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CO_2 Laser Ignition of DAPP Targets

Paul J. Brannon

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CO_2 LASER IGNITION OF DAPP TARGETS

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Division 4214

ABSTRACT

A pulse derived by shuttering a CO_2 laser operating in the cw mode has been used to ignite a diallyl phthalate pyrotechnic (DAPP) material. Data from this work along with some data taken earlier, while operating the laser in the pulse mode, are presented. When operating in the cw mode, a pulse is mechanically chopped out of the beam and focussed onto the DAPP material. It was found that the shuttered cw mode of operation gives a more reproducible pulse and a more accurate determination of the incident energy than the pulse mode does. The pulse widths for threshold ignition (50% ignitions) at different power levels have been determined for 254 and 127 mm-focal-length lenses which were used to focus the beam on the target. It was also found that targets could be penetrated without ignition of the DAPP material. A 2.54 mm-thick DAPP target is penetrated by the laser beam if the energy per unit area exceeds 29 +1 J/mm^2. Based on this study, recommendations are given for improving the present test procedures used for DAPP material.

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Summary

Background

As a standard production sampling test, diallyl phthalate pyrotechnic material (DAPP) was tested by irradiating it with a focussed CO_2 laser beam of sufficient energy to produce ignition. The test laser was operated in the pulse mode at a nominal power level of 30 watts and a pulse width of 110-115 ms. Under these test conditions, the DAPP sample should always ignite. However, ignition did not occur every time, and it was not clear whether this was due to a change in the laser output or a change in the material.

At Sandia National Laboratories, diagnostics were installed on an identical laser to characterize the laser's behavior when operated in the pulsed mode. It was found that the laser output energy could vary by as much as 30 percent while operating in the pulse mode. This result suggested that the laser should be operated in the cw mode and the beam mechanically chopped, since the power level and the time duration of the pulse could be more accurately controlled.

Results of This Study

In this study, the laser was operated in both a pulsed mode and the cw mode. While operating in the cw mode, the laser light was shuttered in order to obtain a pulse. It was found that the cw mode of operation gives a more reproducible pulse and a more accurate determination of the incident energy than the pulse mode.

The DAPP material was subjected to different pulse widths and power levels to determine ignition probabilities. A linear probit analysis pulse width versus probability of ignitions was then performed to determine the threshold of ignition (50 percent ignitions) under the various conditions. It was found that (a) the pulse width necessary for threshold ignition increases with decreased power level, (b) the energy incident on the DAPP material required for threshold ignition increases as the total laser beam power increases in the power range 2.5 to 50 W, and (c) the threshold of ignition is a very weak function of energy or power per unit area.

An unexpected result of this study was that the DAPP target could be penetrated by the laser beam without igniting it. The laser and target parameters important in characterizing this phenomenon were the energy per unit area incident on target and the target thickness. A 2.54 mm-thick DAPP target was penetrated by the laser beam if the energy per unit area exceeded 29 J/mm^2.

Based on the preceding and other results of this study, the following recommendations are made for improving the present test procedures:

- The laser should be operated in the cw mode and mechanically shuttered instead of in the pulse mode because the reproducibility of the pulse and the accuracy of the incident energy measurement are significantly improved.
- A 254 mm-focal-length lens should be used to focus the beam onto the target. This not only reduces the possibility of penetrating of the target, but requires less frequent changes

of the KBr window separating the target chamber from the other optics.

- A power level between 10 and 30 watts should be chosen since the laser operates more reliability in that range. In addition, at lower power levels the ignition probability is less sensitive to changes in pulse width.
- More uniform targets should be made for testing.
- A probit analysis (pulse width vs. probability of ignition) should be made for each new batch of material so that it can be compared with other batches. If the material is changed, then a more thorough analysis at several power levels, similar to those of this study, should be made.
- Acceptance tests should be designed so that the probability of ignition will be in the 50-95 percent range, i.e., a few failures should occur. Acceptance should then be based on an acceptable pulse width for 50 percent ignition probability. This procedure will also give better statistics on the material for comparing one batch to another.

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Introduction

As a standard production sampling test, diallyl phthalate pyrotechnic material[a] (DAPP) was tested by irradiating it with a focussed CO_2 laser beam. The laser was operated in the pulsed mode at a nominal power level of 30 watts and a pulse width of 110-115 ms[1]. Under these test conditions, the DAPP sample should always ignite. However, ignition did not occur every time, and it was not clear whether this was due to a change in the laser output or a change in the material.

At Sandia National Laboratories, diagnostics were installed on an identical laser to characterize the laser's behavior[2] when operated in the pulsed mode. It was found that the laser output energy varied by as much as 30% while operating in the pulse mode. This result suggested that the laser should be operated in the cw mode and the beam mechanically chopped, since the power level and the time duration of the pulse could be more accurately controlled.

Subsequent to the installation of the initial diagnostics, a number of DAPP targets were subjected to radiation pulses at constant power levels but of varying pulse length, and it was noted whether ignition did or did not occur. As a consequence of these preliminary studies, it was found that the focussed laser beam could penetrate the target without ignition. The important parameter for explaining the penetration was the energy per unit area at the center of the focussed beam. If the energy density exceeded 26 ±4 J/mm^2 in the pulsed mode, the beam could penetrate a 2.54 mm thick DAPP target without igniting it. The pulse durations in this case were all less than 140 ms.

(a) The composition of DAPP is given in Appendix A.

It was also found that if the laser were operated at nominal power levels greater than 30 watts, the beam would penetrate a 2.54 mm-thick target in a time shorter than that necessary for threshold ignition (50% ignitions). During all of these tests, a 127 mm-focal-length lens was used to focus the beam onto the target. Further investigations showed that if the target were placed off focus, the threshold ignition pulse width, although greater than for a focussed beam, could be shorter than the pulse width necessary for penetration.

These preliminary results led to the present study with the following goals:

- Measure the amount of radiation specularly reflected off the target.
- Install a mechanical shutter so that the laser could be operated in the cw mode, thus allowing a more accurate determination of the incident energy.
- Make new measurements to determine the energy per unit area required to penetrate the sample, using both a 127 and a 254 mm-focal-length lens to focus the beam.
- Make measurements to determine the pulse widths necessary for threshold ignition at various power levels for both the 127 and 254 mm-focal-length lenses.
- Make recommendations for improving the present production test procedures.

Instrumentation

Figure 1 shows the optical layout of the experimental apparatus used in the previous study.[1] The CO_2 laser beam first passes through an iris and is then incident upon a ZnSe beam splitter, which reflects about 1-2% of the beam's energy onto a monitoring detector; it then passes through another iris which, together with the first iris, defines the beam axis. After passing through the second iris, the beam is incident upon a 127 mm-(5 inch)-focal-length ZnSe lens and then passes through a window mounted to a wall of the cover assembly. This inexpensive KBr (or KCℓ) window isolates the optical apparatus and laser from the target debris; it is easily removed for cleaning or replacement. The target is placed at the focal point of the lens and any reflected light from the target will be recollimated by the lens (if it falls within the collecting cone of the lens) and partially reflected by the beam splitter onto a reflected-light detector (a model P-300 Moletron pyroelectric detector).

Mirrors attached to kinematic mounts were placed in the positions indicated by dotted lines. One mirror can be positioned so that the HeNe laser beam used for alignment can be inserted along the same axis as the CO_2 laser axis. Others can be inserted so that the CO_2 laser beam can be diverted to a power meter or an energy measuring ballistic thermopile which are used for the calibration of the continuously monitoring detector. The two irises mentioned above are used to insure that the HeNe and CO_2 laser beams are colinear.

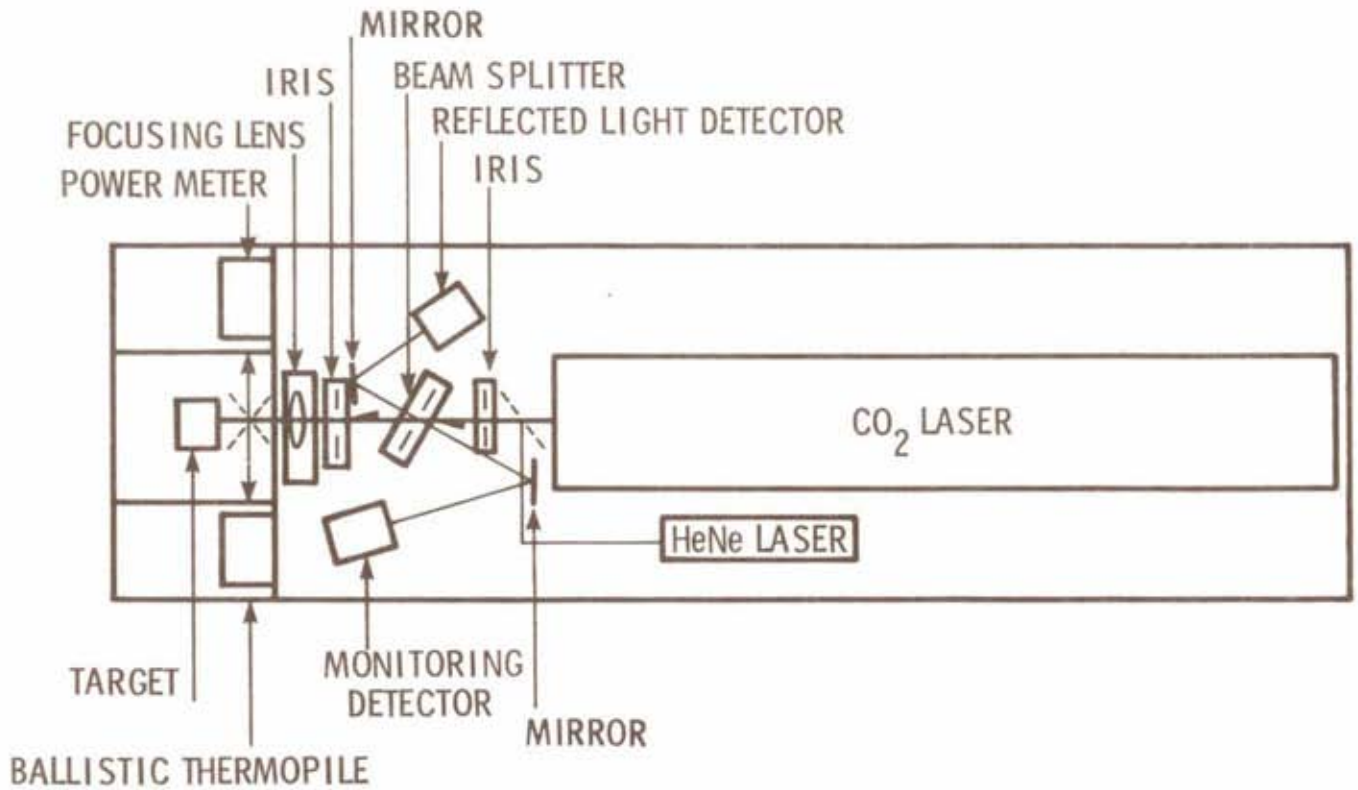


FIGURE 1 OPTICAL LAYOUT OF EXPERIMENT APPARATUS

Figure 2 is a drawing of the mechanical shutter which was placed between the beam splitter and the iris nearest the CO_2 laser. In this configuration, the laser could be operated in the cw mode and beam pulsed by the mechanical shutter. The shutter consisted of a rotary solenoid, a 32 mm-diameter x 6 mm-thick copper mirror, a custom post mount as is shown in Figure 2. The mirror was tapped on the back side so that it would be attached to the post mount with screws.

The mirror of the shutter was placed at 45 degrees to the axis of the laser beam so that when the solenoid was energized the mirror would rotate out of the beam. A programmable timer and a 30 Vdc power supply were used to drive the solenoid. The timer[(a)] consisted of a clock and the associated circuitry to open and close relays at preset times. Two relays (one normally open and one normally closed) were connected in series with the 30 Vdc power supply and the solenoid. The pulse width was then determined by opening the normally closed relay a preset time interval after the normally open relay was closed. This time could be varied in steps of 1 ms.

Experimental Methods and Results

In this section, we discuss the reflected light measurements, the reproducibility and shape of the optical pulse passed by the solenoid shutter, the threshold ignition pulse widths for both the 254 and 127 mm-focal-length lenses, and the values of energy per unit area necessary for penetration of the sample.

(a) Sandia Dwg. No. P96812. A commercial version believed to be equivalent is the Artisan Model EPC-11587A timer.

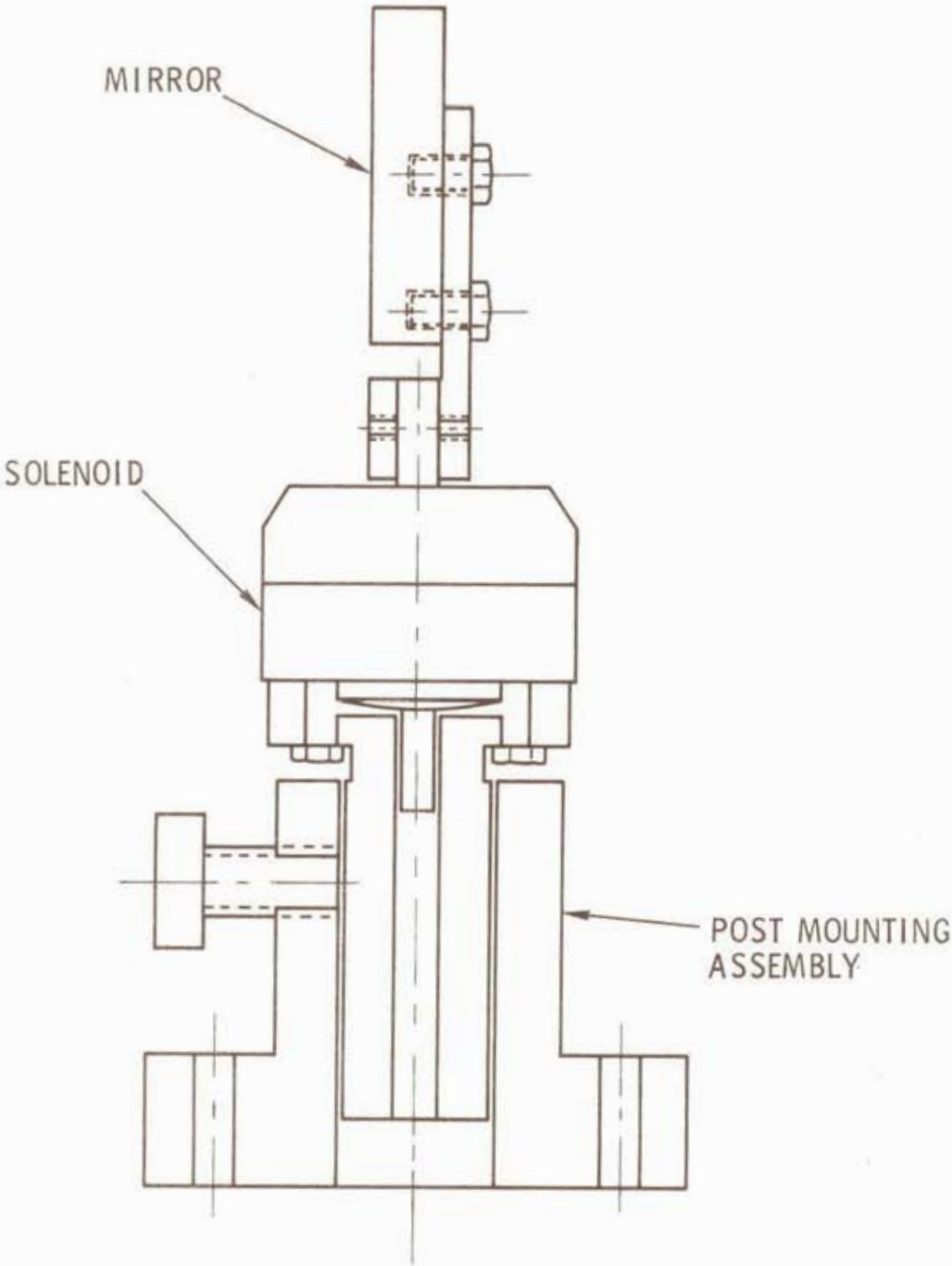


FIGURE 2. SOLENOID SHUTTER

Reflected Light Measurements

The reflected light measurements were all made prior to this study while the laser was still being used in the pulse mode. They are included in this report to illustrate that the reflected light is not a significant correction in determining the absorption and transmission of energy on the target.

In order to calibrate the reflected light detector, a KCℓ reflector was made from a standard KCℓ window. The back side of the window was wedged with respect to the front surface so that any reflected light from the back surface would not fall on the reflected light detector. Because the monitoring light detector shown in Figure 1 was not sensitive enough for the low level of power used in the reflected light measurements, a thermopile was placed immediately behind the KCℓ target so that the transmitted energy of the pulse could be recorded. When the opaque DAPP target was placed in position, the transmitted energy could not be recorded so the incident energy was assumed to be the same as the preceding KCℓ measurement.

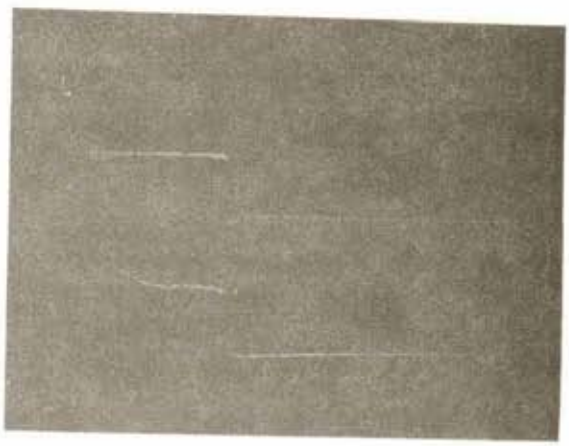
The reflected light detector was positioned by inserting the HeNe alignment laser and observing the reflected beam on the detector. The KCℓ target and the DAPP target both reflected the light specularly. A spike filter was used to block any extraneous radiation other than a wavelength of 10.6 micrometers.

The lower scope picture of Figure 3 illustrates the reflected optical signals from a KCℓ target when 73 mJ of energy were focussed upon the target by the 127 mm-focal-length lens. The electrical pulse shown in the figures is the pulse applied to the laser. The

ELECTRICAL PULSE

OPTICAL PULSE

2ms / DIV, 2mv / DIV
DAPP TARGET



ELECTRICAL PULSE

OPTICAL PULSE

2ms / DIV , 2mv / DIV
KCℓ TARGET

FIGURE 3 REFLECTED LIGHT MEASUREMENTS FOR 73 mJ INCIDENT LIGHT ENERGY

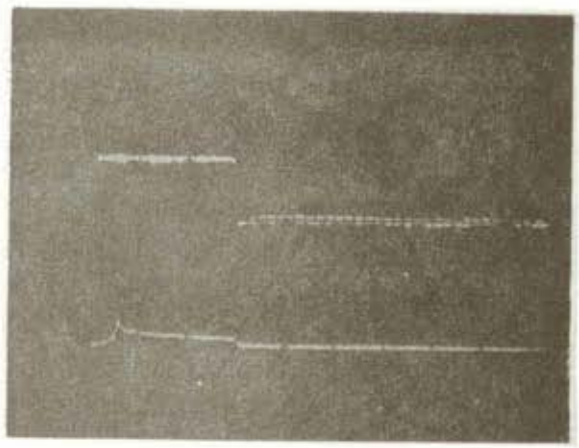
corresponding optical signal from a DAPP target is shown in the upper scope picture of Figure 3. It is noted the DAPP reflected signal deteriorates early in the pulse to a point where it is barely visible. The reason for this is that the surface is damaged by the radiation early; and for the remainder of the pulse, the light is scattered so as to reduce the signal to the reflected light detector. Evidence supporting this explanation is shown in Figure 4. In this case, the beam was apertured down so that only about 15% of the radiation was incident upon the KCℓ and DAPP targets. The reflected signals from the two different targets are about the same magnitude.

The reflected signal from the KCℓ target can be calculated from the reflectance which is given by the general formula.[3]

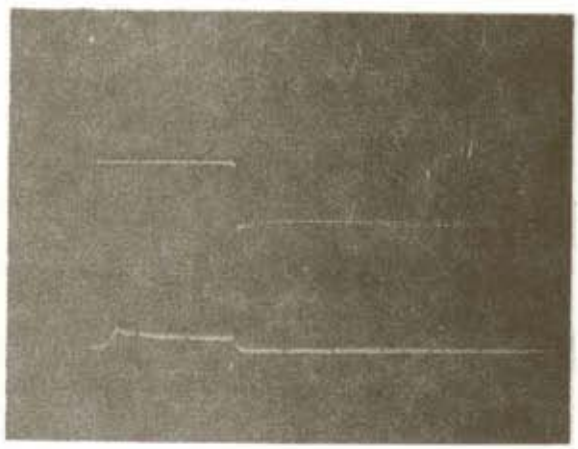
$$R = \left(\frac{n - 1}{n + 1}\right)^2$$

where n is the index of refraction. The index of refraction for KCℓ at 10.6 micrometers is 1.45 which gives a reflectance of 3.4%. Figure 4 shows the reflected light from a DAPP target to be slightly less than that of KCℓ target so that the DAPP reflectance is in the range of 3.0 to 3.4%.

A measurement of the scattered light from the DAPP target is more difficult to accomplish. It would require detectors set at various angles off the optical axis to define the scattering cone. This is not possible with the present experimental apparatus because of limited space. However, assuming the scattering is isotropic, the very small signal noted in Figure 3 for the DAPP target indicates the scattered light signal can be completely neglected.



2ms / DIV , 2mv / DIV
DAPP TARGET



2ms / DIV , 2mv / DIV
KCℓ TARGET

FIGURE 4 REFLECTED LIGHT MEASUREMENTS FOR 10.9 mJ INCIDENT LIGHT ENERGY

Because the error introduced by neglecting the specularly reflected energy is a factor of three less than that due to the other energy measurements and because the scattered energy is judged to be negligible, no corrections for these effects are made in the other experiments reported here. For these same reasons, these corrections are not deemed necessary for production testing.

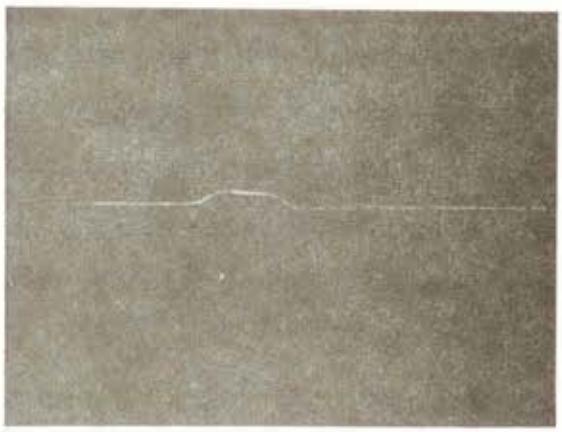
Optical Pulse Characteristics

The shape and reproducibility of the optical pulse passed by the solenoid shutter is illustrated in Figure 5. The upper and lower traces in Figure 5 were taken on a Tektronix 912 storage oscilloscope, which allows three consecutive traces to be superimposed. As can be seen in Figure 5, there is no detectable difference between a single trace and three superimposed traces.

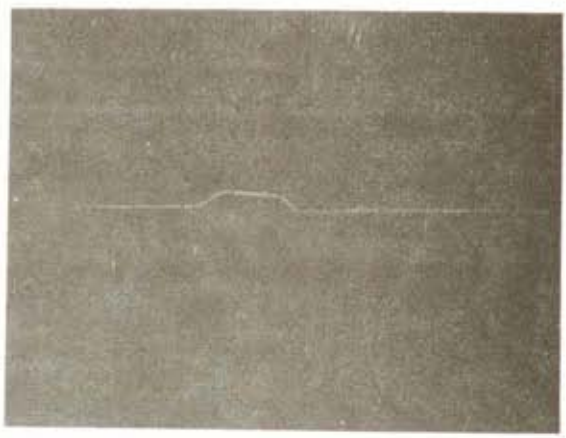
The droop in the flat portion of the trace and the slight undershoot after the radiation has been turned off is due to the overheating of the pyroelectric detector. This effect was reported previously.[1]

The pulse can be approximated by a symmetric trapezoid as shown in Figure 6 where the rise and fall times of the slanted sides are about 5 ms. The time duration of the base of the trapezoid is the dial setting of the programmable timer. The equivalent square pulse duration is obtained by subtracting 5 ms from the dial setting.

Figure 7 is a plot of the measured energy versus the equivalent square pulse width for pulses ranging from 40 to 300 ms at a constant CW power level of 30 W. The maximum deviation from a straight line



THREE TRACES
10 ms / cm



SINGLE TRACE
10 ms / cm

FIGURE 5 PULSE SHAPE USING SOLENOID SHUTTER

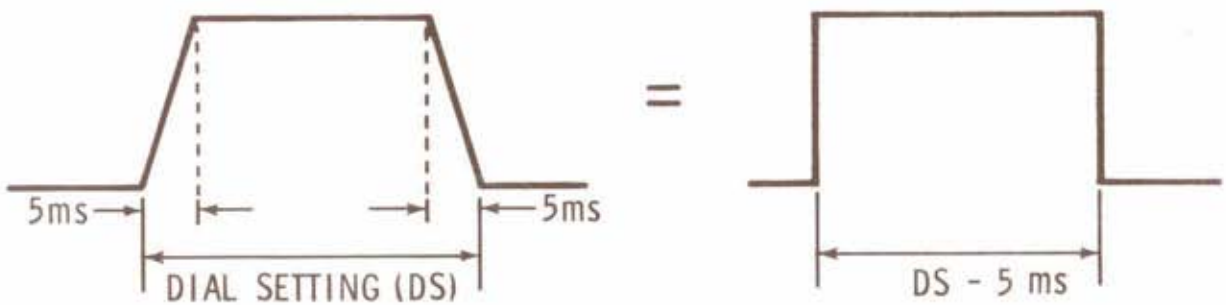


FIGURE 6. APPROXIMATE PULSE SHAPE

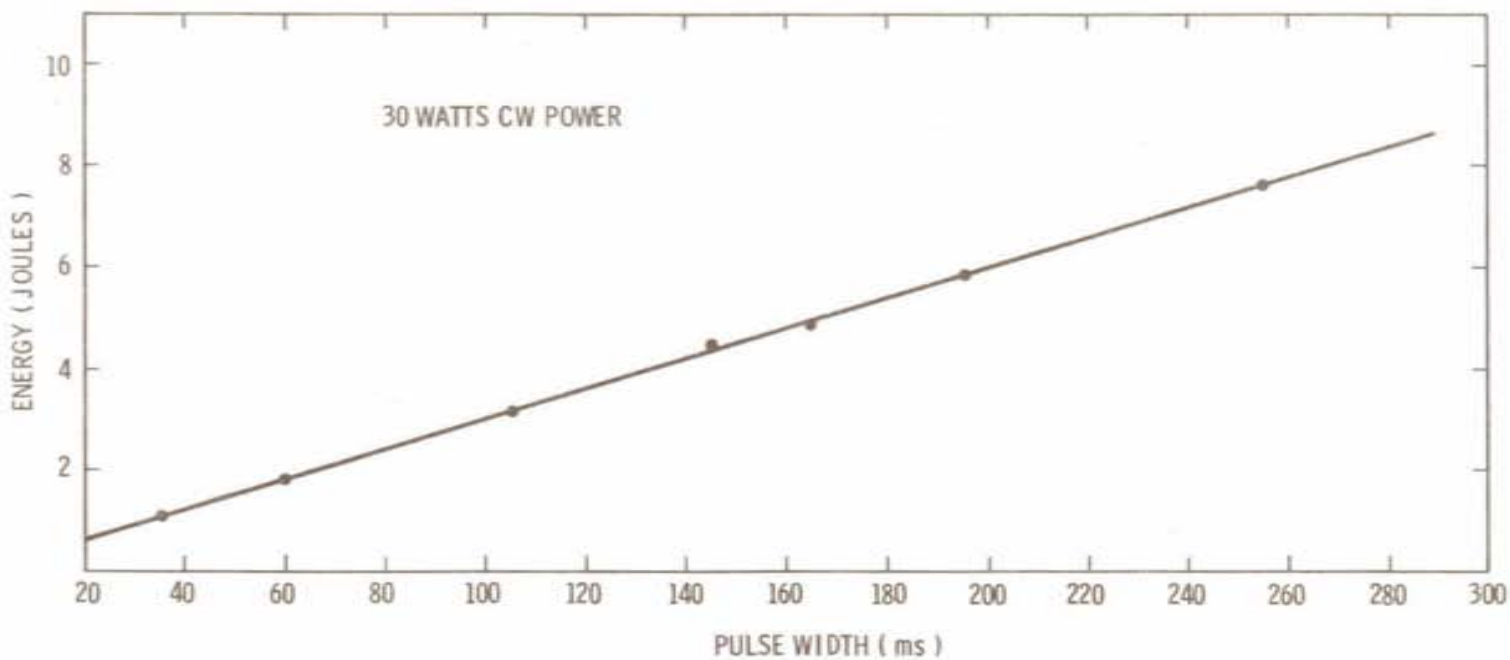


FIGURE 7 MEASURED ENERGY VERSUS PULSE WIDTH FOR CW MODE OPERATION

is about 3% which is well within the reproducibility of the power level setting. The energy measured compared to the energy calculated from the power and pulse width differ by approximately 10%, but this is within the absolute calibration errors of the thermopile and power meters. These meters typically have an absolute accuracy of about 10%.

There are two conclusions that can be drawn from these data. First, the absolute accuracy of the energy passed by the solenoid shutter is about 10%; but the error in the reproducibility of energy in a pulse is less than 3%, which is an order of magnitude improvement over the 10 to 30% variation noted earlier for the pulse mode.[1] Second, the error in the reproducibility of the pulse shape is less than the line width of the scope trace; e.g., for a pulse width of 100 ms or longer, pulse width errors should be not greater than 1 to 2%.

Threshold Ignition Determination

The pulse width corresponding to threshold ignition (50% ignitions) for different power levels was determined by varying the pulse width over a range of values corresponding to a firing probability of 10 to 90%. These data were then plotted on linear and log probability scales as shown in Figures 13 and 14 in Appendix B. R. R. Prairie of Division 1223 did a best fit probit analysis of these data[5] which is illustrated by the solid lines in Figures 13 and 14. (The pulse widths given in Figures 13 through 21 are the timer dial settings; i.e., 5 ms greater than the equivalent square pulse widths.)

The differences between the pulse widths for threshold ignition derived from the linear and log probit analyses differ by much less than the indicated errors for the pulse widths. Since there are no significant differences between these data for the threshold ignition, only the linear values, which are shown in Appendix B, are used for the remainder of this discussion.

A summary of the pulse widths, necessary for threshold ignition, which were derived from the data of Appendix B, is given in Figure 8. All of the data shown in Figure 8 were taken with the laser operating in the cw mode with exception of the two points denoted by the square symbol. These two points were taken previously while operating the laser in the pulse mode. Data are given for both the 127 and 254 mm-focal-length lenses.

These data show that the threshold ignition pulse widths for the 254 mm-focal-length lens are at only slightly higher values than those for the 127 mm-focal-length lens in the power range 10-30 watts. This would not be the case if the ignition threshold was directly dependent upon energy per unit area at the center of the laser spot, or averaged over the spot. The laser focal spot area is four times larger for the 254 mm-focal-length lens than for the 127 mm-focal-length lens.

There is, however, a significant difference in the effects of the two lenses. The change of the probability of firing for a given change in pulse width is greater for the shorter focal length lens; i.e., the threshold sharpens. This greater sensitivity can be observed by comparing the slopes of the probability curves given in Appendix B, namely, Figure pairs 14/19, 15/20, and 16/21.

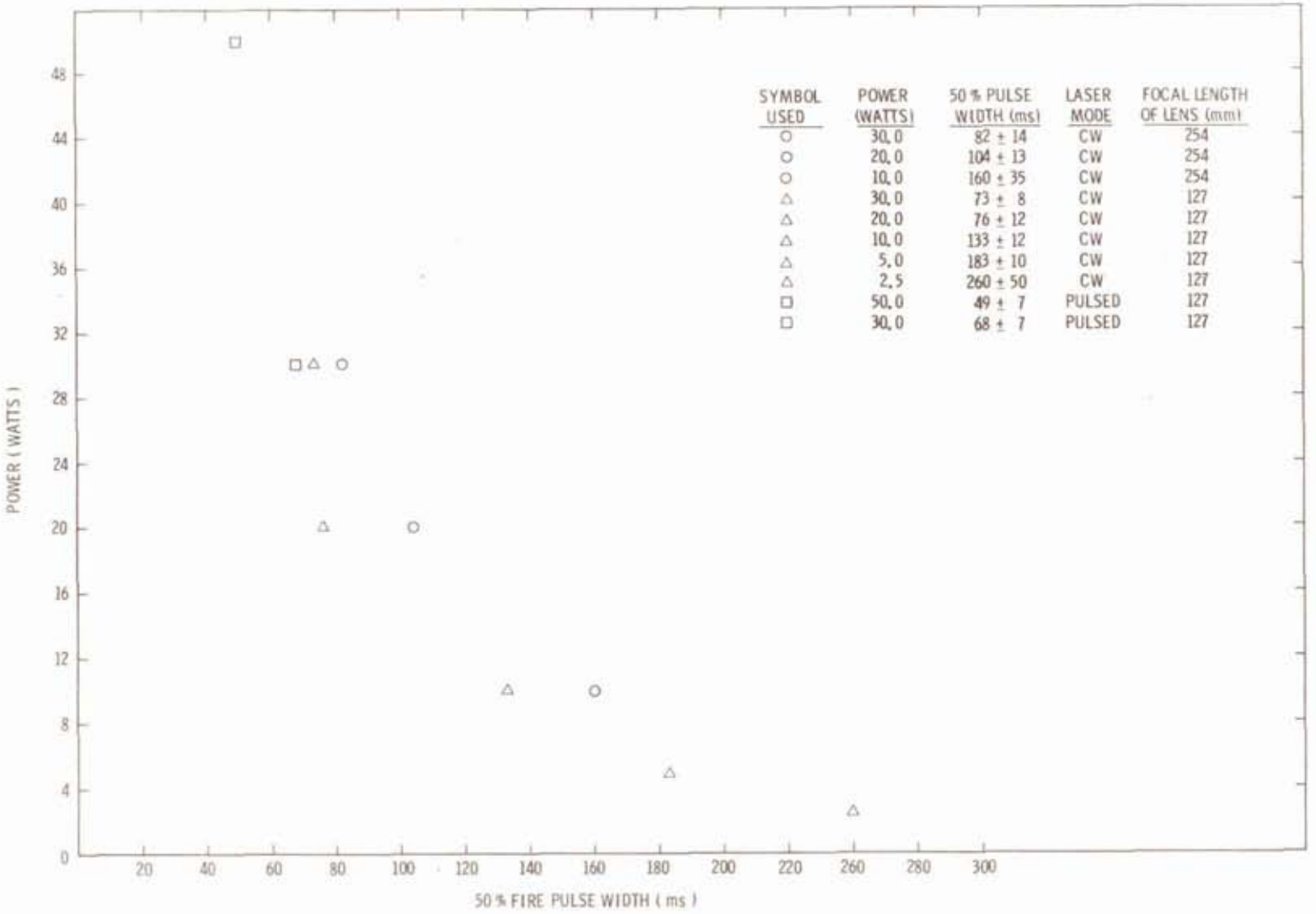


FIGURE 8 THRESHOLD IGNITION PULSE WIDTH VERSUS POWER LEVEL

Figure 9 is another plot summarizing the data of Appendix B, only in this case, power (cw laser power) versus total energy deposited for threshold ignition is plotted. Again the 254 mm-focal-length lens data are shifted from that of the 127 mm-focal-length lens data, but not by a factor of 4 which would be expected if the ignition point were proportional to energy or power per unit area at the center of the spot.

We can conclude from Figures 8 and 9 that: a) the pulse width necessary for threshold ignition decreases with increasing power level, but the relation between power and pulse width is not linear b) the energy required for threshold ignition increases with an increase in total power in the power range 2.5 to 50 watts, and c) the threshold ignition pulse widths are not strong functions of the energy per unit area.

Energy Per Unit Area for Sample Penetration

It was noted early that a DAPP target could be penetrated by the laser beam without igniting it. Figure 10 illustrates this point, by showing the cross section of a hole burned into a DAPP target. The laser was set to operate at 50 W in the cw mode and was then switched to the pulse mode and fired. A pulse width of 22 ms was applied to the target and, as can be seen, the laser beam nearly penetrated the target. The threshold ignition pulse width for this same power level was 49 ms, i.e., the target would usually be penetrated before ignition.

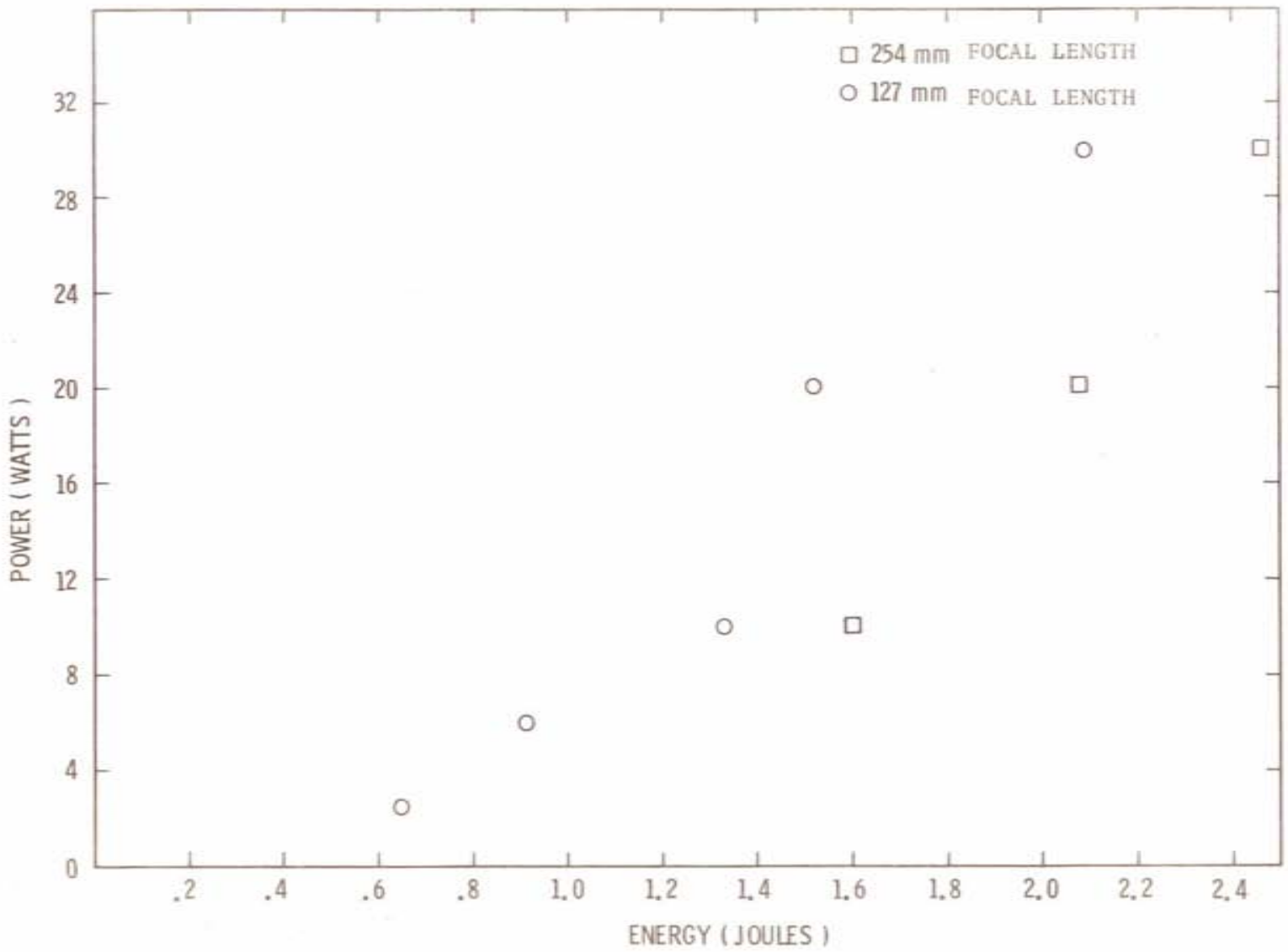


FIGURE 9 POWER REQUIRED VERSUS ENERGY FOR THRESHOLD IGNITION

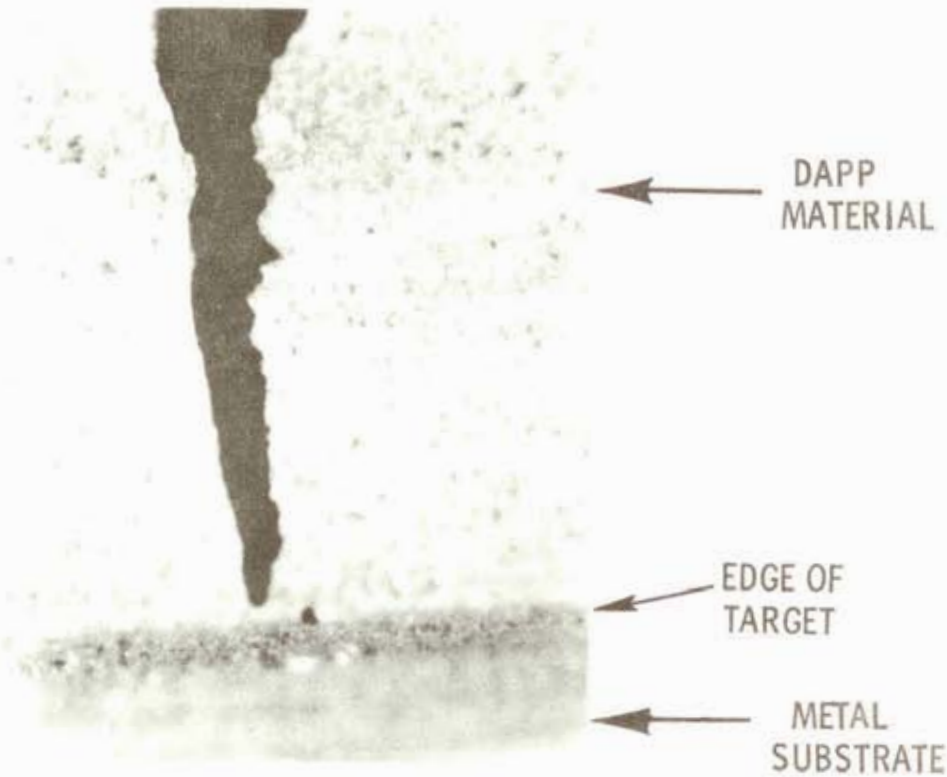


FIGURE 10 CROSS SECTION OF CRATER RESULTING FROM CO_2 LASER INCIDENT ON DAPP TARGET

An examination of the material adjacent to the crater revealed no visible damage which indicated very little heat was transferred to this material. Attempts were made to perform an electron beam microprobe x-ray analysis on $KC\ell O_4$ crystals adjacent to the crater. The crystals were observed to decompose when irradiated by the electron beam. The decomposition could be observed visually by noting the shrinking and cracking of the crystals. Analysis of other $KC\ell O_4$ crystals located a large distance from the rim of the crater showed that these appeared to shrink and crack in the same manner as those located adjacent to the crater. Although the visual and electron beam data are not definitive, they are strong evidence that very little laser energy is transferred to the material adjacent to the crater. It appears from these data that most of the laser energy goes into vaporizing the material of the crater.

The capability of the laser to penetrate the sample prompted a search for a parameter which would predict complete penetration of the target by the laser beam.

The intensity of a gaussian laser beam is given by

$$I = \frac{2}{\pi}\left(\frac{P}{W^2}\right)e^{-\left(\frac{2r^2}{W^2}\right)} \text{ watts/mm}^2$$

where P is the power level set for a square pulse, W is the spot radius, and r is the radial distance from the axis. The integral of I over the total area of the beam is just P, the power of the total beam. The energy per unit area (ε) at a radial distance r for a square pulse of length T is given by

$$\varepsilon(r) = \int_0^T I \, dt$$

$$= \frac{2}{\pi} \frac{PT}{W^2} e^{-\frac{2r^2}{W^2}} \quad J/mm^2$$

$$= \frac{2}{\pi} \frac{E}{W^2} e^{-\frac{2r^2}{W^2}} \quad J/mm^2$$

so that at the center of the beam

$$\varepsilon = \varepsilon(o) = \frac{2}{\pi} \frac{E}{W^2}$$

where E is the total energy in the beam incident upon the target.

It is this parameter ε which was found to be important in predicting the laser beam's penetration of a given thickness of target. For targets of different thicknesses (d), the ratio ε/d is the important parameter for predicting penetration.

Figure 11 displays the pulsed mode laser data reported initially. These data were taken with the 127 mm-focal-length lens for the target on focus and 9.53 and 15.24 mm off focus. The first three series of data starting from the left hand side of the graph were all taken with a 2.54 mm-thick target sample whereas the last set of data on the right had target thicknesses of 0.864 mm. The energy per unit area at the center of the beam for the last set of data were multiplied by 2.94, the ratio of the two thicknesses, in order to normalize that set of data to that of the 2.54 mm-thick targets. A statistical analysis of the data for 9.53 mm off focus gave a value of 26 ±4 J/mm^2 for 50% penetration.

Similar data was taken with the laser operating in the cw mode and using both 127 and 254 mm-focal-length lenses. Those data are

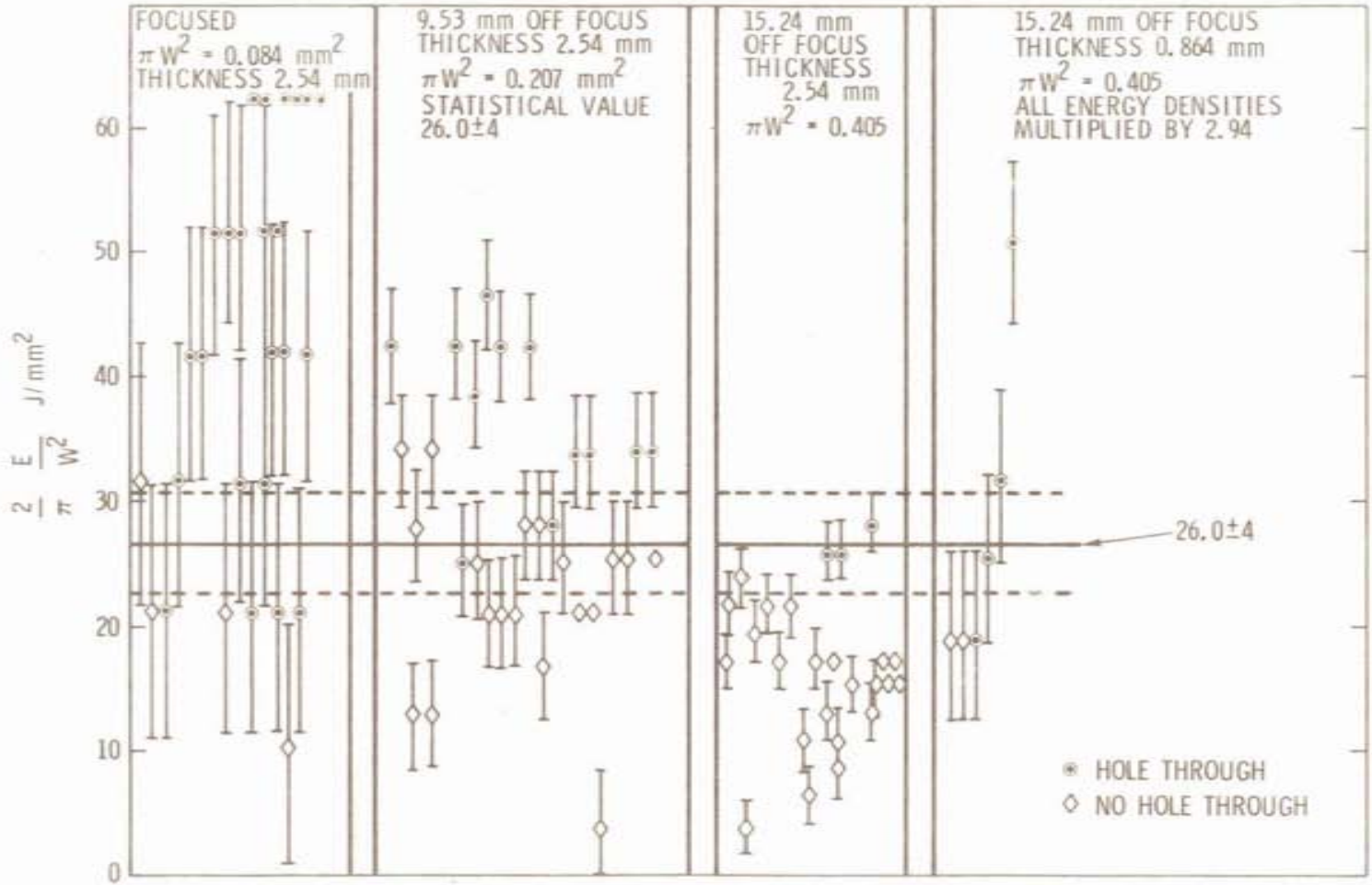


FIGURE 11. PULSE MODE DATA FOR PENETRATION OF DAPP TARGETS

displayed in Figure 12. The numbers beneath each data point are the number of events observed at that energy density. Note in this case, because of the higher accuracy with the cw mode, the penetrating point is defined more sharply. The value found here is 29 ±1 J/mm^2, which is in agreement with previous value found while operating the laser in the pulse mode.

Table I summarizes the experimental data for threshold ignition, the columns of data from left to right are 1) the power level used, 2) the time width of the laser pulse necessary for threshold ignition, 3) the spot area of the lens used, 4) the total energy incident upon the target (power x pulse width), 5) the value of ε which is the total energy per unit area incident upon the target at the center of the laser beam (2 x energy/spot area), and 6) a prediction of whether the value of ε is great enough to cause target penetration (based on the criterion of 29 J/mm^2 for threshold penetration).

To simplify discussion of these data, we shall treat the threshold ignition pulse width value and the value of 29 J/mm^2 for ε as those values for which ignition and penetration will occur, even though rigorously these are the values for which ignition and penetration occur with a probability of 50%.

One conclusion drawn from Table I is that with the 254 mm-focal-length lens the target can be ignited without penetrating it for power levels of 10 to 30 W. This can be done because the pulse widths necessary for ignition give values of ε less than the 29 J/mm^2 required for penetration.

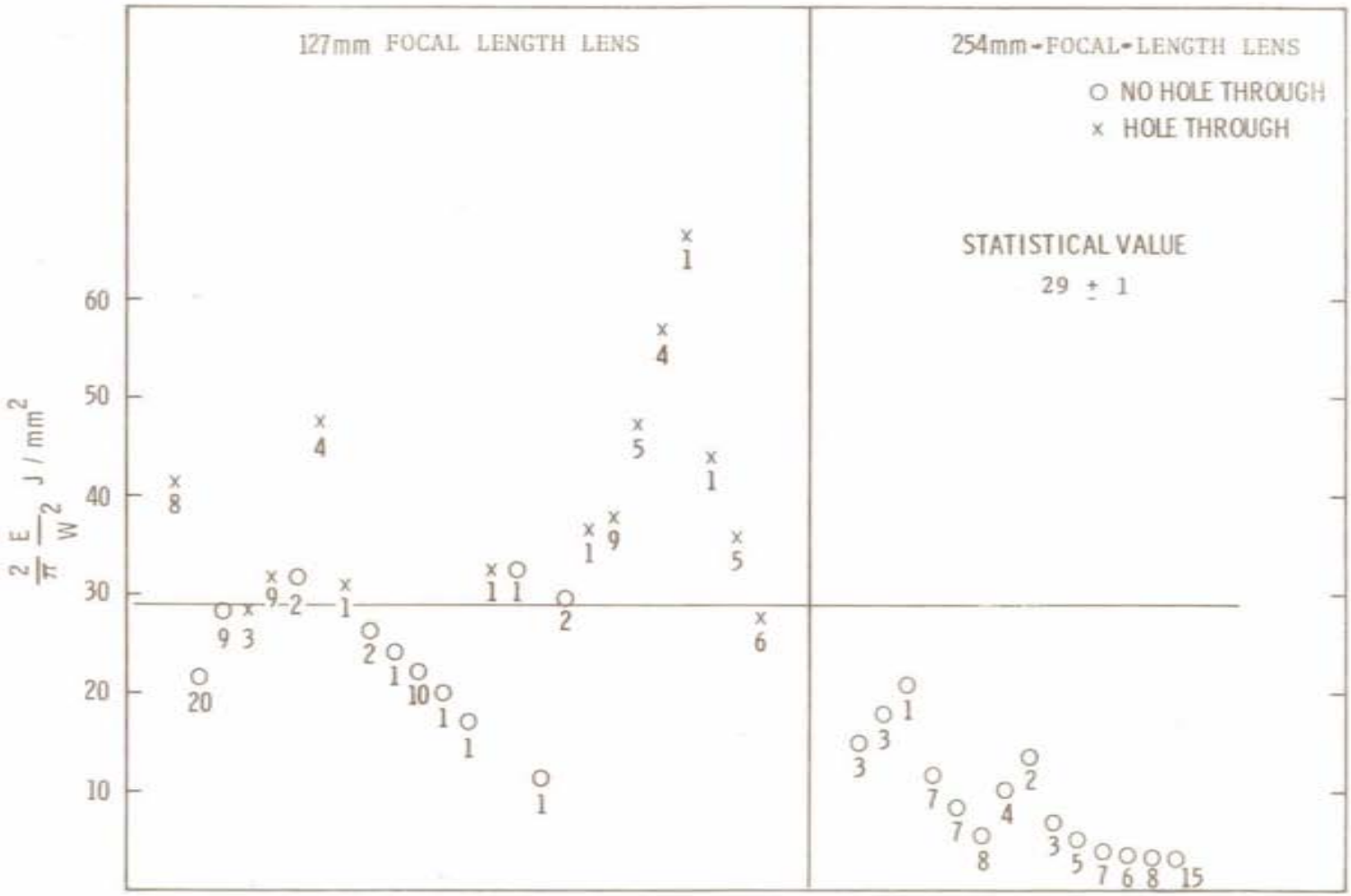


FIGURE 12 CW MODE DATA FOR PENETRATION OF DAPP TARGETS

TABLE I

POWER	THRESHOLD PULSE WIDTH (ms)	SPOT AREA* (mm^2)	ENERGY (J)	$\frac{2E}{\pi\omega^2}$ (J/mm^2)	Pene-tration
30.0	82 ±14	0.336	2.46	14.6	No
20.0	104 ±13	0.336	2.08	12.4	No
10.0	160 ±35	0.336	1.60	9.5	No
30.0	73 ±8	0.084	2.19	52.1	Yes
20.0	76 ±12	0.084	1.52	36.2	Yes
10.0	133 ±12	0.084	1.33	31.7	Yes
5.0	183 ±10	0.084	0.91	21.8	No
2.5	260 ±50	0.084	0.65	15.5	No

*The 254 mm-focal-length lens has a spot area of 0.336 mm^2, and the 127 mm-focal-length lens has a spot area of 0.084 mm^2.

Another conclusion from Table I is that with the 127 mm lens, power levels of less than 10 W must be used to avoid penetrating the target before it ignites. This is because at power levels greater than 10 W, the pulse widths necessary for ignitions give values of ε greater than 31.7 J/mm^2 which exceeds the 29 J/mm^2 necessary for penetration. Also note that in production testing a 127 mm-focal-length lens was used with a power level of 30 W for 110 ms; this corresponds to ε = 79 J/mm^2 and nearly all targets would have been penetrated before ignition.

The last conclusion from Table I and the figures in the appendix is that whenever a pulse width greater than threshold is used to obtain an ignition probability greater than 50%, the power level may have to be lowered to avoid penetrating the target. This is because the threshold pulse width is only weakly dependent upon the power level, but ε is directly proportional to the power level and pulse width.

Conclusions

- The specularly reflected light from a DAPP target is approximately 3 to 3.4% of the incident radiation. The diffusely scattered light appears to be negligible.
- Mechanical shuttering of the laser beam while operating in the cw mode is superior to pulse mode operation with respect to pulse reproducibility and the control of the incident energy.
- The energy per unit area at the center of the laser beam is the determining factor for predicting the penetration of a DAPP target. A value of 29 ±1 J/mm^2 is required for complete penetration of a 2.54 mm-thick sample (50% penetration probability).
- The 254 mm-focal-length lens allows the pulse width necessary for for threshold ignition without the energy per unit area at the center of the beam exceeding 29 J/mm^2 for powers ranging from 10-30 watts. The 127 mm-focal-length requires a power level of less than 10 watts in order to avoid penetration.
- The energy necessary for threshold ignition is not constant; it increases with the power level over the range of 2.5 to 50 watts. It is expected, however, that at very low power levels, the reverse will be true. This would occur when conduction losses become significant.
- The threshold ignition pulse widths are only weakly dependent upon the power or energy per area for the power range of 10-30 watts. This was demonstrated by using two different focal length lenses for which the area of the spot differed by a factor of 4 but the threshold ignition pulse width changed by only 30-40%.

Recommendations for Improving Present Test Procedures

- The laser should be operated in the cw mode and mechanically shuttered instead of using the pulse mode because the reproducibility of the pulse and the accuracy of the incident energy measurement are significantly improved.
- A 254 mm-focal-length lens should be used to focus the beam onto the target. This not only reduces the possibility of penetrating of the target, but requires less frequent changes of the KBr window separating the target chamber from the other optics.
- A power level between 10 and 30 watts should be chosen since the laser operates more reliability in that range. In addition, at lower power levels the ignition probability is less sensitive to changes in pulse width as can be seen from the probit analyses in Appendix B.
- More uniform targets should be made for testing. The targets used here were broken from a manufactured part and consequently may not be exactly the same. A description of target preparation is given in Appendix C.
- A probit analysis (pulse width vs. probability of ignition) should be made for each new batch of material. This allows one to compare batches. If the material is changed, then a more thorough analysis at several power levels, similar to those of this study, should be made.
- Acceptance tests should be designed so that the probability of ignition will be in the range 50-95%, i.e., a few failures should occur. The acceptance should then be based on an acceptable pulse

width for 50% ignition probability. This procedure will also give better statistics on the material for comparing one batch to another.

Appendix A

Composition of DAPP Material[a]

Material	Weight %
potassium perchlorate ($KC\ell O_4$)	44.7
red lead oxide (Pb_3O_4	11.1
calcium silicide ($CaSi_2$)	7.1
boron powder	7.1
diallyl phthalate powder	30.0

(a) Spacer - P/N 302486-01

Appendix B

Probit Analysis of the Ignition Data

The data plotted on the linear and logarithmic probability paper shown below represents at least 10 experiments per point. In a few cases the point represents 20 experiments. The solid line drawn is best fit to the data using a computer program. R. R. Prairie of Division 1223 did the best fit analysis. The data points plotted at the extremes of the linear probability graphs really correspond to zero or 100% successes for the sample size taken.

It is difficult from the data shown to ascertain whether the linear or logarithmic analysis best fits the data. The threshold ignition points, however, are insensitive to the two different analyses, so that either analysis could be used to determine it. Important differences in the two analyses can arise in the probability range 90-100% successes. To determine whether the linear or logarithmic analysis is more correct would require hundreds of experiments in the range 90-100% successes.

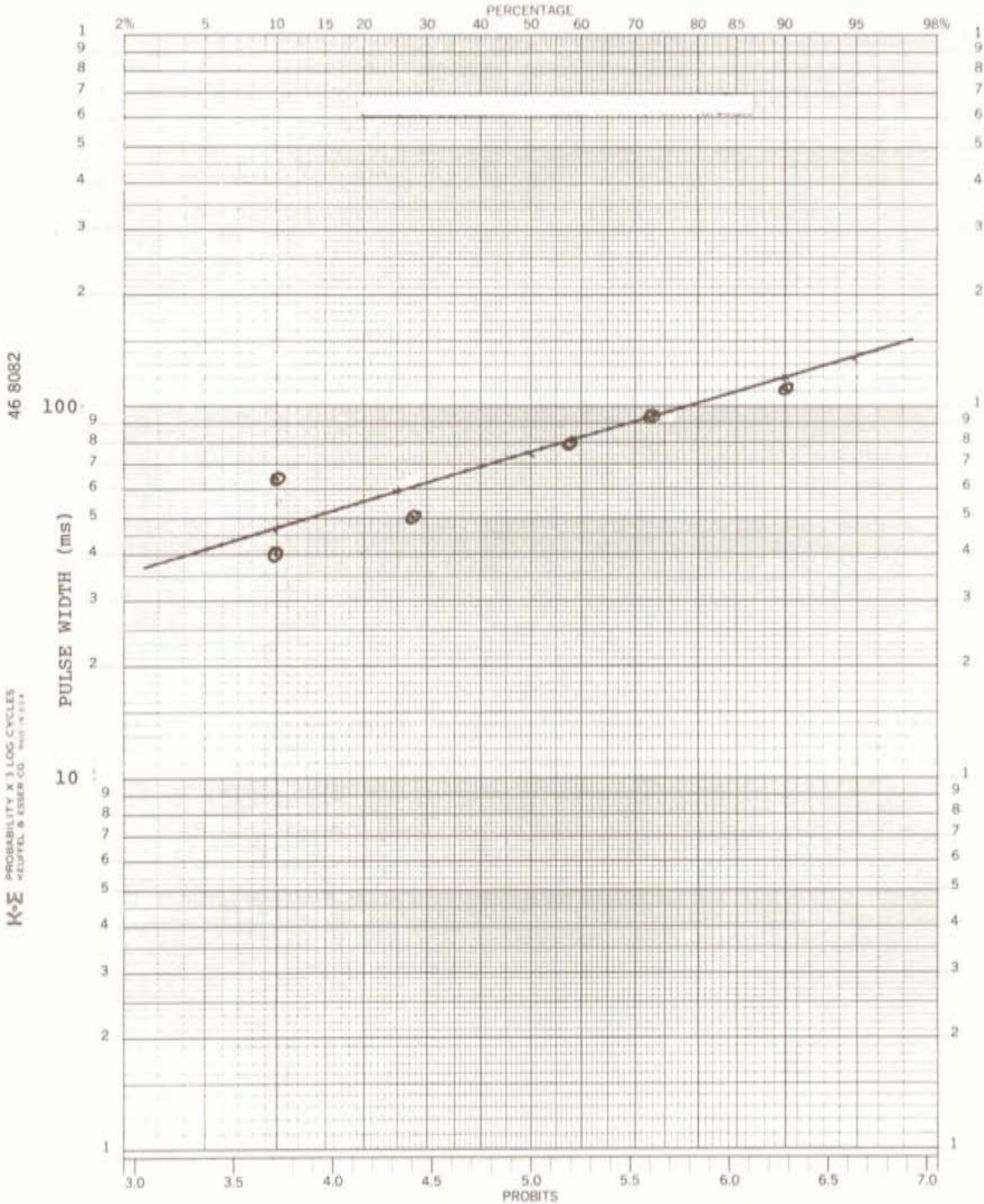


FIGURE 13 LOG PROBIT ANALYSIS - 30 W, 127 mm-FOCAL-LENGTH LENS

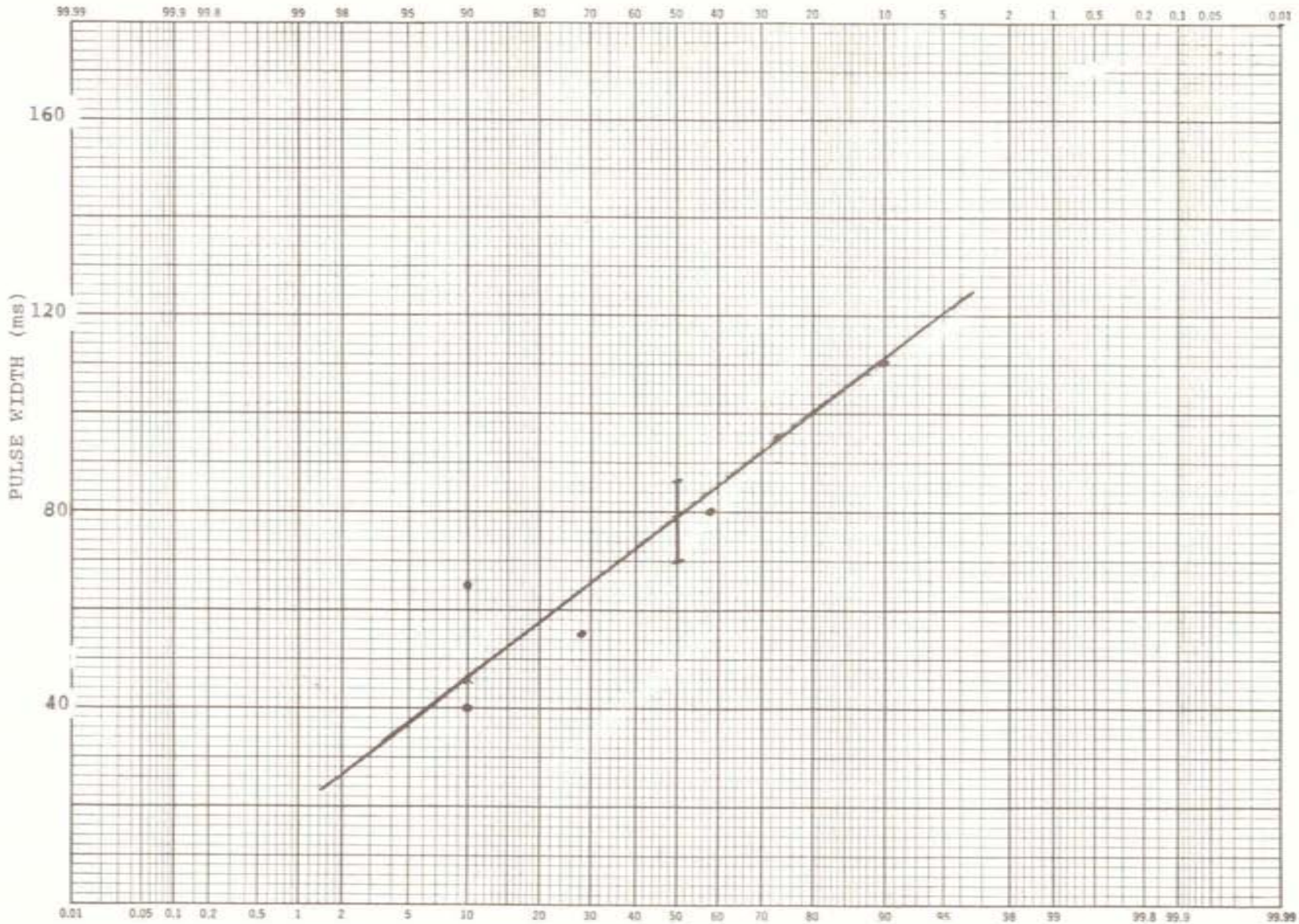


FIGURE 14 LINEAR PROBIT ANALYSIS - 30 W, 127 mm-FOCAL-LENGTH LENS

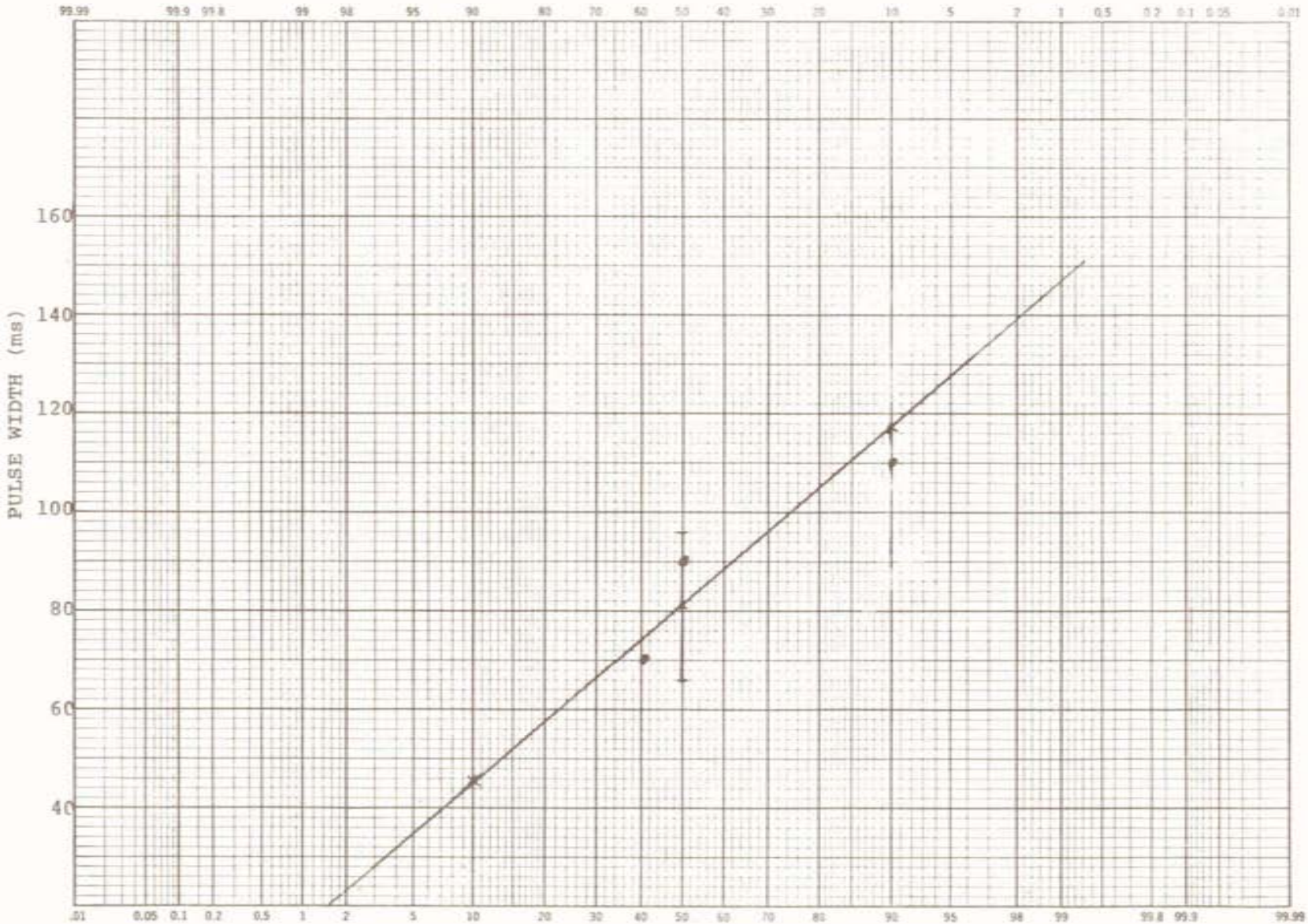


FIGURE 15 LINEAR PROBIT ANALYSIS - 20 W, 127 mm-FOCAL-LENGTH LENS

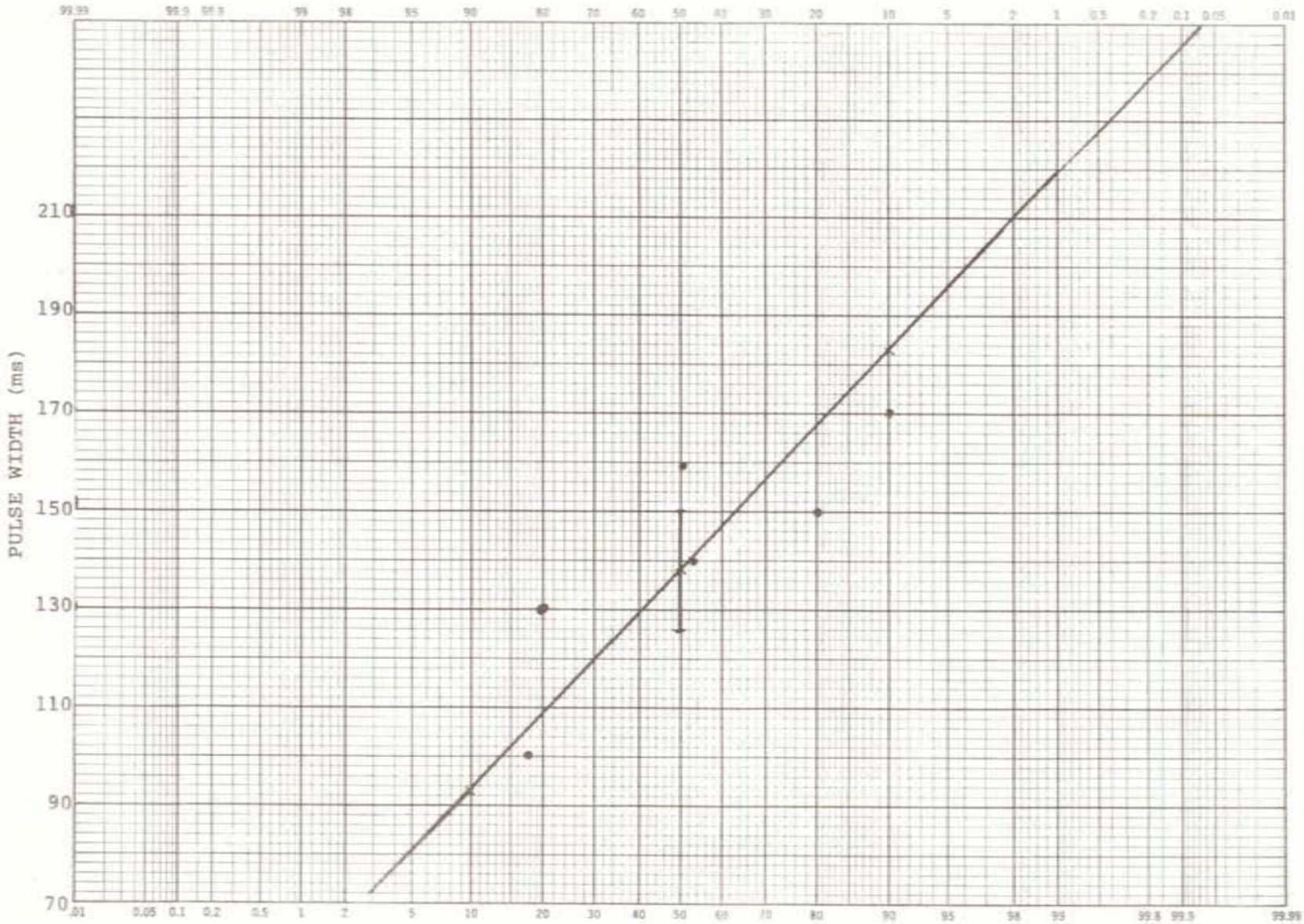


FIGURE 16 LINEAR PROBIT ANALYSIS - 10 W, 127 mm-FOCAL-LENGTH LENS

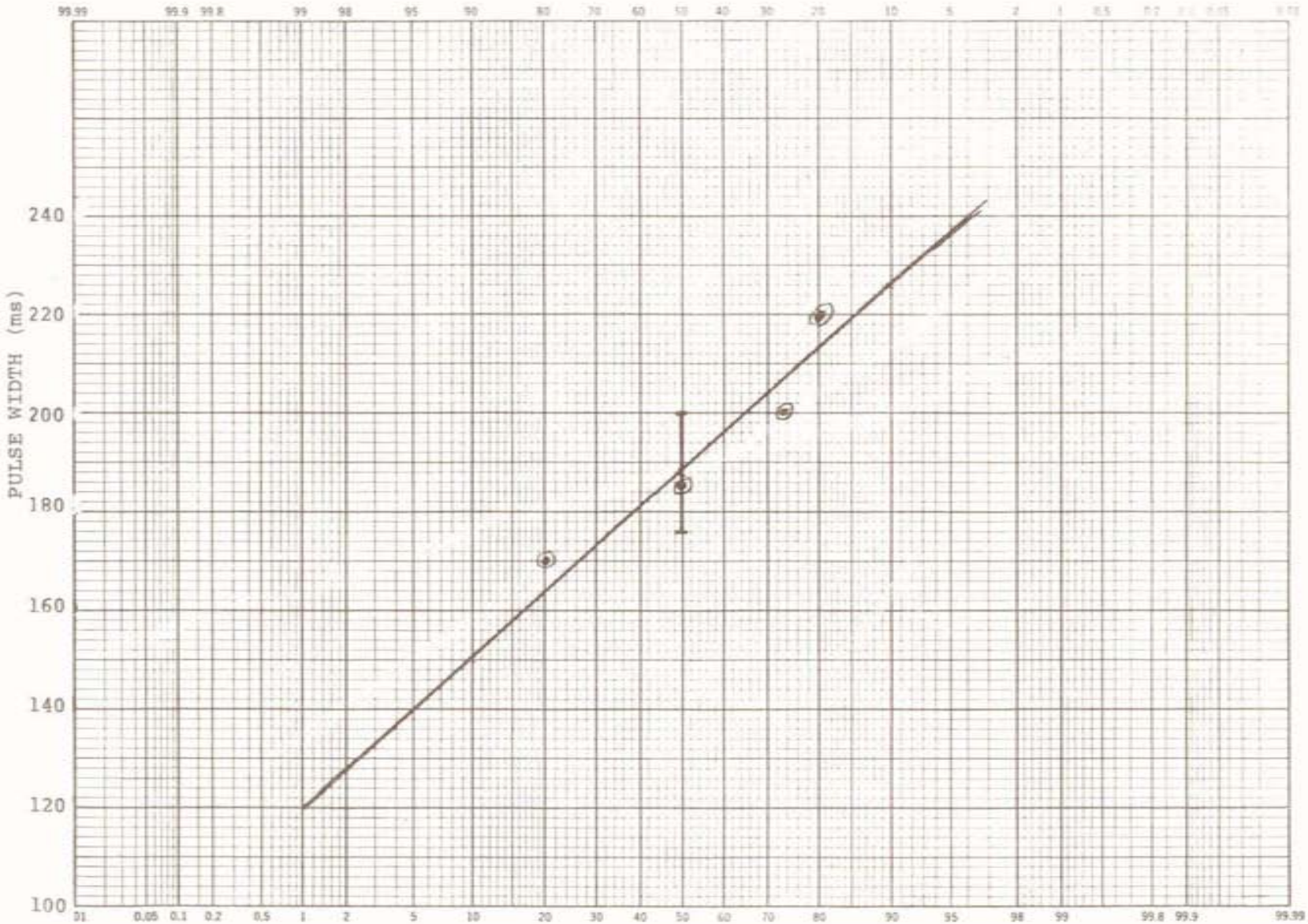


FIGURE 17 LINEAR PROBIT ANALYSIS - 5 W, 127 mm-FOCAL-LENGTH LENS

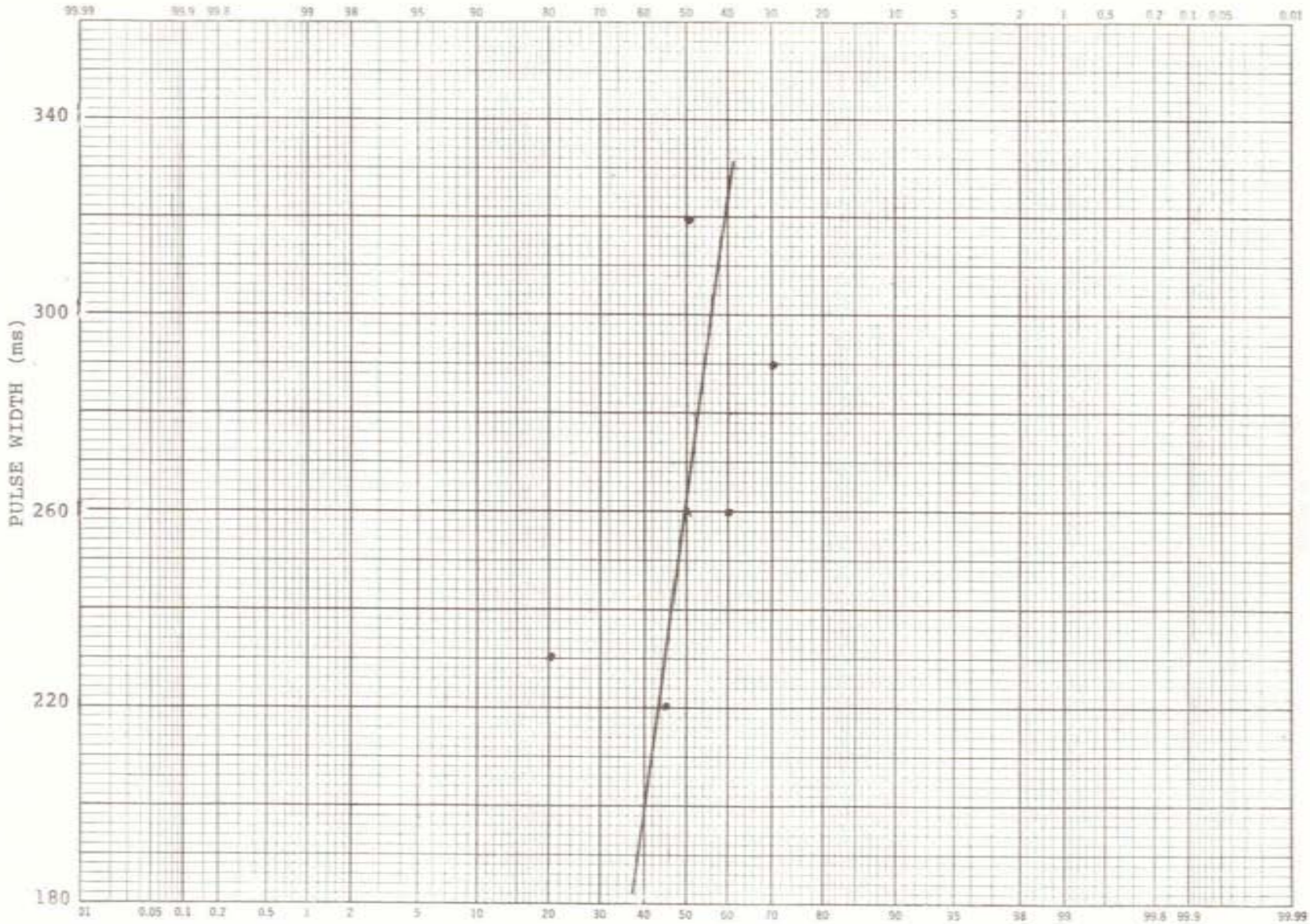


FIGURE 18 LINEAR PROBIT ANALYSIS - 2.5 W, 127 mm-FOCAL-LENGTH LENS

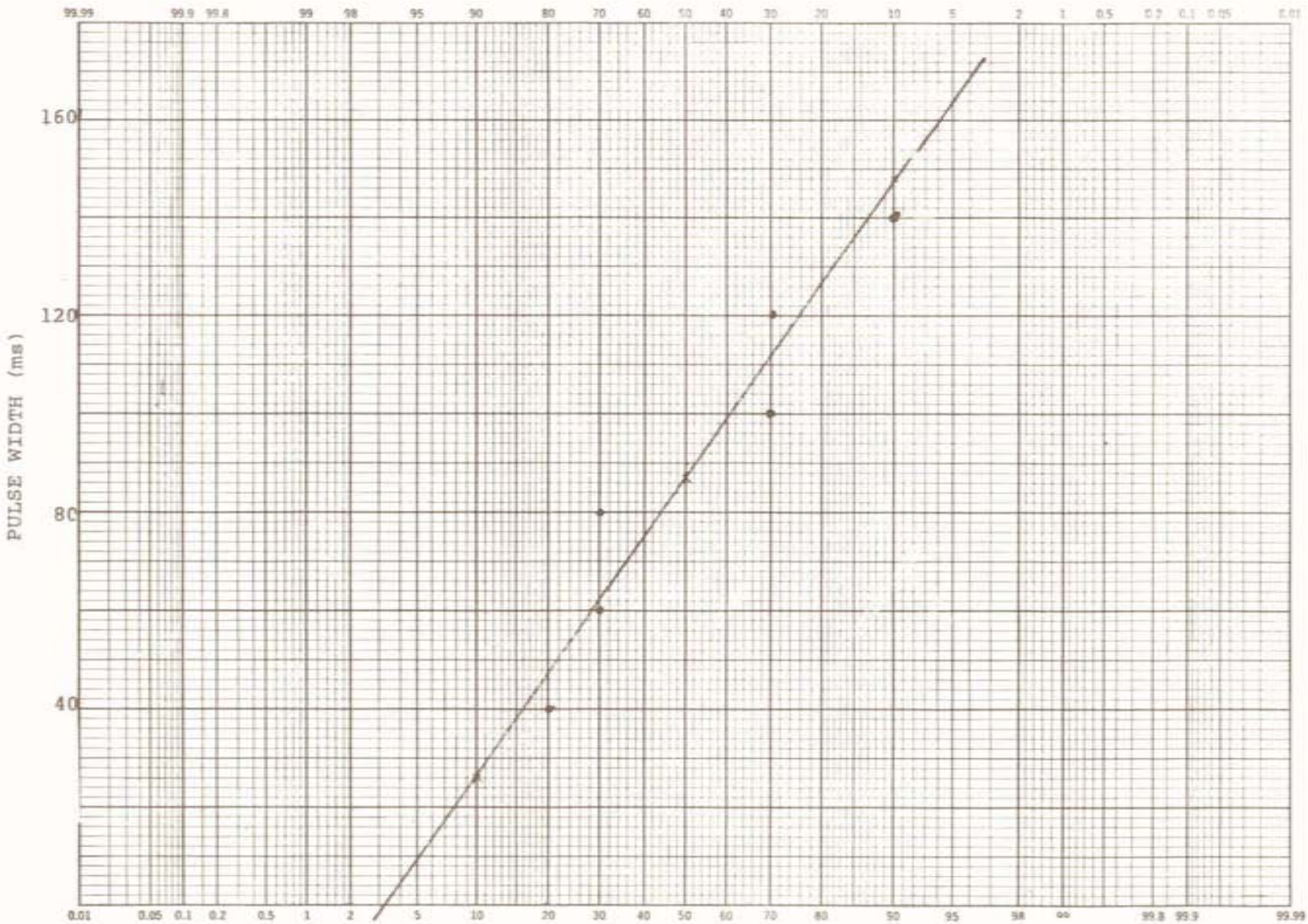


FIGURE 19 LINEAR PROBIT ANALYSIS - 30 W, 254 mm-FOCAL-LENGTH LENS

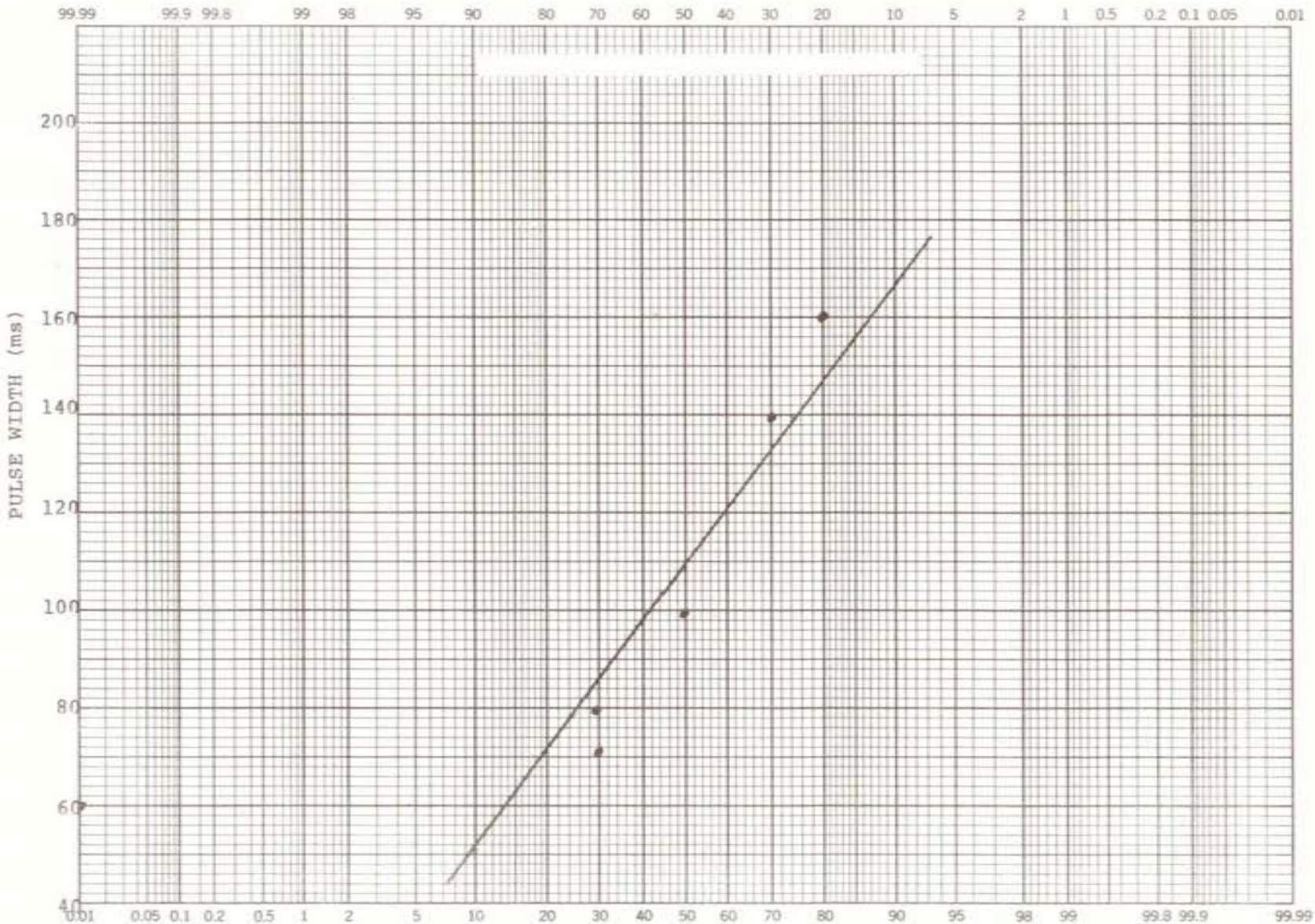


FIGURE 20 LINEAR PROBIT ANALYSIS - 20 W, 254 mm-FOCAL-LENGTH LENS

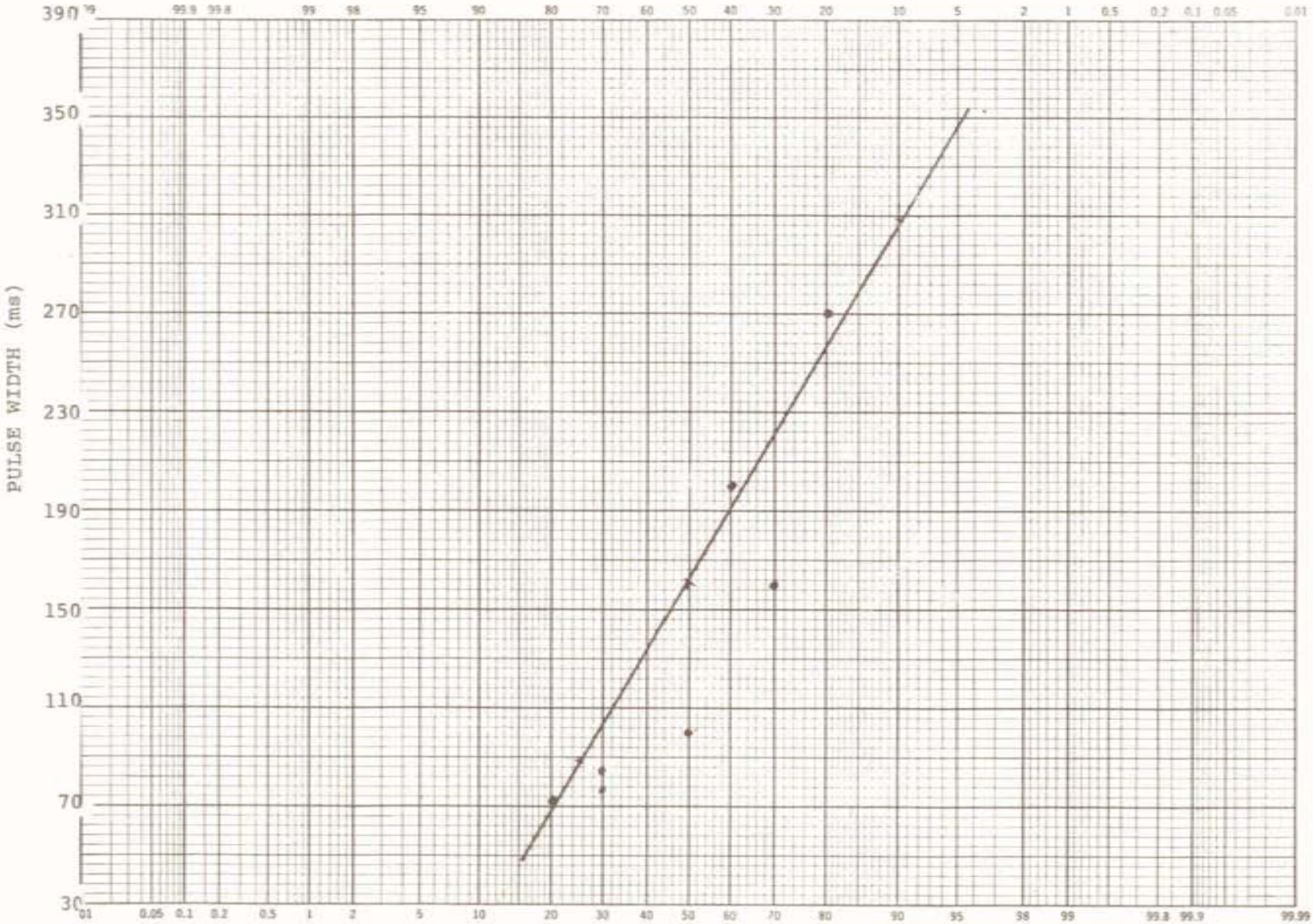


FIGURE 21 LINEAR PROBIT ANALYSIS - 10 W, 254 mm-FOCAL-LENGTH LENS

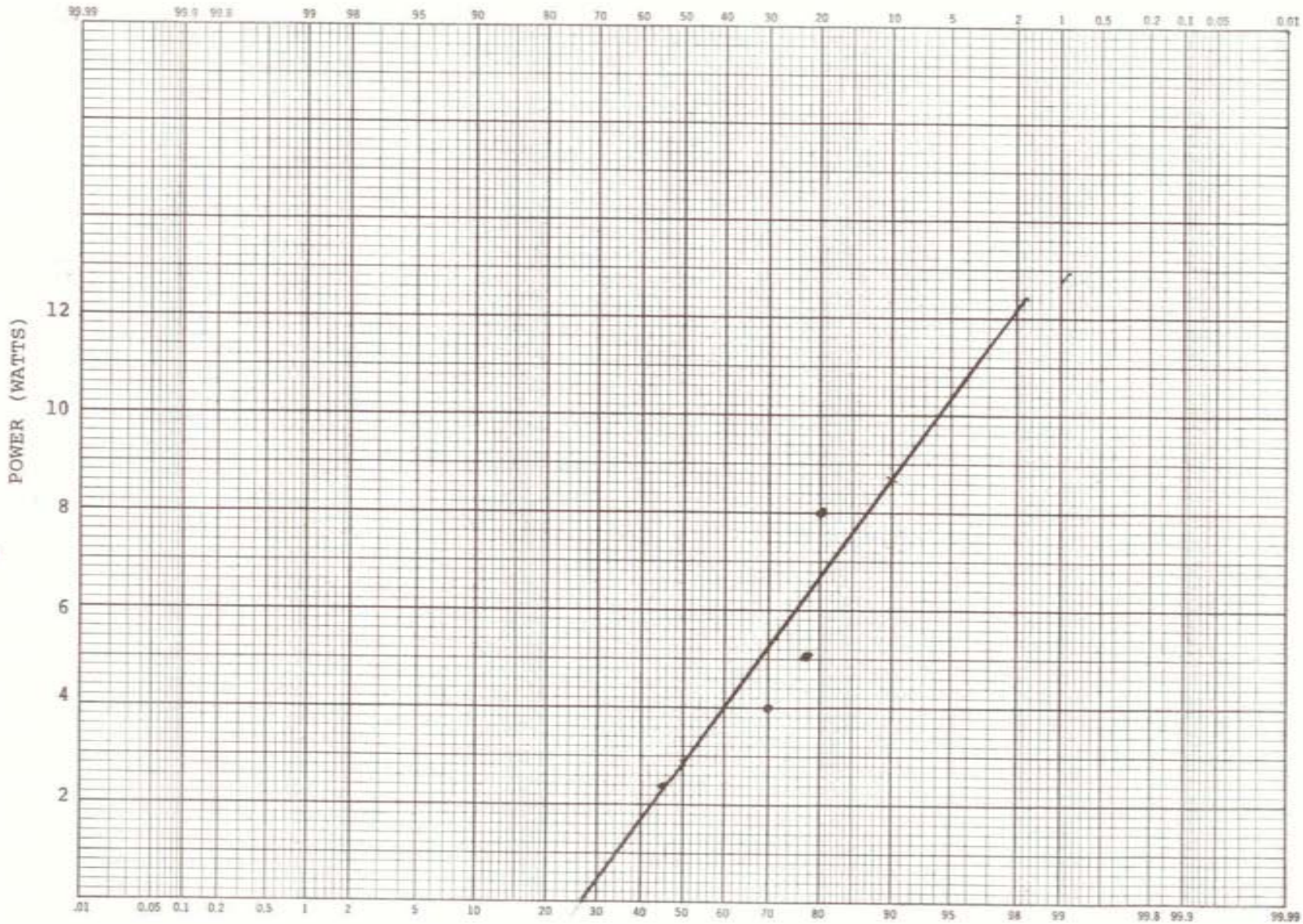


FIGURE 22 LINEAR PROBIT ANALYSIS - 220 ms PULSE WIDTH, 127 mm-FOCAL-LENGTH LENS

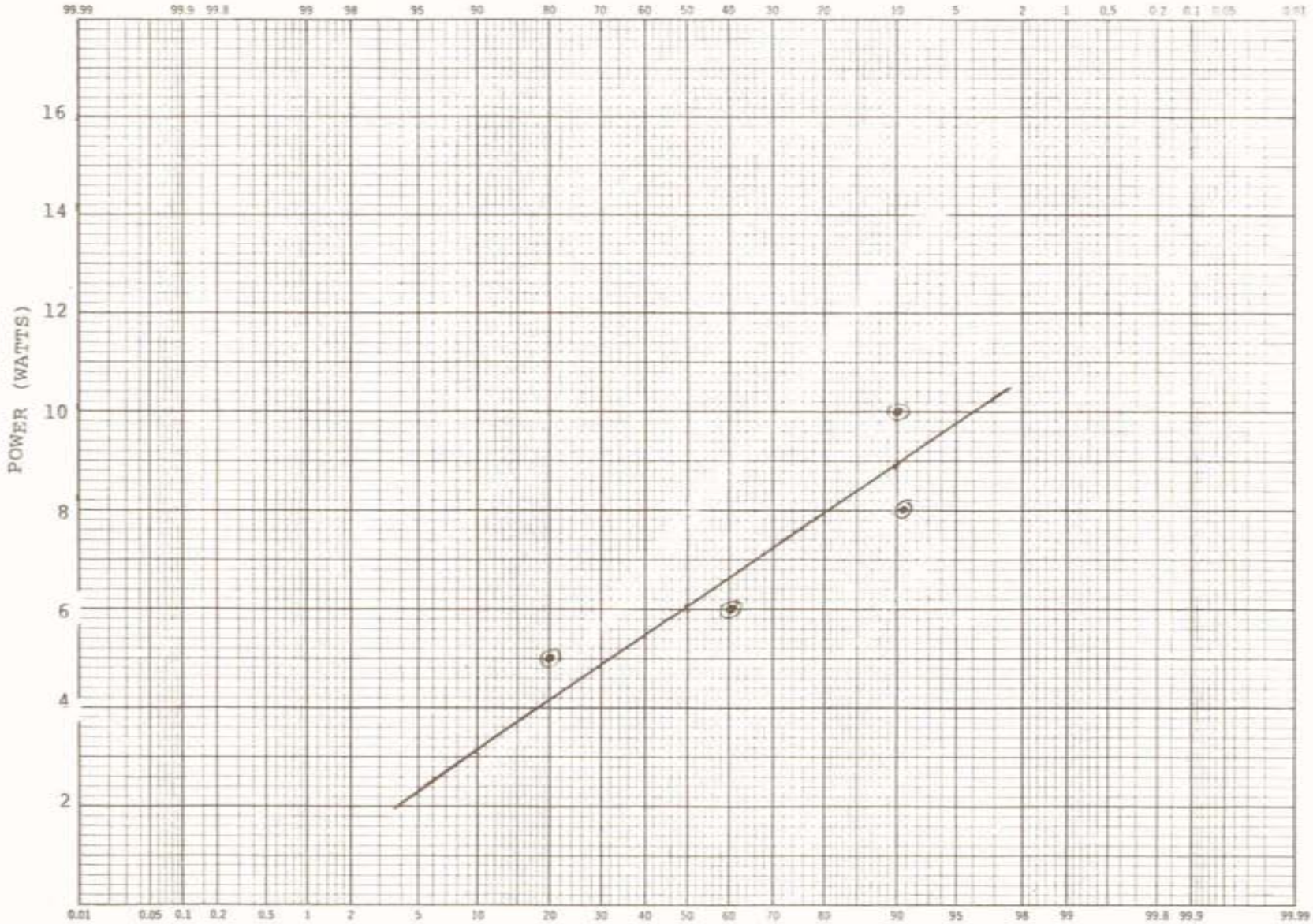


FIGURE 23 LINEAR PROBIT ANALYSIS - 170 ms PULSE WIDTH, 127 mm-FOCAL-LENGTH LENS

Appendix C

Target Preparation

The targets were made by breaking a DAPP Spacer[a] into several parts. The spacer had an area around the periphery which was 2.54 mm thick and 3 mm wide. A cross section of the perimeter would show an additional small step on the very outer perimeter. The beam was not focussed on the step. Approximately 8 to 10 targets could be broken from the outer area. The remaining target material was discarded.

(a) Spacer, P/N 302486-01

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