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APC File 6305

PHOTOPOLYMER HOLOGRAPHIC OPTICAL ELEMENTS

Contract #DAAB-07-87-C-7007

Final Report
June 1987

Prepared for

Night Vision and Electro-Optic Center
Attn: AMSCL-NV-T
Fort Belvoir, VA 22060-5677

Prepared by

Aerodyne Products Corp.
76 Treble Cove Rd.
No. Billerica, MA 01862
617-663-7411

D.E. Willoughby
Principal Investigator

INTRODUCTION

During the 1970's the advantages and disadvantages of holographic materials technology for the notch filter application became apparent to the military community. Holographic elements offered superior optical properties but suffered from environmental stability. Holographic notch filters were fabricated by several contractors from a gelatin based material and all suffered from a decrease or wavelength shift in optical density over extended periods. Sophisticated sealing and processing methods reduced the stability problem but invariable increased the production cost or decreased the optical quality of the filter. The re-emergence of holographic photopolymers in the 1980's created an interest as to the cause of holographic notch filter instability. Subsequent work at the Polaroid corporation with a Polaroid photopolymer called DMP-128 proved that the instability was not inherent to the 'physics of holography' but to the gelatin material used to fabricate the holographic optical elements. The ability to fabricate high quality stable holograms on photopolymers created an interest in non-gelatin materials for the notch filter application. The Aerodyne study represents one of several efforts by the Center for Night Vision & Electro Optics at Fort Belvoir, Virginia to improve the materials available for countermeasure applications.

This report by Aerodyne [illegible] of reflection [illegible] fabricated with a Polaroid photopolymer (DMP-128). Aerodyne was never able to obtain high quality holograms with Polaroid DMP-128. Their study is in contrast to other work at Polaroid, US Army Center for Night Vision @ Electro-Optics, and Ralcon Corporation which demonstrate holograms applicable to countermeasure applications. The poor understanding of Aerodyne in the materials and techniques necessary for high quality holographic production resulted in the termination of this effort at the Phase 1 level.

The optical quality and the stability of Polaroid DMP-128 make it the primary material for holographic notch filter applications. Research in holographic materials and applications continues under several different programs. Related efforts include:

ARMY Research Office support for photopolymer material characterization at the University of Rochester. Effort includes scattering measurements of Polaroid DMP-128.

CECOM Center for Night Vision & Electro-Optics sponsorship of holographic material survey with the RALCON corporation. Work includes evaluation of Polaroid and Dupont holographic photopolymers.

ARMY Materials Command/NATICK effort to produce low cost protective visor on a plastic substrate. Contract with the Polaroid corporation.

U.S. ARMY Missile Command, Redstone Arsenal, AL Huntsville. Work includes photopolymer experiments pertinent to optical computing applications.

Mark Norton, October/88
US ARMY CECOM Center for Night
Vision & Electro-Optics
Fort Belvoir, Virginia

ABSTRACT

Polaroid DMP-128 Photopolymer was investigated for holographic optical element applications, in particular, personnel and optical systems protection from laser light. The holograms should have low transmission in a narrow spectral band and good transmission over the rest of the visible region. Since the low-transmission band is wide using standard procedures, the main focus was to determine the effects of water sensitization and laser exposure on the spectral width of the band. The photopolymer is activated by water impregnation. To ensure uniform water takeup, all procedures were performed in an environmental chamber at controlled temperature and humidity conditions: temperature around 70°F, and relative humidity from below 15% to about 60%. 2" x 2" glass slides with 6 and 12 μm, red sensitive Polaroid DMP-126 Photopolymer were used. The desiccated slides were placed on a balance and the weight of water absorbed was measured. The weight increased until a steady state was reached. For relative humidities below 30%, there was no water takeup. Above 30% relative humidity, the steady state weight increase, Δm in milligrams, is fit by the relation $\Delta m = 1.67\ (VP) - 11.5$, where (VP) is the water vapor partial pressure in torr. The film thicknesses were 6 μm and 7 μm. The unsteady effects in water takeup were investigated by varying the relative humidity. The corresponding rapid change in the weight indicated water takeup near the free surface and little takeup near the glass substrate. Holograms were made using a helium-neon laser: 7 mw/cm^2 laser power, <1 sec to >100 sec exposure time. Up to eight 1/2" diameter exposures were made on each plate. The main result: the lower the water sensitization takeup, the narrower the transmission band. Thus, holograms should be made at low relative humidity consistent with the transmission requirements. Spectral bandwidths below 50 nm can be obtained, close to the theoretical width calculated by Ingwall. On the same plate higher exposure energy shifts the low transmission band to red. The transmission measured with an argon ion laser beam varied between 10^{-3} and 10^{-4} for laser exposures from 30 to 100 mJ/cm^2.

I. INTRODUCTION

The use of holographic optical elements has been under investigation for several applications[1]. The success of some of these applications has been limited due to the properties of the holographic material. The Polaroid DMP-128 Photopolymer has several characteristics that appear suitable for Military Optical Elements. The purpose of this program is to investigate the Polaroid Photopolymer Material in applications requiring protection of personnel and optical systems from laser beams. This requires highly efficient holographic mirrors exhibiting transmissions of less than 10^{-4}, in narrow spectral bands at the laser lines of interest and little attentuation of transmitted light in other spectral regions. In the kickoff meeting at the Night Vision Laboratory in December, it was agreed that the Phase I effort would investigate performance parameters for the Polaroid DMP-128 Photopolymer in the application to holographic mirrors. Of prime importance are the in-band optical density, bandwidth and wavelength shift, and out-of-band transmission.

In conversations with Polaroid personnel relative to the properties of the Polaroid Photopolymer, it was pointed out that the spectral bandwidth for reflection holograms should be narrower than that normally obtained. Thus, the main emphasis of this program was to prepare uniform samples of holographic material and measure the properties described above.

The Polaroid DMP-128 Photopolymer is normally stored dry (in a container with desiccant) and has a long shelf life. Under these conditions it is not active. It is made active by impregnating the photopolymer with water. The presently recommended method for adding water is to circulate humid air over the surface for several minutes and immediately make a hologram by exposing the material to interfering laser beams. Any non-uniformity in the water concentration in the polymer while making the hologram can lead to non-uniform spacing between the holographic grating planes in the finished HOE. This has the effect of broadening the spectral band. The major part of this Phase I program was to study: (1) the effects of water uniformity in the photopolymer and, (2) the effects of the amount of water on the hologram properties.

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[1] "Holographic Optical Elements with Polaroid DMP-128" by Mark Norton and Charles Martin.

The next section describes the measurements of water takeup under controlled environmental conditions. The following section describes the procedures for making holograms and some of the results. The final section summarizes the results of this experimental program.

SECTION II

WATER TAKEUP BY DMP-128 PHOTOPOLYMER

The objective of the initial effort was to control the water sensitization of the photopolymer. The photopolymer is dry and stored with a desiccant. To activate the photopolymer for making holograms, water is added to the photopolymer. Sufficient water is taken up when the photopolymer is exposed for a few minutes to air with roughly 50% relative humidity. The standard humidifying method is to place a plate with a photopolymer coating in a box with a 1/4" layer of water saturated with potassium thiocyanate. This system maintains a steady state relative humidity of 47% at room temperature. A blower transports air over the liquid surface and then onto the photopolymer. The box is opened after several minutes; then the film is placed in a fixture for making holograms with laser light, exposed and processed.

If the water concentration in the photopolymer is not uniform during the laser exposure, then the plate can have varying holographic properties. The standard humidifying method can produce variations in two ways: (1) the plate is taken out of the humidifying box before the water is uniformly distributed in the photopolymer, and (2) the relative humidity in the humidifying box is different from that in the room. In the latter case the change in relative humidity can cause water takeup or evaporation by the photopolymer.

In order to accurately measure the amount of water takeup and the uniformity of humidification, the entire experiment was performed in an environmentally-controlled room. A 10 ft by 10 ft chamber capable of controlling temperature to $\pm 1^{\circ}F$ and relative humidity to $\pm 1\%$ was employed. A vibration isolated honeycomb optical table was installed in the environmental chamber. All the steps in making holograms were performed under rigid environmental control. These steps include: (1) water take-up by film, (2) film exposure to laser light, and (3) chemical processing of the exposed film. DMP-128 photopolymer on 2" by 2" glass slides (obtained from Polaroid) had the following specifications: red spectral sensitivity and 6 and 12 micrometers thickness of the photopolymer. Water takeup was first explored. The experimental procedure was to first desiccate Polaroid DMP-128 material and

weigh the desiccated slide. The slide was desiccated at 60°F and relative humidity below 15%. The temperature and relative humidity of the environmental room was then set to specific values in the range from 10% to 60% relative humidity and temperatures of 60 to 80°F. However, most of the measurements were made around 70°F. A desiccated DMP-128 slide was placed on a balance in the environmental room, and the weight of the slide was measured. The slide weight increased due to absorption of water vapor from the air. Figures 1, 2, and 3 present measurements of the slide weight versus time. For Figure 1, the environmental room was at 71.5°F and relative humidity at 34%. The initial rate of weight increase is 0.02 milligrams per minute. The total weight change from the desiccated to the steady state was 1 milligram. In Figures 2 and 3 the room temperatures were 71°F and 70.5°F; relative humidity, 45% and 56%; initial slope, 0.25 and 0.60 milligrams per minute; and weight change 3.45 and 5.1 milligrams. Figures 4 and 5 show the steady state weight change as a function of relative humidity and absolute humidity, respectively. The temperature varied from 68° to 72°F for the data shown in Figures 4 and 5. Note that there is no (or little) weight change below RH=30%. Above RH=30% the weight change increases almost linearly with absolute humidity (see Figure 5). The steady state weight change can be approximated by the relationship

$$(\Delta m) = (5/3)\,(VP) - 11.5 \qquad (1)$$

where the weight change (Δm) is in milligrams and absolute vapor pressure (VP) is in (mm Hg). The initial water takeup rate versus relative humidity is presented in Figure 6. The initial rate varies from 0.02 to 0.6 milligrams per minute for relative humidities from 34% to 60%. At the lower humidity, the water takeup rate is over 10 times slower, even though the steady state weight increase is less. The time to reach the steady state weight with the initial water takeup rate is presented in Figure 7. This time is obtained from the relation

$$\text{time to reach steady state weight} = \frac{\text{weight increase (Figure 4)}}{\text{initial rate (Figure 6)}}$$

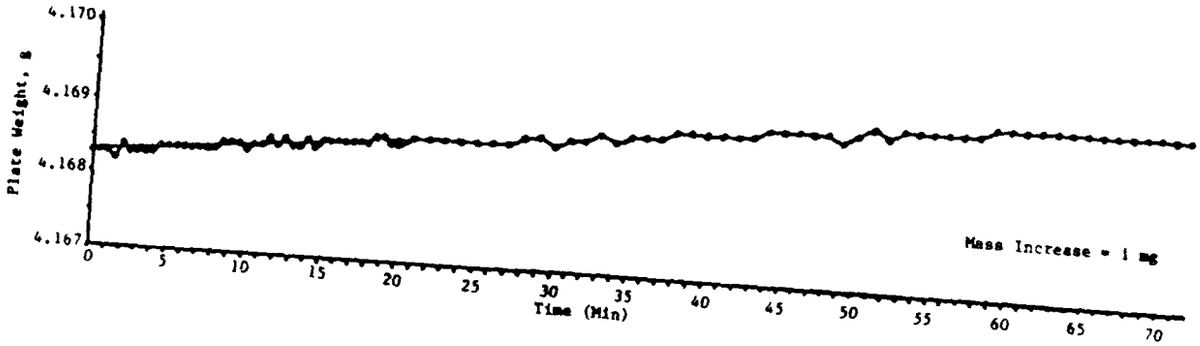


Figure 1. Water Takeup of DMP-128 Film. Weight of Plate versus Time, Room Temperature = 71.5°F, and Relative Humidity = 34%

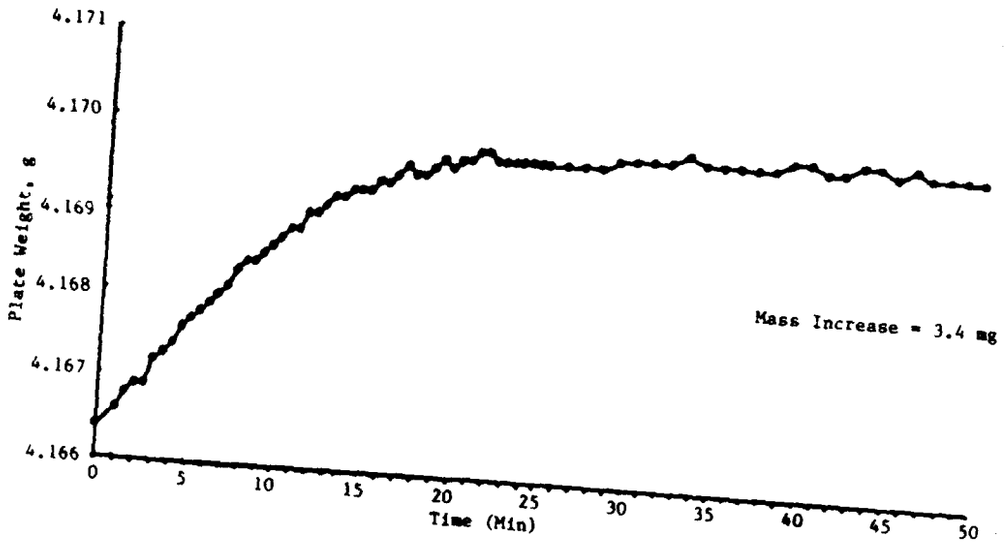


Figure 2. Water Takeup of DMP-128 Film. Weight of Plate versus Time, Room Temperature = 71°F, and Relative Humidity = 45%

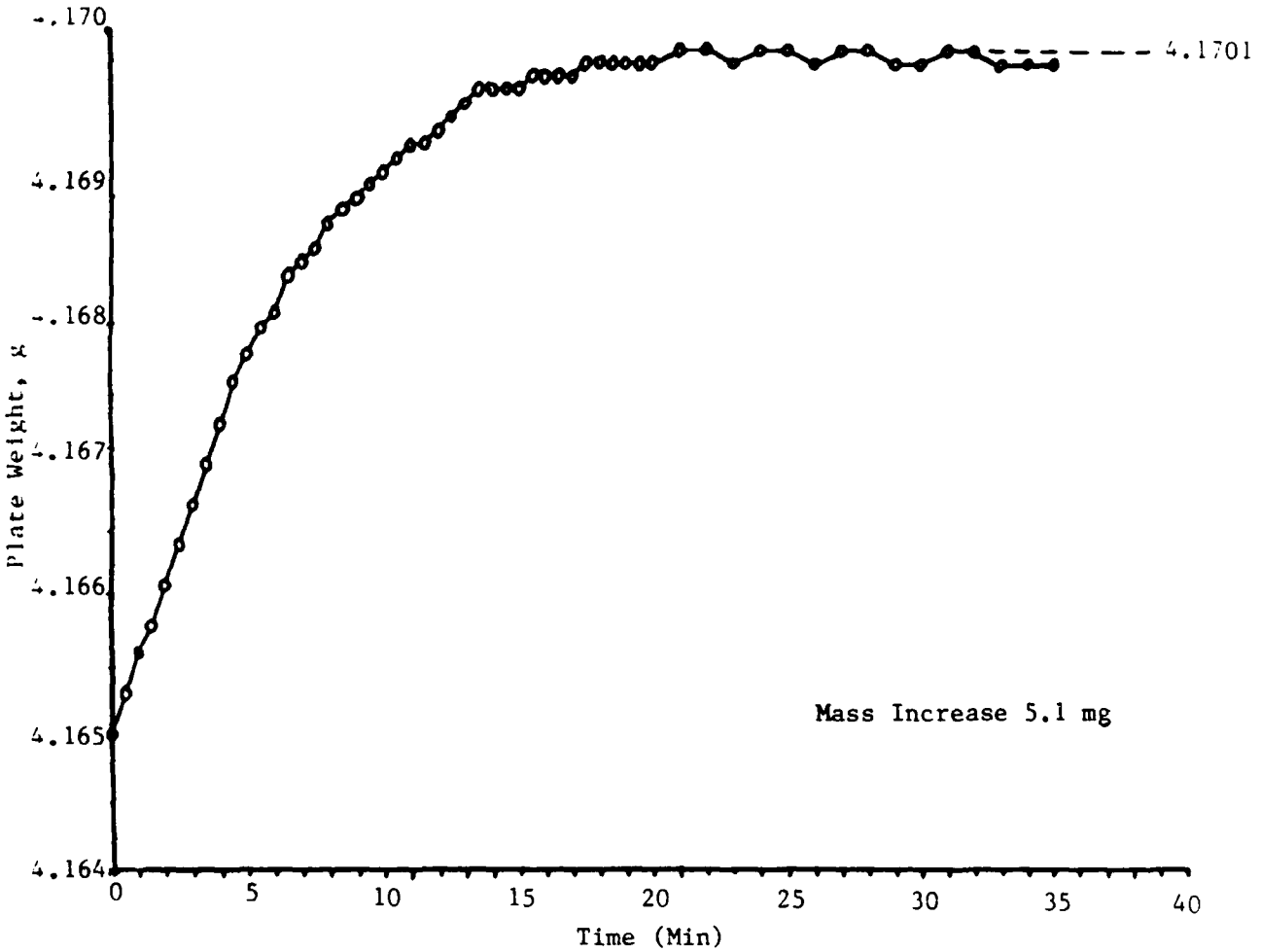


Figure 3. Water Takeup of DMP-128 Film. Weight of Plate versus Time, Room Temperature = 70.5°F, and Relative Humidity = 56%

The time varies from 50 minutes at RH=3.4% to 8.8 minutes at RH=56%. The steady state level is reached in 1.5 to 2 times the time presented in Figure 7; see Figures 1, 2, and 3.

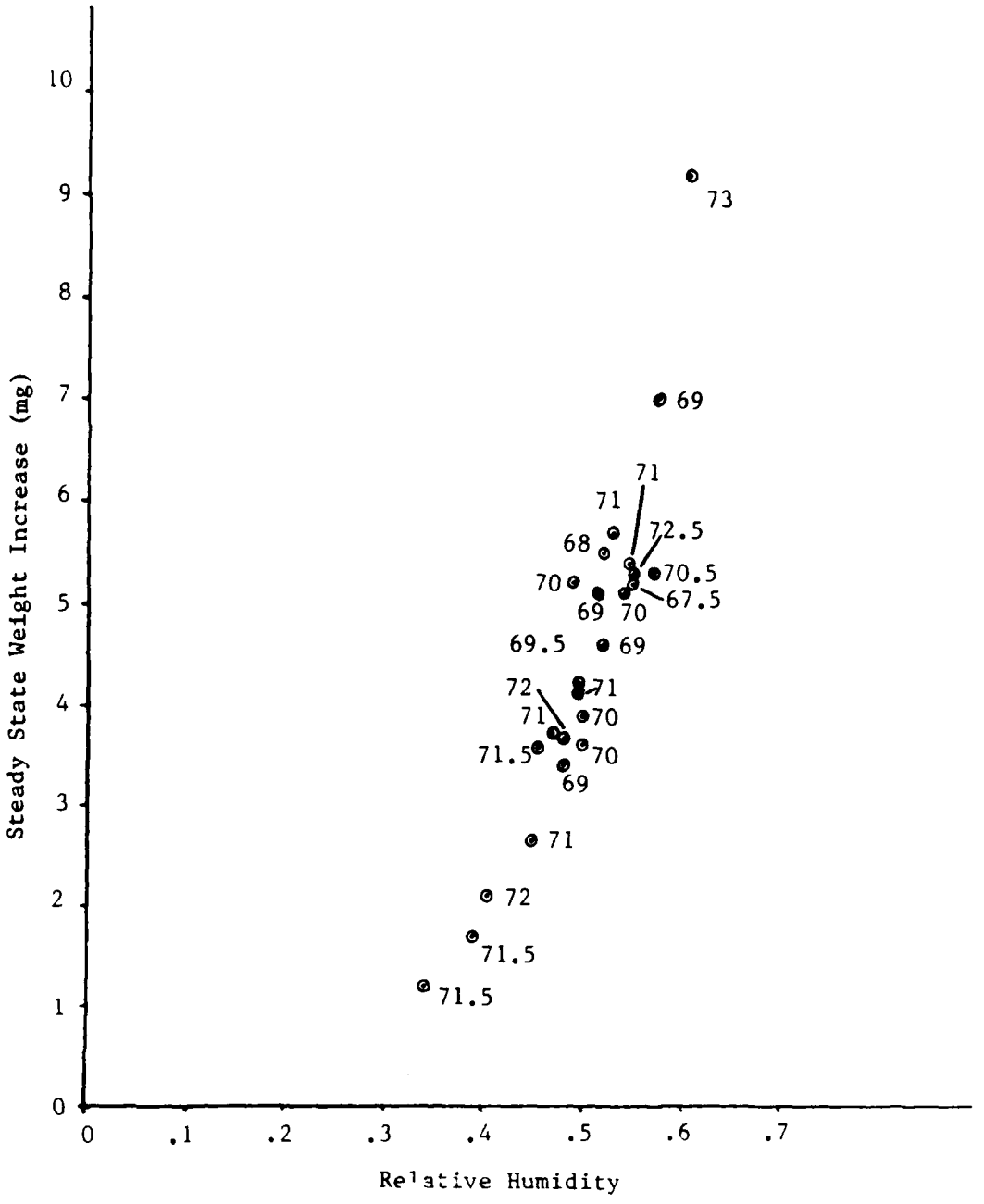


Figure 4. Steady State Weight Increase (Δm) in mg versus Relative Humidity. Temperature in ^{o}F besides Data Points. Film Thickness = 6 and 7 μm

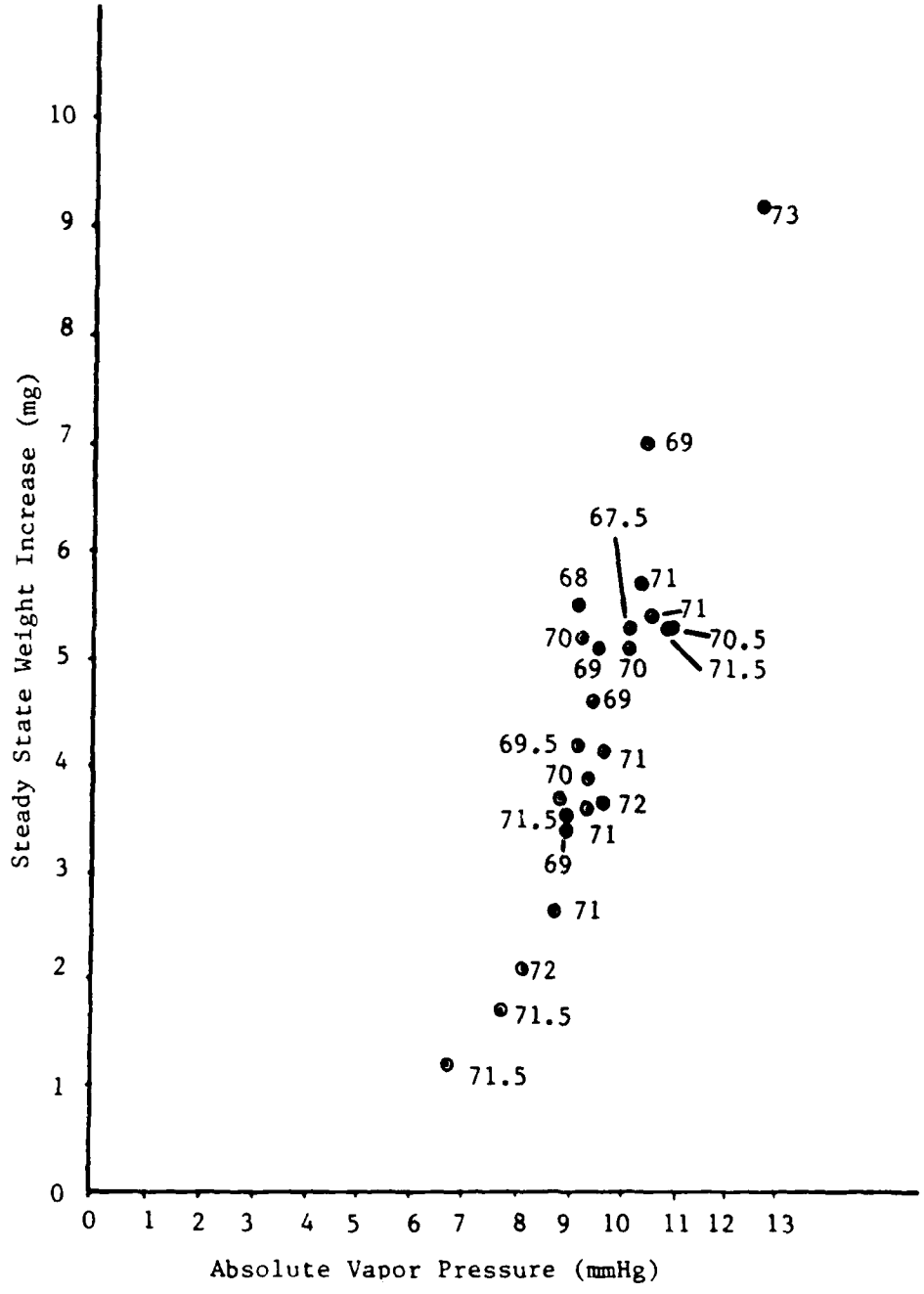


Figure 5. Steady State Weight Increase (Δm) in mg versus Absolute Vapor Pressure. Temperature in ^{o}F besides Data Points. Film Thickness = 6 and 7 μm

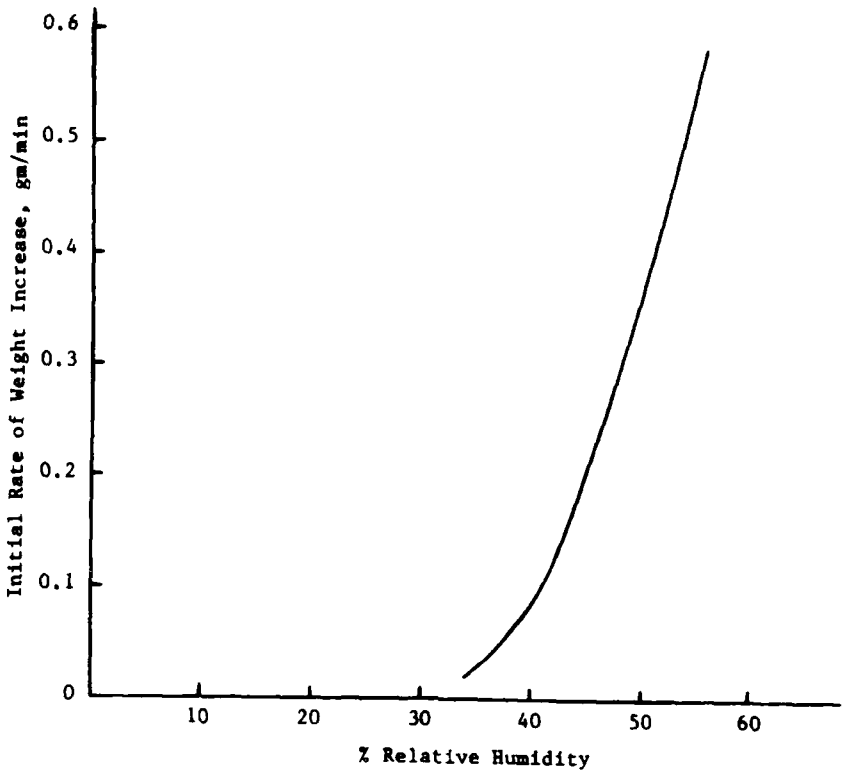


Figure 6. Initial Rate of Weight Increase

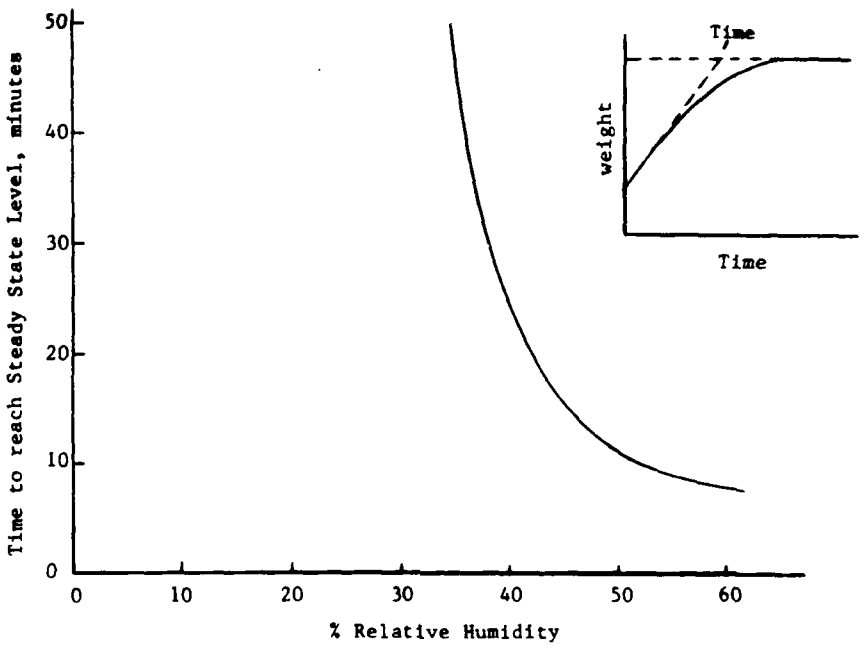


Figure 7. Time to Reach Steady State Level with the Initial Rate of Weight Increase

In these experiments, the air in the room was quiet. There was no attempt to vary the flow of air over the surface to determine flow effects on the takeup time. It was felt that quiescent atmospheric conditions would lead to the most uniform humidification.

We investigated the effect of varying the relative humidity during the water takeup by the photopolymer. A desiccated DMP-128 plate was placed on a balance and the relative humidity in the room was varied by a few percent during the water takeup by the plate. Simultaneous measurements were obtained of the water takeup and the relative humidity. These are presented in Figure 8. Note that there are significant variations in the weight.

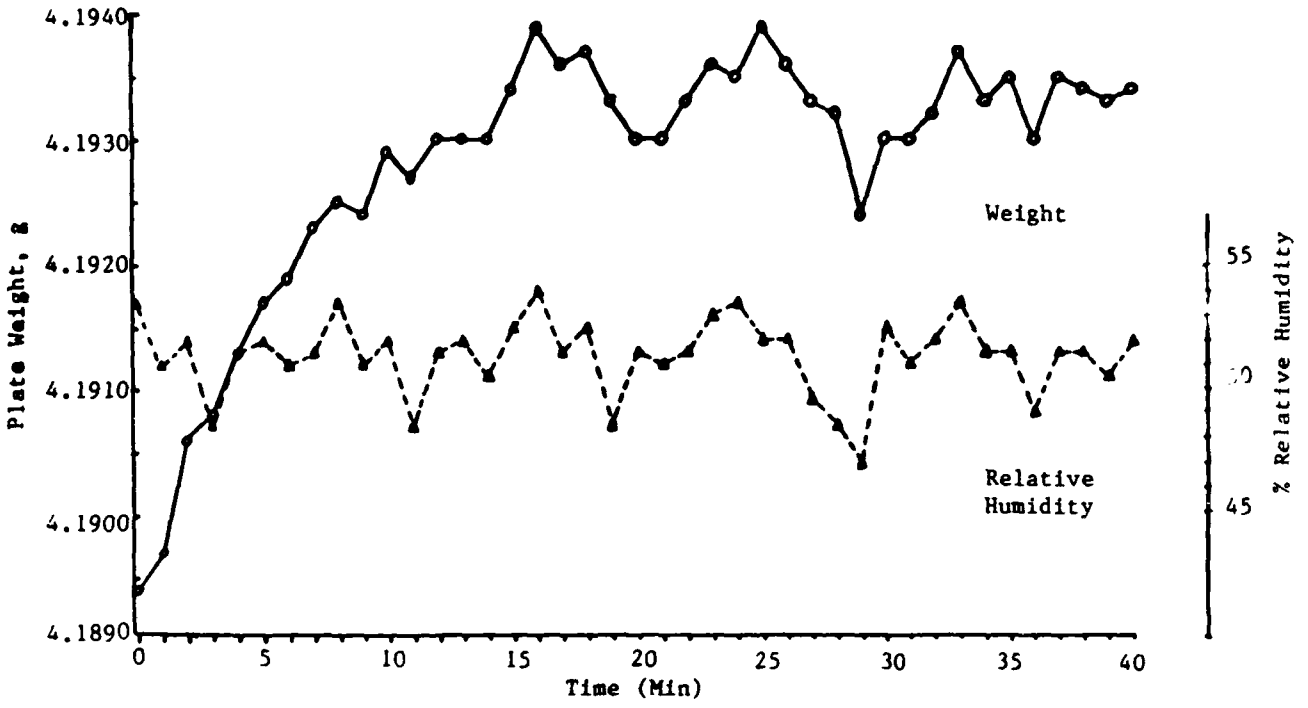


Figure 8. Water Takeup and Evaporation Rate Changes due to the Variations in the Relative Humidity

This result could be applied to the standard method of humidifying the slide in a box containing water and potassium thiocyanate and then transferring the slide from the box to the holder for laser beam exposure. The room and the box could be at different relative humidities. The slide weight changes in a short time. This could produce varying humidification with depth in the photopolymer. The holograms would then have varying grating plane spacing which would broaden the spectral band and yield low transmissions.

Measurements of water take-up in 12 μm thick plates were also made. The time to reach steady state was over a factor of 2 longer than that shown in Figure 7.

SECTION III

HOLOGRAPHIC MEASUREMENTS

Holograms were made with the Polaroid DMP-128 Photopolymer. The environmental chamber described in Section 2 was used. The entire process (including humidification, exposure to laser light, and chemical processing) was performed at constant temperature and relative humidity. Water sensitization of the photopolymer was accomplished by the method described in Section 2. The experimental arrangement for exposing the photopolymer to laser light is shown in Figure 9. A 20 milliwatt helium-neon laser at 633 nm wavelength was used to expose the photopolymer. The light was focused through a pinhole spatial filter and then made parallel at about 1" diameter. A 1/2" aperture limited the photopolymer exposure to the central portion of this beam. A pair of plane mirrors were employed in order to obtain multiple exposures on a single plate. The mirrors were rotated around the laser beam axis, the axis passed through the center of the first mirror. The beam was displaced by 0.65" by the second mirror. Up to 8 exposures on a single 2" x 2" slide were obtained by rotating the pair of mirrors between exposures. The polymer side of the plate was placed against liquid mercury which serves as a highly reflecting mirror returning the incident liquid beam back on itself. In some exposures, an additional plate with an anti-reflection coating was placed against the glass slide using xylene to make an optical coupling. The

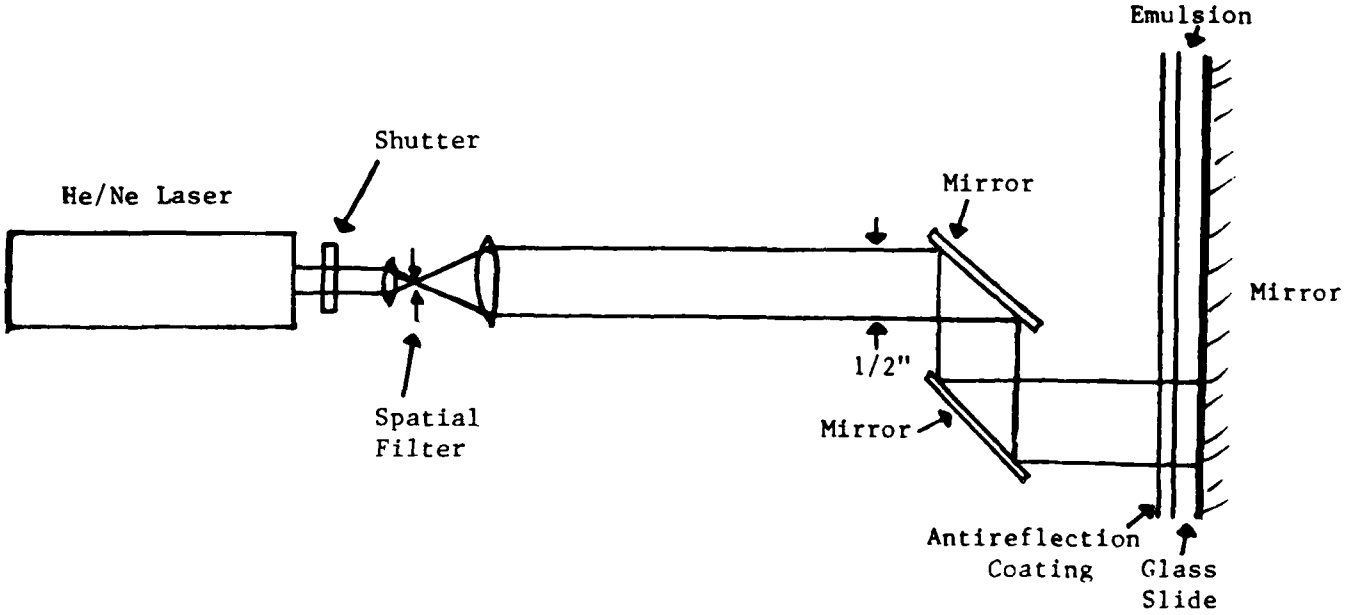


Figure 9. Experimental Set Up for Producing Holograms

intensity of light at the photopolymer was between 6 and 7 mw/cm^2 for most exposures.

Near the end of the Phase I program measurements were made of the amount of depolarization of the laser beam by the pair of mirrors that translate the beam. Figure 10 is a plot of the laser beam intensity measurements. A polarized filter was positioned parallel and perpendicular with respect to the polarized laser beam. The abscissa gives the angular position of the second mirror with respect to the axis of rotation. 0^o and 360^o is up and 90^o is down. The polarization of the incident laser beam is vertical. Note that the intensity with the parallel polarization setting was 4.5 to 5 mw. The perpendicular polarization setting showed intensity variation with angle. At 0^o, 90^o, 180^o, and 270^o the depolarization was less than 0.5%. At 45^o and 225^o the cross-polarization rose to about 4%; while at 135^o and 315^o the cross-polarization was 9%. The vertical marks show the angular position of the two mirrors for essentially all the holograms produced in this program. At these angles the cross-polarizations were 2% and 5%. In future programs, only the parallel (0^o and 180^o) and perpendicular (90^o and 270^o) directions will be used in order to minimize the depolarization. After the holographic exposure the film is irradiated for two minutes with light from a 75 watt tungsten bulb 5 to 6 inches from the film plane. After the white light exposure the film is incubated with constant agitation for one minute at room temperature in a processing bath. The liquid processing bath is composed by weight of 66% methanol, 4% glacial acetic acid, 10% zirconium acetate, and 20% water. It is then rinsed thoroughly with isopropanol. The processed and rinsed film is dried over isopropanol in the final development step for two minutes. A drying apparatus is made from a tall, covered glass chamber containing a 1/4 to 1/2 inch layer of boiling isopropanol. The alcohol is heated to boiling on a hot plate adjusted so that the vapors rise 6 to 8 inches above the liquid. Exposed and processed film is dried by holding the film in the vapors just above the boiling isopropanol. Figure 11 shows DMP-128 plates with holograms. On a single plate the exposure time varied from less than 1 second to over 100 seconds, usually increasing each exposure by a factor of about 3.

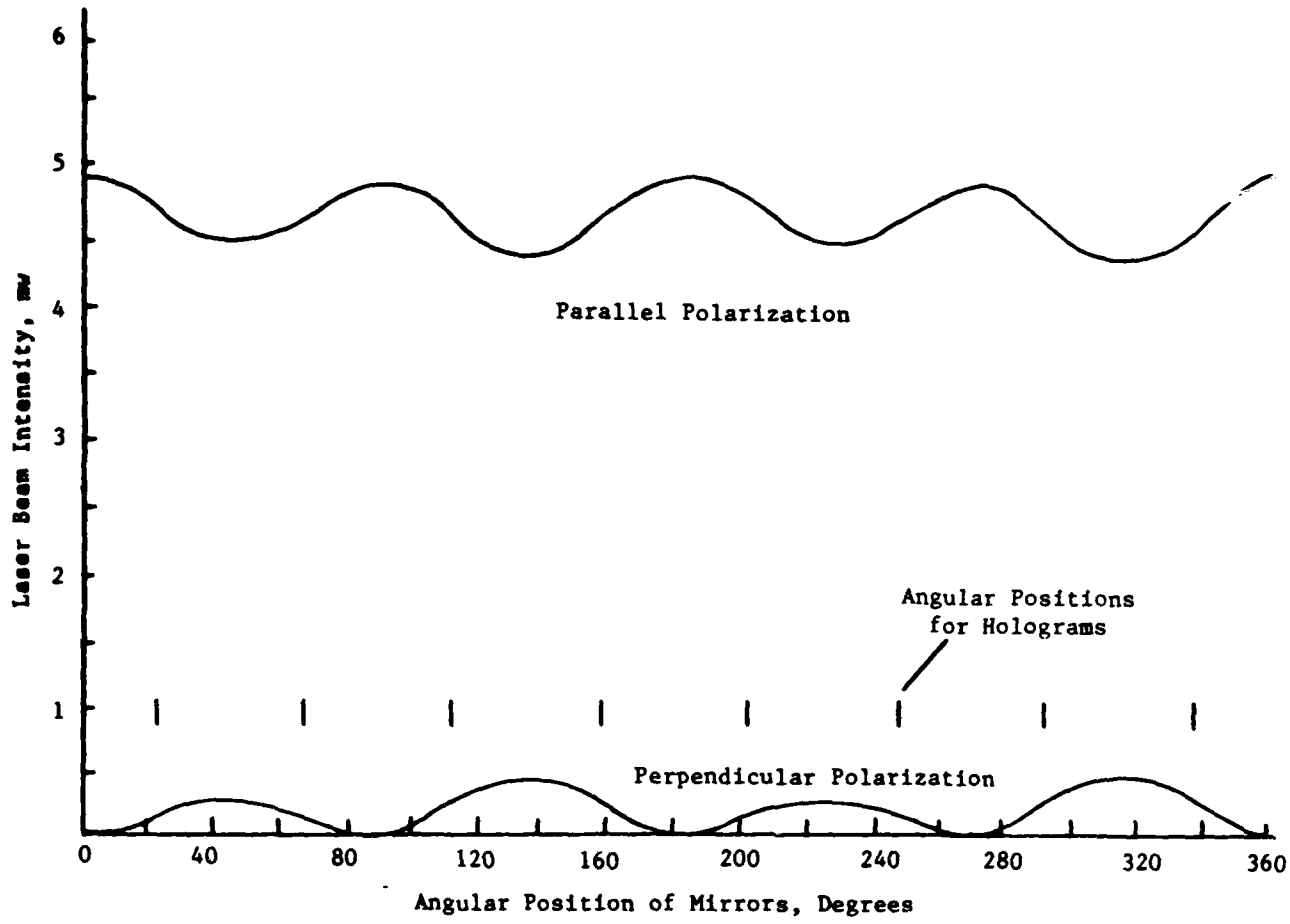


Figure 10. Polarization Measurements of Laser Beam Passing Through Beam Translating System

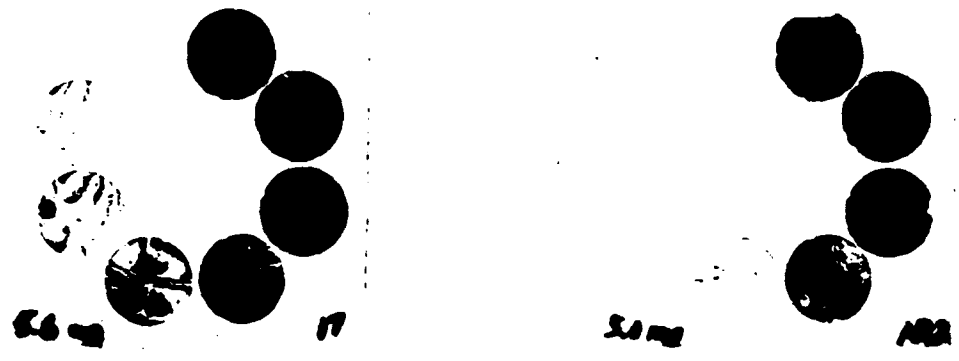


Figure 11. Holograms

Transmission measurements were made with a Beckman spectrophotometer. Figures 12, 13, and 14 present spectral transmission measurements of some of the holograms. Most of the holograms have undesired fringe patterns because the anti-reflection coating was not used. Thus, the transmission varied over the hologram. The measurements give an average transmission over most of the 1/2" diameter hologram. There is a spectral band with low transmission and red and blue spectral regions have high transmission. The data were selected to show specific features. The hologram in Figure 12 had 2.9 mg water takeup. At this low takeup the width of the band is narrow. Figure 13 shows transmission data for a plate with 4.7 mg water takeup. The spectral band with low transmission is broader than the band in Figure 12. Figure 14 presents the transmission of two holograms on the same plate with 5.6 mg takeup. The higher laser beam exposure shifts the band towards the red. A comparison of Figures 12, 13, and 14 show that the width of the low transmission region increases with water takeup.

Figure 15 presents the spectral bandwidth of the low transmission band as a function of water (steady state) take-up. The widths shown in Figure 15 are the wavelengths at 1/2 the transmission at the red and blue sides of the band. The photopolymer thickness was 6 to 7 μm. The temperature was approximately 70°F. The laser energy was 35 ±10 millijoules/cm^2. Note the spectral width decreases with decreasing water (steady state) takeup. The spectral width is about 60 nm at 3 milligrams water takeup (corresponding to 45% relative humidity). The spectral width is about 150 nm at 6 milligrams water takeup (corresponding to 55% relative humidity), 2.5 times the width for 3 mgm takeup.

The width of the low transmission band increases with the amount of exposure. For example, at about 3 mg water takeup the spectral width increases from 60 to 90 nm for an exposure increase from 30 to 100 mJ/cm^2. Also, the transmission decreases with exposure. Thus, by selecting both the water takeup and the exposure, the desired transmission can be obtained at a minimum bandwidth. For vision and optical system protection from laser radiation, the narrower the low transmission band, the better. This produces the least interference with visual observations, or optical system measurements. Thus, the recommended procedure is to make holograms at the lowest water takeup consistent with obtaining sufficient beam attenuation.

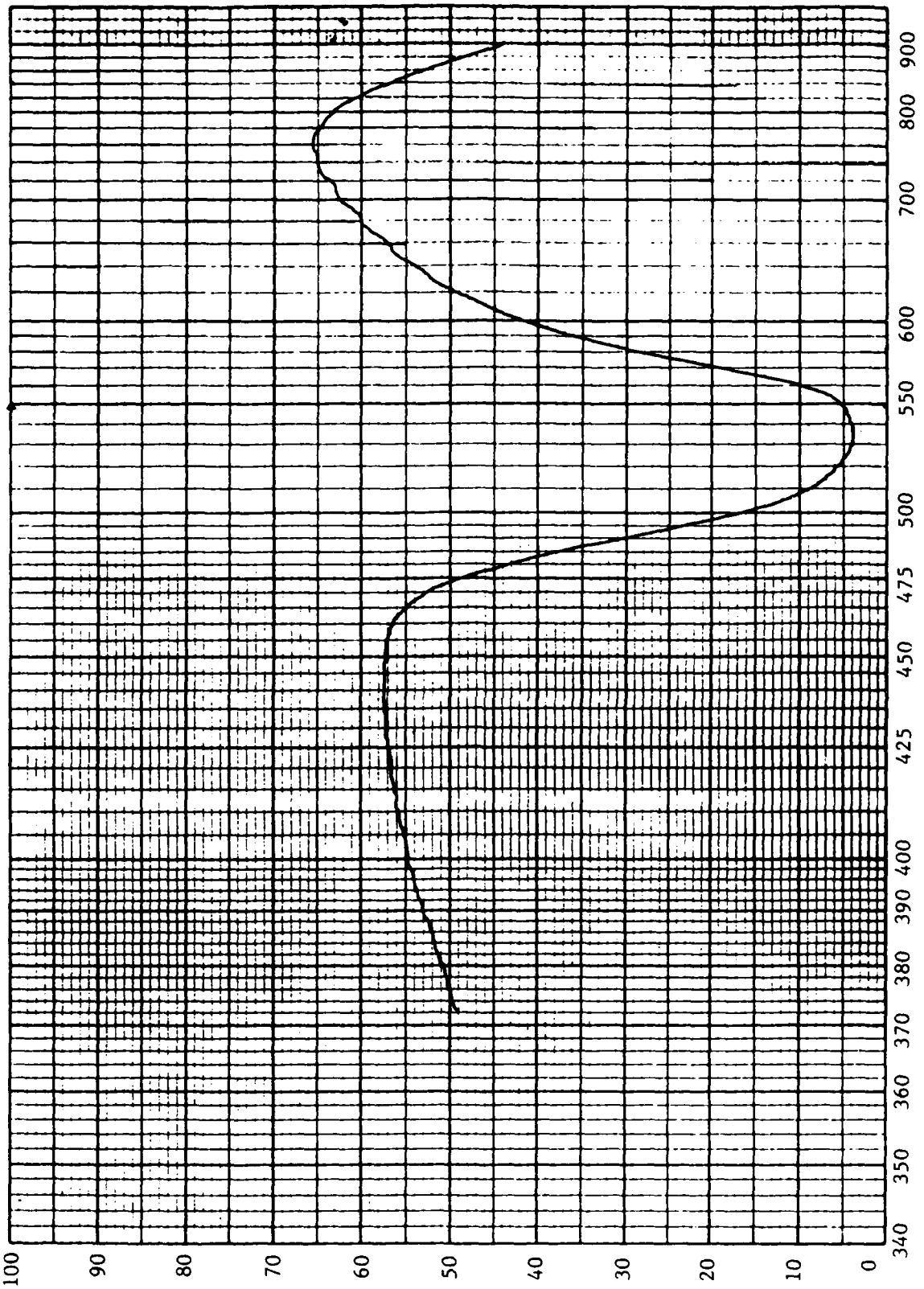


Figure 12. Transmission versus Wavelength. Water Takeup = 2.9 mg. Laser Exposure = 310 mJ/cm^2

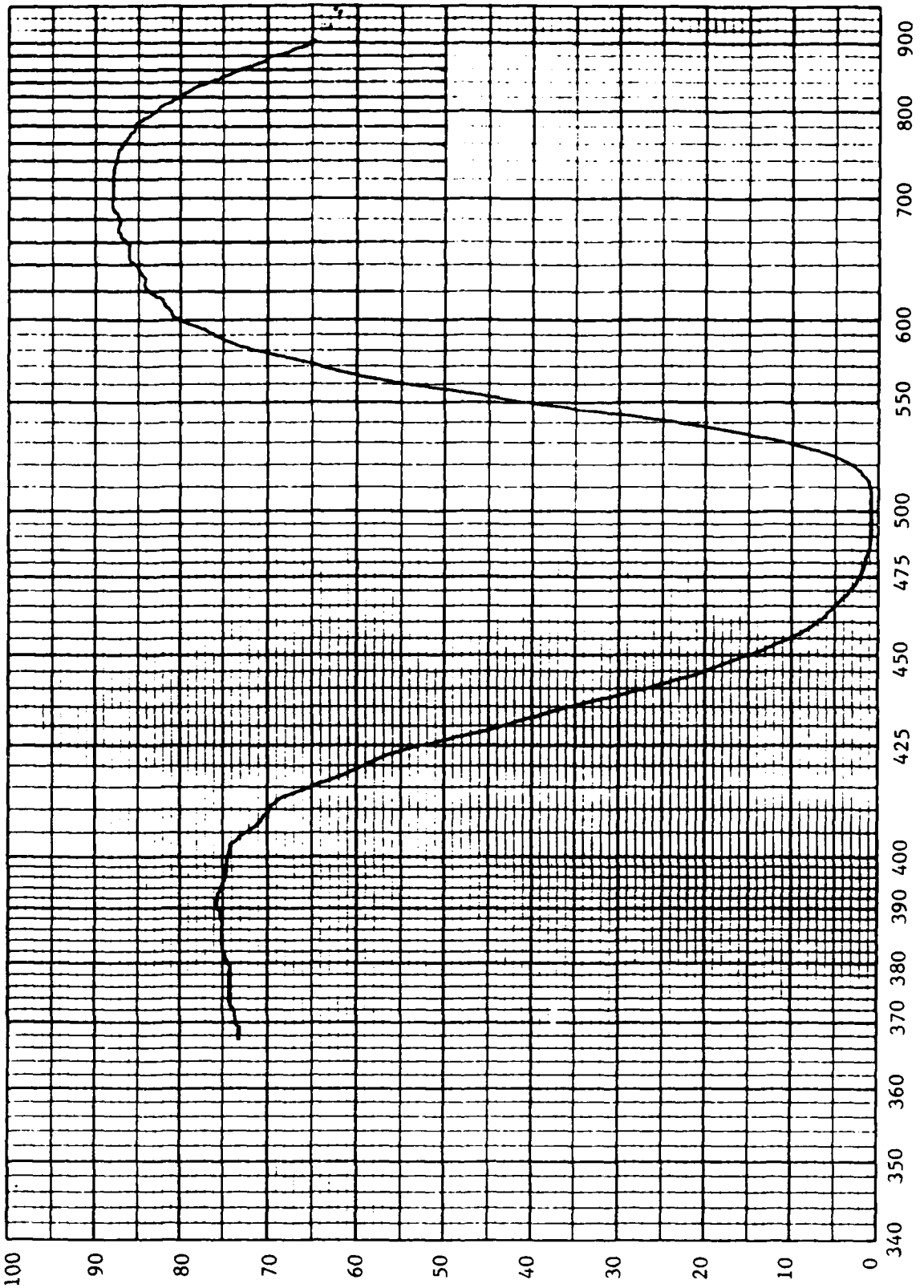


Figure 13. Transmission versus Wavelength. Water Takeup = 4.7 mg. Laser Exposure = 310 mJ/cm^2

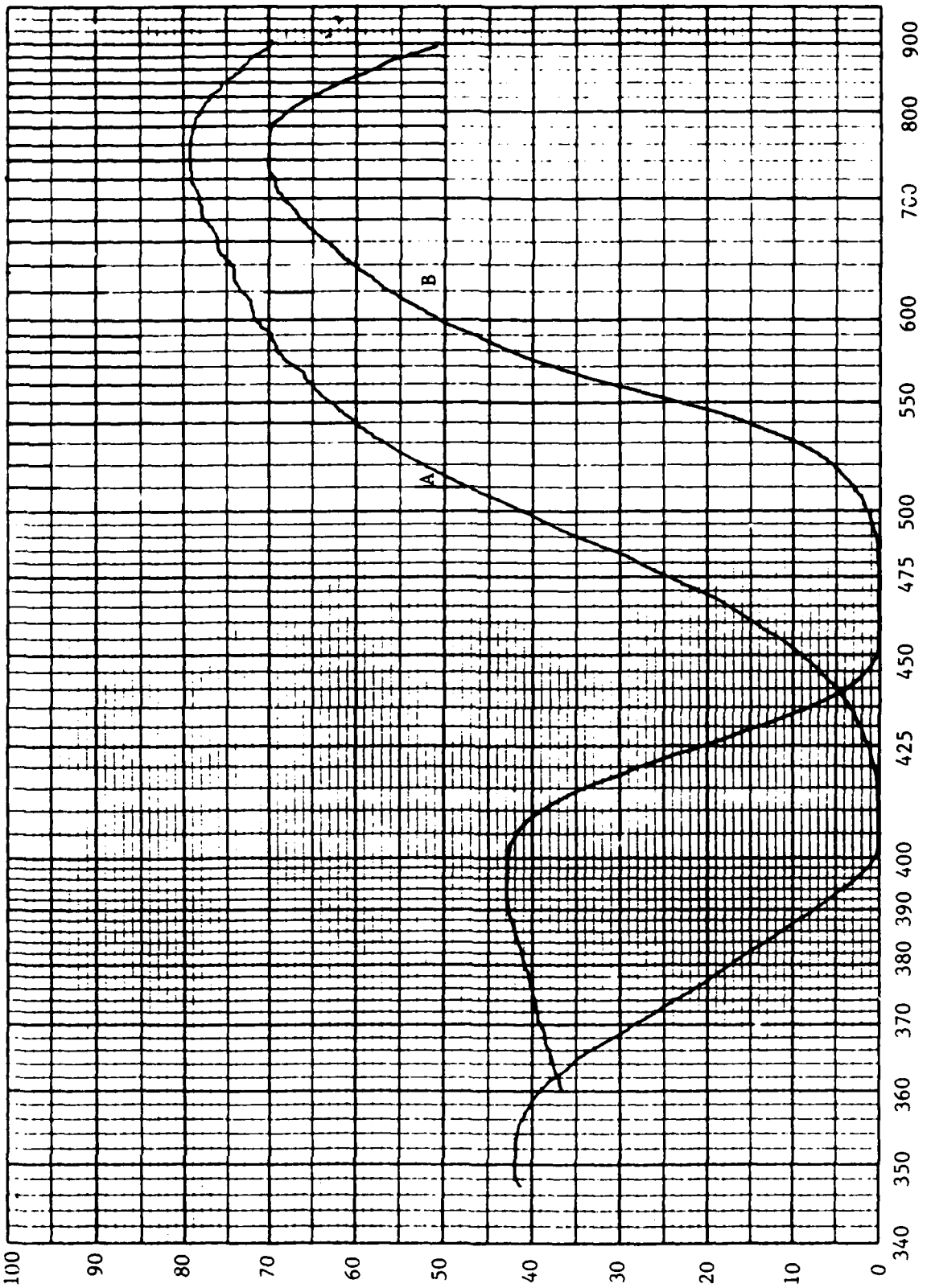


Figure 14. Transmission versus Wavelength, nm. Water takeup = 5.6 mg. Laser Exposure: Curve A = 22 mJ/cm^2, Curve B = 38 mJ/cm^2

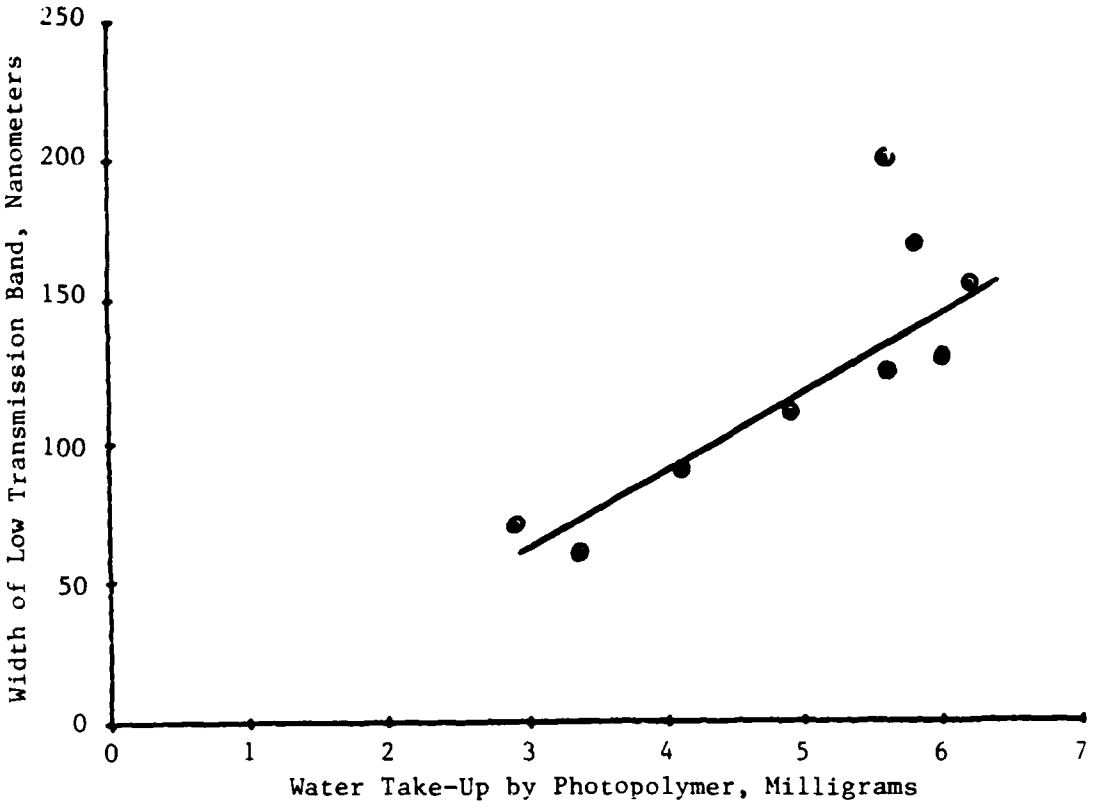


Figure 15. Width of Low Transmission Band versus Water Takeup. Photopolymer Thickness = 6 and 7 μm. Laser Energy = 35 ±10 mJ/cm^2

The theory developed by Ingwall[2] at Polaroid indicates that spectral widths of 30 nm should be obtainable. Extrapolating the curve in Figure 15 one would obtain this theoretical bandwidth with low transmission at about 2 mg water takeup. This corresponds to equilibrium in a 40% relative humidity environment.

Figures 16 and 17 present the average wavelength of the low transmission band as a function of: (1) water takeup, and (2) laser exposure energy. Figure 16 shows the average wavelength of the band with low transmission for the data presented in Figure 15. The exposure energy is 35 ±10 mJ/cm^2. The wavelengths scatter between 440 and 530 nm. The scatter might be due to variations in processing the photopolymer. Figure 16 presents the average

[2] Richard Ingwall private communication.

wavelength of the low transmission band as a function of the laser exposure energy. The lines are for data from the same 2" x 2" plate. The data are for 6 μm thick polymer coating except for one curved (marked "12 μm") with data from a 12 μm thick polymer. Note that the wavelength shifts towards red with increasing exposure. However, the slope and the location of the curves vary. Most of the curves do not vary much with exposure. There are two curves with appreciable variation. The 12 μm thick polymer shows a very large wavelength shift with exposure.

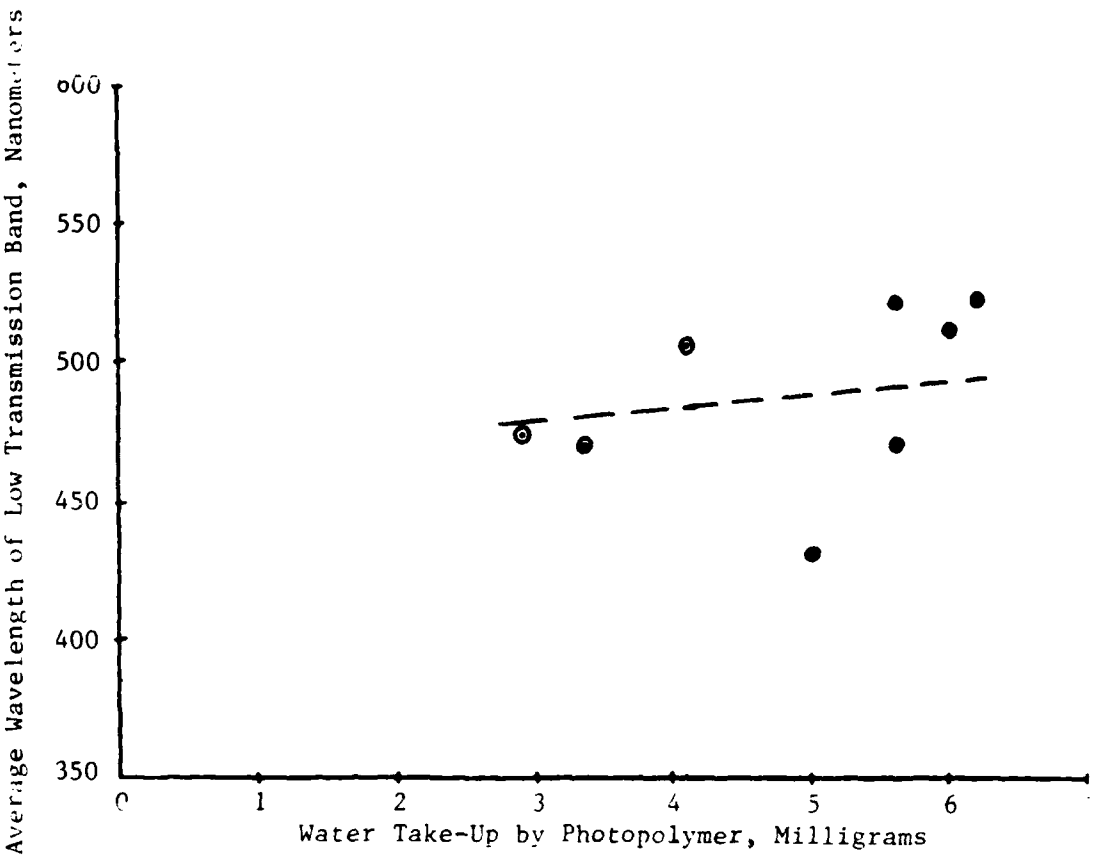


Figure 16. Average Wavelength of Low Transmission Band versus Water Takeup. Data taken from same Holograms used for Figure 15

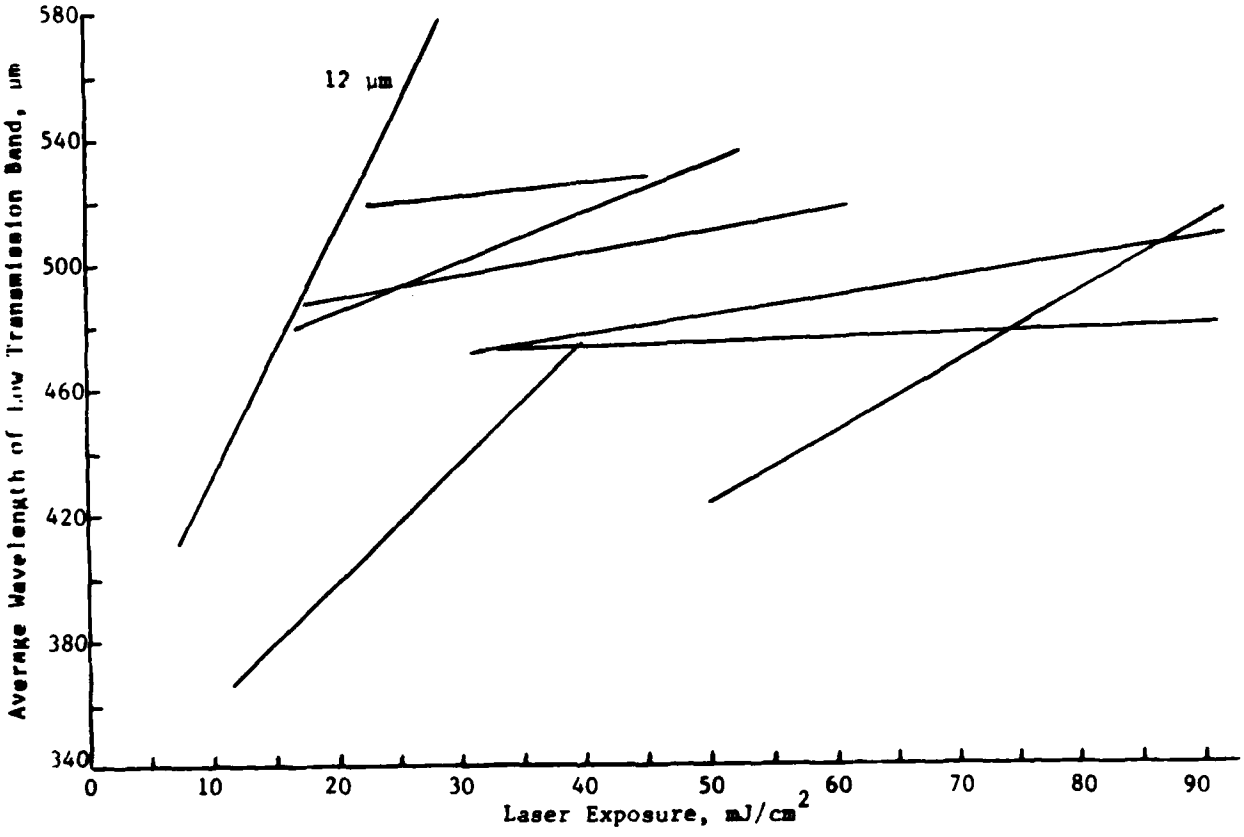


Figure 17. Average Wavelength of Low Transmission Band versus Laser Exposure. 6 µm Polymer Coating except for Curve marked 12 µm

The holograms have significant variations in transmission due to fringe patterns, since most of the data were obtained without the anti-reflection layer. It was difficult to obtain accurate transmission measurements with the spectrophotometer because the area of the spectrometer beam was comparable with the 1/2" size of the hologram. Thus, we employed a focused argon laser beam to determine the hologram transmission from a small region of the hologram. The hologram was tilted with respect to the laser beam until the maximum attenuation was obtained. Figure 18 shows the transmission as a function of exposure for three plates. The energies varied from 30 to several

hundreds mJ/cm^2. Note that the transmission is between 10^{-3} and 10^{-4}. The water takeup was 6 mg for these data.

It is significant that the DMP-128 plates are considerably more sensitive to spurious fringes arising from glass surface reflections than are other materials. We have experienced little difficulty in using conventional silver halide plates or dichromated gelatin plates without anti-reflection coatings. This is perhaps due to an intrinsically lower contrast in the Polaroid material.

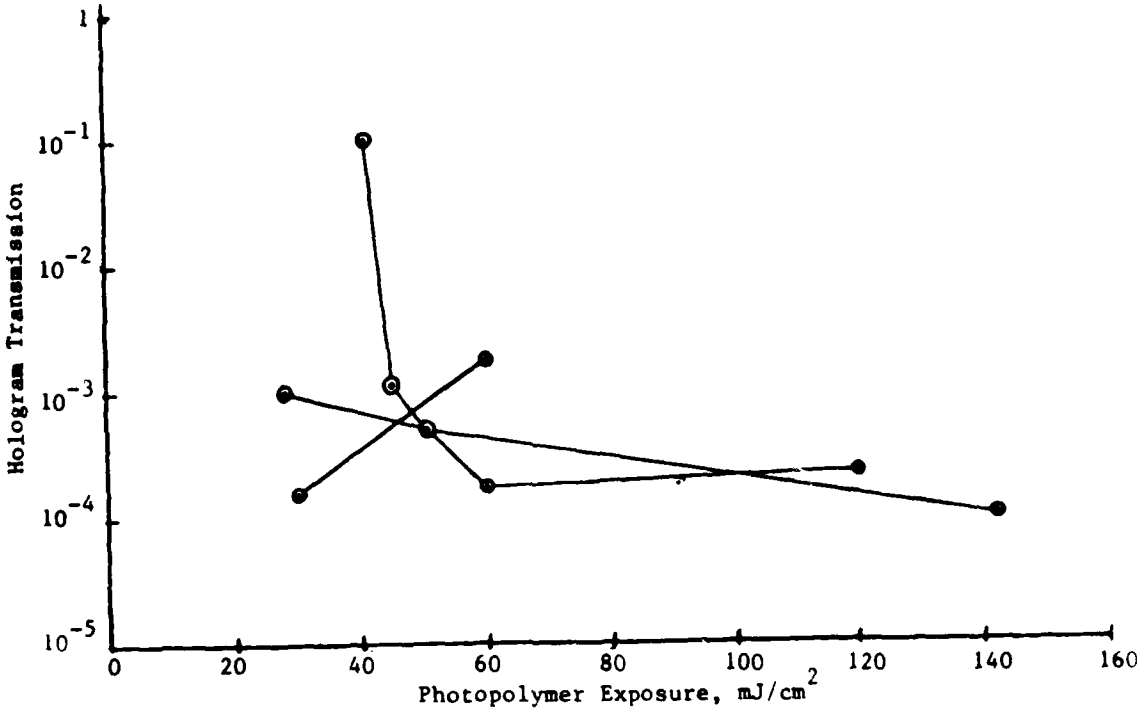


Figure 18. Hologram Transmission versus Laser Exposure. Measurements made with Argon Ion Laser. 6 mg water takeup

SECTION IV
SUMMARY

The objective of this Phase I program is to investigate the Polaroid DMP-128 Photopolymer for holographic optical element applications, in particular, reflection holograms to protect personnel and optical systems from laser light. The reflection holograms should have low transmission in a very narrow spectral band and good transmission over the rest of the visible region. The main focus was to study the parameters that affect the spectral width of the low transmission band. These parameters are preconditioning the photopolymer, selecting the laser exposure energy, and processing the exposed film. We focused on preconditioning and laser exposure. The development process was not varied, we employed the standard Polaroid DMP-128 development procedure.

The preconditioning step consisted of uniformly impregnating the polymer with water. In order to ensure that the amount of water concentration was uniform, all the procedures were performed in an environmental chamber at controlled temperature and humidity conditions. For most of the runs, the temperature was maintained around 70^{o}F. The humidity varied from below 15% to about 60%. 2" x 2" glass slides with the Polaroid DMP-126 Photopolymer layer was placed on a balance and the amount of water absorbed by a desiccated plate was measured as a function of time. The weight increased until steady state was reached. This presumably is when the water in the film was in equilibrium with the air humidity in the environmental chamber. For relative humidities below 30%, there was no water takeup. At RH=30%, there was a small amount of water takeup and it took a very long time. The takeup time decreased as the relative humidity increased. The amount of weight increase as a function of the relative humidity is shown in Figure 4. The same data are plotted as a function of the absolute humidity in Figure 5. For these runs, the film thickness was 6 μm and 7 μm. The unsteady effects in water takeup were investigated by changing the relative humidity. The corresponding rapid change in the water takeup would indicate the layers near the free emulsion surface were changed rapidly while information about the change in the atmospheric conditions did not reach the regions of the polymer near the glass substrate.

Holograms were made using red sensitive Polaroid DMP-128 photopolymer and a helium-neon laser. The laser power level was approximately 7 mW/cm^2. The plates were preconditioned by water takeup in the environmentally controlled room. Up to eight 1/2" diameter exposures were made on each plate. The exposures varied in time from less than one second to several hundred seconds. A few plates had an anti-reflection layer. The main measurements of the holograms were the transmission as a function of wavelength. The main result: the width of the low transmission band is a function of the water takeup. The lower the water takeup, the narrower the transmission band. For the application of personnel or instrument protection against laser beams, the narrower the absorption band the better. Thus, holograms should be made at low relative humidity consistent with the transmission requirements. Spectral bandwidths below 50 nm can be obtained, close to the theoretical width calculated by Ingwall[2].

Most of the holograms were not uniform and had fringe patterns. The spectrophotometer could not be used for transmission measurements, since it obtained an average transmission over areas comparable with the size of the 1/2" hologram. A focused argon laser beam was used to probe a small region of the holograms. The plate was tilted until the transmission was a minimum. The transmission varied between 10^{-3} and 10^{-4} for laser exposures from 30 to 100 mJ/cm^2.

The location of the low transmission band varied from exposure to exposure. This was probably due to the chemistry. Each plate had a series of holograms with varying exposures. The average wavelength with strong attenuation was energy dependent in some plates and not sensitive in others. In all cases the higher exposure produced a shift to the red. More work is needed to identify the causes of the varying location of the low transmission band.

APC File 6305

PHOTOPOLYMER HOLOGRAPHIC OPTICAL ELEMENTS

Contract #DAAB-07-87-C-7007

Appendix to Final Report
June 1987

Prepared for

Night Vision and Electro-Optic Center
Attn: AMSCL-NV-T
Fort Belvoir, VA 22060-5677

Prepared by

Aerodyne Products Corp.
76 Treble Cove Rd.
No. Billerica, MA 01862
617-663-7411

D.E. Willoughby
Principal Investigator

APPENDIX

This appendix presents all the spectral transmission measurements obtained in this Phase I SBIR program. The transmission measurements were obtained with a Beckman spectrophotometer. This apparatus measures transmission with a beam comparable in size with the 1/2 inch hologram. The spectral scans covered the visible and near infrared (to 900 nm). The measurements are presented in Figures A1 to A29. The data are ordered in increasing water takeup by the film from 2.9 mg to 9.2 mg. The polymer thickness was 6 to 7 μm except for 12 μm data shown in Figures A26 and A27. Figures 28 and 29 present measurements of holograms prepared at the Polaroid facility using Polaroid's standard procedures. In general there is a low transmission band and higher transmission in the red and blue regions. The transmission in the blue is less than in the red. Note that the width of the low transmission band is narrower for the lower relative humidity and correspondingly smaller water takeup. Thus, the bandwidth of the data in Figures A1 through A6 is considerably narrower than in Figures A20 to A25. There are some anomalies: broad low transmission bands exhibit oscillations at the higher laser exposures for 4.1 and 4.4 mg water takeup, see Figures A5 to A8. For some holograms with high water takeup, the transmission decreases to zero monotonically from the red, barely recovering in the blue region; see Figures A11, A17, A19, and A24. There were insufficient measurements to determine the causes of these variations. A summary to the data is presented in the table. The first column is the Figure number. The second is the steady state weight increase (water takeup). The third and fourth columns present the average wavelength and the spectral width of the low transmission band.

PROPERTIES OF LOW TRANSMISSION BAND

Figure Number	ΔM Water Takeup mg	Laser Exposure mJ/cm^2	λ Average Wavelength nm	Δλ Band Width nm
A1	2.9	31	474	70
A2	2.9	310	536	94
A3	3.35	31	433	64
	3.35	310	470	58
	3.35	2900	459	92
A4	3.35	97	479	91
A5	4.1	97	518	188
A6	4.1	31	511	207
	4.1	310	514	100
A7	4.4	97	473	171
A8	4.4	310	514	222
A9	4.7	97	504	181
A10	4.7	310	493	112
A11	5.0	49	508	130
	5.0	99	433	107
A12	5.4	10	471	142
A13	5.6	23	540	192
	5.6	46	533	186
A14	5.6	11	368	175
	5.6	17	357	152
A15	5.6	22	486	124
	5.6	38	424	94
A16	5.8	51	552	186
	5.8	51	543	181
A17	5.9	26		
		51		
A18	5.8	14	515	176
	5.8	26	480	155
A19	5.8	60	555	150
	6.0	120	574	198
	6.2	85		
A20	6.0	46	520	135
A21	6.0	-	486	206
A22	6.2	26	502	162

Figure Number	ΔM Water Takeup mg	Laser Exposure mJ/cm^2	λ Average Wavelength nm	Δλ Band Width nm
A23	6.2	11	339	117
	6.2	17	332	104
A24	6.2	47	377	192
	6.2	71	365	170
A25	7.5	12	464	141
	7.5	23	467	122
A26	9.2 (12 μm)	6	481	120
	9.2 (12 μm)	13	394	55
A27	12 μm		456	94
			485	68
			505	60
A28	Polaroid		470	88
A29	Polaroid		531	198

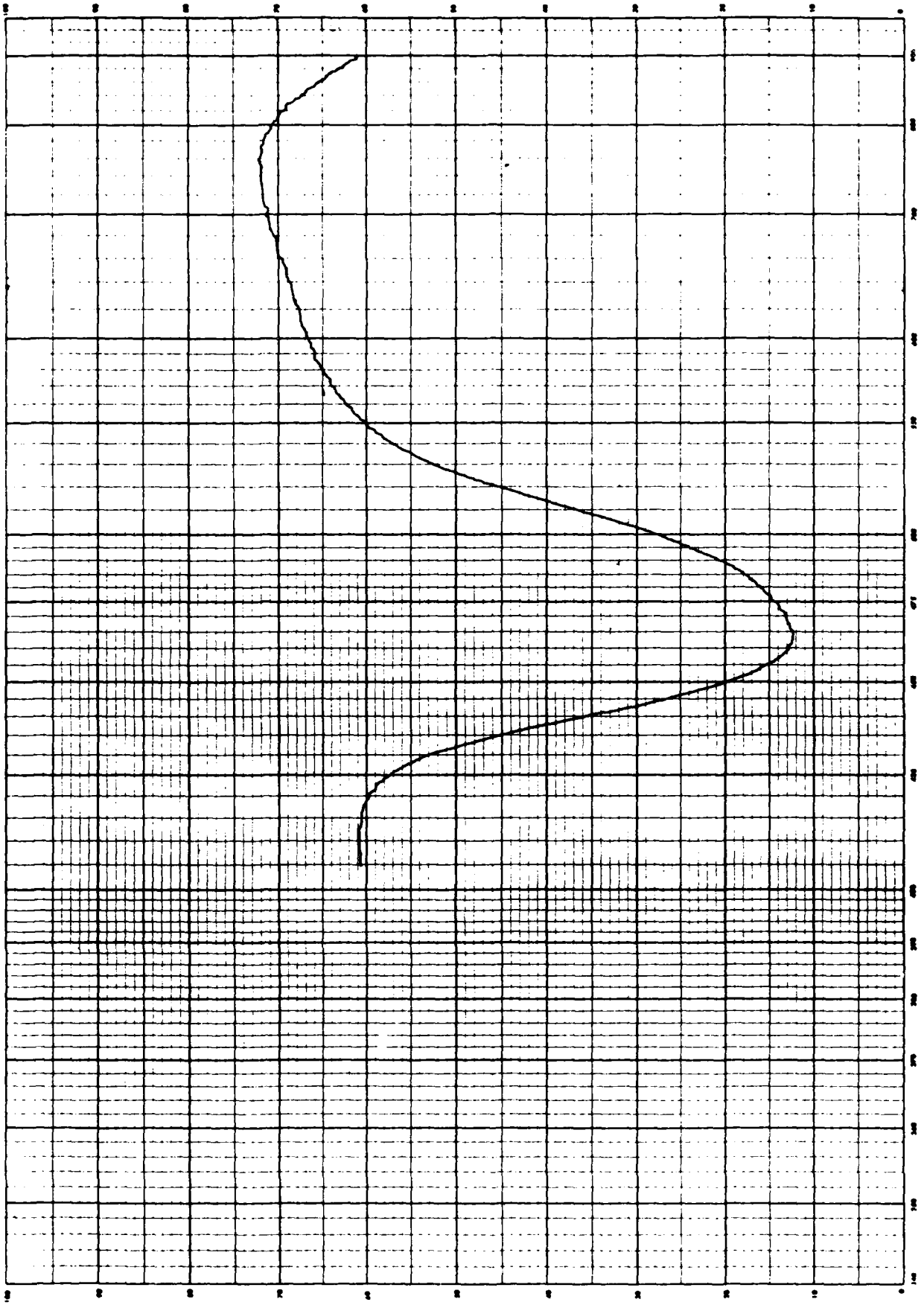
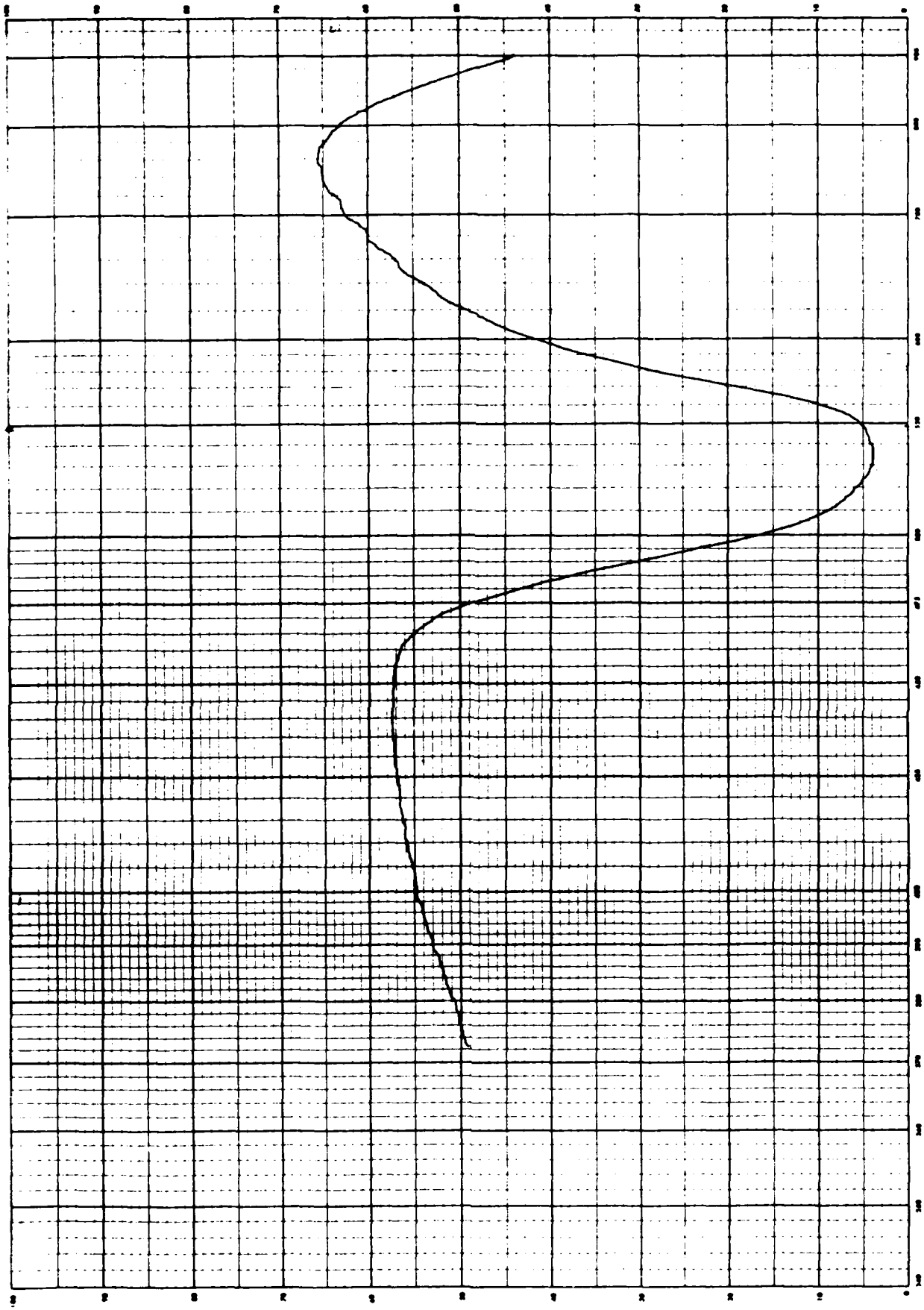


Figure A1. Water Takeup = 2.9 mg. Laser Exposure = 31 mJ/cm^2.



Water Takeup = 2.9. Laser Exposure = 31.

Figure A2

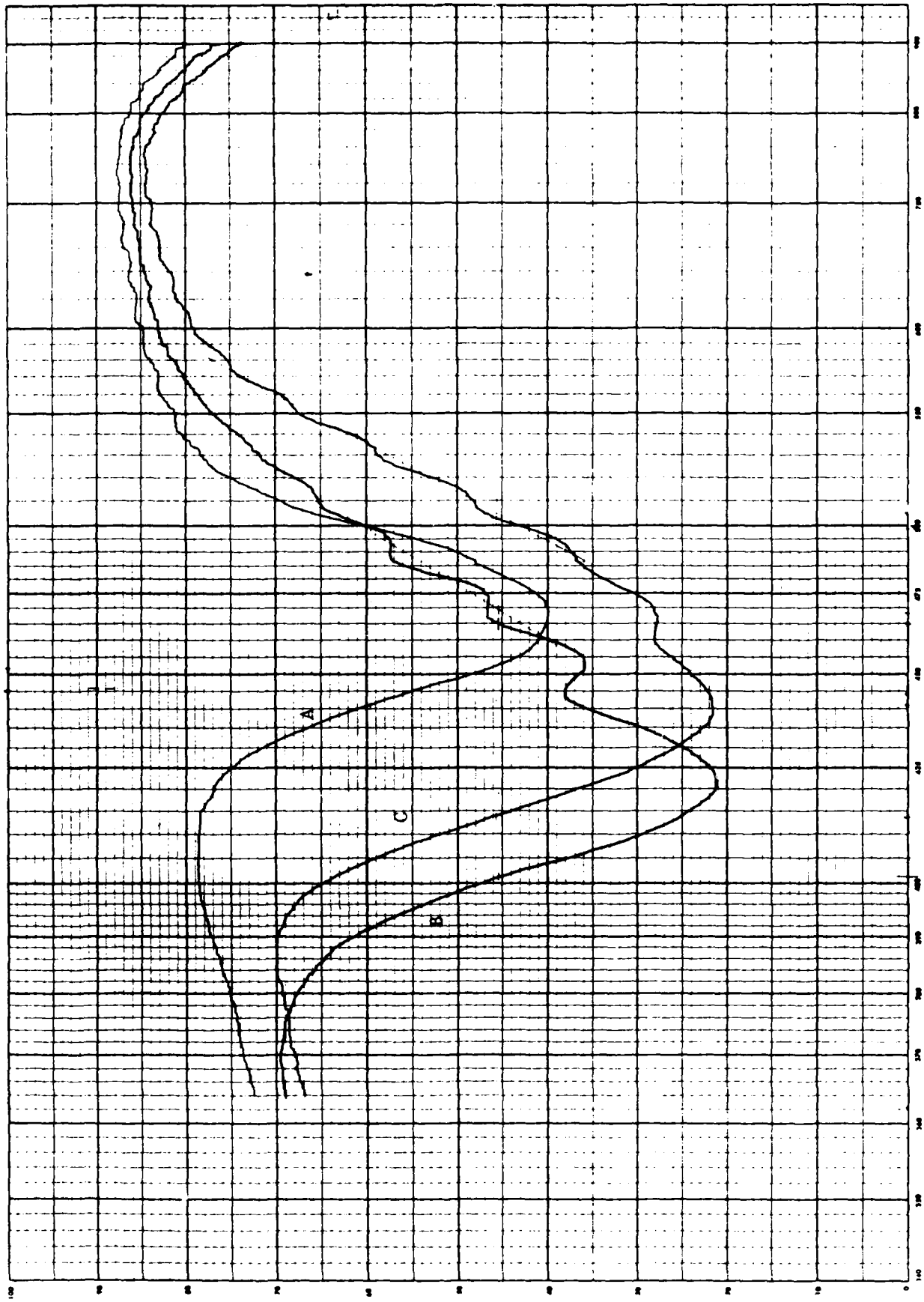
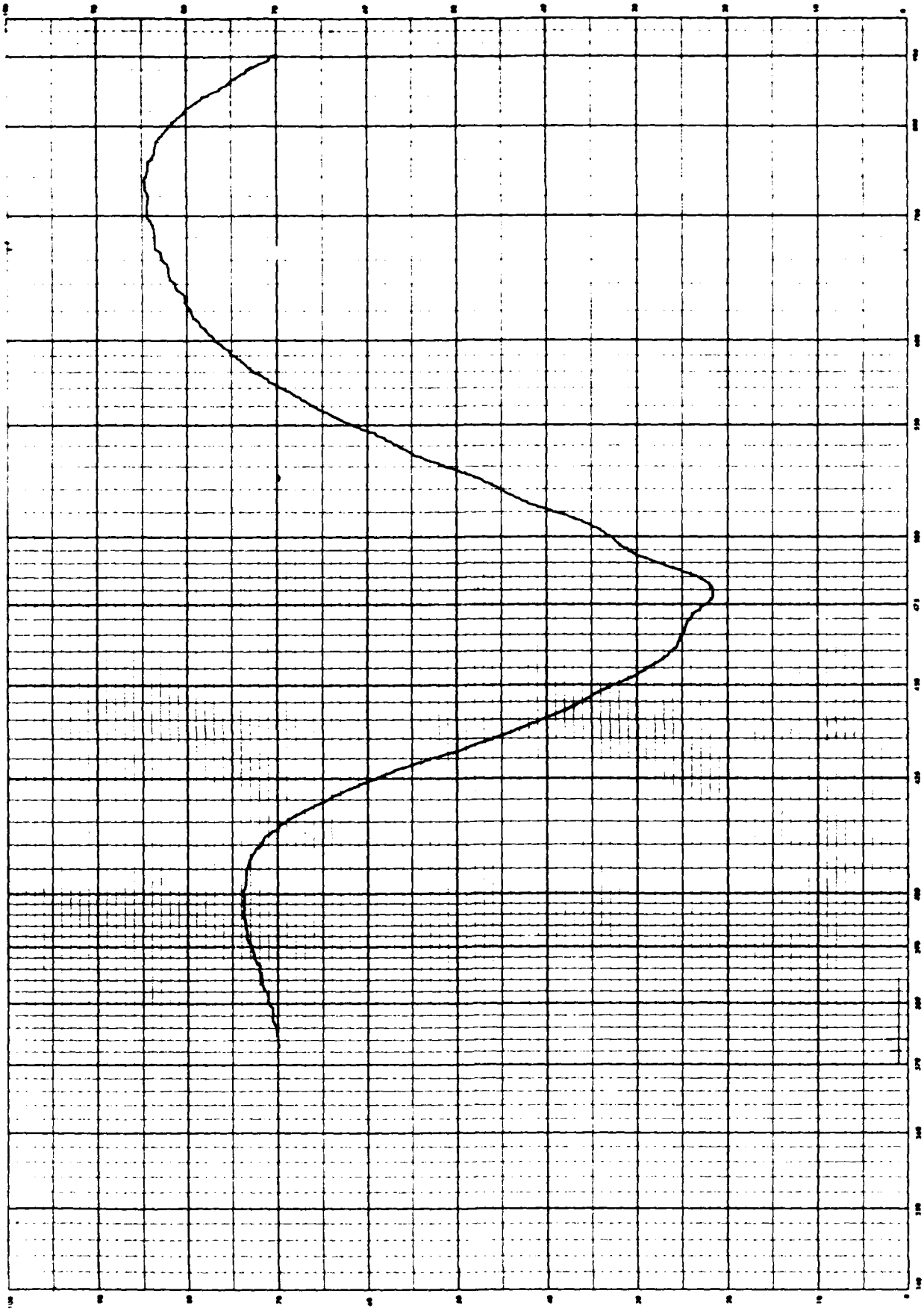
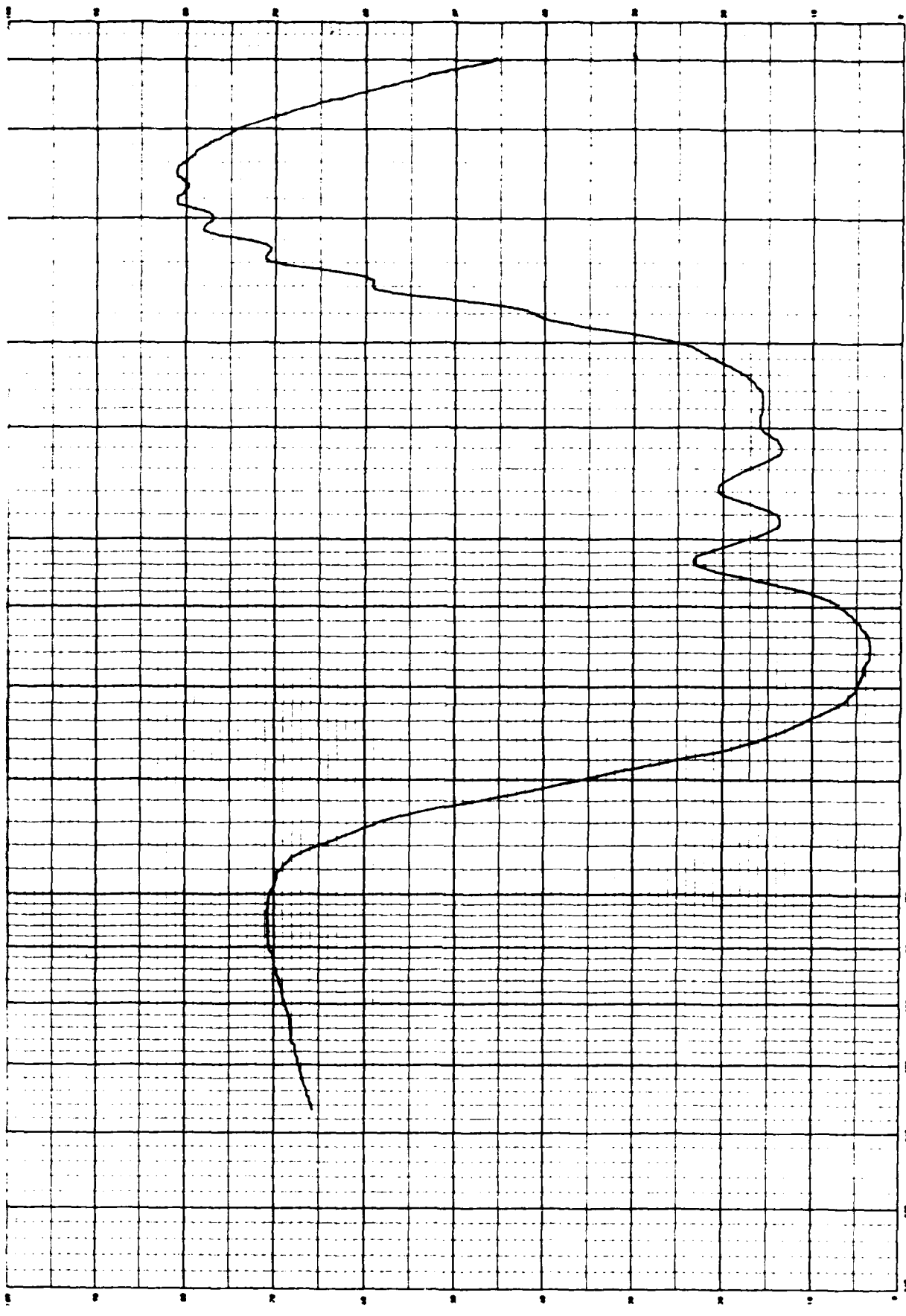


Figure A3. Water Takeup = 3.35 mg. Laser Exposure A = 31 mJ/cm^2, B = 310 mJ/cm^2, C = 2900 mJ/cm^2



Water Takeup = 3.35. Laser Exposure = 97.

Figure A4



Water Takeup = 4.1. Laser Exposure = 97.

Figure A5

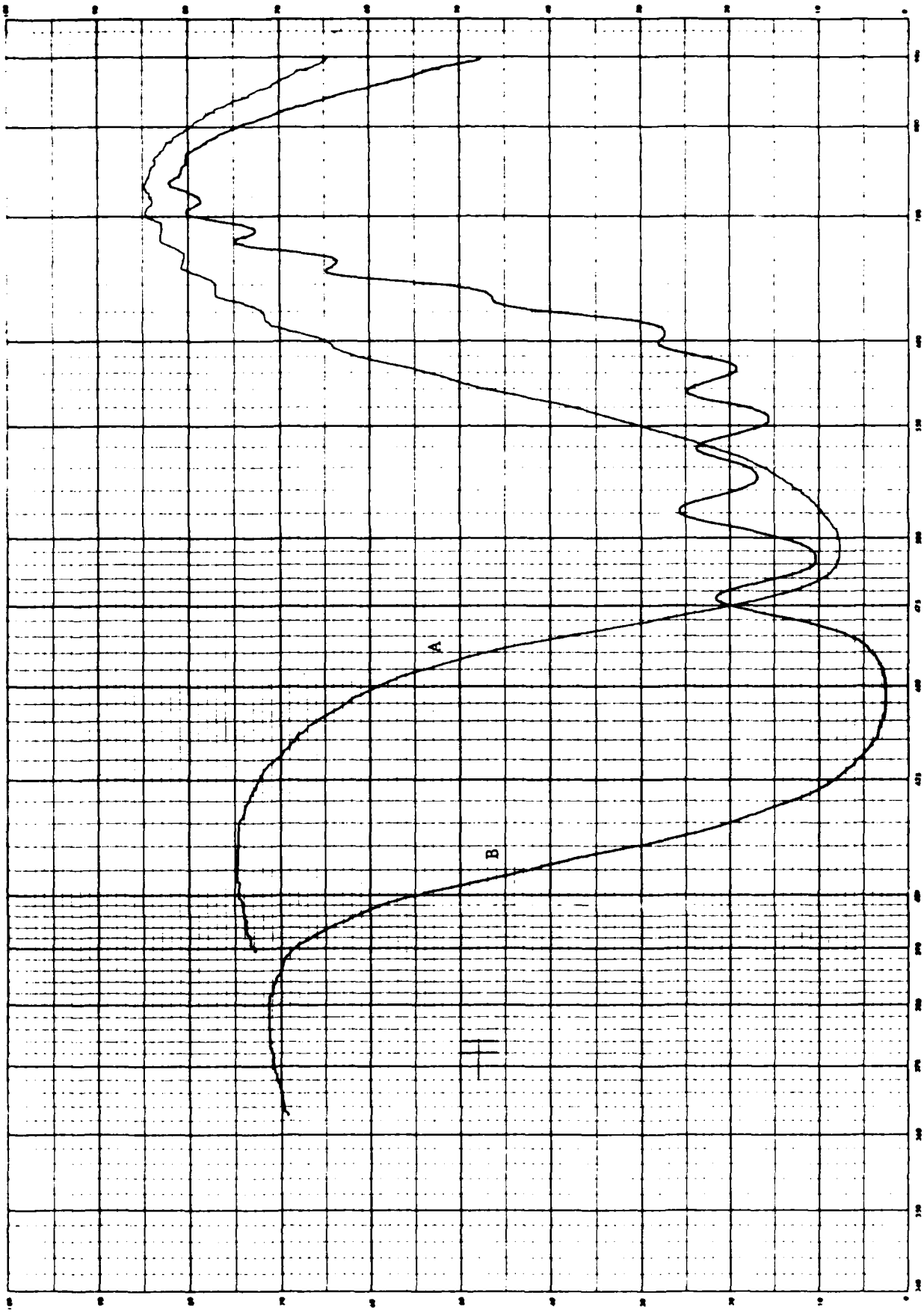
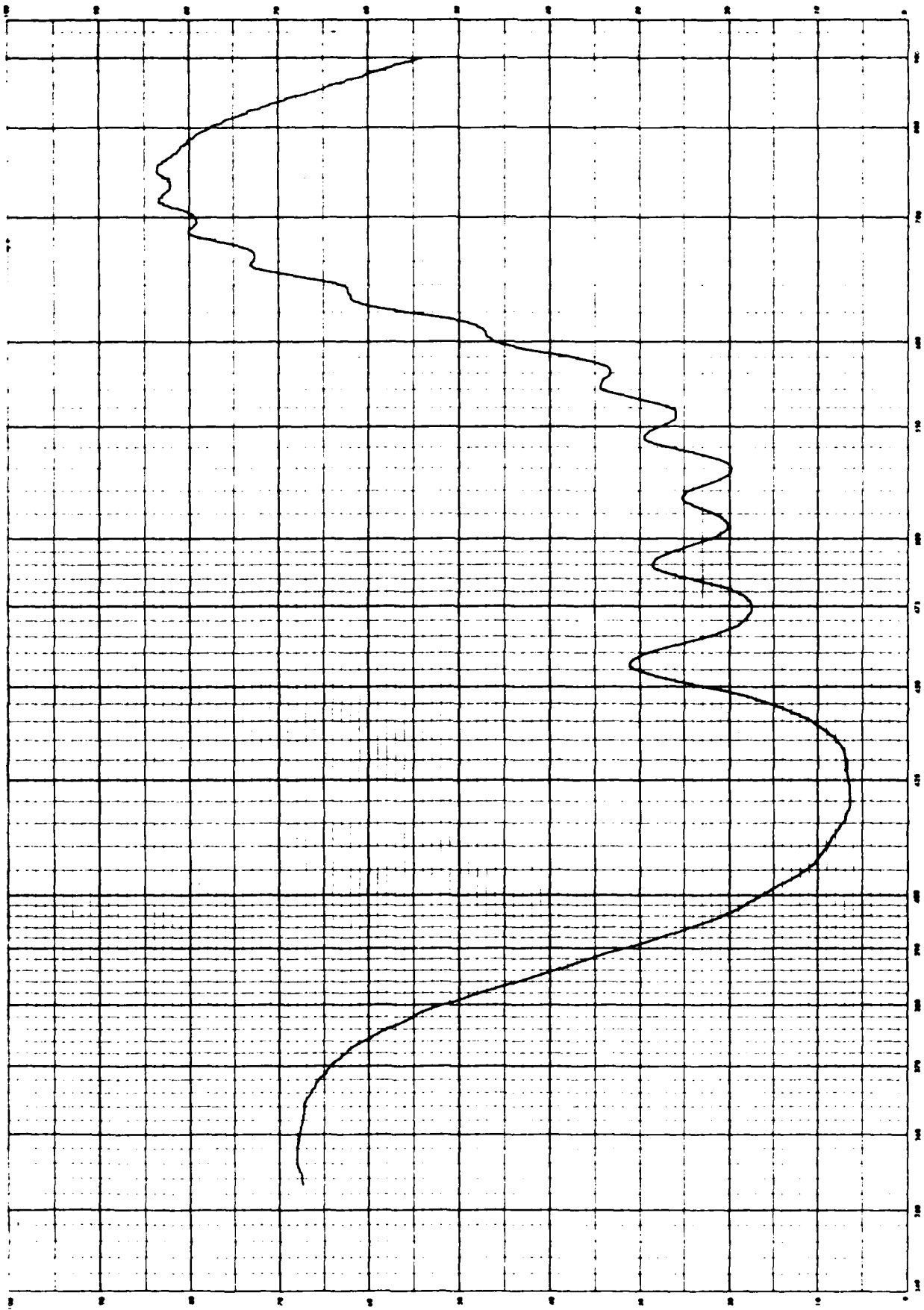
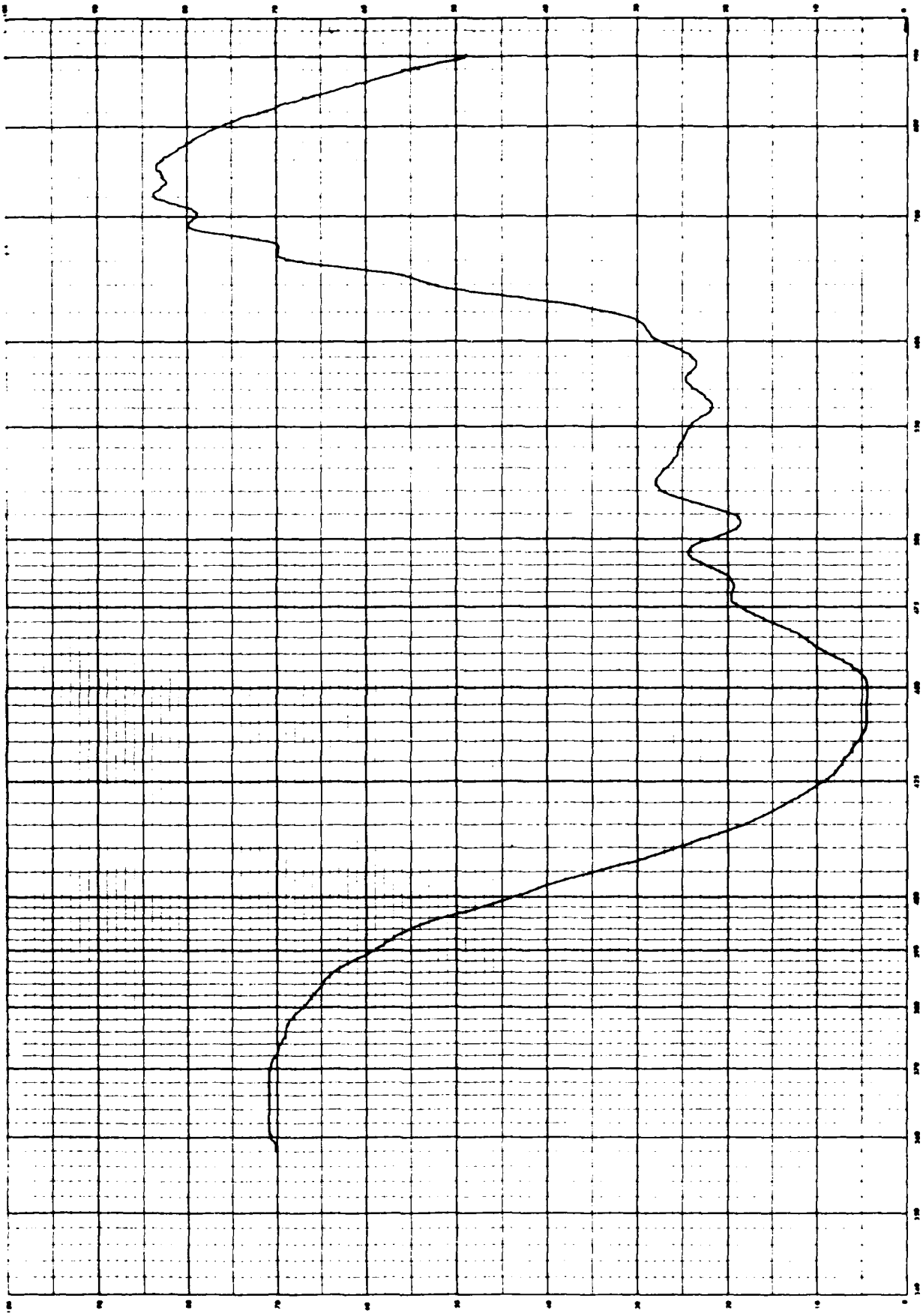


Figure A6. Water Takeup = 4.1 mg. Laser Exposure A = 31 mJ/cm^2, B = 310 mJ/cm^2



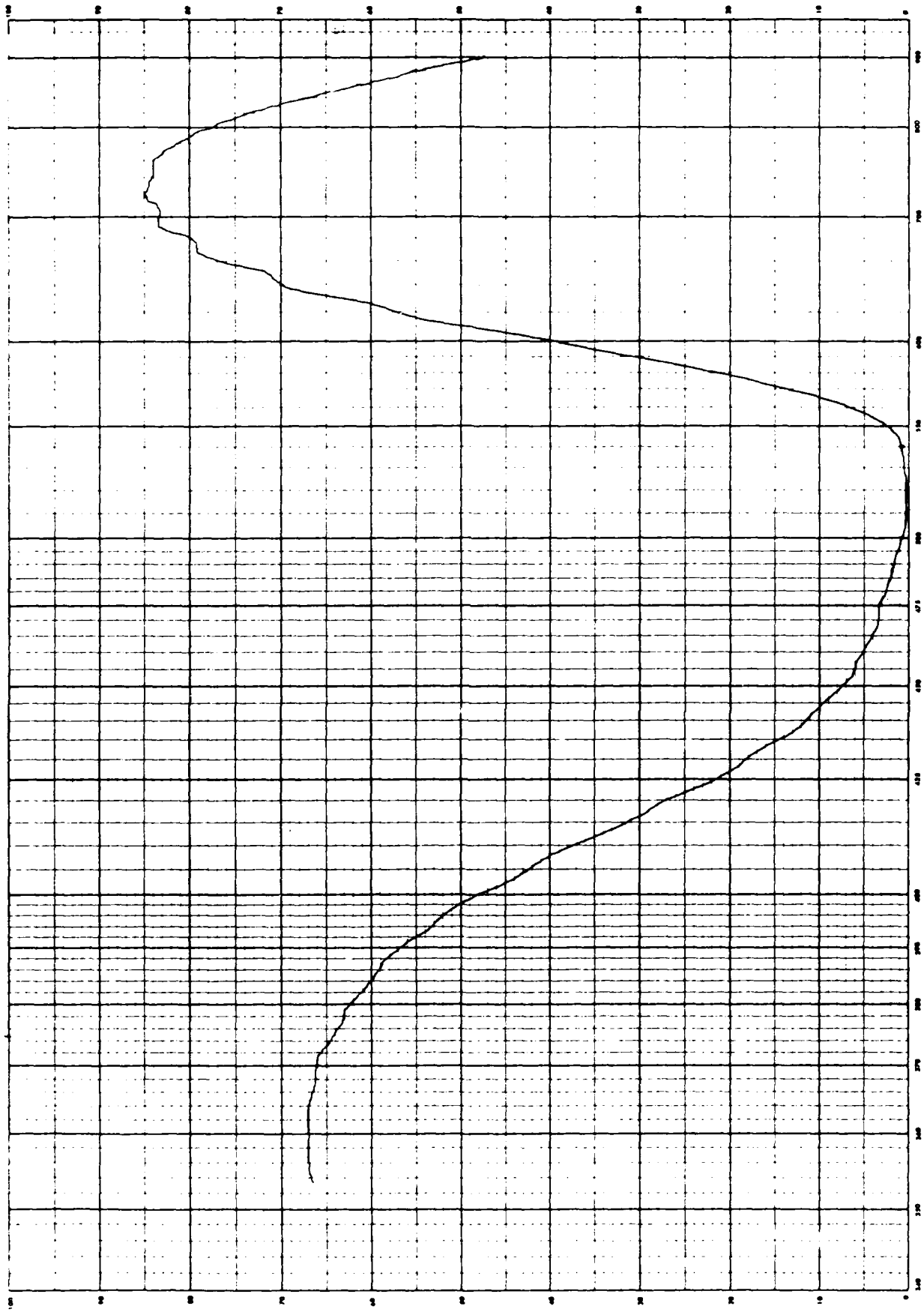
Water Takeup = 4.4. Laser Exposure = 97.

Figure A7



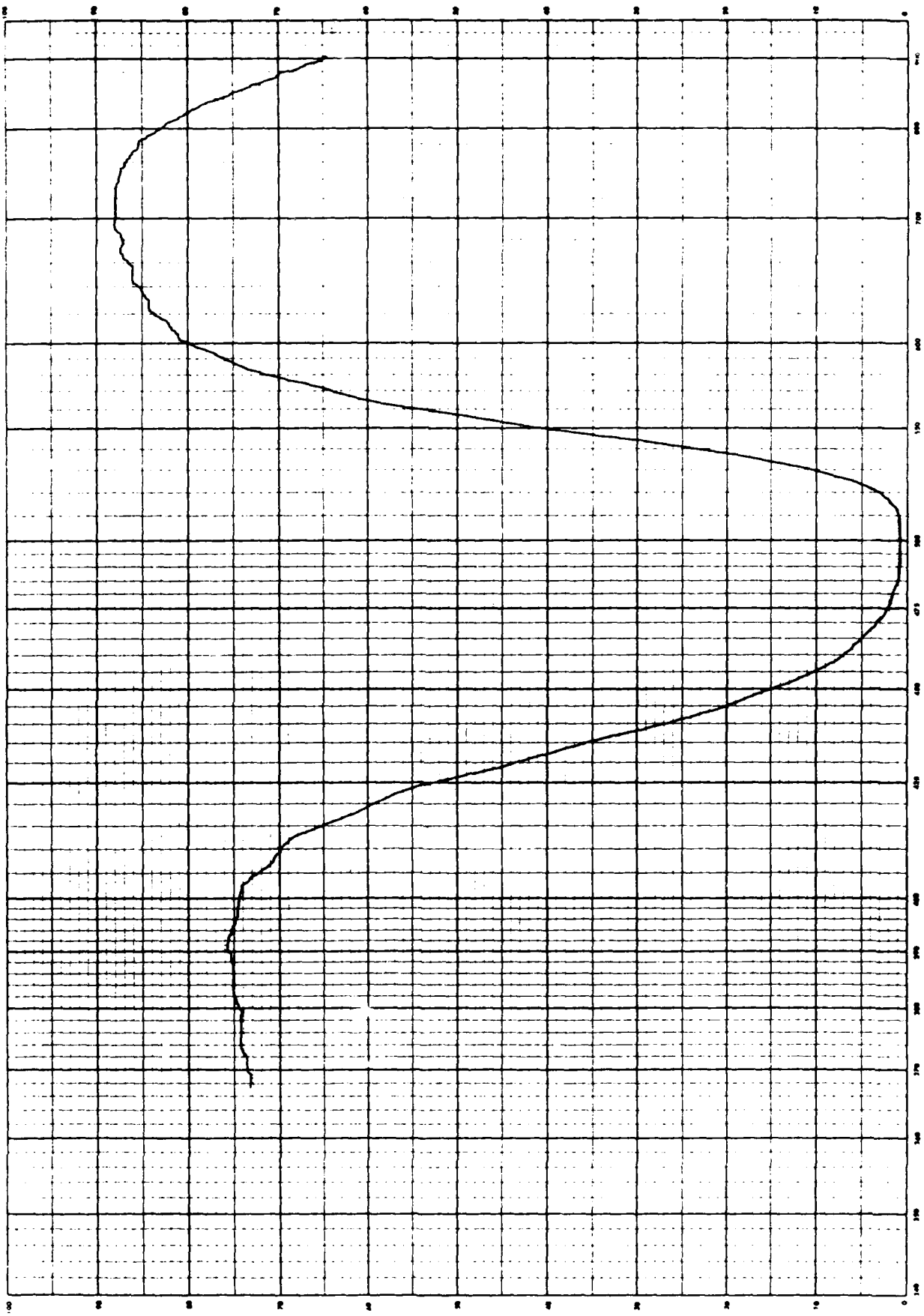
Water Takeup = 4.4. Laser Exposure = 110.

Figure A8



Water Takeup = 4.7. Laser Exposure = 97.

Figure A9



Water Takeup = 4.7, Laser Exposure = 110.

Figure A10

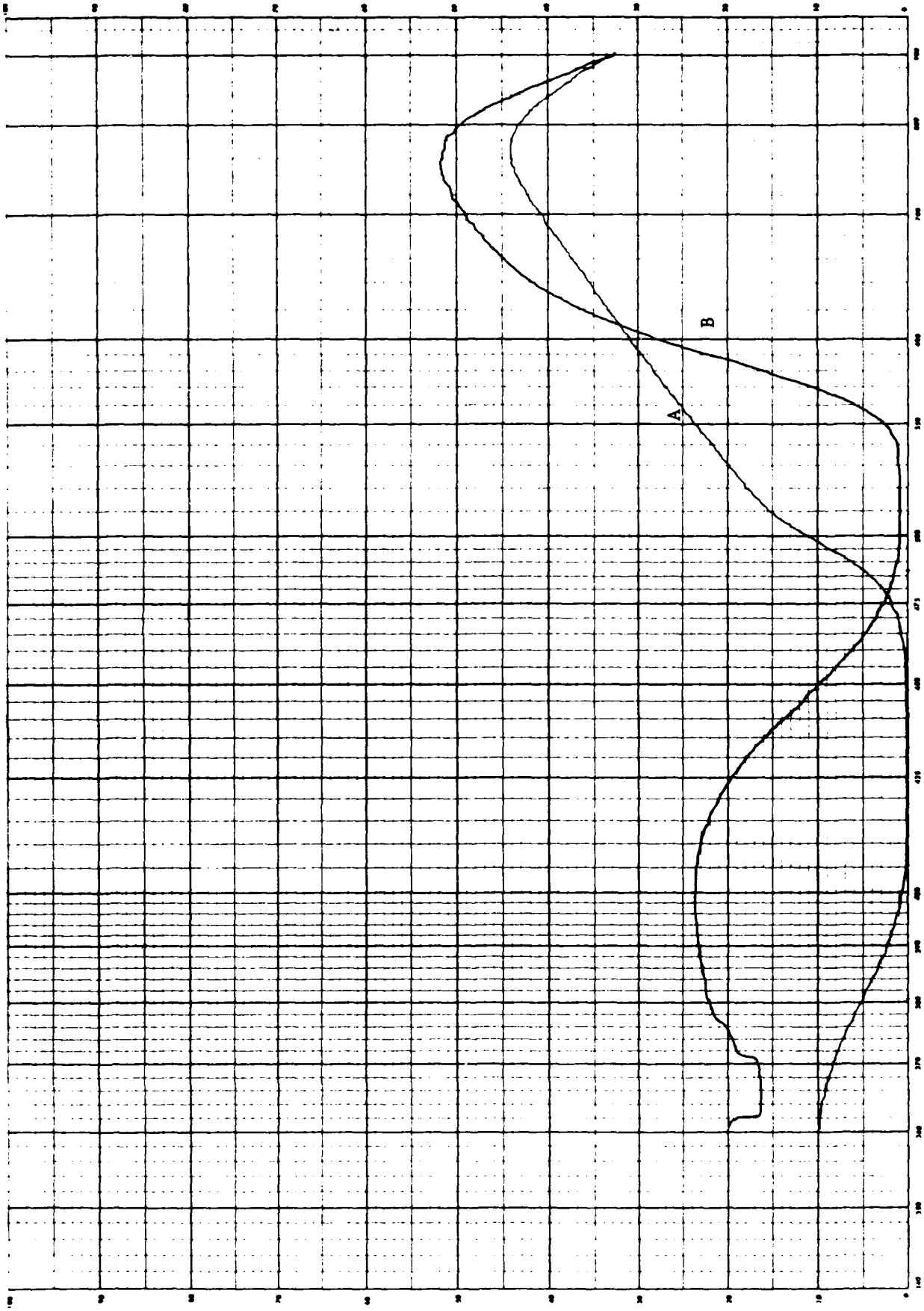


Figure A11. Water Takeup = 5.0 mg. Laser Exposure A = 49 mJ/cm^2, B = 99 mJ/cm^2

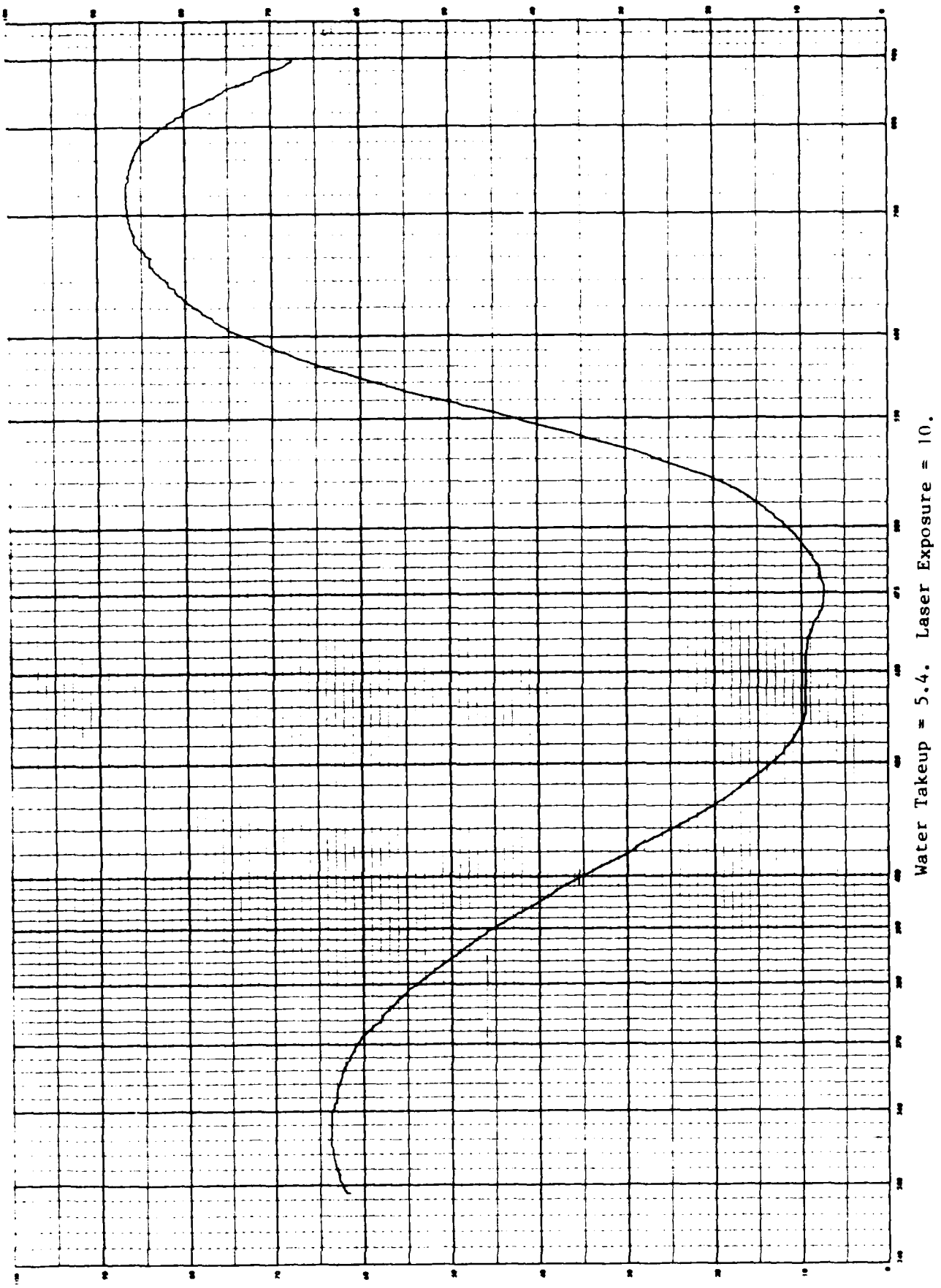


Figure A12

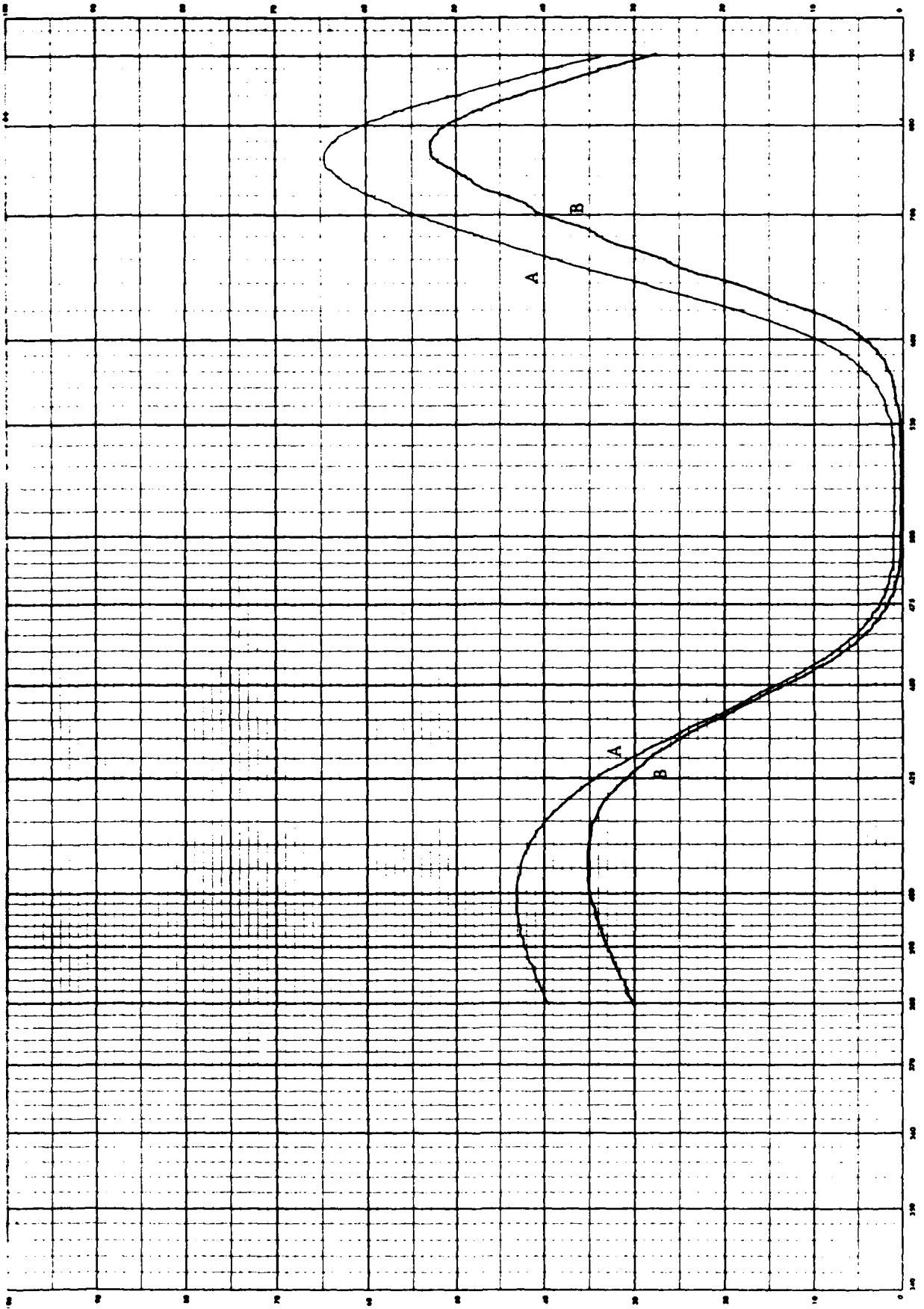


Figure A13. Water Takeup = 5.6 mg. Laser Exposure A = 23 mJ/cm^2, B = 46 mJ/cm^2

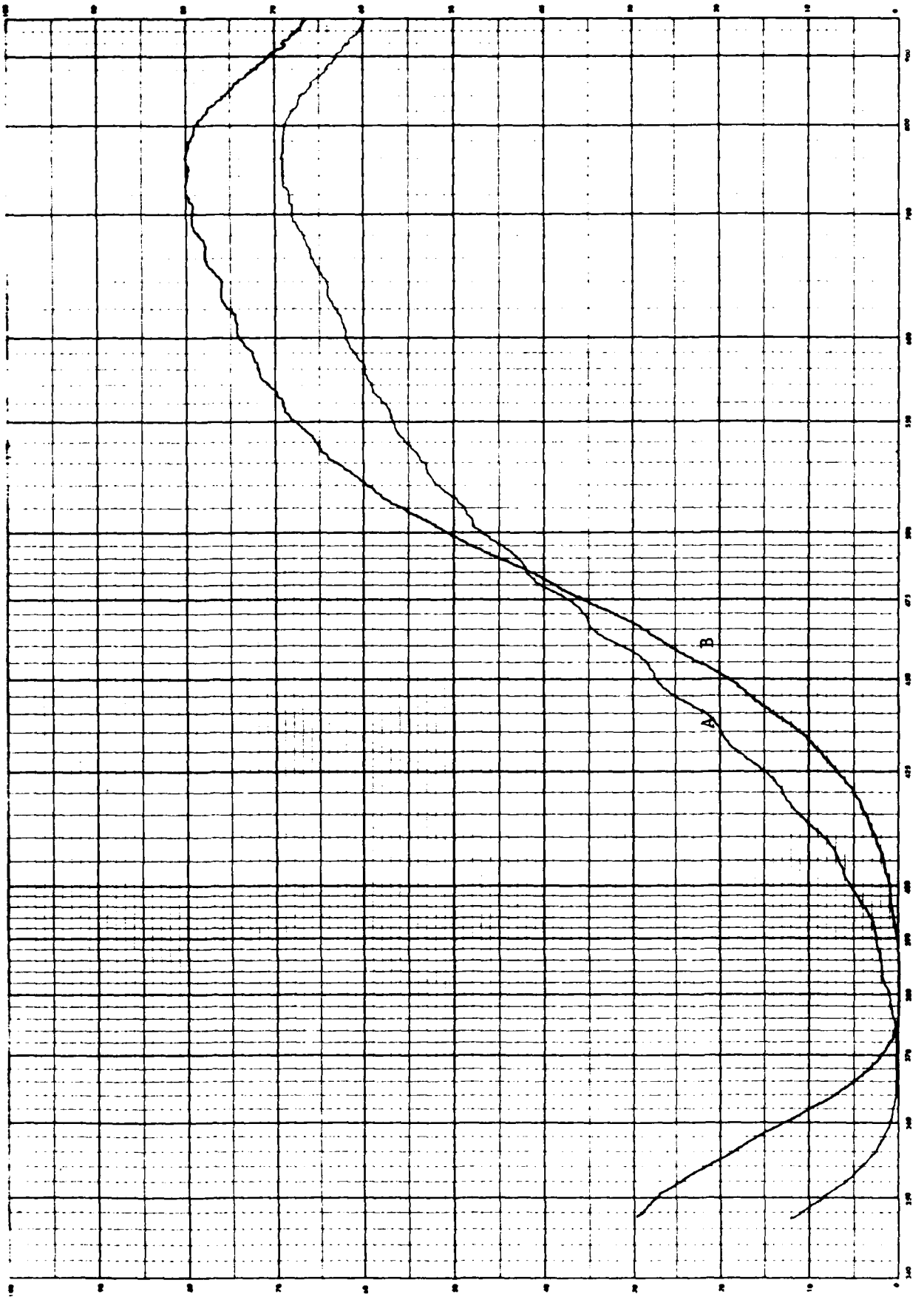


Figure A14. Water Takeup = 5.6 mg. Laser Exposure A = 11 mJ/cm^2, B = 17 mJ/cm^2

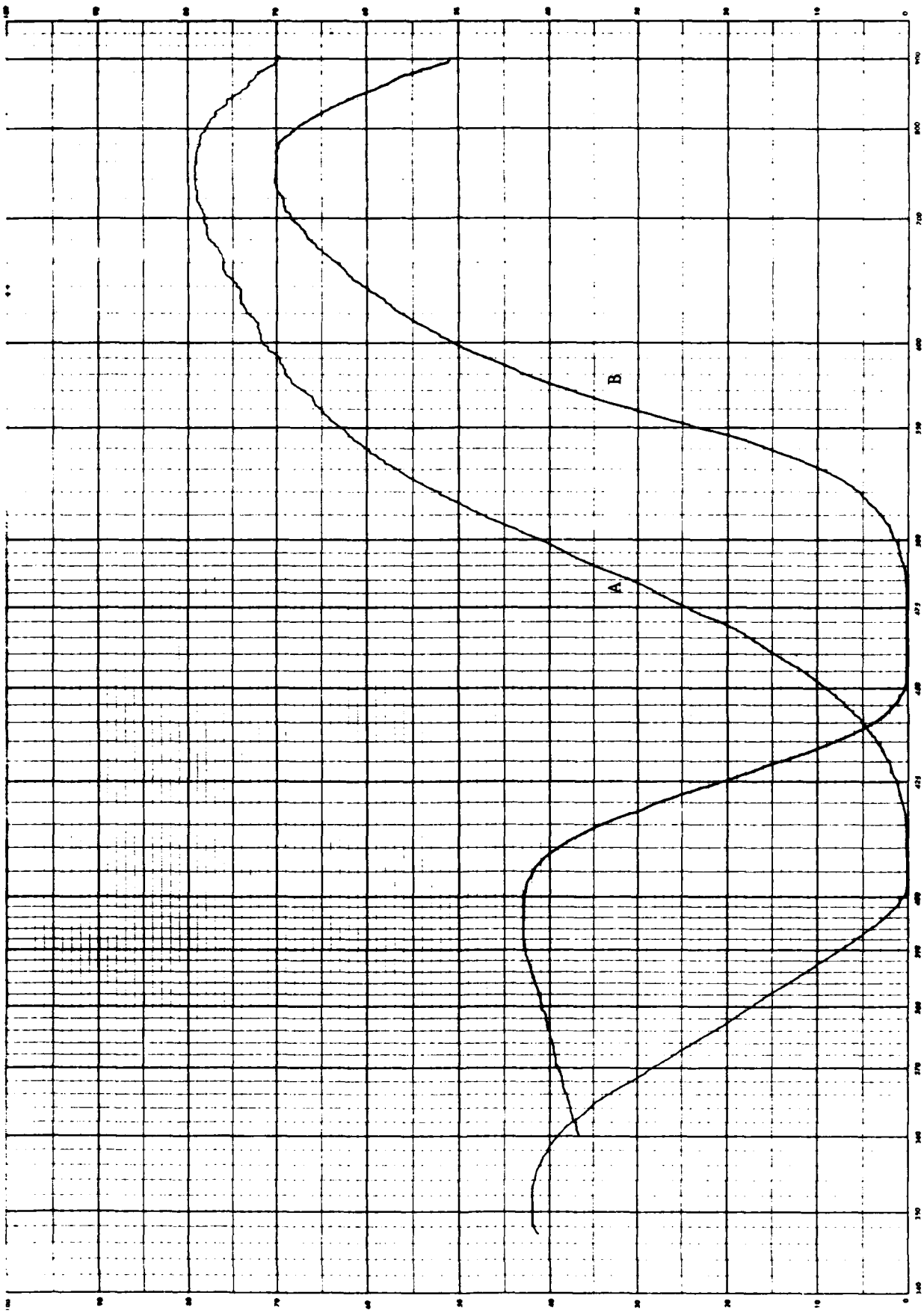


Figure A15. Water Takeup = 5.6 mg. Laser Exposure A = 22 mJ/cm^2, B = 38 mJ/cm^2

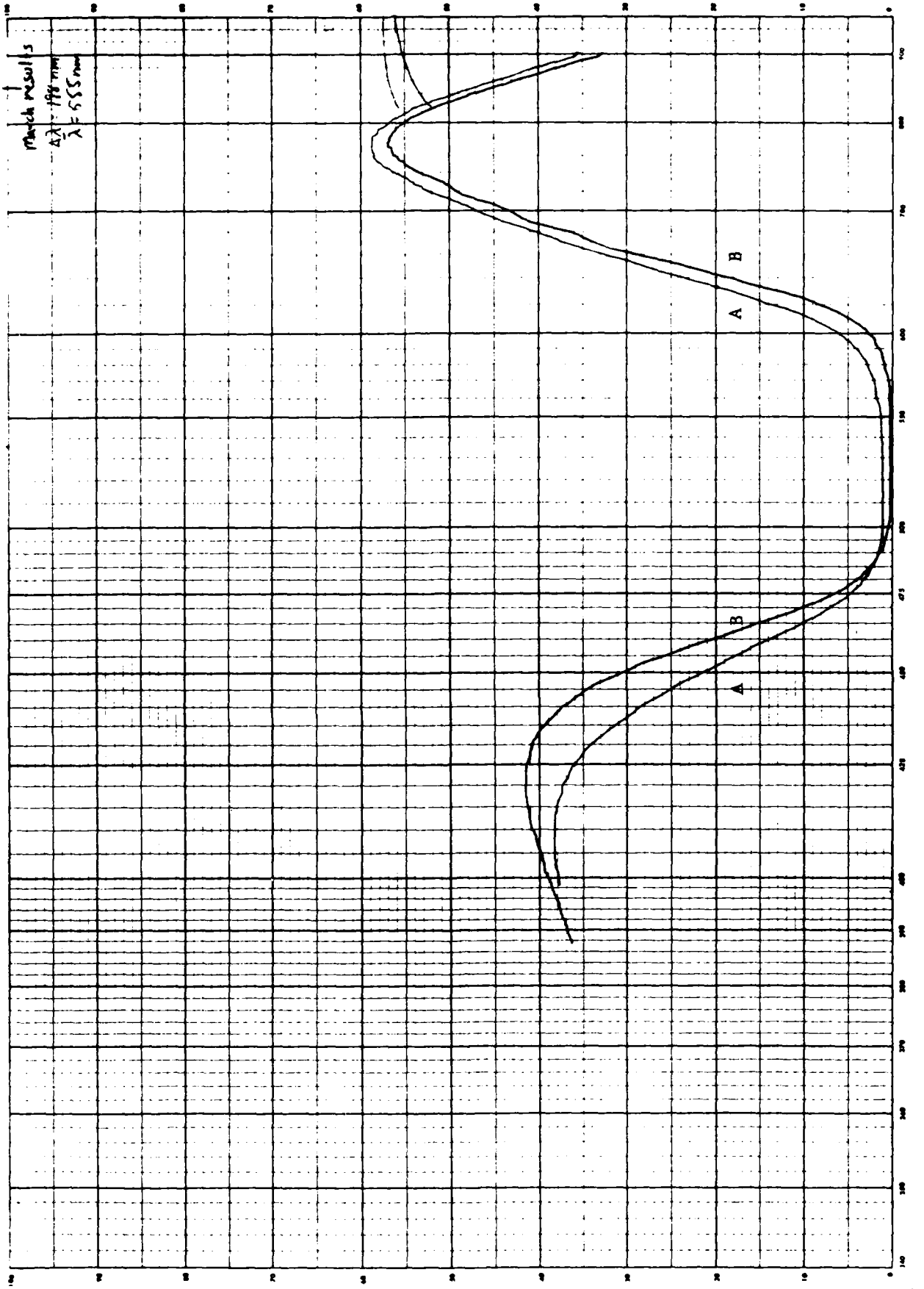


Figure A16. Water Takeup = 5.8 mg. Laser Exposure A = 51 mJ/cm^2, B = 51 mJ/cm^2 repeat

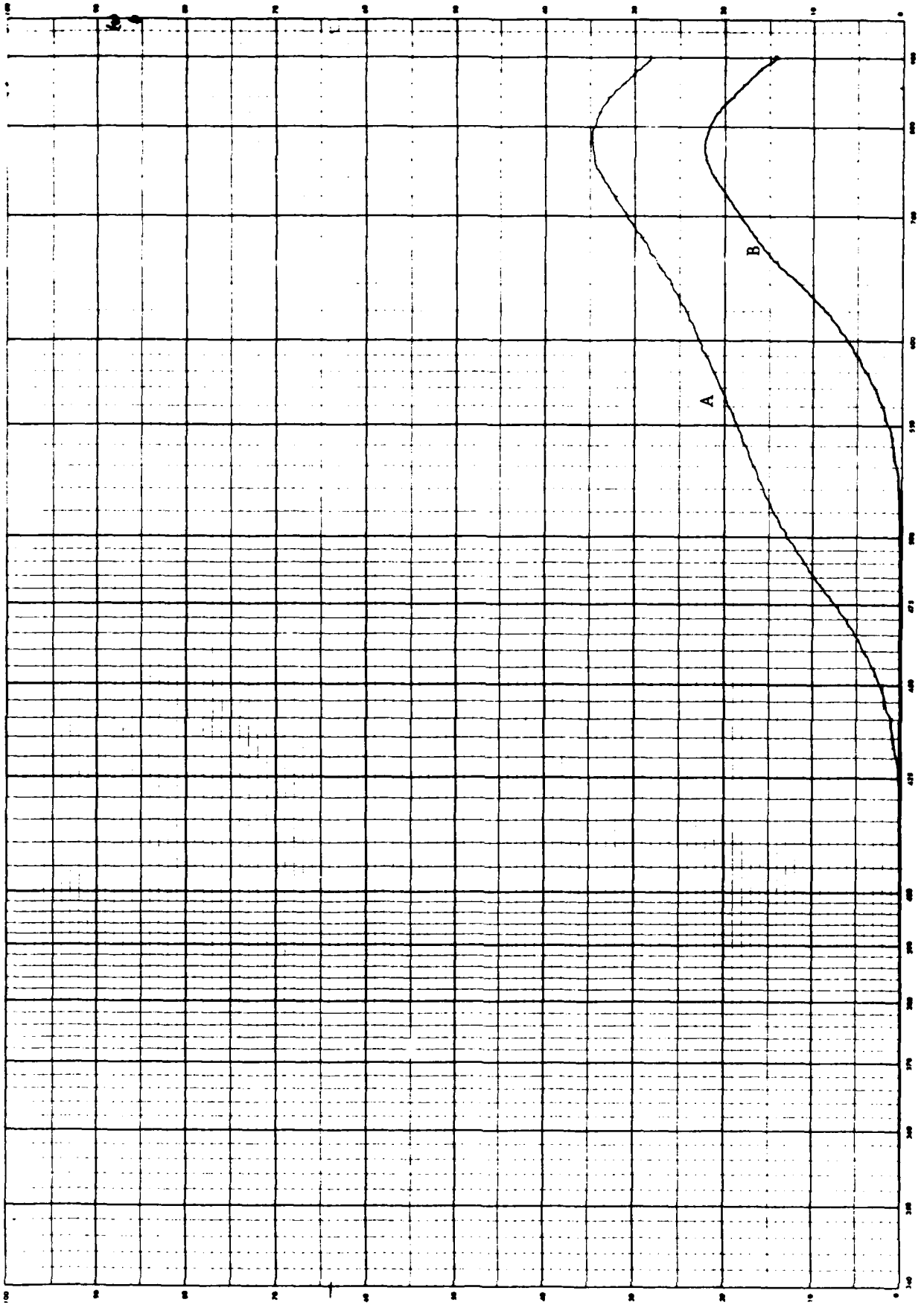


Figure A17. Water Takeup = 5.9 mg. Laser Exposure A = 26 mJ/cm^2, B = 51 mJ/cm^2

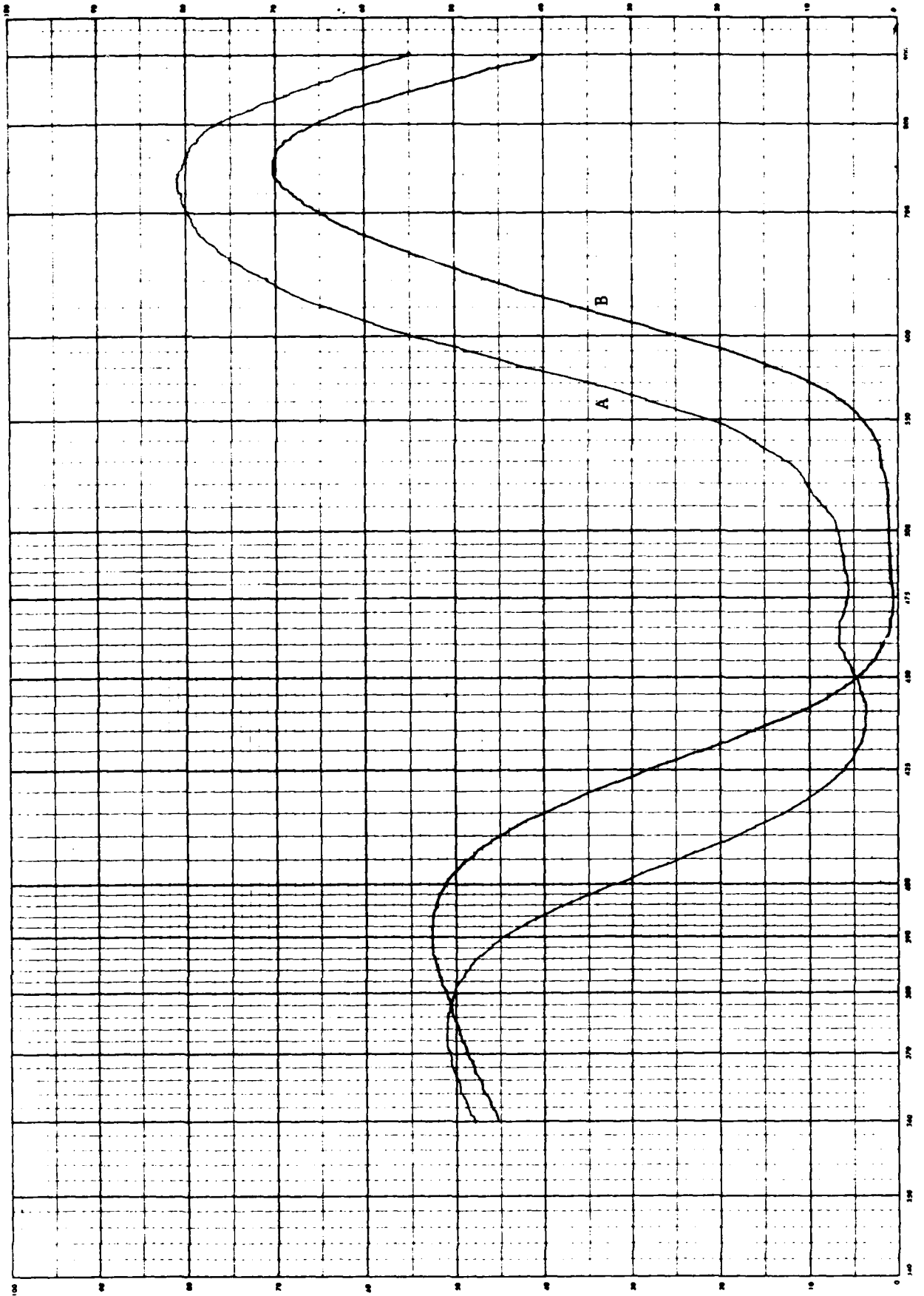


Figure A18. Water Takeup = 5.8 mg. Laser Exposure A = 14 mJ/cm^2, B = 26 mJ/cm^2

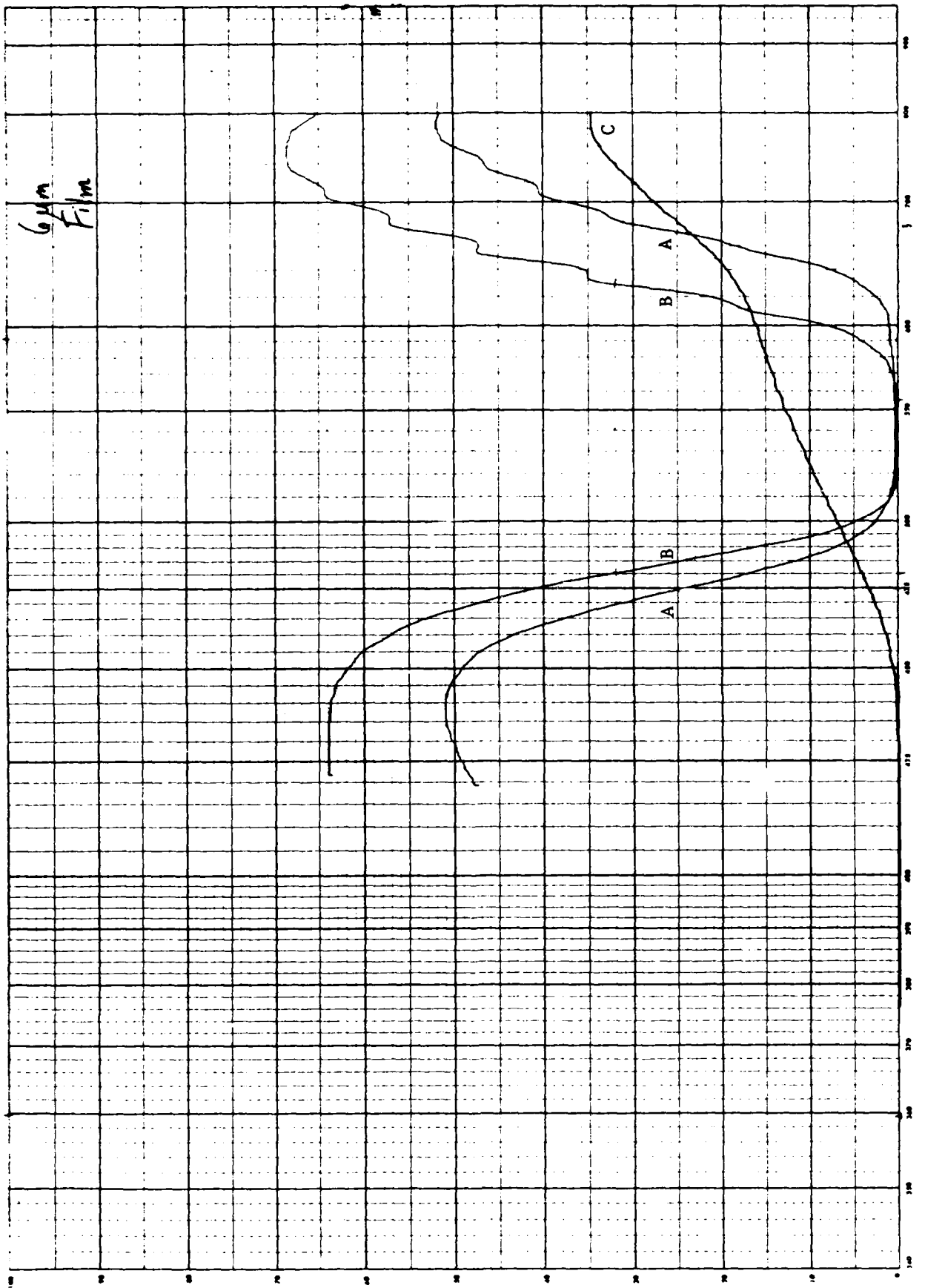
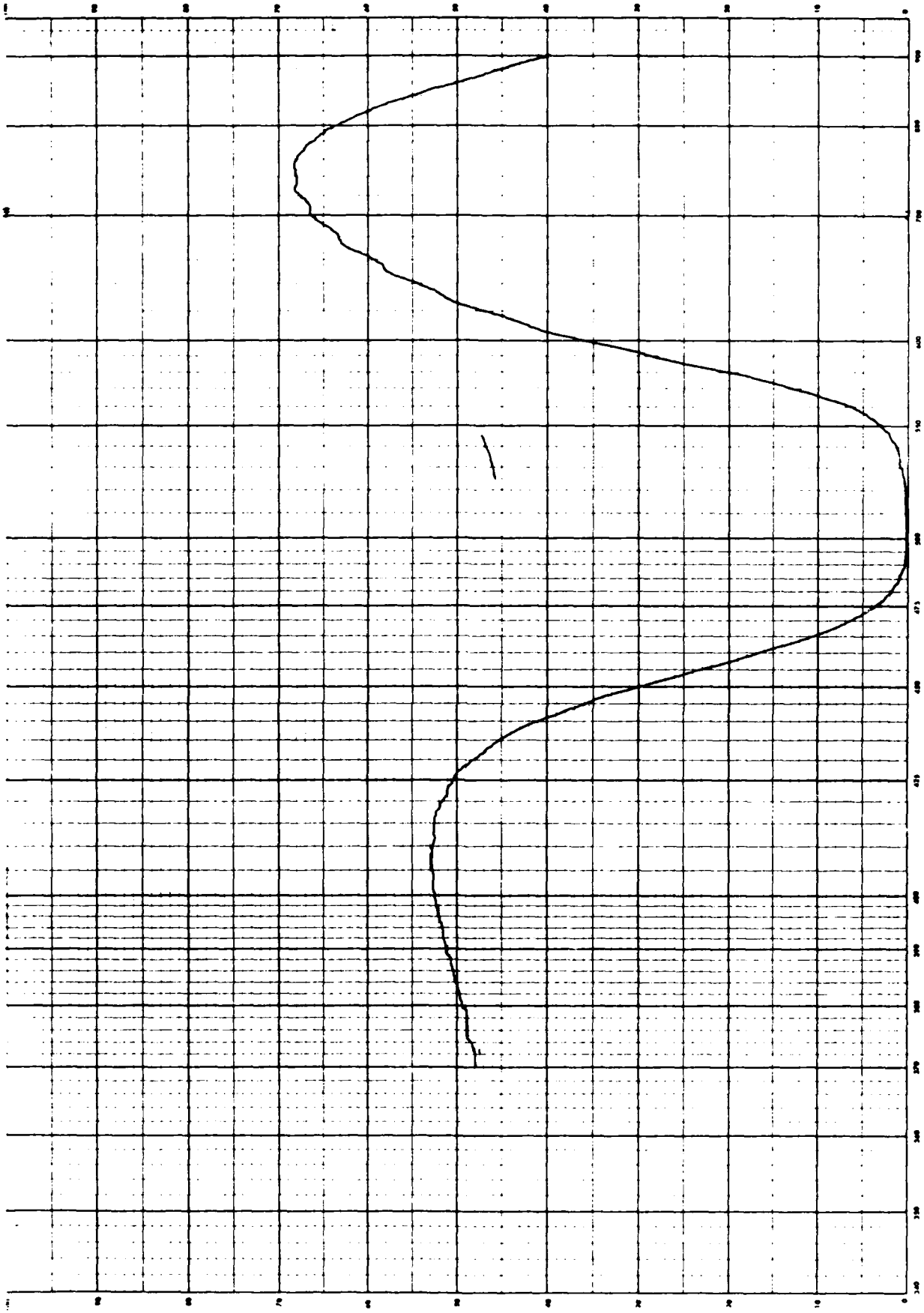
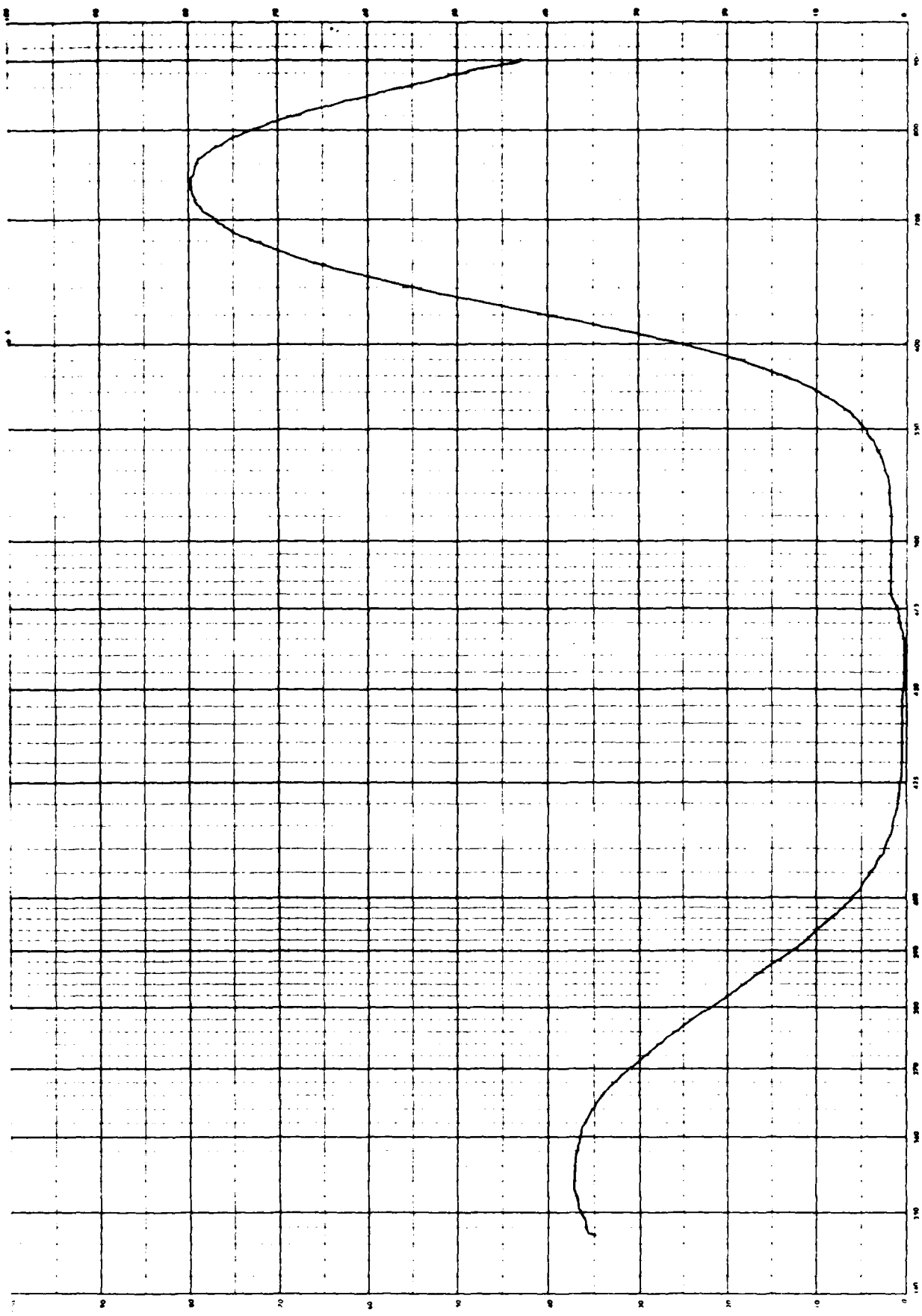


Figure A19. Water Takeup A = 5.8 mg, B = 6.0 mg, C = 6.2 mg. Laser Exposure A = 60 mJ/cm^2, B = 120 mJ/cm^2, C = 85 mJ/cm^2



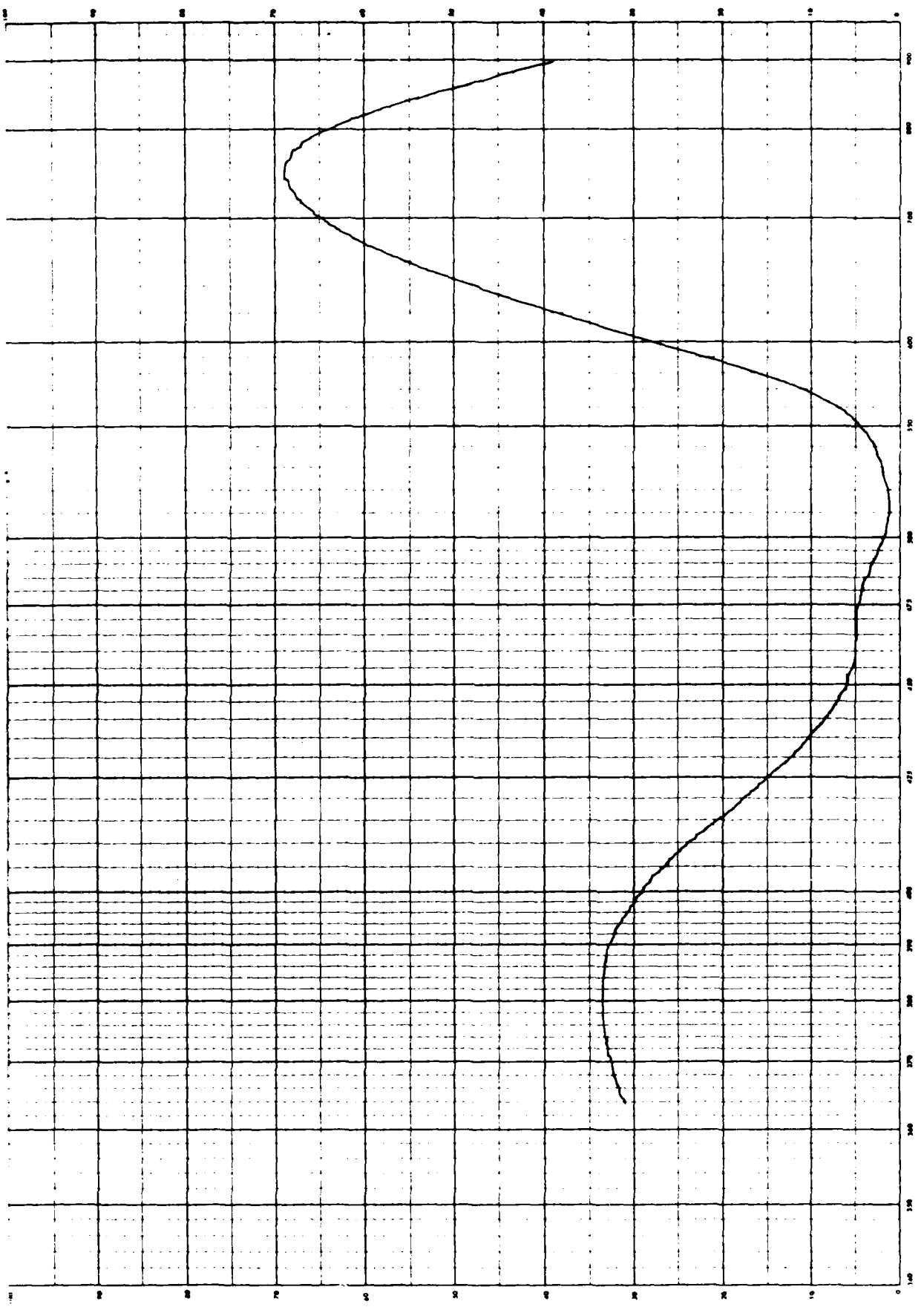
Water Takeup = 6.0. Laser Exposure = 46.

Figure A20



Water Takeup = 6.0.

Figure A21



Water Takeup = 6.2. Laser Exposure = 26.

Figure A22

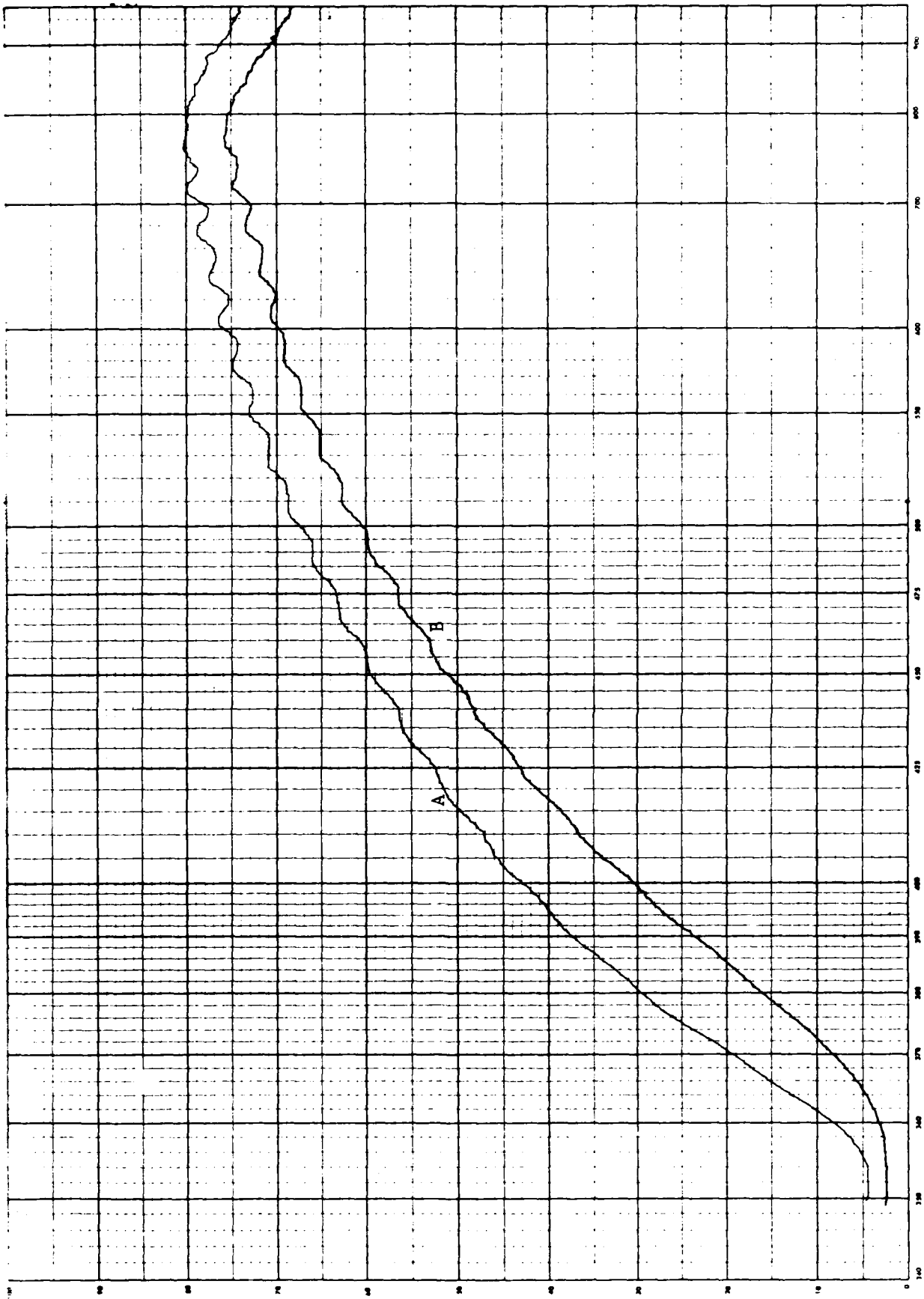


Figure A23. Water Takeup = 6.2 mg. Laser Exposure A = 11 mJ/cm^2, B = 17 mJ/cm^2

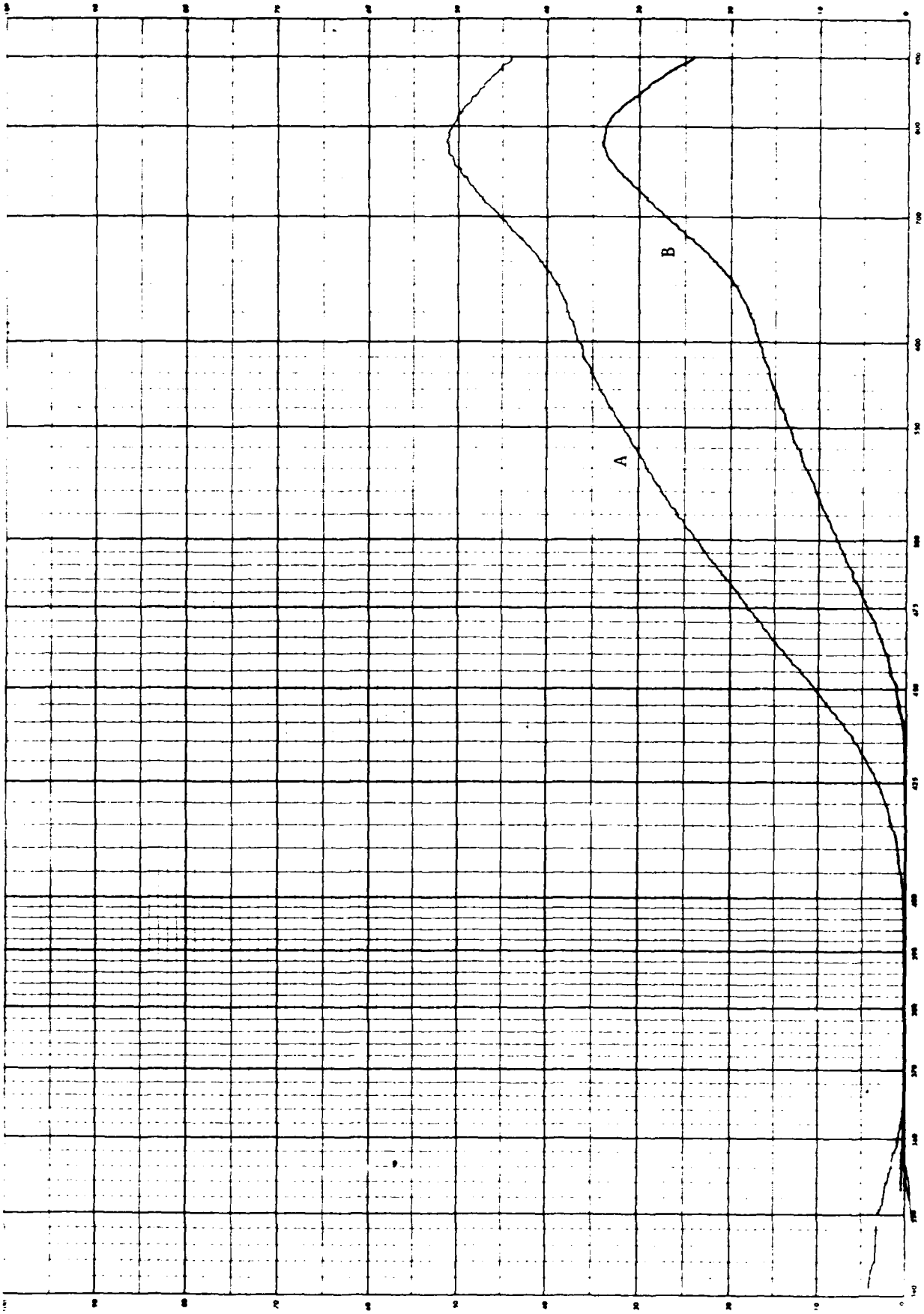


Figure A24. Water Takeup = 6.2 mg. Laser Exposure A = 47 mJ/cm^2, B = 71 mJ/cm^2

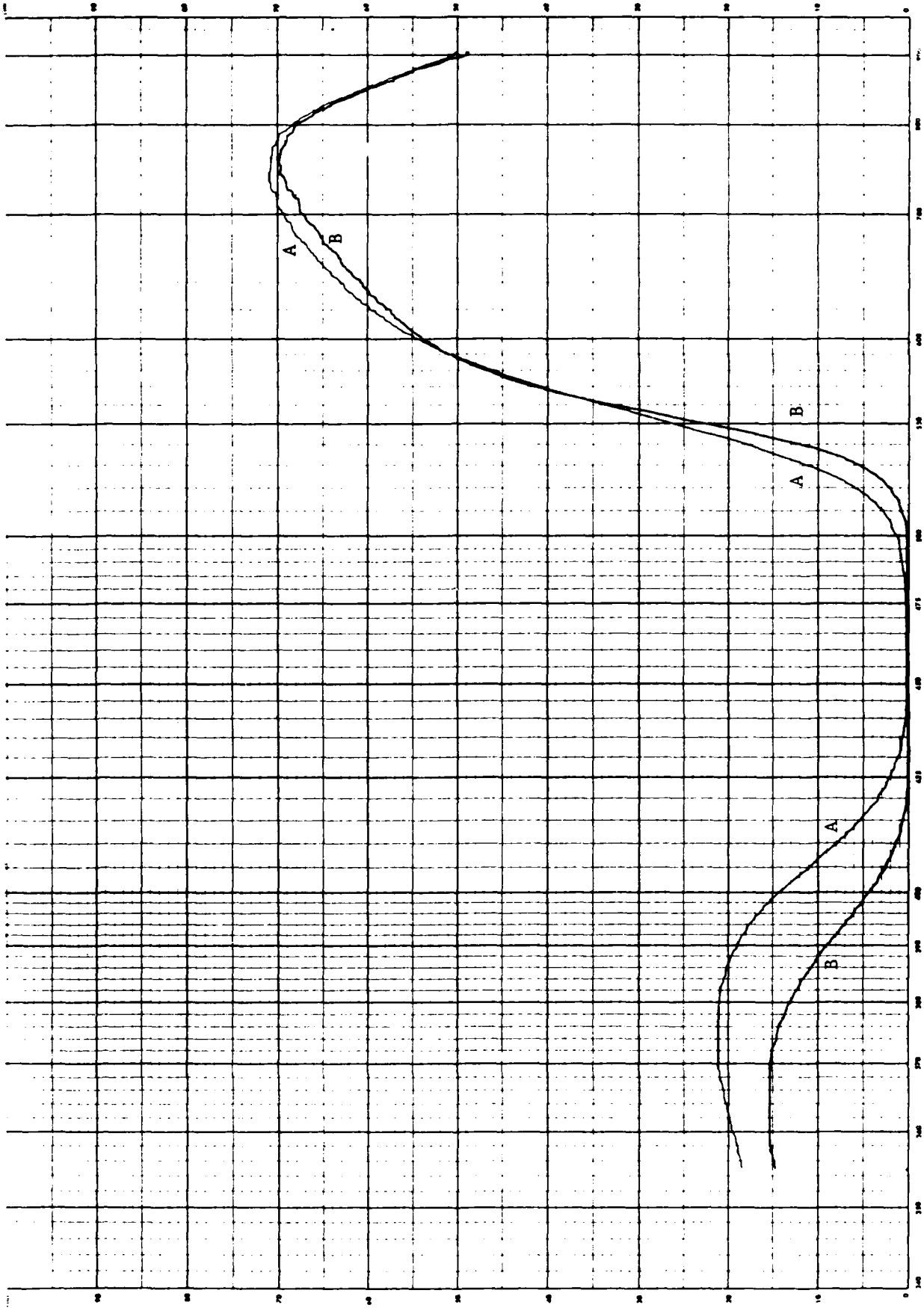


Figure A25. Water Takeup = 7.5 mg. Laser Exposure A = 12 mJ/cm^2, B = 23 mJ/cm^2

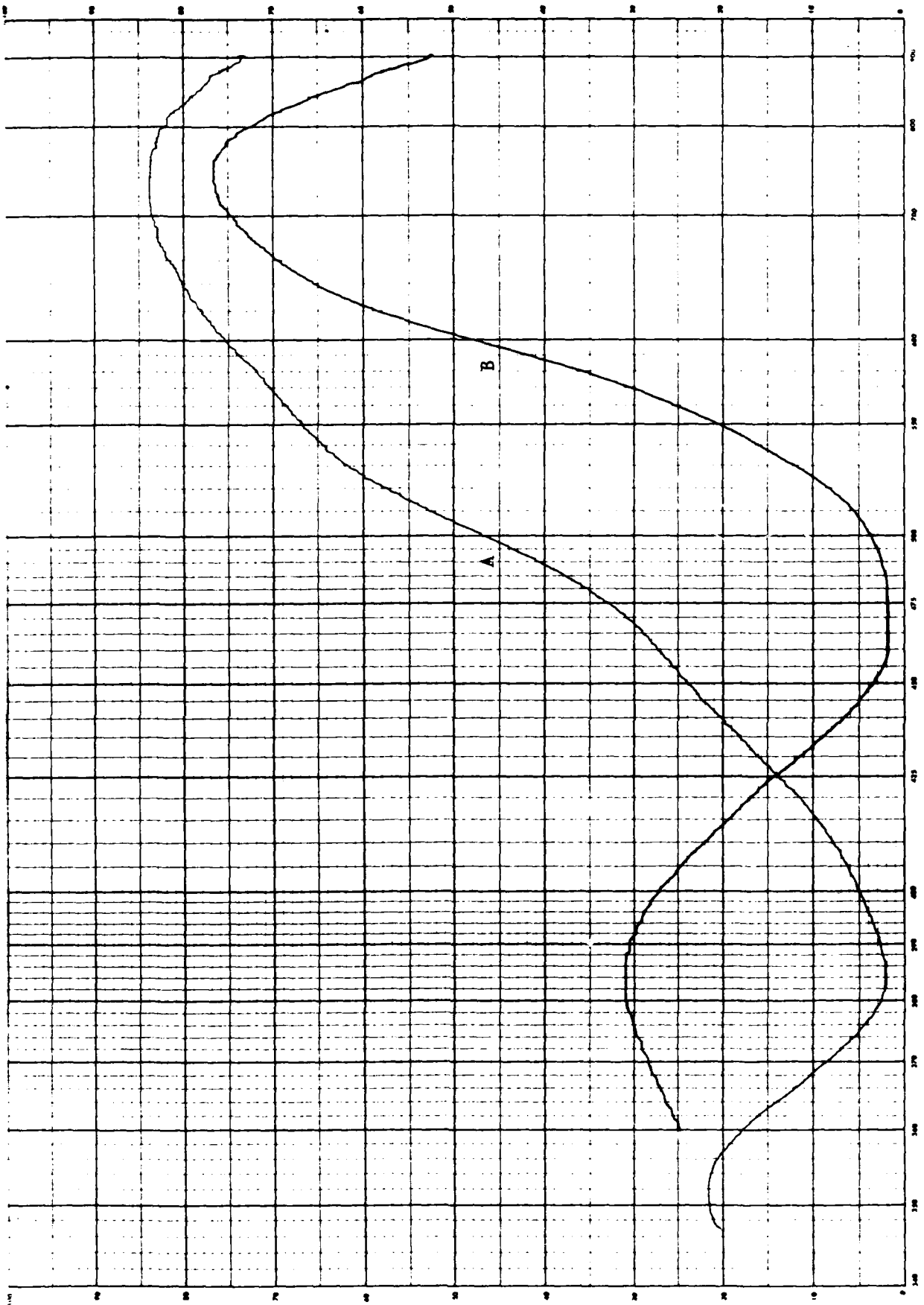


Figure A26. Polymer Thickness = 12 μm. Water Takeup = 9.2 mg. Laser Exposure A = 6 mJ/cm^2, B = 13 mJ/cm^2

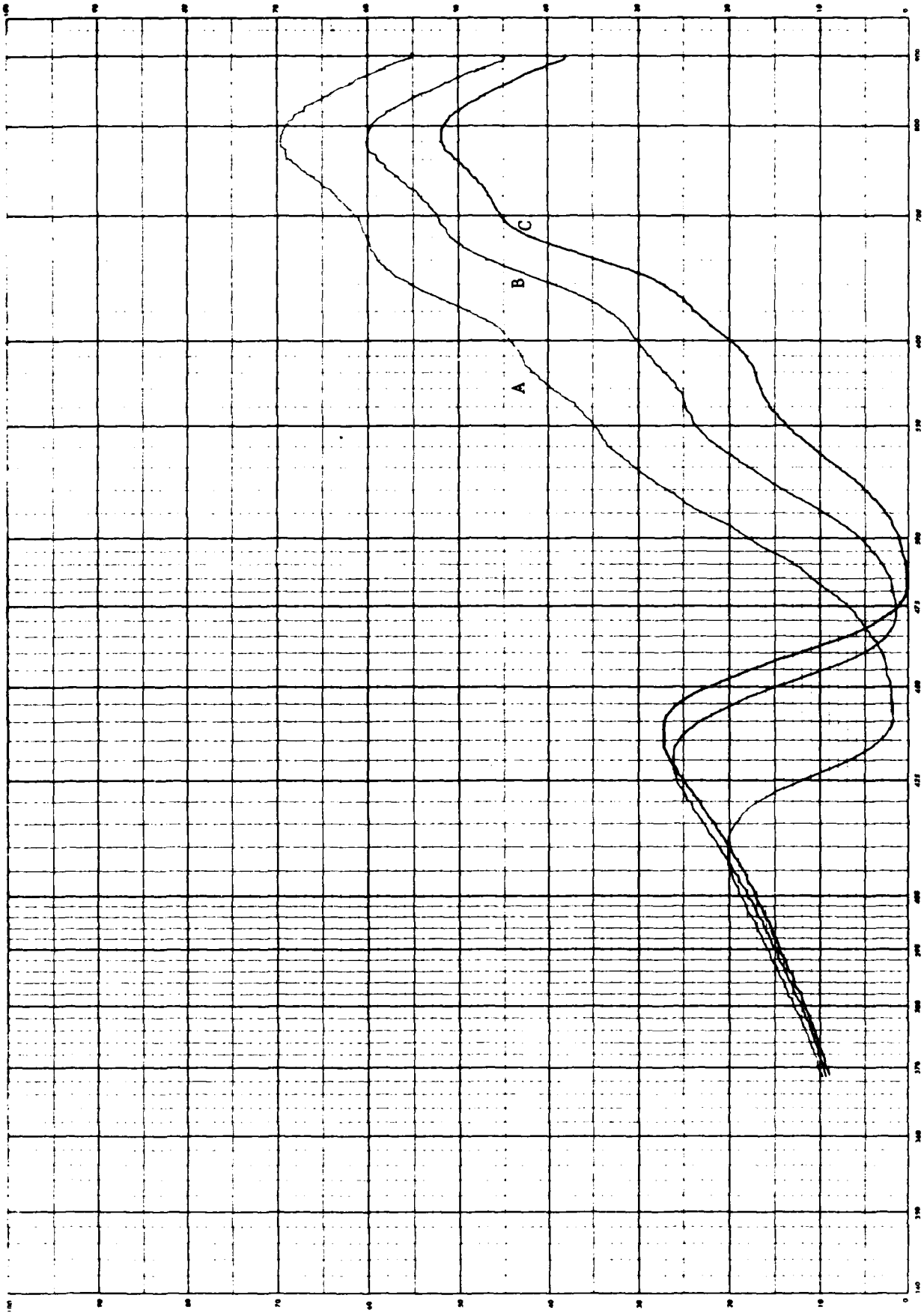


Figure A27. Polymer Thickness = 12 µm. Exposure and Takeup not recorded. Laser Exposure A lowest, B middle, C highest

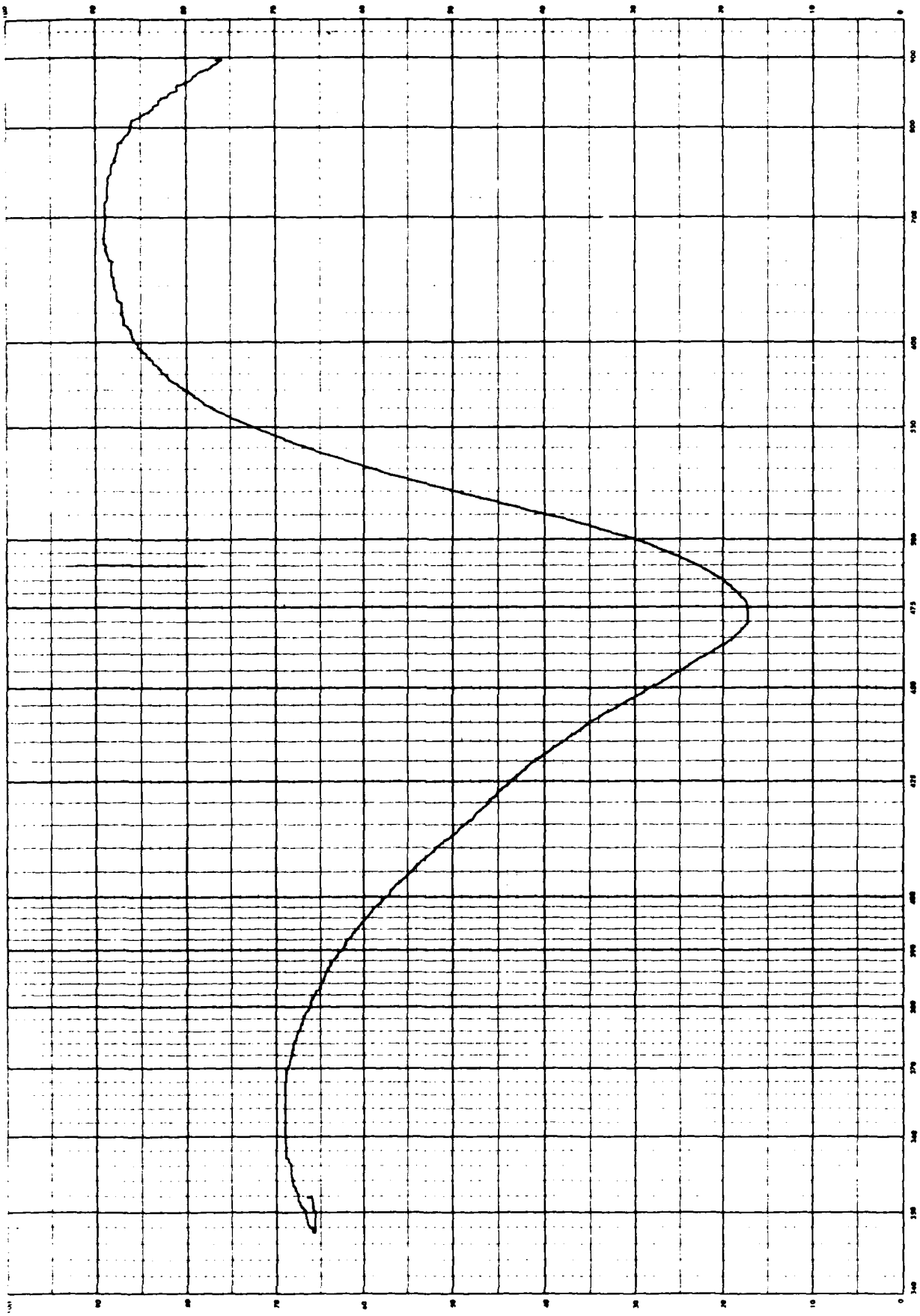


Figure A28. Hologram made at Polaroid

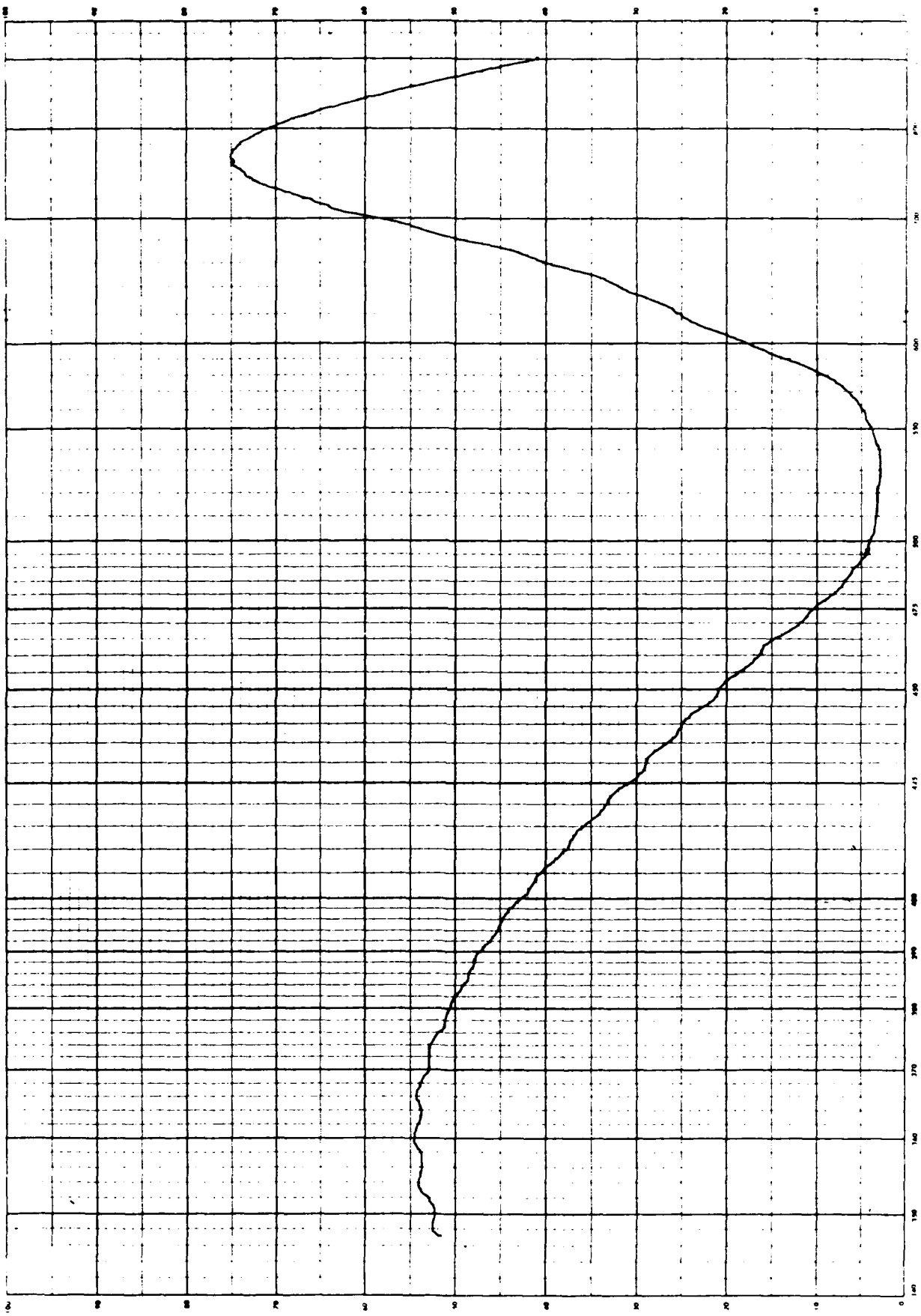


Figure A29. Hologram made at Polaroid