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INVESTIGATION OF 10^{10} BIT OPTICAL MEMORY

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Carson Laboratories, Inc.
Bristol, Connecticut 06010

FINAL REPORT

March, 1968

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Contract NAS 12-125

National Aeronautics and Space Administration

Electronics Research Center

Cambridge, Massachusetts

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ABSTRACT

A series of experiments was conducted to obtain engineering data on the properties of potassium bromide crystals as optical data storage media. Parameters monitored were optical sensitivity, color uniformity, volume sensitivity, readout properties, re-useability and long term retention of information. Recommendations are given for improvements required for utilization of these crystals as high capacity data storage media.

TABLE OF CONTENTS

INTRODUCTION AND SUMMARY ....

I. OPTICAL PROPERTIES OF KBR:H CRYSTALS 1

A. Crystal Sensitivity vs. Light Intensity and Temperature 1

1. Experimental Procedure

2. Experimental Results

B. Uniformity of Sensitivity 5

C. Uniformity of Color Density 6

D. Long Term Retention of Information 7

E. Aging Properties 8

F. Conclusions 11

II. LIST OF ILLUSTRATIONS

Fig. 1. Absorption Bands in Typical KBR:H Crystals 12

Fig. 2. Crystal Sensitivity - Power Density vs. Bleaching Time 13

Fig. 3. Optical Sensitivity - 25°C 14

Fig. 4. Optical Sensitivity - 75°C 15

Fig. 5. Crystal Sensitivity vs. Position - Type I Crystals 16

Fig. 6. Crystal Sensitivity vs. Position - Type II Crystals 17

Fig. 7. Uniformity of Color Density - Crystal No. 22 18

Fig. 8. Uniformity of Color Density - Crystal No. 26 19

Fig. 9. Uniformity of Color Density - Crystal No. 27 20

Fig. 10. Uniformity of Color Density - Crystal No. 28 21

Fig. 11. Uniformity of Color Density - Crystal No. 29 22

Fig. 12. Uniformity of Color Density - Crystal No. 32 23

LIST OF ILLUSTRATIONS (cont'd.)

Fig. 13. Uniformity of Color Density - Crystal No. 33 24

Fig. 14. Aging Properties of Crystals 25

Fig. 15. Crystal Cycle Study I 26

Fig. 16. Crystal Cycle Study II 27

INTRODUCTION AND SUMMARY

The objective of this contract was to provide NASA, Electronic Research Center, with the preliminary design of a large-capacity optical memory system suitable for spa eborne and ground based application. Phase I of the contract was concerned primarily with system design, and reflected techniques and component selection which represent the best presently obtainable performance. Phase II investigated some factors influencing the multiple image storage capacity of "thick" crystal memories. In particular, the properties of KBR:H crystals, as they relate to this application, were studied. Properties such as the angular resolution for multiple images as a function of crystal thickness and selective erasing techniques were investigated.

This report covers Phase III of the contract which is concerned primarily with providing reliable engineering data on the properties of the KBR:H crystals as a high capacity optical storage medium. Parameters investigated were: the sensitivity of the crystals for information storage as a function of light intensity and temperature; the effect of repeated readout on the quality of stored information; the storage properties as they relate to the retention of stored images for long periods of time; the uniformity of crystal sensitivity throughout the volume of the crystal; and the aging properties of the material in terms of the useful life of the crystal as a recording medium.

As is pointed out in the text, substantial improvements in the quality of the crystals as a storage medium are constantly being realized. However, the full potential of the crystal has yet to be obtained. Further ex, rimentation is required to optimize the procedures and techniques required to attain the maximum number of holographic images which can be simultaneously stored in a crystal and the maximum bit density per recorded image.

I. OPTICAL PROPERTIES OF KBR:H CRYSTALS

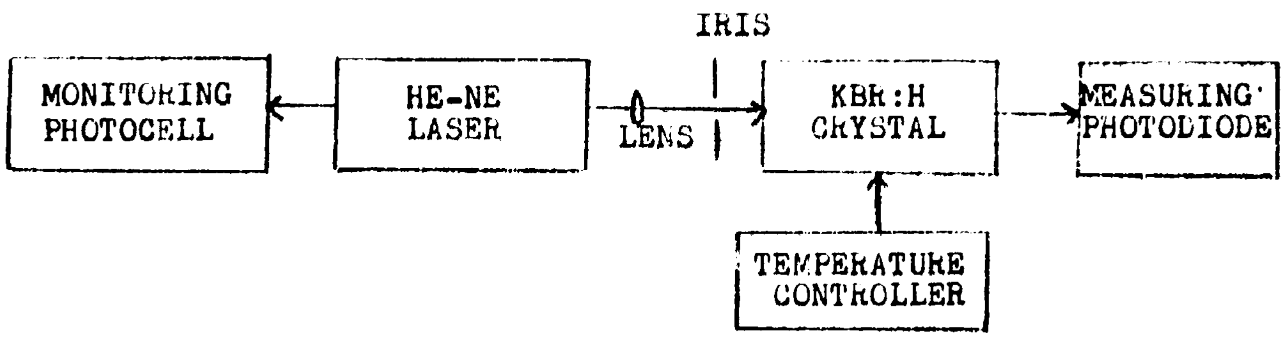
KBR:H crystals are specially prepared alkali-halide crystals containing optically bleachable color centers. The crystals contain two absorption bands; the F-band at 6300 Å in the visible and the U-band at 2280 Å in the ultraviolet (see Figure 1.). Information storage is performed by irradiating into the F-band with laser light in the conventional manner to store a hologram. Miltiple images are recorded by slight rotation of the crystal to select the desired Bragg-Angle. Readout is performed at reduced temperature ($0^{o}C$) with the same wavelength light. At this temperature the crystal sensitivity is greatly reduced and thus the images are not destroyed during viewing.

Erasing the stored information is accomplished by simply exposing the crystal to ultraviolet light absorbed in the U-band from a non-coherent light source. After erasure, the crystals may be used again for recording.

A. Crystal Sensitivity vs. Light Intensity and Temperature

1. Experimental Procedures

The experimental set-up used to obtain most of the engineering data for this program is shown in the block diagram below. This basic configuration was used to measure optical sensitivity as a function of temperature, optical sensitivity throughout the volume of the crystal, the uniformity of crystal color density and the aging properties of crystals.



Experimental Set-up for Measuring Crystal Sensitivity

To determine the crystal sensitivity as a function of light intensity, the crystals were first colored to their maximum color density at room temperature with ultraviolet light using a short-wave mercury lamp, Spectroline V-41. Subsequently, the crystals were bleached with a 15 mw Carson Laboratory Helium-Neon laser. The output power of the laser was kept constant as measured with a monitoring photocell. Power density was varied by converging or diverging the laser beam to a measured area on the crystal. In this manner the power density (mw/cm^2) could be varied over several orders of magnitude. The light transmitted through the crystal was measured with a photodiode, EG&G type SD-100. The change in transmission occuring within a constant time interval was measured and converted into optical density or decibels units where:

$$\text{Optical Density (O.D.)} = \log_{10} \frac{I_1}{I_2} = \text{bels, or}$$

$$\text{Decibels (db)} = 10 \log_{10} \frac{I_1}{I_2} = 10 \times \text{O.D., where}$$

I_1 = light flux incident on the crystal, and

I_2 = light flux transmitted by the crystal.

2. EXPERIMENTAL RESULTS

The sensitivity of the crystals can be described in terms of the time required to produce a given color change (e.g.sec/db) as a function of power density (mw/cm^2) for various temperatures. Figure 2. is a plot of crystal sensitivity at room temperature and 75 degrees centigrade. Approximately fifteen crystals were used to obtain this data. The curves represent the average values and, because of the variation in sensitivity from one crystal to another, are only accurate within a factor of 2.

Figure 3. and 4. are plots of optical density versus time for various power densities in a "typical" crystal at room temperature and 75°C respectively. To put this data in proper prospective, it should be pointed out that a retrievable hologram may be stored in a crystal with as little as a 0.01 optical density change (0.1db). If only a single hologram is stored, the entire range of optical density of the crystal may be utilized if desired (e.g., optical density of 2 or more, or a contrast range of 100:1 or greater) to record the information. When multiple holograms are stored in the same crystal, even though they may be individually and selectively retrieved, the color of the crystal is shared among all the recordings.

The results of the crystal sensitivity measurements can be summarized as follows:

1. Crystal sensitivity increases by approximately a factor of 10 between room temperature and 75°C.
2. Crystal sensitivity has approximately a square root dependance on intensity over the range measured.

It should be pointed out that the sensitivity measurements indicate a failure of reciprocity in that as power density is increased more energy is required to produce a fixed color change in the crystal. Although this effect is detrimental to high speed single-spot information storage, if large amounts of information are distributed over a large area the data rate may be quite high. It also affords the possibility of non-destructive readout at room temperature using a pulsed laser with short pulse duration. A pulsed ruby laser should be particularly suited for this application because its output light (6943 Å) would be absorbed by the F-band.

B. UNIFORMITY OF SENSITIVITY

The uniformity of crystal sensitivity throughout the crystal was measured. Bleaching rates were monitored at from five to eight different locations on the crystal and the rates compared. The experimental set-up was the same as previously described but only two power densities were used, i.e. 133 mw/cm^2 and 40 w/cm^2. All measurements were performed at room temperature.

As mentioned previously, technological improvements in the processing techniques were realized even during the course of this study. These advances were reflected in the optical properties of the crystals. For this reason we now make a distinction between the crystals available at the start of the program (Type I), and those which were subsequently fabricated (Type II).

Figure 5. shows the results of sensitivity measurements on two Type I crystals (Nos. 22 and 26), while Figure 6. shows the results of similar measurements on two Type II crystals (Nos. 29 and 32). Plotted are curves of bleaching rates across the crystal surface normalized to the mean value of each set of measurements. As is indicated the two Type I crystals both show uniformity of sensitivity to within $\pm$ 11.0%, while the two Type II crystals show sensitivity uniformity to within $\pm$ 2.5% and $\pm$ 3.1% respectively. These results are attributed to advances in the crystal fabrication techniques which include coloring, hydriding and polishing.

C. UNIFORMITY OF COLOR DENSITY

The uniformity of color density throughout the volume of crystal material was measured on seven crystals. All crystals were 1" x 1" with thicknesses between two and three millimeters and were polished. The crystals were scanned along three lines on the crystal surface (top, middle and bottom) with a helium-neon laser beam focussed to approximately 200 microns giving a resultant power density of 26 watts per square centimeter.

The crystals were first colored to their saturation color density with a medium output short-wave mercury vapor lamp. They were then inserted into the laser beam and the transmitted light was monitored. The photocell data was converted to optical density units as previously described. The crystals were positioned in a fixture which allowed horizontal and vertical translation with micrometer precision. Generally, 100 to 120 locations on a given crystal were monitored for color density. All measurements were at room temperature.

Here again, improvements in crystal fabrication techniques are demonstrated. Figures 7. and 8. show the results of uniformity of color measurements on two Type I crystals, while Figures 9. through 13. show the results of the same test on five Type II crystals. The former show deviation in color density as large as ± 4.75% across a given scan line and a total deviation between any two points on the crystal as large as ± 6.0%. The type II crystals in general had uniformity across a given scan line of approximately ± 1.0%, and an overall uniformity of approximately ± 2.0%.

D. LONG TERM RETENTION OF INFORMATION

The ability of the crystals to retain stored information for long periods of time was studied. A holographic image of a 3-Bar resolution target was stored in each of two crystals and the maximum visual resolution of each hologram noted. The crystals were stored at +7°C and -7°C, respectively, in the dark. Once a month for seven months the crystals were reinserted onto the interferometer and the quality of the images inspected. Even after seven months there was no loss in image quality in either crystal as monitored by noting the maximum visual resolution of the holograms.

Since loss in image quality would primarily be characterized by loss in resolution and none was noted over a period of seven months, a reasonable conclusion is that the crystals should be capable of storing information for at least several years if they are kept in the dark and cooled to at least +7°C.

Another experiment was conducted to determine the room temperature thermal bleaching of the crystals. Several crystals were colored to their maximum color density and stored in the dark at room temperature. The results indicated an approximate 8 month "half-life" for color center loss. That is, under these conditions the crystals will thermally bleach to 50% of their original color density after 8 months. Depending on the number of holograms stored this would result in loss of contrast ratio if only a few are stored, or complete loss of entire images if many are stored. Therefore, this is not a recommended storage technique for long term retention of information.

E. AGING PROPERTIES

Information storage in crystals containing both F-centers and U-centers is basically a photochemical process involving the transfer of an electron from a negative ion vacancy to a hydrogen atom and the subsequent diffusion of the hydrogen ion to another, or the same, negative ion vacancy. Erasure is the reversal of this process. In a "perfect" crystal, this coloring-bleaching cycle should be repeatable indefinitely. However, commercially available crystals generally contain imperfections in the form of chemical impurities and mechanical defects which may trap and remove electrons from the cycle. Furthermore, the coloring and hydriding processes undoubtedly add more impurities to the crystals. Towards the end of the study, a technique was investigated which apparently overcomes this deficiency or at least greatly extends the useful cycling lifetime of the crystals as recording media. First, the aging properties of crystals fabricated in the normal manner will be described.

The aging properties of KBR:H crystals in terms of the useful cycling life of the material as a recording medium were studied. The crystals were subjected to a series of accelerated coloring-bleaching cycles in which the ability to restore the crystals to their pre-recording condition was monitored. The two crystals used for this study were No. 11, which was polished and No. 12 which was cleaved and without any further surface treatment. Both crystals were inserted in holders for protection and also to allow the crystals to be heated. The crystals were first exposed to an ultraviolet light source and the saturation color density measured with a photocell as previously described.

After coloring, at room temperature, the crystals were heated to approximately 50°C and bleached for 30 minutes with 6328 Å light from a helium-neon laser. The total color change was at least 10 decibels. This treatment represents one cycle. Each crystal was subjected to 22 coloring-bleaching cycles.

Figure 14. shows the results of these experiments. Plotted is the saturation color density attainable as a function of the number of cycles for both crystals. As can be seen, the maximum color density in each crystal decreases gradually with each cycle. In both cases approximately 0.7% of the original color density is lost per cycle. However, it remains questionable as to how far this data can be extrapolated since, as shown below, this effect ultimately ceases.

Based on the assumption that impurity centers and mechanical defects are parasitic "traps" for color-center electrons, it was felt that: (1) the loss in color centers could be overcome by supplying the crystal with an excess of color centers and (2) eventually the impurities might become saturated and hence no longer have a detrimental effect on the crystals. To investigate this possibility, a crystal was processed so as to have approximately three times as many available color centers as is normally required for holographic data storage. The crystal when fully colored had an optical density of 5.92. After completely bleaching the crystal with a tungsten lamp, it was recolored with an ultraviolet lamp to an optical density of 2.0 using a filter which allowed irradiation only into the tail of the ultraviolet absorption band to uniformly color the crystal. The crystal was then bleached with a helium-neon laser (power density-1300 mw/cm^2) to an optical density of 1.0 and the initial bleach rate monitored with a photocell. This process was continued for a total of seventy-five such color-bleach cycles. Figure 15. shows the results of every fifth cycle. No degradation of colorability was observed.

After this series of tests, the crystal was again colored to its maximum color density which was found to be 4.36, a decrease in optical density of 1.56. The crystal was then bleached from this maximum color density to an optical density of 2.0 and the initial bleach rate measured. This process was repeated for 10 cycles. The results are shown in Figure 16. Again, no detrimental effects were noted. The crystal could be recolored to the 4.36 optical density after each cycle. This is in contrast to the earlier mentioned data in which a 0.7% optical density loss was noted per cycle.

The implication of these results is that by using this technique the useful cycling lifetime of the crystals can be greatly extended. Based on the impurity-trapping postulate, it is hypothesized that the parasitic impurities became saturated and no longer competed for the color centers in the crystals.

F. CONCLUSIONS

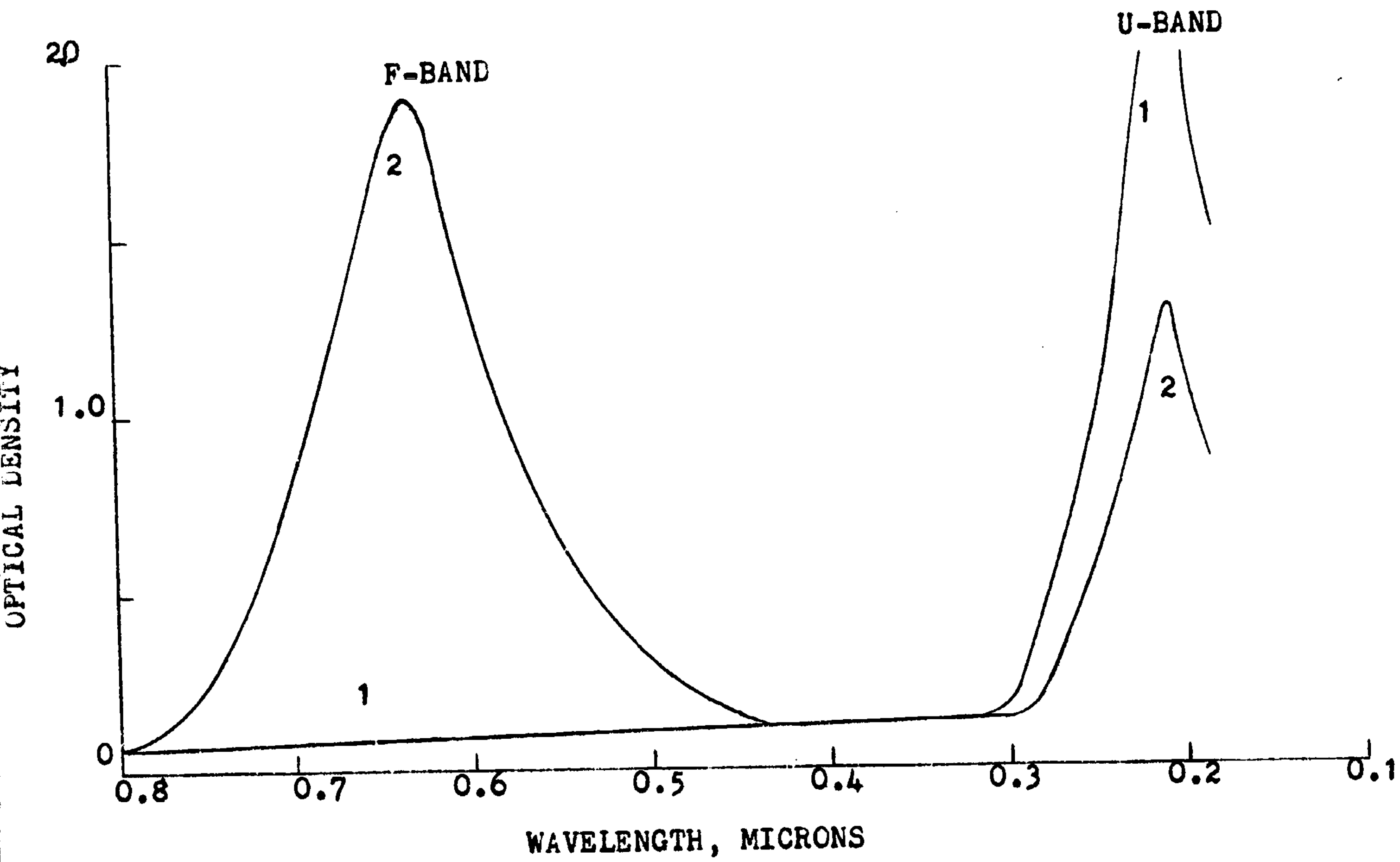
Many investigators have recognized the potential of using thick photochromic crystals as high capacity storage media. The grainlessness of the crystals offer the capability of extremely high resolution, while the thickness of the medium affords the opportunity of multiple holographic storage using Bragg-Angle techniques. The crystal studied herein, hydrided Potassium Bromide, is perhaps the best developed photochromic crystal. The present state of the art can be summarized as follows: the crystals can be fabricated with relatively good uniformity of color density and uniformity of sensitivity; the stored information can be erased, and the crystals reused many tens of times, perhaps hundreds; under proper conditions, the information stored in the crystals can be retained for periods measured in years.

On the negative side: the crystals have relatively low optical sensitivity; although experiments indicate many hundreds of holograms should simultaneously be stored in a single crystal, somewhat less than a hundred have been stored to date; the maximum bit density per recorded image has been severely limited by noise interference in the crystal.

In general, it is felt that the crystal deficiencies are not insurmountable and could be overcome by a program to develop noise suppression techniques and investigate the optimum parameters for holographic storage. Furthermore, since the sensitivity measurements indicate a failure of reciprocity, short pulse readout should be investigated as an alternative to cooling the crystals for non-destructive readout.

FIGURE 1.

ABSORPTION BANDS IN TYPICAL KBr:H CRYSTALS



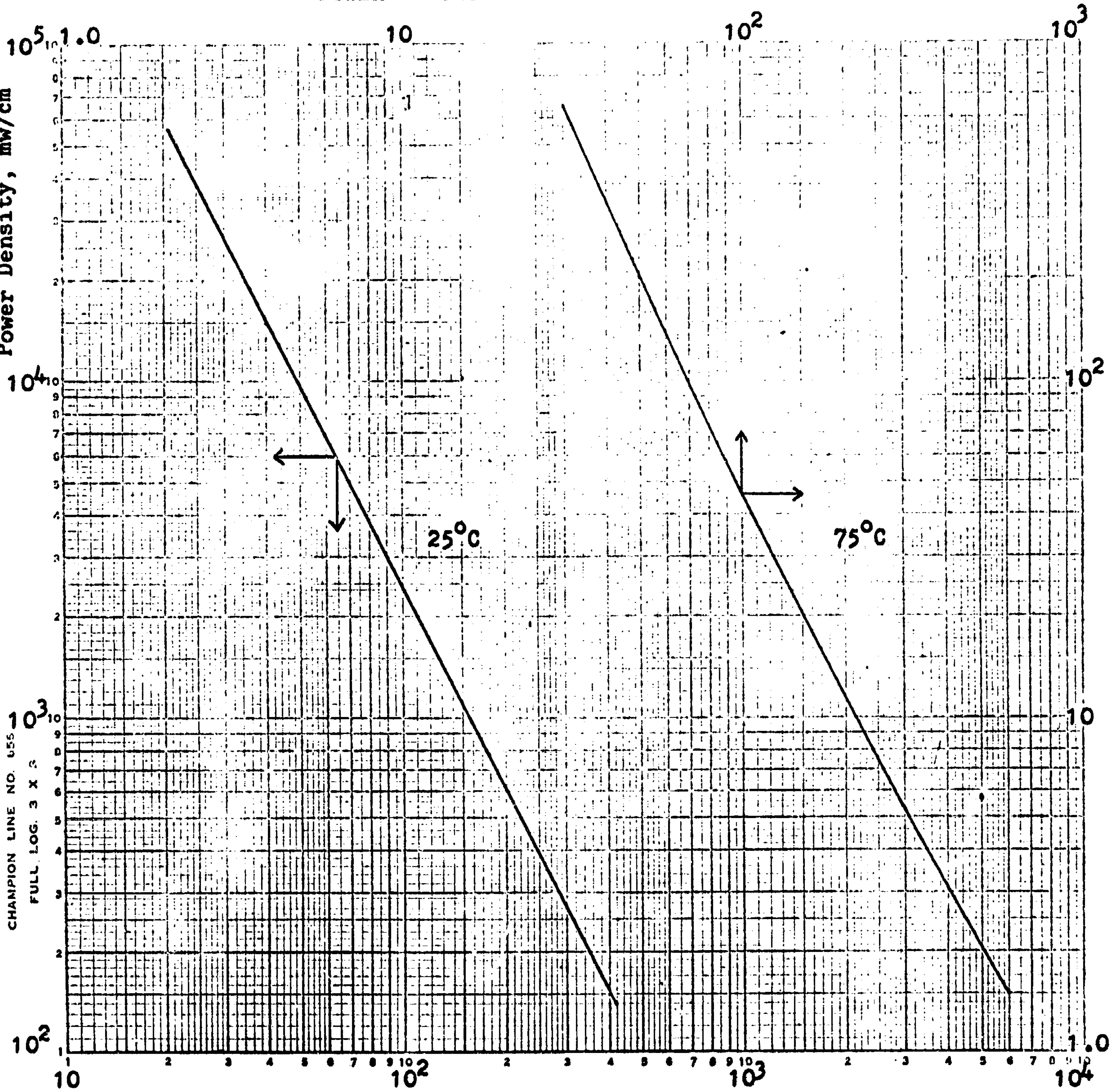
1. Crystal after prolonged exposure to red light.

2. Crystal after exposure to ultraviolet light.

FIGURE 2.

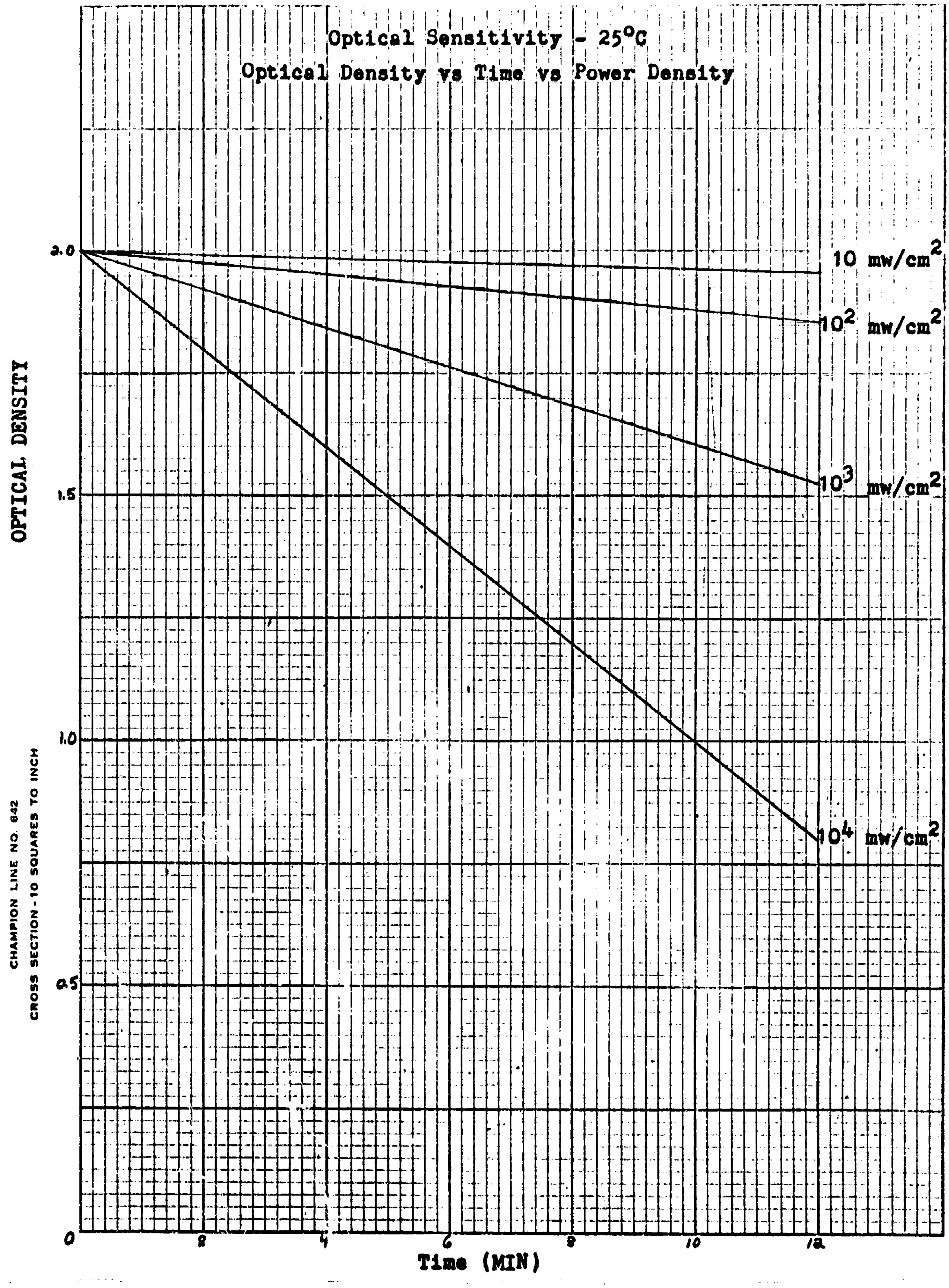
CRYSTAL SENSITIVITY

POWER DENSITY vs. BLEACHING TIME



BLEACHING TIME, sec/db

FIGURE 3.



Optical Sensitivity - 25°C
Optical Density vs Time vs Power Density
OPTICAL DENSITY
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
Time (MIN)
10 mw/cm²
10² mw/cm²
10³ mw/cm²
10⁴ mw/cm²
CHAMPION LINE NO. 642
CROSS SECTION - 10 SQUARES TO INCH

FIGURE 4.

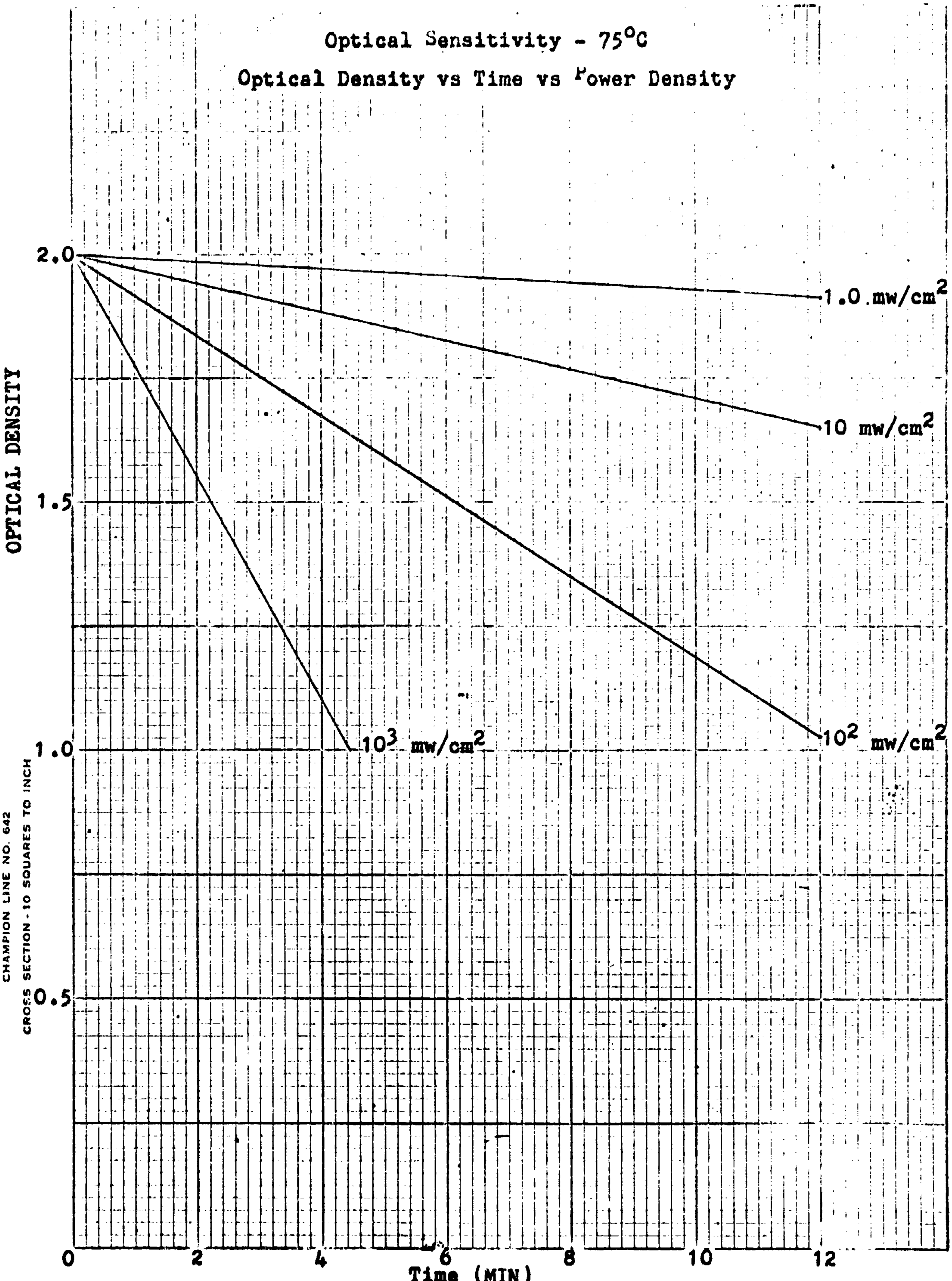

Optical Sensitivity - 75°C
Optical Density vs Time vs Power Density
OPTICAL DENSITY
2.0
1.5
1.0
0.5
1.0 mw/cm2
10 mw/cm2
10^2 mw/cm2
10^3 mw/cm2
0
2
4
6
8
10
12
Time (MIN)
CHAMPION LINE NO. 642
CROSS SECTION - 10 SQUARES TO INCH

FIGURE 5.

Crystal Sensitivity vs Position

Type I Crystals

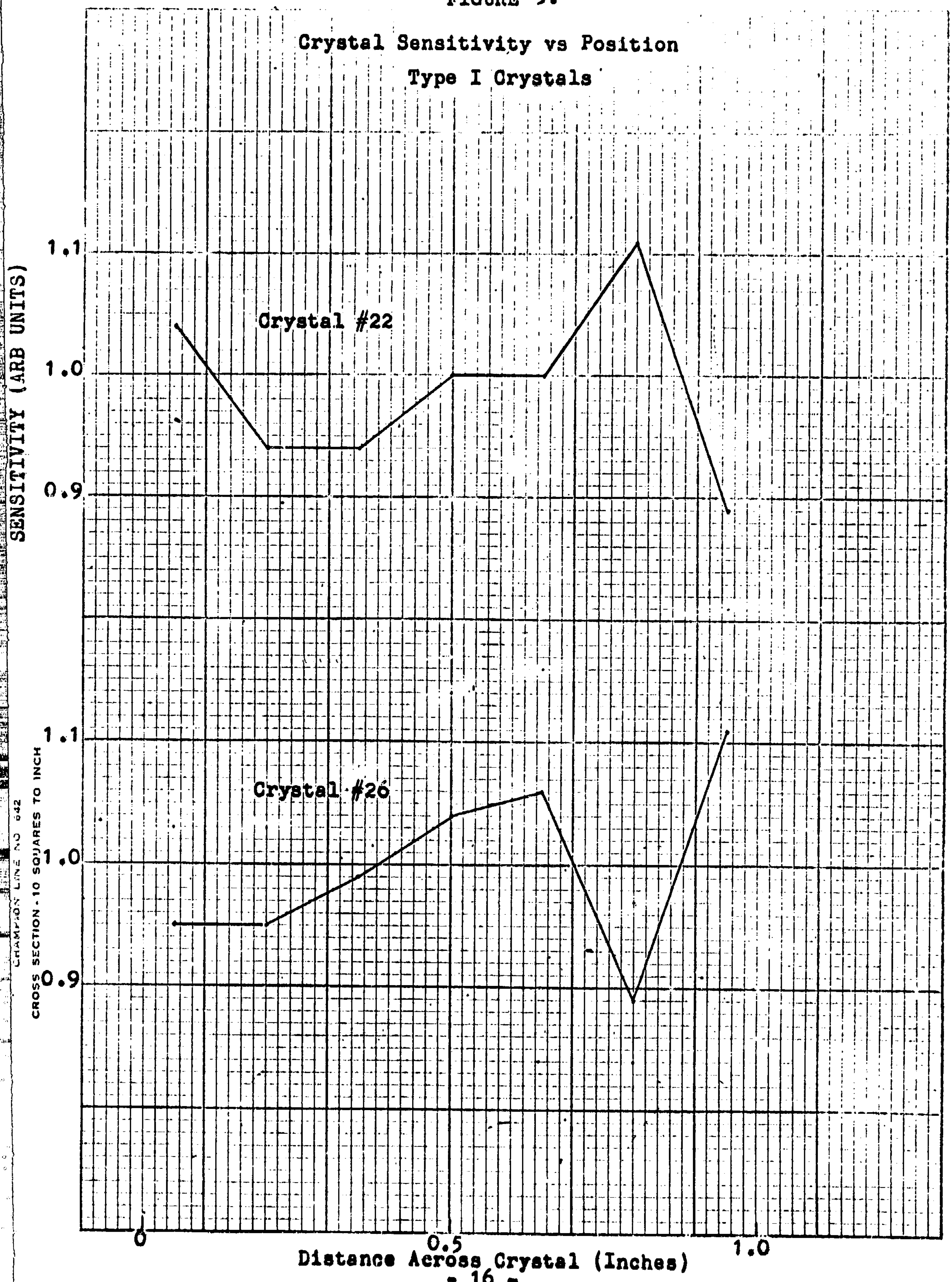


FIGURE 6.

Crystal Sensitivity vs Position

Type II Crystals

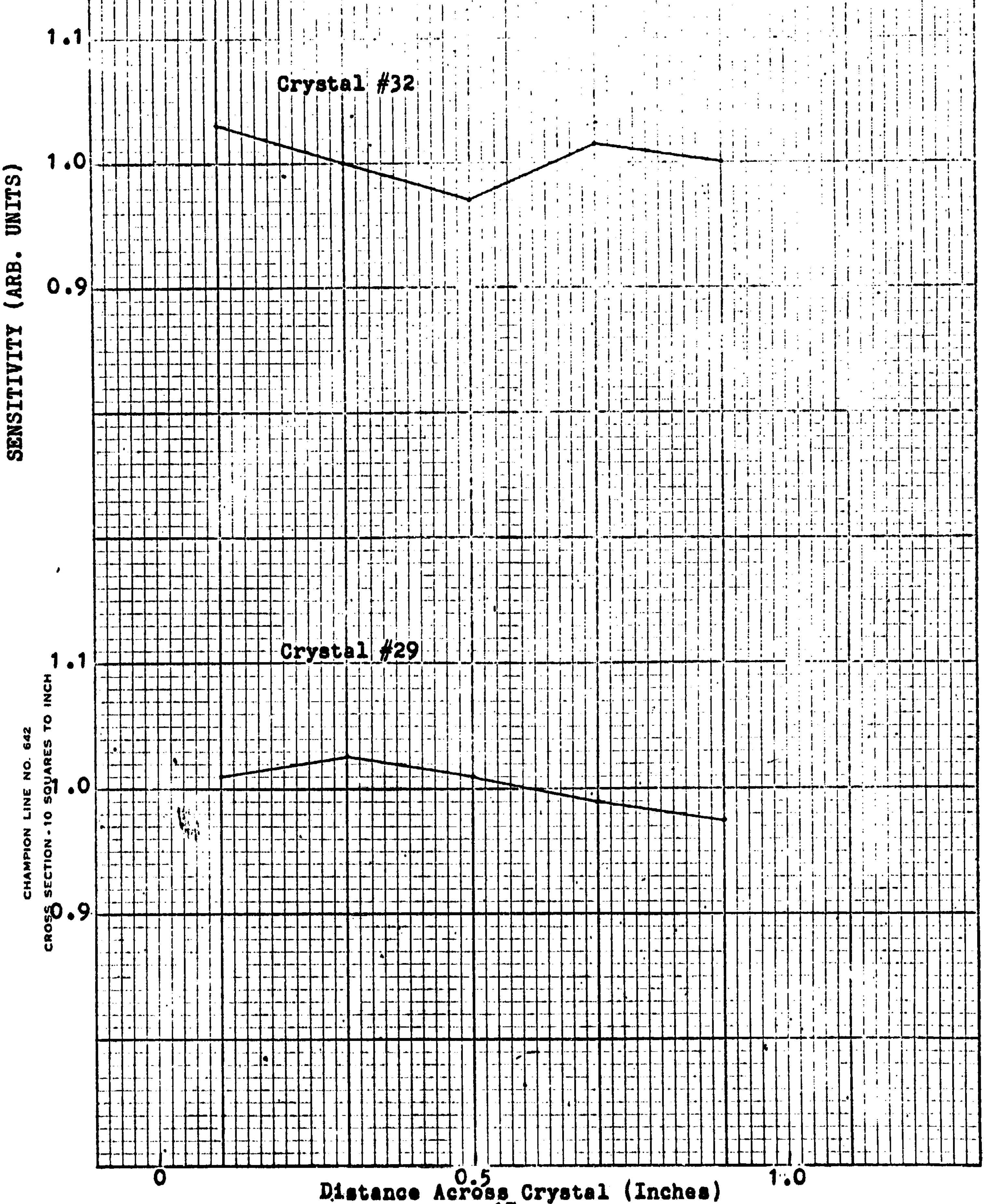


FIGURE 7.

UNIFORMITY OF COLOR DENSITY

CRYSTAL # 22.

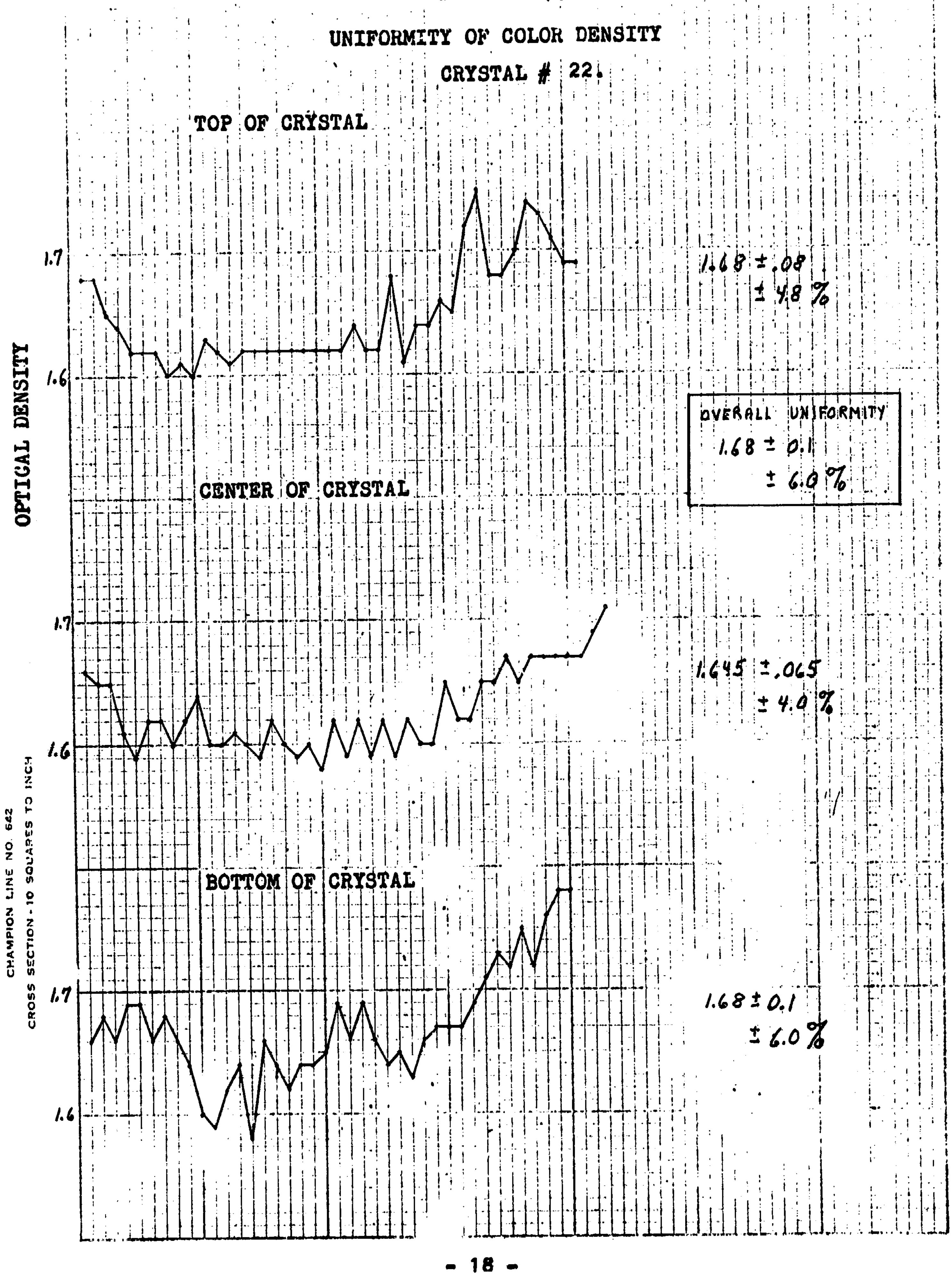


FIGURE 8.

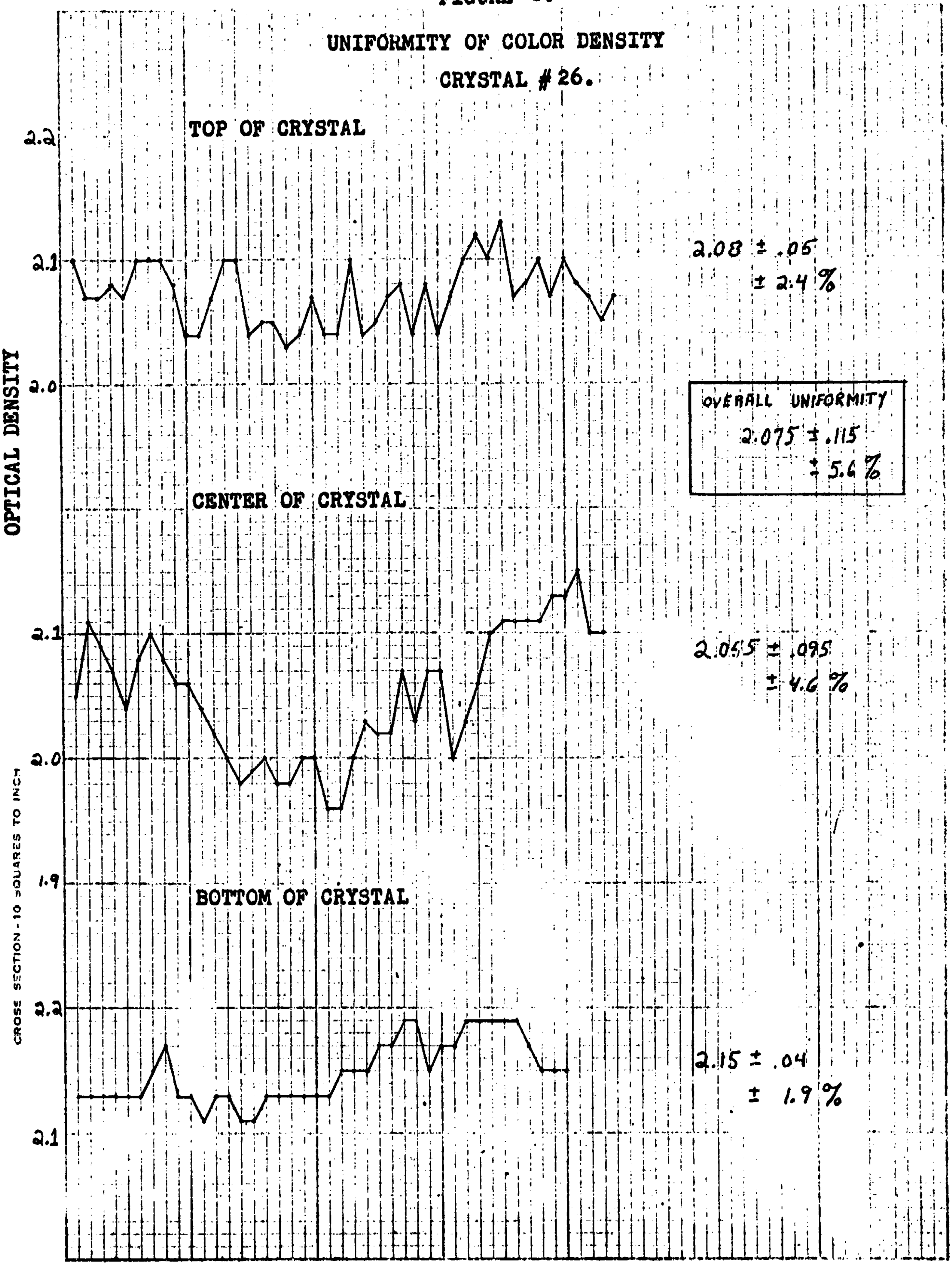

UNIFORMITY OF COLOR DENSITY
CRYSTAL # 26.
OPTICAL DENSITY
TOP OF CRYSTAL
2.2
2.1
2.0
2.08 ± .05
± 2.4 %
OVERALL UNIFORMITY
2.075 ± .115
± 5.6 %
CENTER OF CRYSTAL
2.1
2.0
1.9
2.055 ± .095
± 4.6 %
BOTTOM OF CRYSTAL
2.2
2.1
2.15 ± .04
± 1.9 %
CHAMPION LINE NO. 642
CROSS SECTION - 10 SQUARES TO INCH

FIGURE 9.

UNIFORMITY OF COLOR DENSITY

CRYSTAL # 27.

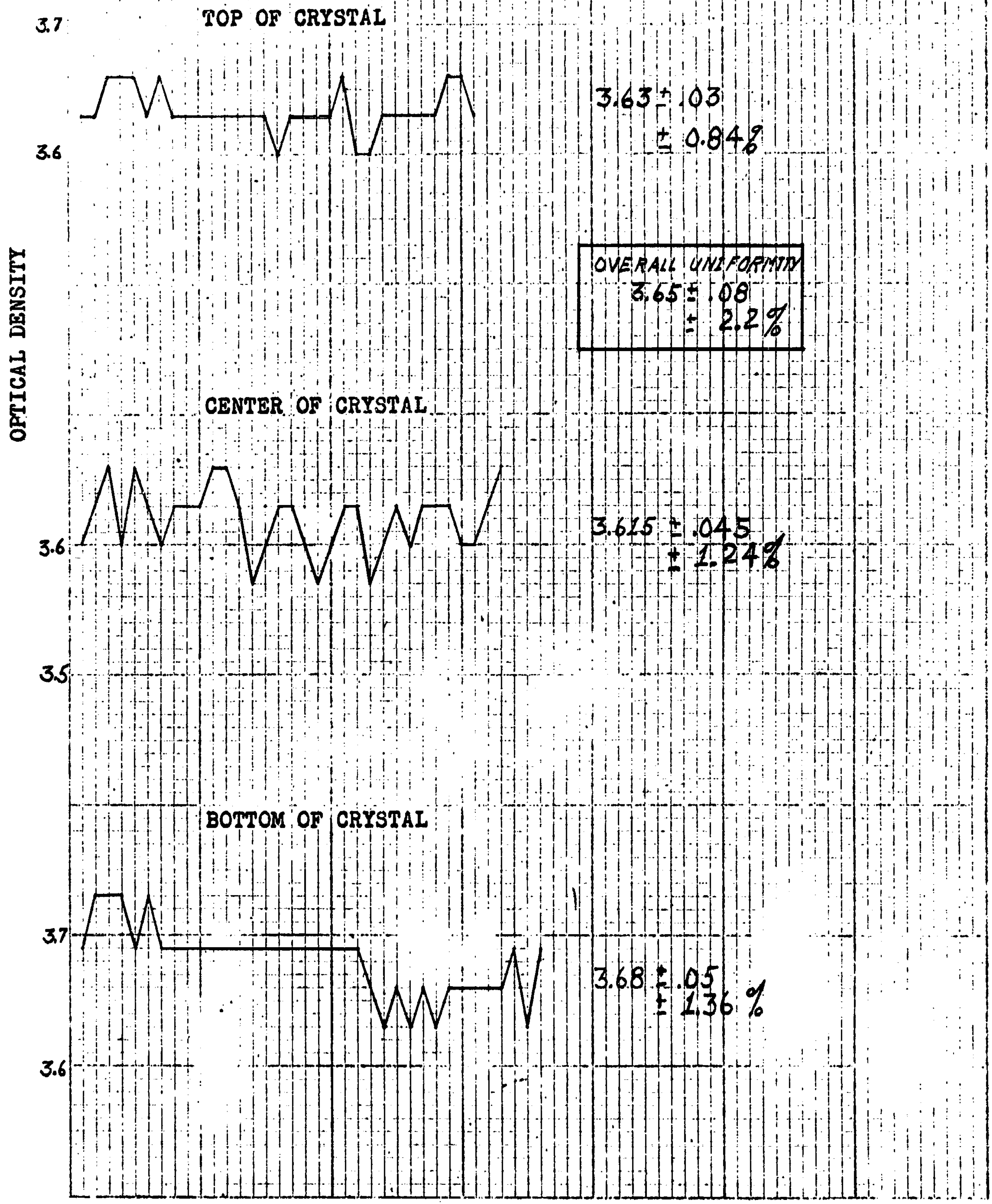


FIGURE 10.

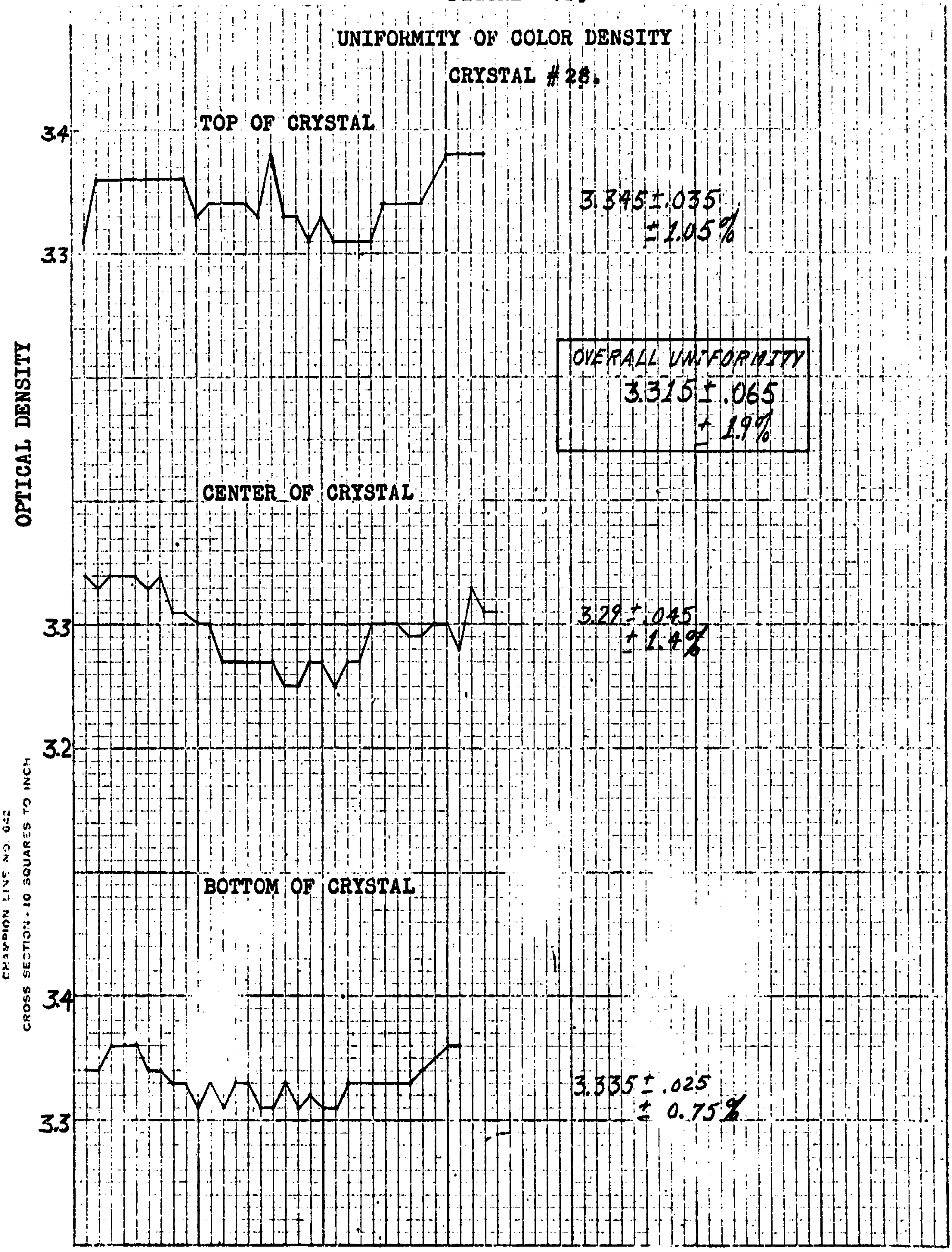

UNIFORMITY OF COLOR DENSITY
CRYSTAL #28.
OPTICAL DENSITY
TOP OF CRYSTAL
3.4
3.3
3.345 ± .035
± 1.05%
OVERALL UNIFORMITY
3.315 ± .065
± 1.9%
CENTER OF CRYSTAL
3.3
3.29 ± .045
± 1.4%
3.2
BOTTOM OF CRYSTAL
3.4
3.3
3.335 ± .025
± 0.75%
CHAMPION LINE NO. 642
CROSS SECTION - 10 SQUARES TO INCH

FIGURE 11.

UNIFORMITY OF COLOR DENSITY

CRYSTAL # 29.

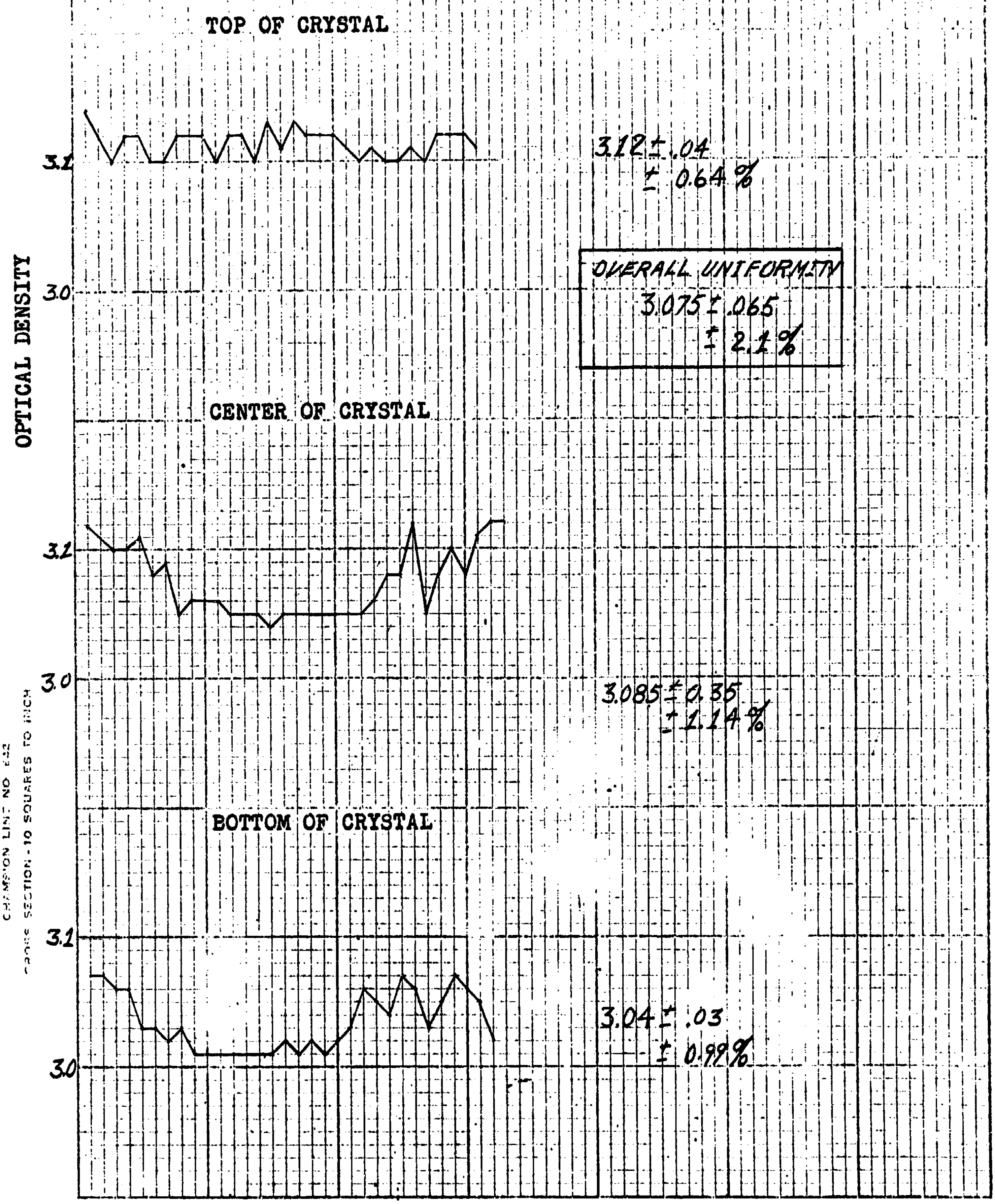


FIGURE 12.

UNIFORMITY OF COLOR DENSITY

CRYSTAL #32.

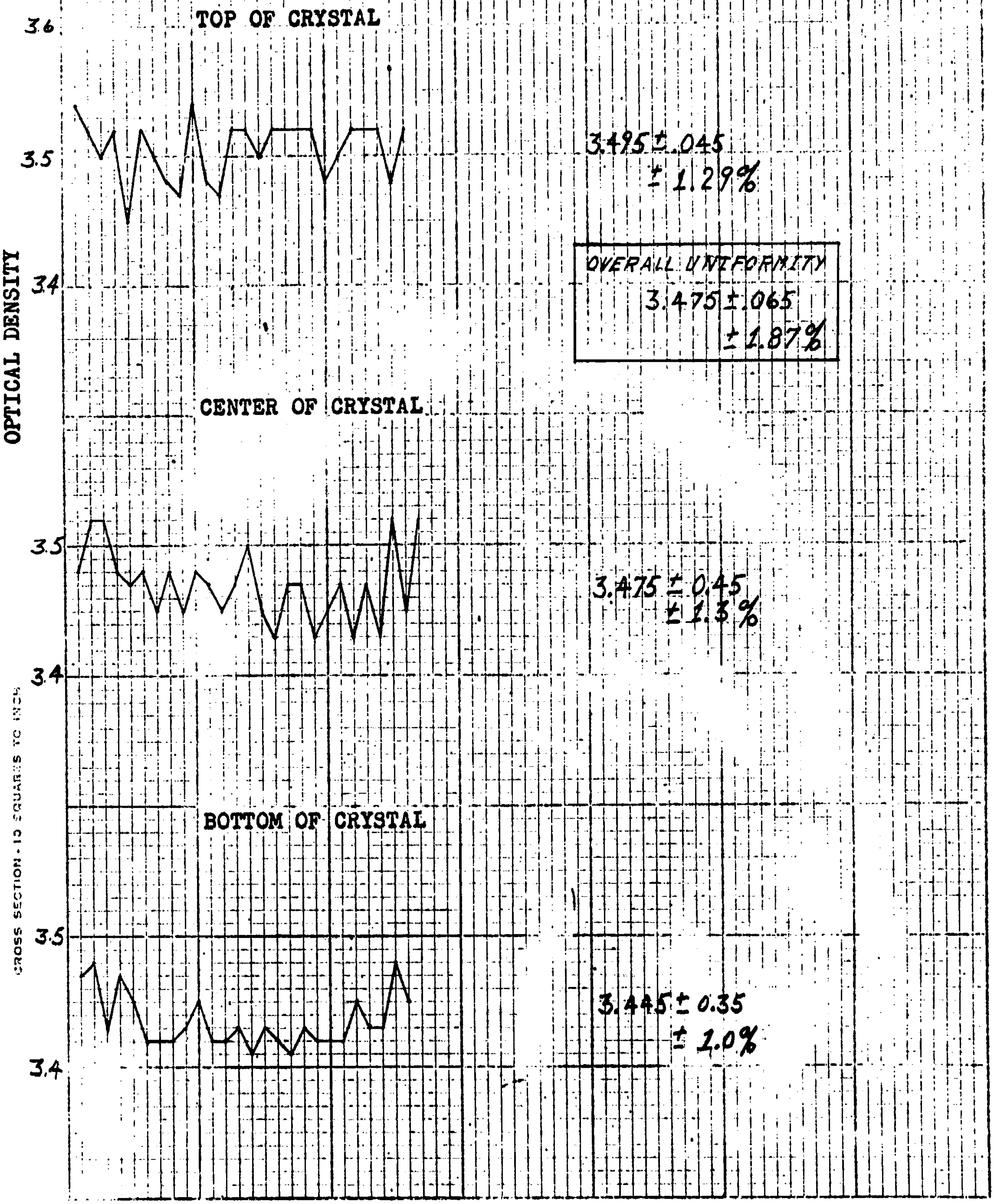


FIGURE 13.

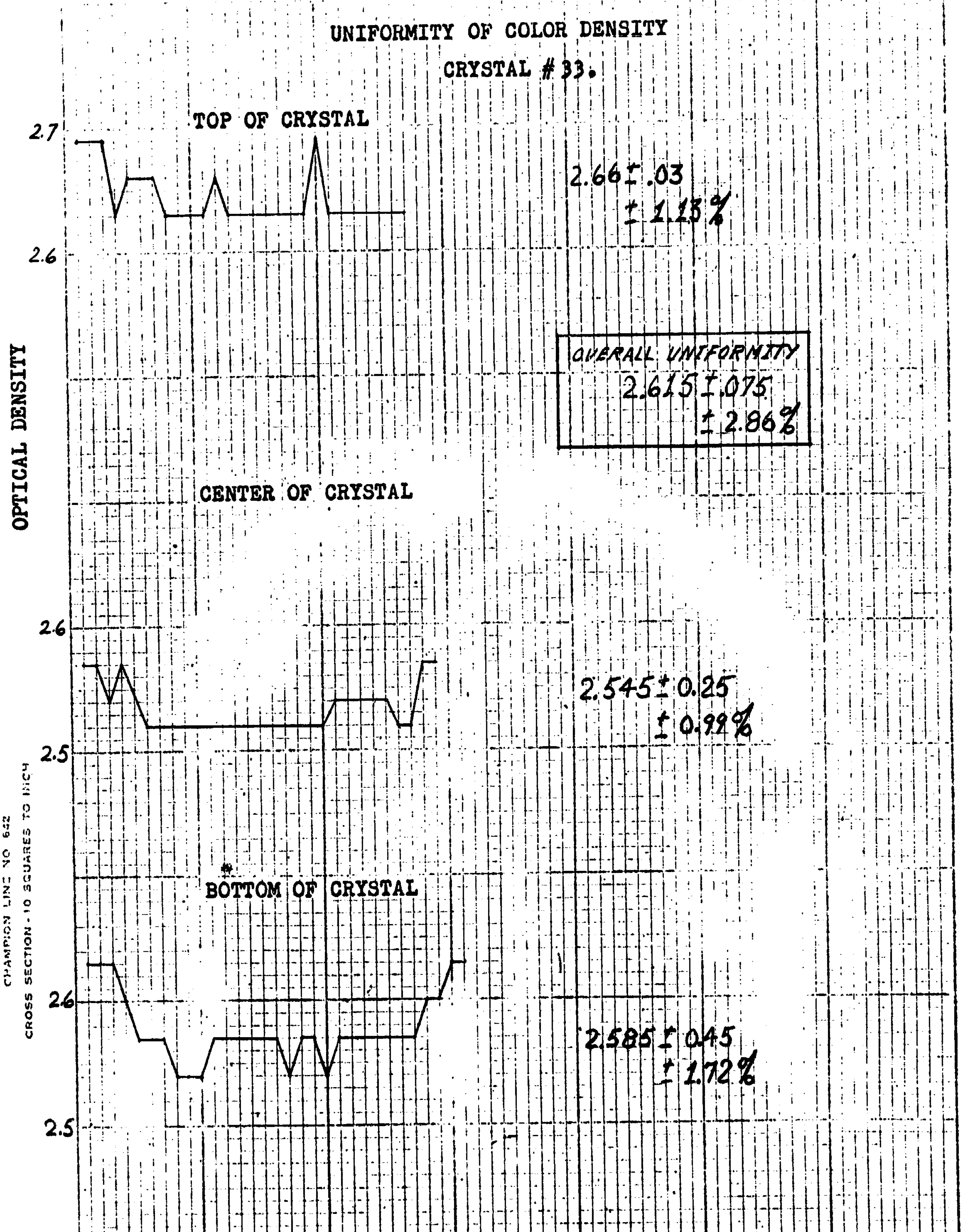

UNIFORMITY OF COLOR DENSITY
CRYSTAL #33.
OPTICAL DENSITY
TOP OF CRYSTAL
2.7
2.6
2.66 ± .03
± 1.13%
OVERALL UNIFORMITY
2.615 ± .075
± 2.86%
CENTER OF CRYSTAL
2.6
2.5
2.545 ± 0.25
± 0.99%
BOTTOM OF CRYSTAL
2.6
2.5
2.585 ± 0.45
± 1.72%
CHAMPION LINE NO 642
CROSS SECTION - 10 SQUARES TO INCH

FIGURE 14.

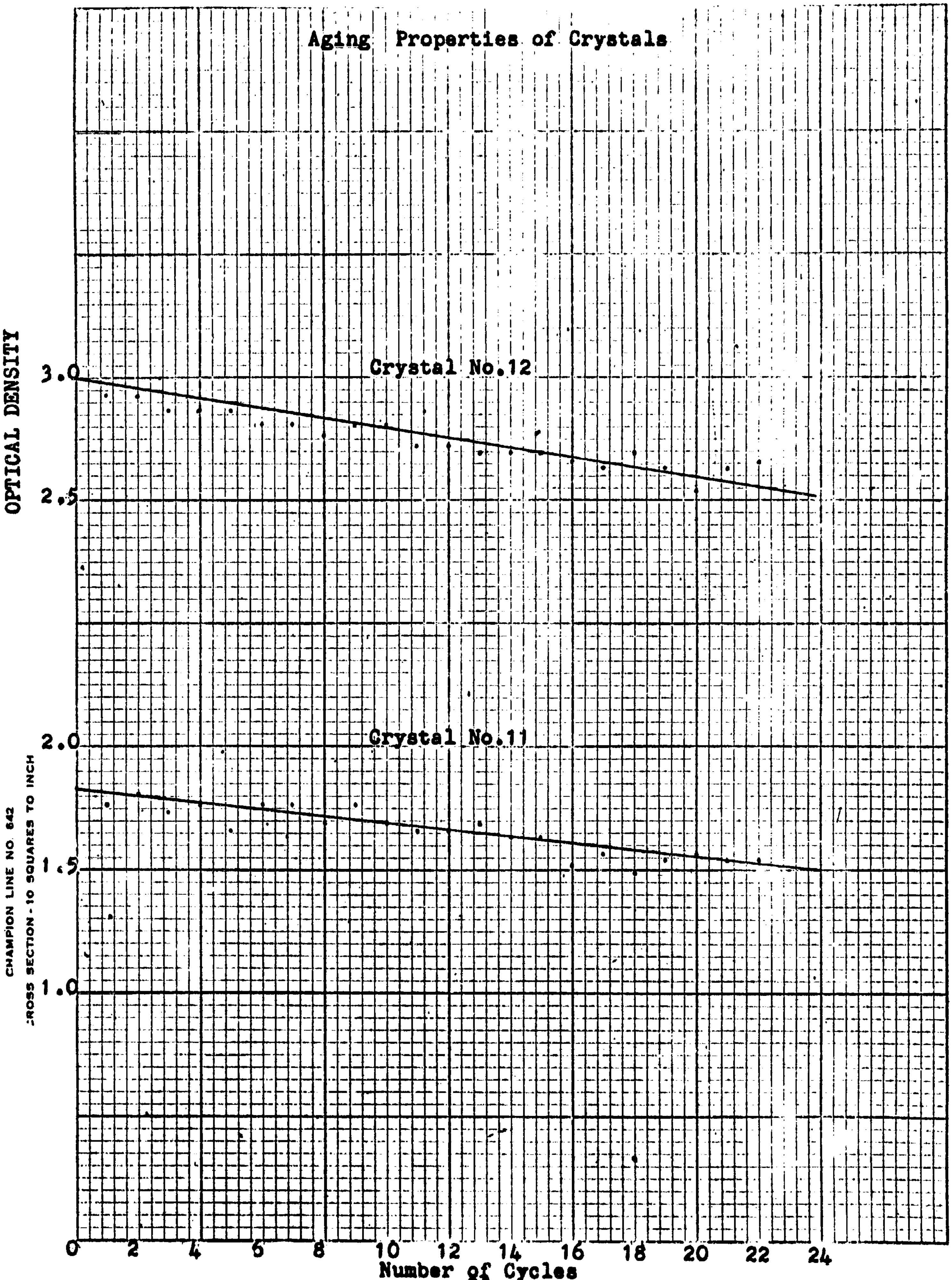
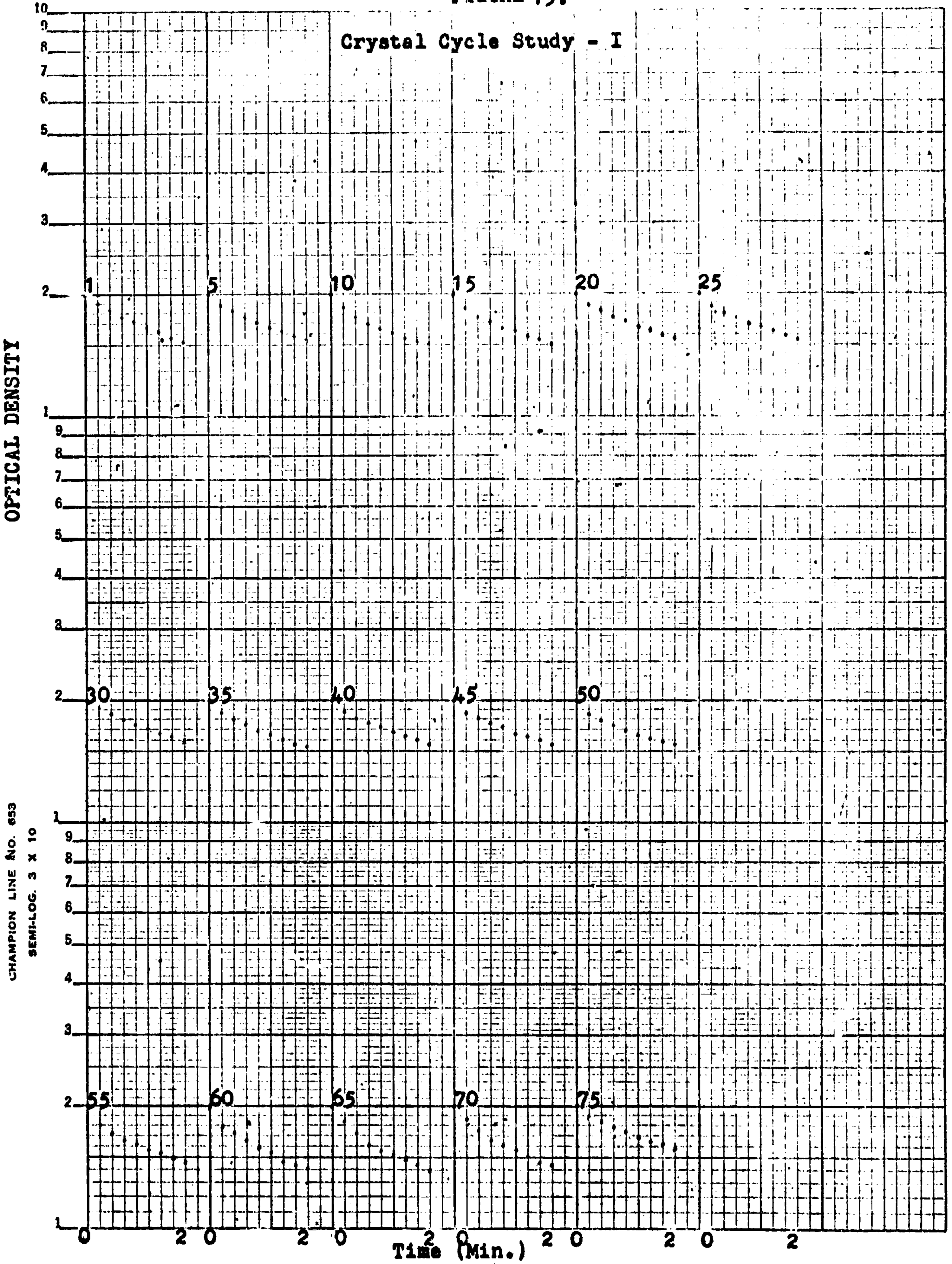

Aging Properties of Crystals
Crystal No.12
Crystal No.11
OPTICAL DENSITY
3.0
2.5
2.0
1.5
1.0
0
2
4
6
8
10
12
14
16
18
20
22
24
Number of Cycles
CHAMPION LINE NO. 642
CROSS SECTION - 10 SQUARES TO INCH

FIGURE 15.



Crystal Cycle Study - I
OPTICAL DENSITY
Time (Min.)
1
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
0
2
CHAMPION LINE No. 653
SEMI-LOG. 3 X 10

FIGURE 16.

Crystal Cycle Study - II