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EFFECTS OF SILICON MONOXIDE OVERLAYS ON THE NORMAL TO SUPERCONDUCTING TRANSITION TIME IN THIN INDIUM FILMS

CHARLES R. MacDOWELL
and
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Submitted in partial fulfillment of
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MASTER OF SCIENCE
IN
PHYSICS

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Monterey, California

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ABSTRACT

This thesis investigates the normal to superconducting transition time (hereafter called the backswitch time) in thin films of indium.

Varying thicknesses of silicon monoxide have been evaporated over the indium films and the effect of these layers has been observed at different temperatures over a considerable range of total current through the specimens.

The writers appreciate the guidance and encouragement given them by Professor J. N. Cooper of the U. S. Naval Postgraduate School and the technical assistance given by Mr. K. C. Smith, also of the U. S. Naval Postgraduate School.

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1. Introduction.

The phenomenon of superconductivity was discovered by H. Kammerlingh Onnes in 1911 and has been in the fore of the many perplexing problems of modern day physics ever since. Although the general answers are known, many questions remain to be answered in the investigation of why many metals lose their resistance entirely at extremely low temperatures. Research is continuing at a rapid pace, and this paper will attempt to add a stone or two to the pyramid of knowledge.

Many interesting sidelights have been observed in these investigations. If a thin film of indium, evaporated onto a glass or quartz substrate, is cooled below 3.4° K, the film becomes superconducting. The temperature, 3.4° K is the "critical temperature" (T_c) of indium and is characteristic of the metal. There are at least 21 known superconducting elements,[1] each with its own associated T_c.

A magnetic field may be applied to a specimen while it is in the superconducting state. If the field is of precisely the minimum magnitude to drive the specimen resistive, this magnetic field is termed the "critical field", H_c. The critical field increases with decreasing temperature. Similarly, the current flowing through a superconducting specimen may be increased to the point

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[1] Lane, Superfluid Physics, p. 217

where the specimen is driven resistive. This current is termed the "critical current", I_c, and also increases with decreasing temperature.

The purpose of the experiments described in this paper was to gain additional information about the "backswitch time" associated with superconducting indium films. The "backswitch time" may be briefly defined as the time required for the specimen to make the transition from the resistive to the superconducting state after removal of a current pulse which has been used to drive the specimen resistive. Previous investigations have shown that the backswitch time observed in superconducting thin films varies in an unusual manner.

The transition time from the resistive to the superconducting state may be observed in the following way. The specimen is cooled to a temperature below T_c, and a DC current of the order of a few milliamperes is passed through it. This DC current is below the I_c for the particular temperature in question. A current pulse, typically 20 microseconds wide and with a repetition rate of 150 pulses per second is now superimposed over the DC current such that the sum of the pulse and the DC current is greater than I_c. The specimen then switches from the superconducting state to the resistive state during the pulse and upon termination of the pulse, switches back to the superconducting state. The latter switch requires a time of from one to a few hundred microseconds and again is the time referred to as the "backswitch time". If at a particular temperature below T_c, the backswitch time is observed for increasing pulse height, the backswitch time is observed to increase to a maximum as the pulse height is increased, then to decrease to a minimum, and finally to rise again.

The minima observed in the backswitch time are of the greatest concern here. Common sense would normally lead one to believe that this minimum should not exist, yet exist it does. Why then should it exist? This is a question as yet unanswered, but the information contained herein may aid in finding the answer. It has been proposed that possibly the dissipation of heat at a more rapid rate with increasing pulse height may cause this minimum. This implies an extraordinary heat conduction process as the one occurring. If this were the case, the application of a suitable insulator to the film to prevent good thermal contact with the helium in which it is immersed should produce observable effects on the backswitch time. To this end, films of indium were covered with varying thicknesses of silicon monoxide, a substance which is a good electrical insulator and which may be used in evaporation techniques. It was expected that, if the process of heat conduction in the specimen were an ordinary one, the observed minimum in the backswitch time would be significantly reduced, and the backswitch times in general for a given film would be raised. This was not found to be the case. Results are discussed in sections four and five.

2. Equipment.

The equipment used for measuring the characteristics of the specimens at low temperatures was nearly identical to that used previously by Eckert and Donnelly.[1] A Textronix Type-541 Oscilloscope with a Type CA dual-channel plug-in preamplifier was used to obtain the voltage and current measurements. Block diagrams of both the electrical and cryogenic configurations are shown in Figs. 1 and 2. A drawing of the specimen holder and its circuitry is shown in Fig. 3.

A new vacuum system was used in the evaporation of the thin films. The system was composed of a Kinney fifteen-cubic-foot-per-minute fore pump and a Veeco four-inch diffusion pump with a modified freon-cooled baffle. (This modification was accomplished by Mr. K. C. Smith of the U. S. Naval Postgraduate School who also designed and built the dual cryogenic well top for the vacuum jar). Fig. 4 illustrates the vacuum system.

Appendix I describes in some detail the making of the specimen masks and the specimens, both of which are illustrated in Fig. 5.

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[1] J. A. Eckert and R. G. Donnelly, Temperature Dependence of the Normal to Superconducting Transitions, U. S. Naval Postgraduate School Thesis, 1960.

EXPERIMENTAL ELECTRICAL CIRCUIT

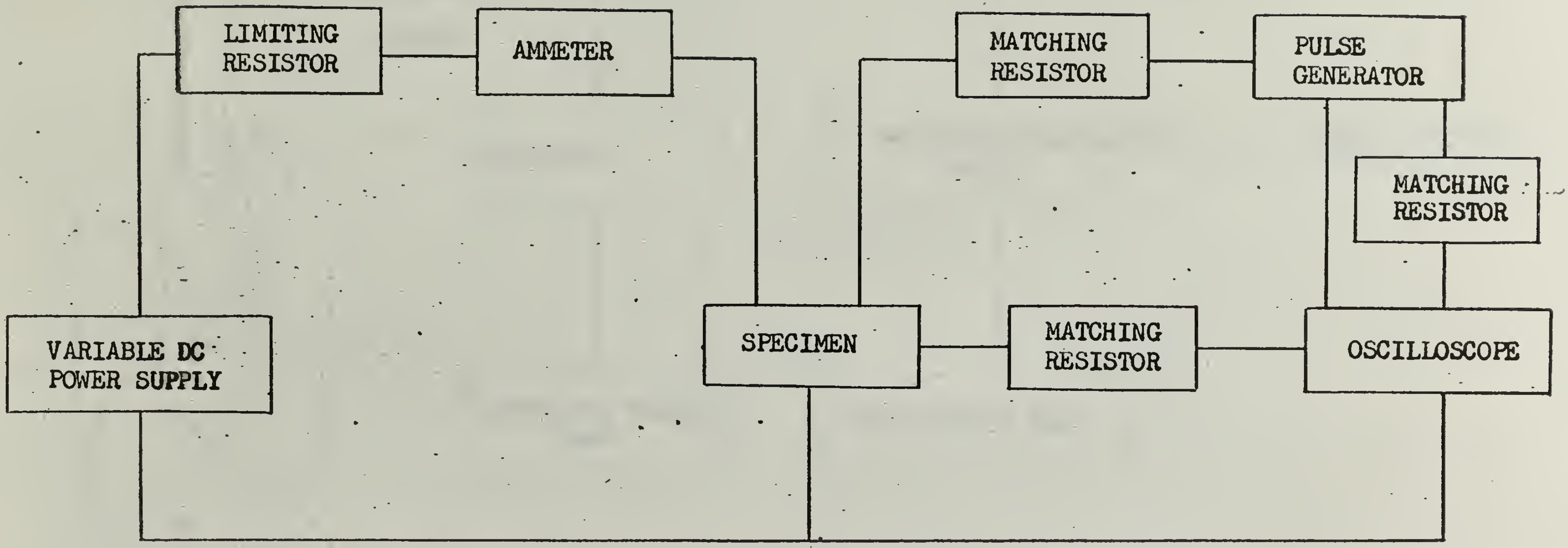


FIGURE 1

PHYSICAL APPARATUS DIAGRAM

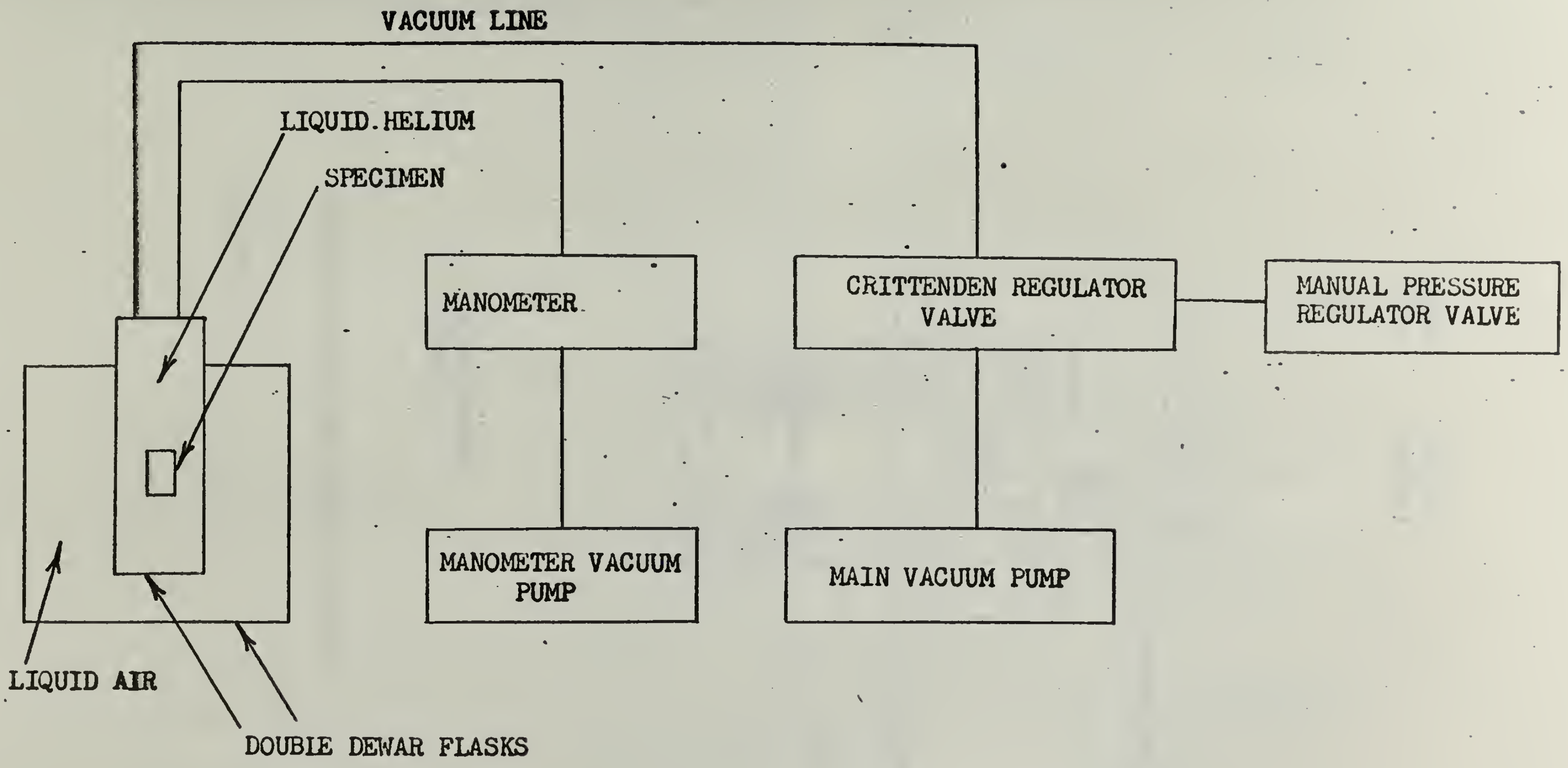
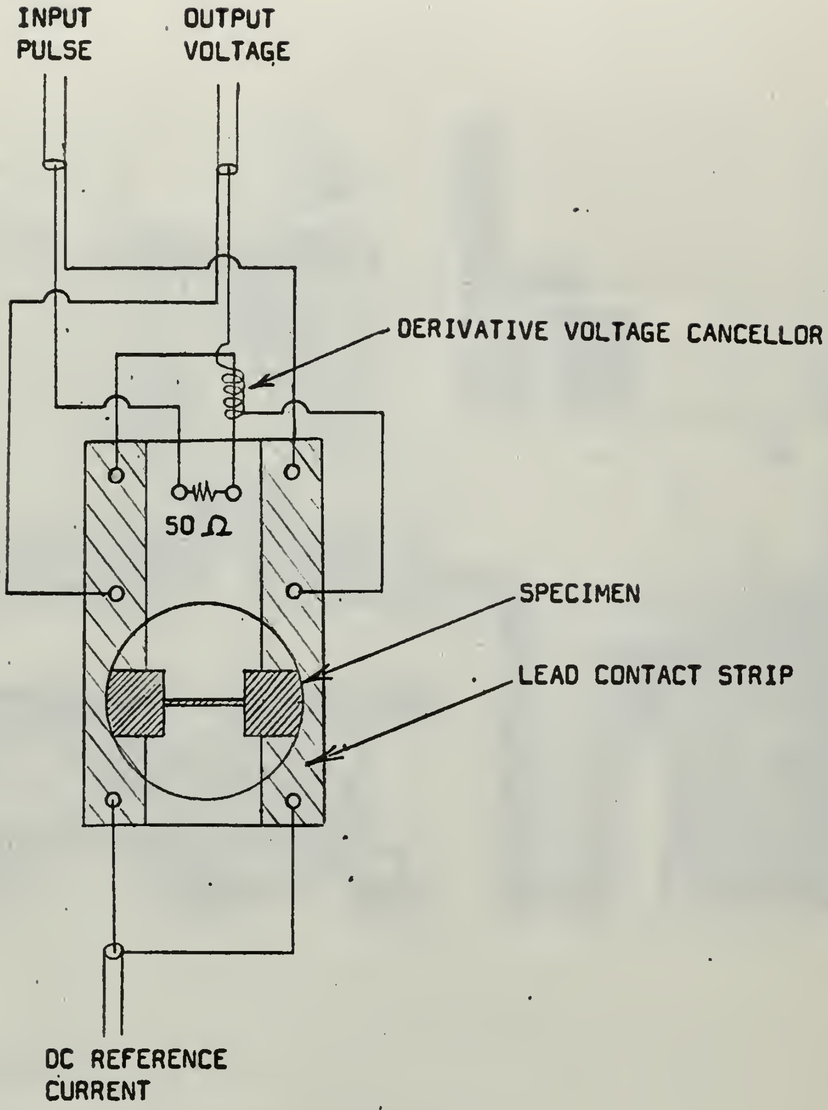


FIGURE 2



SPECIMEN HOLDER AND WIRING DIAGRAM

Figure 3

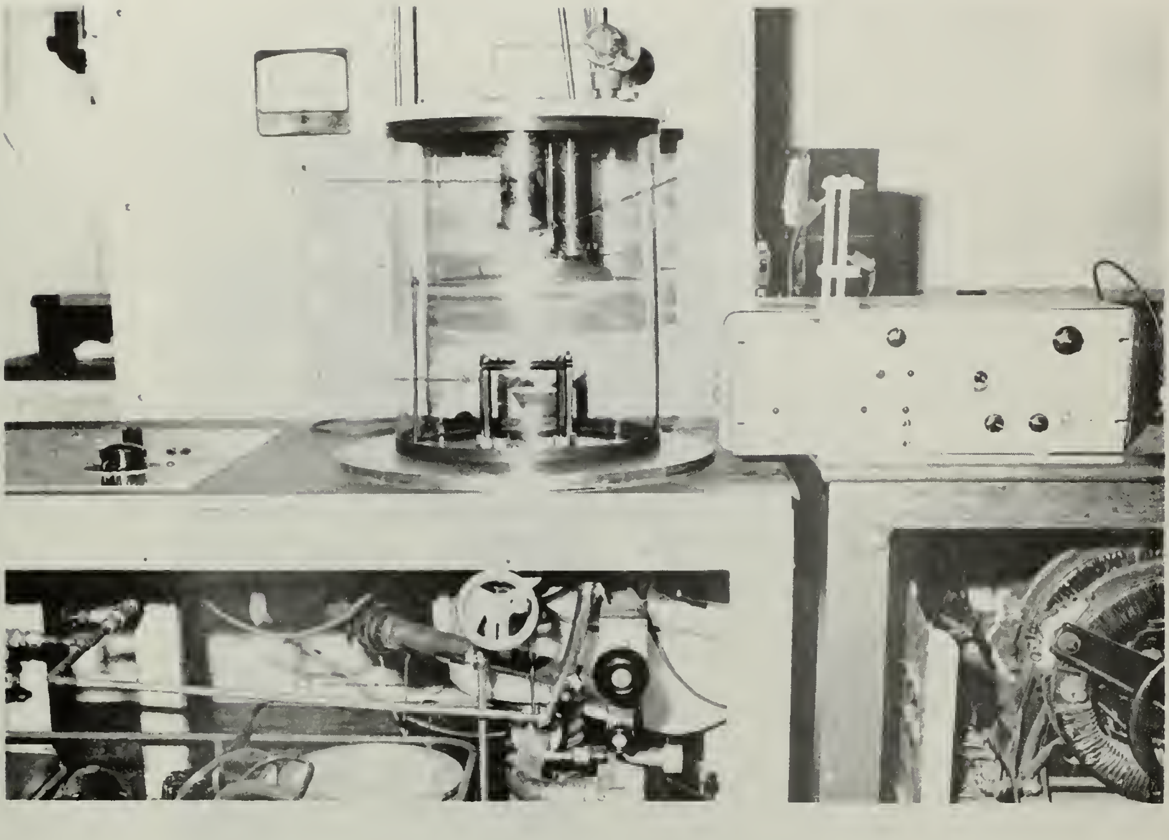


Figure 4

Vacuum system for thin film evaporations

a. Central well with specimen and mask mounted

b. Side well and attached annular baffle for additional cryogenic pumping

c. Mounting posts with evaporating boats in place

d. Diffusion pump and freon cooled baffle

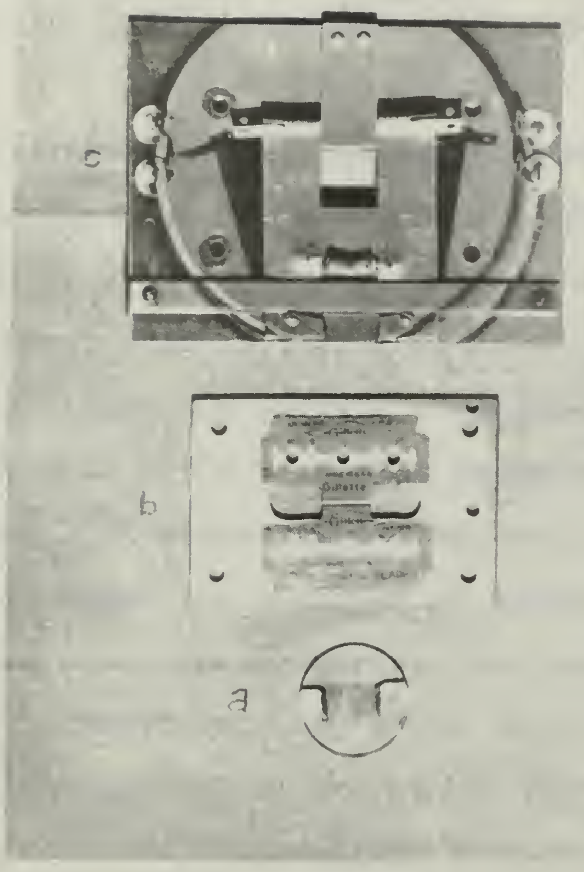


Figure 5

a. Indium specimen with silicon monoxide overlay

b. Specimen mask

c. Mask with spring loaded shutters to shield the specimen contact areas during silicon monoxide evaporations

3. Experimental Procedures.

All thin films used in this paper were made by the authors in the laboratory. The vacuum system used is described in Section 2. Appendix I gives a detailed account of the procedures used in thin film evaporation and a summary of the problems encountered therein by the authors.

The measurement of the backswitch time of a superconducting specimen can be made quite readily. The specimen is immersed in a liquid helium bath, the temperature of which is controlled by variation of the pressure of the helium gas above the liquid. The critical temperature for indium is 3.4°K. At some temperature below critical a small DC reference current is maintained through the specimen and a series of voltage pulses (input pulse) are also applied across the specimen. The input pulse is of sufficient magnitude to drive the specimen resistive during the pulse, and the DC reference current small enough to allow the specimen to return to the superconducting state prior to the initiation of the next input pulse. The time required to return from the resistive to the superconducting state is then the time from the cessation of the input pulse to the point at which there remains no noticeable voltage drop across the specimen.

The six parameters physically controllable and external to the specimen are: temperature, DC reference current, input voltage pulse (pulse height), pulse shape, pulse repetition frequency (PRF) and pulse duration (PD). The latter three were held constant for all experimental runs. A square wave form was chosen with a rise and fall time of less than 0.01 microsecond to full pulse height. A PRF of 150 pulses per second and a PD of 20 microseconds were chosen since the backswitch times in these ranges are insensitive to minor variations of these two parameters, indicating thermal equilibrium is attained during the pulse application.

The temperature range was limited to 3.255° to 2.569°K for all specimens, these temperatures being well below the critical temperature for indium yet well above the lambda point of liquid helium. The DC reference current was applied and the input pulse height increased until a maximum in the backswitch time was noted. This would be recorded and data would be taken at small intervals of increasing input pulse height until the backswitch time passed through a minimum and increased again. In all instances runs were ceased before the specimen showed evidence of excessive overheating. Where possible, several values of DC reference current were used at each temperature.

Since a dual-channel preamplifier was used on the oscilloscope, both the input pulse height and the voltage across the specimen could be measured simultaneously. Conversion of the voltage across the specimen during the pulse (output pulse height) to current through the specimen (output current) was accomplished by calibrating the scope for each thin film at 4.2°K. The DC current required to raise the voltage output trace one centimeter on the 0.05 volt per centimeter scale gave the current conversion for that scale directly. In addition, this procedure yields the specimen resistance at liquid helium temperatures.

4. Experimental Results.

Of the specimens made by the authors and examined for backswitch time properties, only three sets were utilized in the writing of this paper. The greatest difficulty encountered was obtaining sufficiently well matched pairs of specimens so as to permit valid comparisons to be drawn between uncoated indium specimens and those with varying thicknesses of a silicon monoxide overlay. A discussion of the procedures used and some of the problems encountered in the thin film evaporations may be found in Appendix I.

Four criteria were used for determining how well each pair was matched. These are: the mass of the indium evaporated, the physical appearance under microscopic examination (400X), the resistance at liquid helium temperatures (4.2°K), and the plot of the critical current (DC) vs temperature. Although the variation of the mass of indium evaporated was held generally to less than 0.3 per cent, mass deposition on the substrate is not felt to be as precise. As the indium melts it initially forms a spherical ball in the boat, but as the temperature increases prior to evaporation, the indium loses its spherical shape and wets a portion of the boat. In some instances the indium would cover different portions of the depression in the boat and thus give rise to slight variations in the dispersion pattern.

Small inclusions along the length of the superconducting strip, caused by microscopic dust particles and irregularities of the razor blade edges, give rise to localized variations in the specimen widths. Even specimens not appearing to vary significantly with respect to the above two criteria were sometimes found to have significantly different resistances in liquid helium.

Of the three pairs of specimens used, specimens 212 and X were found to be the most comparable on the basis of the above criteria. Resistance at liquid helium temperatures was found to vary only 11 per cent, and the critical current plots (Fig. 6) were identical. Specimens 71 and 224, although having a 25 per cent difference in resistance were found to have fairly comparable critical current plots. These two specimens also had large inclusions in the indium strip due to dust particle shielding of the substrate. These inclusions however, were remarkably similar in size, shape and resultant minimum width of the strip. Specimens X-1 and Y also had a relatively high difference in resistance, 23 per cent, and in addition, were found to have a more pronounced difference in critical current plots. The data obtained from each of these sets of specimens must therefore be weighed individually with the greatest reliability being placed on specimens 212 and X, the least reliability assigned to specimens X-1 and Y, and with specimens 71 and 224 being of intermediate reliability.

For a comparison of the backswitch time obtained with the specimens with variations in temperature, DC reference current, and superimposed voltage pulse, plots of the backswitch time vs total current through the specimen were made. Each of these plots (Figs. 16 to 52) displays this data for an individual set of specimens at one temperature and a given value of the DC reference current used. A more revealing comparison of the data was obtained by specifically examining the maximum and minimum backswitch times for each set of specimens. To accomplish this, the maximum backswitch time for the uncoated indium film at each temperature and DC reference current was used as a factor to normalize the maximum backswitch time for the coated specimens. A plot of the relative maximum backswitch time vs temperature was then made with the points plotted being the normalized value for the various DC reference currents used at the given temperature. The uncoated specimen thus has a constant value of one. Similar procedures were followed to obtain plots of the minimum relative backswitch time vs temperature for the three sets of specimens. These plots appear in Figs. 9 to 14. It should be noted however, that this comparison of the relative maximum and minimum backswitch times cannot be considered valid to more than one or (above a relative value of 1.0) at most two significant figures, since the precise value of the backswitch time at these two points could not be determined. In many instances a specimen would not have fully switched to the resistive state at a maximum. The relative minimum backswitch times are rendered less conclusive when it is considered that measurement of the minimum backswitch time on the oscilloscope with precision is difficult. It is therefore felt that the relative maxima are valid to a limited degree for the conclusions drawn from the data, and that the relative minima, though displaying a general trend, are not sufficiently valid for a conclusive comparison.

For the most reliable set of specimens, 212, 212(a), X, and X(a), the maximum backswitch times were found to be uniformly depressed to approximately one-half of the value found for the uncoated indium specimen, 212. This trend was observed down to 2.792°K and appears to be relatively independent of the thickness of the silicon monoxide layer. However, at 2.569°K a significant departure from the above behavior was found. The maximum backswitch times observed for the coated specimens at this temperature showed a pronounced increase. Again, no dependence of this increase on the thickness of the silicon monoxide layer can be determined due to the relatively wide variation in the maximum backswitch time for each specimen and the lack of a well defined trend. It should be noted however, that specimen X(a) with the heaviest silicon monoxide layer (74 mg) was found to have a greater relative maximum backswitch time at 2.569°K than the specimens with lesser masses of silicon monoxide. For this same set of specimens the relative minimum backswitch times for specimens 212(a) and

X were similarly found to be depressed with the greatest occurrence in the area of 0.5 to 0.6. Again at 2.569°K an increase was observed, though not as well defined as for the maximum backswitch time. For specimen X(a) however, the relative minimum backswitch times were found to group at a value of about 2.5 with a slightly greater value, 2.8, occurring at 2.569°K.

For the set of specimens 71 and 224 the above trend of reduction of the maximum backswitch times is again observed with the exception that the pronounced increase, which was observed above at 2.569°K, is not present. A relative maximum backswitch time of 0.6 was observed throughout the entire temperature range. For this same set, the relative minimum backswitch times show too little correlation to warrant any valid conclusions.

Specimens X-1 and Y show no consistent correlation in either the relative maxima or minima and hence no conclusion as to the effects of the silicon monoxide layer on the backswitch time can be drawn. There does appear to be an increase in the relative maximum and minimum backswitch times to above a value of 1.0. As discussed above, the criteria for matching specimens is felt to be sufficient to preclude the data obtained from these two specimens being accorded sufficient weight to reverse the trend noted from the other two sets.

It is of interest to note that the relative current at which the minimum backswitch time is observed for the set of specimens 212, 212(a), X and X(a) (relative to 212) is in all cases less than or equal to 1. In the plot of the relative current vs temperature (Fig. 15), a correction has been made to account for the difference in resistance of the two specimens, 212 and X, at 4.2°K. A similar comparison of the currents at which the maximum backswitch time occurred is not made due to the fact that in many instances, the specimens were only partially resistive when maxima were observed thus leaving some doubt as to the validity of such a comparison.

5. Conclusions.

The results of these experiments indicate that the phenomenon of heat flow from a superconductor in terms of the effects on the observed backswitch time is one of the areas in which much more work is necessary. It was believed by the authors, prior to conducting these experiments, that the application of a layer of silicon monoxide would inhibit the flow of heat from the specimen to the helium bath. It was projected that this should be evidenced by a general increase of the observed backswitch time and a reduction in the tendency for the backswitch time to pass through a minimum or at least for the minimum to be raised significantly. The results show the opposite effect. If heat flow is the dominant mechanism, it appears that the flow of heat from the specimen is actually facilitated by the silicon monoxide layer.

Only a limited amount of valid data was obtained, and it must be weighed as to its relative credibility as discussed in Section 4. It is felt, however, that the following conclusions may be drawn on the basis of the results of specimens 212, 212(a), X, and X(a) as supported to a limited degree by specimens 71 and 224.

1. The effect of the deposition of a layer of silicon monoxide over the superconducting film is to lower the maximum backswitch time within certain temperature ranges. A factor of approximately one half was found for the range 2.792° to 3.255°K.

2. This phenomenon of reduction of backswitch time is not independent of temperature as is indicated by a pronounced rise in the relative maximum backswitch time for 2.569°K in all specimens of the most similar set.

3. The uniformity in the reduction of the maximum backswitch times indicates that this reduction is relatively independent of the thickness of the silicon monoxide layer within the range used for these experiments.

4. The thinner silicon monoxide layers also decrease the minimum backswitch times significantly. However for specimen X(a) (74. mg silicon monoxide) the effect is reversed, and a pronounced increase of the minimum backswitch is observed. Therefore, it is concluded that a reduction of backswitch time in general will be observed and will be relatively independent of thickness of the silicon monoxide layer at or below a critical thickness. The last is just a conjecture since it is substantiated only by the data for specimen X(a) which displayed a general flattening of the backswitch time vs total current through the specimen curve while still maintaining a pronounced reduction of the maximum backswitch time.

The authors cannot advance any clear cut or definite explanation of this phenomenon. However, an analogy to the effects of a magnesium flouride film deposited on the surface of glass may yield a possible solution to the description of the observed behavior. If the heat conduction from the superconducting film to the helium bath were due to the transmission of phonon waves, the application of a silicon monoxide layer between the indium film and the helium bath could conceivably facilitate passage of these phonon waves by reduction of the surface reflection coefficient for the phonon waves. This would be parallel to the phenomenon observed in the reduction of the surface reflection coefficient of light waves passing from a glass surface into air by the application of a magnesium flouride coating to the glass. This could tend to explain the comparative independence of the silicon monoxide film thickness up to a limiting value. It is proposed that this limit was approached with specimen X(a).

6. Recommendations.

Since the variations in the backswitch time in superconducting materials may be of vital importance with respect to the use of these materials in computer memory or switching circuits, further investigations to expand the findings of this work is desirable. The following recommendations are therefore made with a view toward obtaining further and more definite data concerning the effects observed and to provide a better basis on which an analysis may be made.

1. Using a single indium specimen, make successive evaporations of silicon monoxide over this specimen with data runs following each evaporation. This procedure has been found workable, and the difficulties encountered due to the lack of precise similarity of the indium films are reduced significantly.
2. Broaden the temperature range to investigate more fully the temperature dependence of the backswitch time as noted in Section 4. It is further recommended that this temperature range be extended to include the lambda point of liquid helium.
3. Examine the effects on the backswitch time of a broader range of silicon monoxide thickness than used herein.
4. Utilize other materials, such as magnesium flouride, as insulating layers over the indium films.

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Appendix I Thin film evaporation procedures.

All thin films described in this paper were made by the authors in the vacuum system described in Section 2. The substrates upon which the films were evaporated were glass discs one inch in diameter and one-eighth inch thick. The first step in the process of making thin films is the fabrication of a mask of the desired dimensions. A suitable mask was made using Gillette thin double edge razor blades secured with Duco cement onto a steel plate which is bolted over the substrate. The thin blades provide separation between the defining edges of the mask and the substrate to avoid stripping off or damaging the film upon removal of the mask, while minimizing the penumbra effect caused by this separation. Considerable care must be used to select blades which have satisfactorily smooth edges. Microscopic examination can ensure this. The blades are ground as desired to allow a suitable length of film and contact areas at each end of the strip which was nominally chosen 50 to 60 microns in width. Fig. 5 shows the mask and the subsequent film configuration.

In early film evaporations, the authors used tantalum boats which were made by them in the laboratory. Use of these boats produced generally acceptable results as far as the film quality was concerned but were later deemed unsatisfactory due to nonuniformity of the boats and hence of the films themselves. The films used in this paper were evaporated using molybdenum boats obtained from the

Rembar Company, Dobbs Ferry, New York.

In order to obtain an estimate of the thickness of the films, a cosine law distribution of the evaporated material was assumed. In this approximation, the mass of the material deposited is a function of the angle of elevation of the substrate from the boat. In all cases this angle was 90°. This then gives an expression of the form:

$$t = \frac{m}{\rho \pi r^2}$$

where t is the thickness of the film, m the mass of the material evaporated, ρ its density, and r the distance from the substrate to the boat. It is to be noted that the cosine distribution assumes a flat evaporating surface. Hence, with a significantly dimpled boat, the above formula will yield a lesser thickness than actually deposited. Since we are interested only in the mass thickness ratio, we may still use the cosine law as an approximation.

Inherent in the evaporation of thin films is the problem of dust, and considerable care must be exercised to prevent dust particles from settling on the substrate or mask prior to placing them in the vacuum system. The substrate is thoroughly cleaned with acetone and distilled water before it is glued in place using Duco cement. The mask is then placed over the substrate and the vacuum system is assembled and evacuated with utmost dispatch to allow as little time as possible for dust accumulation. During the actual evaporation of the indium films, the two wells in the top plate of the vacuum jar are filled with liquid air. This procedure provides additional cryogenic pumping on the well surfaces in addition to the large baffle attached to the outer well. The central well is filled since it is desirable to have the substrate at a low temperature during the indium evaporation. Pressures of the order of 10^{-7} Torr were maintained during the majority of the evaporations thus minimizing contamination of the deposited films.

The silicon monoxide used as an insulator over the films created many more problems than had been anticipated. Silicon monoxide has been used for several years in evaporation processes and considerable information on its properties is available.[1] Holland gives an approximate density for silicon monoxide as 2.15 gr/cm^3 and states that evaporation can be accomplished at temperatures of about 1200-1250° C. Silicon monoxide sublimes rather than evaporates from a liquid state. It has a tendency, possibly due to absorbed moisture and differences in thermal expansion rates, to hop about in the boat as the temperature is elevated. This property was particularly noted when evaporations with finely divided silicon monoxide were attempted. Accordingly particles of the order of 3 to 5 milligrams mass were found to yield the best results as this mass prevents most of the movement if care is exercised

[1] Holland, L., Vacuum Deposition of Thin Films, Wiley, 1956.

in bringing the boat temperature up to that necessary for sublimation. Any rapid change of temperature of the boat should be avoided since even particles of the size recommended fell from the boats on both raising and lowering the temperature at moderate rates.

In initial attempts to evaporate silicon monoxide overlays on indium films, tungsten boats made by the authors from five-mil tungsten strip were used. Tungsten is a difficult material to work, and these boats were generally found to be unsatisfactory. Conical baskets of closely wound tungsten wire were then tried and found to allow rapid evaporation but yielded a generally unsatisfactory dispersion pattern. Satisfactory results were finally obtained using tungsten boats identical in size to the molybdenum boats described above. These were also obtained from the Rembar Company. In every silicon monoxide evaporation, a residue, variable in amount, is left in the boat after evaporation. This residue must be weighed and taken into account in approximating the film thickness. In order to produce a uniformity of results, it is recommended that:

1. Both boat and silicon monoxide to be evaporated be weighed before and after the evaporation.
2. Evaporation temperature be brought slowly up to approximately 1500°C and held constant at that value. Higher tamperatures tend to fuse the silicon monoxide to the boat and cause excessive residue.

It should be noted that the time required for the silicon monoxide evaporation is of the order of 30 to 50 minutes as compared with 40 to 70 seconds for indium. During the silicon monoxide evaporation, the specimen should not be cooled by filling the central well in the top plate of the vacuum jar as is done during the indium evaporation. Such a procedure will result in chipping of the indium film.

In order to permit evaporation of both the indium film and the silicon monoxide overlay without breaking open the vacuum system between evaporations an auxiliary mask was constructed. The mask has spring loaded shutters held open during the indium evaporation by burn out wires (Parr oxygen bomb wire). Prior to the evaporation of the silicon monoxide, the burn out wires were parted by a 10-volt pulse allowing the shutters to close and cover the contact areas on the specimen. This mask is shown in Fig. 5.

Table 1: Specimen Data

Specimen	In Mass Evaporated (mg)	SiO Mass Evaporated (mg)	Minimum Width (μ)	In Thickness (μ)	Resistance at 4.2°K (ohms)	Notes
212	141.6	--	45	0.1	1.96	1
212(a)	141.6	18.5	45	0.1	1.96	1,2
X	141.9	37.0	50	0.1	1.73	1
X(a)	141.9	74.0	50	0.1	1.73	1,3
71	142.0	--	12	0.1	1.52	1,4
224	141.8	32.7	12	0.1	1.13	1,4
X-1	120.4	--	42.5	0.08	2.86	1
Y	120.5	40.1	45	0.08	2.20	1

Notes:

1. All specimens are 1.232 cm in length.
2. Specimen 212(a): 18.5 mg of SiO were evaporated over the indium film after data was taken for the uncoated specimen 212.
3. Specimen X(a): 37.0 mg SiO were evaporated over the initial 37.0 mg SiO overlay after data was taken for specimen X.
4. Specimens 71 and 224: Both had inclusions along the length of the indium strip due to dust particles. Inclusions were very nearly identical in size, shape and residual minimum specimen width.

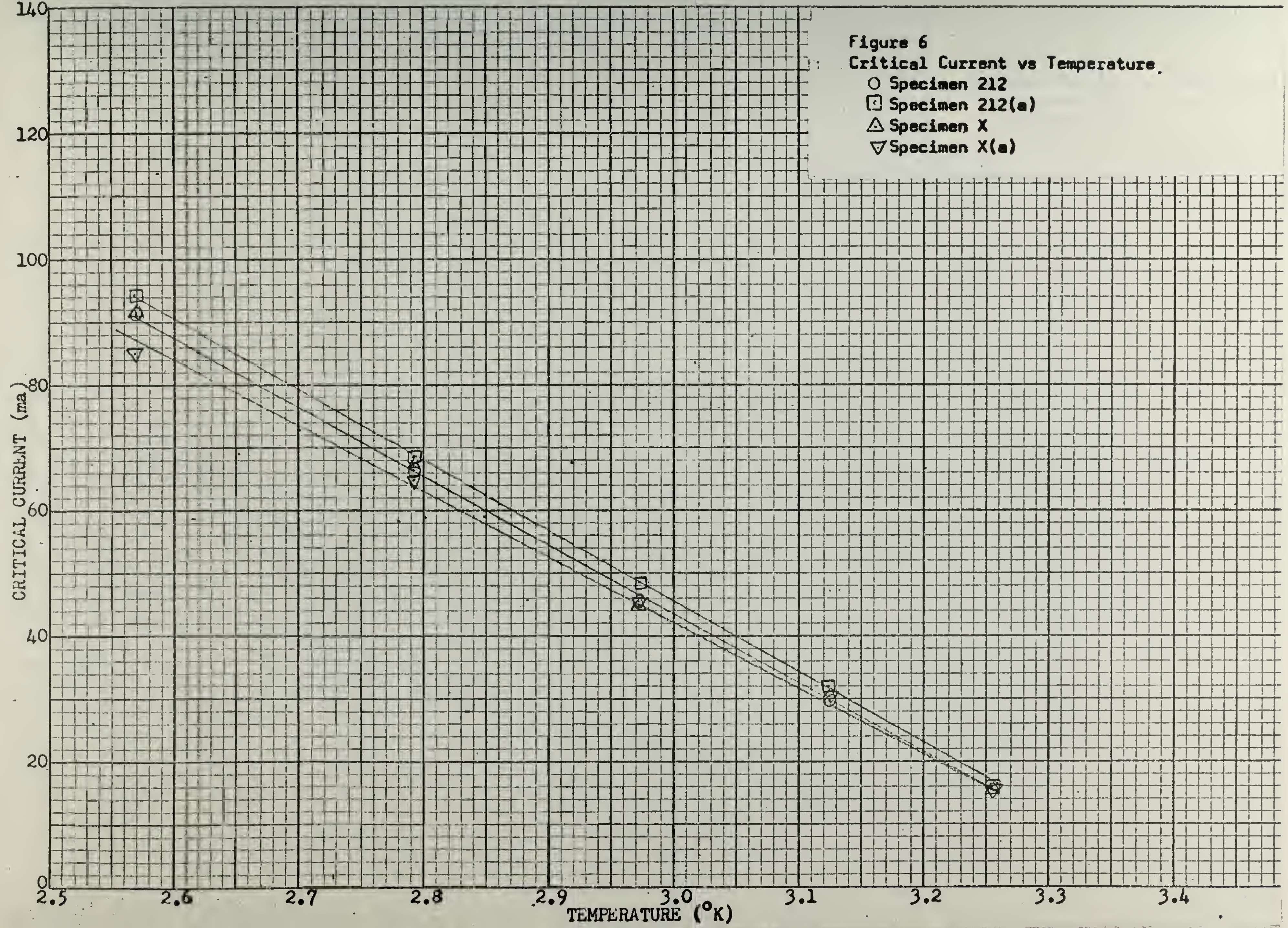


Figure 6
Critical Current vs Temperature

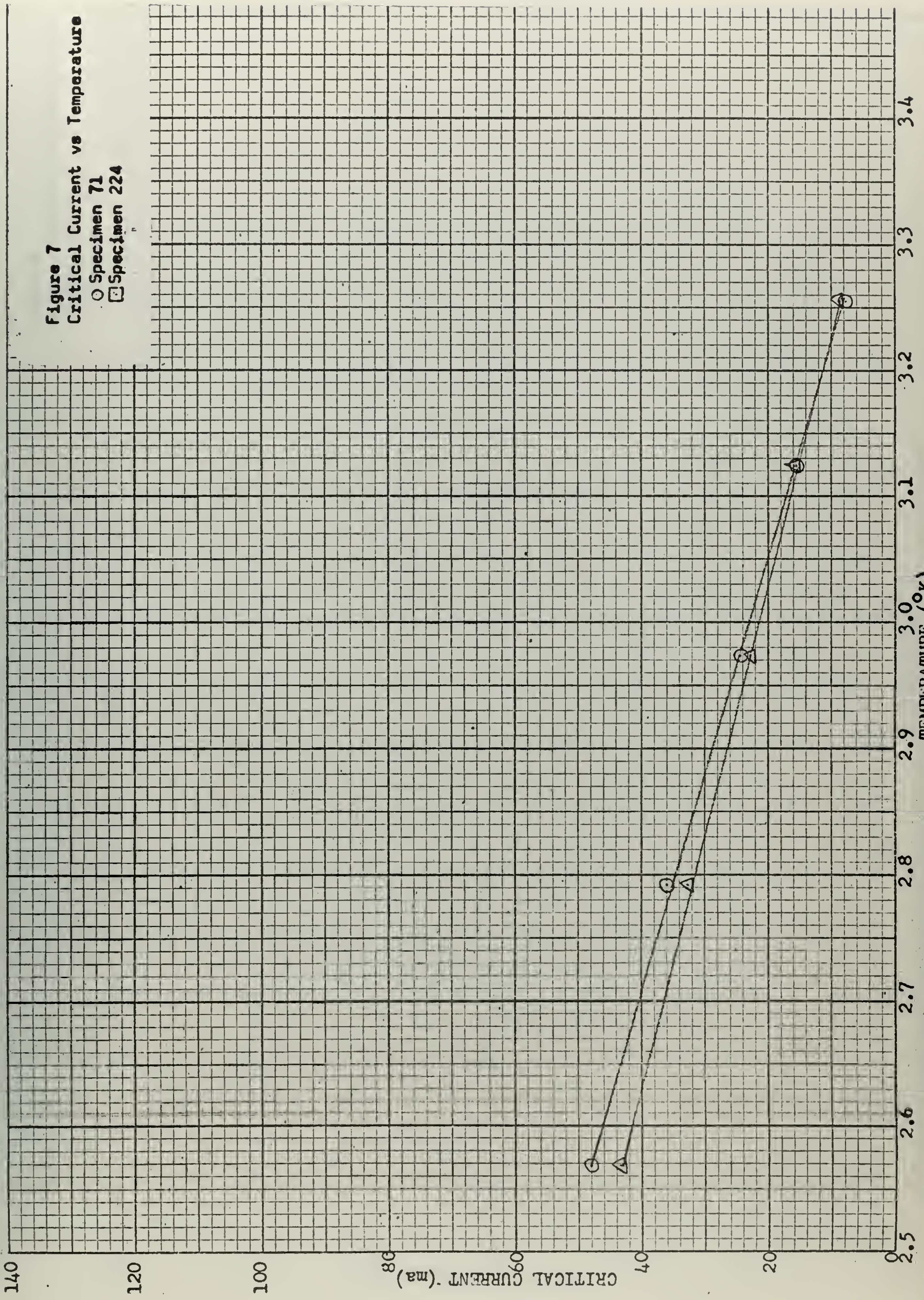


Figure 7
Critical Current vs Temperature

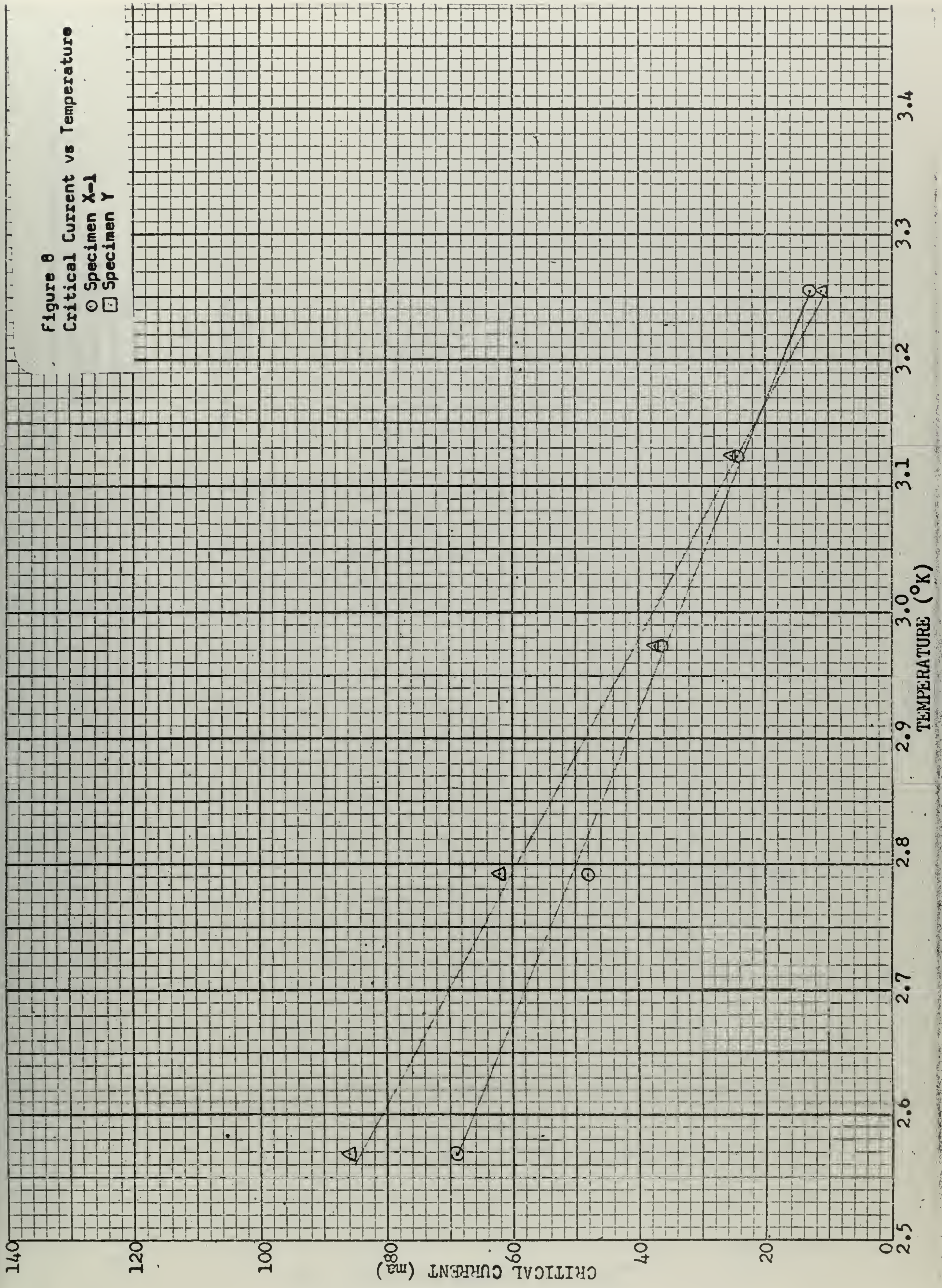


Figure 8
Critical Current vs Temperature

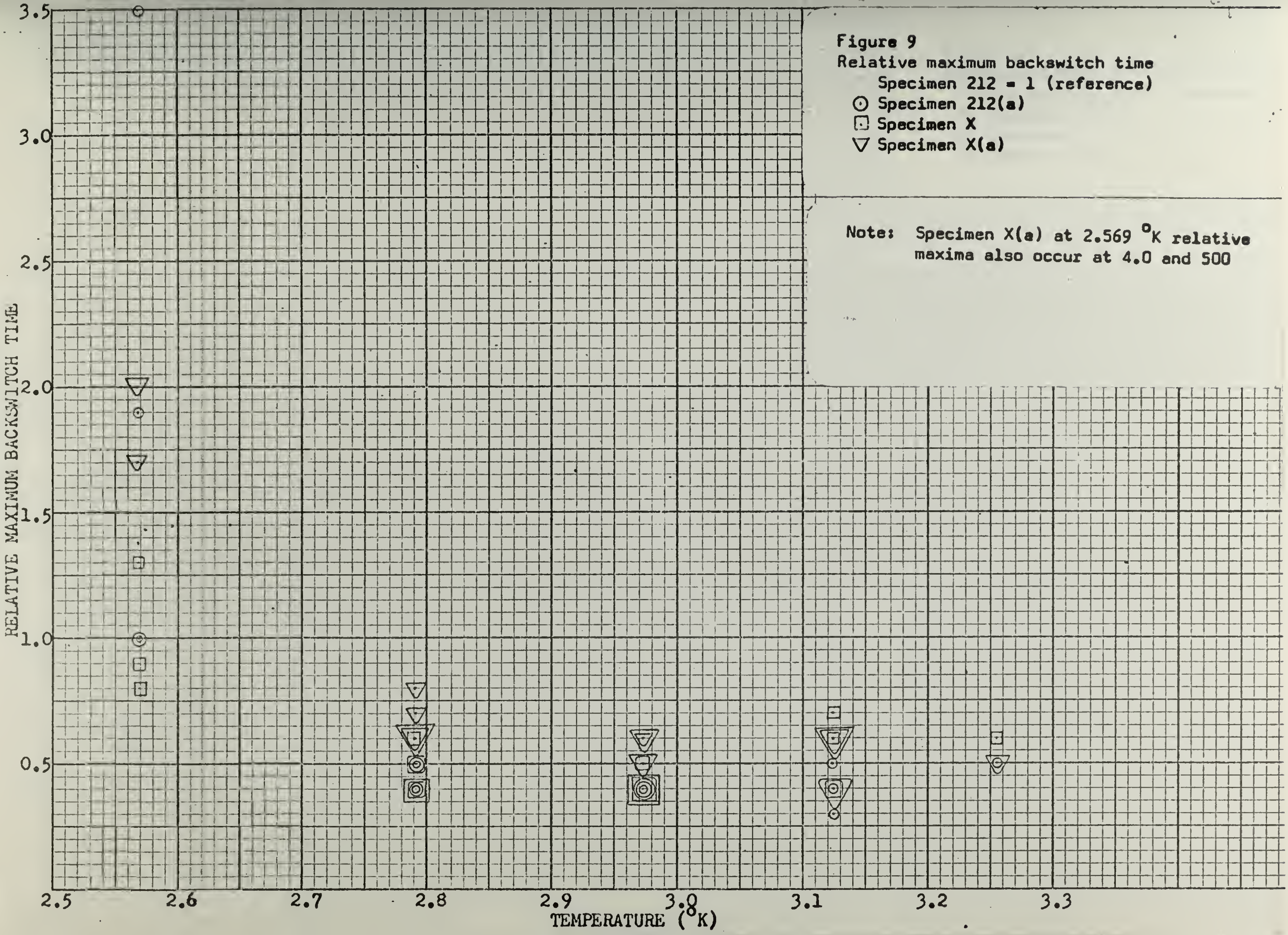


Figure 9
Relative maximum backswitch time

Note: Specimen X(a) at 2.569 °K relative maxima also occur at 4.0 and 500

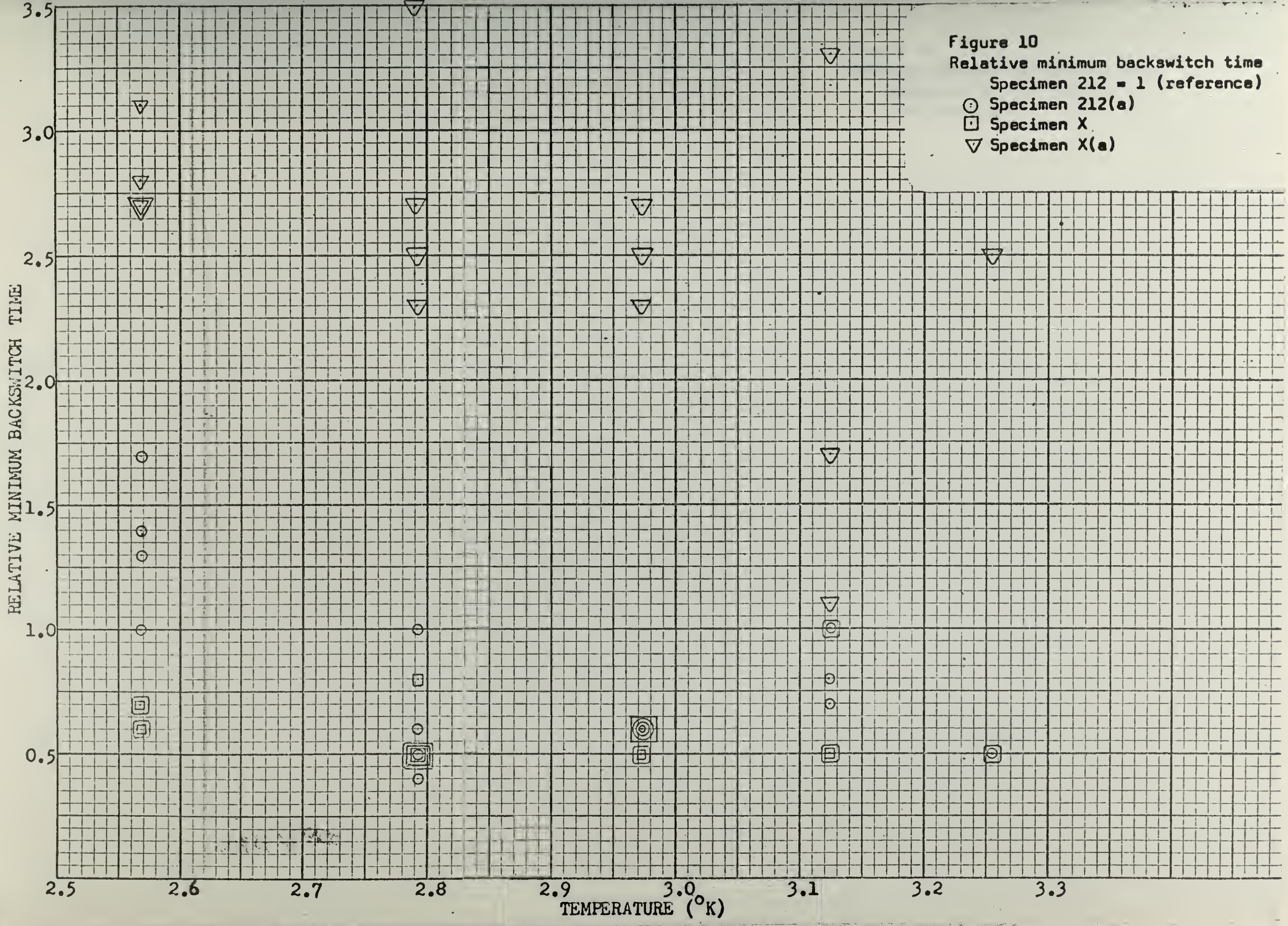


Figure 10
Relative minimum backswitch time
Specimen 212 = 1 (reference)

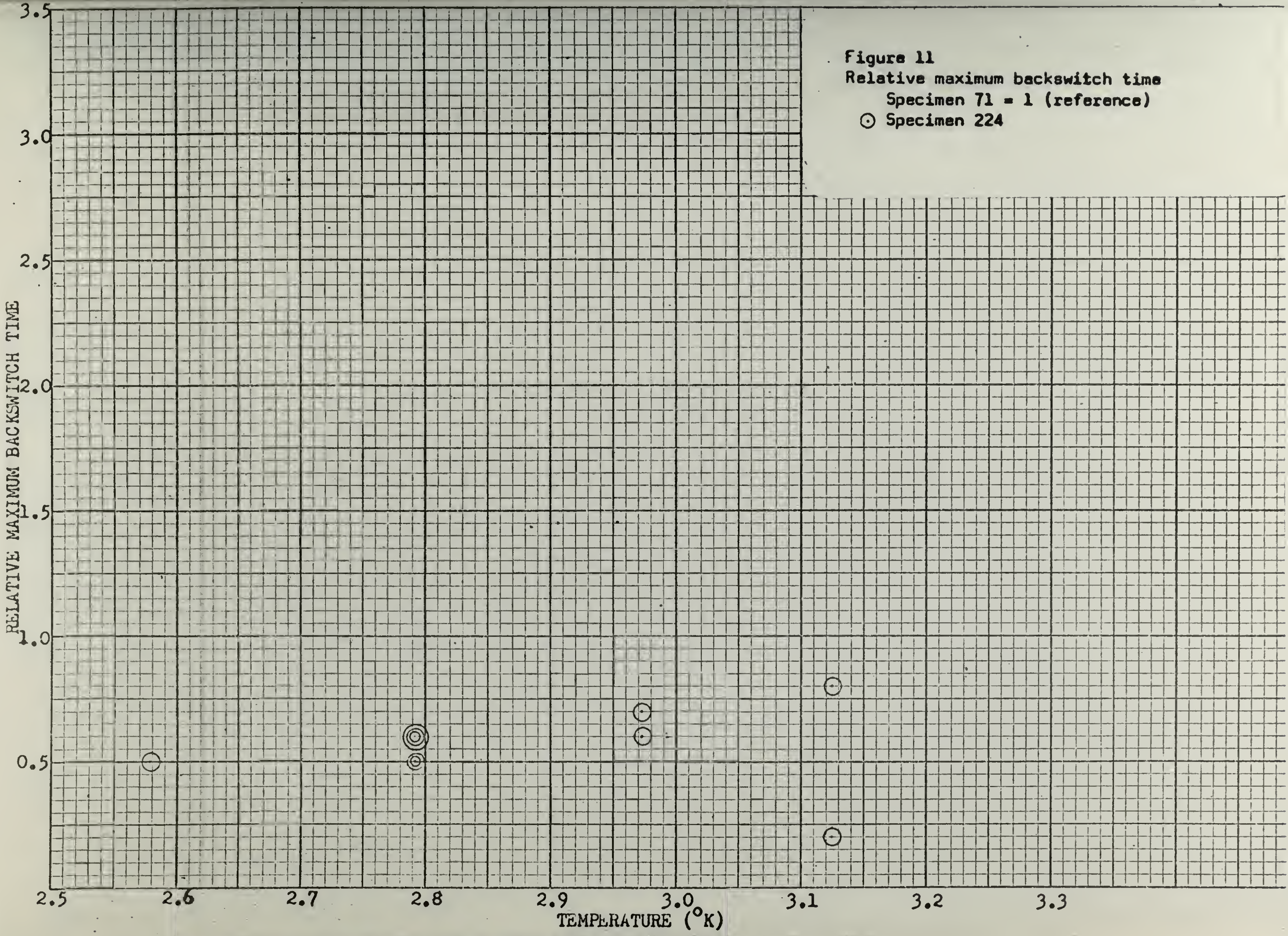
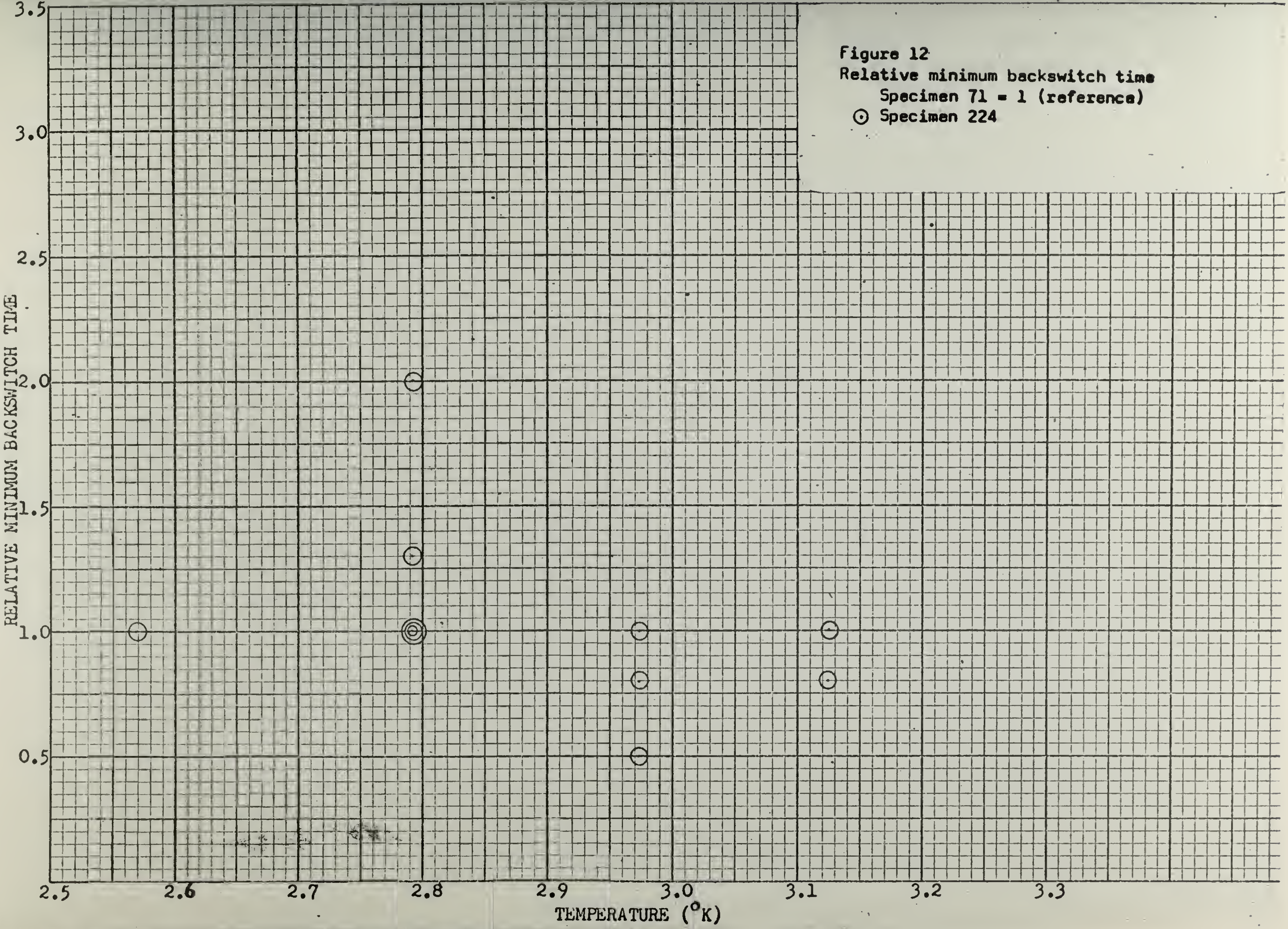


Figure 11
Relative maximum backswitch time



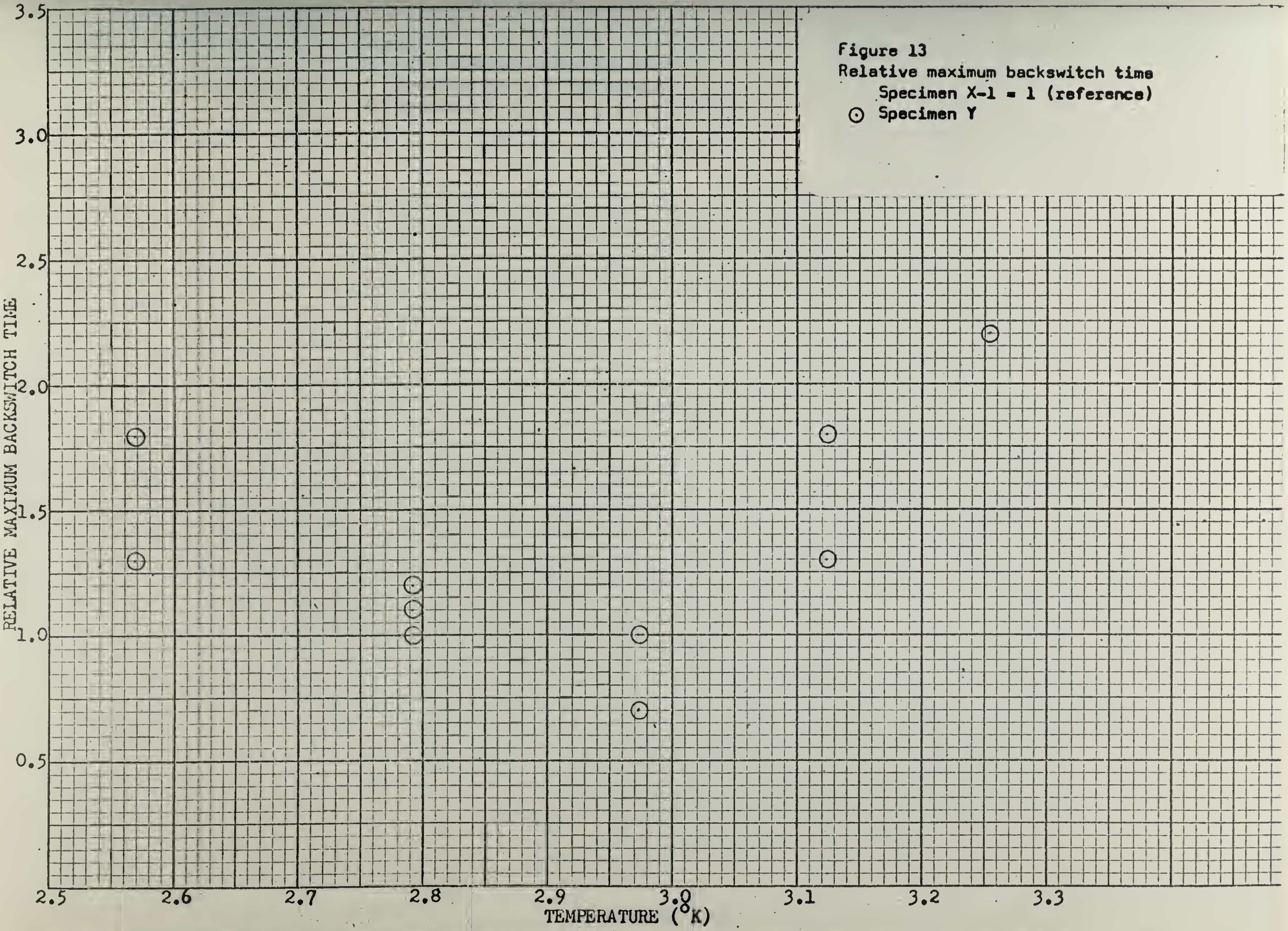


Figure 13
Relative maximum backswitch time
Specimen X-1 = 1 (reference)
⊙ Specimen Y

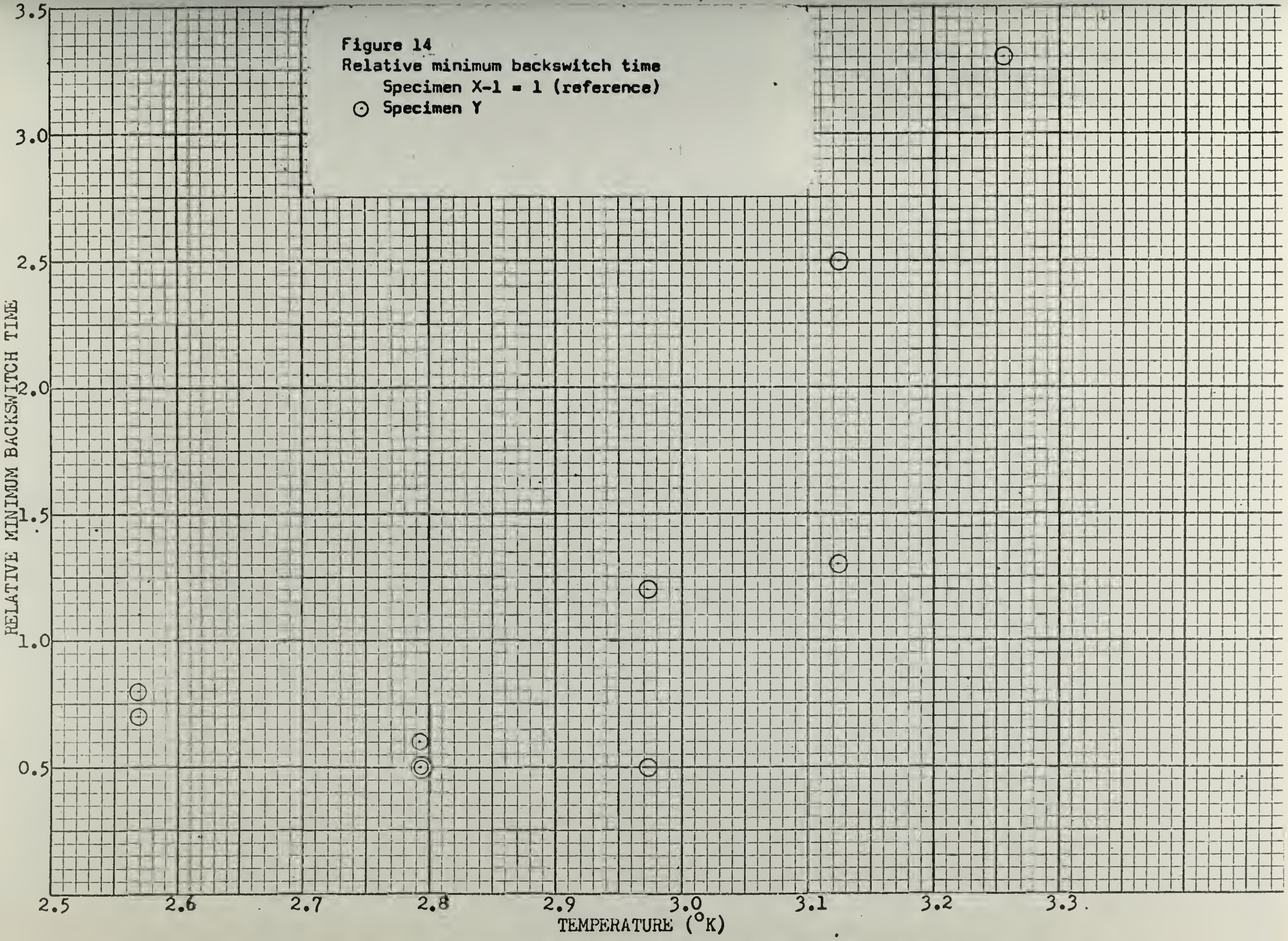


Figure 14
Relative minimum backswitch time
Specimen X-1 = 1 (reference)
⊙ Specimen Y

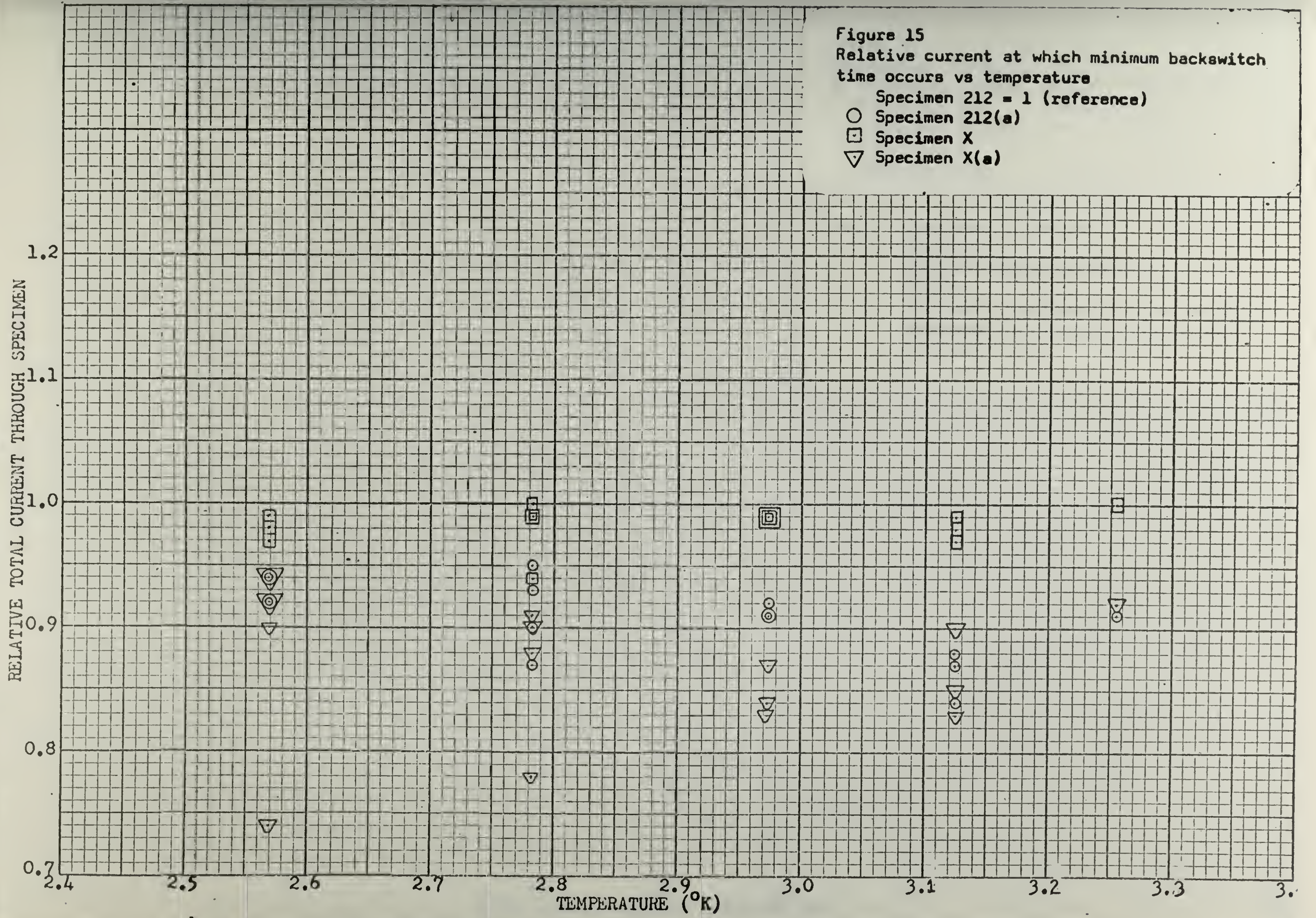


Figure 15
Relative current at which minimum backswitch time occurs vs temperature

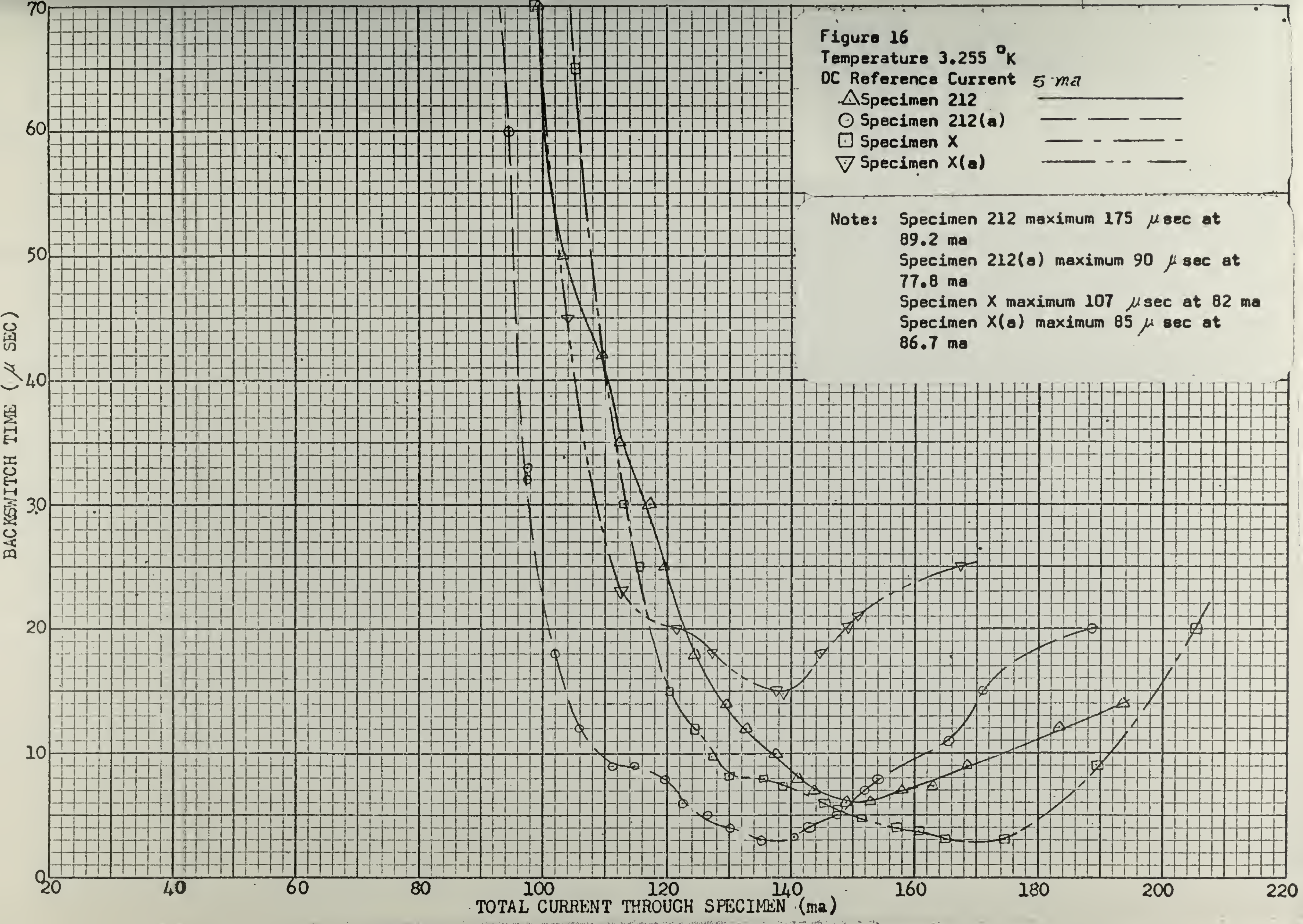


Figure 16
Temperature 3.255 °K
DC Reference Current 5 ma

Note: Specimen 212 maximum 175 μsec at 89.2 ma
Specimen 212(a) maximum 90 μsec at 77.8 ma
Specimen X maximum 107 μsec at 82 ma
Specimen X(a) maximum 85 μsec at 86.7 ma

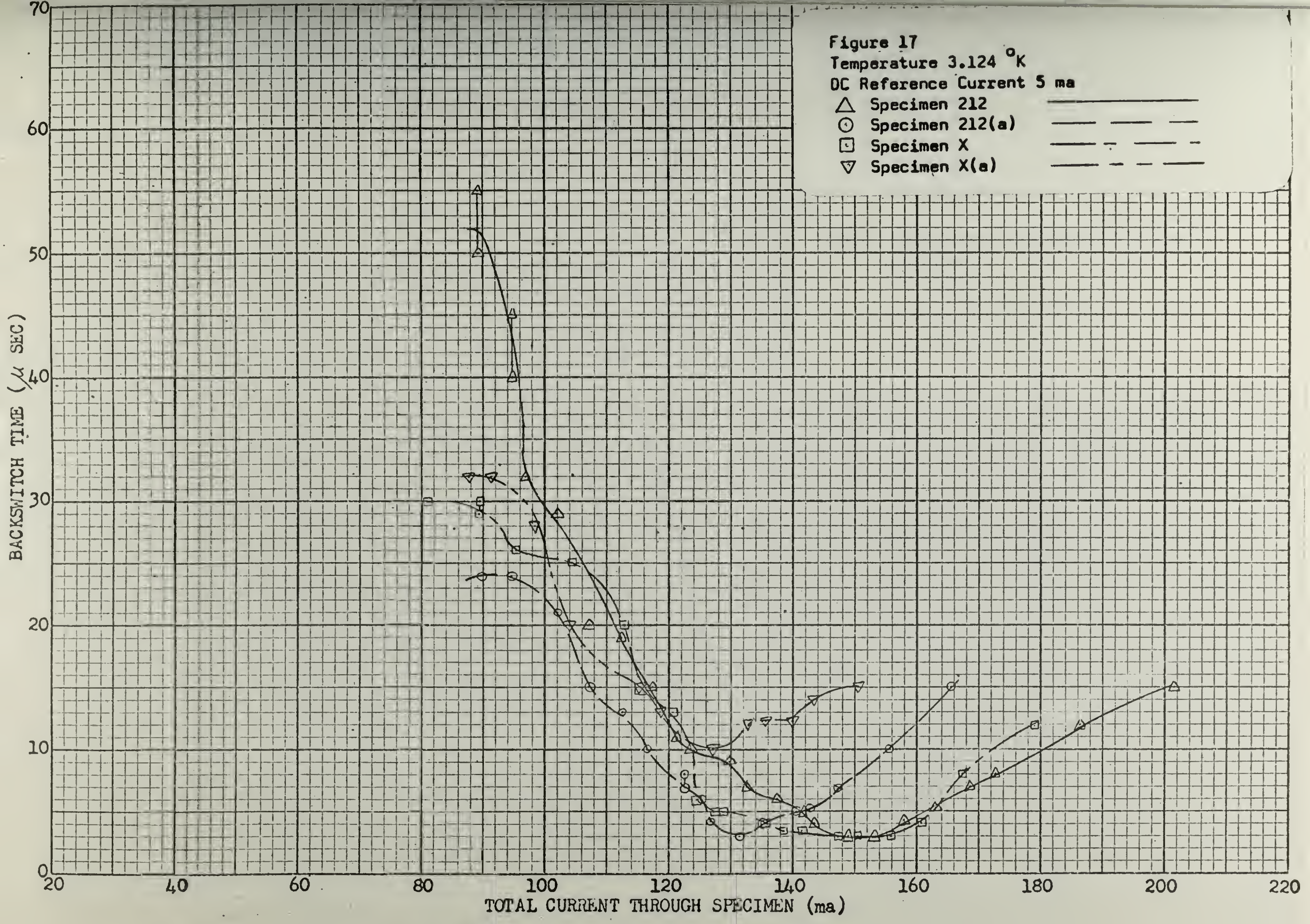


Figure 17

Temperature 3.124 °K
DC Reference Current 5 ma
△ Specimen 212
⊙ Specimen 212(a)
⊡ Specimen X
▽ Specimen X(a)
BACKSWITCH TIME (μ SEC)
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
220
TOTAL CURRENT THROUGH SPECIMEN (ma)

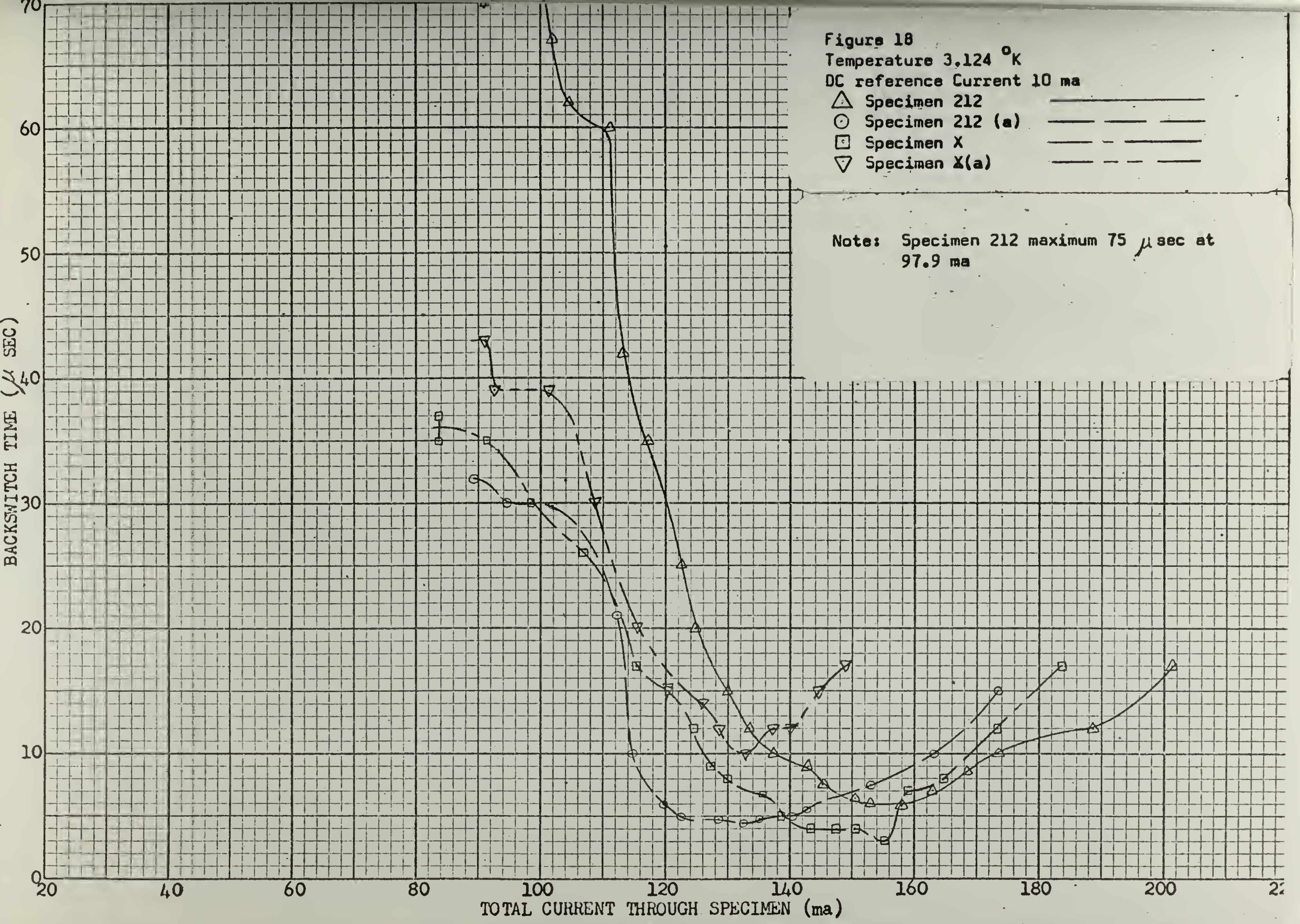


Figure 18
Temperature 3.124 °K
DC reference Current 10 ma

Note: Specimen 212 maximum 75 μ sec at 97.9 ma

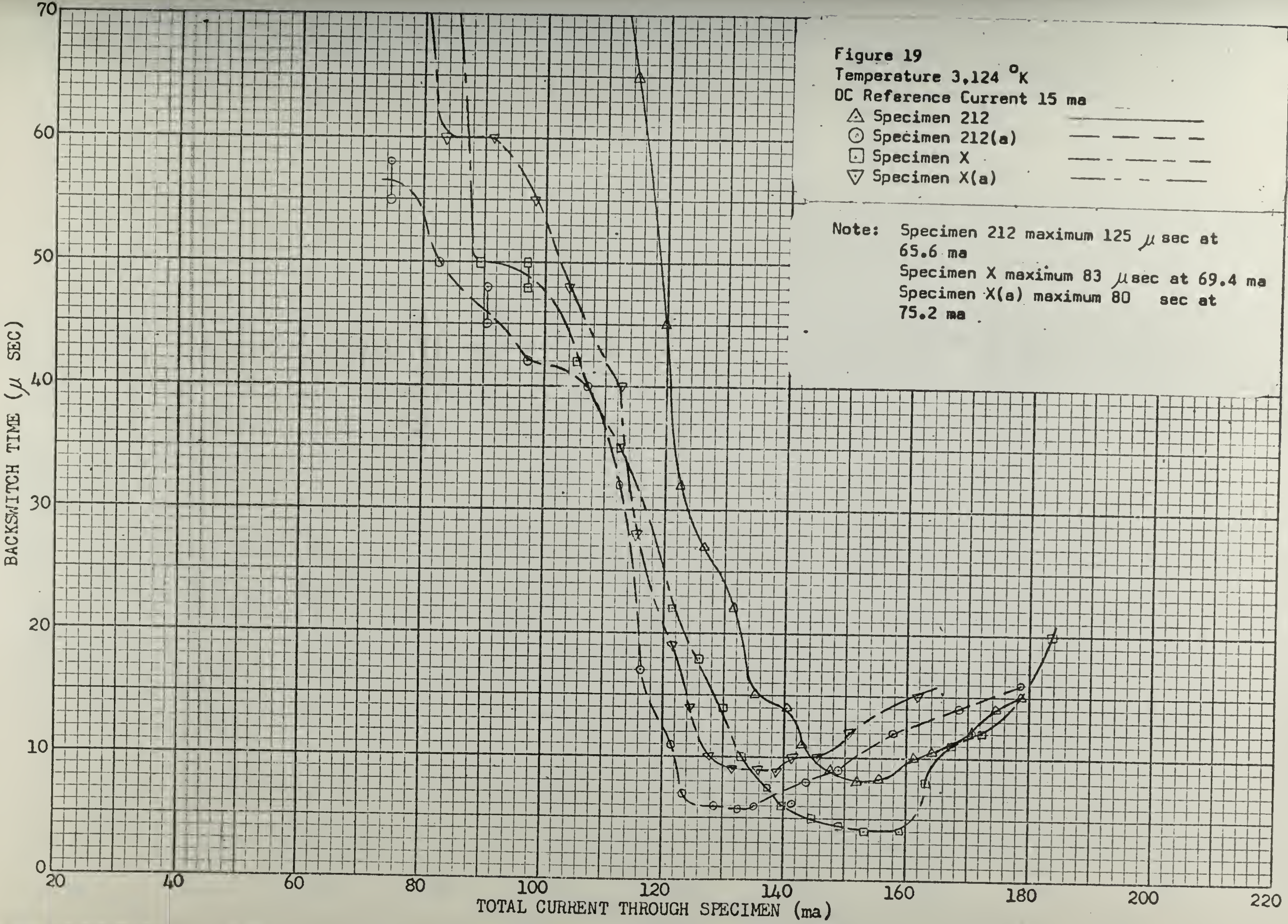


Figure 19
Temperature 3.124 °K
DC Reference Current 15 ma

- △ Specimen 212 ———
- ⊙ Specimen 212(a) — — —
- ⊡ Specimen X —- — —
- ▽ Specimen X(a) —- - —

Note: Specimen 212 maximum 125 μ sec at 65.6 ma
Specimen X maximum 83 μ sec at 69.4 ma
Specimen X(a) maximum 80 sec at 75.2 ma

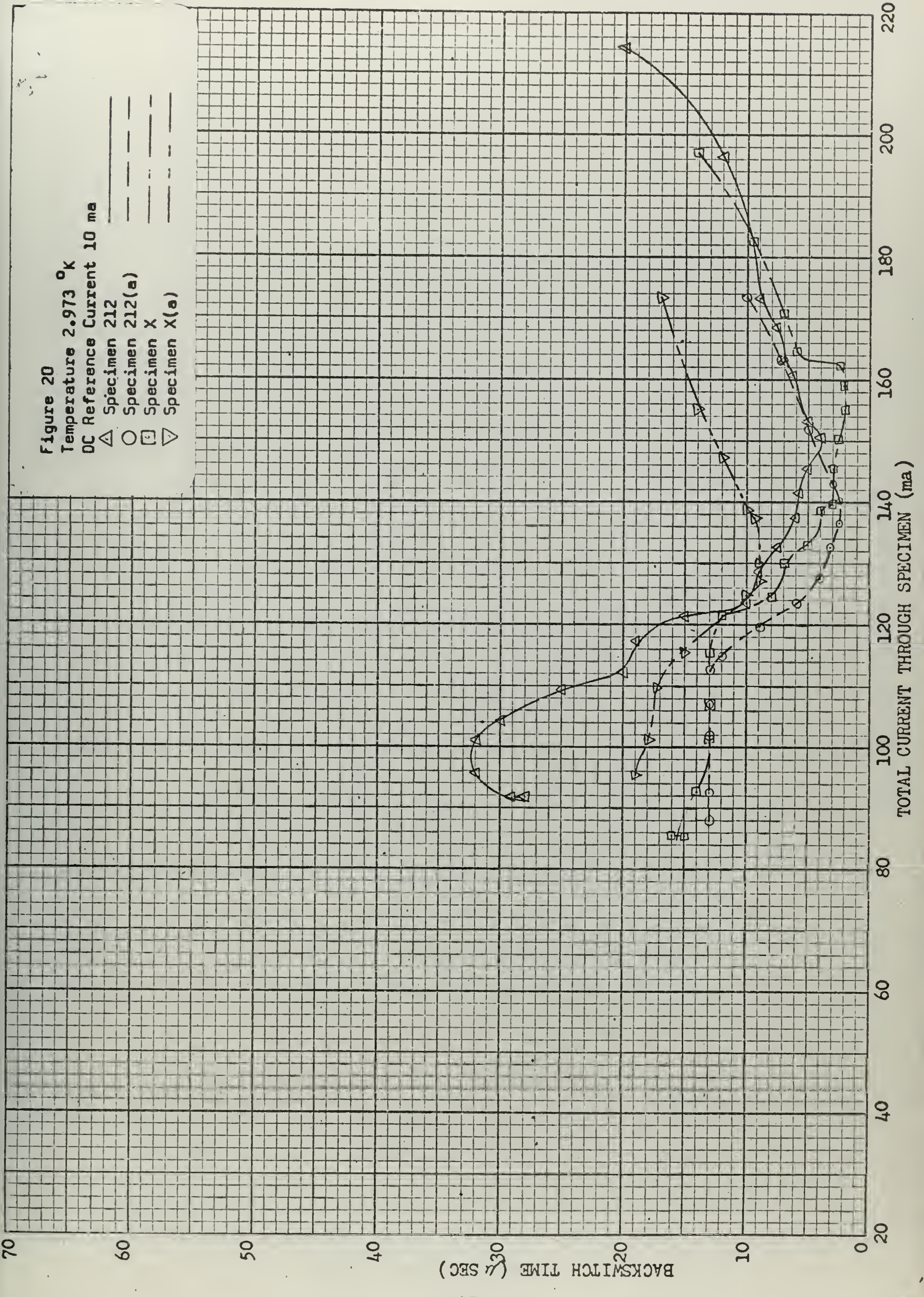


Figure 20

Temperature 2.973 °K
DC Reference Current 10 ma
△ Specimen 212
○ Specimen 212(a)
⊡ Specimen X
▽ Specimen X(a)
TOTAL CURRENT THROUGH SPECIMEN (ma)
20
40
60
80
100
120
140
160
180
200
220
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70

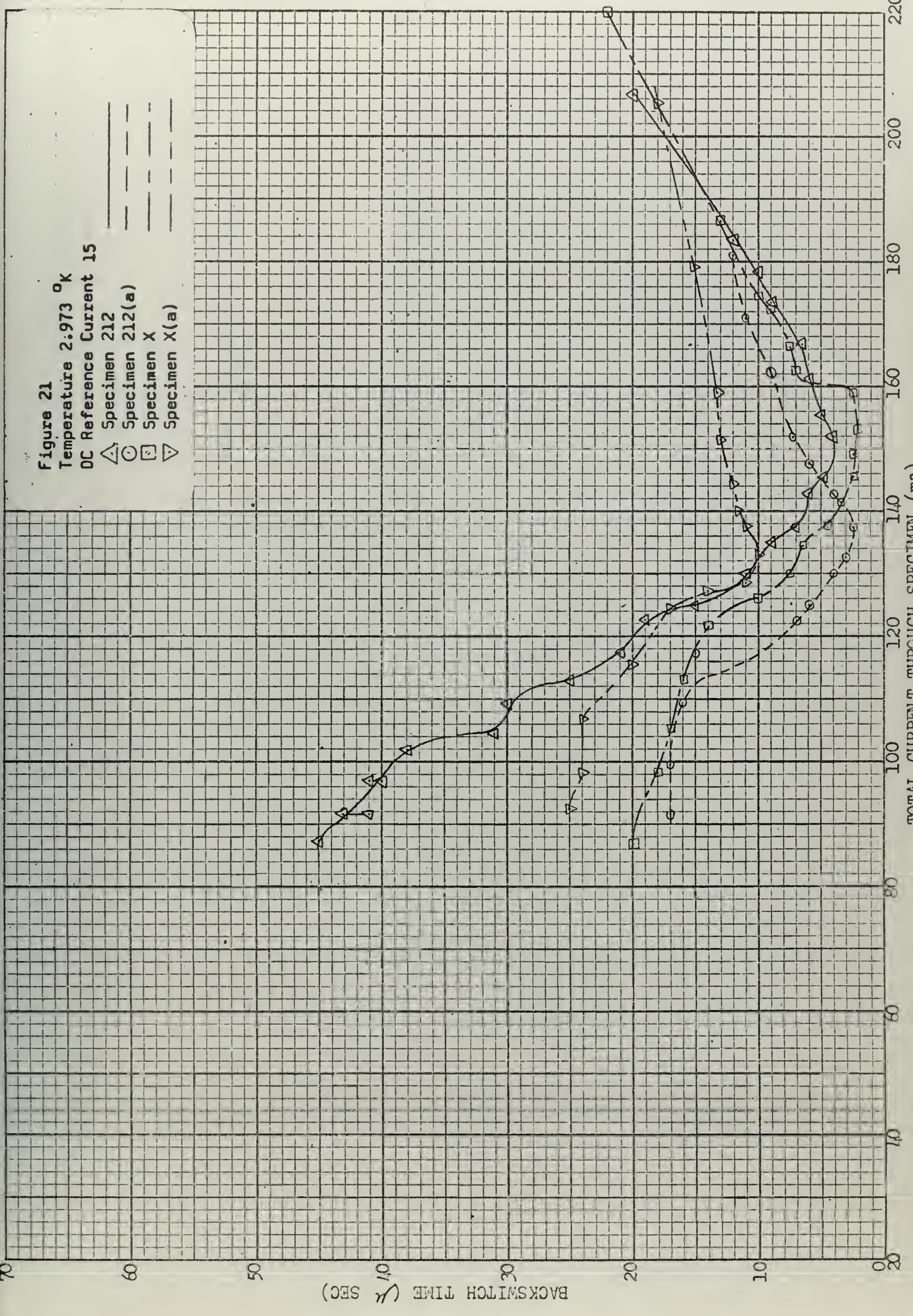


Figure 21

Temperature 2:973 °K
DC Reference Current 15
△ Specimen 212
⊙ Specimen 212(a)
⊡ Specimen X
▽ Specimen X(a)
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
20
40
60
80
100
120
140
160
180
200
220

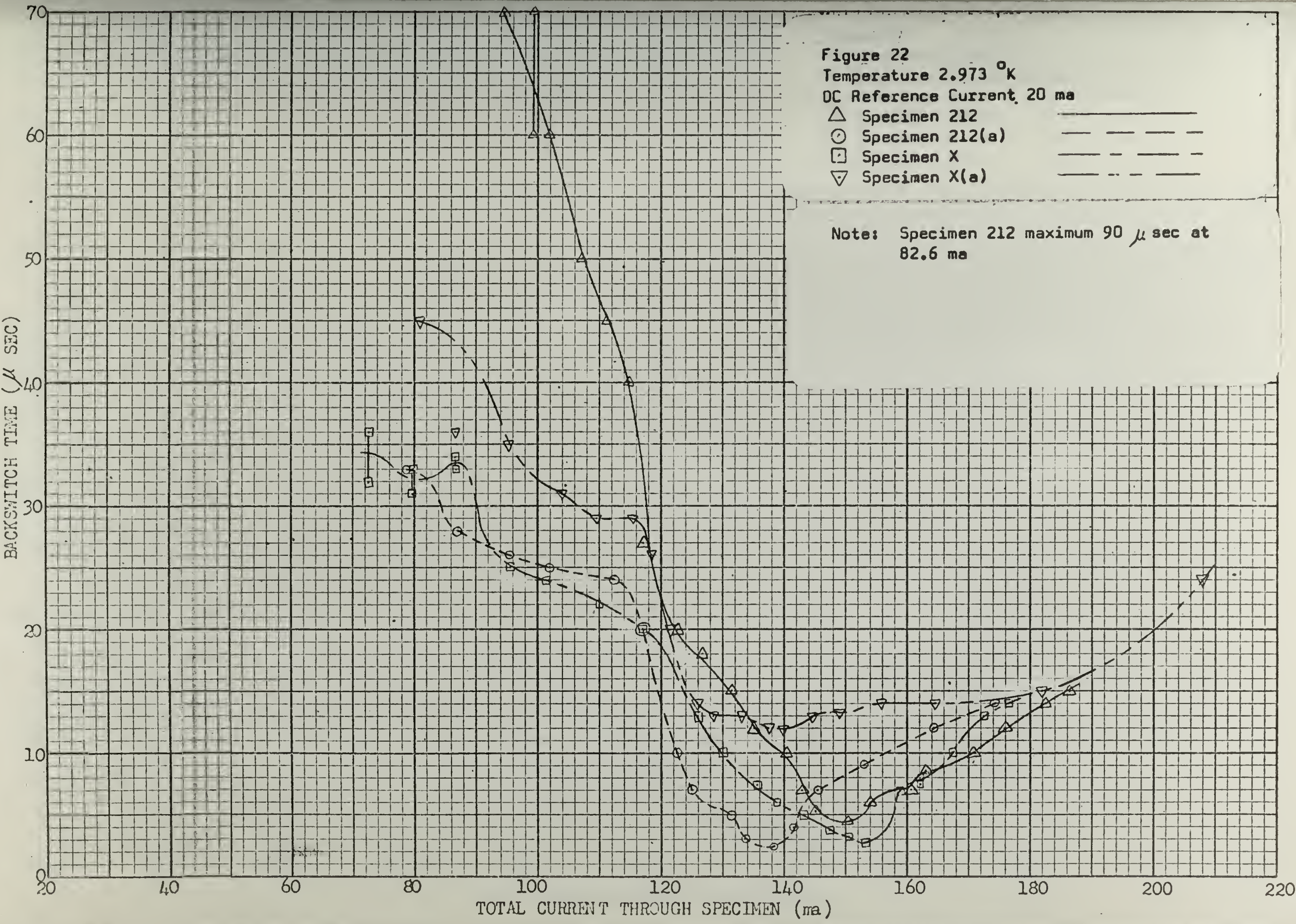


Figure 22

Temperature 2.973 °K

DC Reference Current 20 ma

Note: Specimen 212 maximum 90 μ sec at 82.6 ma

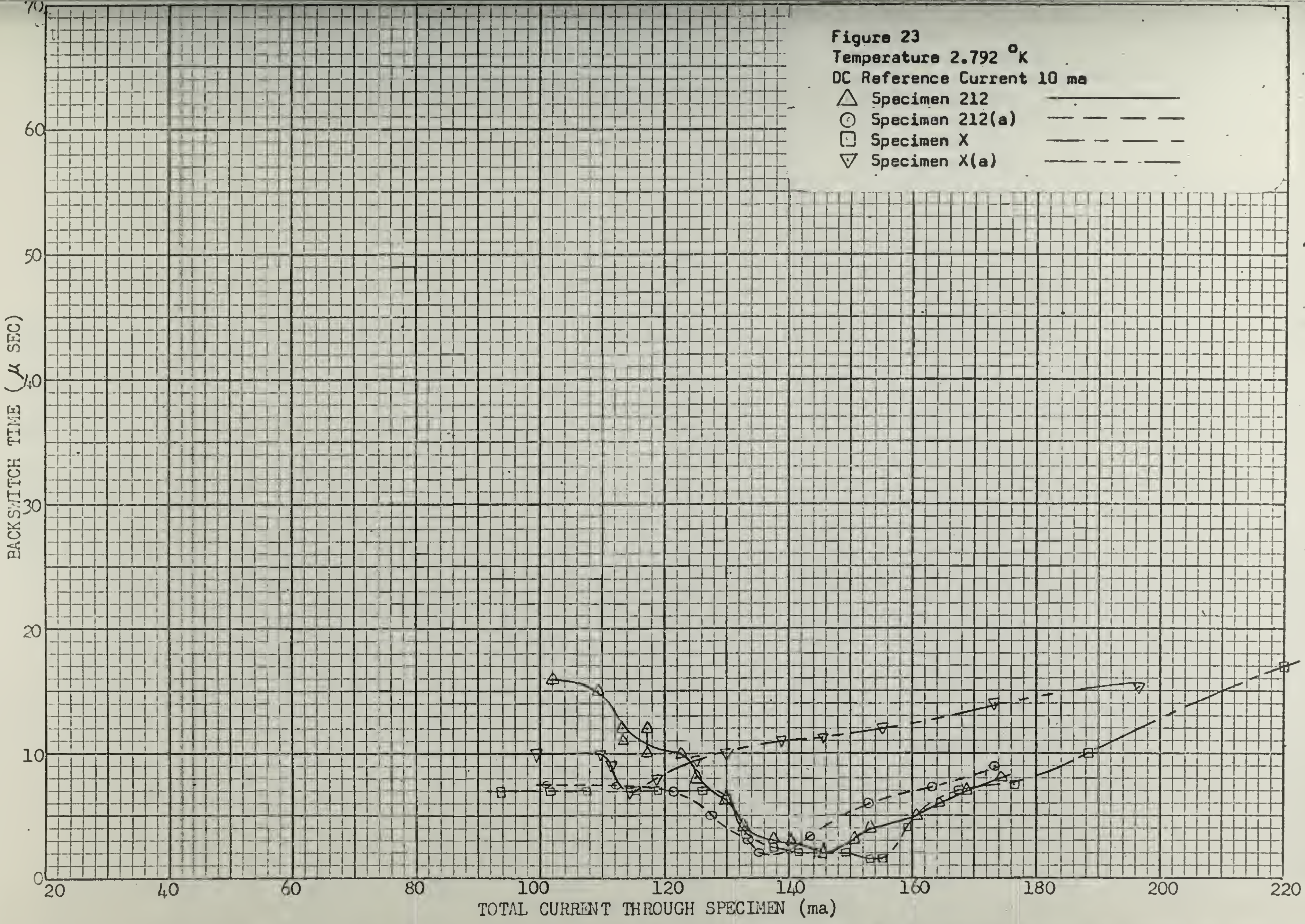


Figure 23
Temperature 2.792 °K
DC Reference Current 10 ma

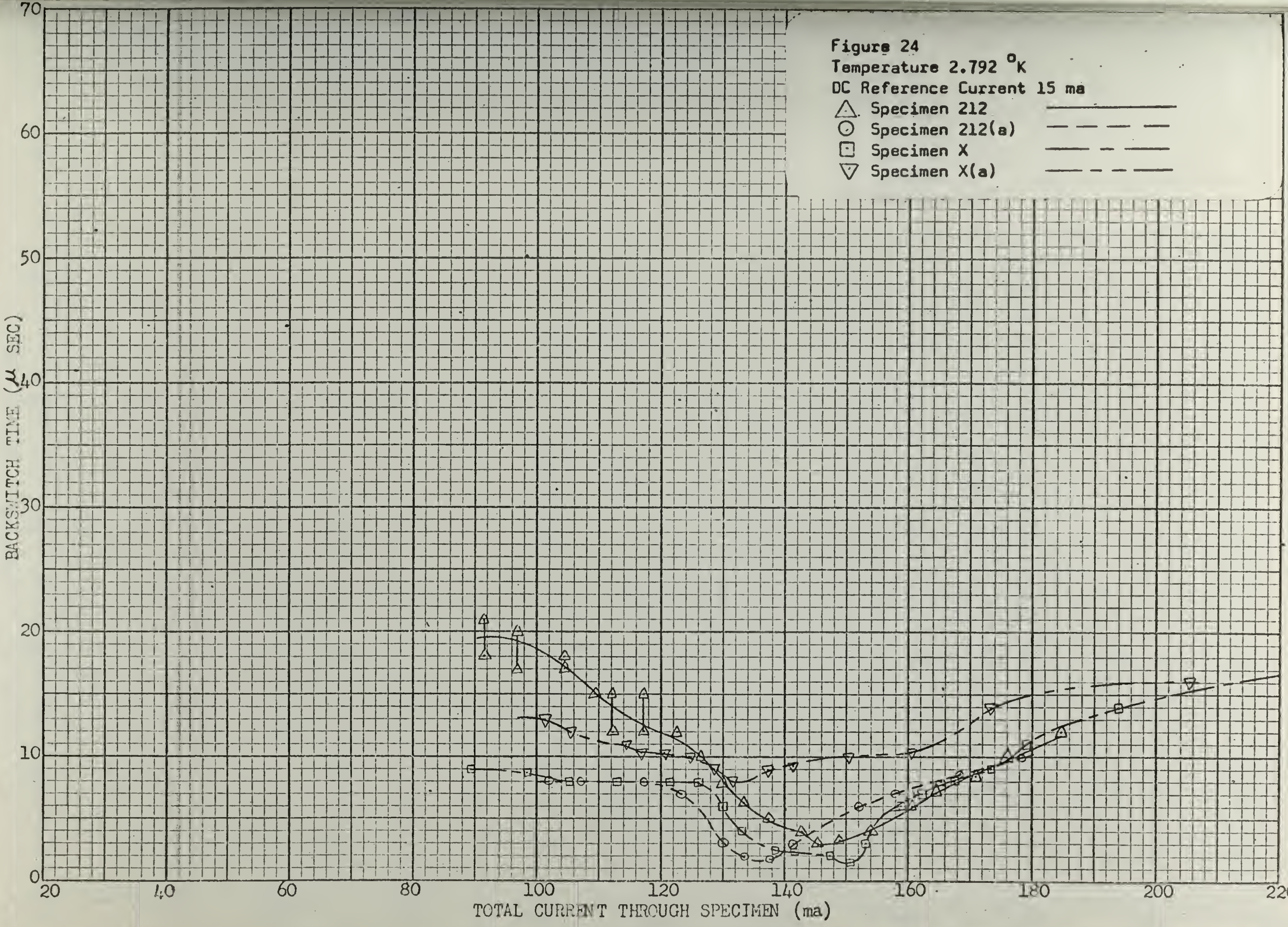


Figure 24
Temperature 2.792 °K
DC Reference Current 15 ma

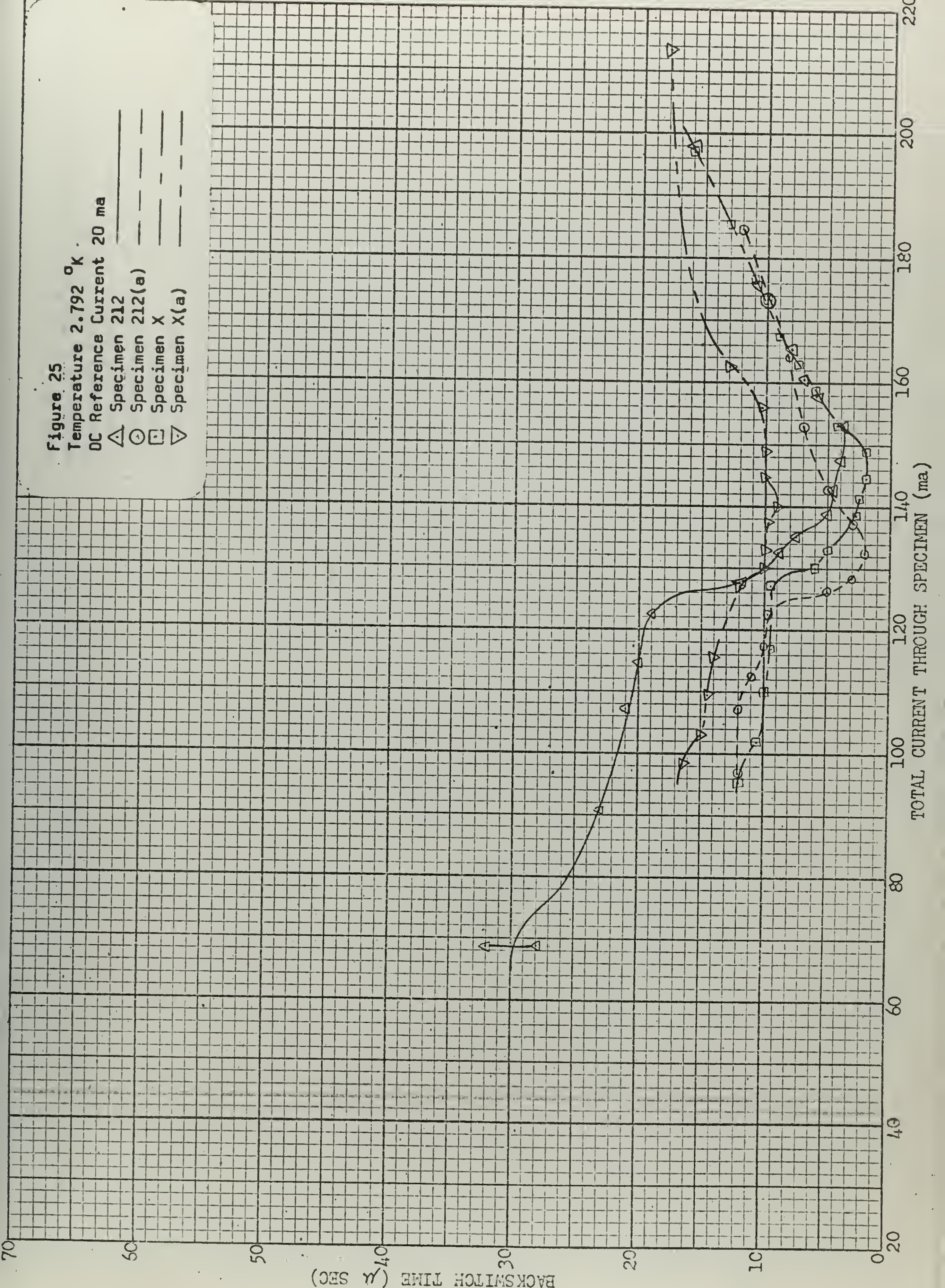


Figure 25

Temperature 2.792 °K
DC Reference Current 20 ma
△ Specimen 212
⊙ Specimen 212(a)
⊡ Specimen X
▽ Specimen X(a)
TOTAL CURRENT THROUGH SPECIMEN (ma)
BACKSWITCH TIME (μ SEC)
20
40
60
80
100
120
140
160
180
200
220
0
10
20
30
40
50
60
70

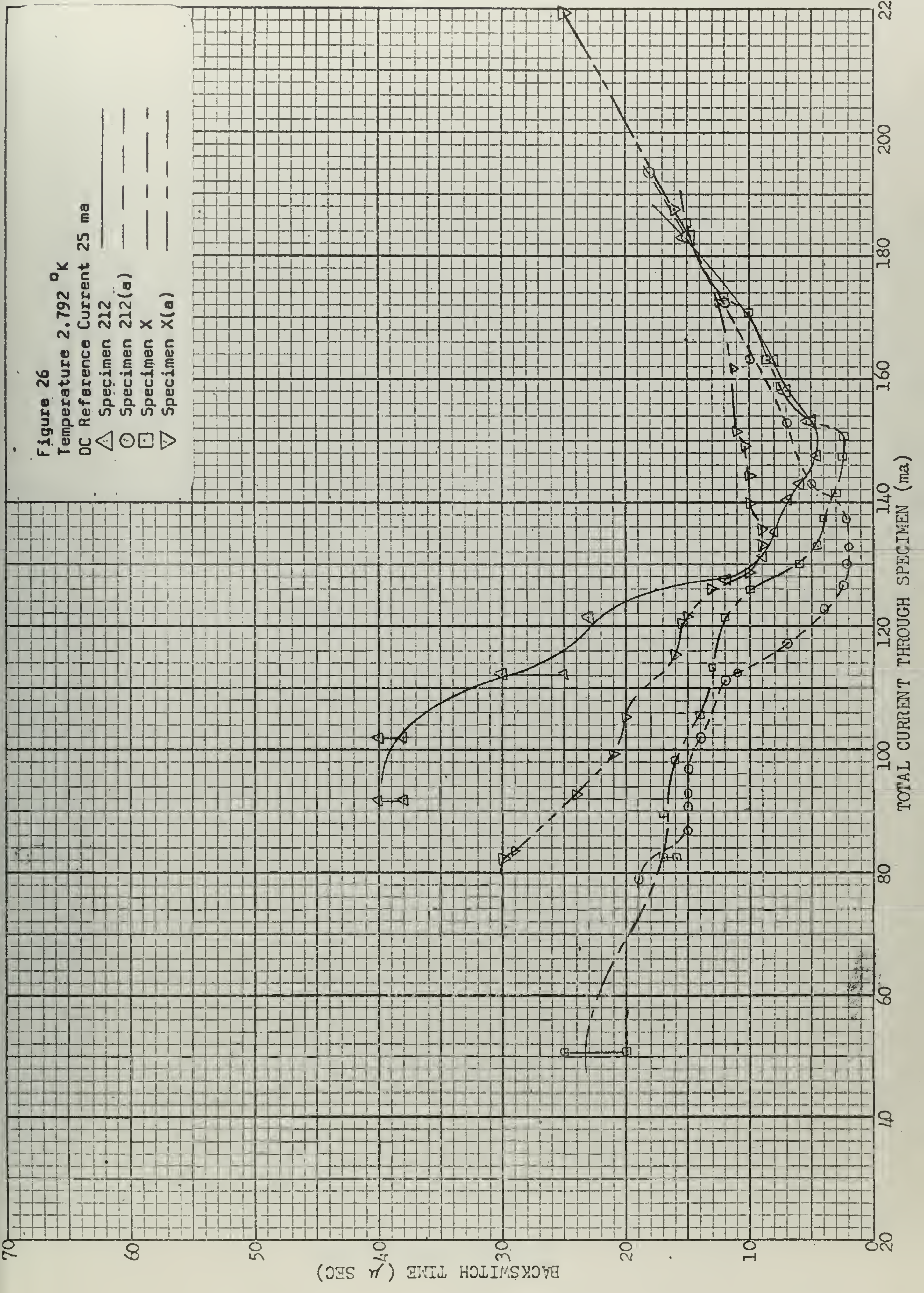


Figure 26

Temperature 2.792 °K
DC Reference Current 25 ma
△ Specimen 212
⊙ Specimen 212(a)
⊡ Specimen X
▽ Specimen X(a)
TOTAL CURRENT THROUGH SPECIMEN (ma)
BACKSWITCH TIME (μ SEC)
20
40
60
80
100
120
140
160
180
200
220
0
10
20
30
40
50
60
70

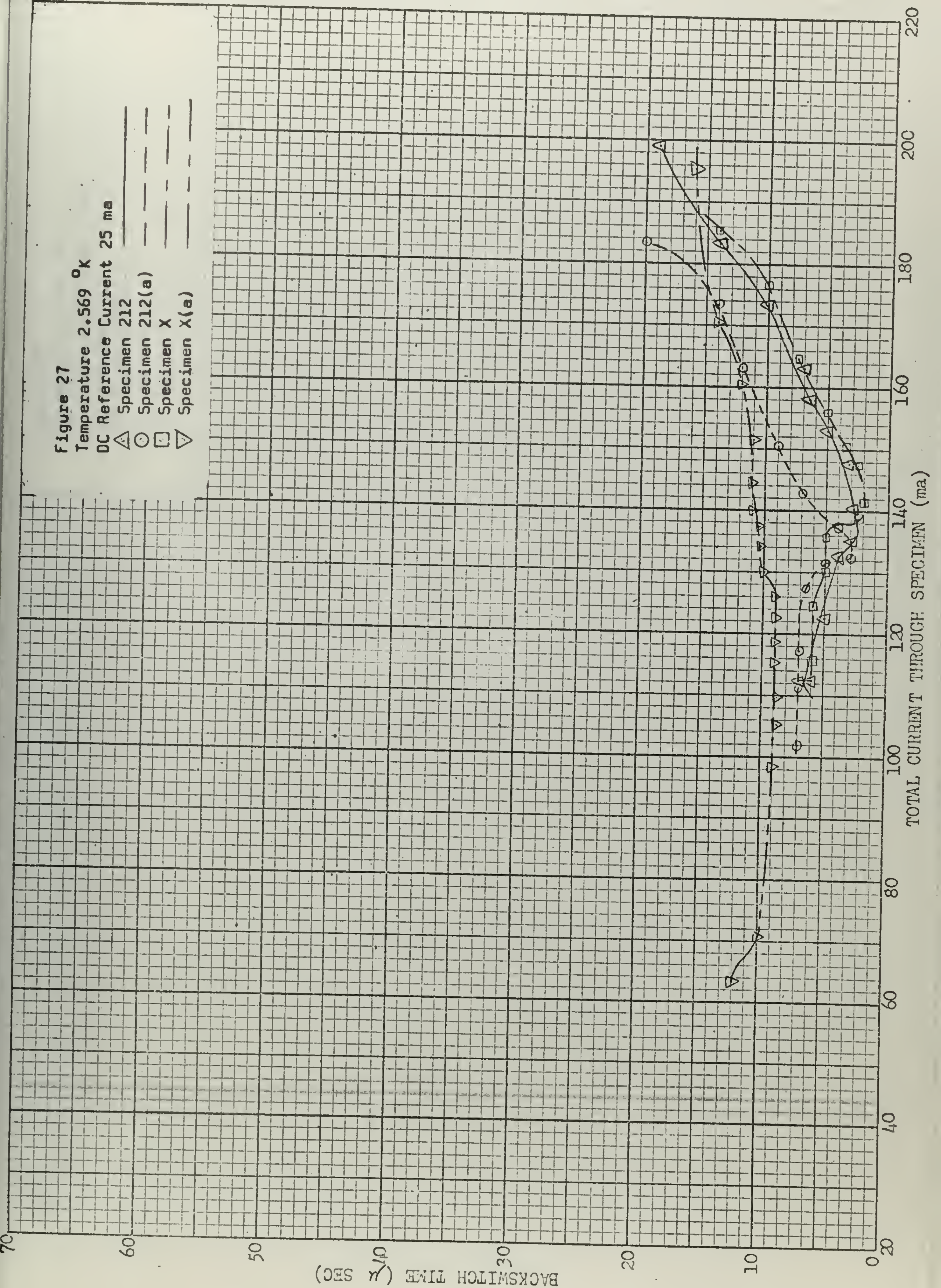


Figure 27

Temperature 2.569 °K
DC Reference Current 25 ma
△ Specimen 212
○ Specimen 212(a)
□ Specimen X
▽ Specimen X(a)
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
20
40
60
80
100
120
140
160
180
200
220

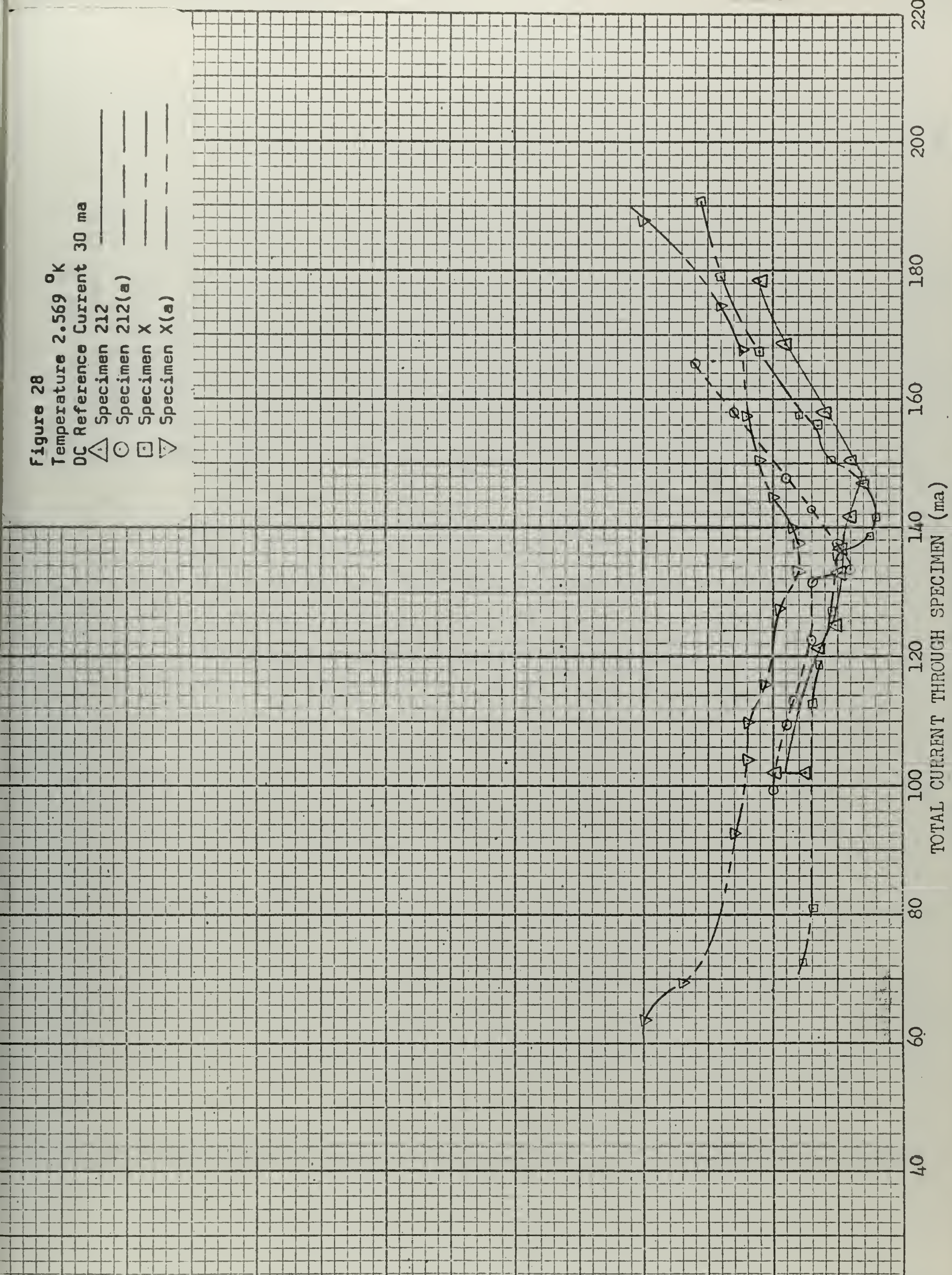


Figure 28
Temperature 2.569 °K
DC Reference Current 30 ma
△ Specimen 212
⊙ Specimen 212(a)
⊡ Specimen X
▽ Specimen X(a)
BACKSWITCH-TIME (μ SEC)
0
10
20
30
40
50
60
TOTAL CURRENT THROUGH SPECIMEN (ma)
20
40
60
80
100
120
140
160
180
200
220

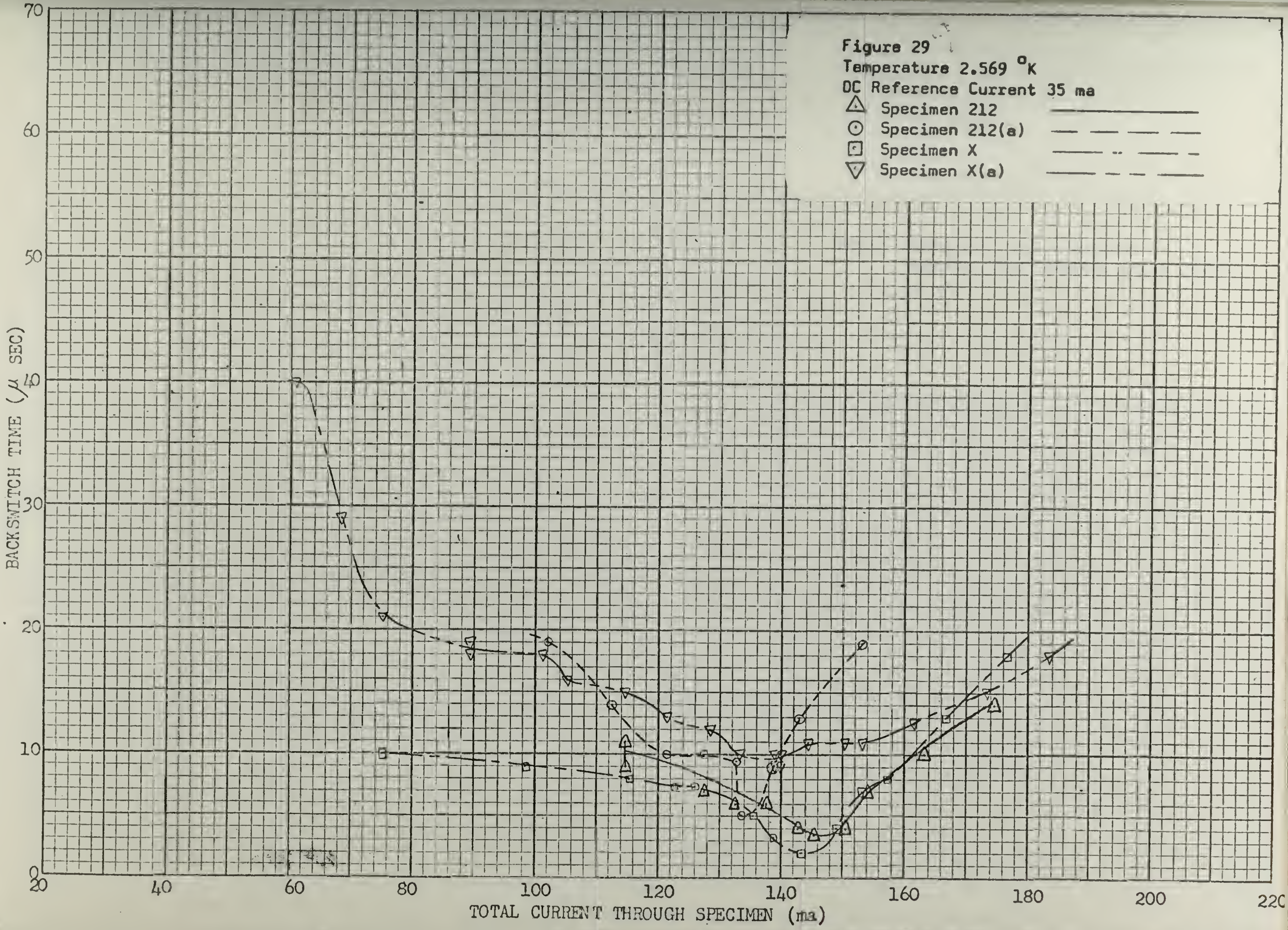


Figure 29

Temperature 2.569 °K

DC Reference Current 35 ma

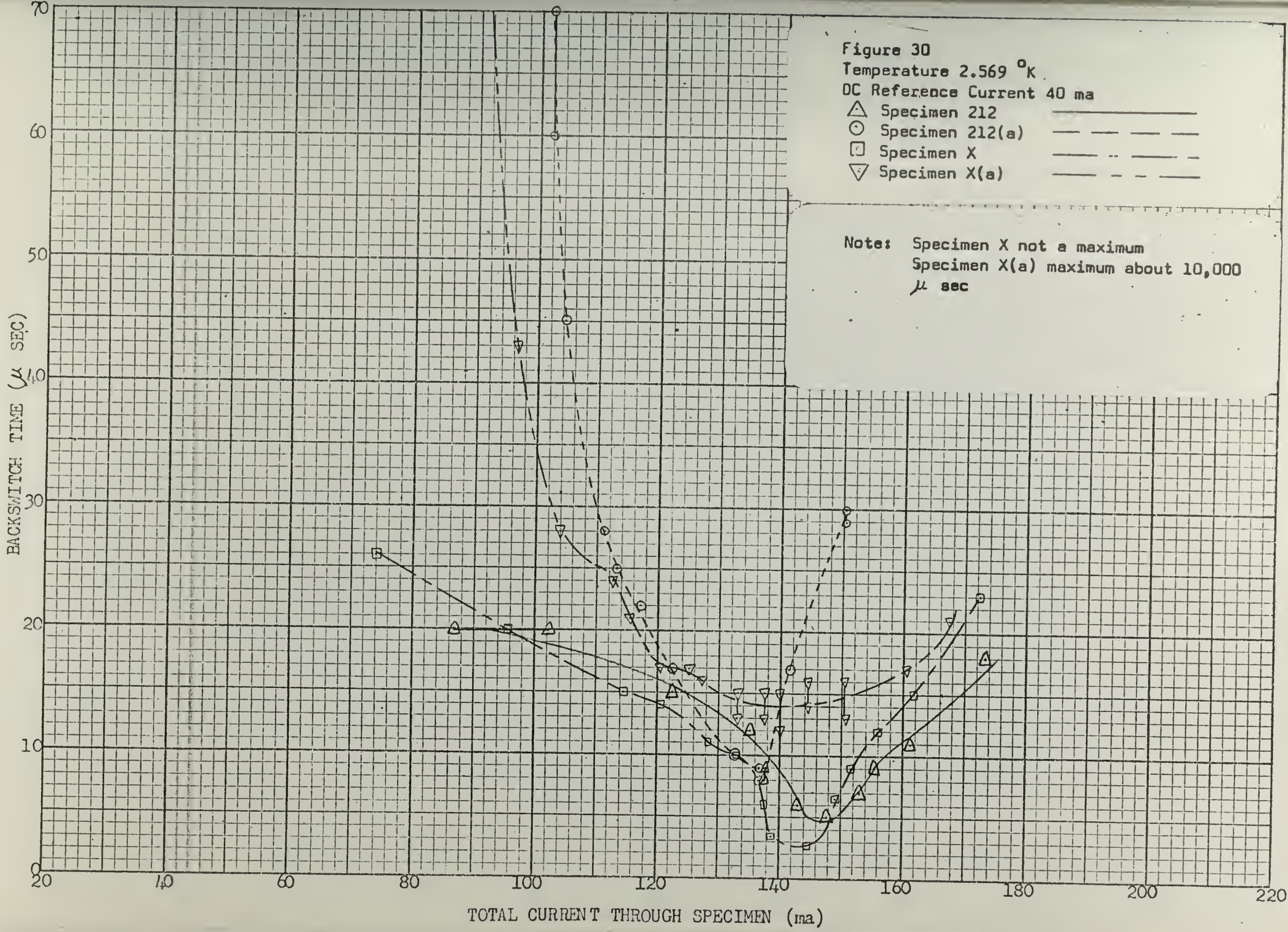


Figure 30

Temperature 2.569 °K
DC Reference Current 40 ma
△ Specimen 212
⊙ Specimen 212(a)
⊡ Specimen X
▽ Specimen X(a)
Note: Specimen X not a maximum
Specimen X(a) maximum about 10,000 μ sec
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
20
40
60
80
100
120
140
160
180
200
220

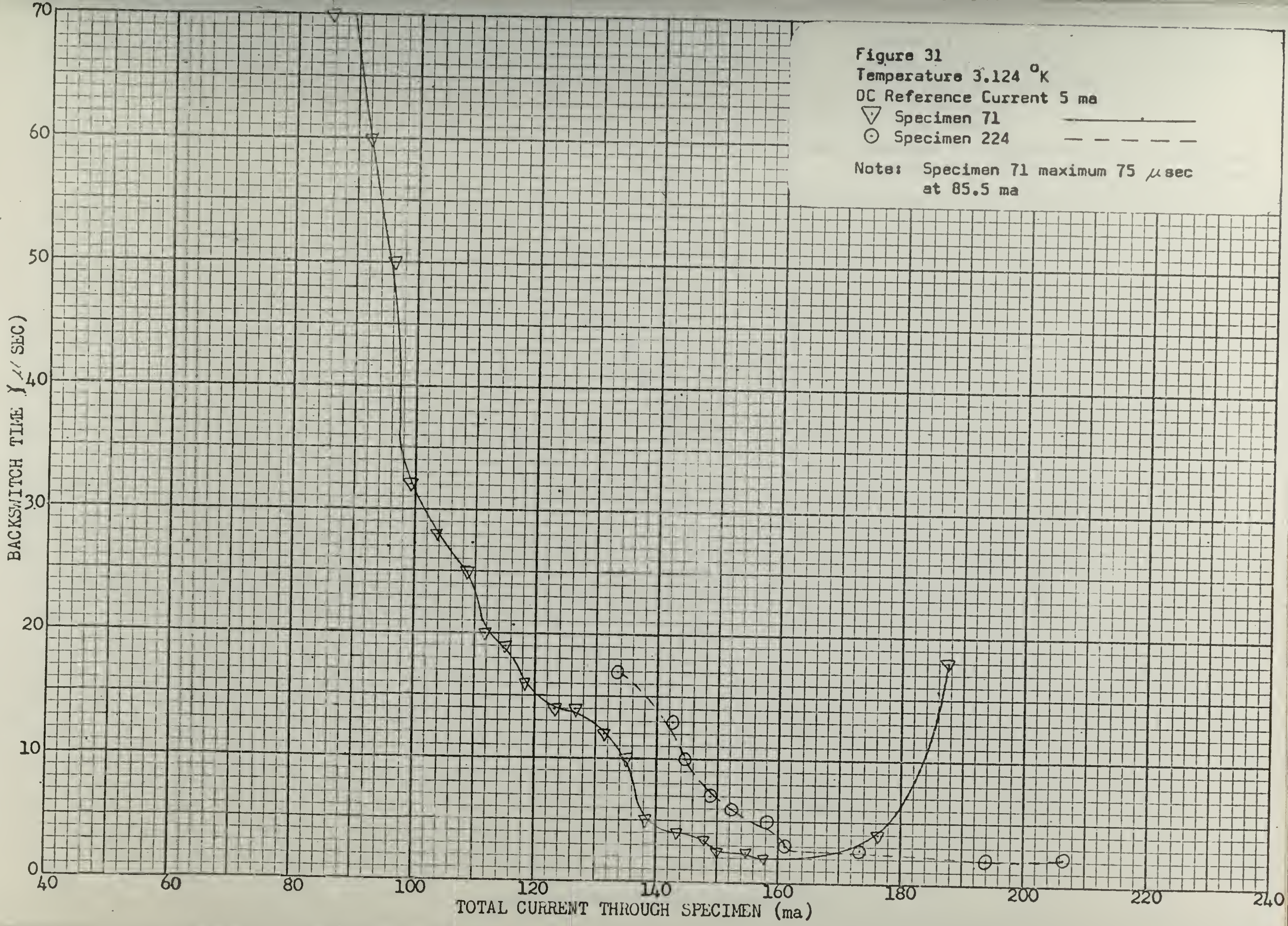


Figure 31

Temperature 3.124 °K
DC Reference Current 5 ma
▽ Specimen 71
⊙ Specimen 224
Note: Specimen 71 maximum 75 μsec at 85.5 ma
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
40
60
80
100
120
140
160
180
200
220
240

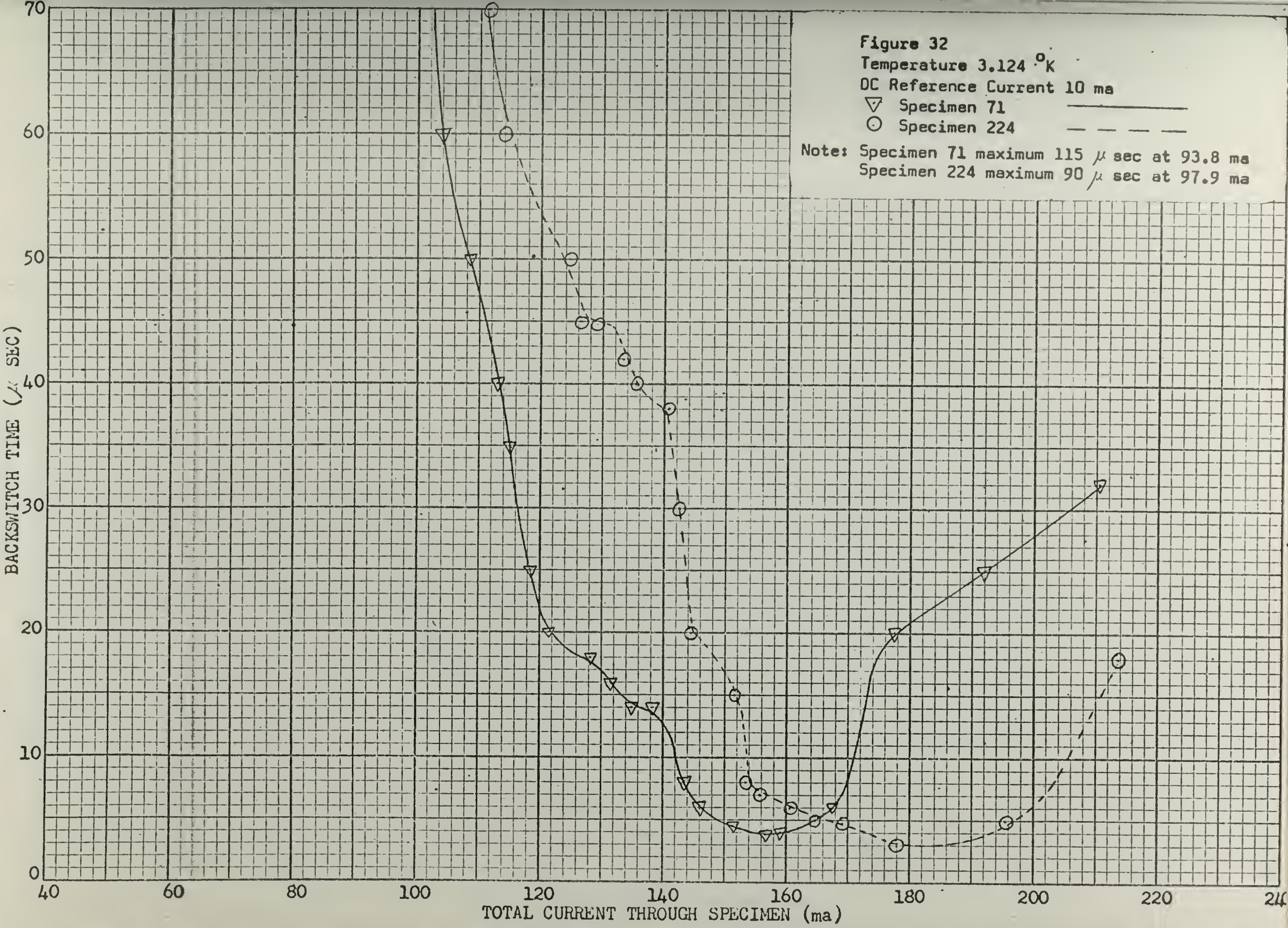


Figure 32

Temperature 3.124 °K
DC Reference Current 10 ma
▽ Specimen 71 ———
⊙ Specimen 224 — — — —
Note: Specimen 71 maximum 115 μ sec at 93.8 ma
Specimen 224 maximum 90 μ sec at 97.9 ma
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
40
60
80
100
120
140
160
180
200
220

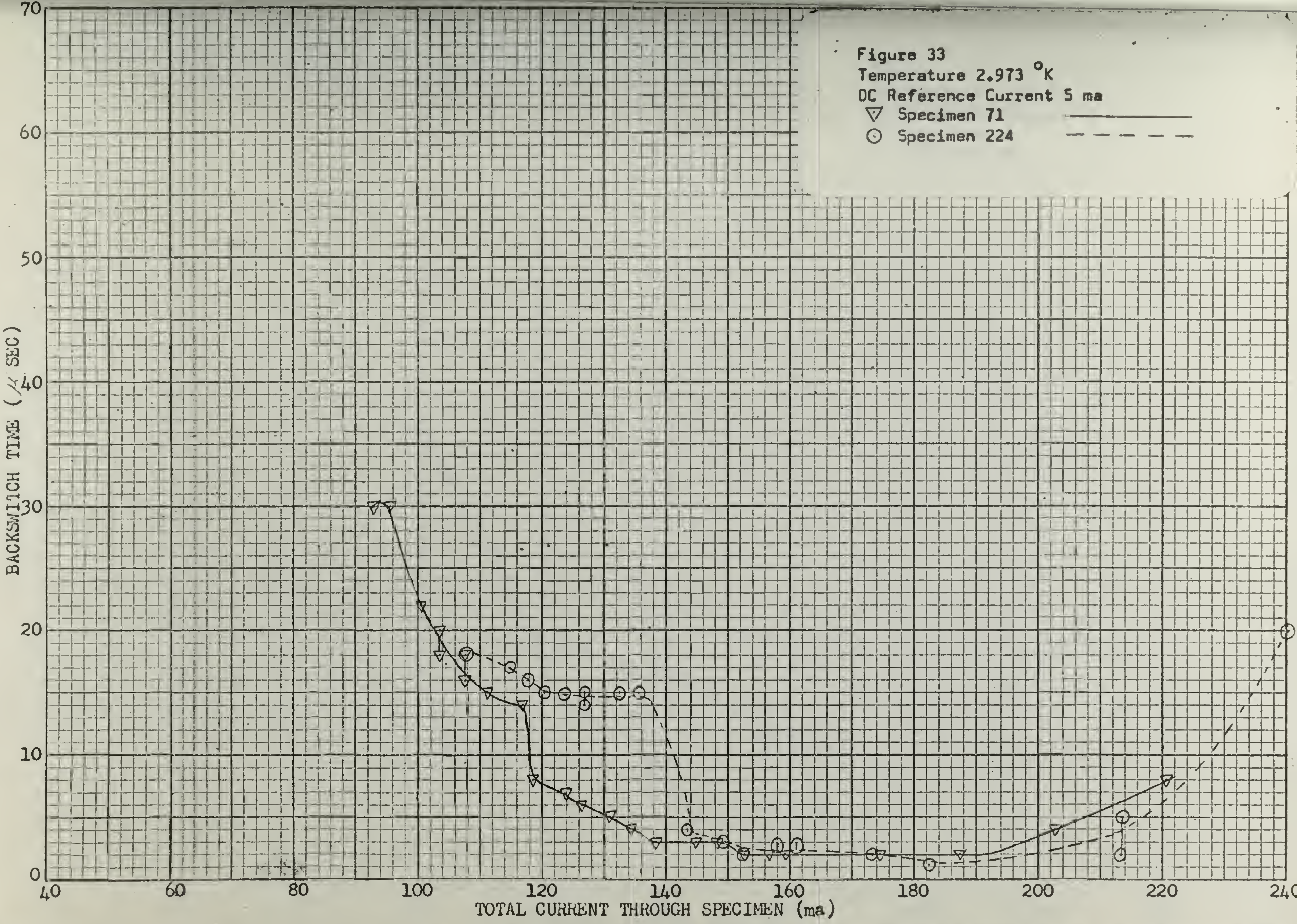


Figure 33

Temperature 2.973 °K
DC Reference Current 5 ma
▽ Specimen 71
⊙ Specimen 224
BACKSWITCH TIME (μ SEC)
70
60
50
40
30
20
10
0
40
60
80
100
120
140
160
180
200
220
240
TOTAL CURRENT THROUGH SPECIMEN (ma)

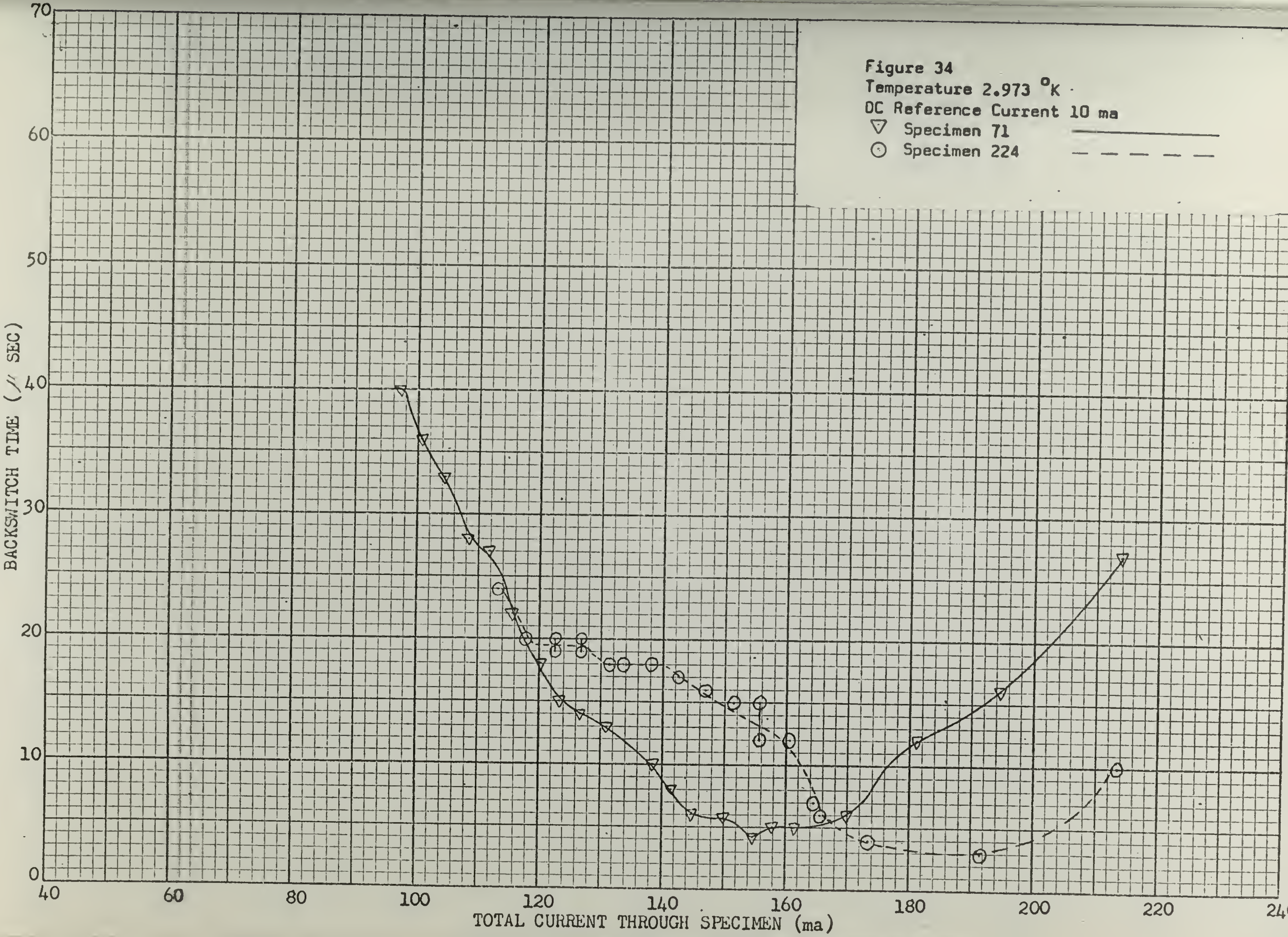


Figure 34
Temperature 2.973 °K
DC Reference Current 10 ma
▽ Specimen 71
⊙ Specimen 224
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
40
60
80
100
120
140
160
180
200
220

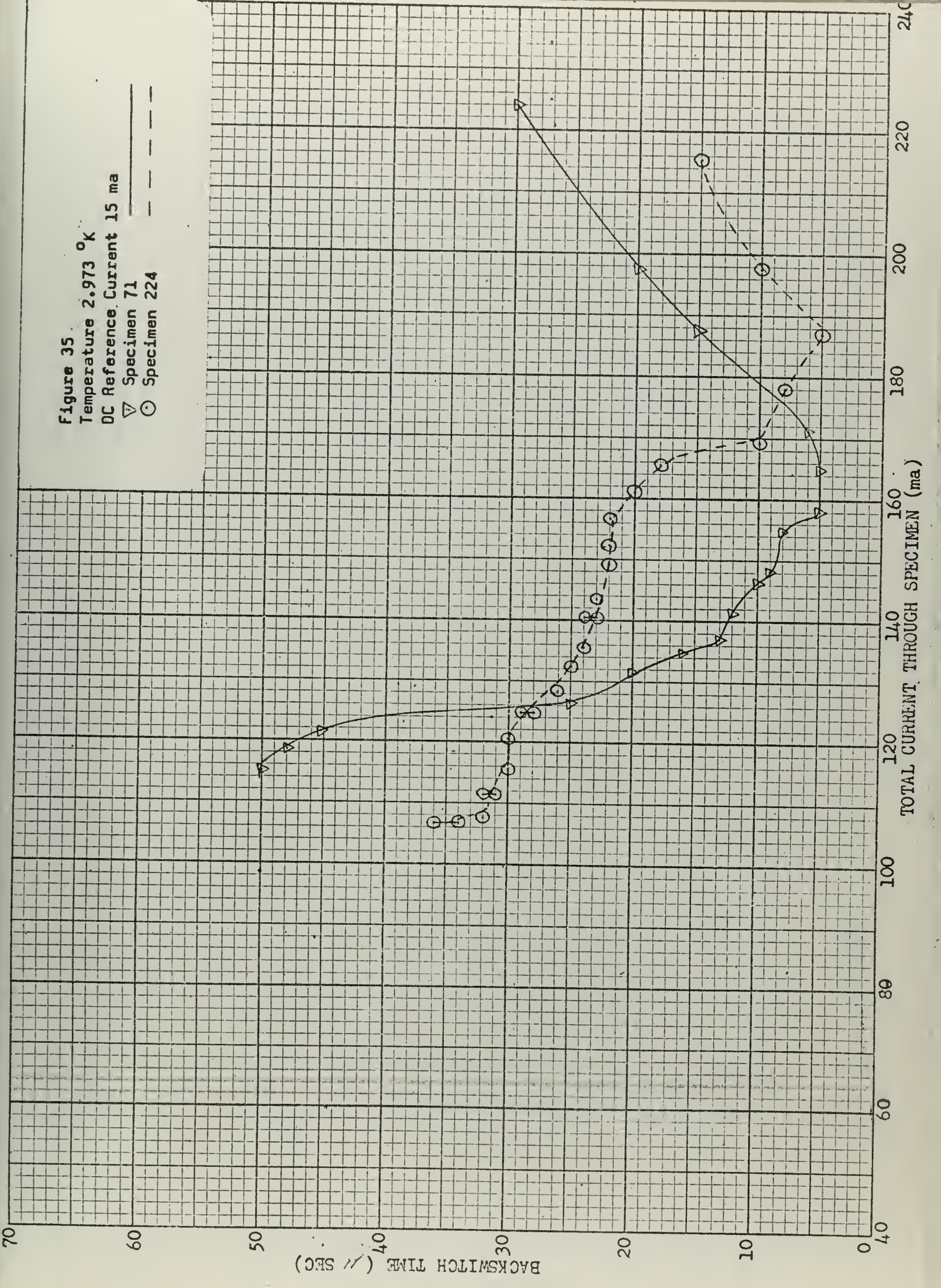


Figure 35

Temperature 2.973 °K
DC Reference Current 15 ma
▽ Specimen 71
⊙ Specimen 224
TOTAL CURRENT THROUGH SPECIMEN (ma)
40
60
80
100
120
140
160
180
200
220
24
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70

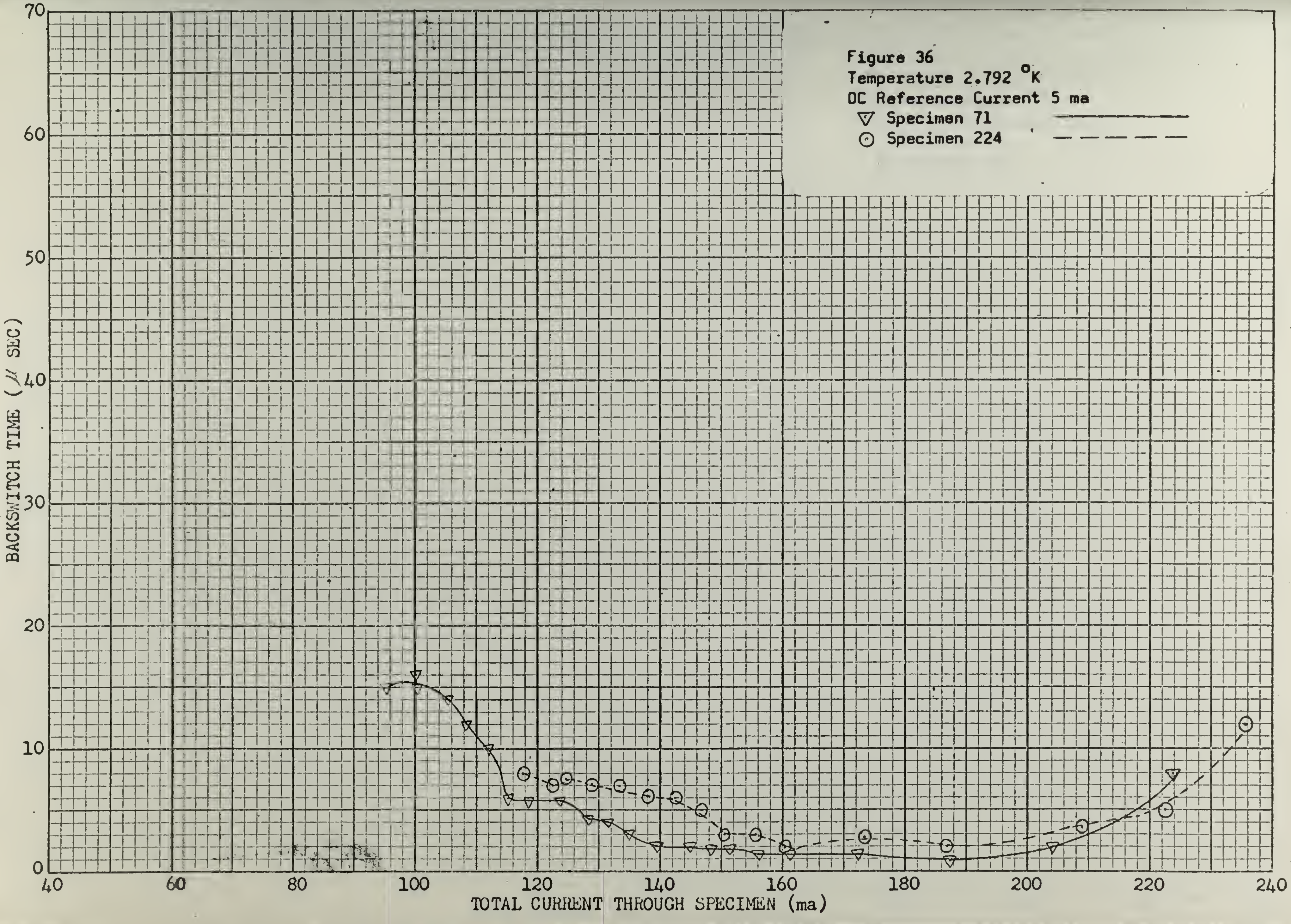


Figure 36
Temperature 2.792 °K
DC Reference Current 5 ma
▽ Specimen 71
⊙ Specimen 224
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
40
60
80
100
120
140
160
180
200
220
240

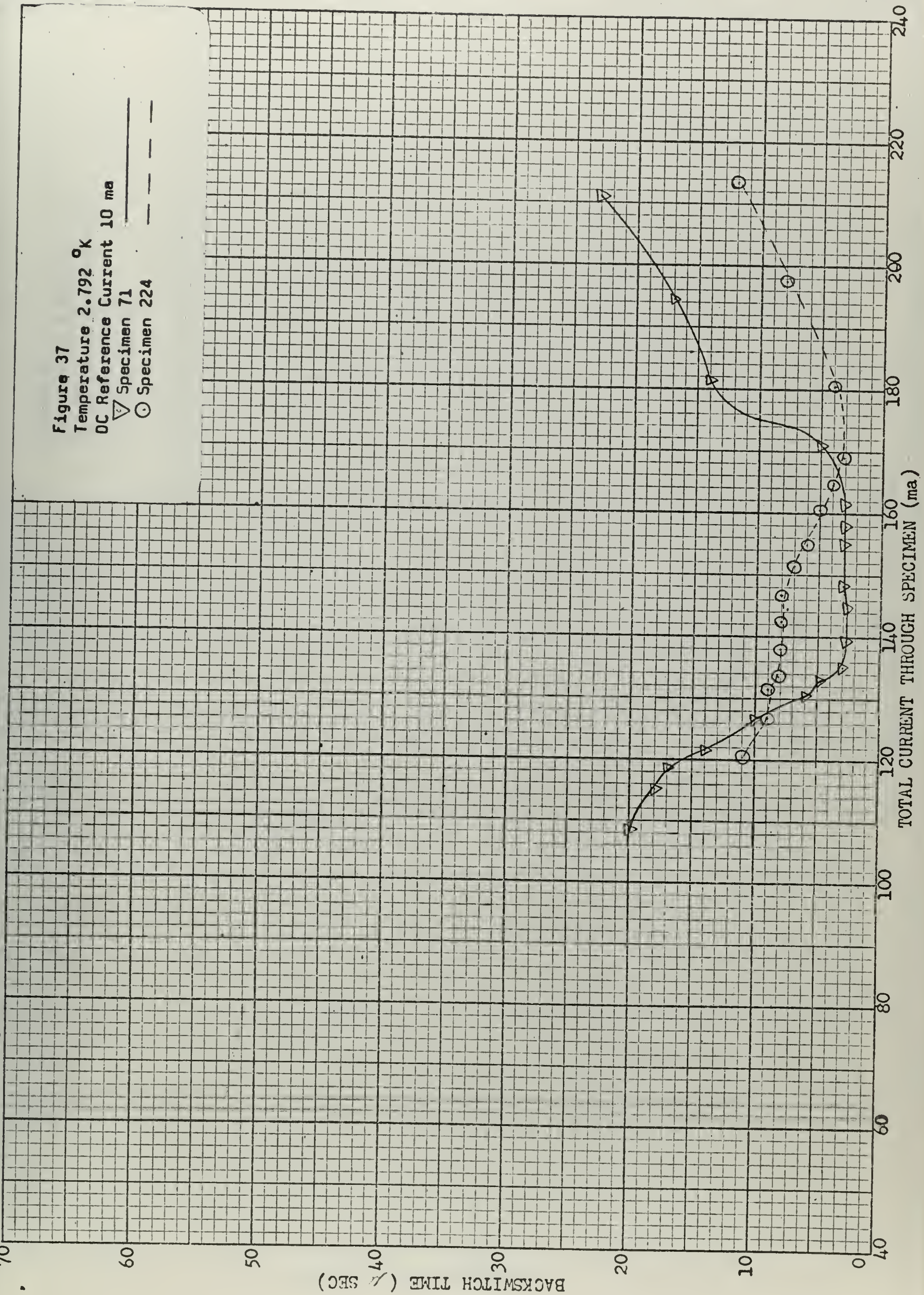


Figure 37
Temperature 2.792 °K
DC Reference Current 10 ma
▽ Specimen 71
⊙ Specimen 224
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
40
60
80
100
120
140
160
180
200
220
240

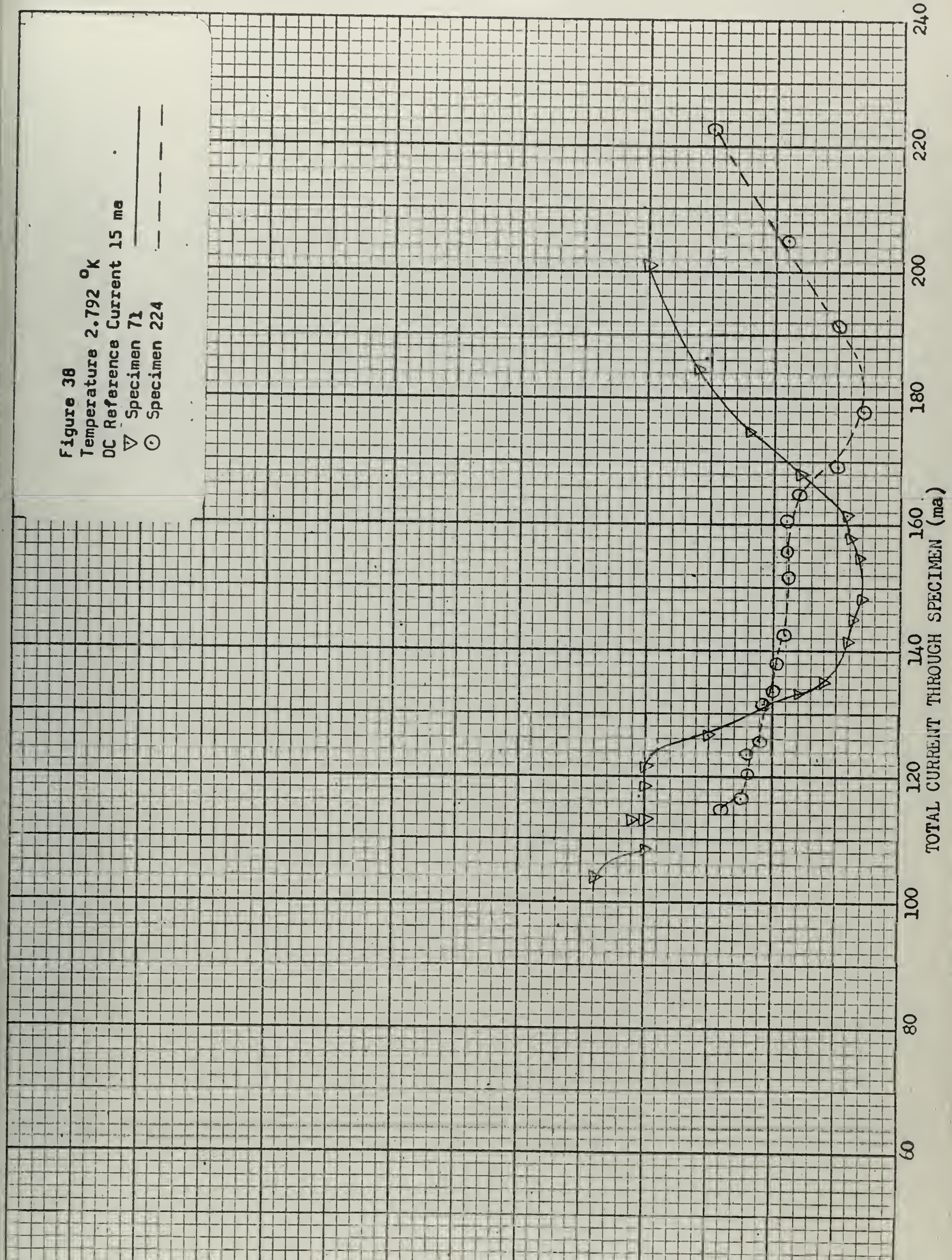


Figure 38

Temperature 2.792 °K
DC Reference Current 15 ma
▽ Specimen 71 ———
⊙ Specimen 224 — — —
TOTAL CURRENT THROUGH SPECIMEN (ma)
40
60
80
100
120
140
160
180
200
220
240
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70

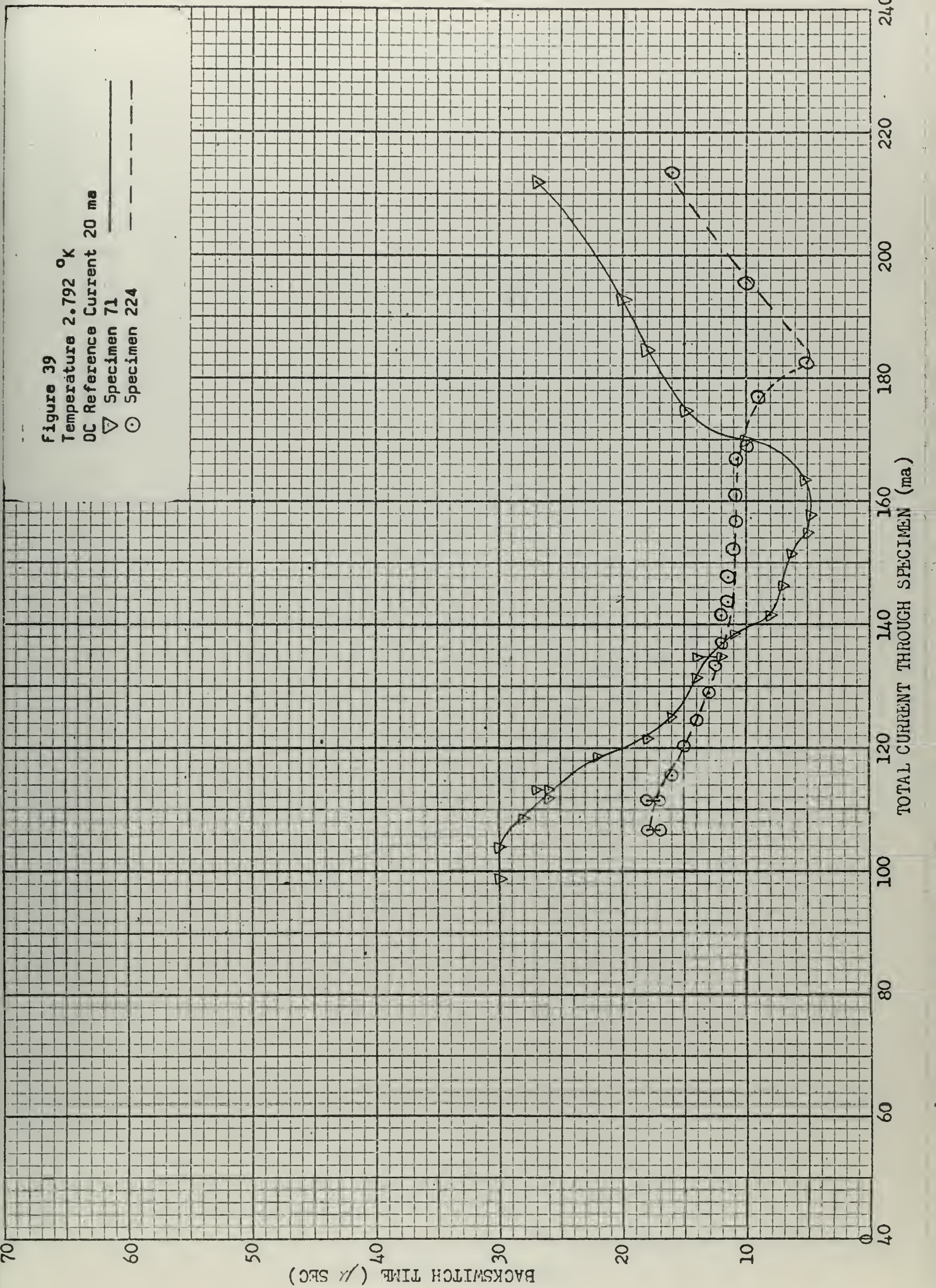


Figure 39

Temperature 2.792 °K
DC Reference Current 20 ma
▽ Specimen 71
⊙ Specimen 224
TOTAL CURRENT THROUGH SPECIMEN (ma)
40
60
80
100
120
140
160
180
200
220
240
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70

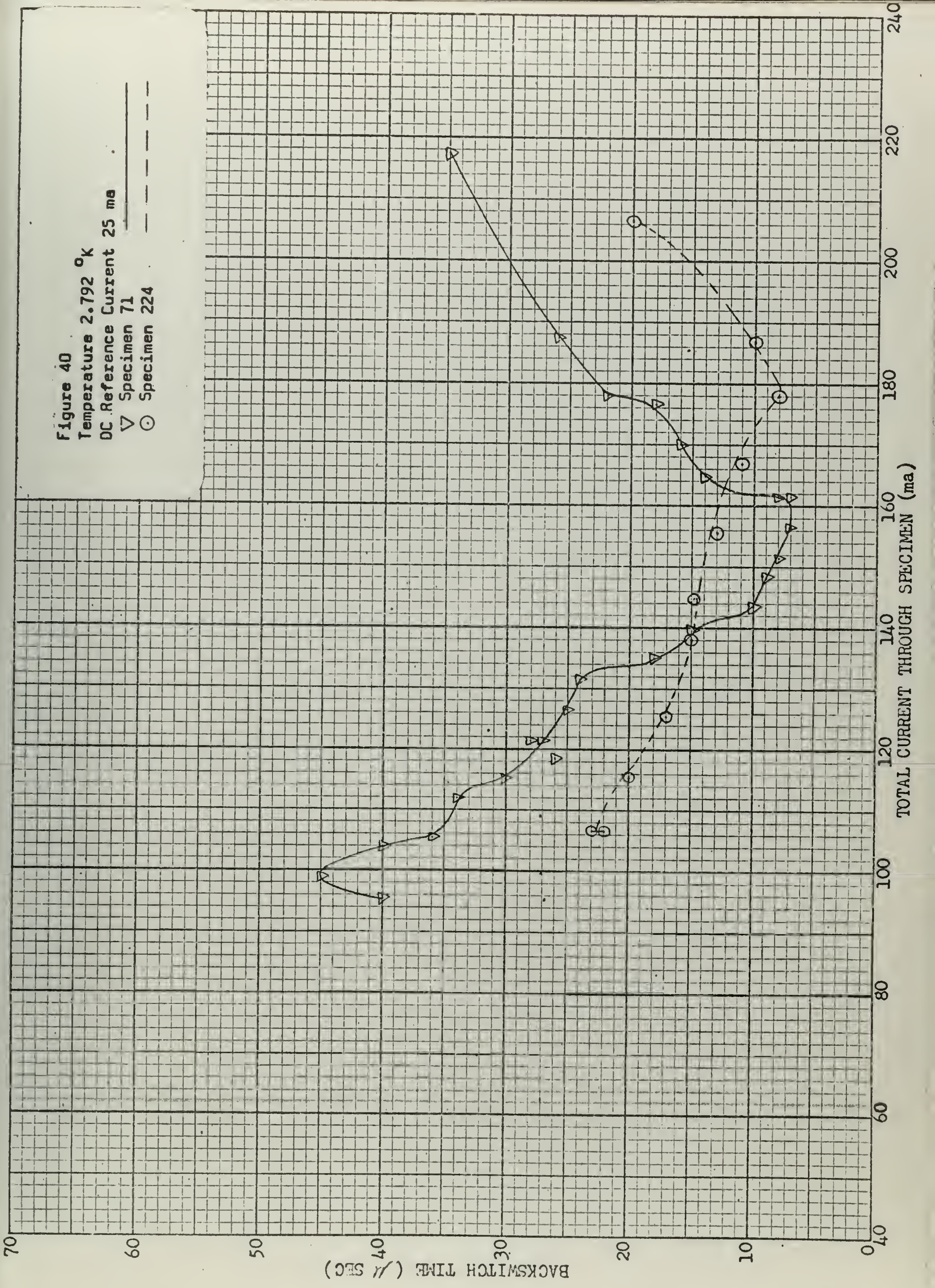


Figure 40
Temperature 2.792 °K
DC Reference Current 25 ma
▽ Specimen 71
⊙ Specimen 224
TOTAL CURRENT THROUGH SPECIMEN (ma)
40
60
80
100
120
140
160
180
200
220
240
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70

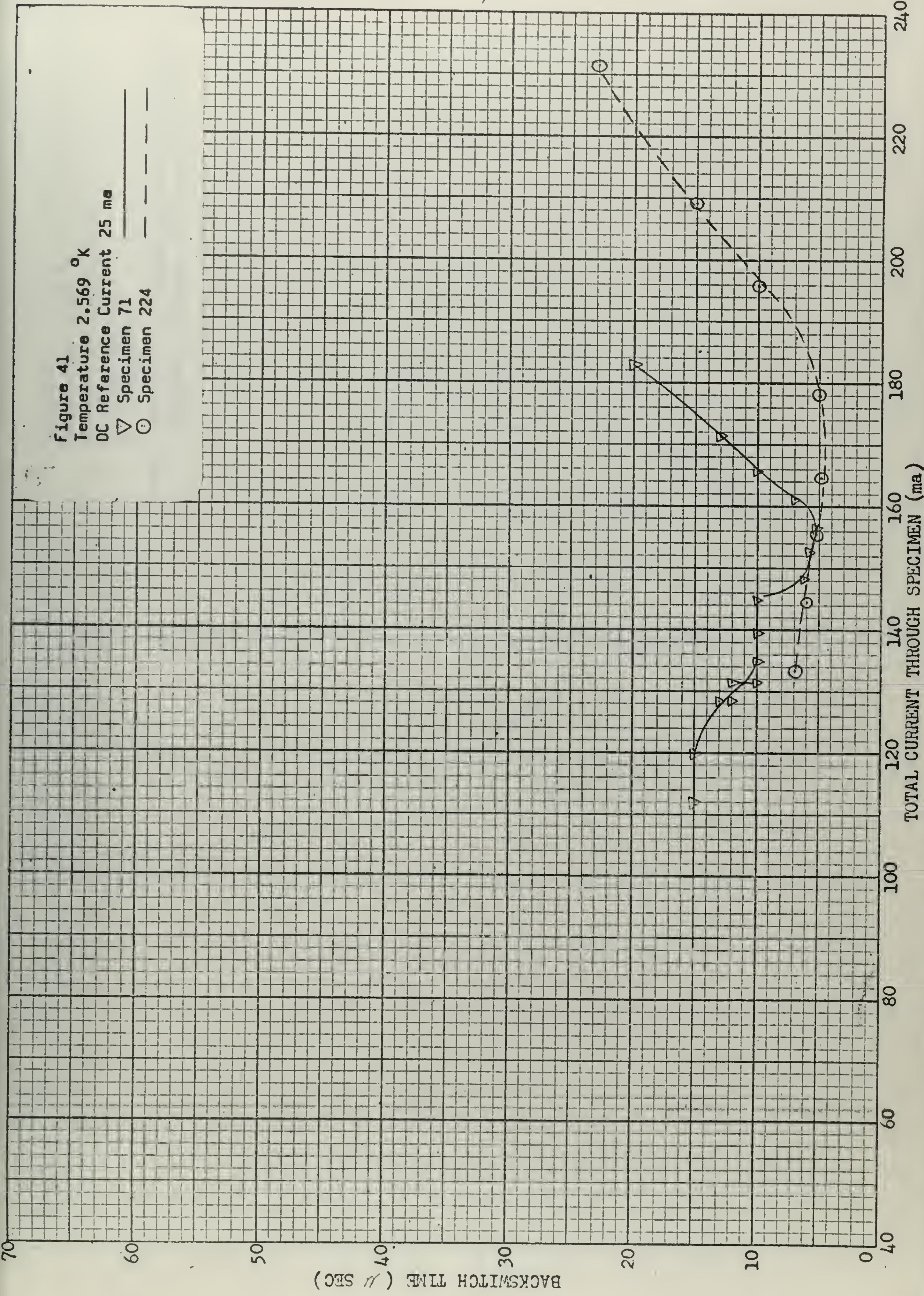


Figure 41

Temperature 2.569 °K
DC Reference Current 25 ma
▽ Specimen 71
⊙ Specimen 224
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
40
60
80
100
120
140
160
180
200
220
240

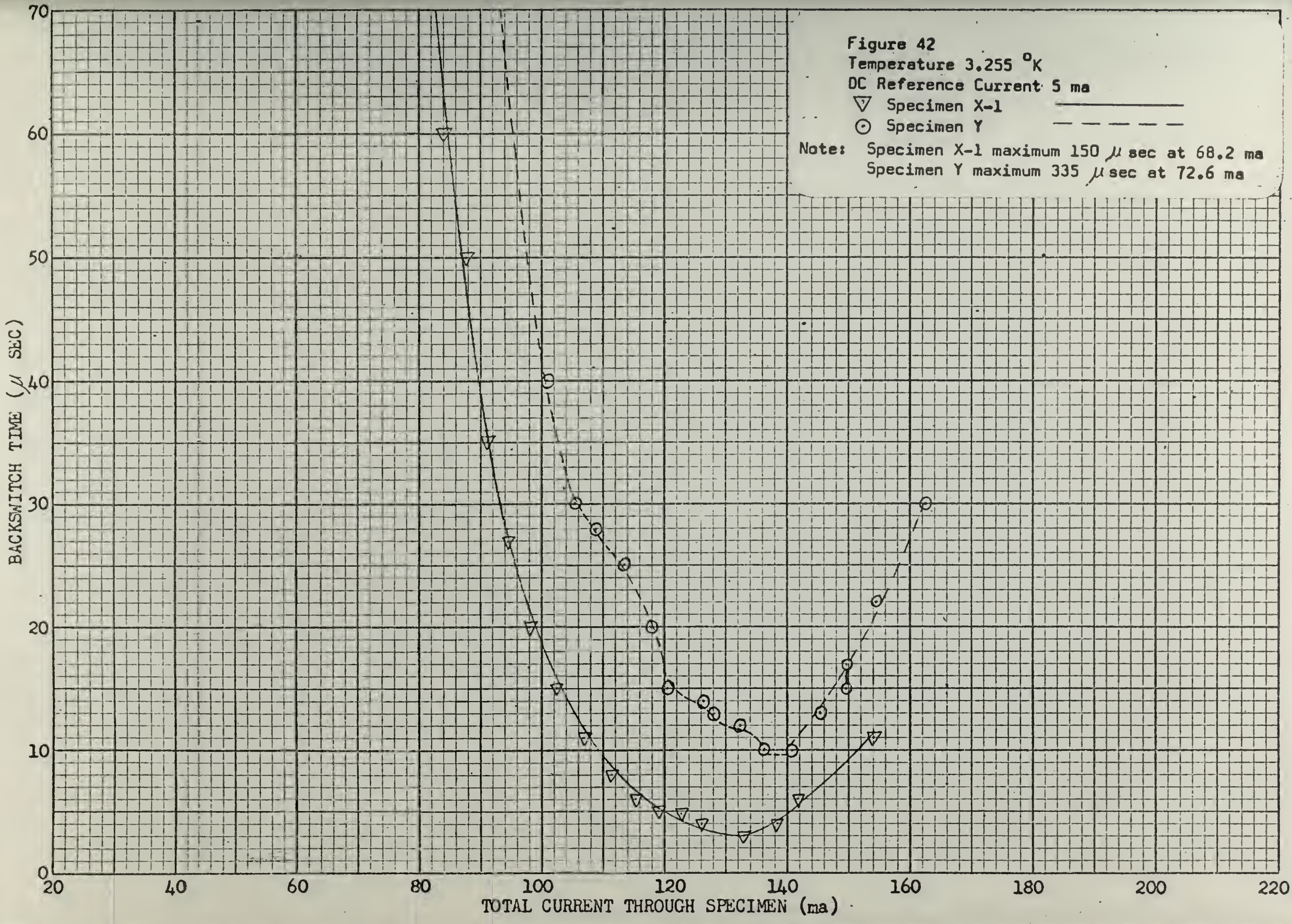


Figure 42

Temperature 3.255 °K
DC Reference Current 5 ma
▽ Specimen X-1
⊙ Specimen Y
Note: Specimen X-1 maximum 150 µ sec at 68.2 ma
Specimen Y maximum 335 µ sec at 72.6 ma
BACKSWITCH TIME (µ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
20
40
60
80
100
120
140
160
180
200
220

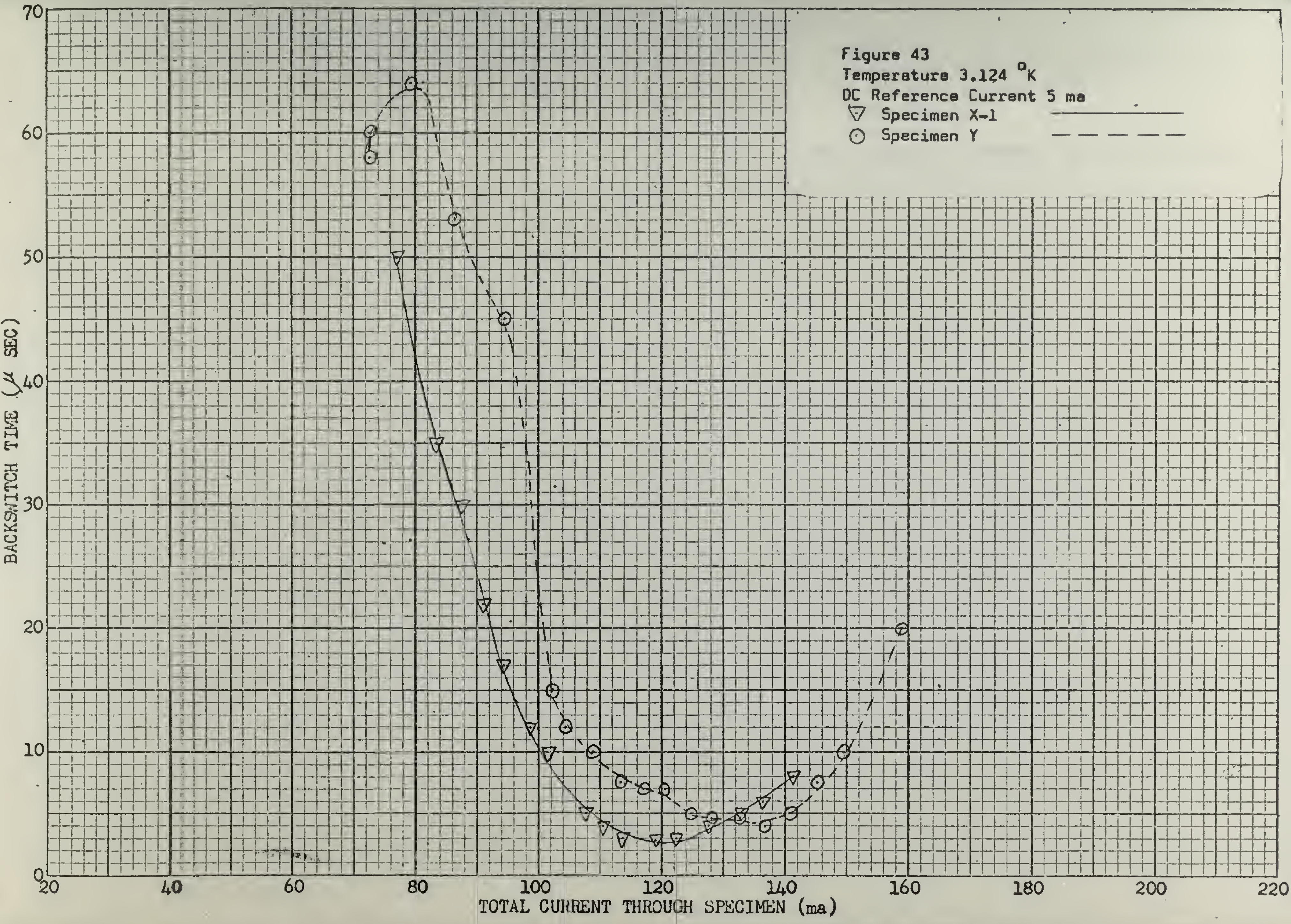


Figure 43

Temperature 3.124 ^{o}K

DC Reference Current 5 ma

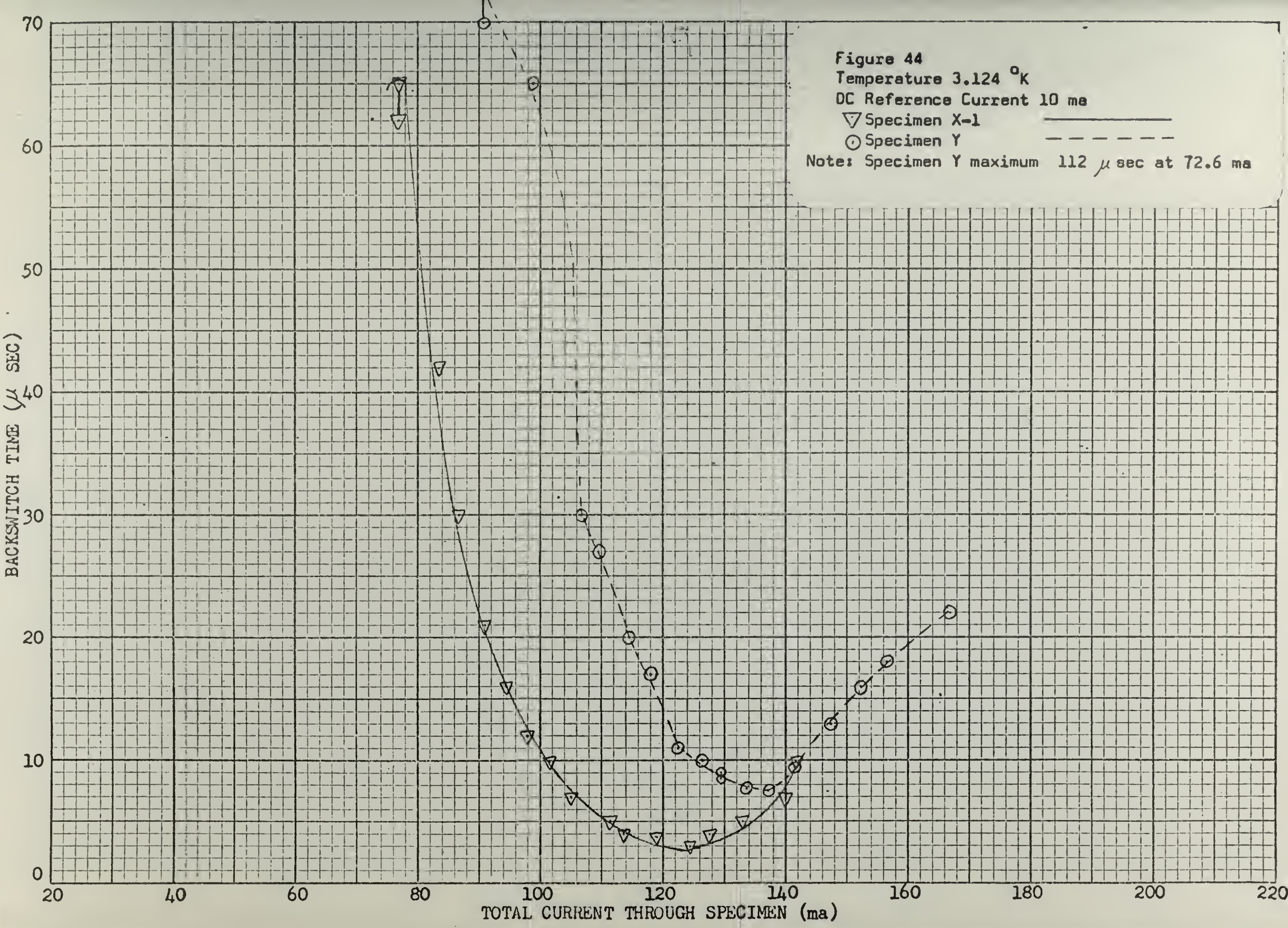


Figure 44

Temperature 3.124 °K
DC Reference Current 10 ma
▽ Specimen X-1
⊙ Specimen Y
Note: Specimen Y maximum 112 μ sec at 72.6 ma
BACKSWITCH TIME (μ SEC)
0
10
20
30
40
50
60
70
TOTAL CURRENT THROUGH SPECIMEN (ma)
20
40
60
80
100
120
140
160
180
200
220

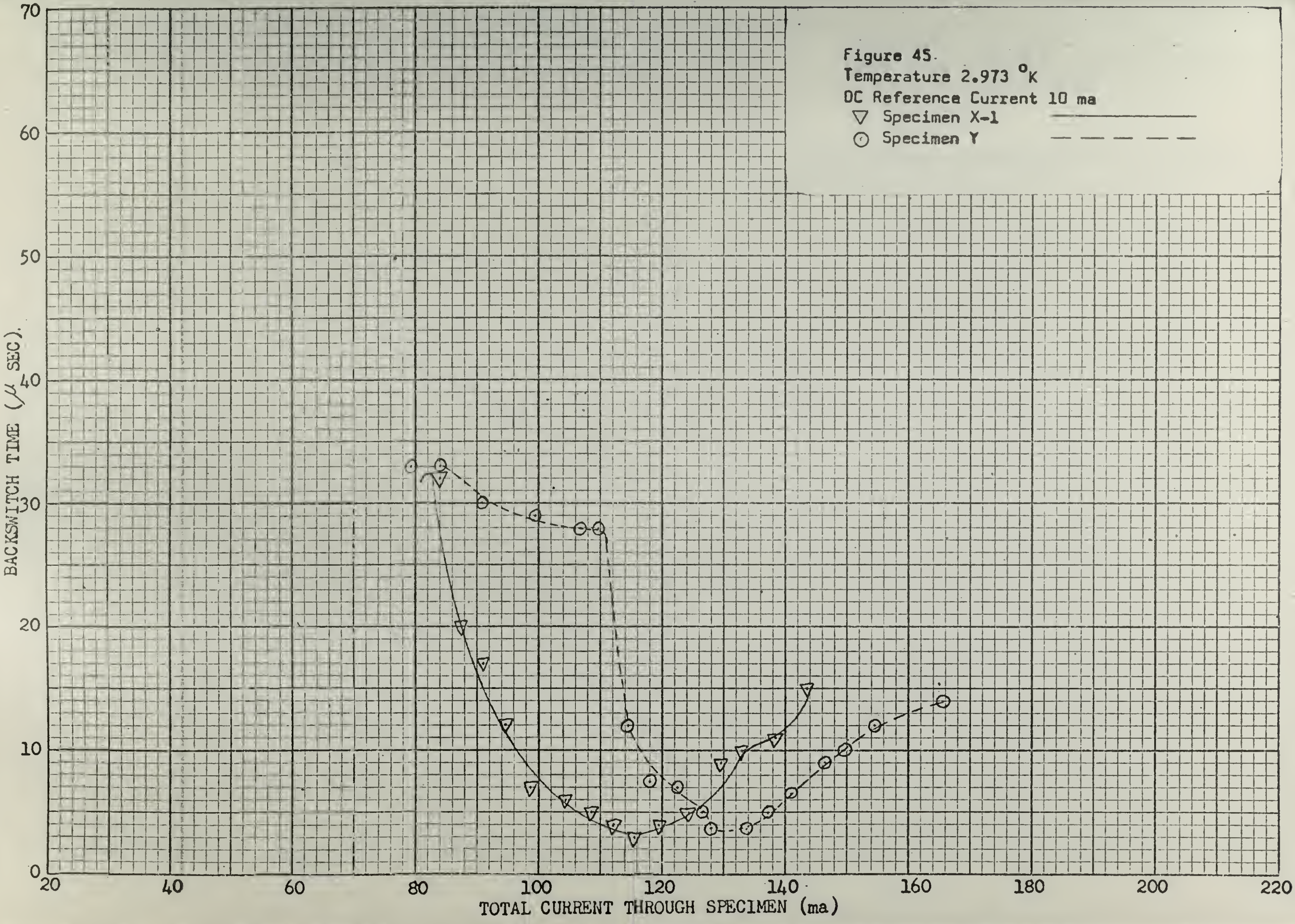


Figure 45.
Temperature 2.973 °K
DC Reference Current 10 ma

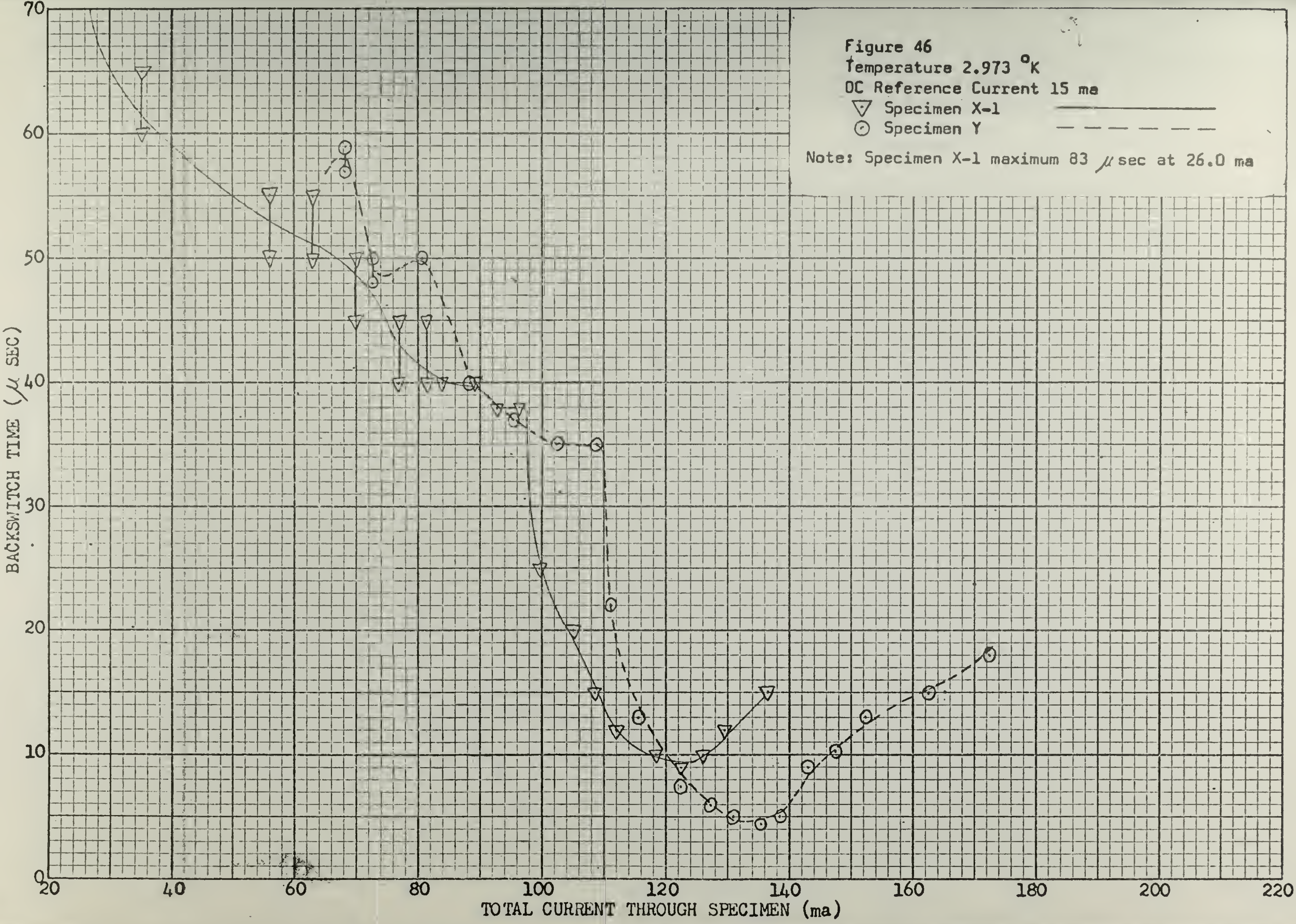


Figure 46

Temperature 2.973 °K

DC Reference Current 15 ma

Note: Specimen X-1 maximum 83 μsec at 26.0 ma

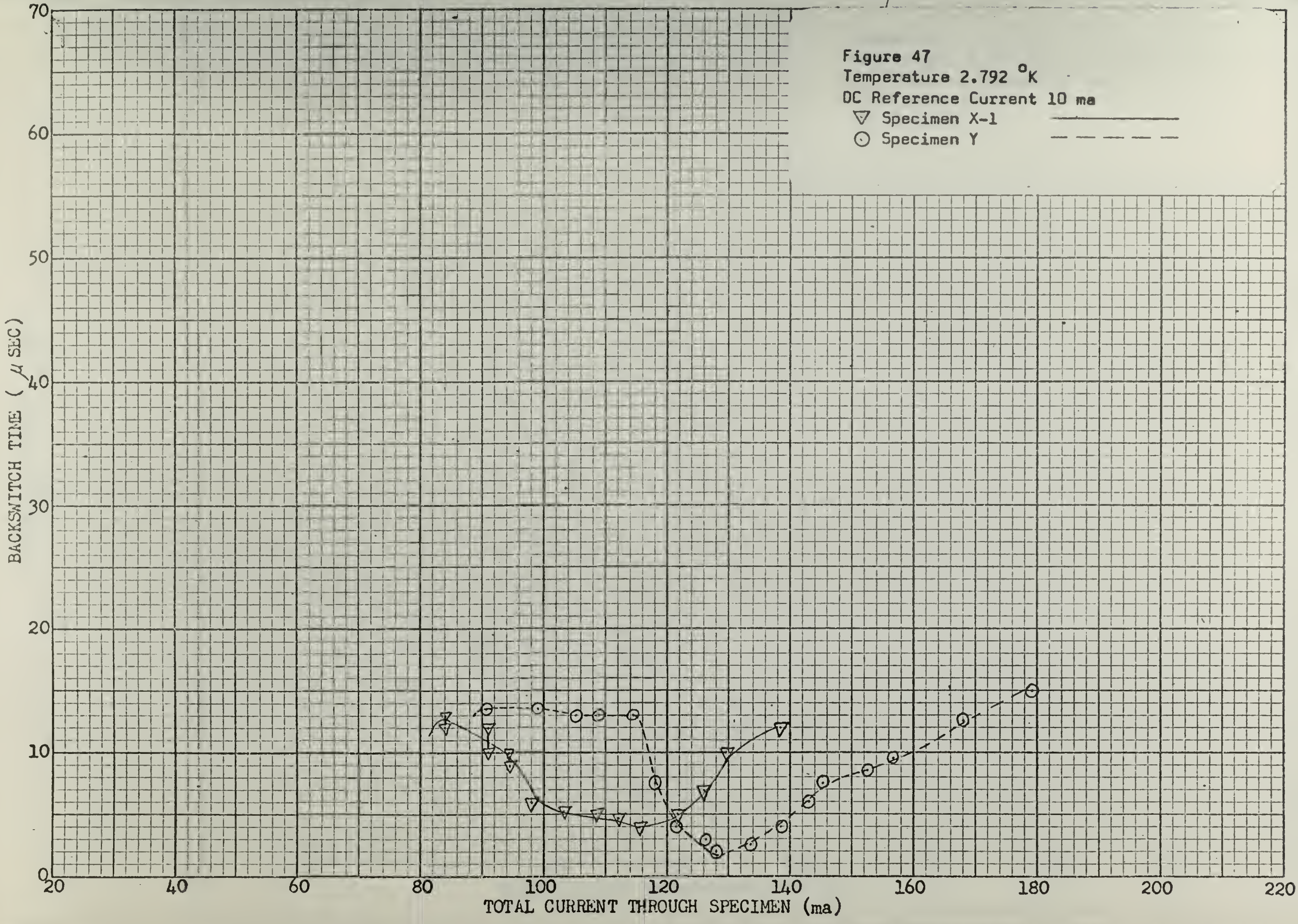


Figure 47
Temperature 2.792 °K
DC Reference Current 10 ma

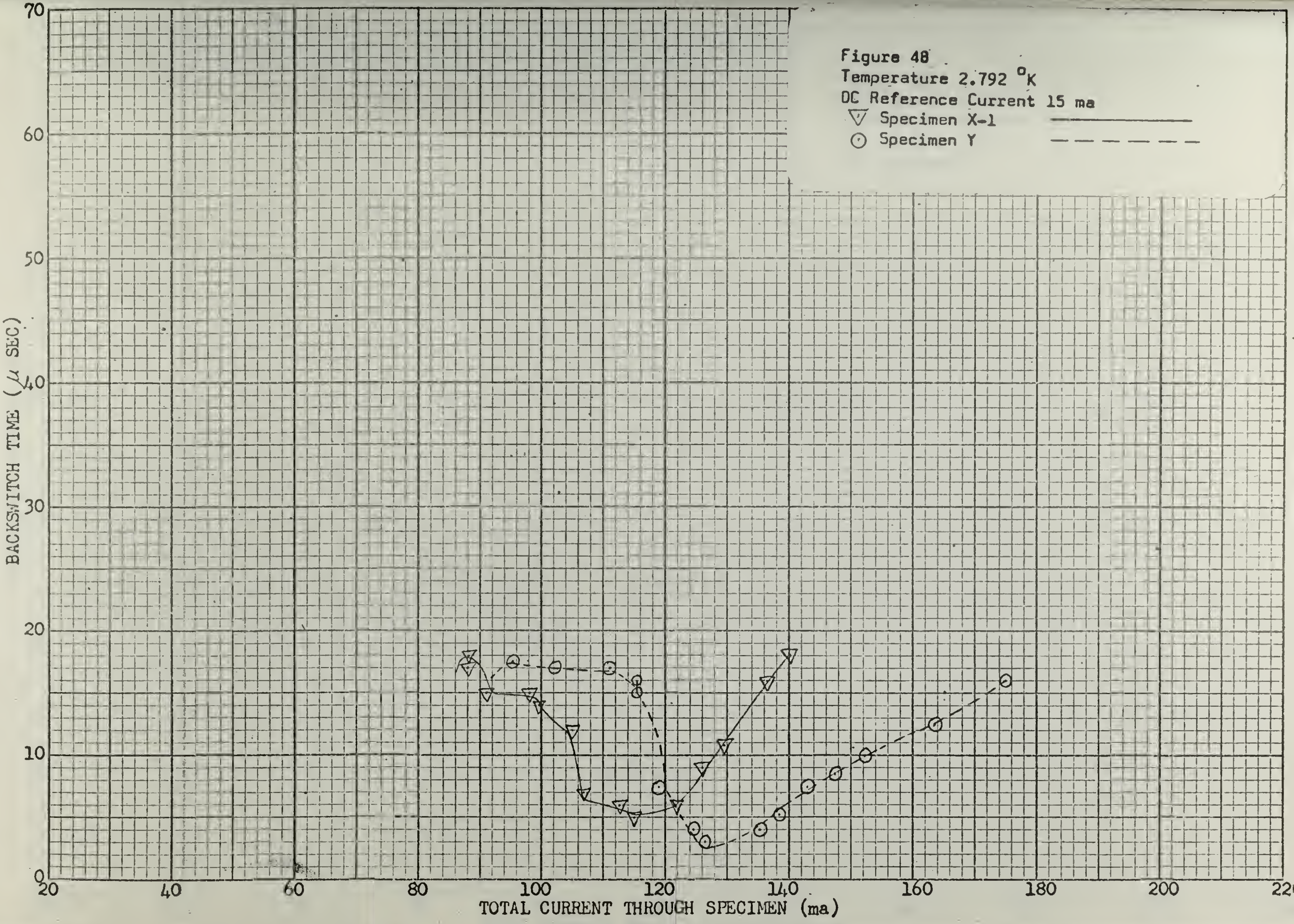


Figure 48

Temperature 2.792 °K

DC Reference Current 15 ma

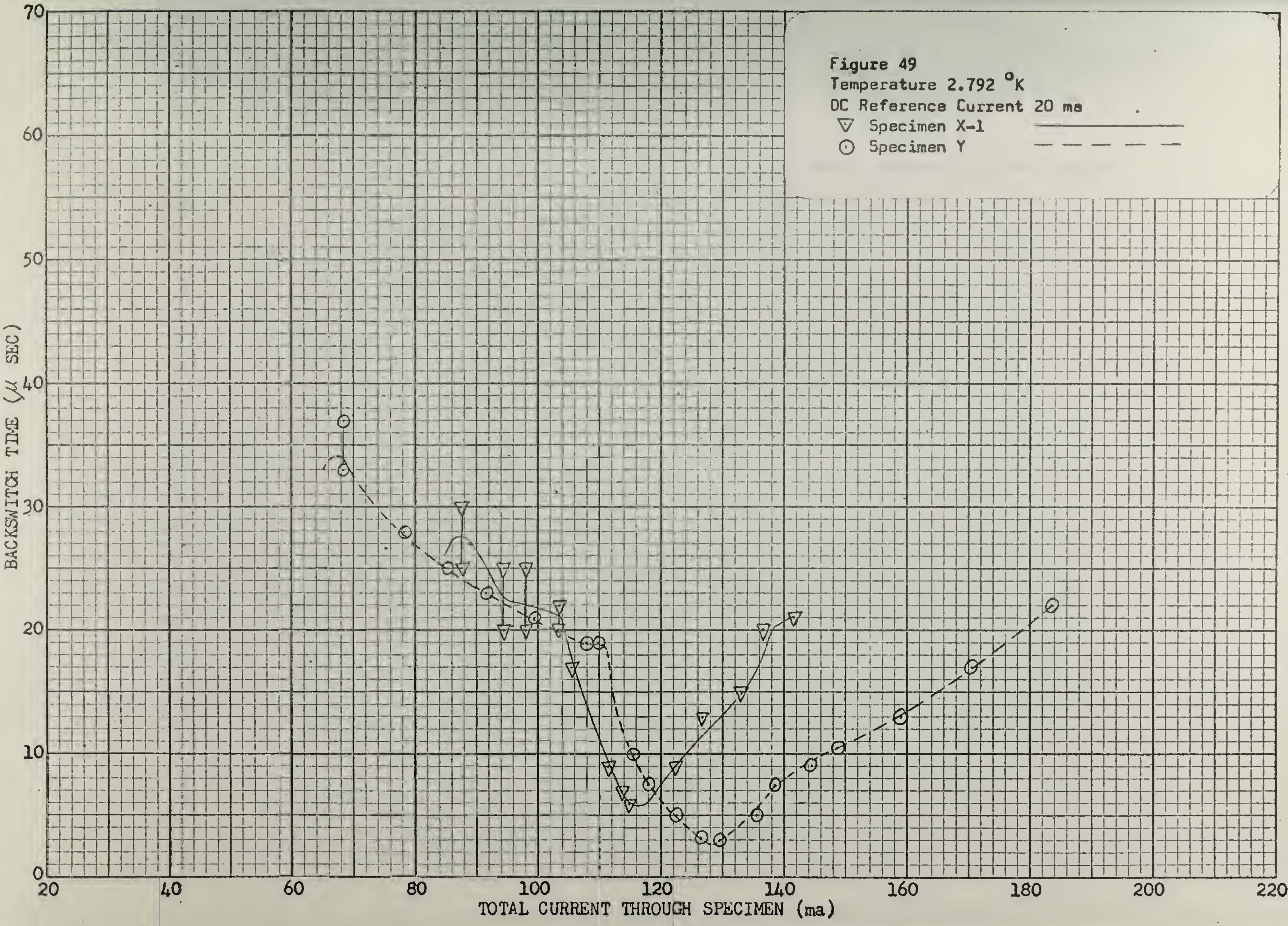


Figure 49

Temperature 2.792 °K

DC Reference Current 20 ma

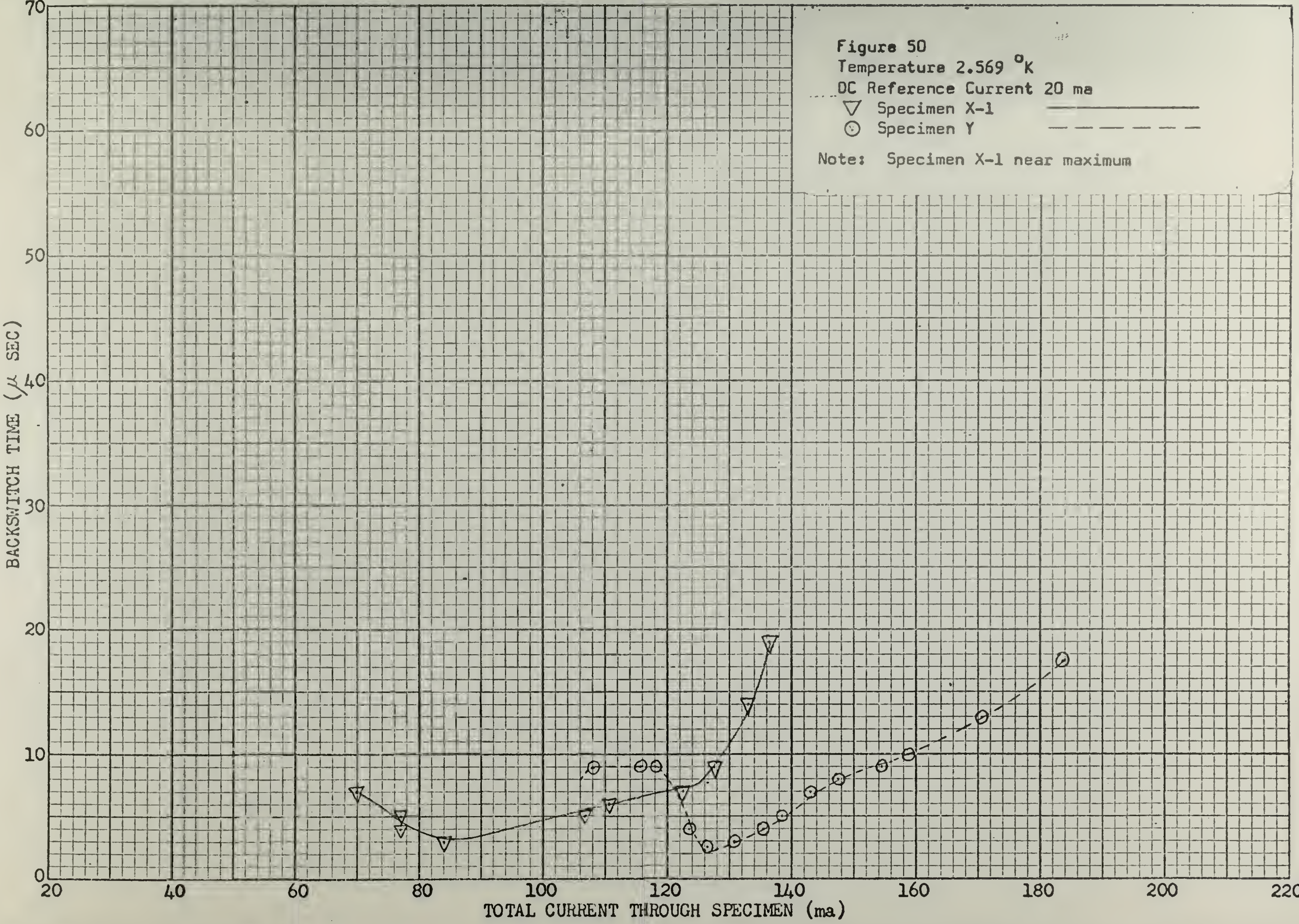


Figure 50
Temperature 2.569 °K
DC Reference Current 20 ma
▽ Specimen X-1 ———
⊙ Specimen Y — — —
Note: Specimen X-1 near maximum

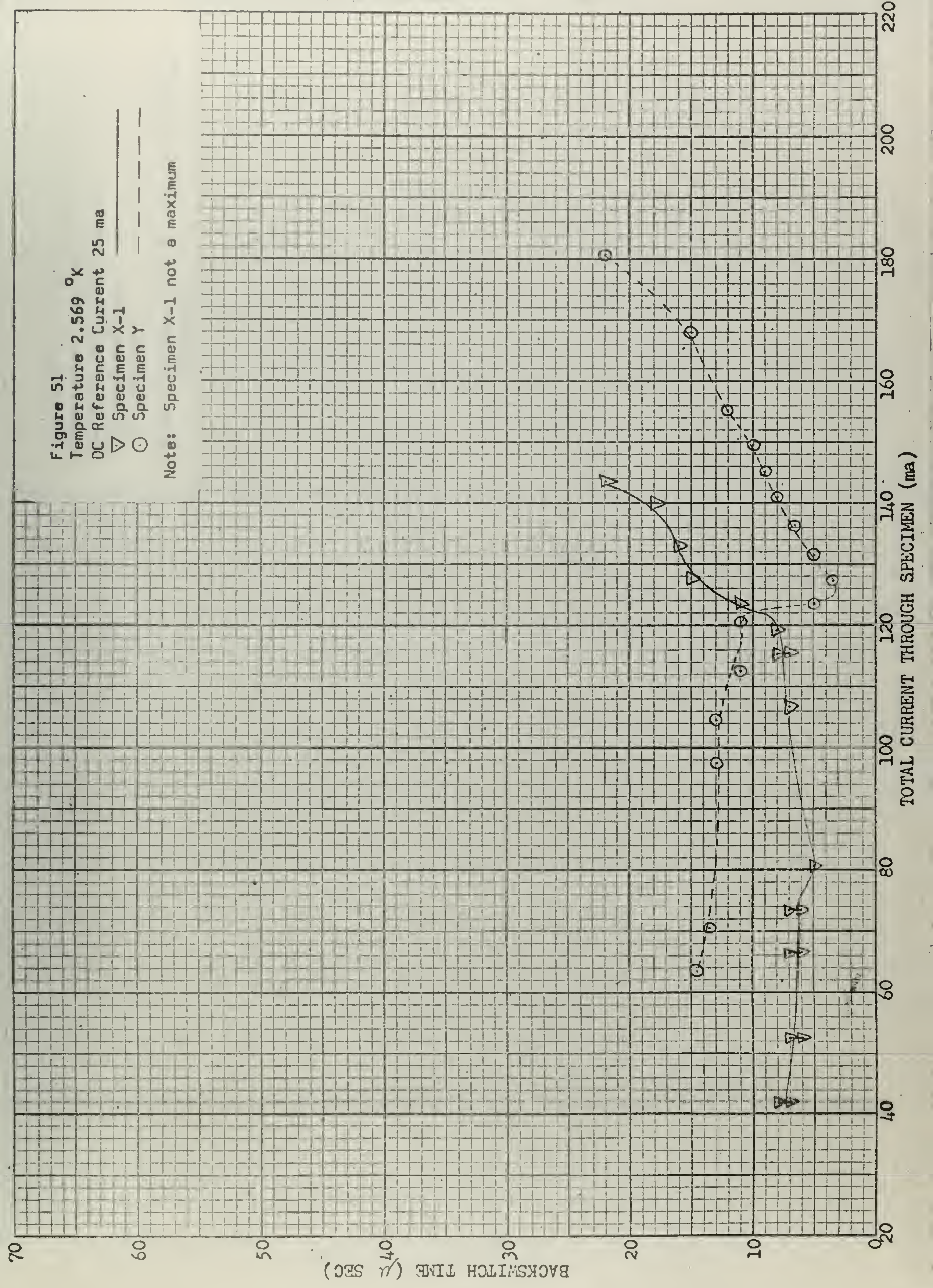


Figure 51

Temperature 2.569 °K
DC Reference Current 25 ma
▽ Specimen X-1
⊙ Specimen Y
Note: Specimen X-1 not a maximum
TOTAL CURRENT THROUGH SPECIMEN (ma)
BACKSWITCH TIME (μ SEC)
20
40
60
80
100
120
140
160
180
200
220
0
10
20
30
40
50
60
70

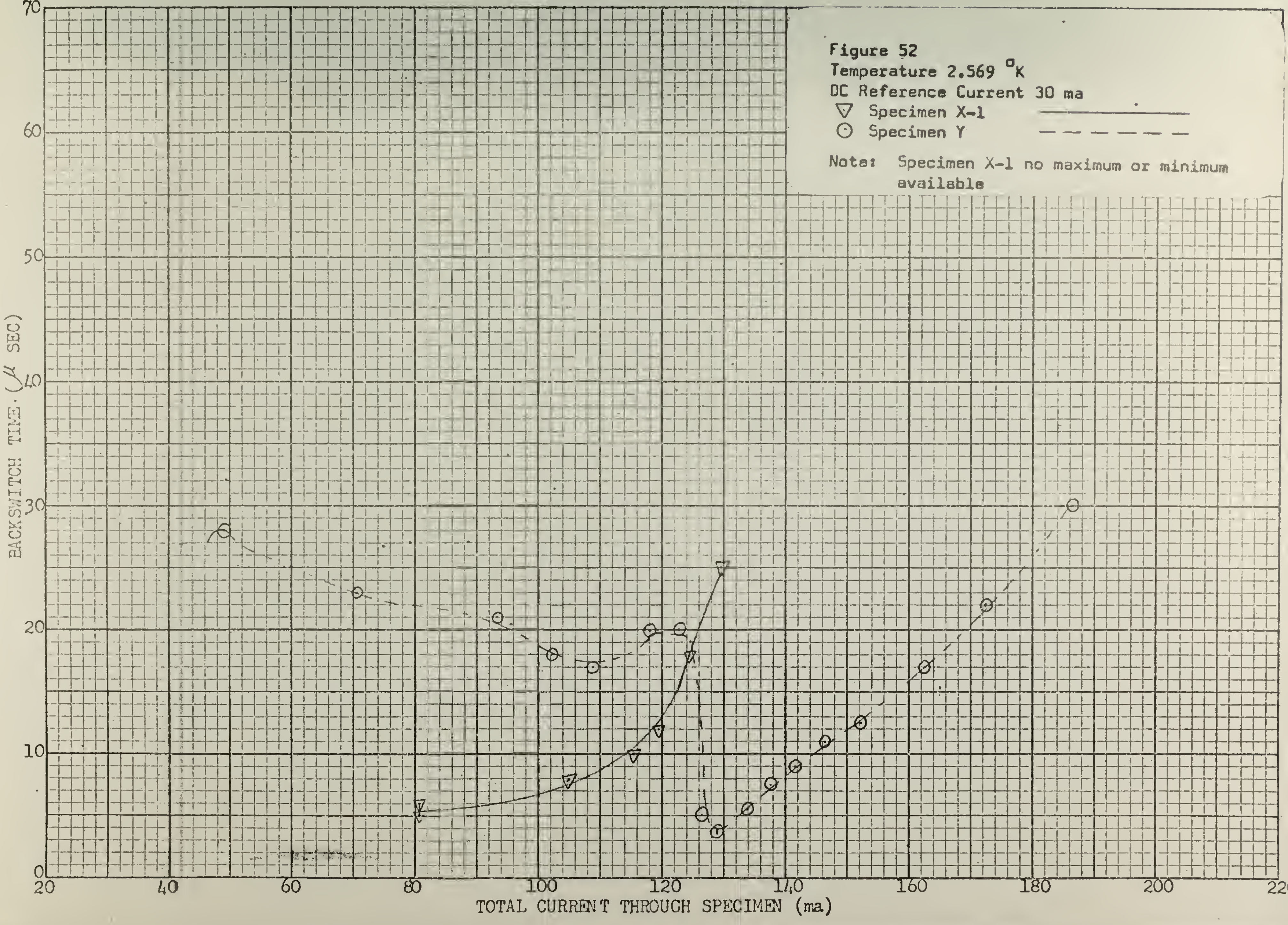


Figure 52
Temperature 2.569 °K
DC Reference Current 30 ma