yield strength, with little effect on the increase of U.T.S. With the mill-annealed specimens, the higher temperature of irradiation actually caused an increase in percent elongation.

The property changes shown in Table VI were based on the properties of the <u>as-received</u> material. Table VII shows the properties of the material: as-received; as-irradiated for 27 days at a nominal temperature of 250°C to an integrated flux of 3.1×10^{19} n/cm^2; and after ageing (unirradiated) for 27 days at 270°C. Thus, the effect of irradiation is partly separated from thermal effects.

Low-temperature (250°-300°C) ageing would have been expected to have little effect on these materials, and this was generally the case. All properties of the X-ST specimens appeared to be slightly lower after extended ageing at 250°C, while those of the mill-annealed specimens were somewhat higher. The differences were not significant. The properties of the annealed Inconel alloy were unchanged. In all cases therefore, the strength increases on elevated-temperature irradiation are not attributable to thermal effects. The X-CD was affected little either, apart from a slight reduction of yield strength,by ageing alone or with irradiation.

(c) Recovery of Irradiation Damage in Specimens Irradiated at 50°C

Following irradiation, recovery of the damage was studied by annealing specimens for periods of one hour or ten hours at various temperatures in a vacuum of 1-2 microns, followed by air cooling and testing. Unirradiated specimens were usually annealed and tested at the same time. It was noted that, under the low air pressure at which this annealing was done, the unirradiated specimens developed a metallic blue tarnish while the irradiated specimens retained their pre-annealed appearance. This effect was only noted near the completion of the test program, so does not apply to all specimens tested. It would appear that an adherent, transparent, colourless oxide film had developed on the specimens during irradiation, so they were not subject to subsequent oxidation and tarnishing during the post-irradiation anneals, as were the unirradiated specimens.

Figure 7 shows the legend which applies to all graphs in the group on recovery. The recovery data are shown in Figures 8 - 14.

Figures 8 and 9 show the recovery of X-ST after post-irradiation annealing. The U.T.S. appears to recover fully after 1 hour at 400°C , at which temperature it does not matter whether the specimen is annealed for 1 or for 10 hours. At 600°C and 700°C, the tensile strengths of the irradiated specimens are slightly lower than those of the unirradiated controls even though marked ageing is evident.

Yield strength and hardness properties are not restored to normal values by one-hour anneals at temperatures below 600°C. There appears to be no difference, with respect to yield strength and hardness, between 1 and 10 hour anneals at 400°C, while at 600°C ageing is well advanced in 10 hours and just started in 1 hour. Unlike the U.T.S. results (after annealing at 600°C or 700°C) the yield strength and hardness of the irradiated specimens was equal to or slightly greater than the unirradiated specimens.

The effect of post-irradiation annealing on the elongation of solution-treated specimens follows the same trend as the strength properties (Figure 9). There is a marked spread, after annealing at 400°C between specimens irradiated in the Mark I rod and those from the Mark II rod. While the unirradiated specimens showed a considerable difference between one-and ten-hour anneals at 400° and 600°C, the irradiated specimens showed little variation with time of anneal. Though the strength of both irradiated and unirradiated specimens were approximately equal after one-hour anneals at 600° and 700°C, the elongation of the irradiated specimens was, at 600° and 700°C, 14% and 25% respectively, less than the unirradiated specimens.

The effect of post-irradiation annealing on X-A is shown in Figures 10 and 11. By annealing at 50C° intervals, it was shown that there is no sharp change in the properties between the 200°C and the 300°C anneal. The yield strength of mill-annealed specimens, annealed after irradiation, follows much the same pattern as that of the solution-treated specimens in which ageing appears to start slightly before irradiation damage is fully annealed out. The total elongation of the mill-annealed material (irradiated to 1.2×10^{20} n/cm^2) is fully recovered after 1 hour at 500°C. Up to 300°C, the material irradiated to 1.3×10^{20} n/cm^2 shows no tendency to a faster recovery of U.T.S. or percent elongation on annealing, though the recovery of yield stress in the same specimens appears to be more rapid than that of the specimens irradiated to 1.2×10^{20} n/cm^2.

The limited recovery data shown in Figure 12 for X-CD indicate that all properties were practically fully recovered after a one-hour anneal at 400°C.

As shown in Figure 13, the same was not true of I-CD where, despite rise in both U.T.S. and yield strength of unirradiated control specimens annealed at 200° and 400°C, these values after a one-hour anneal were still well below those for irradiated specimens similarly annealed. By annealing for 10 hours at 600°C, irradiated specimens were brought to the same conditions as their unirradiated controls.

Figure 14 shows that the elongation of cold-drawn Inconel alloy was only slightly affected by irradiation.

(d) Recovery of Specimens Irradiated at 300°C

The strength of X-ST irradiated at 250°C and 300°C and subsequently annealed at 400°C is shown in Figure 15. Points are also shown for an unirradiated specimen annealed 10 hours at 400°C. The solid lines are the recovery curves for specimens irradiated at 50°C to 1.3 x 10^{20} n/cm^2, and subsequently annealed (see Figure 8). Corresponding elongation curves are shown in Figure 16.

The mill-annealed specimens (Figure 17) showed strength effects similar to the solution-treated specimens. In all cases (Figure 18) the elongation of the X-A specimens was considerably higher than the X-ST specimens.

Figure 19 shows the recovery curves for I-A irradiated at 300°C. Unlike Figures 15-18, the curves drawn are for the points shown, and are not transposed from other figures for recovery of samples irradiated at 50°C and subsequently annealed. Full recovery of the yield strength does not occur even with a 10-hour anneal at 600°C, but is complete after one hour at 700°C. Despite the effect of elevated-temperature irradiation on the strength of Inconel alloy, there is no reduction in the percent elongation. As shown in Figure 20, various annealing treatments on specimens both irradiated and unirradiated produce essentially comparable results.

While X-CD irradiated at 50°C (1.3×10^{20} n/cm^2) appeared to recover its unirradiated properties (Figure 12) at about 400°C, the properties of the same material, irradiated at 250°C (3.1×10^{19} n/cm^2) were not significantly affected, as shown in Figure 21. The points for yield strength and elongation agree with values for unirradiated specimens.

DISCUSSION

The general pattern of irradiation damage at 50°C to the four types of specimens was similar to that found in most metal systems. It involved large increases in the proportional limit and yield strength of the annealed (X-ST and X-A) structures, with much smaller increases in these properties in the cold-drawn specimens. Relatively small (10-20%) increases in the ultimate tensile strength were found for all types. Although there was a considerable reduction in elongation in all cases (ranging from a 25-40% decrease in percent total elongation) the remaining ductility as expressed by percentage elongation was quite high. The flow curve of the irradiated specimens after yielding exhibits a region of lower work hardening than the unirradiated material. This is shown by the reduced uniform elongation and the increased ratio of proportional limit to ultimate tensile strength.

The shapes of stress-strain curves are often remarkably altered by neutron irradiation. With the changes mentioned above, there was also a slight development of a yield point in annealed Inconel "X" alloy. This yield point was more marked in X-CD, and well-developed in I-CD. This effect has been observed in several other materials including austenitic stainless steels. The curves (Figures 2-4) show the slow descent of the stress-strain curve from the upper yield point (compared with the sharp breakaway in unirradiated normalized carbon steel). This effect suggests that a delay time is required either for dislocation breakaway or for dislocation motion after breaking away.

For irradiated austenitic stainless steels it has also been shown that the yield stress is strongly strain rate dependent[6] although this is not the case in the same alloys unirradiated. Within the limit of strain-rate variation (4-fold) that could be made in the present tests, there did not appear to be a significant increase in yield stress with increased strain rate for solution-treated Inconel "X" alloy specimens irradiated at 50°C or for annealed Inconel alloy irradiated at 300°C.

Due to inadequate control, it was not possible to repeat elevated-temperature irradiations at identical temperatures. Nevertheless the data indicate saturation of radiation damage at low integrated fluxes.

Increased ductility after irradiation has been noted previously in two cold-worked aluminum alloys[7] and in two age-hardenable nickel alloys irradiated at 540°F[8]. At both 250°C and 300°C, it has now been found that Inconel "X" alloy both cold-drawn and annealed, and annealed Inconel alloy also show slight (up to 11%) increases in percent total elongation.

In most cases it was found that ageing unirradiated control specimens for times and at temperatures comparable to those used for irradiation resulted in very little change of the mechanical properties. Thus, the changes which occurred under irradiation could be divorced from thermal effects.

The recovery curves for material irradiated at 50°C showed that recovery of annealed structures was not completed in one hour at temperatures below 600°C, at which time ageing had already started in unirradiated controls. Thus the mechanism for the radiation damage recovery appears to involve high activation energies. While many metals show a marked recovery over a fairly narrow temperature range, recovery here started at 200°C and continued gradually to 600°C. There is no evidence of ageing, during the post-irradiation anneal, in the irradiated specimens prior to that in unirradiated controls.

Because the integrated fluxes attained with elevated-temperature irradiations did not reach those of irradiations at 50°C, it is not certain whether there was considerable recovery of radiation damage at the elevated temperatures. However, the fact that damage appears to reach saturation at fairly low fluxes suggests considerable damage recovery at the higher temperatures.

Although the data are not sufficiently complete, there is no evidence to suggest radiation-enhanced ageing either of specimens irradiated at higher temperatures and tested as-irradiated or after annealing.

In addition to the absence of ageing under irradiation, there appeared to be no recovery of cold work in Inconel "X" alloy on irradiation at 250°C. The properties after irradiation were almost exactly those of unirradiated specimens.

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TABLE I

ANALYSES

Element	Inconel "X" Alloy %	Inconel Alloy I-A %	Inconel Alloy I-CD %
C	0.04	0.03	0.04
Mn	0.50	0.22	0.19
Fe	6.65	7.38	7.11
S	0.007	0.007	0.007
Si	0.28	0.23	0.23
Cu	0.09	0.10	0.04
Cr	15.30	15.78	15.91
Al	0.70	0.15	0.12
Ti	2.32	0.31	0.31
Cb	0.63	-	-
Ta	0.23	-	-
Co	0.08	0.14	0.11
Ni	Remainder	Remainder	Remainder

TABLE II

IRRADIATION HISTORY

Material: Condition	Material: Test Series	Irradiation Period	Reactor Position	Trans-former Insert	Reactor Output MWD	Calculated Integrated Fast Flux over 500 eV n/cm^2
X-A	(9-22)	9-7-58 to 28-9-58	M-16	Mk.I	1820.8	1.2×10^{20}
X-ST	(238-248)	2-10-58 to 12-12-58	M-16	Mk.I	2007.7	1.3×10^{20}
X-ST, X-A, X-CD, I-CD	(201-219)	2-10-58 to 10-12-58	H-10	Mk.II	2007.7	1.3×10^{20}
X-ST, X-A, X-CD	(249-259)	2-10-58 to 8-10-58	S-15	HTFN	204.4	
		8-10-58 to 29-10-58	R-20	HTFN	571.4	3.1×10^{19}
X-ST, X-A, I-A	(220-235)	31-10-58 to 6-1-59	R-20	HTFN	1813.0	7.4×10^{19}

TABLE III

ROOM TEMPERATURE PROPERTIES OF IRRADIATED (50°C) AND UNIRRADIATED NICKEL-CHROMIUM ALLOYS

Material		Irradiation History (n/cm^2)	Hardness RB	Prop. Limit (kips)	0.2% Offset Y.S. (kips)	U.T.S. (kips)	% Elongation Total	% Elongation Uniform	PL/UTS
Inconel "X" Alloy	X-ST	Unirradiated	78	47.8	53.0	109.8	56	52	.44
		1.3×10^{20} (a)	94.5	99.5	104.5	121.4	37	31	.82
		" (b)	91.5	102.0	107.0	122.4	34	29	.84
		" (c)	93.0	103.5	108.5	122.4	36	31	.85
		" (d)	-	97.0	102.0	118.4	32	28	.82
	X-A	Unirradiated	70	32.8	40.2	98.2	63	55	.33
		1.2×10^{20}	-	67.8	75.4	104.0	52	44	.65
		1.3×10^{20} (d)	89.5	90.5	93.5	117.4	46	37	.77
	X-CD	Unirradiated	90	116.9	121.9	138.0	33	23	.85
		1.3×10^{20} (e)	-	144.3	149.3	152.2	21	4★	.95
		" (d)	104	145.8	150.7	153.2	22	4★	.95
Inconel Alloy	I-CD	Unirradiated	98	129.3	138.3	142.3	12	6	.91
		1.3×10^{20} (e)	-	166.7	170.6	170.6	9	4	.98
		" (d)	104	164.2	169.2	169.2	9	4	.97

(a) Irradiated near bottom of Mk-I rod
(b) " " centre " " "
(c) " " " " " " - tested at strain rate of 0.2 in./in./min.
(d) " " " " Mk-II rod
(e) " " bottom " " "
★ Taken at yield point. See text for discussion of this value. 14% would probably be more correct figure.

TABLE IV

CHANGES IN ROOM-TEMPERATURE PROPERTIES OF NICKEL-CHROMIUM ALLOYS DUE TO IRRADIATION AT 50°F (122°F) TO 1.3 x 10^{20} n/cm^2

Material		% Increase			% Decrease, % Elongation	
		Prop. Limit	Y.S.	U.T.S.	Total	Uniform
Inconel "X" Alloy	X-ST	103-117	93-105	8-12	34-43	40-46
	X-A	176	133	20	27	33
	X-CD	25	24	11	36	83*
Inconel Alloy	I-CD	29	23	20	25	33

* See text for discussion of this value.

TABLE V

ROOM-TEMPERATURE PROPERTIES OF NICKEL-CHROMIUM ALLOYS IRRADIATED AT ELEVATED TEMPERATURES

Material		Irradiation History (n/cm^2)		Hardness RB	Prop. Limit (kips)	0.2% Offset Y.S. (kips)	U.T.S. (kips)	% Elongation Total	% Elongation Uniform	PL/UTS
Inconel "X" Alloy	X-ST	Unirradiated✰		78	47.8	53.0	109.8	56	52	0.44
		$3.1x10^{19}$	(a)	87.5	71.1	76.1	116.9	54	49	0.61
		"	(b)	86	72.1	77.1	114.4	44	41	0.63
		$7.5x10^{19}$	(c)	-	71.1	76.1	116.9	50	46	0.61
		"	(d)	86.5	66.2	71.1	115.4	47	43	0.57
	X-A	Unirradiated		70	32.8	40.2	98.2	63	55	0.33
		$3.1x10^{19}$	(a)	78	61.2	66.2	110.4	63	53	0.55
		"	(c)	82	59.7	64.7	110.0	65	56	0.54
		$7.5x10^{19}$	(a)	74.5	54.7	59.7	111.9	70	61	0.49
		"	(b)	78	54.7	59.7	111.9	69	58	0.49
	X-CD	Unirradiated		90	116.9	121.9	138.0	33	23	0.85
		$3.1x10^{19}$	(b)	100	111.9	116.9	146.8	32	26	0.76
		"	(c)	102	112.9	117.9	146.8	33	25	0.77
Inconel Alloy	I-A	Unirradiated		56	31.3	36.3	90.5	53	42	0.35
		$7.5x10^{19}$	(b)	72	49.8	54.7	99.5	59	47	0.50
		"	(c)	75	46.3	50.7	98.5	54	45	0.47
		"	(d)	-	49.8	53.7	99.5	53	43	0.50

Code: (a) Irradiated near bottom of H.T.F.N. rod
(b) " " centre " " "
(c) " " top " " "
(d) " " " " " " - tested at strain rate of 0.2 in./in./min.

Note: The shorter irradiation was at 250°C (482°F) and the longer at 300°C (572°F).
✰ The unirradiated specimens were as received with no further heat treatment.

TABLE VI

CHANGES IN ROOM-TEMPERATURE PROPERTIES OF NICKEL-CHROMIUM ALLOYS IRRADIATED AT ELEVATED TEMPERATURES

Material	Irrad. History Integrated Flux $x10^{19}$ n/cm^2	Prop. Limit	Y.S.	U.T.S.	% Elongation Total	% Elongation Uniform
		% Increase ☆			% Decrease ☆	
X-ST	3.1	50	45	5	13	13
	7.5	43	39	6	12	13
X-A	3.1	84	63	12	- 2	0
	7.5	67	48	14	-11	- 9
X-CD	3.1	- 4	- 4	6	0	- 9
I-A	7.5	50	45	9	- 8	-10

☆ Changes shown are relative to as received material. See Table V.

TABLE VII

ROOM-TEMPERATURE PROPERTIES OF NICKEL-CHROMIUM ALLOYS AGED AT ABOUT 250°C FOR 27 DAYS, WITH AND WITHOUT IRRADIATION

Material	Condition	Prop. Limit (kips)	Yield Strength (kips)	U.T.S. (kips)	% Elongation Total	% Elongation Uniform
X-ST	As received	47.8	53.0	109.8	56	52
	Unirradiated(Aged)	45.0	50.0	106.7	53	50
	Irradiated(Aged)	71.6	76.6	115.7	49	45
X-A	As received	32.8	40.2	98.2	63	55
	Unirradiated(Aged)	37.3	40.7	99.0	66	62
	Irradiated(Aged)	60.5	65.5	110.2	64	55
X-CD	As received	116.9	121.9	138.0	33	23
	Unirradiated(Aged)	109.5	114.4	141.0	33	24
	Irradiated(Aged)	112.4	117.4	146.8	33	25
I-A	As received	31.3	36.3	90.5	53	42
	Unirradiated(Aged)	31.1	34.0	90.0	60	49
	Irradiated* (Aged)	47.0	52.7	99.0	57	46

* Irradiated to 7.5×10^{19} n/cm^2 at 300°C for 67 days.
All others irradiated to 3.1×10^{19} n/cm^2.

As received values are as shown on Table III except for I-A which is first reported here. Unirradiated (Aged) values are average of two or more.

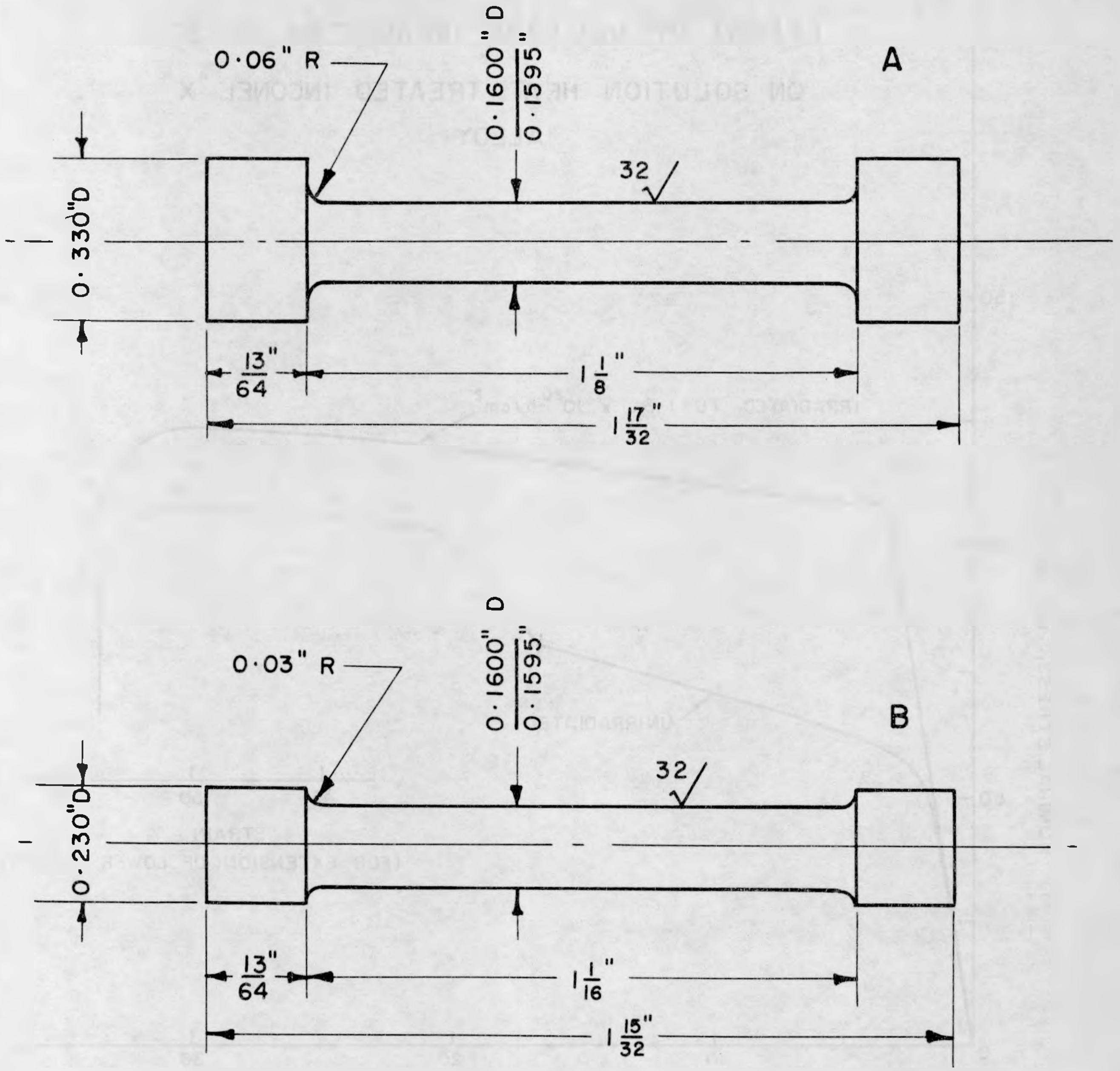

FIGURE 1

INSTRON TENSILE TEST SPECIMENS

GAUGE LENGTH 1" IN EACH CASE

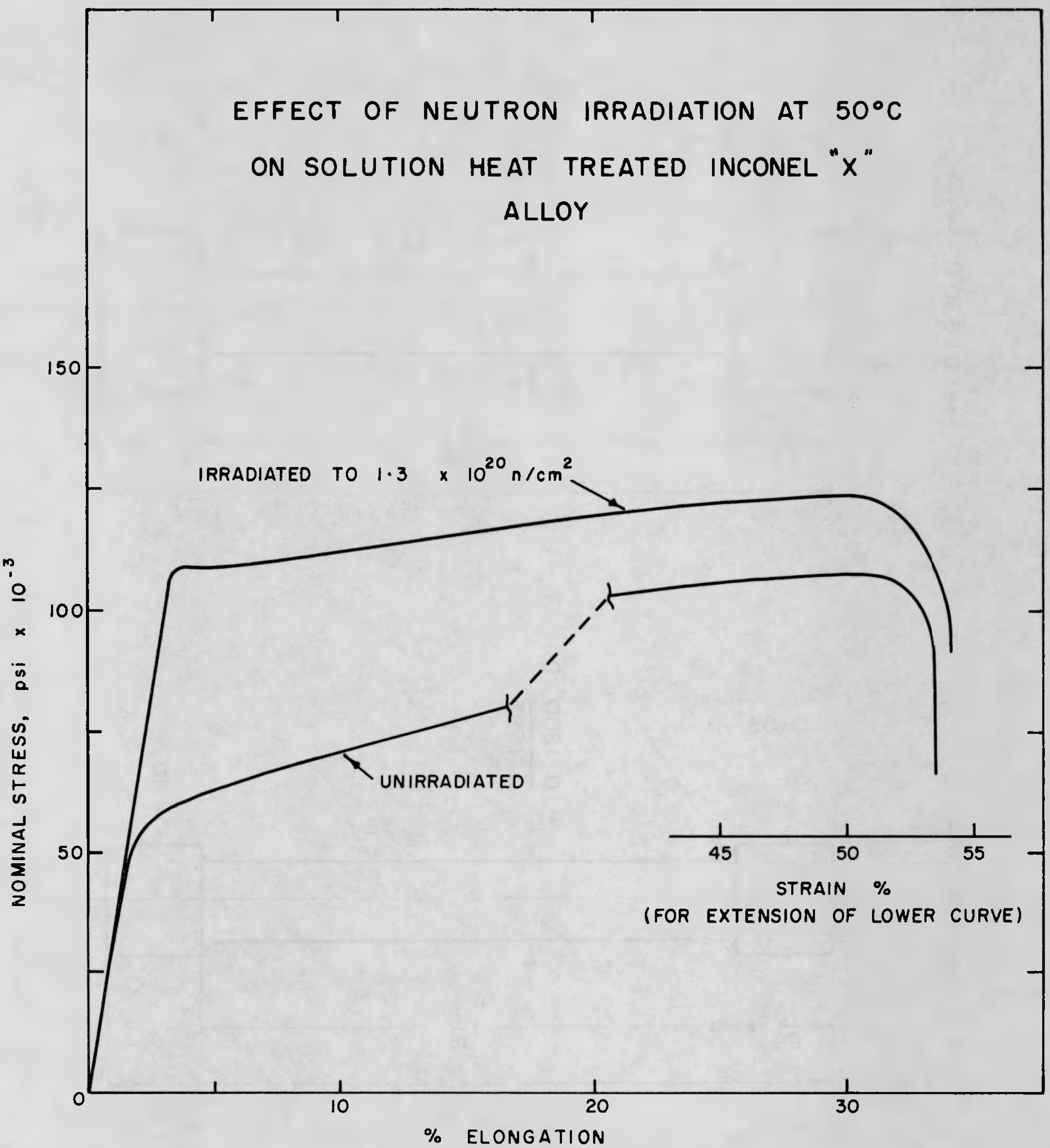
EFFECT OF NEUTRON IRRADIATION AT 50°C
ON SOLUTION HEAT TREATED INCONEL "X"
ALLOY
IRRADIATED TO 1·3 x 10^20 n/cm^2
UNIRRADIATED
NOMINAL STRESS, psi x 10^-3
150
100
50
0
10
20
30
% ELONGATION
45
50
55
STRAIN %
(FOR EXTENSION OF LOWER CURVE)

FIGURE 2

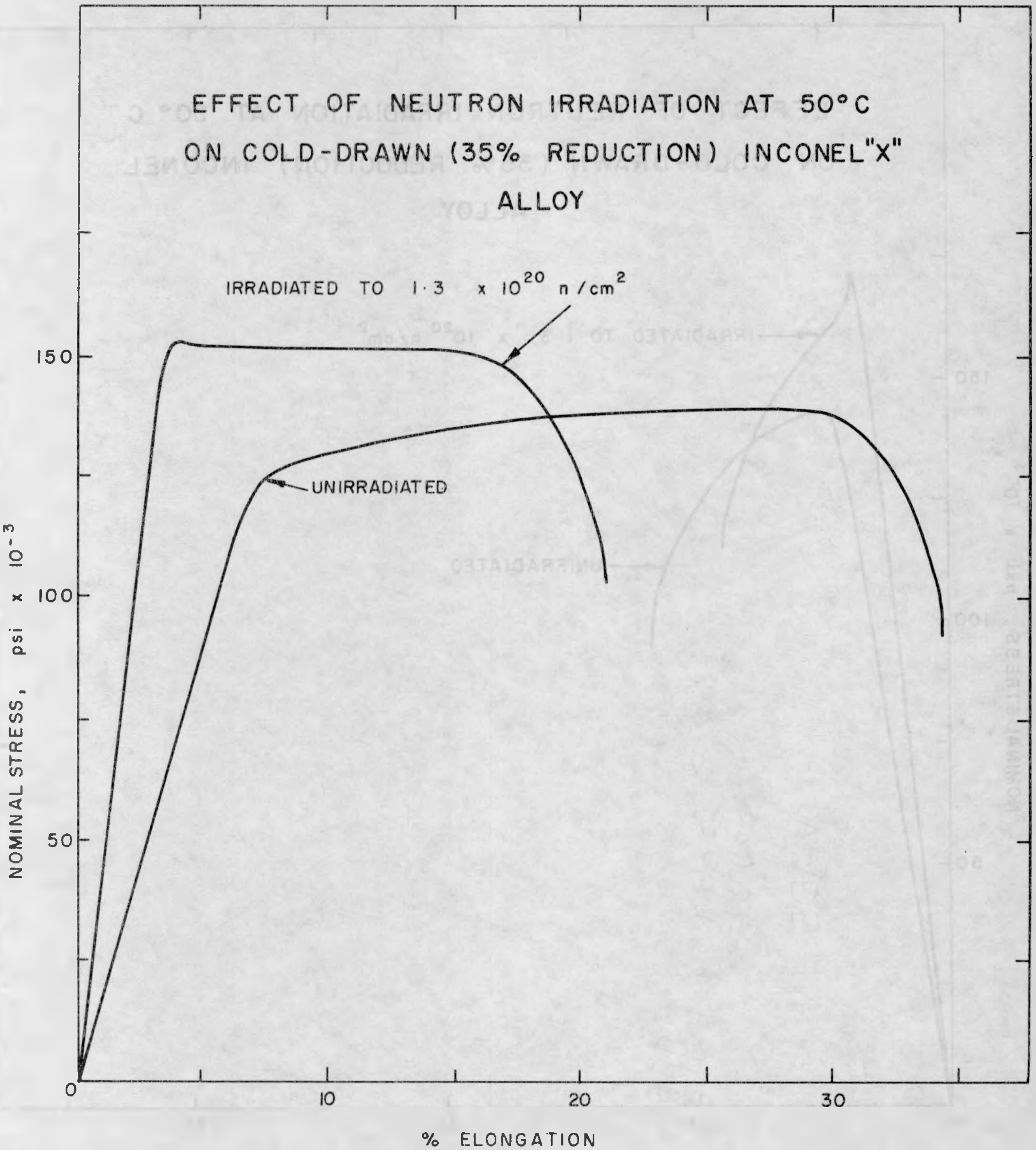
EFFECT OF NEUTRON IRRADIATION AT 50°C
ON COLD-DRAWN (35% REDUCTION) INCONEL"X"
ALLOY
IRRADIATED TO 1·3 x 10^20 n/cm^2
UNIRRADIATED
150
100
50
0
10
20
30
NOMINAL STRESS, psi x 10^-3
% ELONGATION

FIGURE 3

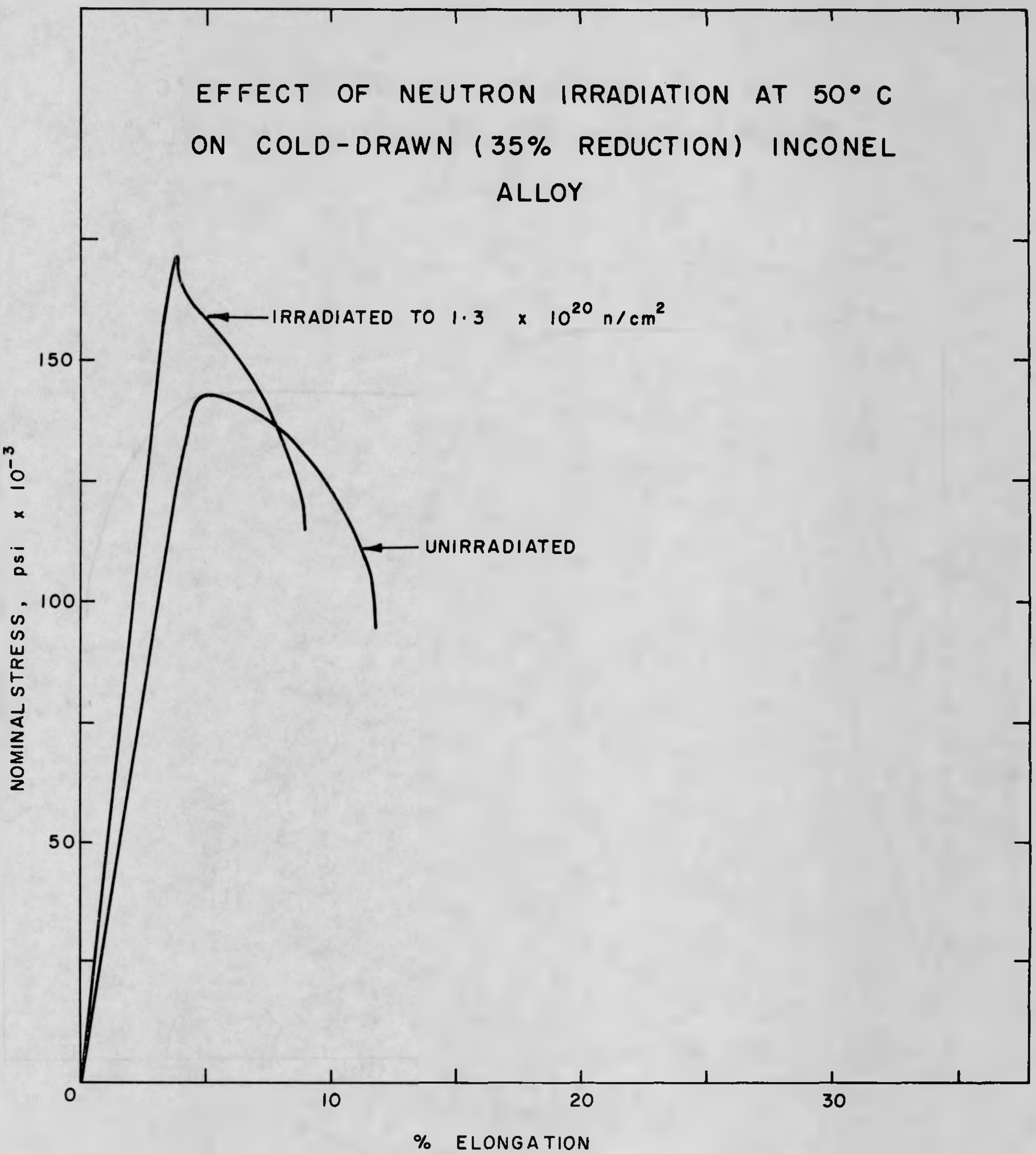
EFFECT OF NEUTRON IRRADIATION AT 50° C
ON COLD-DRAWN (35% REDUCTION) INCONEL
ALLOY
IRRADIATED TO 1·3 x 10^20 n/cm^2
UNIRRADIATED
NOMINAL STRESS, psi x 10^-3
150
100
50
0
10
20
30
% ELONGATION

FIGURE 4

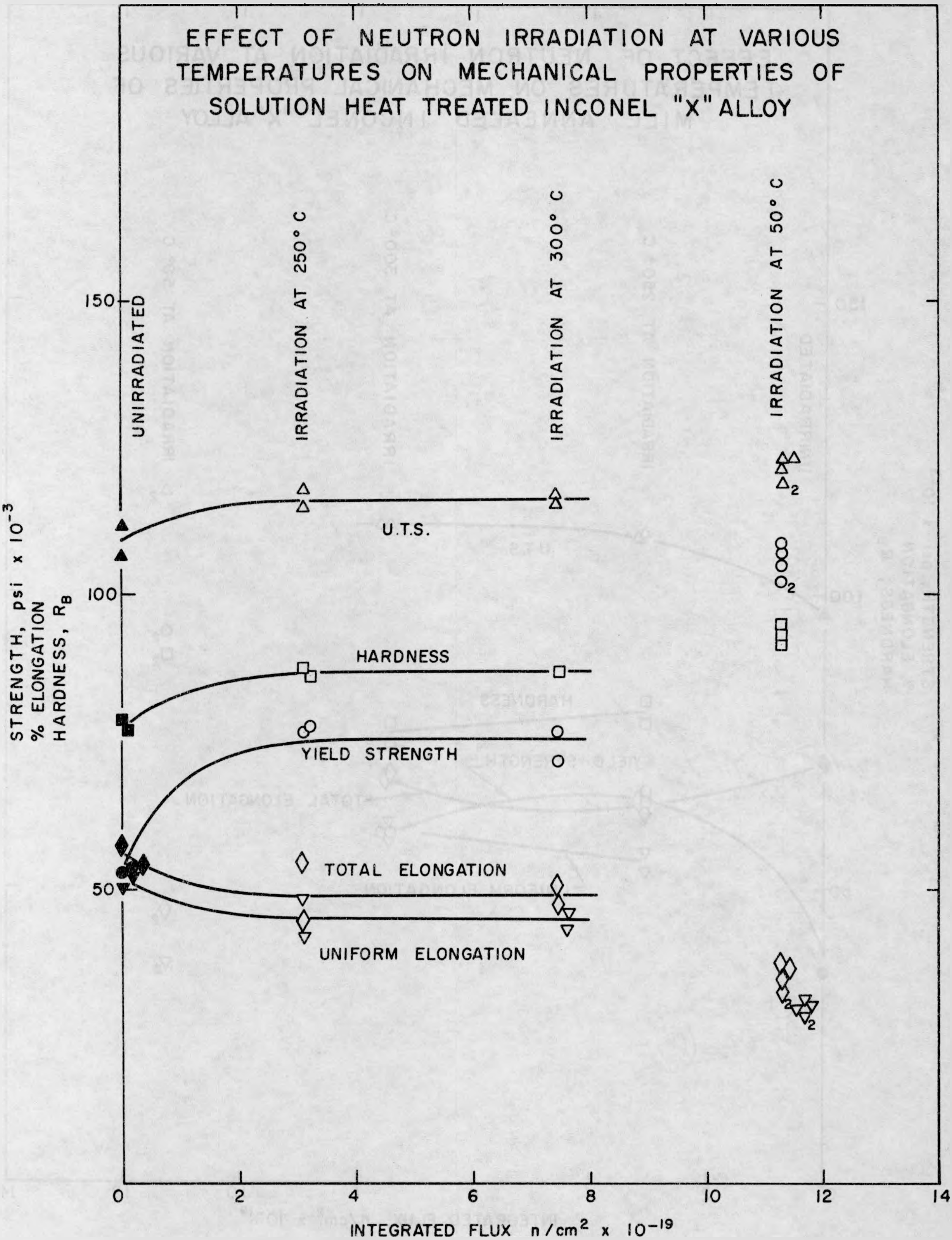
EFFECT OF NEUTRON IRRADIATION AT VARIOUS TEMPERATURES ON MECHANICAL PROPERTIES OF SOLUTION HEAT TREATED INCONEL "X" ALLOY
UNIRRADIATED
IRRADIATION AT 250° C
IRRADIATION AT 300° C
IRRADIATION AT 50° C
U.T.S.
HARDNESS
YIELD STRENGTH
TOTAL ELONGATION
UNIFORM ELONGATION
STRENGTH, psi x 10⁻³
% ELONGATION
HARDNESS, R_B
150
100
50
0
2
4
6
8
10
12
14
INTEGRATED FLUX n/cm² x 10⁻¹⁹

FIGURE 5

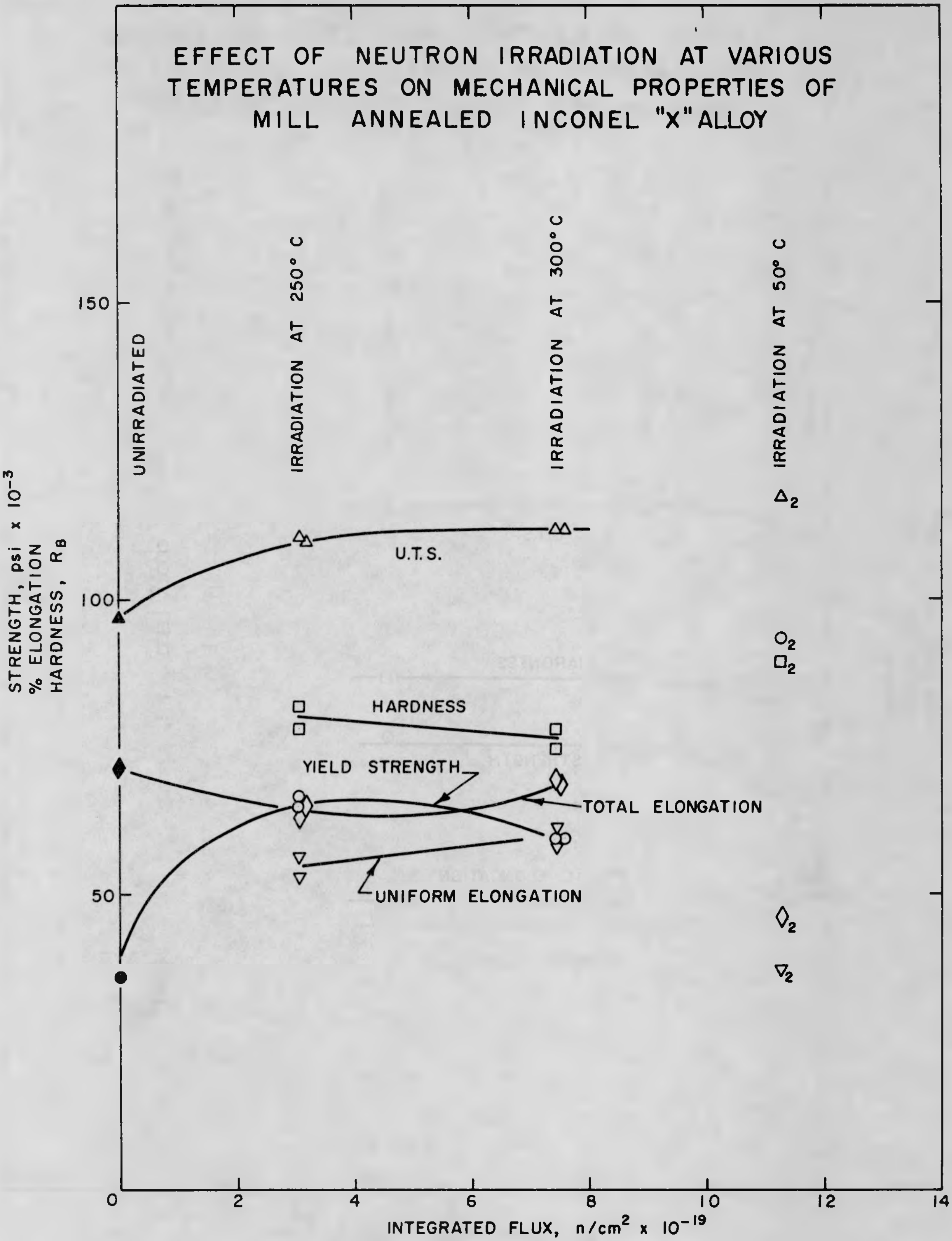
EFFECT OF NEUTRON IRRADIATION AT VARIOUS TEMPERATURES ON MECHANICAL PROPERTIES OF MILL ANNEALED INCONEL "X" ALLOY
UNIRRADIATED
IRRADIATION AT 250° C
IRRADIATION AT 300° C
IRRADIATION AT 50° C
STRENGTH, psi x 10-3
% ELONGATION
HARDNESS, RB
U.T.S.
HARDNESS
YIELD STRENGTH
TOTAL ELONGATION
UNIFORM ELONGATION
150
100
50
0
2
4
6
8
10
12
14
INTEGRATED FLUX, n/cm2 x 10-19

FIGURE 6

LEGEND FOR ALL FIGURES

PROPERTY	ANNEALING TIME – HOURS (PRIOR TO TEST)	MARK IRRADIATED	MARK UNIRRADIATED
ULTIMATE TENSILE STRENGTH	1	△	▲
	10	△̍	▲̍
YIELD STRENGTH (0·2% OFFSET)	1	○	●
	10	○̍	●̍
HARDNESS, R_B	1	□	■
	10	□̍	■̍
TOTAL ELONGATION, %	1	◇	◆
	10	◊̍	♦̍
UNIFORM ELONGATION, %	1	▽	▼
	10	▽̍	▼̍

ALL TESTS WERE MADE AT ROOM TEMPERATURE

STRAIN RATE IN TENSILE TESTS – 0·05 in./in. UNLESS NOTED

STRAIN RATE IN TENSILE TESTS FOR POINTS MARKED " f " – 0·2 in./in.

POINTS WITH SUBSCRIPT " 2 " ARE FOR SPECIMENS IRRADIATED IN MARK II TRANSFORMER ROD

TEMPERATURE OF IRRADIATION AND INTEGRATED FLUX (> 500 ev) ARE SHOWN IN EACH FIGURE

SOLID LINES ARE FOR ONE HOUR POST-IRRADIATION ANNEALS

BROKEN LINES ARE FOR UNIRRADIATED SPECIMENS ANNEALED FOR ONE HOUR

FIGURE 7.

EFFECT OF POST-IRRADIATION ANNEALING ON SOLUTION HEAT TREATED INCONEL "X" ALLOY

(IRRADIATED TO 1·3 x 10^{20} n/cm^2 AT 50°C)

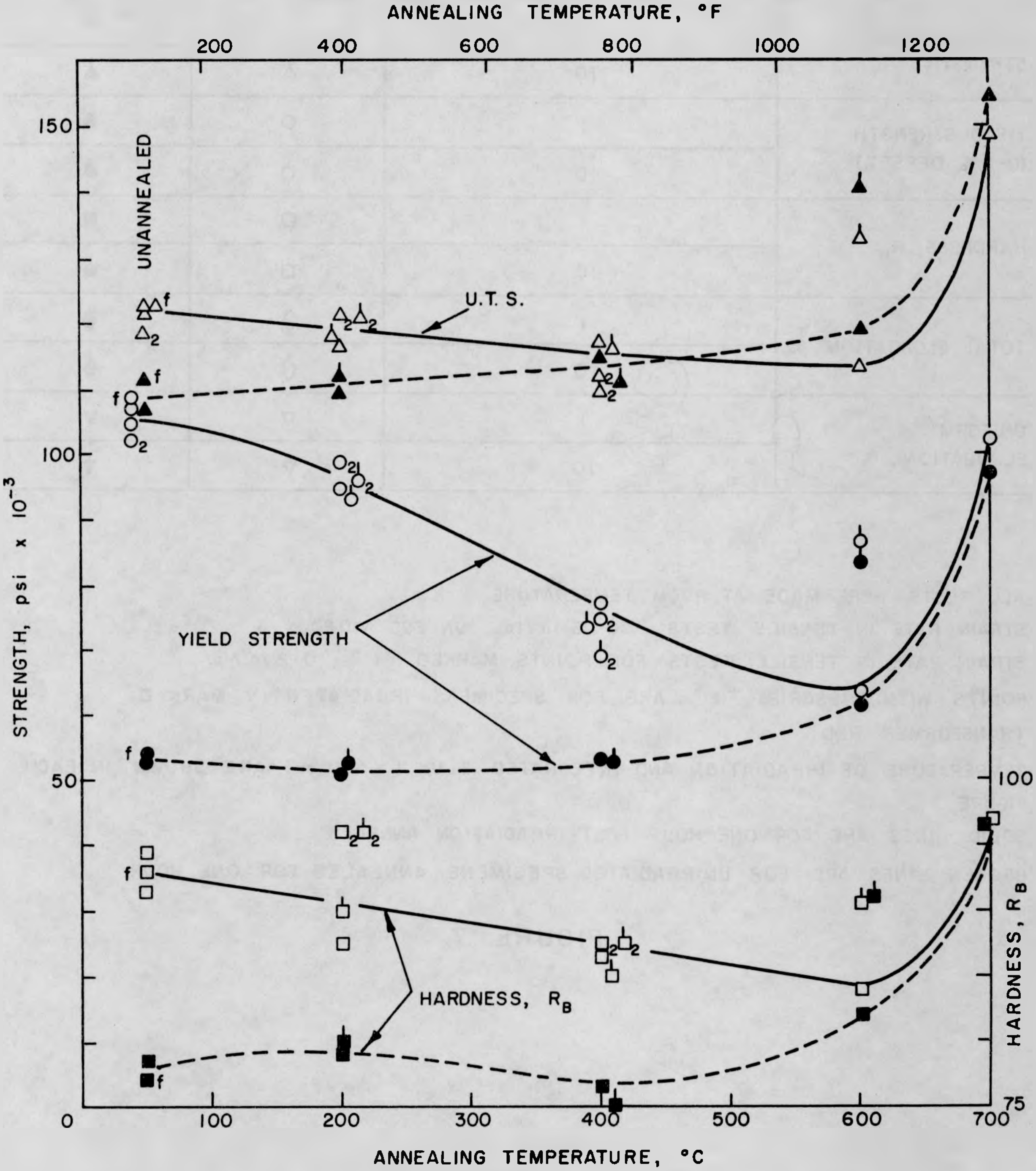

FIGURE 8.

EFFECT OF POST-IRRADIATION ANNEALING ON SOLUTION HEAT TREATED INCONEL "X" ALLOY

(IRRADIATED TO 1·3 x 10^{20} n/cm^2 AT 50° C)

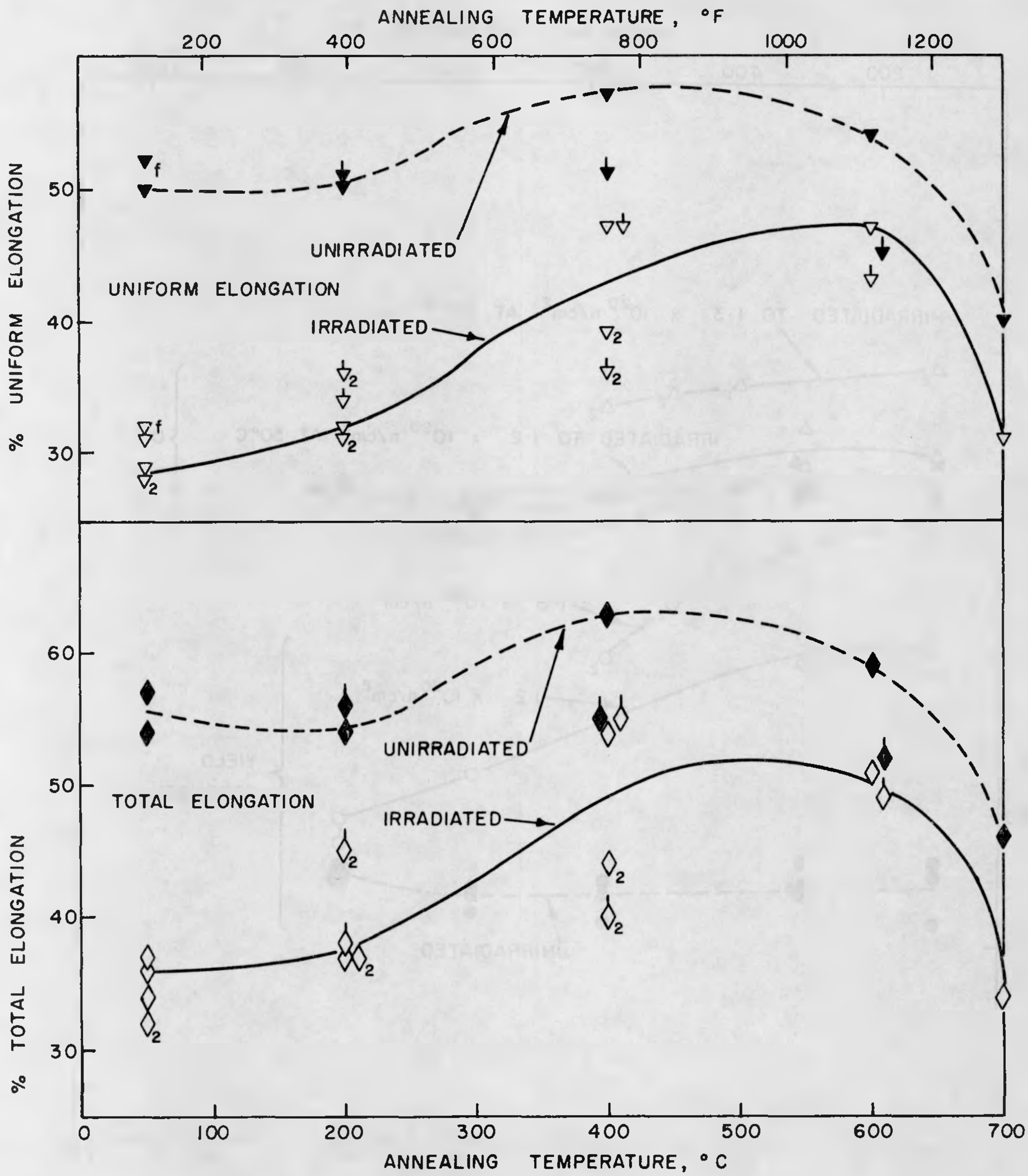

FIGURE 9

EFFECT OF POST-IRRADIATION ANNEALING ON MILL ANNEALED INCONEL "X" ALLOY

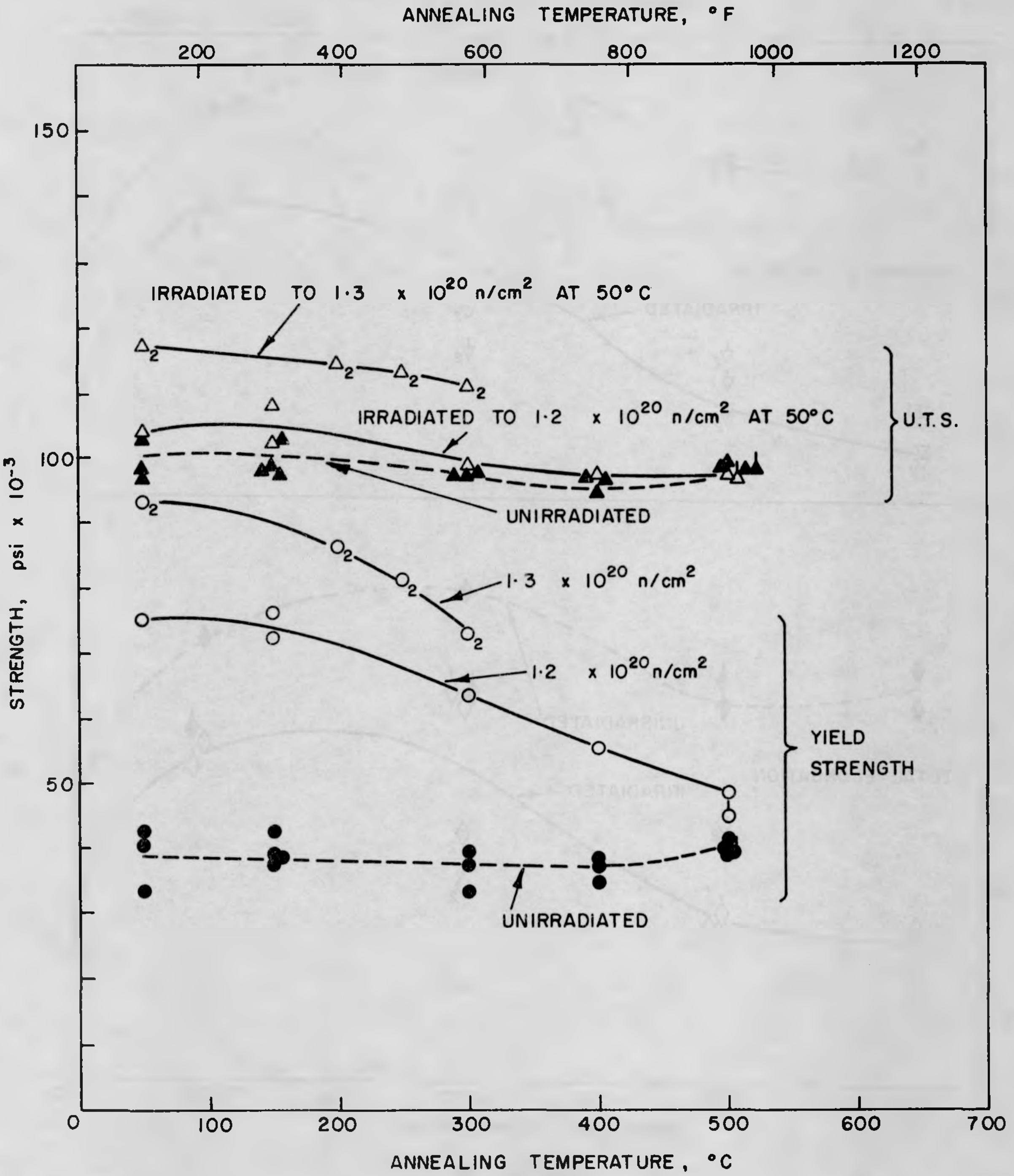

FIGURE 10

EFFECT OF POST-IRRADIATION ANNEALING ON MILL ANNEALED INCONEL "X" ALLOY

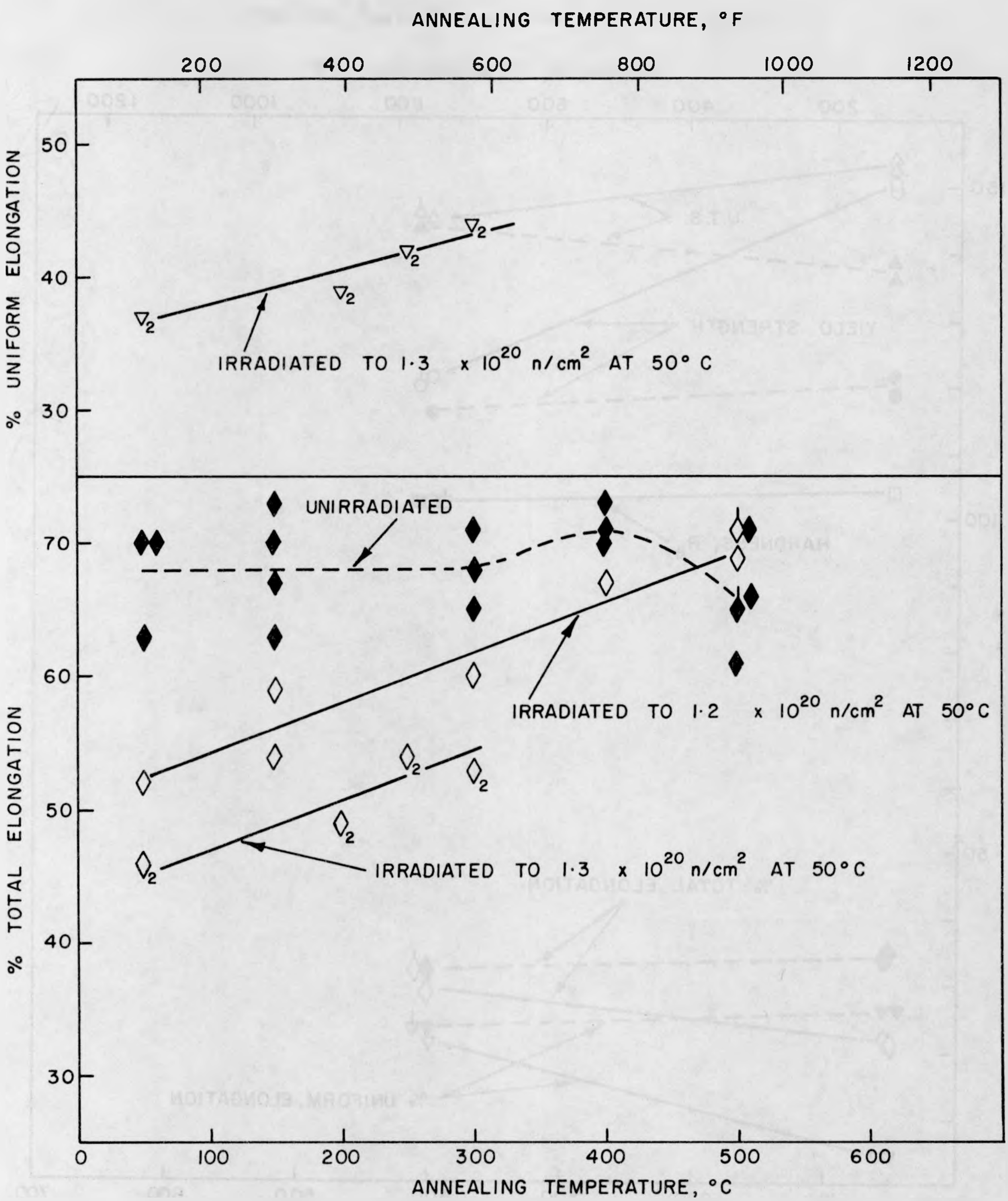

FIGURE 11

EFFECT OF POST-IRRADIATION ANNEALING ON COLD-DRAWN INCONEL "X" ALLOY

(IRRADIATED TO 1·3 x 10^{20} n/cm^2 AT 50°C)

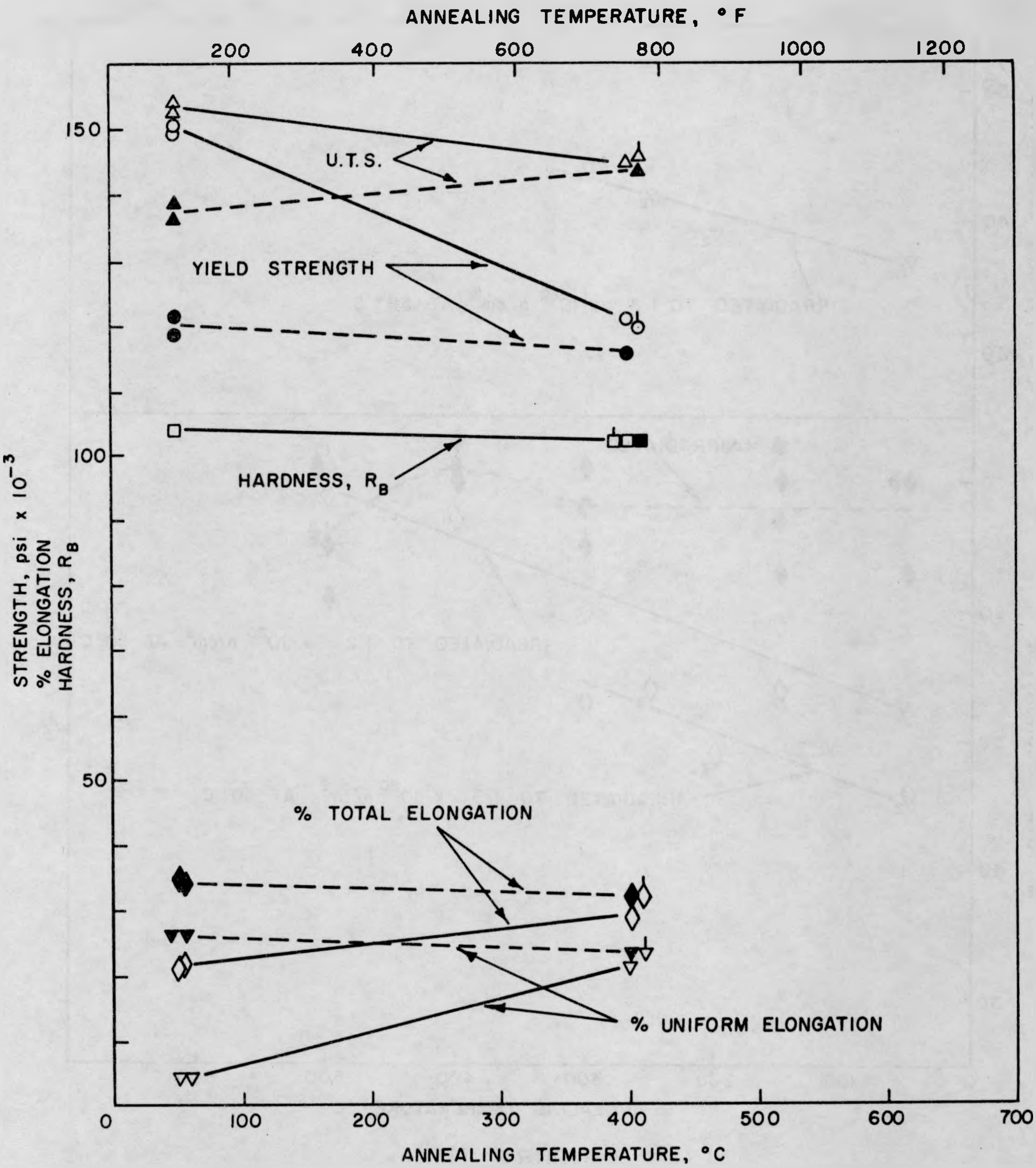

FIGURE 12

EFFECT OF POST-IRRADIATION ANNEALING ON COLD-DRAWN INCONEL ALLOY

(IRRADIATED TO $1 \cdot 3 \times 10^{20}$ n/cm^2 AT 50°C)

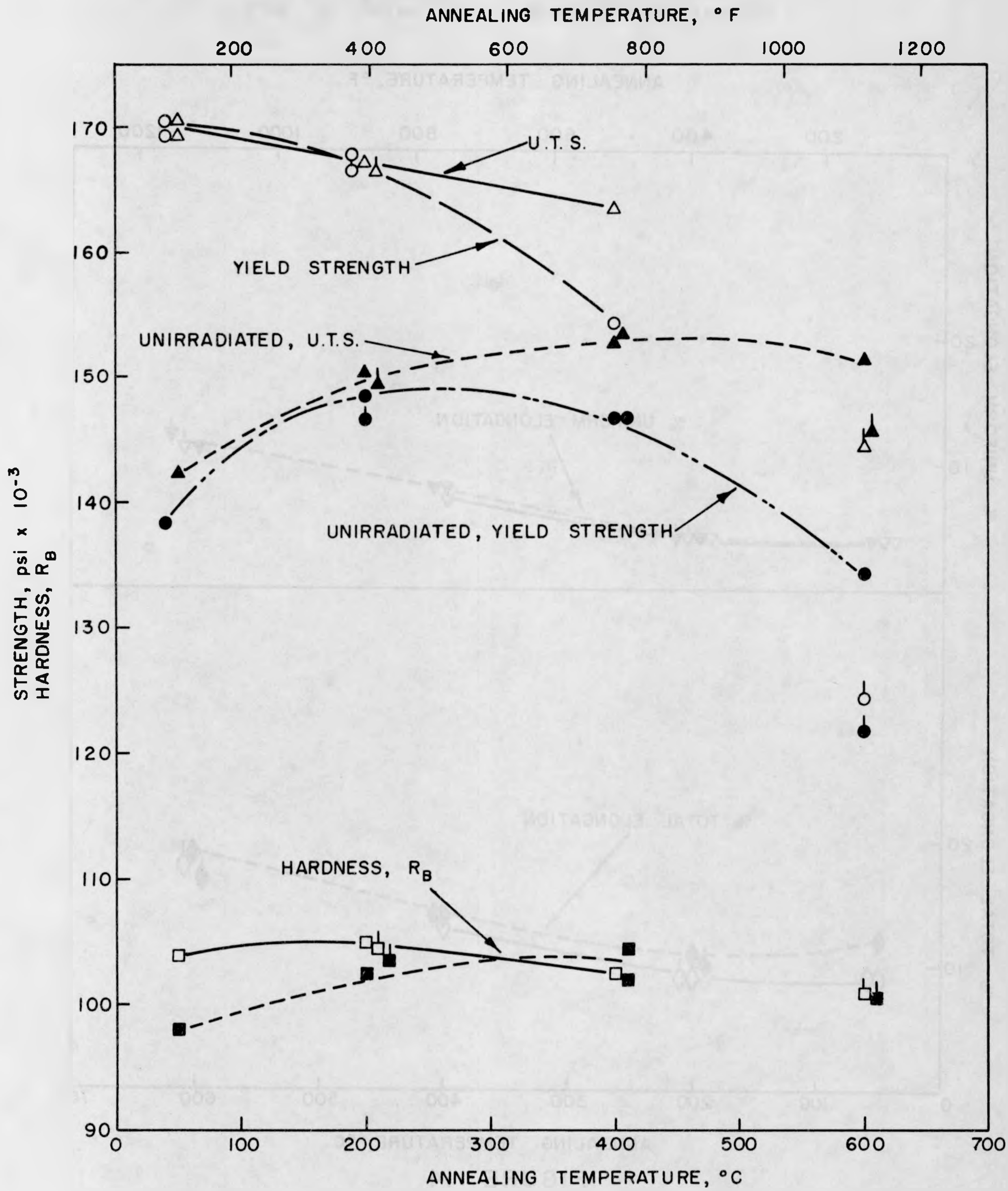

FIGURE 13

EFFECT OF POST-IRRADIATION ANNEALING ON COLD-DRAWN INCONEL ALLOY

(IRRADIATED TO 1·3 x 10^{20} n/cm^2 AT 50°C)

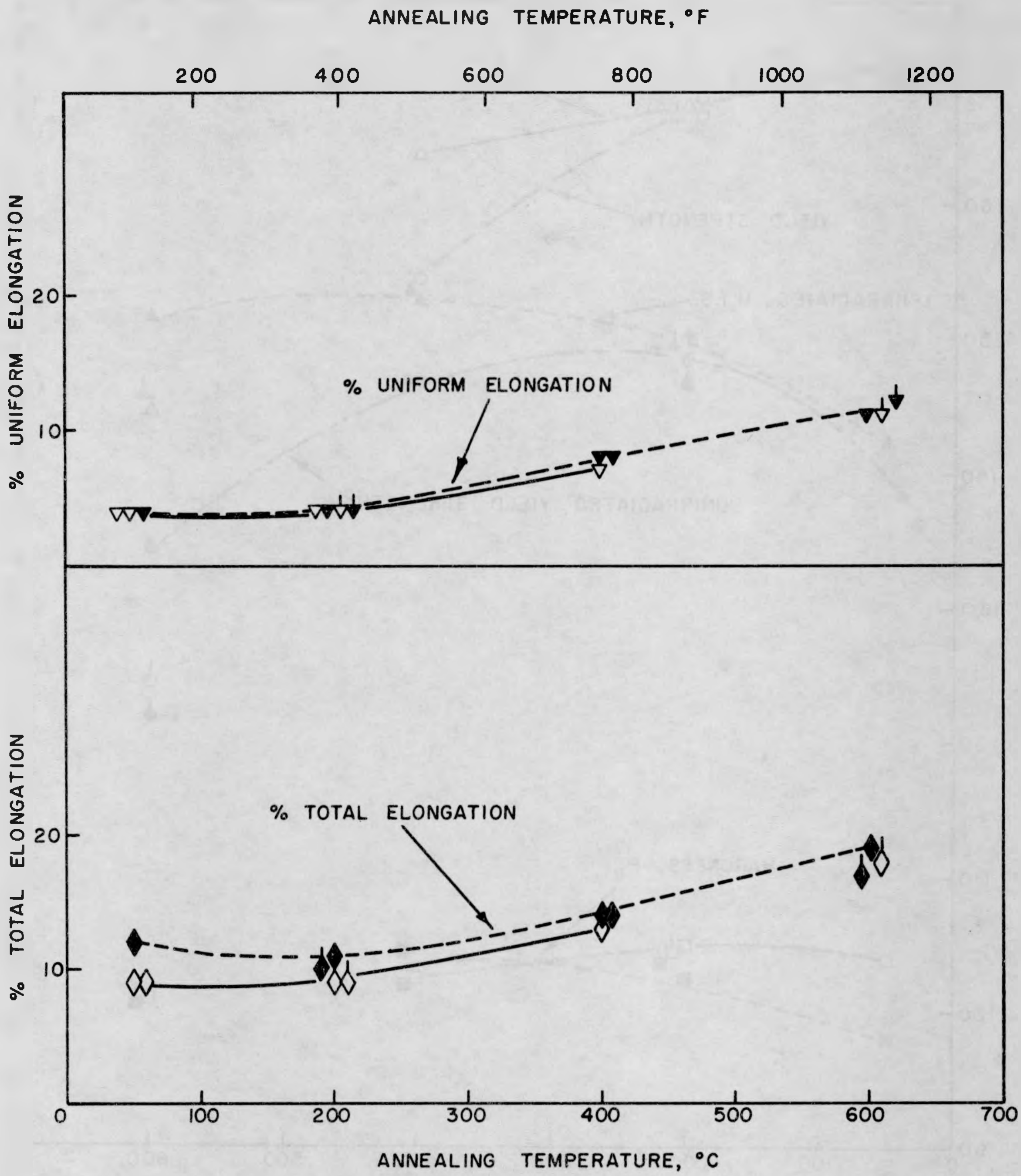

FIGURE 14

EFFECT OF POST-IRRADIATION ANNEALING ON SOLUTION HEAT TREATED INCONEL "X" ALLOY

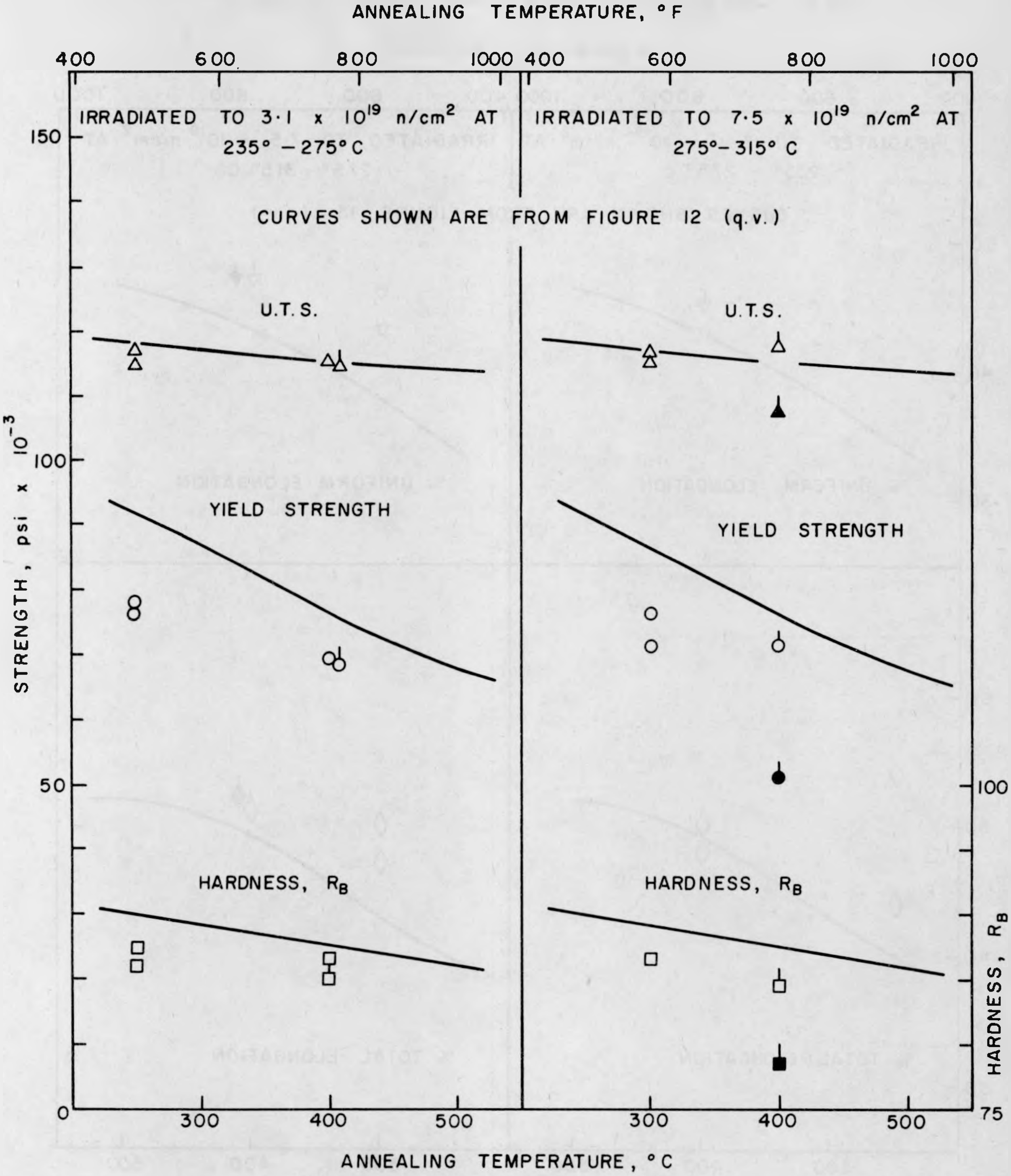

FIGURE 15

EFFECT OF POST-IRRADIATION ANNEALING ON SOLUTION HEAT TREATED INCONEL "X" ALLOY

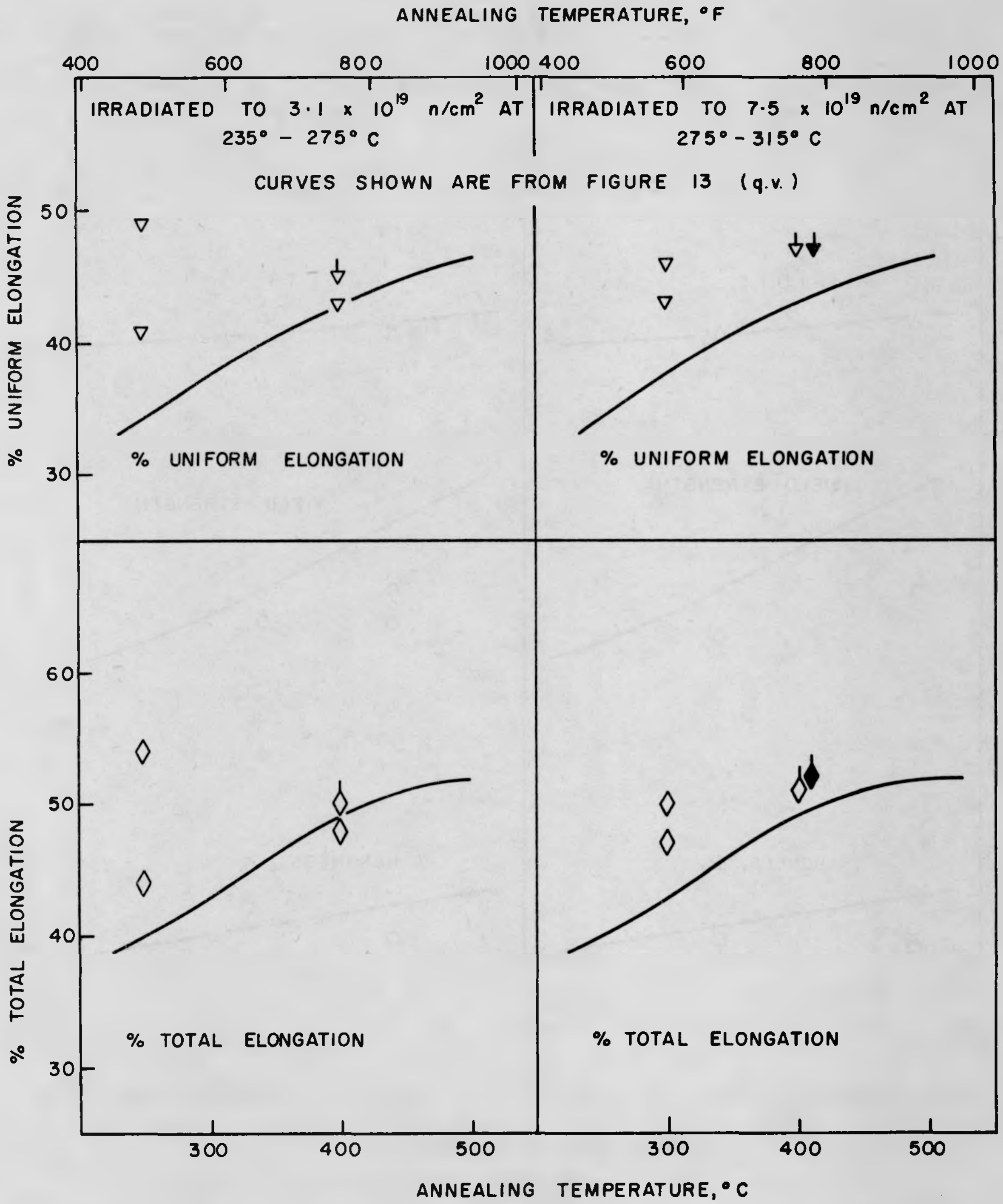

FIGURE 16

EFFECT OF POST-IRRADIATION ANNEALING ON MILL ANNEALED INCONEL "X" ALLOY.

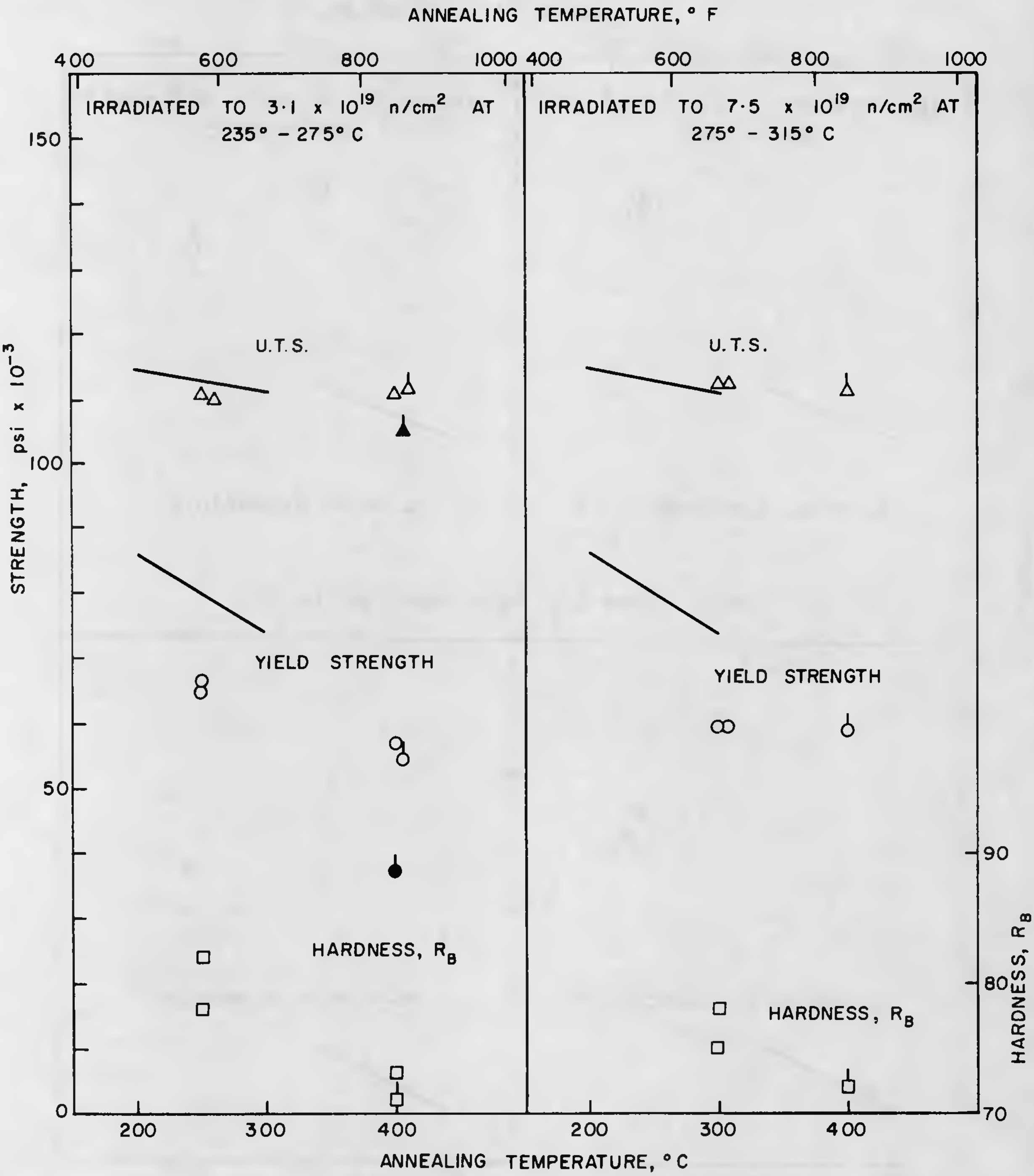

FIGURE 17

EFFECT OF POST-IRRADIATION ANNEALING ON
MILL ANNEALED INCONEL "X" ALLOY

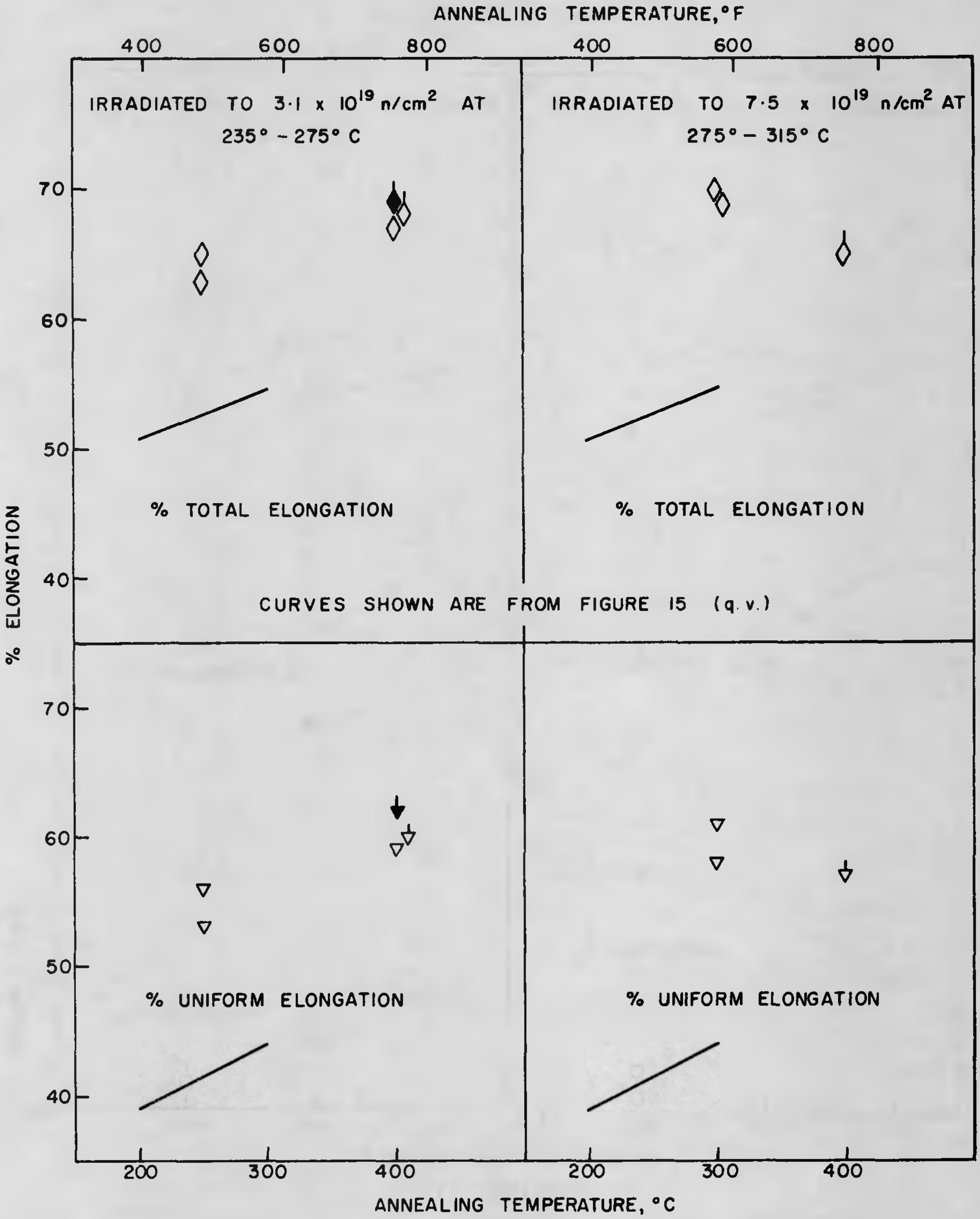

FIGURE 18

EFFECT OF POST-IRRADIATION ANNEALING ON ANNEALED INCONEL ALLOY.

(IRRADIATED TO $7 \cdot 5 \times 10^{19}$ n/cm^2 AT 275°-315°C)

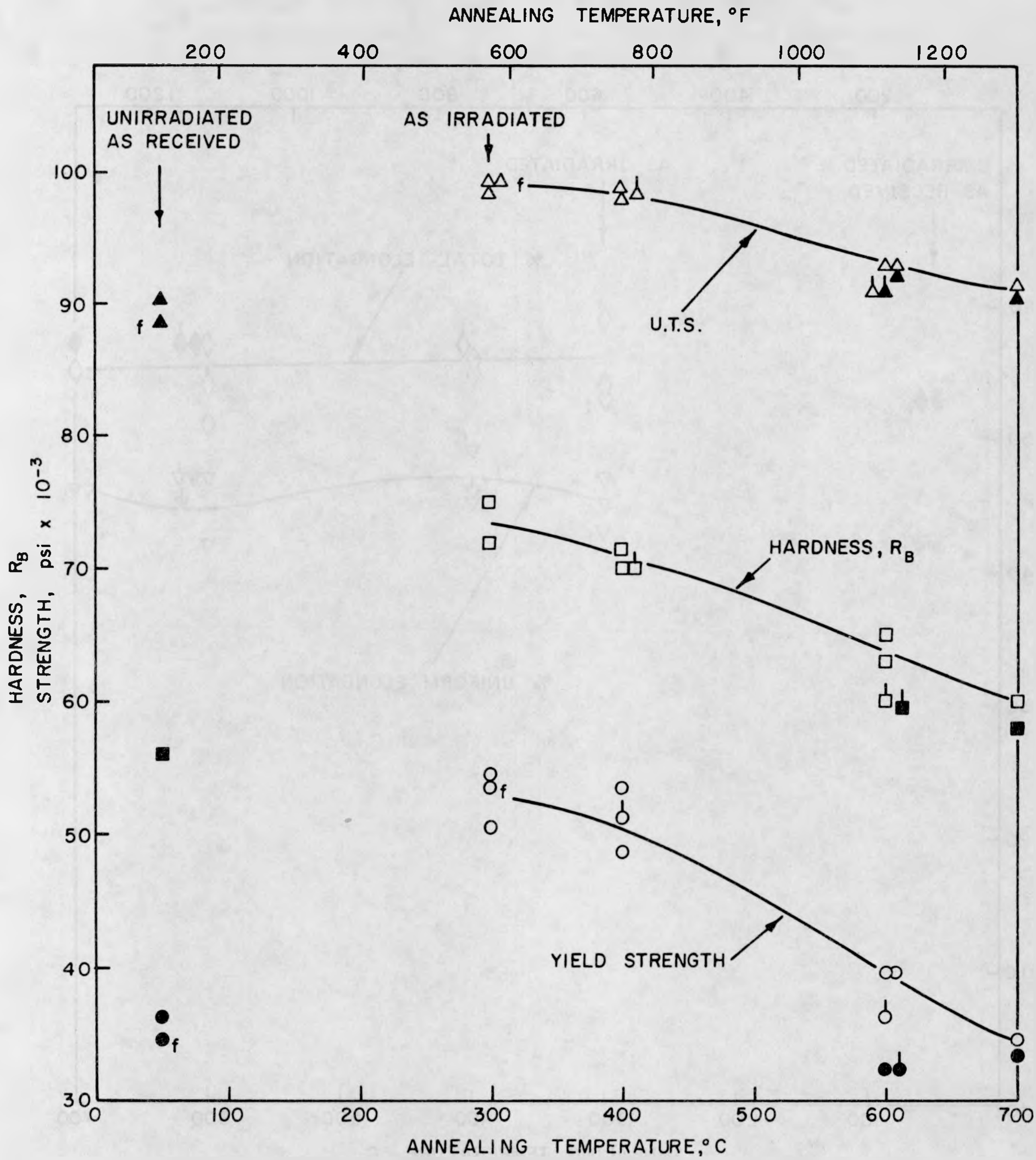

FIGURE 19

EFFECT OF POST-IRRADIATION ANNEALING ON ANNEALED INCONEL ALLOY.

(IRRADIATED TO 7·5 x 10^{19} n/cm^2 AT 275° -315°C)

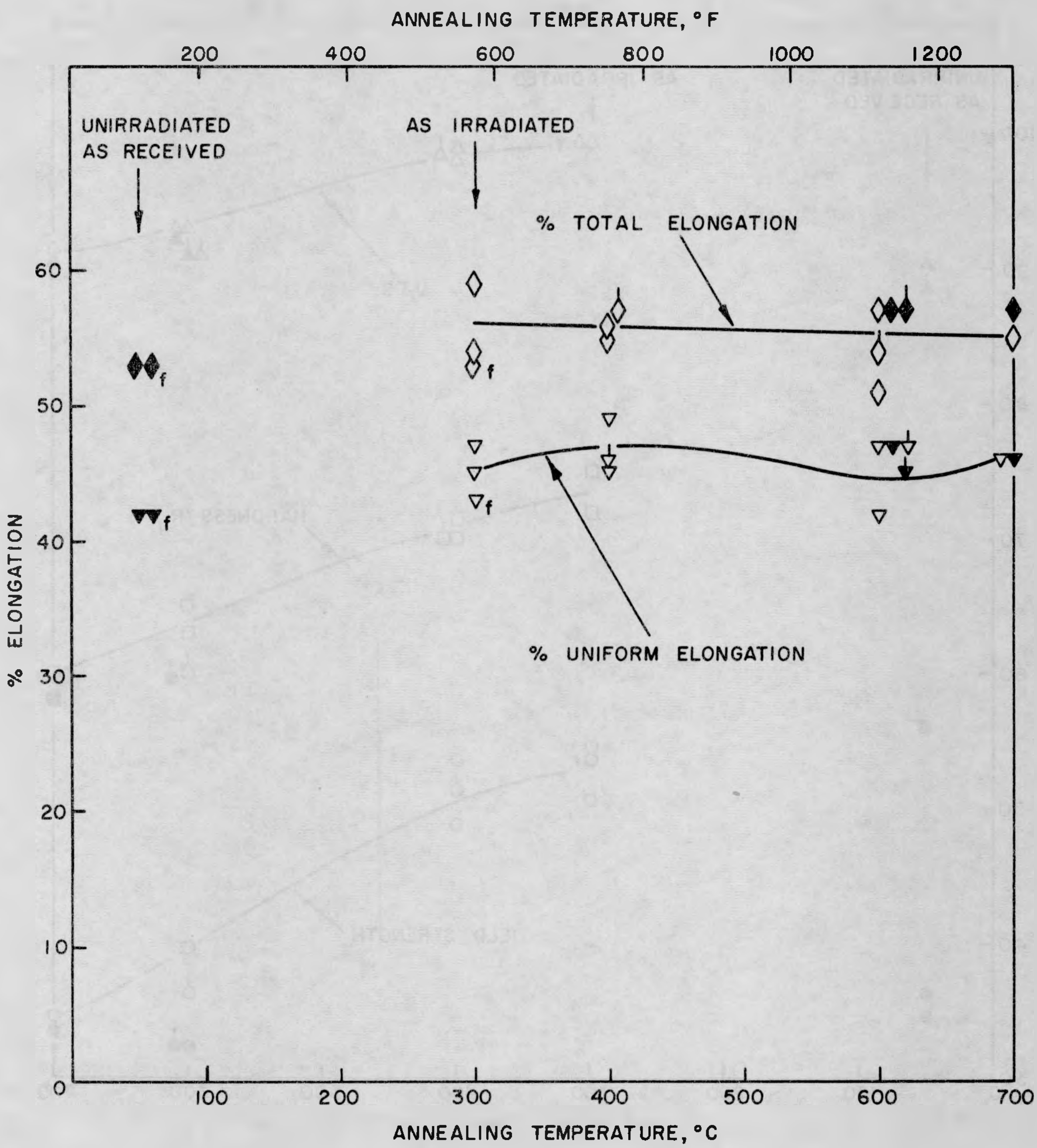

FIGURE 20

EFFECT OF POST-IRRADIATION ANNEALING ON COLD-DRAWN INCONEL "X" ALLOY.

(IRRADIATED TO $3 \cdot 1 \times 10^{19}$ n/cm^2 AT 235° – 275° C)

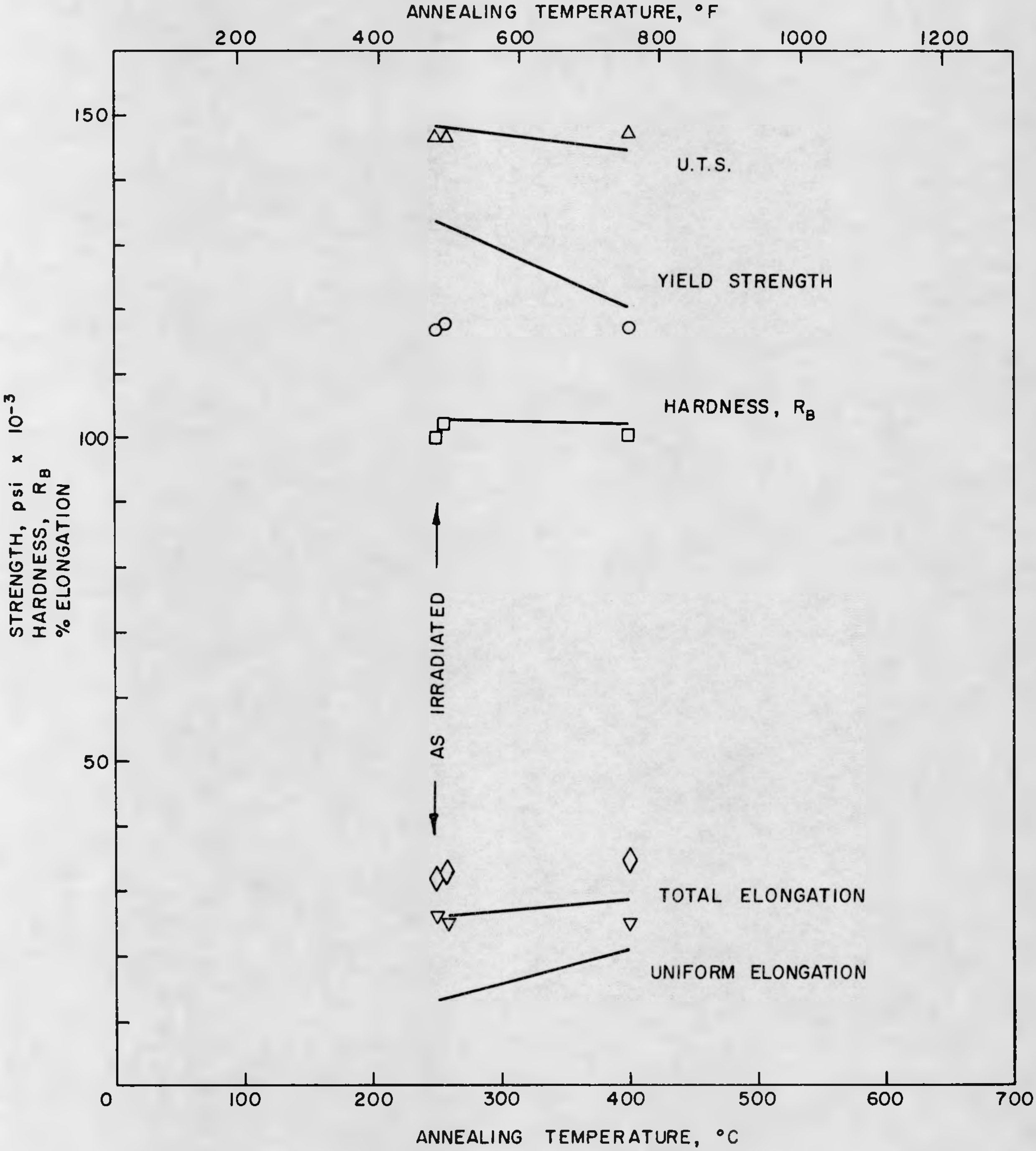

FIGURE 21

APPENDIX I

Reference Code to Materials

Material		Code
Inconel "X" Age-Hardenable Nickel-Chromium Alloy		
	Annealed Temper	X-A
	Solution Treated Temper	X-ST
	Cold Drawn	X-CD
Inconel Nickel-Chromium Alloy		
	Annealed Temper	I-A
	Cold Drawn	I-CD