ATTENUATION OF GAMMA RAYS BY WOOD

DISSERTATION

Presented in Partial Fulfillment of the Requirements
for the Degree Doctor of Philosophy in the
Graduate School of The Ohio State
University

By

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The Ohio State University
1958

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ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. Willard C. Myser, Assistant Professor in the Department of Zoology and Entomology, who, in the capacity of adviser, was a constant source of advice and encouragement; to Dr. M. L. Pool, Professor, Department of Physics, for his wise counsel; to Dr. D. F. Miller, Chairman, Department of Zoology and Entomology, for his critical reading of the manuscript; to R. P. Sullivan and W. E. Carey, Research Assistants, Department of Physics, for their helpful suggestions; to O. Keith Hutchison, Forester at the Central States Station, for his cooperation in acquiring materials. This work was made possible by cooperative-aid funds provided by the Central States Forest Experiment Station and the U. S. Forest Products Laboratory.

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INTRODUCTION

The purpose of this study was (1) to determine if defects in wood could be detected by means of the attenuation of gamma rays, (2) to determine the extent of a defect regardless of its location in the wood, by these means, (3) to determine the approximate radiation energies that would be most suitable to use in detecting defects in wood, (4) to determine the type of radiation detector most suitable to use in the detection of defects in wood, and (5) to determine the effect that moisture content of wood has upon the gamma attenuation.

Previous to the discovery of x-rays by W. C. Roentgen in 1895, the chief non-destructive means of testing living trees for defects was that of visual inspection and sounding the tree with an axe or a hatchet. It was 25 years after the discovery of x-rays that they were used as a non-destructive means of testing wood, and even then the wood tested was not in the living state.

In a recent release of the Timber Engineering Company, the use of radioactivity in wood research was visioned as follows:

> Radioactive isotopes and gamma rays have possible uses in wood product and process developments. They offer avenues to more concise knowledge of wood and its behavior, and suggest new approaches to solving old problems and forestalling new ones. Radioactive isotopes are visioned as tracers for studying wood's moisture flow, and determining the penetration and retention of preservatives and other impregnations. Gamma rays might be used in measuring wood densities, rapid glue curing, sterilization of wood against fungi and insects, and to accelerate fermentation. These rays could lend themselves to developing a radically new pulping process and new plastic adhesives. Perhaps wood products will be coated with thin plastic, exposed to gamma radiation to change the plastic's molecular structure, to produce a case-hardened material that would be moisture-proof, fire-proof, and insect proof. The value of such developments is apparent.

REVIEW OF THE LITERATURE

During the World War I the British used wood in the construction of their aircraft. The wood had to be strong and flawless, so x-rays were employed as a non-destructive means of testing the timbers to be used (7).

The first non-destructive testing of living trees by means of x-rays was described by Maloy and Wilsey (9) in 1930. They devised a bucky diaphragm, which is a lead grid system, which they moved between the film and the tree, during exposure, to eliminate scattered radiations. The authors agreed at the time of writing the article that the problem of transporting this equipment in the field was of the highest order. They foresaw in the future the possibility of x-ray inspection of utility poles because of the close association of the poles and the highways.

Ten years later the prophecy of Maloy and Wilsey came true. Zucker (16) describes a technique of x-raying utility poles by wrapping rubber tire inner-tubing around the pole to be x-rayed. The metallic elements in the rubber absorb radiations which bring the outer edges of the pole image to the same range of density as the center of the pole. If the density of the pole is evened, then the film exposed by such conditions can be analyzed with increased accuracy. Since the utility poles and highways are closely associated, the problem of mobility was solved by motorized transportation.

About the same time that Zucker described his technique of inspecting wood poles by means of x-rays, Gregory (2), and Australian sciantist, x-rayed poles with known defects, then split them open and compared the defects with the x-ray negatives. He found that most of the defects were shown distinctly by the x-rays. He also believed the method especially valuable for the examination of timbers in bridges and similar structures in order to save unnecessary replacement costs.

In the meantime, x-rays were not only being applied to the detection of defects in trees but also to chemical, anatomical, and pathological studies of wood. Harris (3) used x-rays in the study of lignin, and its significance for the structure of living matter. Pasinetti (11) used x-rays in the study of the normal anatomy and histological variations of various plant organs and their ultimate internal alterations. Fischer *et al*. (1) describe the detection of wood-boring insects by means of x-rays, and Rankin (12) made a study of the rate of decay of wood by means of x-ray photography. Rivera (14) describes some experiments in which he studied wood tumors by means of x-rays.

In analyzing x-ray photographs of trees, two confusing factors must be properly allowed for: the distortion due to the pattern of the x-ray field and the cylindrical shape of the tree trunks. The degree of distortion increases directly with the size of the tree.

Experiments were made in a plantation of Scotch Pine infested by *Fomes annosus* (4). From a distance of 1 meter, x-ray photographs were taken of logs from freshly felled trees in order to show their longitudinal sections. Severe infestations of *Fomes annosus* could easily be distinguished, but it was difficult to distinguish between slight and fairly heavy infestations.

To present an idea of comparison between visual inspection of utility poles and inspection by means of x-rays, Truman (15) x-rayed 33 poles which were condemned by the visual method by pole inspectors. Of these 33 poles, 9 were found to be sound by means of x-rays, 11 were considered to contain from 60 to 100 per cent of sound wood and to be suitable for retention, and 7 to contain from 40 to 60 per cent sound wood, which warranted their removal. Although the classification of the other 6 poles was not mentioned, it is presumed that they contained less than 40 per cent of sound wood and should also be removed.

In 1955, work was being done by the New South Wales Forestry Commission (17) on a non-destructive method of determining the soundness of logs. A method based on the use of a source of low energy gamma radiations, and measuring either the transmission pattern or the backward scattering, has been examined in a preliminary way. The results so far obtained have indicated that this method is capable of differentiation between sound wood and holes. The Forest Commission of New South Wales has applied for a patent on a gamma radiation machine.

From the preliminary notes on research being performed by the Timber Engineering Company (6), in cooperation with the X-ray Division of Westinghouse Electric Corporation, into the development of a rapid non-destructive test of wood which would reveal hidden defects, the following disadvantages were noted: (1) the length of time required in the preparation of x-ray photographs and (2) the low screen brightness when using fluoroscopy. However, this low screen brightness was being improved upon by the construction of an image amplifier by which the original image is intensified on a second screen.

An electrical test for decay in wood was devised by Richards (13). Previously weighed pieces of sapwood of Loblolly Pine and Red Gum were subjected to decay by pure cultures of white and brown-rot organisms. At two-week intervals up to 14 weeks, samples were removed from the decay chamber, tested electrically at 5 megacycles with a Q meter, weighed, measured, oven-dried, and reweighed. It was found that the moisture content of wood had the greatest effect on electrical properties, but tnere was also a highly significant partial regression (1) of the conductivity of the wood on the per cent weight loss due to decay and (2) of the dielectric constant of the wood on its specific gravity. In the moisture content range studied, the difference between a conductivity moisture meter reading and a dielectric constant moisture meter reading seemed to be a fairly good non-destructive test for decay, the former being consistently higher than the latter for decayed pieces of wood.

As previously mentioned by Gregory (2), a good non-destructive test of wood would be of value not only in the testing of standing trees but also in the testing of timbers which have been in use for a period of time. Marine piling, which supports many marine docks, is often infested with marine borers. The piling become weakened and may give way under stress. If this weakened piling could be located and replaced before it gives way, it would be of economic value. Battelle Memorial Institute (19), in an attempt to develop a gamma radiographic method for the underwater inspection of marine piling, found that under water radiographs made with iridium-192 did not permit the detection of marine borers present in wooden piles. The energy of the radiation was too high to produce a detectable contrast in the radiographic image.

By using thulium-170, which is free of radiation above 100 Kev, radiographic images from water-logged piling, 3.5 inches thick, in air, showed clear evidence of burrows. Radiographic images of water-logged piling, 3.5 inches thick, under water, showed only faint evidence of burrows. The research group concluded that, in general, the lower the energy of radiation, the greater the difference in the degree of absorption by different materials. Consequently, better contrast should result from the use of low energy radiation. However, a very high flux is necessary if a radiograph is to be produced in a reasonable length of time.

Madson, and McNabb (8)(10) have developed a new light-weight (13 lbs.) x-ray unit, which partially solves the problem of mobility. This includes the radioactive source (thulium) and shielding which is contained in a 4 x 4 inch housing. Film was used as the detector. Decayed areas of trees are revealed along with other imperfections, such as knots and water-filled cavities. By taking a number of pictures, the size and location of defective areas can be determined accurately. The device can be strapped to the side of a tree during the time the radiographic image is formed. The film is then developed and analyzed in the laboratory.

With the thulium x-ray unit, a 9-inch soft maple can be x-rayed in 4 minutes, and a 12-inch tree in 8 minutes. The authors mention the fact that the intensity of the source is going to be increased by a factor of 10. The total weight of the unit will then be 20 pounds.

A method has been developed on the non-destructive detection of the rotten state in standing trees and wood materials utilizing radioactive isotopes by Iisuka (5). This method has been applied to a number of trees and found to work fairly well. The source used was Co 60.

METHODS AND MATERIALS

Radioactive Sources Used

Each experiment consisted of 3 separate components: a source, an absorber, and a detector. The sources used were Sn 113, I 129, Yb 169, Cs 137, Ce 144, and Sm 144 + n. The radiations used, which were emitted by these sources, ranged in energy from a Sn 113 x-ray of 23 Kev to a Cs 137 gamma ray of 661 Kev.

Species and Shape of Wood Used

The species of wood chosen to serve as absorbers were sugar pine, poplar, hickory, and black oak. Pine has a specific gravity of approximately 0.36 at 12 per cent moisture content. This is a relatively low density compared with hickory or black oak which have specific gravities from 0.64 to 0.74 at 12 per cent moisture content. Poplar is a medium density wood, having a specific gravity between 0.40 and 0.50 at 12 per cent moisture content.

The wooden absorbers were used in the form of boards or logs. The wooden boards, which were used as absorbers, were 12 x 12 x 1/2 inches. They were sawed from healthy, sound timber and kiln dried to a moisture content from 8 to 10 per cent. Both sound and defective black oak logs, about 11 inches in diameter and 3 feet long, were used in those experiments involving the use of logs.

Detectors Used

The detectors used were of 3 kinds: (1) a scintillation spectrometer, (2) a G-M counter circuit, and (3) film.

1. Scintillation Spectrometer

The scintillation spectrometer consists of a NaI crystal, a photocathode, a photomultiplier tube, a preamplifier, a linear amplifier, a pulse height discriminator, and a scaler. With this arrangement only one gamma or x-ray energy which strikes the NaI crystal is measured. This arrangement is described as follows: When a gamma or x-ray energy strikes the crystal of a scintillation spectrometer, it may be absorbed by an electron of an atom within the crystal. The electron, which has absorbed this energy, is released from its orbit, and moves with a corresponding energy. It is now designated as a photoelectron and loses its energy in its passage through the crystal, in the form of small bursts of light called scintillations. The sum of all the light produced by a photoelectron corresponds to the initial energy of that photoelectron and, therefore, corresponds also to the energy of the absorbed gamma ray.

Adjacent to the crystal is a photomultiplier tube which consists of a photocathode and a series of dynodes. The photocathode, which is immediately adjacent to the crystal, is sensitive to light. When the scintillations from the crystal strike the photocathode, a corresponding number of electrons is released.

The first dynode, of the series of dynodes, is in close proximity to the photocathode, and the voltage potential between the two is such that the first dynode has a higher potential than the photocathode. The electrons released by the photocathode are directed toward the first dynode, as a result of this difference in potential, and strike the metal dynode with such velocity that secondary electrons are produced. Dynode 2 has a higher potential than dynode 1; therefore these secondary electrons are directed toward dynode 2 and produce there more secondary electrons. For example, if one electron, upon striking dynode 1, produces 4 secondary electrons, then it is likely that 16 secondary electrons would be produced at dynode 2. In a like manner the secondary electrons produced at dynode 2 are directed toward dynode 3. Modern photomultiplier tubes may have from 10 to 16 dynodes in series. The gain of such tubes may be as much as 10^6 or more.

The electron avalanche finally leaving the last dynode is collected and gives rise to a voltage pulse which is fed into the preamplifier and is further amplified. From the preamplifier, the pulse is fed into a linear amplifier which amplifies the pulse to such a height that it can be measured by a suitable circuit. This pulse height, then, corresponds to the energy of the gamma or x-ray energy which was absorbed by the crystal.

The pulse from the output of the linear amplifier is fed into the pulse height discriminator. This discriminator actually consists of two discriminator circuits. The one discriminator circuit, called the bias voltage, can only be triggered by a pulse of minimum height. That is, if the voltage of this circuit is set at 20 volts, this circuit cannot be triggered unless the incoming pulse corresponds to 20 volts or more.

The second discriminator circuit, called the window width or channel width, cannot be triggered unless the incoming pulse corresponds to a channel width which is limited on one side by the bias voltage and on the other side by the bias plus the channel width voltage. That is, if the bias voltage is set at 20 volts and the channel width at 5 volts, only those pulses corresponding in height from 20 to 25 volts will trigger this second discriminator circuit. Finally, both discriminator circuits must be triggered by the same pulse in order for the pulse to be eventually fed into the scaling circuit. By this arrangement, only one energy gamma or x-ray may be counted by the scaler, even though other pulses resulting from different energy gamma or x-rays travel as far as the two discriminator circuits.

2. G-M Counter Circuit

The G-M counter circuit consists of a Geiger-Muller tube, an amplifier, and a scaler. The Geiger-Muller tube is a gas-filled, two-electrode, ionization chamber. The outer wall of the tube serves as the cathode, and a centrally located wire serves as the anode. The ions produced in the gas by an ionizing radiation are swept toward the electrode by the applied field, thus inducing a certain charge on the anode. This charge is fed into an amplifier and then to the scaler.

A gamma or x-ray energy may be detected by a G-M counting circuit if it is absorbed in the wall of the G-M tube and ejects an electron or a positron into the sensitive volume of the tube.

3. Film

X-ray film was used as the detector of radiations because of its high sensitivity to x-rays and gamma rays. In some cases both front and back fluorescent screens were used with the film in order to increase its sensitivity to the radiations.

The Use of the Scintillation Spectrometer

When using the scintillation spectrometer in conjunction with wooden boards, the geometrical arrangement consisted of a radioactive source placed about 14 inches from the sensitive crystal of the spectrometer. In the 14 inch space was placed 1 to 24 of the boards of the type of wood to be measured as shown in Plate 1. As each board was inserted, a reading of the intensity of the penetrating radiations was made on the spectrometer. The results were then plotted on semi-logarithmic graph paper.

In order to make a space in the absorber, twenty-four 12 x 12 x 1/2 inch sugar pine boards were placed in a vertical pile and numbered from 1 to 24 inclusive. As 1, 2, or 3 boards were removed from the pile, 4 small posts, about 1 inch in diameter and of respective lengths, were inserted at each corner to maintain the space left by the number of boards removed. The location of these spaces was varied in the pile, and measurements were made on the boards remaining in the pile.

An experiment was conducted in which water was used as an absorber. A glass battery jar containing tap water was placed between a source and a crystal and the water siphoned out. A reading of the intensity of penetrating radiations was made at each half-inch change in the water level.

In another experiment involving the use of the scintillation spectrometer, a log was passed in a direction parallel to its diameter between a gamma ray source and the detector and measurements made through its cross section at one-half inch intervals. Both sound and defective logs were measured in this manner as shown in Plate 2.

By the same method as the one just described, the cavity within the defective log was filled with water, and similar measurements were made. Then the log was emptied of water and measurements made while the internal surface of the cavity of the log was still wet.

In all the experiments involving the use of the scintillation spectrometer, the crystal was collimated in such a way that only those radiations forming a straight line beam between the source and the crystal were counted.

The Use of the G-M Counter Circuit

By using a similar geometrical arrangement, as previously described for the scintillation spectrometer, a series of experiments was carried out with the G-M counter circuit. Pine, poplar, and hickory boards were each used separately as absorbers, and the results of each experiment were plotted on semi-logarithmic graph paper. The Geiger-Muller tube was collimated in such a way that only those radiations forming a straight line beam between the source and the tube were counted.

Also, as when using the spectrometer, measurements were made using a sound log and a defective log as absorbers. As before, the log was passed in a direction parallel to its diameter between a source and the tube, and measurements made through its cross section at intervals of one-half inch. The same logs were used as with the scintillation spectrometer.

The Use of Film

In the experiments using film as the detector of radiations, both a sound log and a defective log were used. A solid black oak log was placed on its end a few inches away from a similarly placed black oak log with a visible hole. The source was placed between the logs in such a way that both logs were irradiated equally at the same time.

Film wrapped in light-proof paper was placed around one-half the circumference of the log opposite the source. In this way, all of the radiations reaching the film had to penetrate a certain portion of the log. After exposure, the film was developed and a relative comparison of the degree of exposure was made with the aid of a photodensitometer.

Moisture Experiments

A series of experiments was conducted to gain information on the values of the mass absorption coefficient of wood of varying moisture content. Twenty-seven boards, approximately 3 x 3 x 1/2 inches, were dried to 0 per cent moisture and placed in a wooden box containing P_2O_5 as a drying agent. The 27 boards consisted of 9 boards each of pine, poplar, and hickory. The box was 30 x 14 x 18 inches with a close fitting top of transparent plastic. The cracks between the plastic and wood were sealed with masking tape to help prevent moisture from entering. The box contained armholes in each side fitted with long-sleeved plastic gloves for internal manual manipulations. Also placed in the box was a balance and a pair of calipers. To prevent warping, all boards were placed in the box in such a way that no one board was in contact with another.

The box with its contents was placed between the source and the collimated crystal of the spectrometer. The contents of the box were placed in such a way that they did not interfere with the straight line beam between the source and crystal. The radiations passed in order through the bottom of the box, the plastic top, the hole in the collimator, and into the crystal.

Board number 1 was then measured in three dimensions and weighed inside the box. This board was then placed on the bottom of the box directly between the source and the crystal, and a measurement of penetrating radiations was made. Number 2 board was similarly measured and placed on top of the number 1 board, and another measurement of penetrating radiations was made. This procedure was repeated for the 9 boards of each species, at which time the results were graphed and designated as series one.

At the completion of series one, the boards were removed from the box and immersed in water for a few seconds, to increase their moisture content, and placed in the box as before. The box was unopened for several days to allow the moisture to become more evenly distributed. Similar measurements were made, as in series one, and the results graphed anddesignated as series two. This procedure was repeated until 8 series of measurements were completed, each series representing an increase in the moisture content of the boards.

As the moisture content of the boards increased above that of boards in a normal atmosphere, which is approximately 8 per cent moisture content in this locality, the P_2O_5 was removed from the box and a container of water was placed in the box to keep the humidity near 100 per cent. This was done in order to prevent excessive evaporation of water from the surface of the boards.

DISCUSSION

When a parallel beam of monoergic x-rays or gamma rays passes through any material, the intensity of the emergent beam is less than that of the incident beam. If the rate of the emergent beam is subtracted from the rate of the incident beam, the rate of absorption by the material is obtained. Therefore, the measurement of radiations, as described in this study, is that of the emergent beam and is the reciprocal of the rate of absorption by the absorber.

The decrease in intensity of the beam when it traverses a small thickness (dx) of the material depends upon the degree of absorption per unit of thickness. The basic mathematical assumption is

$$\frac{-dI}{I_o} = \mu_\ell dx \qquad (1)$$

where I_o is the density of the radiations before passing through the absorber and -dI represents the decrease in intensity after passing through an absorber of increasing thickness dx. The linear absorption coefficeint μ_ℓ is a symbol representing the fraction of energy removed from a gamma ray beam per centimeter of path of the absorber.

By integration

$$\log_e I - \log_e I_o = \mu_\ell x \tag{2}$$

and

$$\log_e \frac{I}{I_o} = -\mu_\ell x \ . \tag{3}$$

Therefore

$$\frac{I}{I_o} = e^{-\mu_\ell x} \tag{4}$$

and

$$I = I_o e^{-\mu_\ell x} \ . \tag{5}$$

Half thickness is a term that is somewhat more convenient to use than the absorption coefficient and is defined as that thickness of an absorber necessary to decrease the radiation intensity by one-half. In solving for half-thickness values ($x\frac{1}{2}$), I may be set equal to 1 and I_o equal to 2. By substituting these values in equation (2)

$$\log_e 1 - \log_e 2 = -\mu_\ell x \tfrac{1}{2} .$$

Since $\log_e 1$ is equal to 0,

$$x\tfrac{1}{2} = \frac{0.693}{\mu_\ell} \ , \tag{6}$$

or

$$\mu_\ell = \frac{0.693}{x\frac{1}{2}} \ . \tag{7}$$

If x is in cm., μ_ℓ must be in cm^{-1}, since the product of $\mu_\ell x$, as an exponent, must be a dimensionless number.

The mass absorption coefficient is sometimes used instead of the linear absorption coefficient. It is defined as the fraction of energy removed from the gamma ray beam per gram of absorber and may be solved for by dividing the linear absorption coefficient by the density (ρ) of the absorber.

Thus

$$\mu_m = \frac{\mu_\ell}{\rho} , \tag{8}$$

where μ_m is expressed in cm^2/gm. Therefore, if μ_m is substituted for μ_ℓ in equation (5), x must be expressed in gm/cm^2 in order to cancel the dimensions of μ_m.

The values of I_o, e, and μ_ℓ (or μ_m), from equation (5), are constants; therefore, I and x are the only variables. Since x is an exponent, I will vary exponentially with a linear change in x. If the values of I are plotted on the logarithmic ordinate, of semilogarithmic paper, and x on the linear ordinate, a straight line curve will be formed.

Scintillation Spectrometer Experiments

The radiations from Sn 113 were absorbed in sugar pine and the x-ray of 23 Kev was measured with a scintillation spectrometer. The resulting curve is shown in Fig. 1. This absorption curve was the final result of many individual absorption experiments. In the first few experiments, the source was placed directly beneath the pine absorber, and the crystal was not collimated. The intensity of the measured radiations increased above the value of I_o until the pine absorber was approximately 2.5 inches thick. With an increase in absorber thickness above 2.5 inches, there was a decline in the intensity of the measured radiations. The increase in intensity above the value of I_o

seemed to indicate that the radiations were being scattered by the pine absorber and were entering the crystal at an oblique angle.

In the next experiments, with the same pine absorber, various shaped collimators were tried in order to minimize the number of scattered radiations entering the crystal. When the degree of collimation was such that a straight line absorption curve was formed, it was assumed that a parallel beam of x-rays was being measured by the scintillation spectrometer after passing through the pine absorber. The straight line absorption curve, shown in Fig. 1, indicates that the ratio of the kinds of atoms composing the structure of the pine absorber was consistent throughout its thickness.

The radiations from Cs 137 were absorbed in a black oak log and the gamma ray of 661 Kev was measured with a scintillation spectrometer. The resulting curve is shown in Fig. 2. This absorption curve is also a straight line and indicates that the ratio of the kinds of atoms composing the structure of the oak absorber was also consistent throughout its thickness.

Sugar pine and black oak are two species of wood whose densities are near the extremes. Yellow poplar has a density between that of sugar pine and black oak. For this reason an absorption curve for yellow poplar was made with a Sm 144 + n x-ray of 38 Kev. These data, when plotted, also form a straight line, as shown in Fig. 3, as did the data for pine and oak. Thus, wood from 3 species of trees each having a different density show consistency of structure. It is reasonable to believe that other species of wood would show similar consistency. Therefore, if an inconsistency in wood is noted by means of attenuation of gamma rays, it may be attributed to an inconsistency or defect in the wood and not to a variation in the ratio of the kinds of atoms composing the wood.

The wood used in these preliminary experiments had a low moisture content, approximately 8 - 10 per cent. The moisture content of the wood of living trees is known to be as high as 30 per cent or more. If an absorption curve for water were made and found to form a straight line, it would be reasonable to expect the absorption curve of any homogenous mixture of wood and water would form a straight line. For this reason an absorption curve for water was made. The source used was a Ce 144 gamma ray of 135 Kev as shown in Fig. 4. The results when plotted form a straight line curve; therefore, it is reasonable to believe that regardless of the density of any one tree, providing its moisture content is consistent, the ratio of the kinds of atoms composing its structure would be consistent throughout its thickness.

Could a defect in wood be detected by means of the rate of attenuation of gamma rays? And, if the defect could be detected, could it be detected at any position within the absorber?

The most extreme defect in wood would be a space within the wood, in which case there would be a difference in the specific gravity of wood and that of air which occupies the space. Three curves showing the ability to detect spaces in sugar pine boards at various positions with a Sn 113 xpray of 23 Kev are shown in Fig. 5. The measurements for these curves were made with the scintillation spectrometer, and the same geometry was used as that in making the absorption curve shown in Fig. 1.

Each point on each graph represents both the size and location of a space. In each of the three curves a measurement was made with no boards removed. This point was located on its respective curve. In this way the resolution of each sized space and its location is shown. It can be seen that even a one-half inch space or defect can be easily detected and that its location in the pile has little to do with its resolution. The one and one-half inch space caused by the removal of 3 boards shows approximately a 35 per cent difference from that point at which no boards were removed. The one-inch space showed approximately a 24 per cent difference and the half-inch space showed approximately an 11 per cent difference from that point at which no boards were removed.

Figure 6 shows the half-thickness values in inches of dry pine necessary to decrease the intensity of radiations, ranging in energies from 23 Kev to 190 Kev, by one-half. It is evident that from 190 Kev to 117 Kev there is little change in half-thickness values; however, below 50 Kev the half-thickness values decrease quite rapidly with decreasing energies. By extrapolation, it is predicted that energies lower than 23 Kev would give a still more sensitive relationship between half-thickness and diameter measurements.

The next experiment consisted of using a solid black oak log as an absorber. Because of the circular shape of the log, the absorber could not be increased or decreased in thickness by even increments as all previous absorbers were. Instead, thickness measurements were made every one-half inch across the diameter of the log. At each thickness measurement, a measurement of the intensity of radiations was made.

The radiations from Ce 144 were absorbed in the black oak log and the gamma ray of 135 Kev was measured with a scintillation spectrometer. The resulting absorption curve is shown in Fig. 7. These data were plotted on semi-logarithmic graph paper in order to show that the results of the attenuation of gamma rays by a circular shaped absorber also form a straight line absorption curve as did those curves when conveniently shaped boards were used.

The data, used in the construction of Fig. 7, were then plotted on linear graph paper, the only difference being that the count rate was plotted against the respective distances across the diameter of the log, instead of the thickness measurements every one-half inch across the diameter of the log, as shown in Fig. 8. In this manner the defects, if present, would be better illustrated. The data used in Fig. 7 are also shown in Fig. 8 in linear form and represent the transition from the semi-logarithmic graph to the linear graph. The slight variations in the linear curve are probably due to the fact that the log was not perfectly circular or to the irregularities of the bark on the log.

Another apparently solid oak log was similarly analyzed and the absorption curve is shown in Fig. 9. There was a defect in the log which was not seen until the data were graphed. Upon closer examination, a portion of the log was found to be partially decayed. Therefore, it is safe to assume that the decayed portion was less dense than the wood surrounding it.

Many trees in the living state contain defects which originate from a broken limb or injury far above the ground level. If the progressive decay is downward from the point of injury, it is possible that a hollow pocket may be formed which in time would fill with water. Could a water-filled hole in a tree be resolved by means of the attenuation of gamma rays? To answer this a series of three experiments was designed and carried out.

A black oak log, 3 feet long and approximately 10 inches in diameter, with a visible hole in one end and solid at the other, was chosen as the absorber to be used. The solid end was placed in hot paraffin in order to seal any openings which might have permitted water to leak out. A Ce 144 source was used which emitted a gamma ray of 135 Kev. The source and the collimated scintillation crystal were mounted 3 feet from the floor and 3 feet apart.

The first of the three experiments consisted of moving the sealed log, with no water in its cavity, between the source and the crystal. Measurements of the intensity of radiations were made every one-half inch across the diameter of the log. These results were plotted on linear paper and are shown in Fig. 10. The cavity in the log is clearly defined, and even decayed portions which were not visible were also defined.

The second experiment consisted of moving the sealed log, with its cavity filled with water, between the source and the crystal and making measurements every one-half inch across the diameter of the log. The geometry was exactly the same as in the previous experiment. The results of this experiment were plotted and are shown in Fig. 11. In this instance the cavity is not readily defined, although some irregularities are shown.

The third experiment consisted of moving the sealed log, with the water emptied from its cavity, between the source and the crystal and measurements made every one-half inch across the diameter of the log. Again the same geometry was used. These results were plotted as before and are shown in Fig. 12. Even though the sides of the cavity in the log were wet, it is clearly defined. It has been shown, then, that decayed portions or cavities in a log can be detected by means of the attenuation of gamma rays, when using a scintillation spectrometer, but, when the cavities in the log are filled with water, they would be difficult to detect by these means.

G-M Counter Experiments

All previous absorption experiments made with a scintillation spectrometer were based on equation (5). By the use of the pulse height discriminator, only one gamma ray energy from a particular spectrum was selected. In the G-M counter circuit, as used in these experiments, all pulses resulting from direct or indirect ionizing radiations were of the same amplitude. Thus, a pulse height discriminator, if used with the G-M counter circuit, would yield no useful information.

Most radioactive isotopes emit more than one radiation energy. As previously described, equation (5) describes the rate of attenuation of gamma or x-rays by an absorber only when a parallel beam of monoergic gamma or x-rays is measured. Therefore, equation (5) must be adapted if it is to describe the interaction of an absorber with more than one gamma or x-ray energy. Such is the case when using a G-M counter circuit to measure the attenuation of more than one gamma ray energy by an absorber. If two or more gamma ray energies are measured the equation becomes

$$I = I_1 + I_2 \cdots = I_{o1}\, e^{-\mu_{\ell 1} x} + I_{o2}\, e^{-\mu_{\ell 2} x} + \cdots \quad .$$

The lower energy gamma ray will be attenuated faster than the higher energy gamma ray; therefore, the values of I_1 and I_2 will not vary in proportion to each other and when the over-all intensity, I, is plotted on semi-logarithmic paper, the curve formed will not be a straight line.

Another factor which contributes to a wide range of gamma ray energies is compton scattering. This may be described as a photon glancing off a particle, or particles, somewhere within the absorber and continuing on with diminished energy. Some of these scattered photons may also be counted.

The radiations from Sm 144 + n were absorbed in sugar pine and measured with a G-M counter. The resulting absorption curve is shown in Fig. 13. This absorption curve was the final result of many individual absorption experiments. The collimation of the Geiger-Muller tube was increased, after each individual absorption experiment, until no further change was noted in the slope of the absorption curve. The collimation was then considered as sufficient and that only a parallel beam of gamma rays was striking the tube.

The slope of the curve, Fig. 13, decreases as the thickness of the absorber was increased. Using the same geometry, absorption curves for yellow poplar and hickory were made as shown in Figs. 14 and 15, respectively. The slope of these two curves also decreases as the thickness of the absorbers were increased.

It was thought that the change in the slope of the curves, shown in Figs. 13, 14, and 15, may be due to the particular energy spectrum of Sm 144 + n. For this reason an absorption curve for hickory was made with a G-M counter circuit and Ce 144 radiations, as shown in Fig. 16. The slope of this curve also decreases with an increase in the thickness of the absorber. Thus, it may be inferred that regardless of the density of the wood, absorption curves made with a G-M counter circuit show a decrease in slope with an increase in the thickness of the respective absorber.

By using the same geometry that was used in the four previous experiments, absorption curves were made for black oak logs with the G-M counter circuit and Ce 144 radiations. The first such absorption curve is shown in Fig. 17. This absorption curve may be compared with that shown in Fig. 8, since the same solid black oak log was used as the absorber in both cases. Since the data used in Fig. 8 were obtained when using the scintillation spectrometer, a direct comparison of the results of the two kinds of detectors can be made.

The shape of the curve shown in Fig. 17, when compared with that shown in Fig. 8, indicates that the detection of a defect in the thicker portions of the tree would be more difficult when using a G-M counter circuit than when using a scintillation spectrometer, because of the flatness of the curve near its center. This portion of the curve corresponds to the center of the log. This is especially important, since it is expected that most of the defects to be found in trees will occur near the center of the tree.

An absorption curve for a black oak log with a visible hole made with a G-M counter circuit and Ce 144 radiations is shown in Fig. 18. This absorption curve may be compared with that shown in Fig. 10, since the same log was used as the absorber in both cases. This large defect can be detected when using the G-M counter circuit but not in as great detail as when using the scintillation spectrometer.

Film Experiments

A series of experiments was performed using film as the detector of radiations to find defects in the same two black oak logs that were used in the previous experiments. X-ray film and film with front and back fluorescent screens were used with each of the two sources as described in Methods.

After exposure the film was developed, and a relative comparison of the degree of exposure was made with the aid of a photodensitometer. The variations in the exposure of the films from the solid log were somewhat comparable to the absorption curves of both the scintillation spectrometer and the G-M counter circuit. The variations in exposure of the film from the log with the visible hole did not correspond to a definite hole in the log. When the film from the solid log was compared with the film from the defective log, a difference in exposure was noted. However, neither the position nor the size of the defect could be satisfactorily determined. There was very little difference in the relative exposure of the film, regardless of which source was used. The film with the front and back fluorescent screens was a little superior to the x-ray film in the delineation of the defect in the log.

When using film to detect hidden defects in wood, all the radiations emanating from the source may take part in exposing the film. These radiations include all scattered radiations and may include more than one energy gamma ray. Also, the area of differential exposure of the film may vary according to whether the defect in the wood is closer to the film or closer to the source, depending upon the angle subtended by the defect and the source.

Moisture Experiments

In all previous absorption experiments, with wood boards, the wood used had a constant moisture content for any one absorption curve. It is known that the moisture content in some trees is not consistent throughout the thickness of the tree. μ_ℓ is designated as a constant, but, if the moisture content varies within the absorber, then I would not vary as an exponential function of x only. Instead, I would vary according to the value of $\mu_\ell x$, and the value of μ_ℓ may vary with each succeeding centimeter of path through the absorber. This means that the results of such an absorption curve may not form a straight line when plotted on semi-logarithmic paper.

In order to gain information on the attenuation of gamma rays by wood of varying moisture content, a study of the relationship of the values of μ_ℓ and μ_m to wood of varying moisture content was made.

The per cent moisture content of wood is defined as

$$\frac{\text{wet wt.} - \text{dry wt.}}{\text{dry wt.}} \times 100 = \text{per cent moisture.}$$

As previously stated, the mass absorption coefficient is defined as the fraction of energy removed from the gamma ray beam per gram of the absorber. By simply stating that 1 gram of one absorber is the same weight as 1 gram of another absorber would seem to indicate that the value of μ_m would always be the same. However, different atoms have different absorption cross sections, and the value of μ_m for 1 gram of one kind of an absorber may be different from that for 1 gram of another kind of an absorber. Thus, the value of μ_m for 1 gram of wood at 0 per cent moisture content may be different from that for 1 gram of wood at 100 per cent moisture content, because of the ratio of the kinds of atoms composing the absorber.

Since the determination of the values of μ_m was the first objective, μ_m was substituted for μ_ℓ in equation (5). By dividing the weight of each board by the product of its two longest dimensions, the thickness was expressed in terms of gm/cm^2. The values for μ_m, in terms of cm^2/gm, were obtained by dividing 0.693 by the respective values of $x_{\frac{1}{2}}$. The values of $x_{\frac{1}{2}}$ were obtained from the respective absorption curves for each species of wood of each series of experiments.

As the moisture content of the wood increased, in all three species, the values of μ_m decreased as shown in Fig. 19. The values of μ_m changed approximately 0.17 per cent with every 1 per cent change in the moisture content of pine. For poplar there was approximately a 0.14 per cent change, and for hickory a 0.10 per cent change in the values of μ_m for every 1 per cent change in its moisture content. From this data, it can be inferred that the value of μ_m for water is lower than that of dry wood. Also, that with a like change in the moisture content, the change in the values of μ_m of wood may vary inversely with the density of the wood.

By multiplying the value of μ_m by the density of the wood, μ_ℓ is obtained in terms of cm^{-1}, and x can then be expressed in cm. As shown in equation (4), the intensity of the radiations measured may be expressed as a fraction (I/I_o), whose value lies between 1 and 0. By setting x equal to 1 cm. of wood of each species of each series, I/I_o may be expressed as a relative intensity with respect to the moisture content of 1 cm. of wood of the absorber as shown in Fig. 20. There is little change in the relative intensity when the moisture content is increased from 0 per cent to 30 per cent in all three species of wood because of the little change in the density of the wood. It is known that most all wood swells with an increase in its moisture content; however, most of this swelling occurs between 0 per cent and 30 per cent moisture content. Wood swells very little above 30 per cent moisture content. The relative intensity changes approximately 0.04 per cent for every 1 per cent change in the moisture content above 30 per cent for pine. Likewise, poplar shows a 0.09 per cent change, and hickory shows a 0.14 per cent change for every 1 per cent change in moisture content above 30 per cent.

SUMMARY AND CONCLUSIONS

It is known that when a parallel beam of gamma or x-rays passes through any material, the intensity of the emergent beam is less than that of the incident beam. The degree of attenuation of the radiations is determined by the kind and number of atoms composing the absorber.

Wood consists of many kinds of atoms; therefore, if the ratio of the kinds of atoms composing wood is shown to be consistent, any inconsistency in an absorption curve may then be attributed to a defect in the absorber.

Various energies of radiations were absorbed in pine, poplar, and oak boards and measured with a scintillation spectrometer. With this instrument a parallel beam of monoergic gamma or x-rays may be measured. The radiations decrease exponentially in passing through the wood, and when the results of such an absorption experiment are plotted on semi-logarithmic paper, a straight line curve is formed. The absorption curves for each species of wood were straight lines; therefore, it was assumed that the ratio of the kinds of atoms composing the wood was consistent throughout its thickness.

The next step was to determine whether a defect could be detected in a wood absorber. And, if the defect could be detected, could it be detected at any position within the absorber. To make this determination, a measurement was made of the penetrating radiations through a pile of 24 boards. A space was then created in the pile by removing one or more boards and maintaining the space created by their removal. Another measurement was then made on the remaining boards. The space was then varied according to location in the pile, and at each location similar measurements were made on the remaining boards. It was shown that even a one-half inch space can be detected easily by these means and that the position of the space has little to do with its resolution. Therefore, it was assumed that a defect can be detected in wood regardless of the position of the defect.

By using the scintillation spectrometer, an absorption curve was made for an oak log. It was shown that the intensity of the emergent beam varies exponentially according to the thickness of the log being measured, as was the case when using conveniently shaped boards. Similar absorption curves were then made for an oak log with a visible hole, then with the hole filled with water, and finally when the inner sides of the visible hole were wet. The defects were easily detected in all cases except when the hole was filled with water.

Absorption experiments, similar to those previously mentioned, were carried out by using a G-M counter circuit as the detector. It was shown that the absorption curves, when using boards for absorbers, showed a decrease in slope with an increase in the thickness of the absorber. This decreasing slope was considered especially important, since most of the defects in trees are expected to occur near the center of the tree. When this method of detecting defects was applied to defective logs, the defects were not resolved as well as when using the scintillation spectrometer.

Film was used to detect the penetrating radiations through both a sound and defective oak log. Based on measurements of the relative exposure of the developed film, there was a difference in exposure of the film between that of the sound log and that of the defective log. However, the defect was not resolved as well as when using the scintillation spectrometer.

A study of the relationship of the values of the linear and mass absorption coefficients to wood of varying moisture content was made. It was found that the values of the mass absorption coefficient decreased with an increase in the moisture content of the three species of wood studied. It was also shown that there was less change in the values of the mass absorption coefficient in the denser species of wood than in the less dense species of wood with like changes in moisture content. There was very little change in the relative intensity of penetrating radiations through wood from 0 per cent to 30 per cent moisture content, because of the little change in the density of the wood. Above 30 per cent moisture content, there was a greater change in the relative intensity in the denser species of wood than in the less dense species of wood with like changes in moisture content.

In the first paragraph of this report five separate problems were stated. In view of these problems five separate conclusions are given:

1. Defects in wood can be detected by means of the attenuation of gamma rays.

2. The extent of a defect can be determined regardless of its location in the wood by these means.

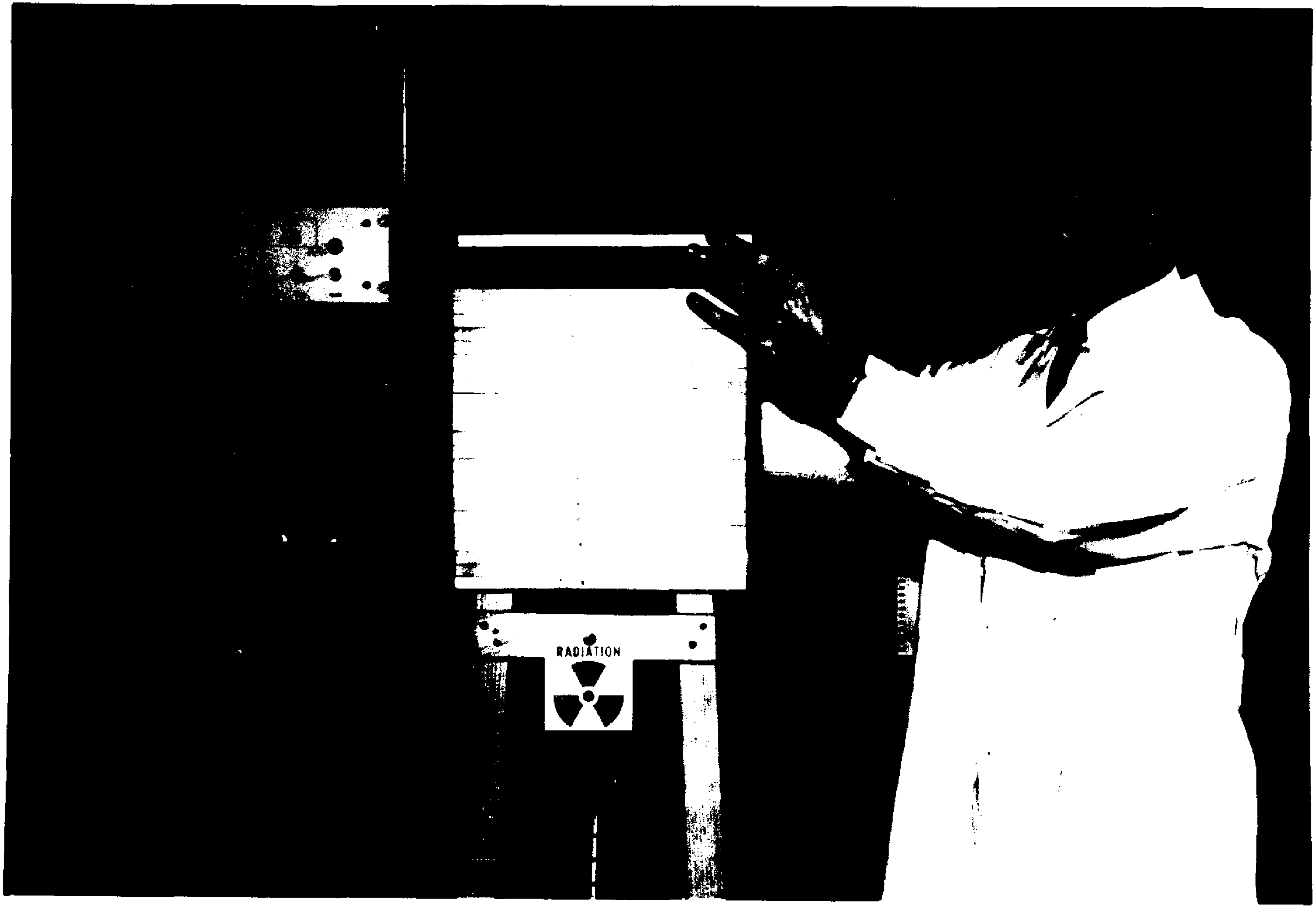
3. It appears that radiation energies between 50 and 150 Kev would be the most suitable energies to use to detect these defects.

4. The scintillation spectrometer appears to be the most suitable radiation detector for detecting defects in wood.

5. Variations in the moisture content of wood appears to vary the rate of attenuation of gamma rays by wood, but, the mass absorption coefficient of water is less than that of dry wood; therefore, the degree of attenuation is less than that indicated by the percentage variations of the moisture content of the wood.

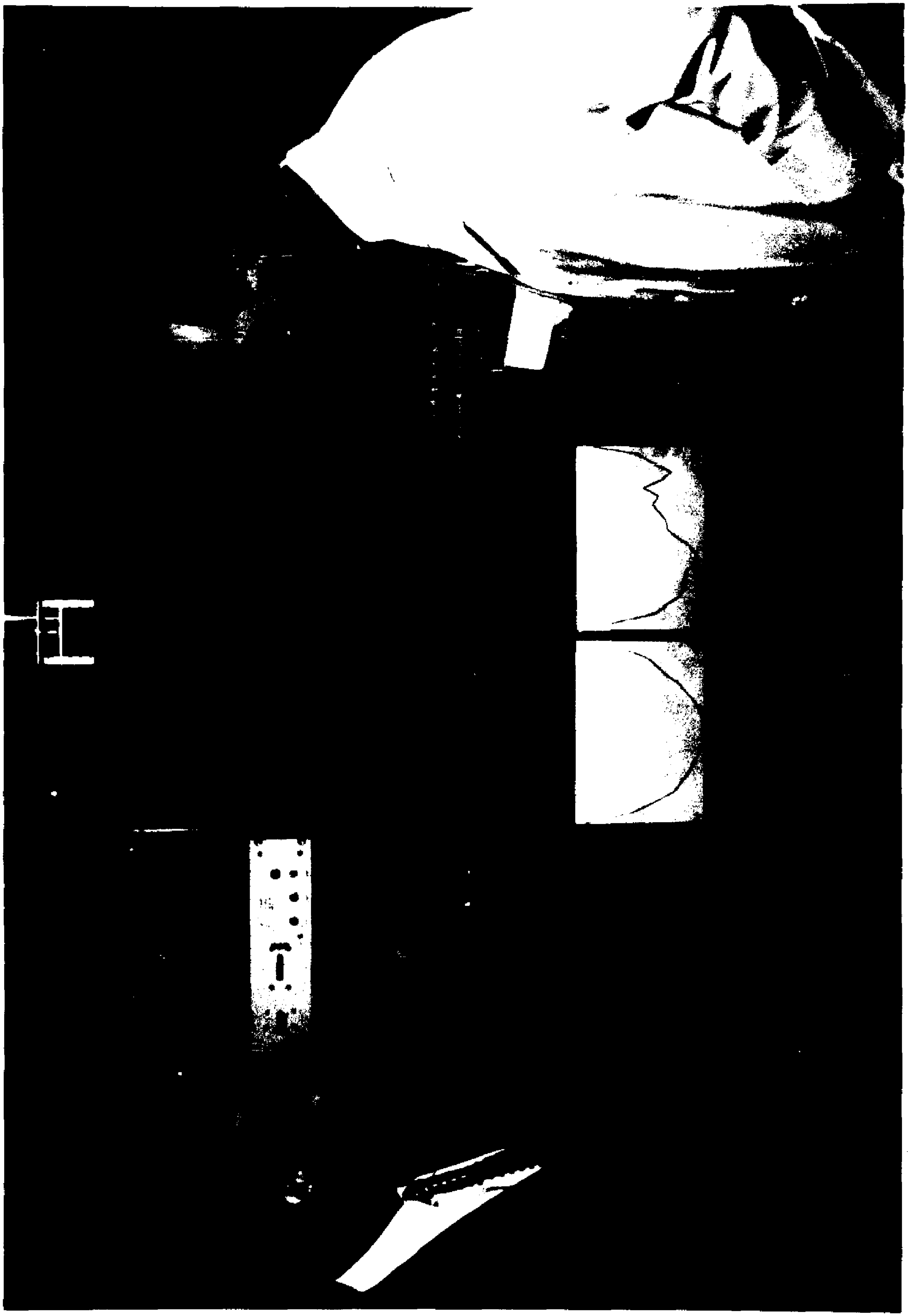
Legend for Plate I.

The author places a board on the absorber pile, underneath which is the radioactive source and above which is the scintillation crystal (not shown). The scintillation spectrometer can be seen in the background.


RADIATION

Legend for Plate II.

A solid and defective log lie above their respective absorption curves, with the author pointing to a cavity in the defective one.



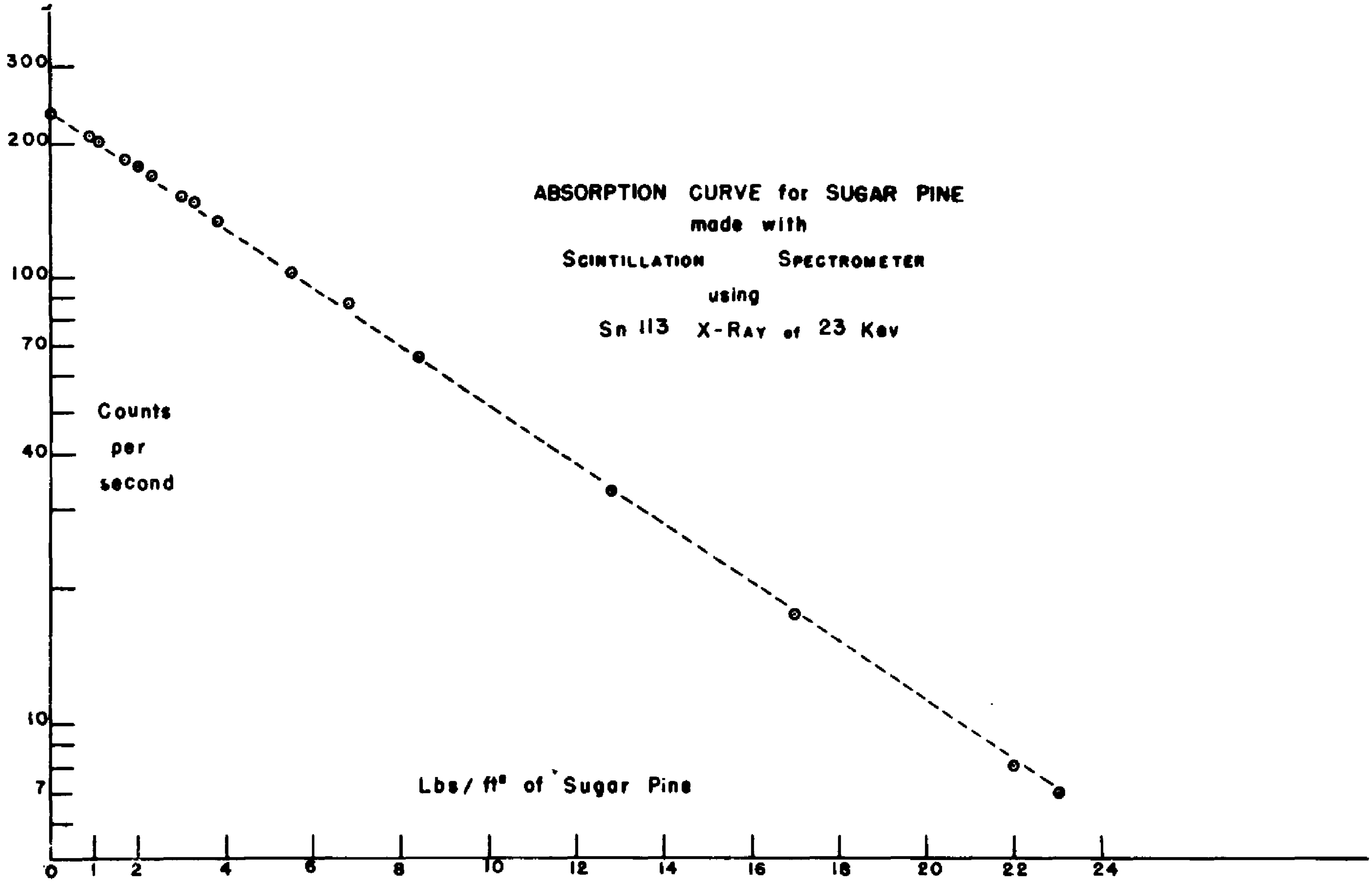
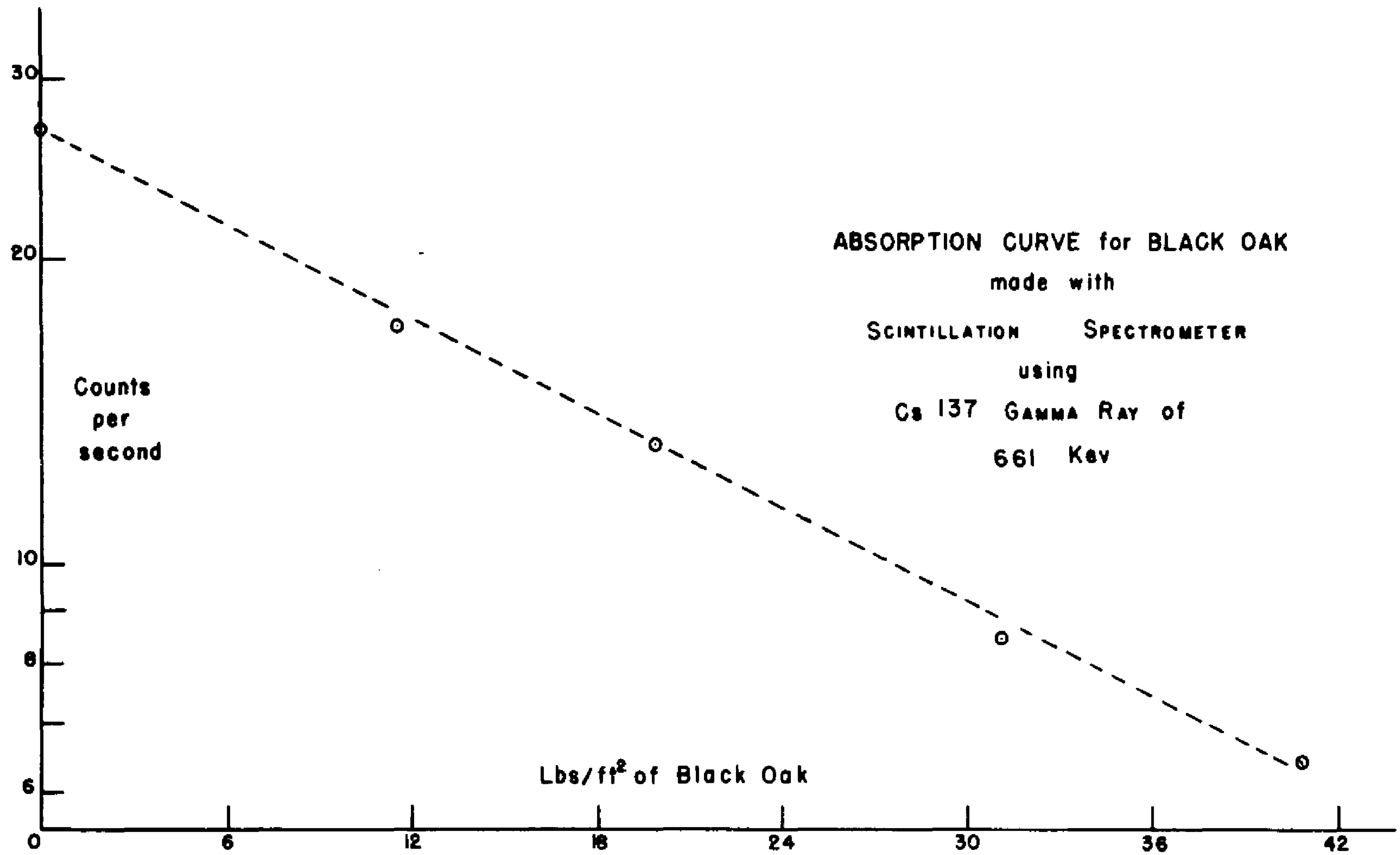

ABSORPTION CURVE for SUGAR PINE
made with
SCINTILLATION SPECTROMETER
using
Sn 113 X-RAY of 23 Kev
Counts per second
Lbs / ft² of Sugar Pine
300
200
100
70
40
10
7
0
1
2
4
6
8
10
12
14
16
18
20
22
24

Figure 1



ABSORPTION CURVE for BLACK OAK
made with
SCINTILLATION SPECTROMETER
using
Cs 137 GAMMA RAY of
661 Kev
Counts
per
second
Lbs/ft^2 of Black Oak
30
20
10
8
6
0
6
12
18
24
30
36
42

Figure 2

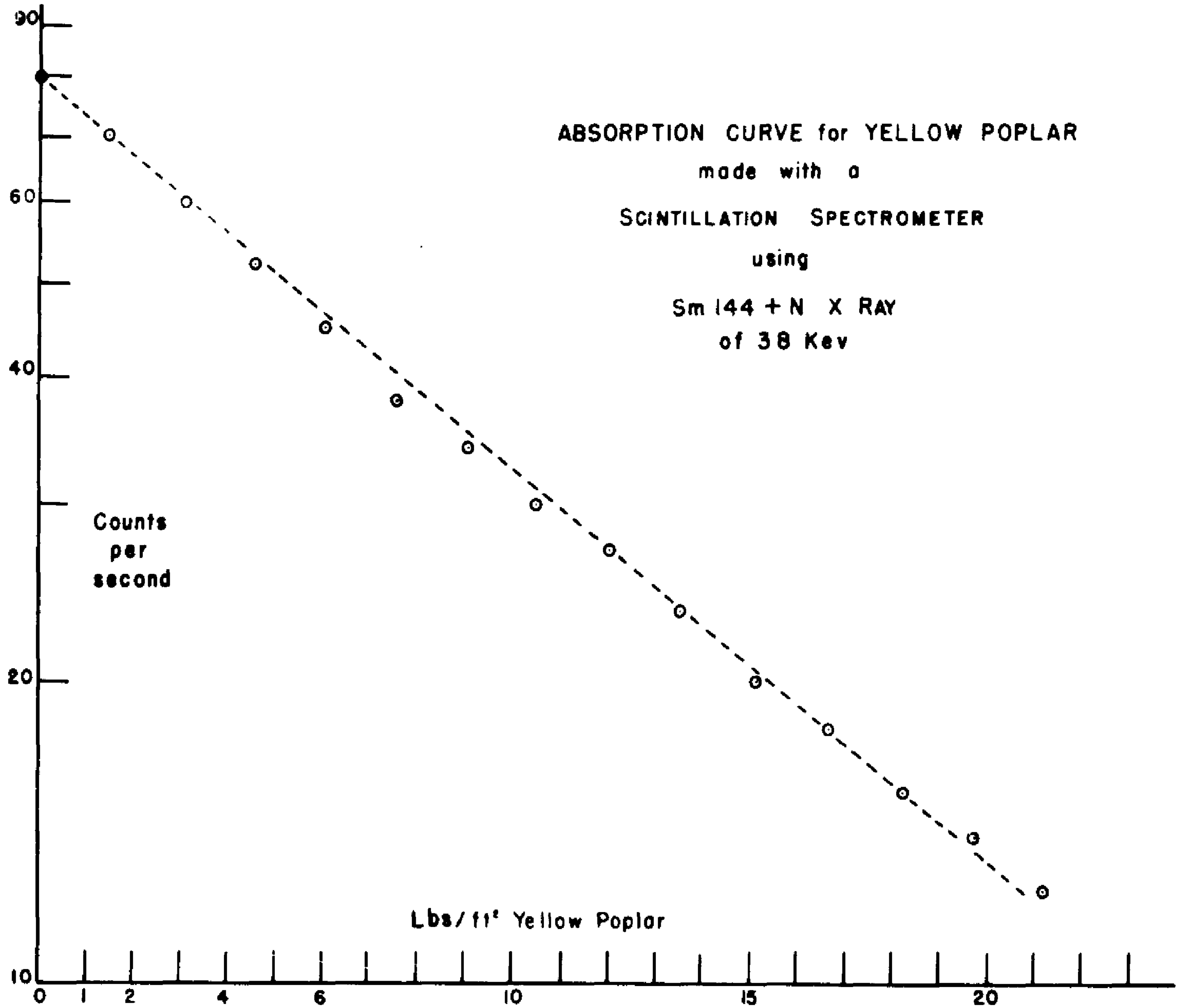

ABSORPTION CURVE for YELLOW POPLAR
made with a
SCINTILLATION SPECTROMETER
using
Sm 144 + N X RAY
of 38 Kev
Counts per second
Lbs/ft² Yellow Poplar
90
60
40
20
10
0
1
2
4
6
10
15
20

Figure 3

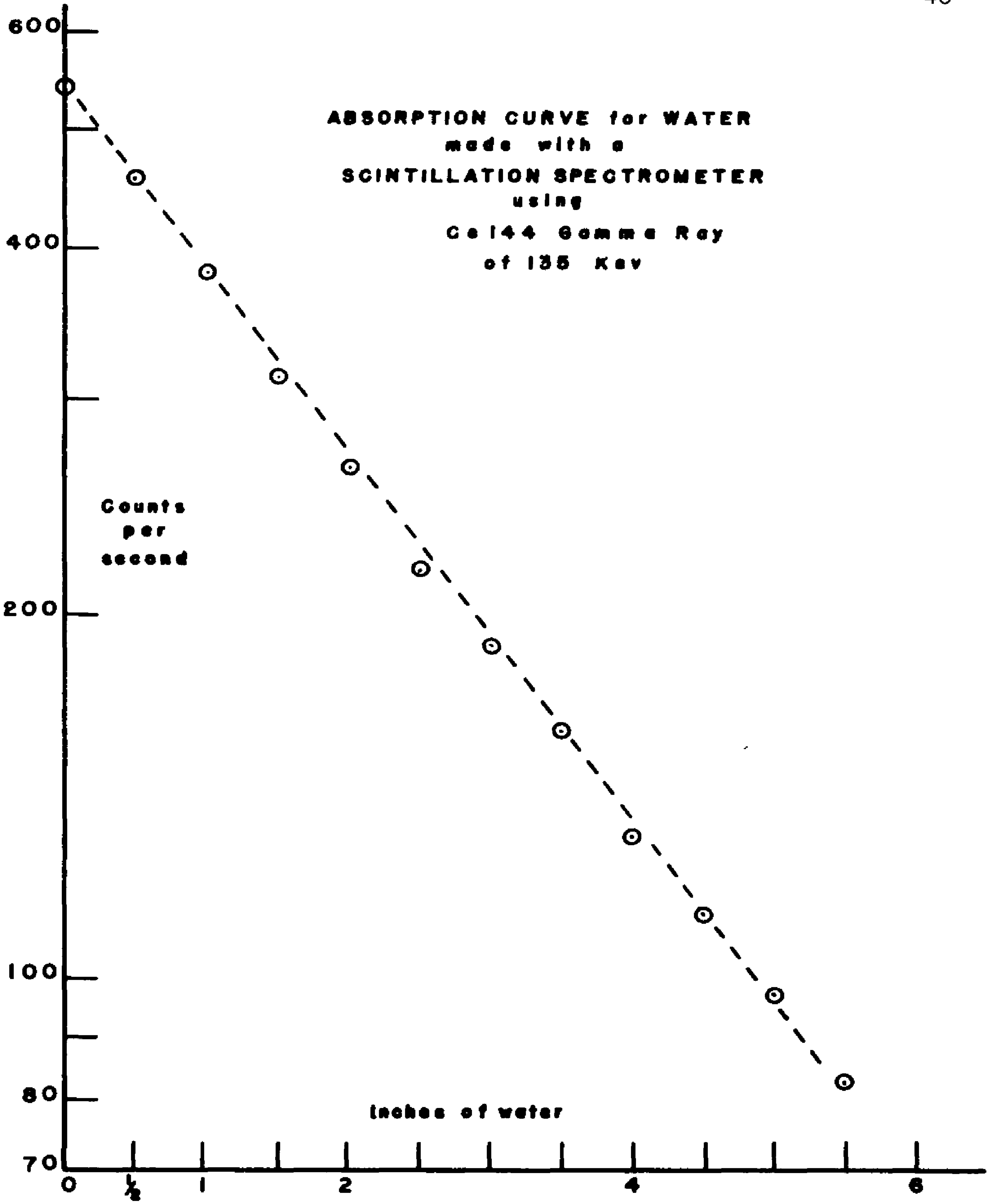
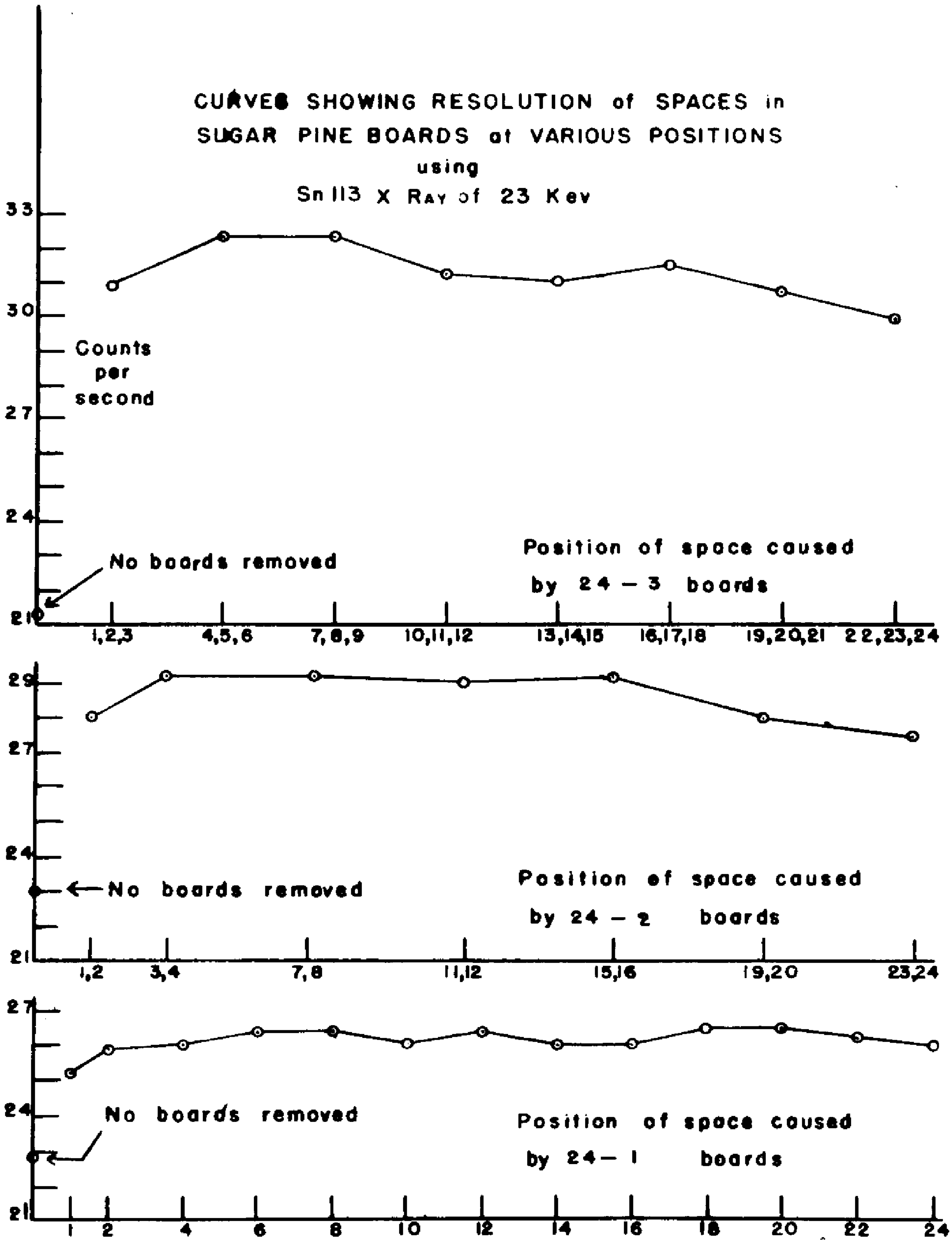
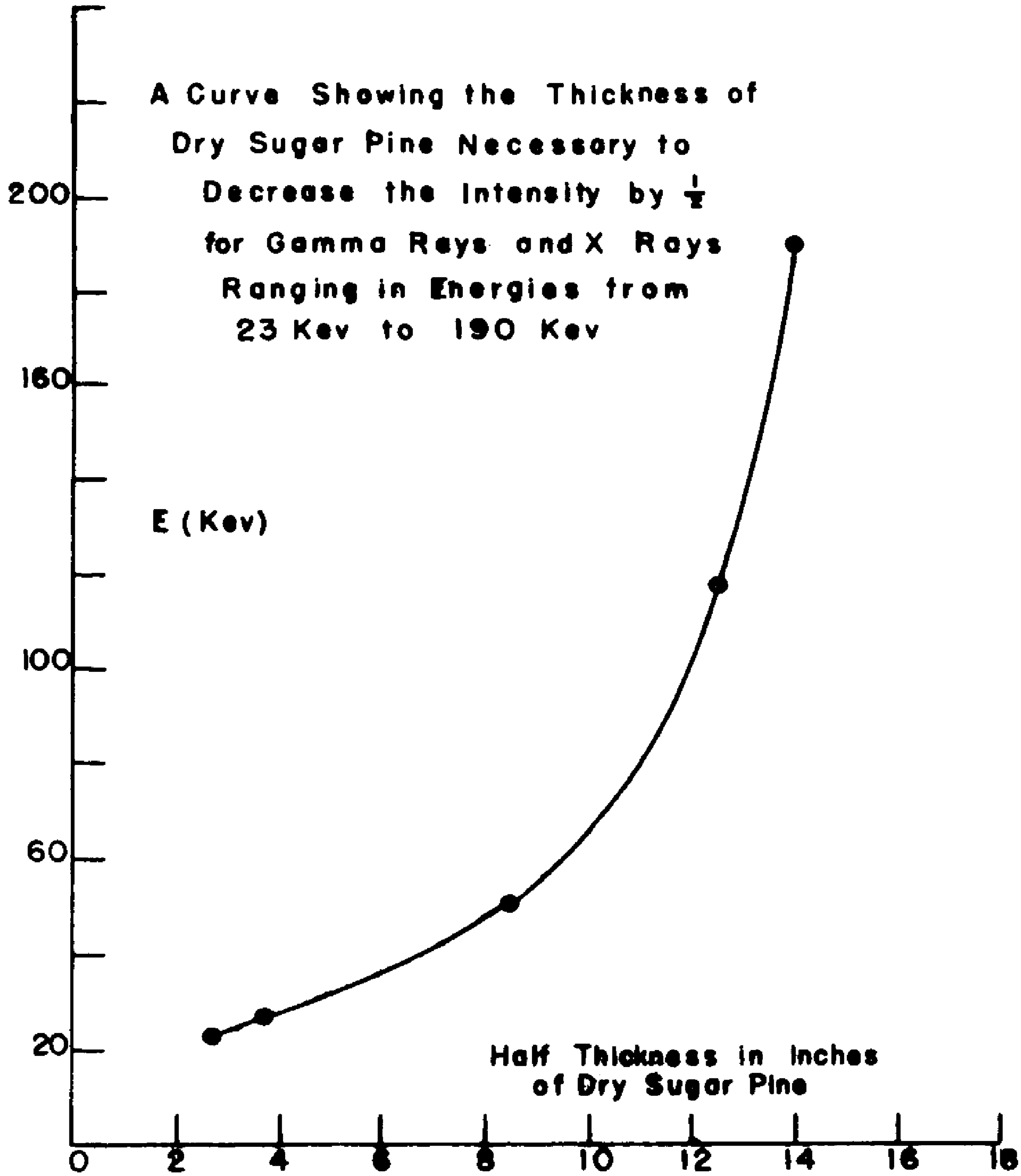

ABSORPTION CURVE for WATER
made with a
SCINTILLATION SPECTROMETER
using
Ce144 Gamma Ray
of 135 Kev
Counts
per
second
600
400
200
100
80
70
inches of water
0
½
1
2
4
6

Figure 4



CURVES SHOWING RESOLUTION of SPACES in
SUGAR PINE BOARDS at VARIOUS POSITIONS
using
Sn 113 X Ray of 23 Kev
Counts
per
second
33
30
27
24
21
No boards removed
Position of space caused
by 24 – 3 boards
1,2,3
4,5,6
7,8,9
10,11,12
13,14,15
16,17,18
19,20,21
22,23,24
29
27
24
21
No boards removed
Position of space caused
by 24 – 2 boards
1,2
3,4
7,8
11,12
15,16
19,20
23,24
27
24
21
No boards removed
Position of space caused
by 24 – 1 boards
1
2
4
6
8
10
12
14
16
18
20
22
24

Figure 5



A Curve Showing the Thickness of Dry Sugar Pine Necessary to Decrease the Intensity by 1/2 for Gamma Rays and X Rays Ranging in Energies from 23 Kev to 190 Kev
E (Kev)
200
160
100
60
20
Half Thickness in Inches of Dry Sugar Pine
0
2
4
6
8
10
12
14
16
18

Figure 6

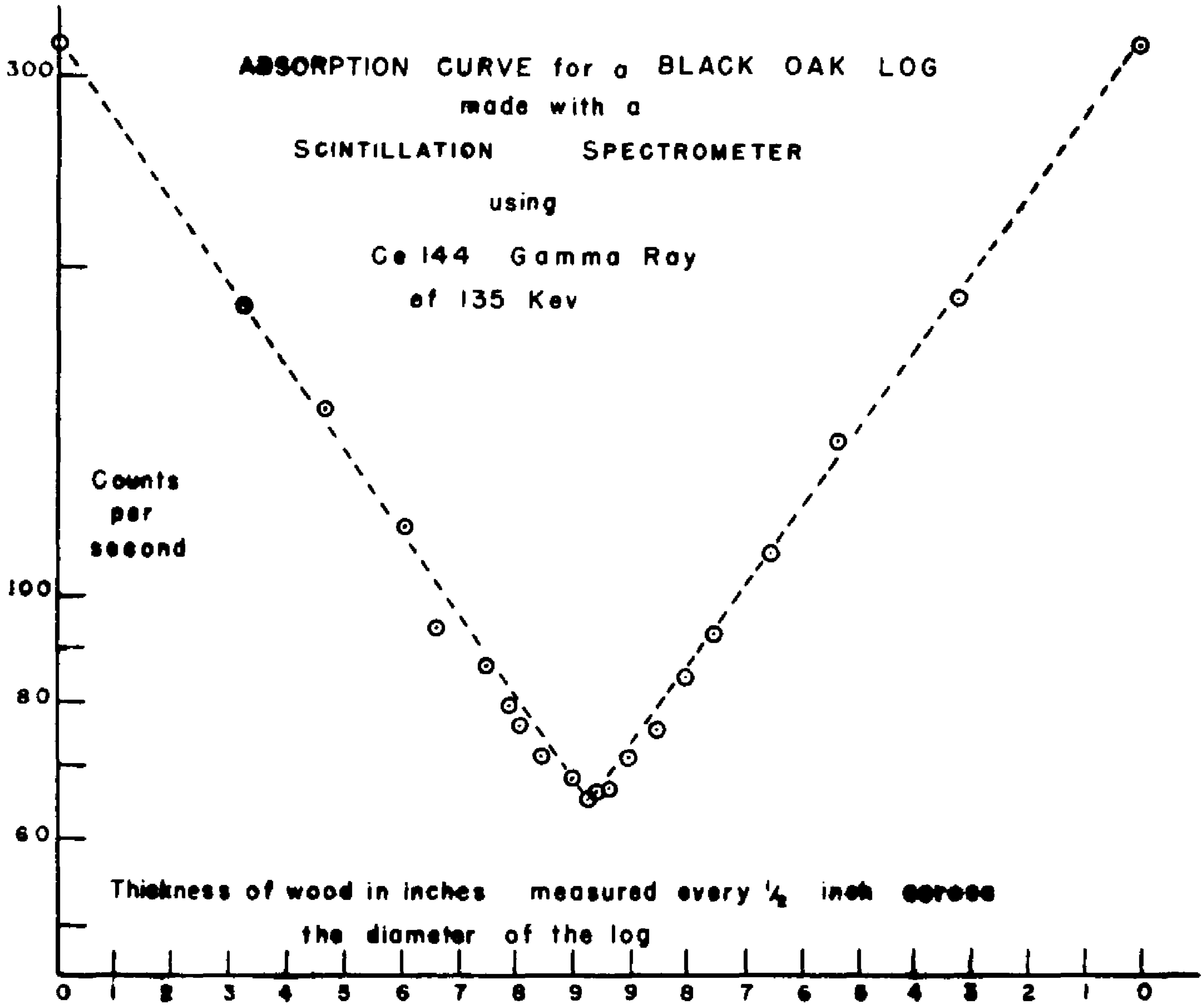

ABSORPTION CURVE for a BLACK OAK LOG
made with a
SCINTILLATION SPECTROMETER
using
Ce 144 Gamma Ray
of 135 Kev
300
100
80
60
Counts
per
second
Thickness of wood in inches measured every 1/2 inch across
the diameter of the log
0 1 2 3 4 5 6 7 8 9 9 8 7 6 5 4 3 2 1 0

Figure 7

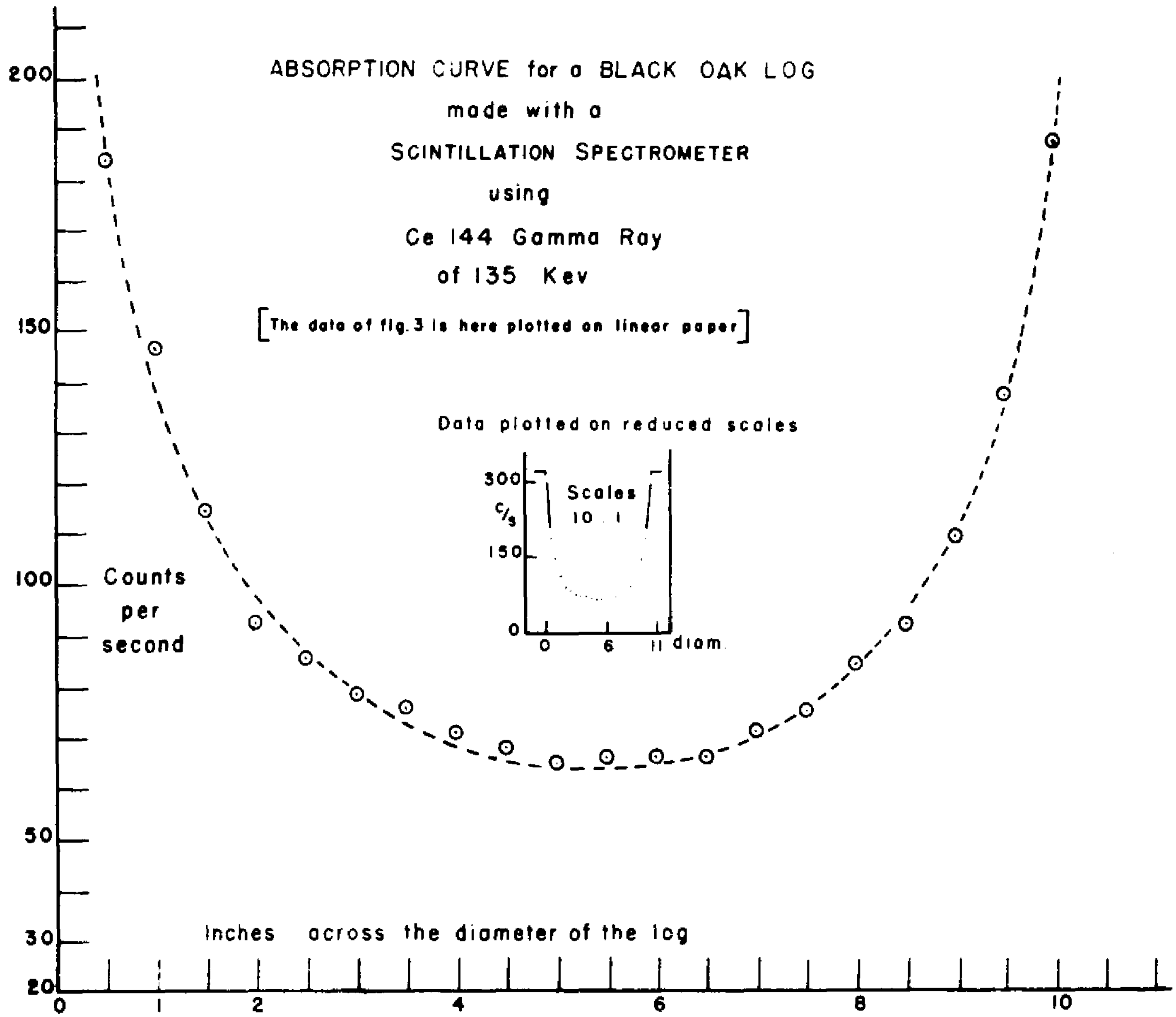

ABSORPTION CURVE for a BLACK OAK LOG
made with a
SCINTILLATION SPECTROMETER
using
Ce 144 Gamma Ray
of 135 Kev
[The data of fig. 3 is here plotted on linear paper]
Data plotted on reduced scales
300
c/s
150
0
Scales
10 : 1
0
6
11
diam.
200
150
100
50
30
20
Counts
per
second
Inches across the diameter of the log
0
1
2
4
6
8
10

Figure 8

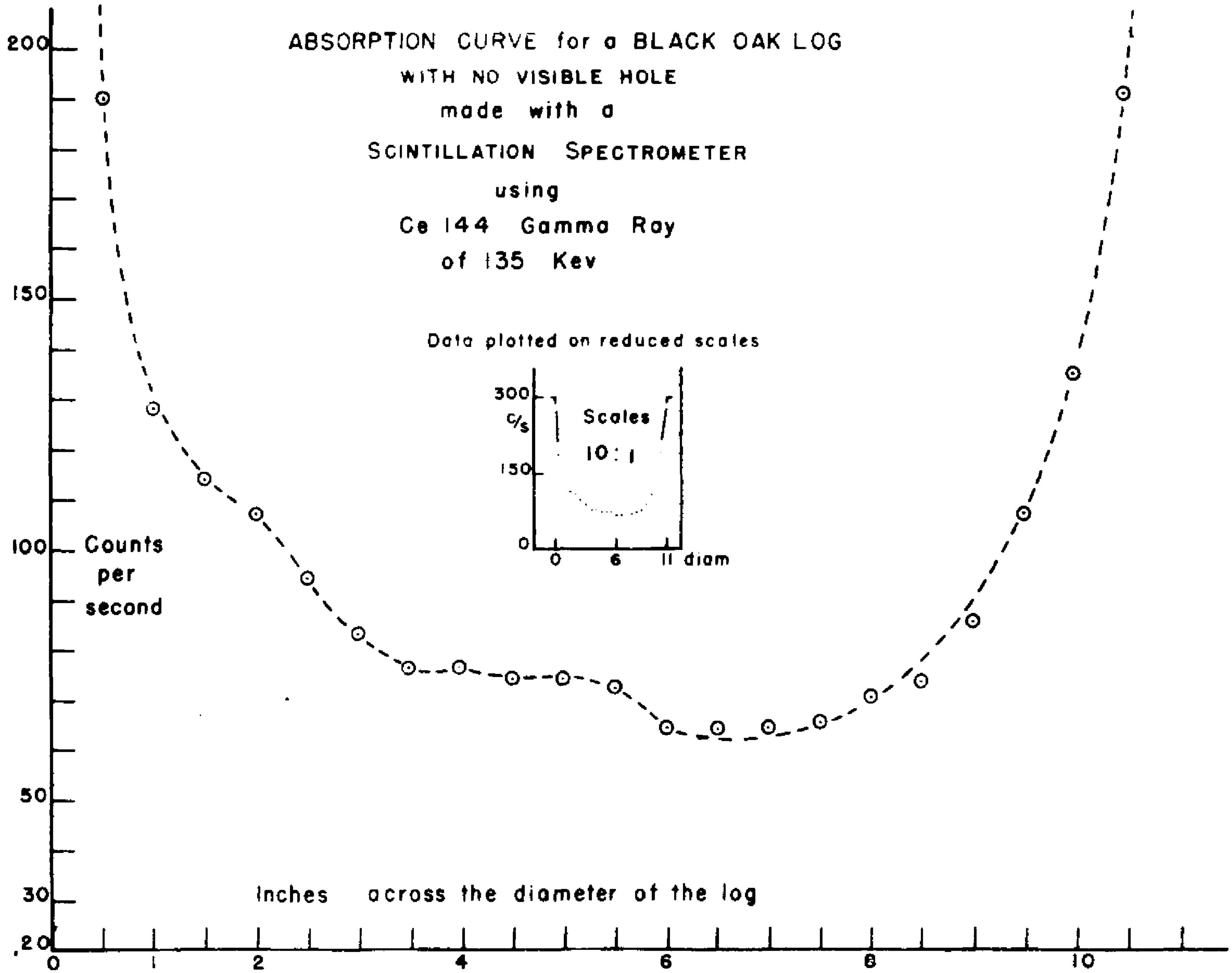

ABSORPTION CURVE for a BLACK OAK LOG
WITH NO VISIBLE HOLE
made with a
SCINTILLATION SPECTROMETER
using
Ce 144 Gamma Ray
of 135 Kev
Data plotted on reduced scales
300
c/s
150
0
Scales
10 : 1
0
6
11 diam
200
150
100
50
30
20
Counts
per
second
Inches across the diameter of the log
0
1
2
4
6
8
10

Figure 9

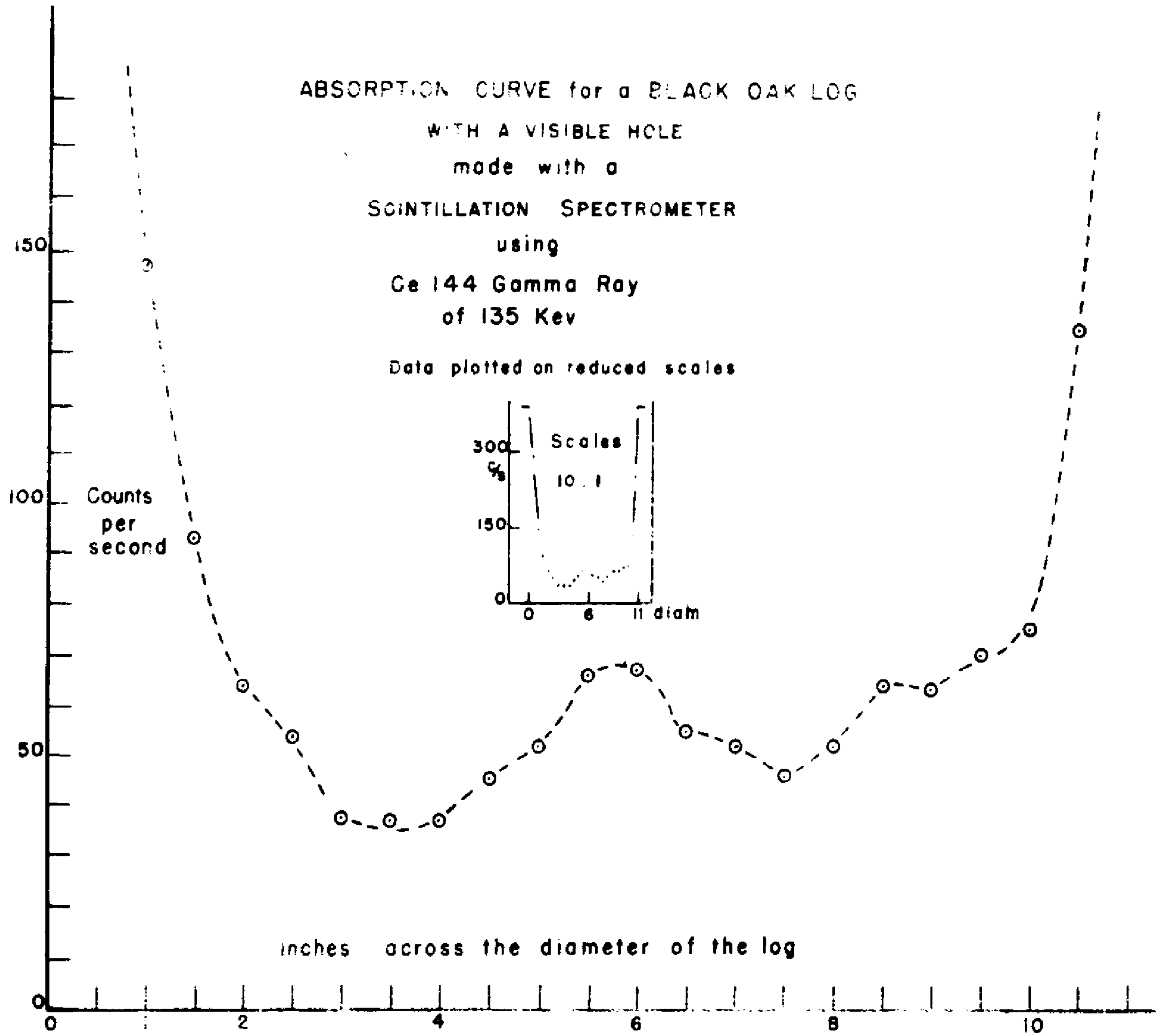

ABSORPTION CURVE for a BLACK OAK LOG
WITH A VISIBLE HOLE
made with a
SCINTILLATION SPECTROMETER
using
Ce 144 Gamma Ray
of 135 Kev
Data plotted on reduced scales
Scales
10 : 1
300
c/s
150
0
0
6
11 diam
150
100
50
0
Counts
per
second
inches across the diameter of the log
0
2
4
6
8
10

Figure 10

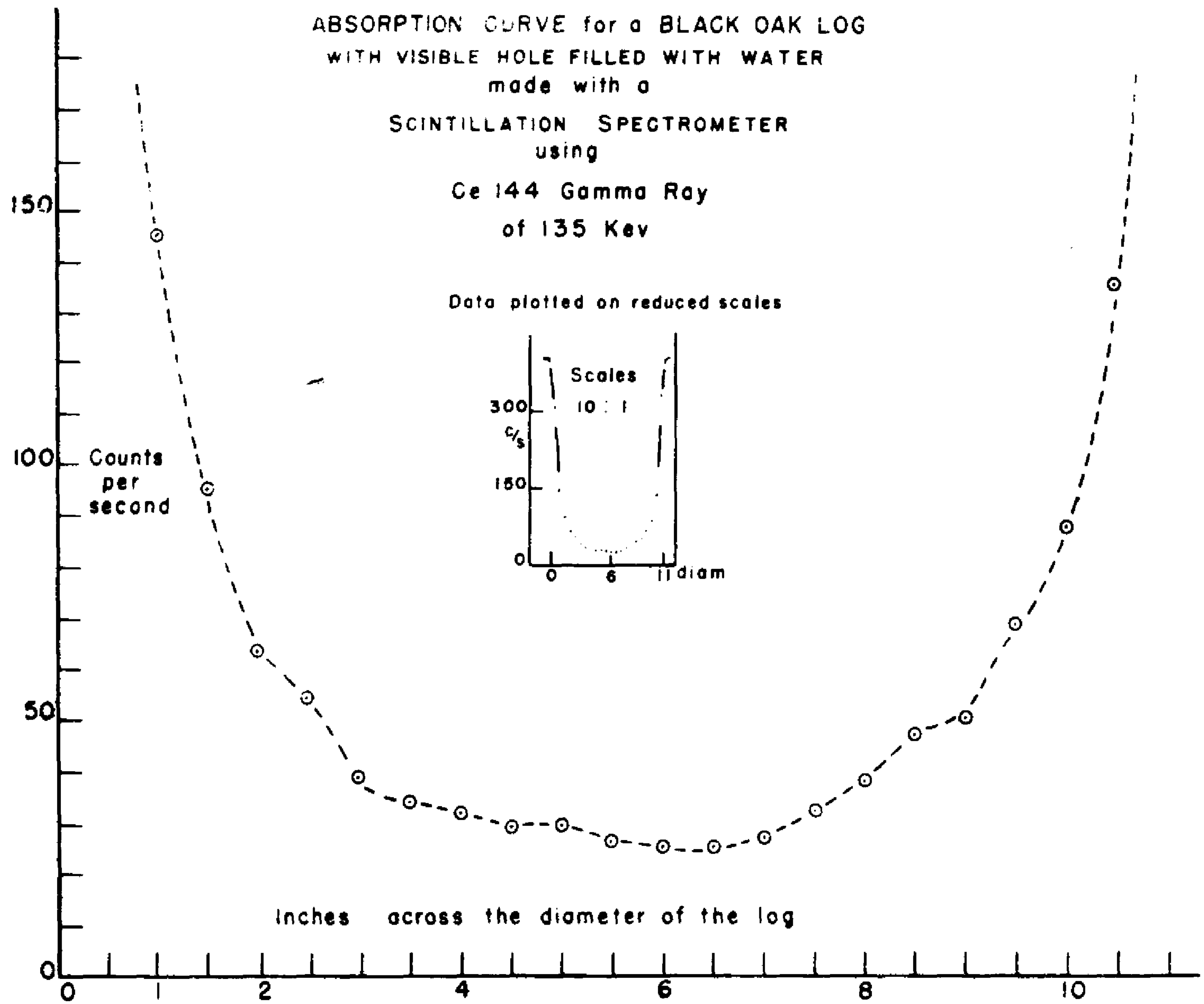

ABSORPTION CURVE for a BLACK OAK LOG
WITH VISIBLE HOLE FILLED WITH WATER
made with a
SCINTILLATION SPECTROMETER
using
Ce 144 Gamma Ray
of 135 Kev
Data plotted on reduced scales
Scales
10 : 1
300
c/s
150
0
0
6
11 diam
150
100
50
0
Counts
per
second
Inches across the diameter of the log
0
1
2
4
6
8
10

Figure 11

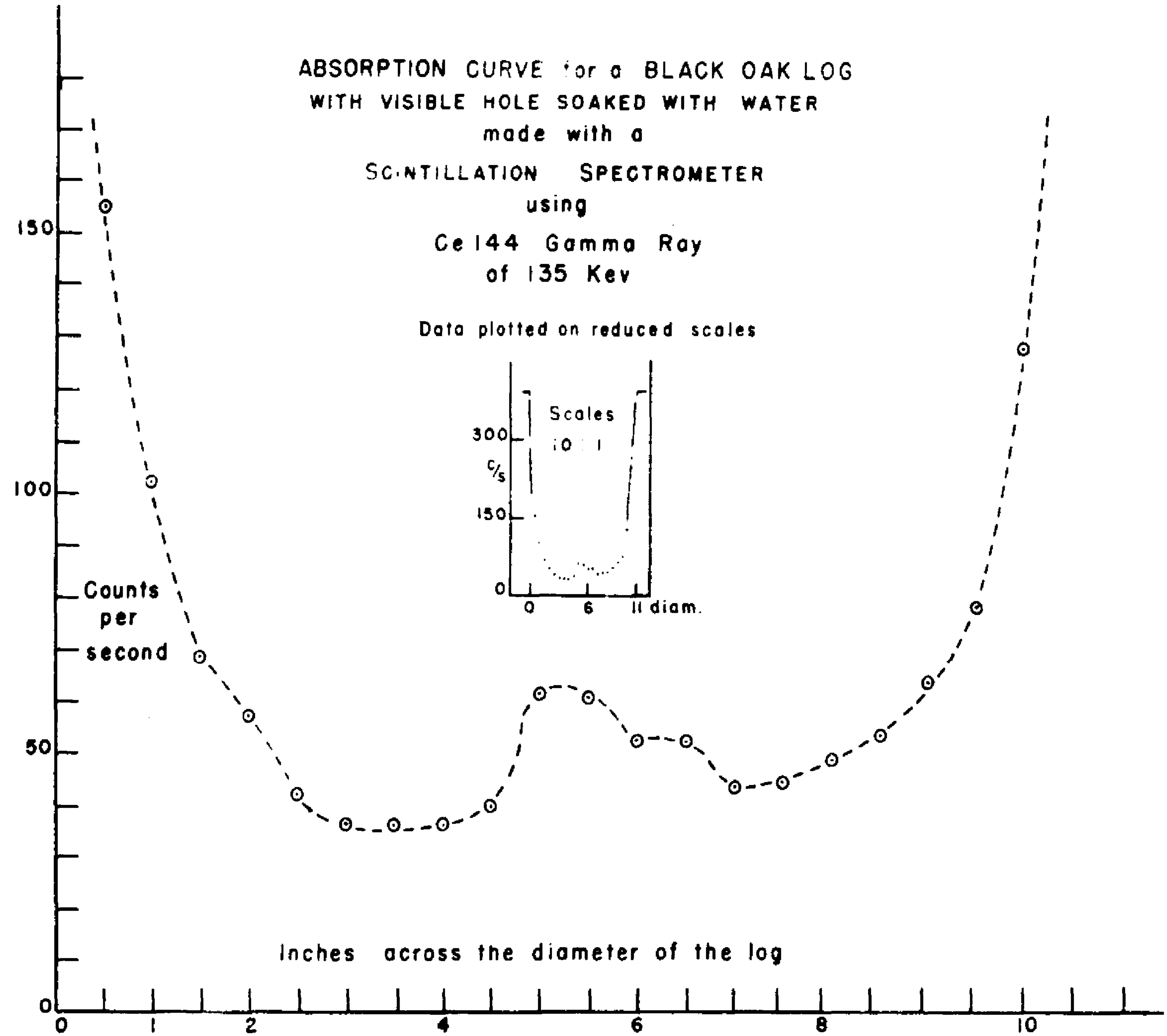

ABSORPTION CURVE for a BLACK OAK LOG
WITH VISIBLE HOLE SOAKED WITH WATER
made with a
SCINTILLATION SPECTROMETER
using
Ce 144 Gamma Ray
of 135 Kev
Data plotted on reduced scales
Scales
300
c/s
150
0
0
6
11 diam.
150
100
50
0
Counts
per
second
Inches across the diameter of the log
0
1
2
4
6
8
10

Figure 12

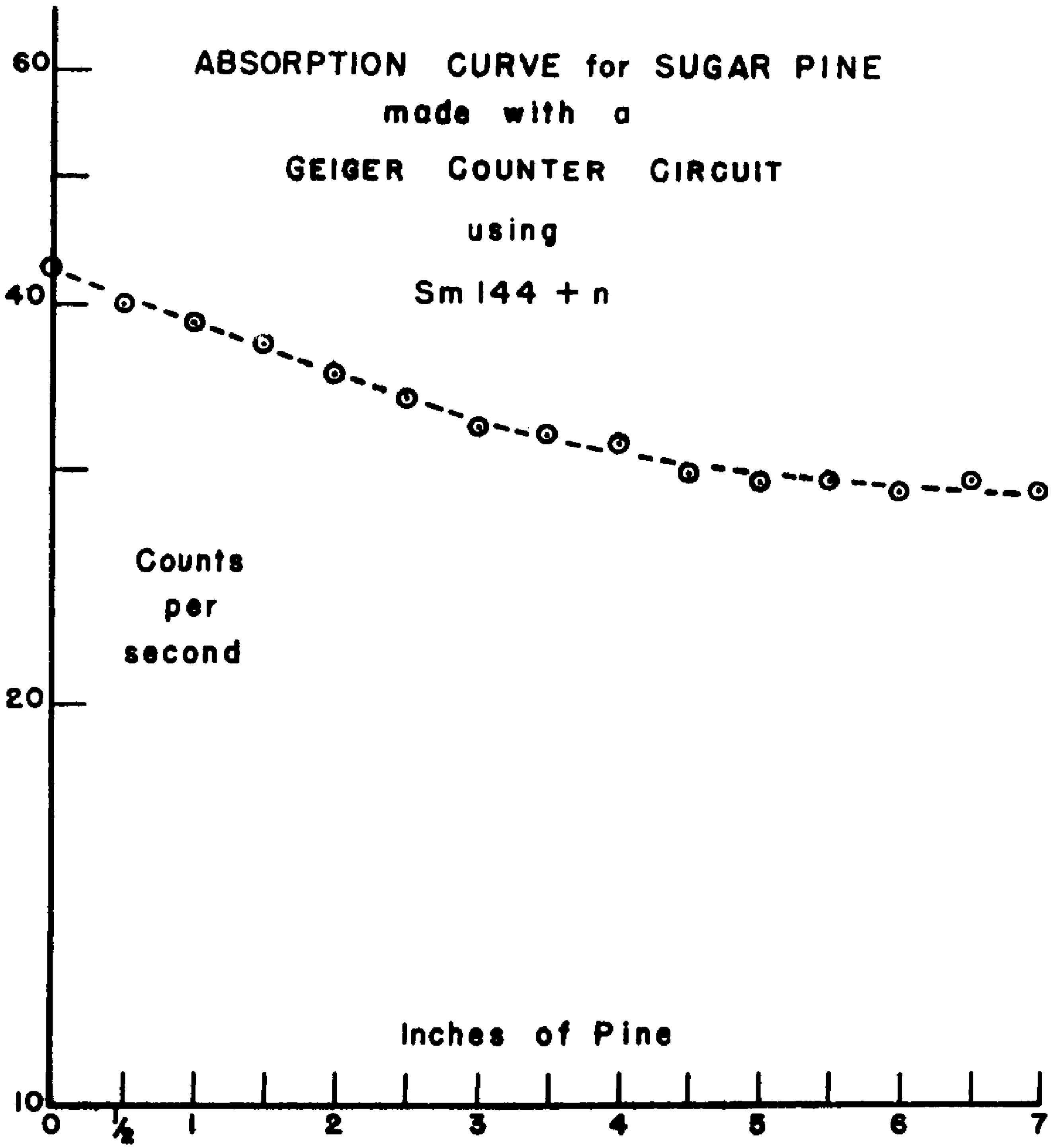
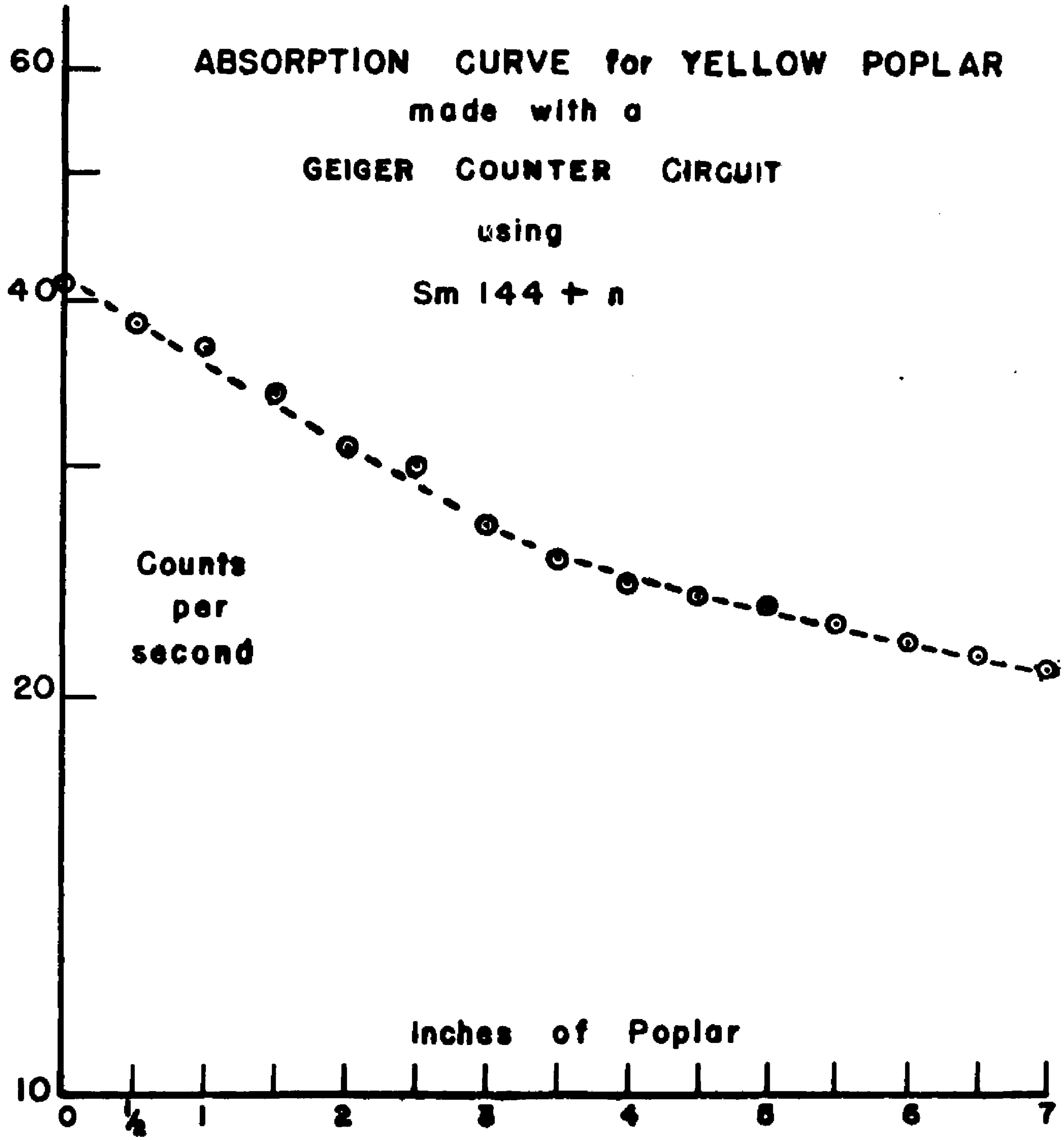

ABSORPTION CURVE for SUGAR PINE
made with a
GEIGER COUNTER CIRCUIT
using
Sm 144 + n
60
40
20
10
Counts
per
second
Inches of Pine
0
½
1
2
3
4
5
6
7

Figure 13



ABSORPTION CURVE for YELLOW POPLAR
made with a
GEIGER COUNTER CIRCUIT
using
Sm 144 + n
Counts
per
second
Inches of Poplar
60
40
20
10
0
½
1
2
3
4
5
6
7

Figure 14

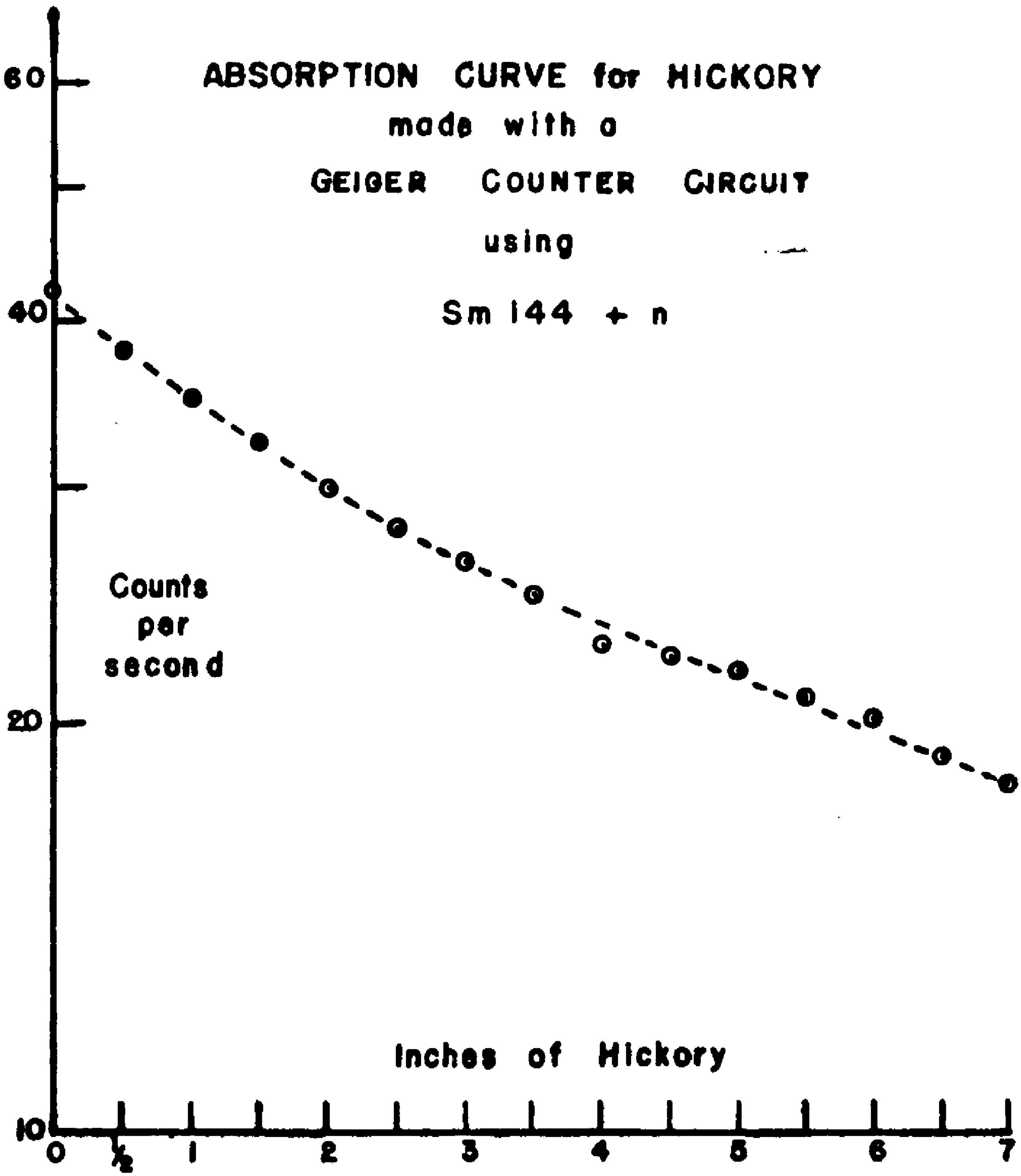

ABSORPTION CURVE for HICKORY
made with a
GEIGER COUNTER CIRCUIT
using
Sm 144 + n
Counts
per
second
60
40
20
10
Inches of Hickory
0
½
1
2
3
4
5
6
7

Figure 15

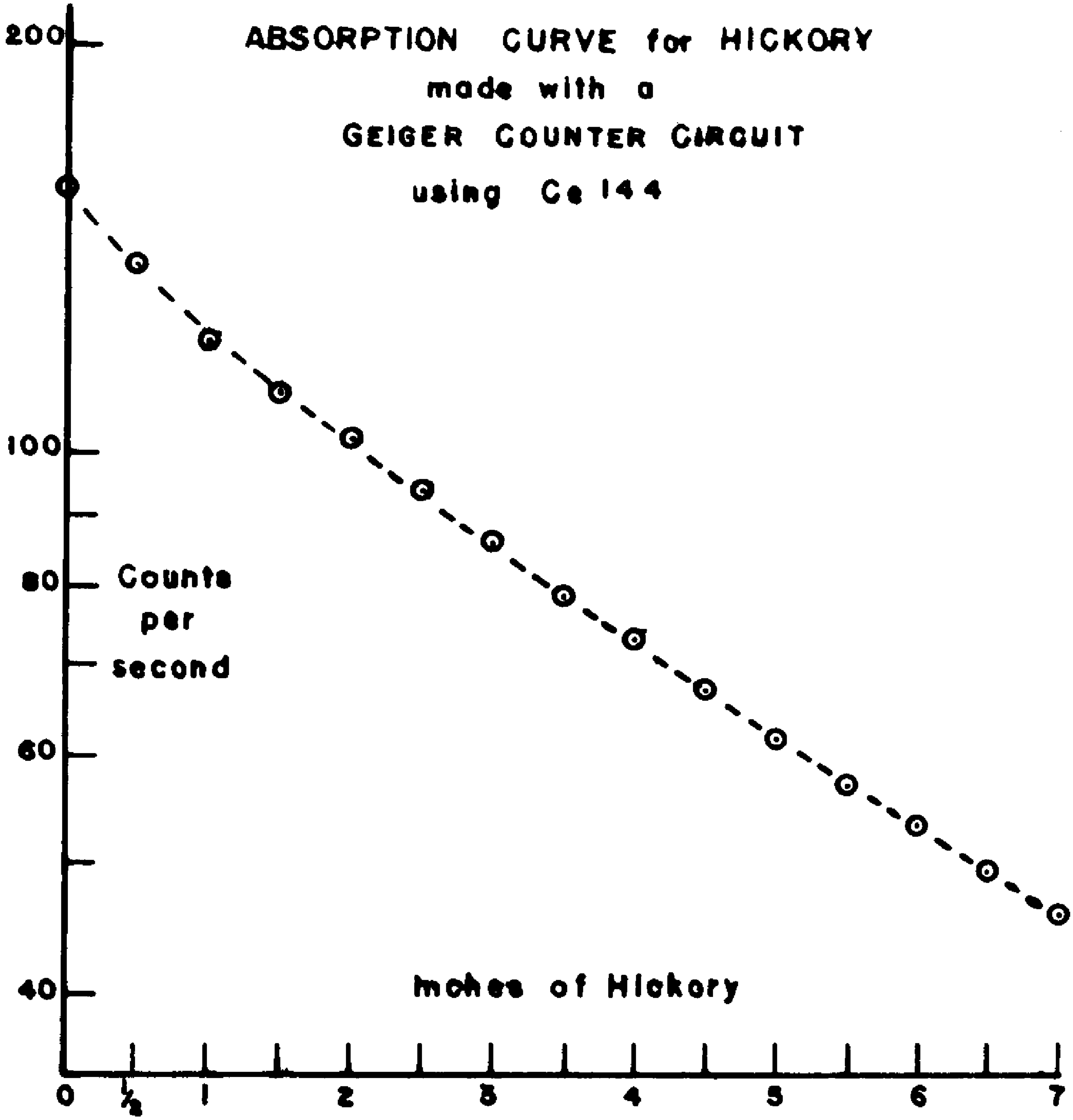

ABSORPTION CURVE for HICKORY
made with a
GEIGER COUNTER CIRCUIT
using Ce 144
200
100
80
60
40
Counts
per
second
Inches of Hickory
0
½
1
2
3
4
5
6
7

Figure 16

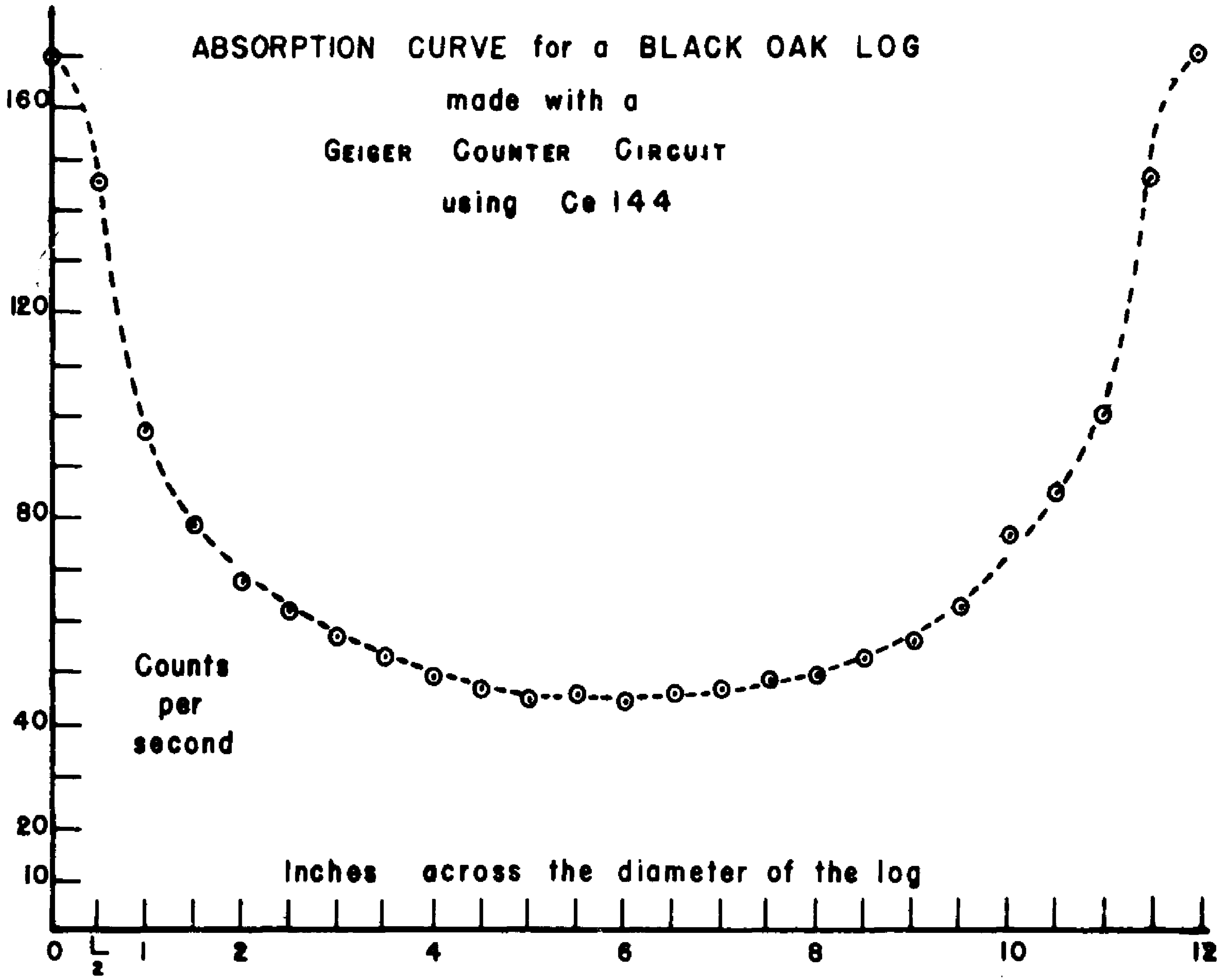
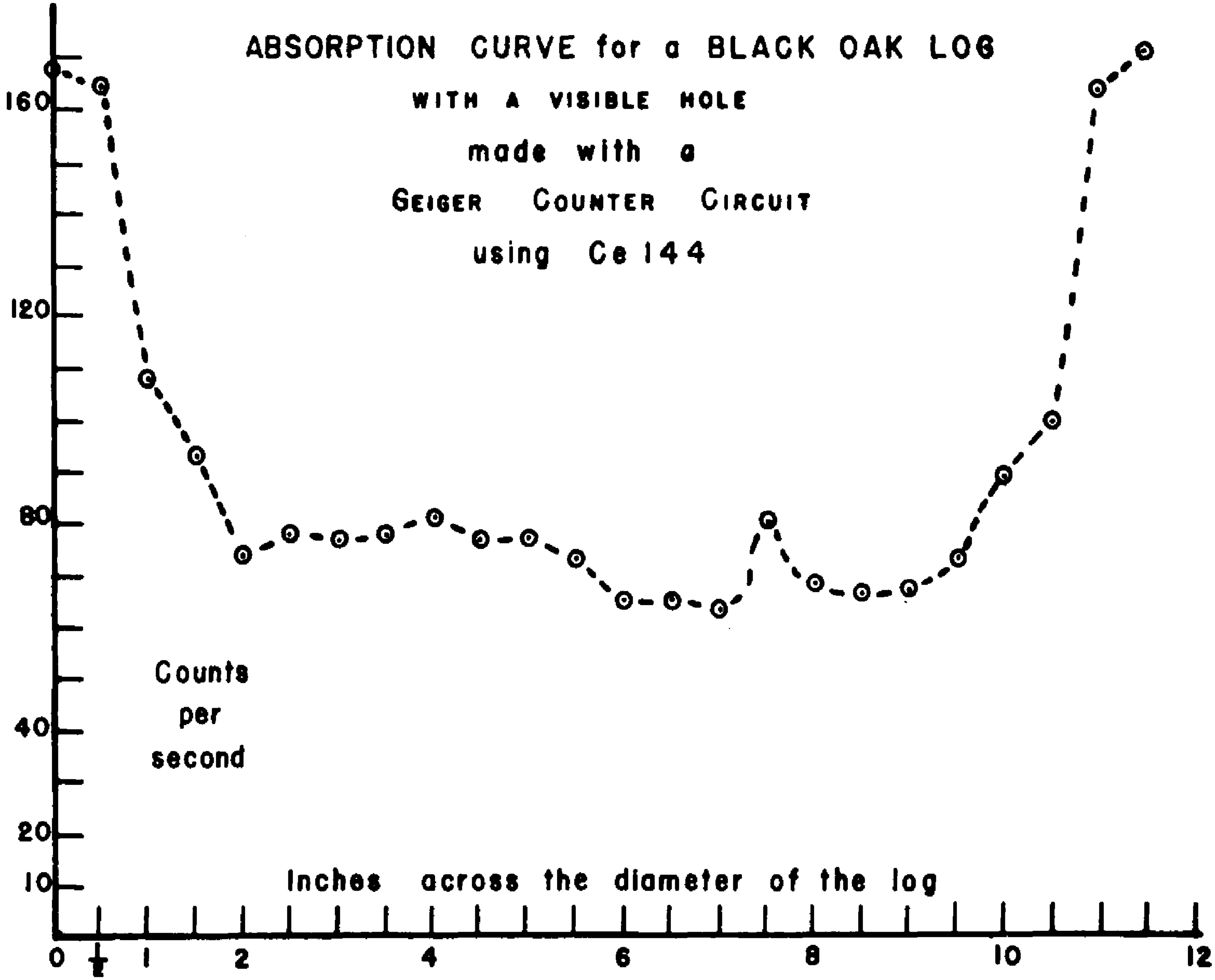

ABSORPTION CURVE for a BLACK OAK LOG
made with a
GEIGER COUNTER CIRCUIT
using Ce 144
160
120
80
40
20
10
Counts
per
second
Inches across the diameter of the log
0
1/2
1
2
4
6
8
10
12

Figure 17



ABSORPTION CURVE for a BLACK OAK LOG
WITH A VISIBLE HOLE
made with a
GEIGER COUNTER CIRCUIT
using Ce 144
160
120
80
40
20
10
Counts
per
second
Inches across the diameter of the log
0
½
1
2
4
6
8
10
12

Figure 18

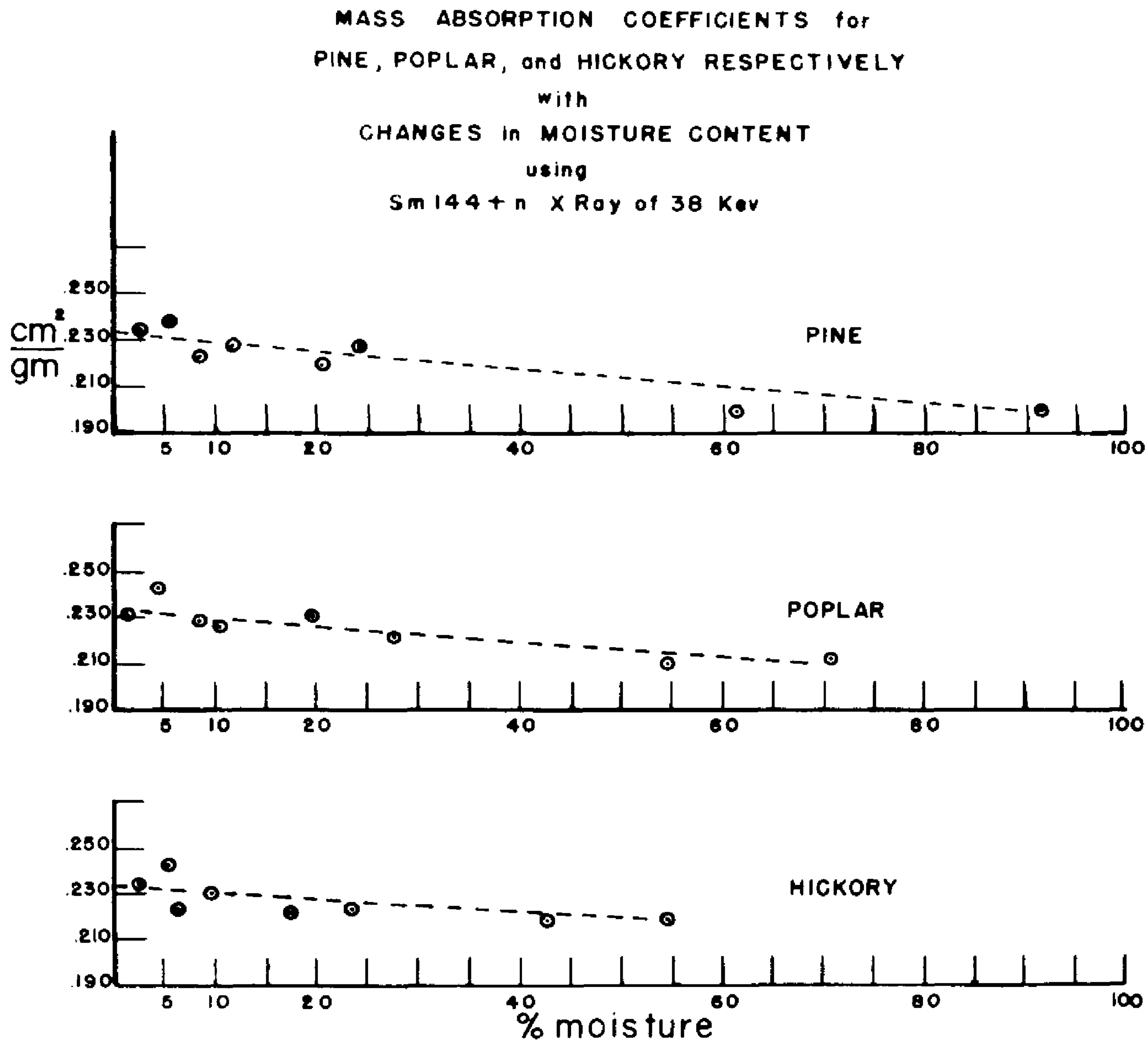

MASS ABSORPTION COEFFICIENTS for
PINE, POPLAR, and HICKORY RESPECTIVELY
with
CHANGES in MOISTURE CONTENT
using
Sm 144 + n X Ray of 38 Kev
cm²/gm
.250
.230
.210
.190
PINE
POPLAR
HICKORY
5
10
20
40
60
80
100
% moisture

Figure 19

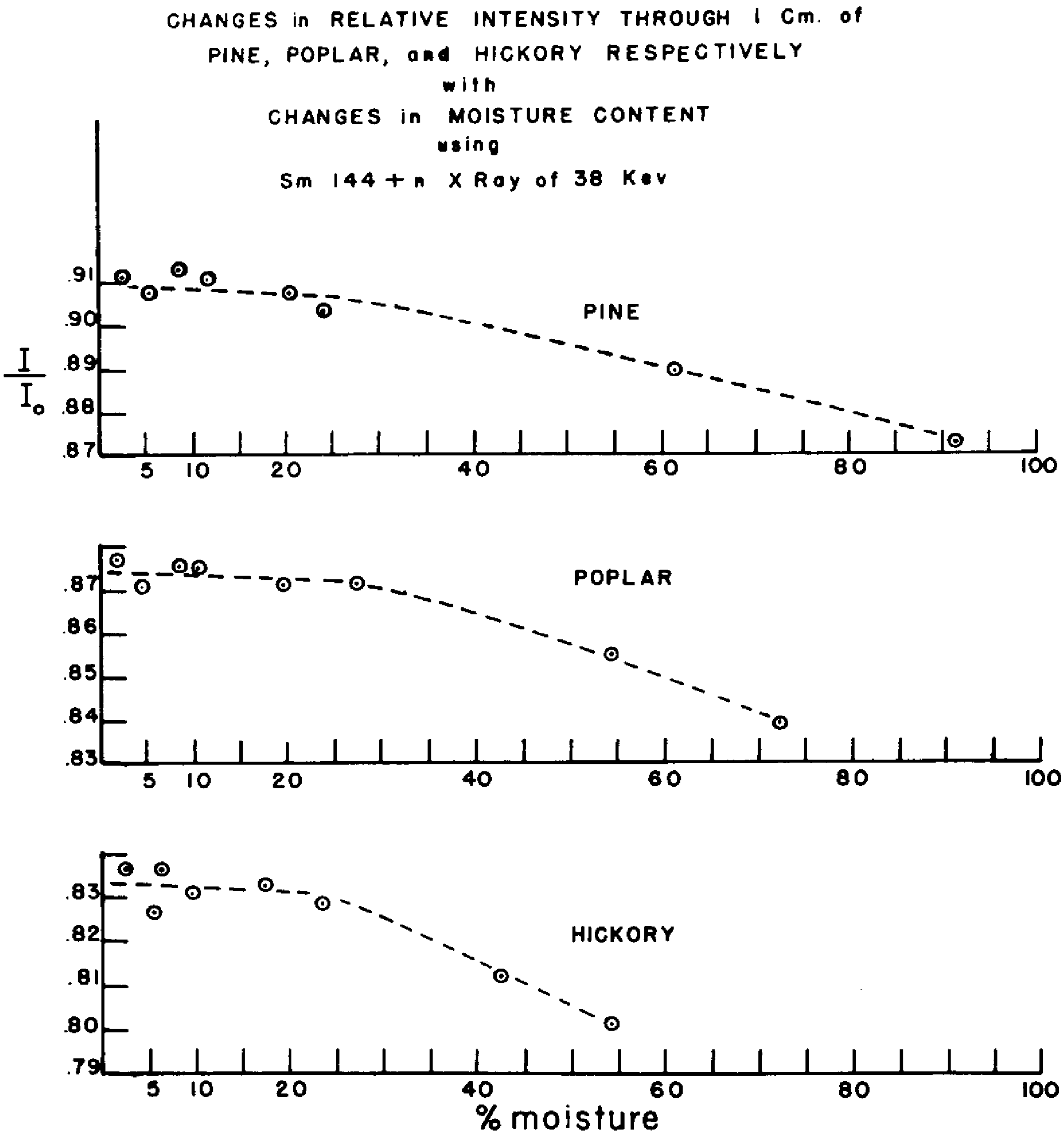

CHANGES in RELATIVE INTENSITY THROUGH 1 Cm. of
PINE, POPLAR, and HICKORY RESPECTIVELY
with
CHANGES in MOISTURE CONTENT
using
Sm 144 + n X Ray of 38 Kev
I/I0
.91
.90
.89
.88
.87
PINE
5
10
20
40
60
80
100
POPLAR
.87
.86
.85
.84
.83
HICKORY
.83
.82
.81
.80
.79
% moisture

Figure 20

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AUTOBIOGRAPHY

I, Wayne B. Parrish, son of Homer D. and Mary K. Parrish, was born in Walnut Township, Fairfield County, Ohio, December 18, 1920. I received my secondary school education in the Millersport public school, Millersport, Ohio, and my undergraduate training at Ohio State University, which granted me the Bachelor of Science degree in 1948. Also from the Ohio State University I received the Master of Science degree in 1955. In October, 1955, I began my doctorate study and while in residence there, I was appointed Graduate Assistant in the Department of Zoology and Entomology during the years 1954-56. In April, 1956, I was appointed Research Assistant in the Department of Zoology and Entomology in which position I completed the research presented herein. In October, 1957, I was appointed Research Assistant in the Department of Cancer Research, University Hospital, Columbus, Ohio. I held this position for nine months while completing the requirements for the degree Doctor of Philosophy.