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DETERMINATION AND EVALUATION OF THE RADIATION FIELD ABOVE WHITE OAK LAKE BED

P. K. Lee
S. I. Auerbach

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HEALTH PHYSICS DIVISION

DETERMINATION AND EVALUATION OF THE RADIATION FIELD ABOVE WHITE OAK LAKE BED

P. K. Lee and S. I. Auerbach

Submitted as a thesis to the Faculty of the Graduate School of Vanderbilt University in partial fulfillment of the requirements for the degree of Master of Science in physics.

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TABLE OF CONTENTS

		Page
I.	Introduction	1
	Purpose of Investigation	1
	History of White Oak Lake	2
	Current Use of White Oak Lake Bed	5
II.	Description of the Area	7
III.	Description of Radiation Detectors	12
	Ionization Chamber	12
	Film	14
IV.	Field Measurements	17
	Ionization Chamber	17
	Film	19
V.	Results	22
VI.	Discussion	36
	Appendix I	45
	Bibliography	62

LIST OF FIGURES

Figure		Page
1.	Aerial Photograph of White Oak Lake Bed Soon After Draining, 1955	4
2.	Map of White Oak Lake Bed Showing Location of Ecology Study Areas	8
3.	Average Concentration of Radionuclides Present in the Top Four Inches of White Oak Lake Bed Soil (Grid Area, 1958)	10
4.	View of Ecology Grid Area (White Oak Lake Bed)	18
5.	Aerial View of Agricultural Plot and Observation Pole (White Oak Lake Bed)	21
6.	Relative Response of Radiation Detectors to Radiation Field of White Oak Lake Bed	23
7.	Air Dose Rates One Meter Above the Ecology Grid Area (Lower Lake Bed)	26
8.	Air Dose Rates One Meter Above the Ungridded Ecology Study Area (Upper Lake Bed)	28
9.	Air Dose Rates One Meter Above White Oak Lake Bed in 15 mr/hr Increments	30
10a.	Sediment Deposit and Associated Radiation Field (White Oak Lake Bed)	31
10b.	Sediment Deposit and Associated Radiation Field (White Oak Lake Bed)	32
11.	Comparison of Gamma Radiation Dose Rates at Heights Above White Oak Lake Bed with that Above a Fallout Type Source	35
12.	Aerial View Showing Relative Location of ORNL Waste Disposal Pits to White Oak Lake Bed	39

ABSTRACT

The radiation above the contaminated soil of White Oak Lake bed was characterized in terms of horizontal and vertical distribution of air dose rates over most of the bed. These data are needed for studies investigating effects of this chronic low-level radiation upon mammals and other organisms inhabiting the area.

Radiation measurements were made with dosimeter film and with a portable ionization-chamber-type instrument (cutie pie) employing two separate chambers (gamma-and-beta-sensitive; gamma-sensitive). The radiation intensity was determined at heights of 5, 25, 50, and 100 cm above the ground, and at one location at heights upward to 15 meters.

The surveys disclosed that the radiation was predominately (90%) gamma; consequently, variations of intensity with height were slight. The radiation field was nonuniform over the lake bed. The range of dose rates was from less than 1 mr/hr to a maximum of 100 mr/hr. In general, regions having associated radiations of higher dose rates (50 mr/hr) were located near the inlet end of the lake bed, while lower dose rates (10 mr/hr) were registered above regions along the shore line.

Some marked variations of the radiation field are related to changes in distribution and quantity of radionuclides in the lake bed soil. These changes are induced by soil erosion in the lake bed, periodic flooding of the contaminated creek flowing through the area, and by seepage from

radioactive waste disposal pits in the vicinity. Of these environmental factors the radioactive seepage from the waste disposal pits introduces the greatest alteration of the radiation field. Weekly fluctuations over portions of the lake bed in which the radioactive material (Ru^{106}) is being deposited were as much as 50 mr/hr during the course of the investigation.

K. Z. Morgan of ORNL has derived the equation

$$D = \sum_{i = 1,2,3\ldots} \frac{2\pi}{u_i} Nn_i G_i \left[1 - E_2 (u_i h_i) \right].$$

which determines the expected dose rate (D) above a large slab source of thickness (h_i) in which radionuclides (i) of concentrations Nn_i are uniformly distributed. This equation was applied to a section of the lake bed, utilizing absorption coefficients of soil (u_i), dose rates 1 cm distant from a 1-mc point source of gamma-emitting nuclei in the lake bed soil (G_i), and exponential integrals of the second order (E_2). Solution of this equation after scattered radiation was considered gave a theoretical value of 18 mr/hr, which compared favorabley with the measured mean value of 16 mr/hr. Based on the above mathematical analysis it was estimated that because of decay of the radionuclides, the average dose rate above the area will decrease 20% in the next two years and 50% in the next ten years (1968).

I. INTRODUCTION

Purpose of Investigation

The atomic energy industry has produced a considerable quantity of radioactive wastes. Although most of this radioactive material has been confined to restricted and isolated situations, a part of it has been released into the environment. The fate of the radionuclides contained in the waste material once they have entered an environment has not been adequately established. This lack of knowledge, coupled with the probability that larger quantities of radioactive waste material will be released in the future, has required that more research be undertaken to gain information about the changes induced in nature by the addition of radionuclides. The broad objectives of this research are to help evaluate the direct and indirect hazards to the human population.

The White Oak Lake bed area, which has been used as a disposal site for low-level radioactive waste effluent from ORNL, is one of the few sites in the world which has received significant quantities of radioactive material. Because of this contamination the area affords an unusual opportunity for ecological research concerning the effects and fates of radionuclides in a natural environment. A knowledge of the radiation fields resulting from the contamination of the lake bed is needed for such research. The intensity of the radiation field is closely related to the distribution of the radionuclides. Therefore, the measurement of this radiation field not

only defines the external dose rates to which organisms are subjected at various parts of the lake bed, but also indicates the general distribution of the contaminants. This investigation provides detailed information of dose rates and characterizes the radiation field above the lake bed.

History of White Oak Lake

In 1943 White Oak Lake was constructed to serve as a final settling basin for radioactive waste material being carried by White Oak Creek from Clinton Laboratories (now ORNL). A dam .6 mile above the Clinch River impounded the waters of the creek, forming a lake of about 35 acres. In the interim of twelve years that the area served as a settling basin, radionuclides settled to the lake bottom and became intermixed with silt depositions, forming a radioactive mud. In conjunction with the use of the lake as a waste impoundment, surveys were conducted by TVA and ORNL to determine the capacity of the lake[1] and the rate and quantity of silt deposition on the lake bottom.[2,3] Also, periodic analyses of the bottom muds were made

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[1] L. S. Setter and O. W. Kochtitzky, Studies of the White Oak Creek and Drainage System, ORNL-562 (1950).

[2] A. S. Frye, Sediment Investigation of White Oak Creek and Lake, Roane County, Tennessee, TVA, Hydraulic Data Branch, Chattanooga (1951).

[3] A. S. Frye, Sediment Investigation of White Oak Creek and Lake, Roane County, Tennessee, TVA, Hydraulic Data Branch, Chattanooga (1953).

to determine the quantity and kinds of radionuclides present.[4,5,6]

The contaminated lake was a unique environment in which investigations could be made of the consequences resulting from the dissemination of radionuclides into an aquatic habitat. In the period 1950-1953 TVA in cooperation with AEC conducted a comprehensive survey[7] in which the botany, limnology, and fisheries biology of the lake were studied. The uptake and accumulation of radioactive materials by fish[8] and the effects of the radionuclides upon the fish population[9] were also determined by other surveys.

By 1954 the lake had come into equilibrium with White Oak Creek in terms of its ability to dilute and otherwise hold up radioactive materials. The fish populations were poisoned and removed, and the lake was drained in October, 1955. This draining was done slowly so that the contaminated silt would not be disturbed. Figure 1 is an aerial photograph showing

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[4] K. Z. Morgan and J. S. Cheka, Radioactive Fission Product Contamination in Mud of White Oak Drainage System, Mon H-258 (1947).

[5] H. H. Abee, Radioactivity in the Mud of White Oak Lake, ORNL-1580 (1953).

[6] H. H. Abee, Annual Mud Survey Data White Oak Lake, 1954-55, Oak Ridge National Laboratory, unpublished work.

[7] An Ecological Survey of White Oak Creek, 1950-1953, conducted by TVA for AEC, February, 1954, unpublished work.

[8] V. I. Knobf, Studies of Radioactivity in Fish from White Oak Lake and the Clinch River, ORNL-1031 (July 9, 1951).

[9] L. A. Krumholz, "Observations of the Fish Population of a Lake Contaminated by Radioactive Waste," Bulletin of the American Museum of Natural of Natural History 110, Article 4 (1956).

Fig. 1. Aerial Photograph of White Oak Lake Bed Soon After Draining, 1955.

the condition of the lake bed immediately after this draining. The dam (indicated by arrow in Fig. 1) has been kept in operation and is used to control the concentrations of radionuclides released from the Laboratory to the Clinch River. In the event that large concentrations of radionuclides are released into the White Oak Creek, the dam can be completely closed, thus impounding the contaminated water.

Current Use of White Oak Lake Bed

The main function served by the lake bed, in addition to being an emergency hold-up basin, has been that of a terrestrial ecological research site. This research is broad in scope and is concerned with the fates of fission products in a terrestrial habitat and with effects of radiation upon populations living in this habitat. Soil-to-plant transfer of Sr^{90} and Cs^{137} is being studied in various parts of the lake bed.[10,11] The accumulation of fission products by insects and mammals and the effects of radiation on the resident small mammal populations are also under investigation. Concentrations of radionuclides present in the lake bed are being

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[10] E. R. Graham, "Uptake of Waste Sr^{90} and Cs^{137} by Soil and Vegetation," Soil Science 86, 9197 (1958).

[11] S. I. Auerbach and D. A. Crossley, Jr., Strontium-90 and Cesium-137 Uptake by Vegetation under Natural Conditions, Paper 401, International Conference on Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1958.

determined by extensive soil analyses.[12,13,14] A detailed description of the various projects being conducted can be found in the 1957 and 1958 ORNL Health Physics Division Annual Progress Reports.[15,16]

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[12] S. I. Auerbach *et al.*, Oak Ridge National Laboratory, unpublished data.

[13] H. R. DeSelm, University of Tennessee, unpublished data.

[14] G. L. Plummer, University of Georgia, unpublished data.

[15] "Ecological Research," Health Physics Division Annual Progress Report for Period Ending July 31, 1957, ORNL-2384, 10-23 (1957).

[16] "Ecological Research," Health Physics Division Annual Progress Report for Period Ending July 31, 1958, ORNL-2590, 30-41 (1958).

II. DESCRIPTION OF THE AREA

Present ecological studies were begun on White Oak Lake bed soon after the lake was drained. In order to facilitate these investigations the area was divided into two sections, referred to as the upper lake bed and lower lake bed. The natural boundary between these sections was the line formed where the creek flows across the lake bed from the south shore toward the north shore (Fig. 1).

The radiation surveys required coordinate systems containing many reference points. A rectangular grid previously surveyed and prepared over a portion of the lower lake bed fulfilled the requirements of such a reference system above this area. The grid consists of metal fence posts set at 10-meter intervals, and covers approximately 10 acres of the lake bed (Fig. 2). No permanent grid system was available in the upper portion of the lake bed. However, a row of 25 stakes (represented by line A-B in Fig. 2) placed at 10-meter intervals was present near the northern shore line. This line of stakes was extended and then used as a base line from which a temporary reference system was formed. Points in this system were identified by placing stakes at 30-meter intervals perpendicular to the base line. This reference system covers a major portion of the upper lake bed (Fig. 2).

An agricultural plot approximately 100 x 250 ft is located in the upper lake bed within the nongridded ecology area. This plot is used for

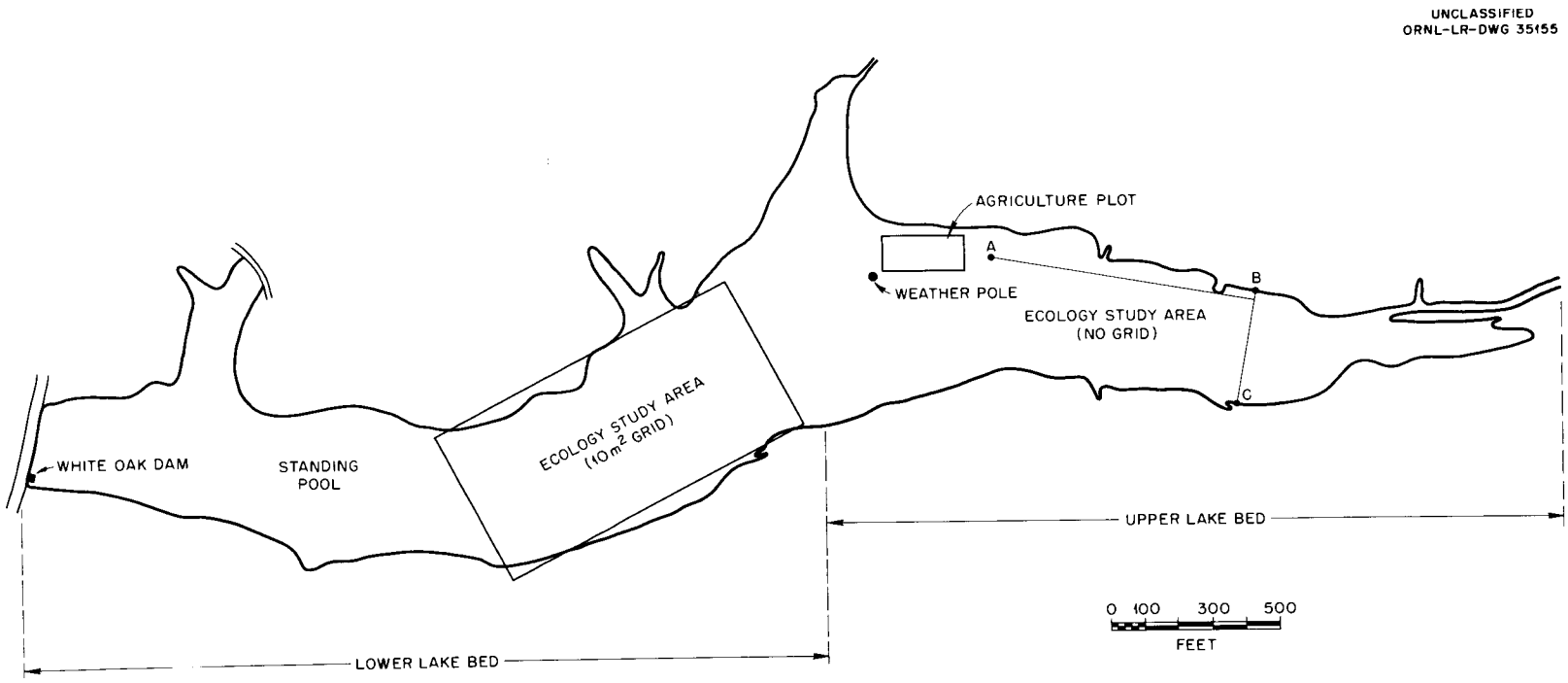

Fig. 2. Map of White Oak Lake Bed Showing Location of Ecology Study Areas.

crop studies and is plowed, planted, and harvested each year. Near this agricultural plot is a 50-ft pole which serves as a weather station and observation tower. Instruments for recording rainfall, temperature, and wind velocity are on or near this pole.

Other than the two ecology study areas, the lake bed contains a region between the gridded area and the White Oak Dam which is covered by water or mud and also contains a region of thick undergrowth beyond the line B-C in Fig. 2. Since these areas are nearly inaccessible, radiation measurements were confined to the two ecology study areas.

The radiation field above the two ecology areas is, of course, closely related to the species, concentration, and distribution of radionuclides in the soil. As has been mentioned in Chapter I of this report, these data have been obtained by analyzing lake bed soil. Results of the analyses indicated that most of the radionuclides are heterogeneously distributed in the top 4 in. of soil. Because of this distributional pattern, it is difficult to obtain representative samples from any particular area. Consequently, a composite sample made by mixing soil from several points in an area probably affords the best approximation of the species and concentration of radionuclides present. Such sampling techniques were used in the grid area by making composite samples of the soil taken from about two hundred points. The results[17] obtained from the analysis of these composite samples are shown in Fig. 3. The same radionuclides found in the grid area

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[17] S. I. Auerbach, Oak Ridge National Laboratory, unpublished data.

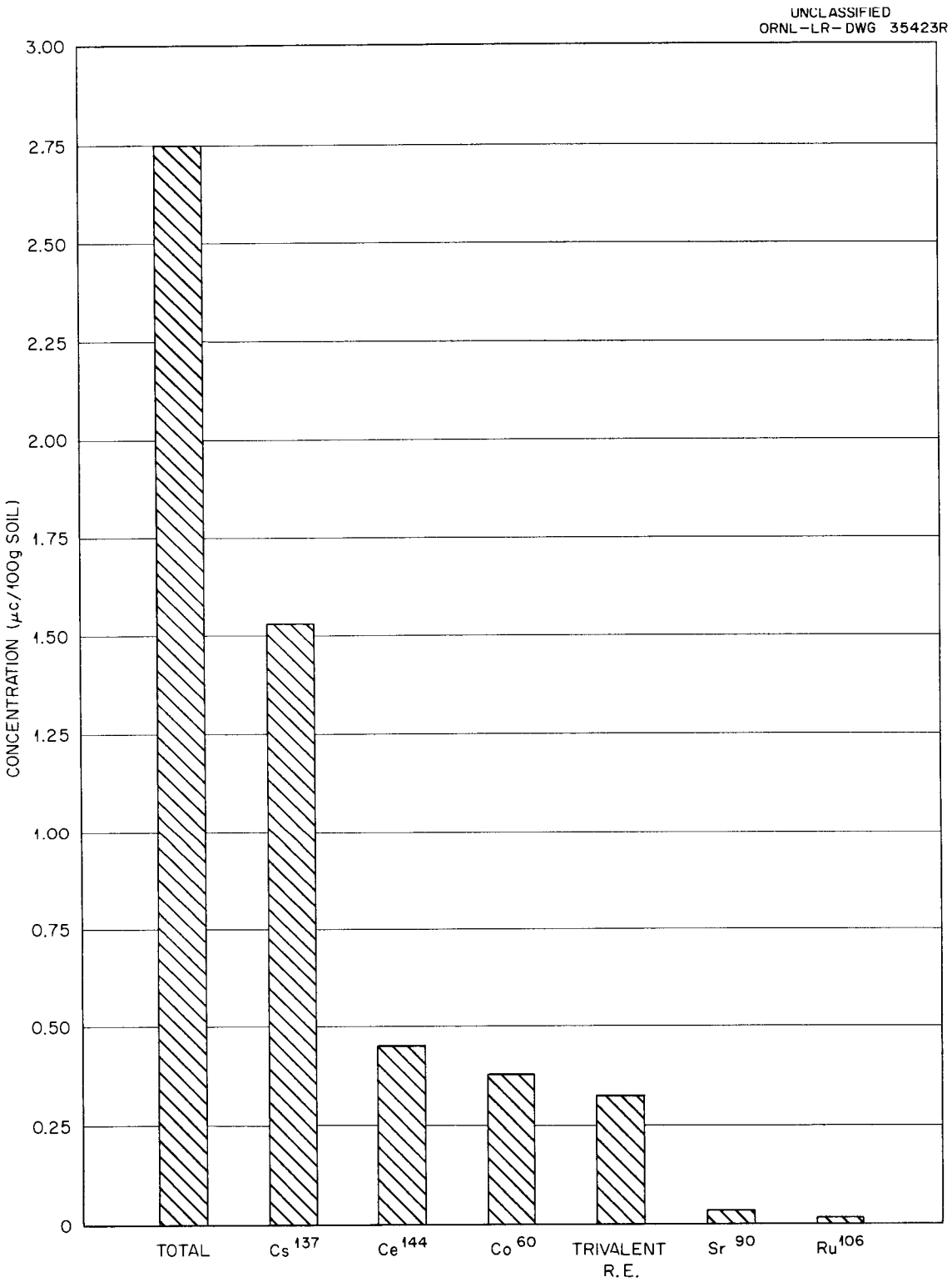

Fig. 3. Average Concentration of Radionuclides Present in the Top Four Inches of White Oak Lake Bed Soil (Grid Area, 1958).

also contaminate the upper lake bed. However, concentrations in the latter region are from 50 to 100% greater than those of the lower lake bed.

III. DESCRIPTION OF RADIATION DETECTORS

Ionization Chamber

An ionization chamber type instrument known as the "cutie pie" was chosen as being the feasible instrument with which to monitor the radiation field above the lake bed. This instrument has a number of inherent features which render it useful for field surveys. These desirable features include the following: it is (1) portable, (2) rugged yet fairly accurate, (3) zero-adjustable in the presence of a radiation field, (4) able to respond rapidly to radiation, and (5) simple to calibrate.

The lake bed soil is contaminated by both gamma and beta emitters; consequently, it is desirable that a differentiation be made between the beta and gamma components of the radiation field. This was accomplished by using two types of chambers. One of these was the ORNL plastic chamber[18] constructed of 1/16 in. bakelite, and will be referred to as the thick-walled chamber. This chamber detects gamma rays and beta rays above an energy of .6 Mev. Since the radiation detected by the instrument with this chamber in place is essentially all gamma, the dose rate registered on the scale is in milliroentgens per hour.

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[18] D. M. Davis, E. D. Gupton, and J. C. Hart, Applied Health Physics Radiation Survey Instrumentation, ORNL-382 (1st rev.), 207-230 (1954).

The other chamber was an ORNL modified paper chamber[19] which is constructed of 7 mg/cm^2 photographic paper placed on a bakelite form. This chamber, which will be referred to as the thin-walled chamber, permits the detection of gamma rays and all beta rays above an energy of .06 Mev. The thin-walled chamber, therefore, detects the beta and gamma external radiation usually considered to be hazardous to humans. Since the instrument detects both gamma and beta radiation, milliroentgen units, a term connoting only X or gamma radiation,[20] cannot be used. Although a dose unit such as the rad[21] considers all ionizing radiation, the method needed to calibrate the instrument so as to register rad/hr units would be extremely difficult. Consequently, dose rates as registered by the instrument with the thin-walled chamber in place were considered to have no expressed units, but being equal in magnitude to the number of milliroentgens necessary to give the same instrument response.

Each time before field use the instrument was calibrated with a 1-g radium source at the ORNL health physics calibration station. Standard calibration procedure[22] was followed with the exception that the X-1 scale

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[19] Ibid.

[20] National Bureau of Standards Handbook 62, Report of the International Commission on Radiological Units and Measurements (ICRU), Washington, D. C., 5 (1956).

[21] Ibid.

[22] D. M. Davis, E. D. Gupton, and J. C. Hart, ORNL-382 (1st rev.), 217-219.

(0-100 mr/hr range) was calibrated at each 10 mr/hr increment. If the response of the instrument indicated more than a 5% variation at any of these dose rates, it was repaired.

Film

Dosimeter film was employed to monitor the radiation field at points not accessible to the ionization chamber. Films were mainly used for measurements at close proximity to the ground surface and for measurements at different heights up to fifteen meters. Also, several films were placed at heights of one meter so that comparisons of responses could be made between the film and the ionization chamber.

Du Pont industrial film packets type 552 were used as film dosimeters in the survey. This packet contains type 502 film which is sensitive to doses between .02 and 25 roentgens and type 510 which is sensitive to doses between .4 and 70 roentgens. The exposure limits of the 502 type film are better adapted for monitoring the radiation field above the lake bed. Therefore, all film measurements were restricted to this more sensitive film.

Each film packet was placed between two plastic filter holders which contained an open window and plastic, cadmium, and aluminum filters. Since the films would be subjected to weather conditions, the film filter holder units were sealed in "pouch paper." This lightweight, waterproofing material consists of paper-backed aluminum foil which is coated with a thin layer of heat-sealing plastic.

The thickness of the "pouch paper" and the lightproof film wrapper was about 40 mg/cm^2. Since this thickness absorbs an appreciable amount of the beta particles, the film was used only to monitor gamma radiation.

A set of calibration films was obtained by exposing films to a 500 milligram radium source. The set consisted of seven groups with each group containing five films. Each of the groups was exposed to the source for a predetermined period of time so that calibration exposures were made at spaced intervals between 0 and 2,000 milliroentgens. A group of five unexposed (blank) films was also included in the calibration set. The calibration films as well as the films exposed at the lake bed were developed by the ORNL health physics monitoring group. Development procedure was that as followed in developing personnel films at the Laboratory.

An Ansco densitometer was used to determine the density of the developed films. This instrument recorded density measurements to an accuracy of three significant figures. A zero adjustment of the instrument was made by using the blank (unexposed) films as standards. Film densities behind all filters were determined on the first 250 films. The results of these first measurements indicated that little if any beta radiation was registered on the films. The results of these first measurements also showed that an approximation of the gamma ray energies could not be made by comparing the densities behind the different filters. Because the integrated gamma dose was all that could be determined by the film density readings, only the density measurements behind one type of filter were needed. Due to the characteristics of the cadmium filter, the densities behind this

filter were more nearly energy independent than those behind the other filters. For this reason the densities behind the cadmium filter were used to determine the radiation doses.

A radium gamma calibration curve was constructed by plotting the densities behind the cadmium filters of the calibration films in relation to the associated exposures in milliroentgens. Each of the seven calibration points of the curve was evaluated by averaging the densities of the five films exposed to the particular dose. At each of the calibration points the average deviation of the five densities used to determine the point was 3% of their mean value. The densities behind the cadmium filter of the films exposed at the lake bed were converted to milliroentgen dose readings by means of the calibration curve. These doses were then divided by the time the films were exposed, resulting in mr/hr dose rates.

IV. FIELD MEASUREMENTS

Ionization Chamber

Ionization chamber measurements were taken regularly over a period of four months, from the first of September until the latter part of December. During this time the radiation field was examined several times at all reference points in the two ecology study areas. The thin-walled chamber was used for a major portion of these surveys, because it was considered essential to determine the total beta and gamma radiation field. The thick-walled chamber was used, however, at a sufficient number of reference points so that a comparison between responses of the two chambers could be made.

More emphasis was placed on defining the radiation field above the gridded area than that above the ungridded area because of the permanent reference system in the grid area. Figure 4 is a photograph of this area showing the arrangement of the metal fence posts marking the coordinates of the grid. To minimize any scattering effects, readings were taken at a distance of about two meters from these metal posts. Radiation measurements were taken at heights of 25, 50, and 100 cm above the ground. Before taking each set of three readings the instrument was zero-adjusted. During the investigation four such separate appraisals were made by using the thin-walled chamber. Three additional surveys were made at about seventy of the

Fig. 4. View of Ecology Grid Area (White Oak Lake Bed).

reference points by using the thick-walled chamber. These latter readings, however, were taken at only the 100-cm height.

Only the thin-walled chamber was used for measurements in the ungridded ecology area. The procedure for taking measurements was the same as followed in the grid area. Because the reference points were fairly far apart (30 meters), measurements were taken at points approximately midway between each reference stake. Three separate surveys were taken in this area during the study.

Film

More than four hundred films were exposed to the radiation field above the lake bed during the period of time in which the ionization chamber readings were taken. Films were placed near the ground at 250 of the reference points in the two ecology study areas and at 30 points above the agricultural plot. About ninety film monitors were placed at 100-cm heights upon the reference posts in the grid area (Fig. 4), and a few films were used to determine the radiation dose rates at heights up to 15 meters.

The film dosimeters used to measure the radiation field near the ground were taped to wire wickets. These wickets were constructed of No. 9 wire sharpened at both ends and bent to form a wicket 10 cm across with legs 18 cm long. The wickets with the attached film were set into the ground 1 meter away from the reference posts and in such a manner that the film was parallel to and 5 cm above the ground surface.

The procedure used in the placement of the films above the agricultural plot was somewhat different. In this case a rope, supported by rods pushed

into the ground, was stretched 25 cm above the central part of the agricultural plot. The film packets were then attached to this rope at intervals of 5 meters and in a manner such that the films were 10 cm above the ground. Also, 10 films were used to compare the radiation at the ground level in the agricultural plot to that in the surrounding lake bed. This was done by placing five of the film packets around the periphery of the agricultural plot and the other five alongside these but in the adjacent unplowed area. For this comparison the films were mounted on the wickets and placed at a height of 5 cm. Figure 5 is an aerial photograph of the lake bed showing the agricultural plot.

Film packets placed 100 cm above the ground were hung on a support which incorporated the metal fence posts marking the reference points in the grid area. A metal rod 120 cm in length was connected perpendicular to the post by means of wire, forming an arm which was about 125 cm above the ground surface. The film units were then attached to this arm by thin wire so that they were situated 1 meter from the metal post and 1 meter above the ground.

The observation pole (note arrow in Fig. 5), located near the agricultural plot, was used to support films to heights from 3 upward to 15 meters above the ground. The film units were taped at 1-meter intervals to a rope which went through a pulley fastened to the top of the pole. Ten films were also placed at the ground level in the vicinity of this pole.

All films were exposed for approximately seventy hours to the radiation field above the lake bed. Immediately after collection the waterproof wrapper was stripped off the film units, thus removing any contamination.

Fig. 5. Aerial View of Agricultural Plot and Observation Pole (White Oak Lake Bed).

V. RESULTS

Several methods were used to determine the radiation field above the lake bed. The dose rate values tabulated in the Appendix are the averages of all trial measurements made at the listed reference point of the grid area by each of the methods. Dose rate values listed in the Appendix for the thin-walled ionization chamber measurements are the averages of four separate trials. In general, the average deviations of the four trials from their mean value was 4%. However, at a few points where the average dose rate was less than ten scale units, the average deviation was as high as 14%. Three trials were used to calculate the mean value of measurements taken with the thick-walled ionization chamber. The average deviation of the measurements taken by this instrument was 5%. Dose rates listed for film measurements are those of the single survey made by the film monitors.

The methods used to determine the radiation field above the lake bed gave varied results depending upon the detector used and its distance from the ground. For this reason comparisons using different combinations of instruments and heights were made. The values tabulated in the Appendix were utilized for this purpose. The relative responses of the detection devices to the radiation field at various heights are summarized in Fig. 6. These values were calculated by first averaging all readings in the grid area taken with a particular instrument at a given height. This mean value was then related to the average reading obtained with the thin-walled ionization

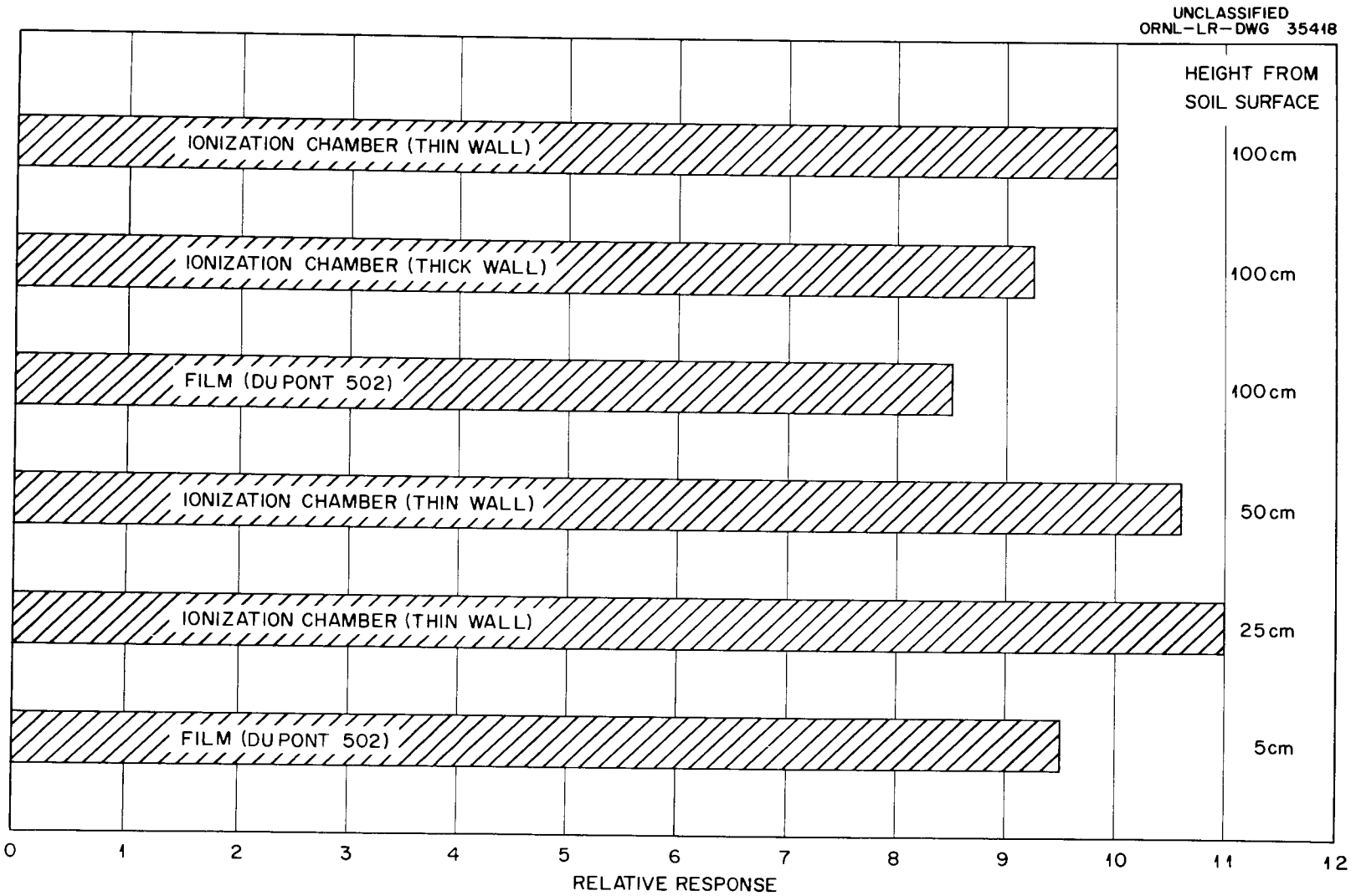

Fig. 6. Relative Response of Radiation Detectors to Radiation Field of White Oak Lake Bed.

chamber held 100 cm above the ground at the same reference points. In all cases an arbitrary value of ten units was used as the response of the thin-walled ionization chamber.

The measurements obtained at the 100-cm height with the thick-walled ionization chamber and the thin-walled chamber were approximately the same (Fig. 6). Because the thick-walled chamber detects only gamma radiation and the thin-walled chamber detects both beta and gamma radiation, the similarity of readings obtained by the two chambers indicates that the beta component of the radiation field at the 100-cm height is negligible. The absence of a sizable beta component is a result of the distribution of radionuclides within the lake bed soil (Chapter II). Because beta rays of energies one Mev or less would be absorbed by .025 cm of soil, only a small fraction of the beta rays would be detected above the ground level. A precise mathematical determination of the beta radiation above the lake bed in relation to the distribution of radionuclides would be difficult to evaluate. However, an approximate value of between one and two mrad/hr was made by considering only the beta-emitting radionuclides in the upper layers of the soil.

The radiation dose rates above the lake bed decreases with distance from the ground level. This phenomena is indicated by the comparison of measurements obtained by the thin-walled ionization chamber at the 25 and the 100 cm heights (Fig. 6). An analysis was made to determine if this difference was consistant at each of the individual reference points. In this analysis dose rates at the two heights which are listed in the Appendix were compared at 50 randomly selected reference points. The result of the

analysis was that the difference at 90% of the reference points was greater than the 5% standard deviation of the measurements taken with the instrument. The analysis, therefore, showed that the dose rates at the 25-cm height were consistently higher than at the 100-cm height. The increased dose rate measurements obtained with the thin-walled ionization chamber at points nearer the ground may denote an increase of beta radiation, but this increase is greatly exaggerated by ground-scattered gamma rays. The increase of this scattered gamma radiation near the ground is also observed in the difference of film responses at the 5-cm and 100-cm heights.

A difference of measurements made with the film monitors and the thin-walled chamber is shown by Fig. 6. This difference in part is due to the small beta component which is detected by the thin-walled chamber, but is not registered by the film monitors. Because only one survey was made with the film monitors, the measurements taken by this method were not considered to be as representative of the radiation field as the ionization chamber measurements.

The average readings of the surveys taken at 100 cm with the thin-walled ionization chamber were used to define the configuration of the radiation field above the lake bed. The configuration is represented by isodose lines delineated upon maps of the lake bed area. Dose rates are expressed in milliroentgens per hour because the radiation at this height is more than 90% gamma.

Radiation measurements above the grid area (Fig. 7) ranged from a low of no detectable radiation along the southern shore line to a high of 30 mr/hr

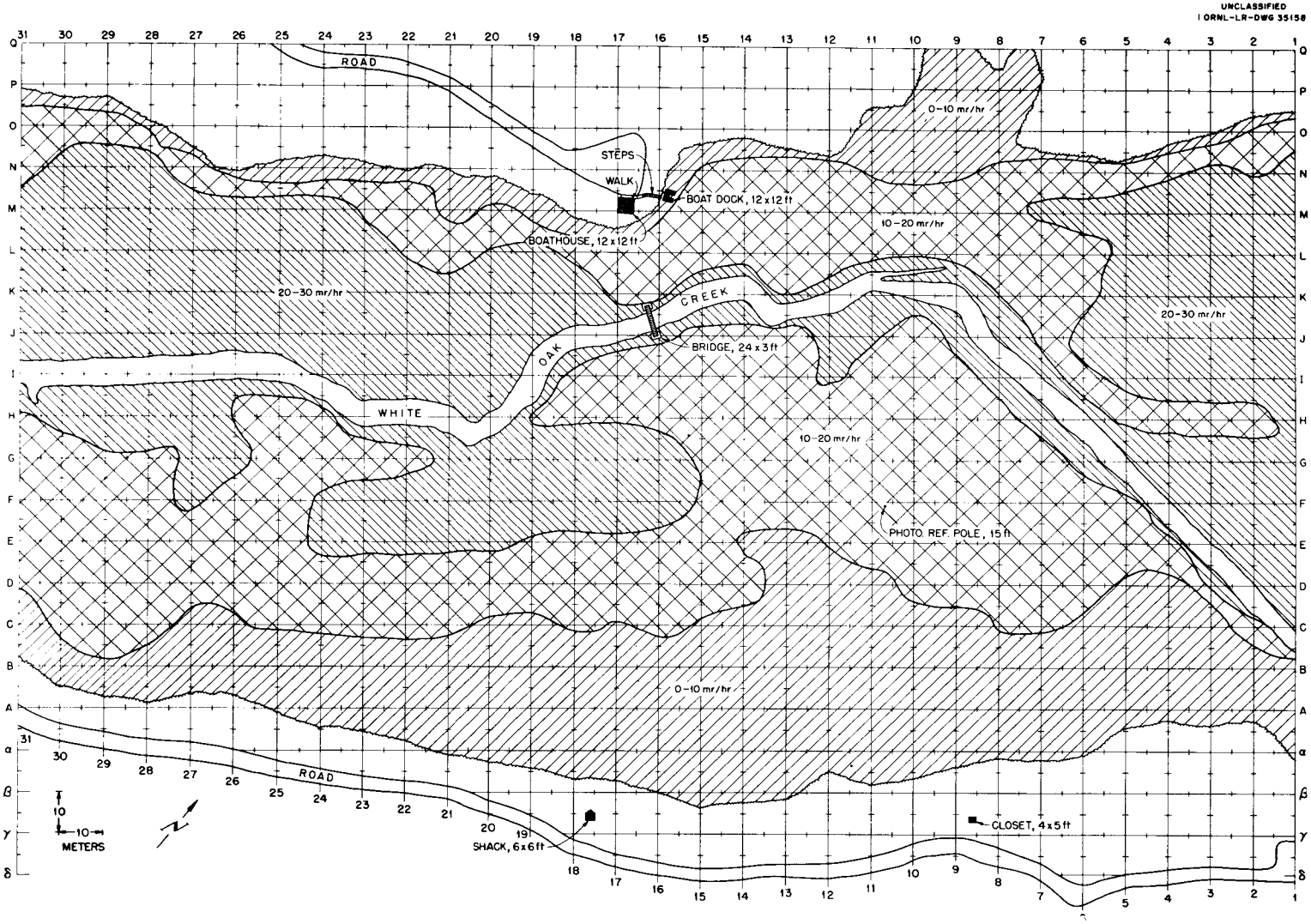

Fig. 7. Air Dose Rates One Meter Above the Ecology Grid Area (10-meter Grid of Lower White Oak Lake Bed).

at reference points on the creek bank. A few readings as high as 75 mr/hr were obtained above sand bars in the creek, but measurements taken within the creek channel were not considered in defining the radiation field above the lake bed proper. The average 100-cm dose rate of 16 mr/hr over the grid area was obtained by calculating the mean of the 100-cm measurements at all reference points.

Only small fluctuations of the dose rates above the grid area were observed during the period of study. An analysis of the measurements obtained in the four separate surveys disclosed an average absolute fluctuation at each reference point of about 1 mr/hr. The error of measurements taken by the thin-walled ionization chamber is usually considered to be also 10% for all readings above 5 mr/hr. This error is primarily due to the fact that the instrument scale can only be read to the nearest mr/hr. Also there are small errors introduced by the slight nonlinear response of the instrument to the different radiation energies. Because the average absolute fluctuation of the radiation field was within the 10% error, the radiation field above the grid area was considered to be stable.

Dose rates above the ungridded area (Fig. 8) were, on the average, about 75% higher than those above the grid area. It was found that readings at some points in this area varied as much as 50 mr/hr at different surveys. The fluctuating radiation field was mainly confined to a region within the central portion of the upper lake bed. This region receives an influx of Ruthenium-106 from a set of radioactive waste pits in the vicinity and is also characterized by a high and variable water table. The Ru^{106} is

Fig. 8. Air Dose Rates One Meter Above the Ungridded Ecology Study Area (Upper Lake Bed).

transported across the lake bed by the water. Accordingly, as the ruthenium moves, the radiation field will fluctuate at points in the region. The fluctuating radiation field is also a result of the water level itself. When the water level is relatively high, it produces a media which absorbs a part of the radiation. As the water level drops, this absorbing media is, of course, decreased. The fluctuating radiation field is then the result of the moving of the ruthenium and the variable water table. At isolated points within this region the air dose rates were observed to be as high as 100 mr/hr. Since reference points were 30 meters apart in this area as opposed to the 10-meter distance in the grid area, the configuration of the radiation field was not as well defined.

The pattern of the radiation field above the lake bed was delineated by isodose lines at intervals of 15 mr/hr. Figure 9 shows the nonuniformity of the radiation field above the ecology areas. The regions with associated radiation of high dose rates are located at the eastern or inlet end of the lake bed within the ungridded ecology area. The dose rates progressively decline with distance from the inlet end of the lake bed. Regions of lowest dose rates are located along the shore lines. Dose rate transects of the radiation field above the two ecology areas (Figs. 10a and 10b) also show this horizontal pattern of the radiation field. The six separate diagrams represent transects at different distances from White Oak Dam. The radiation as revealed by each of the diagrams is at a minimum above the shore lines and increases to a maximum above the body of the lake bed.

An attempt was made to correlate the radiation as represented by the dose rate transects with the depth of sediment as determined by TVA in 1953

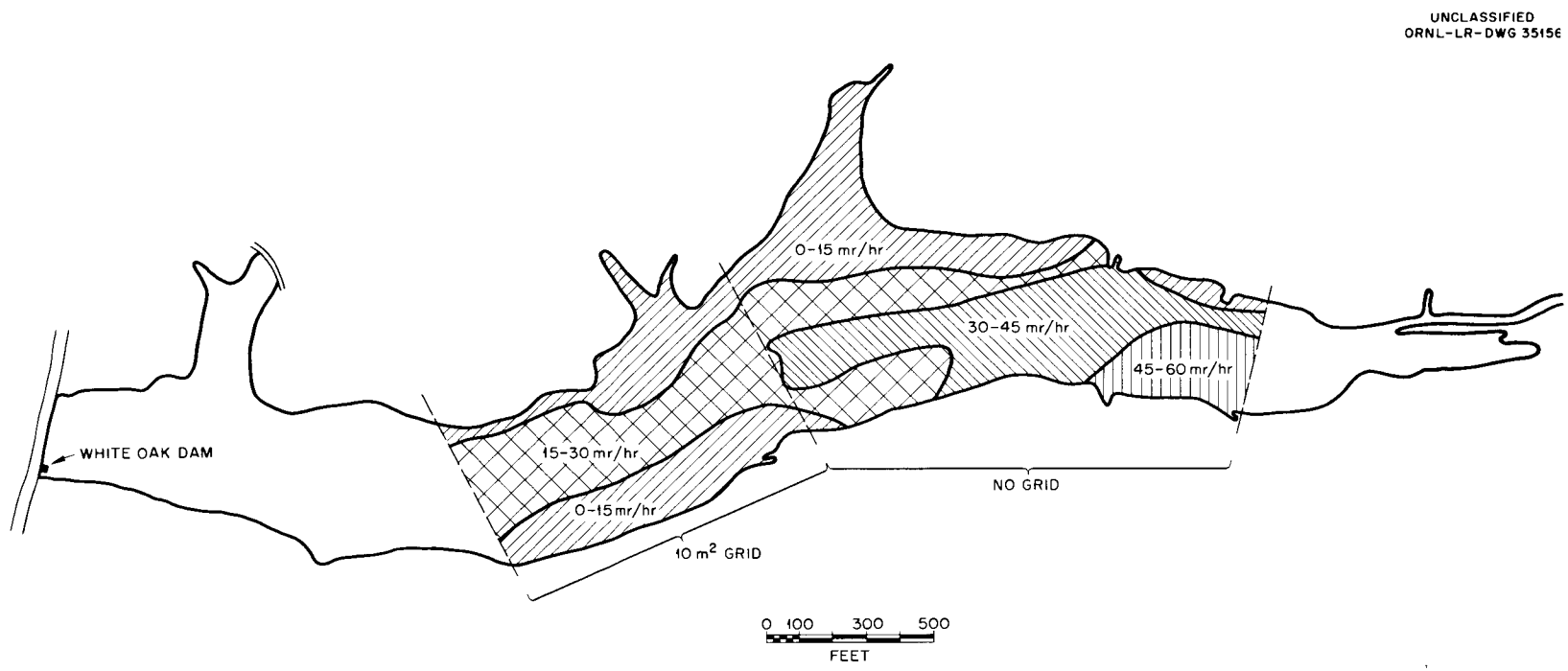

Fig. 9. Air Dose Rates One Meter Above White Oak Lake Bed in 15 mr/hr Increments.

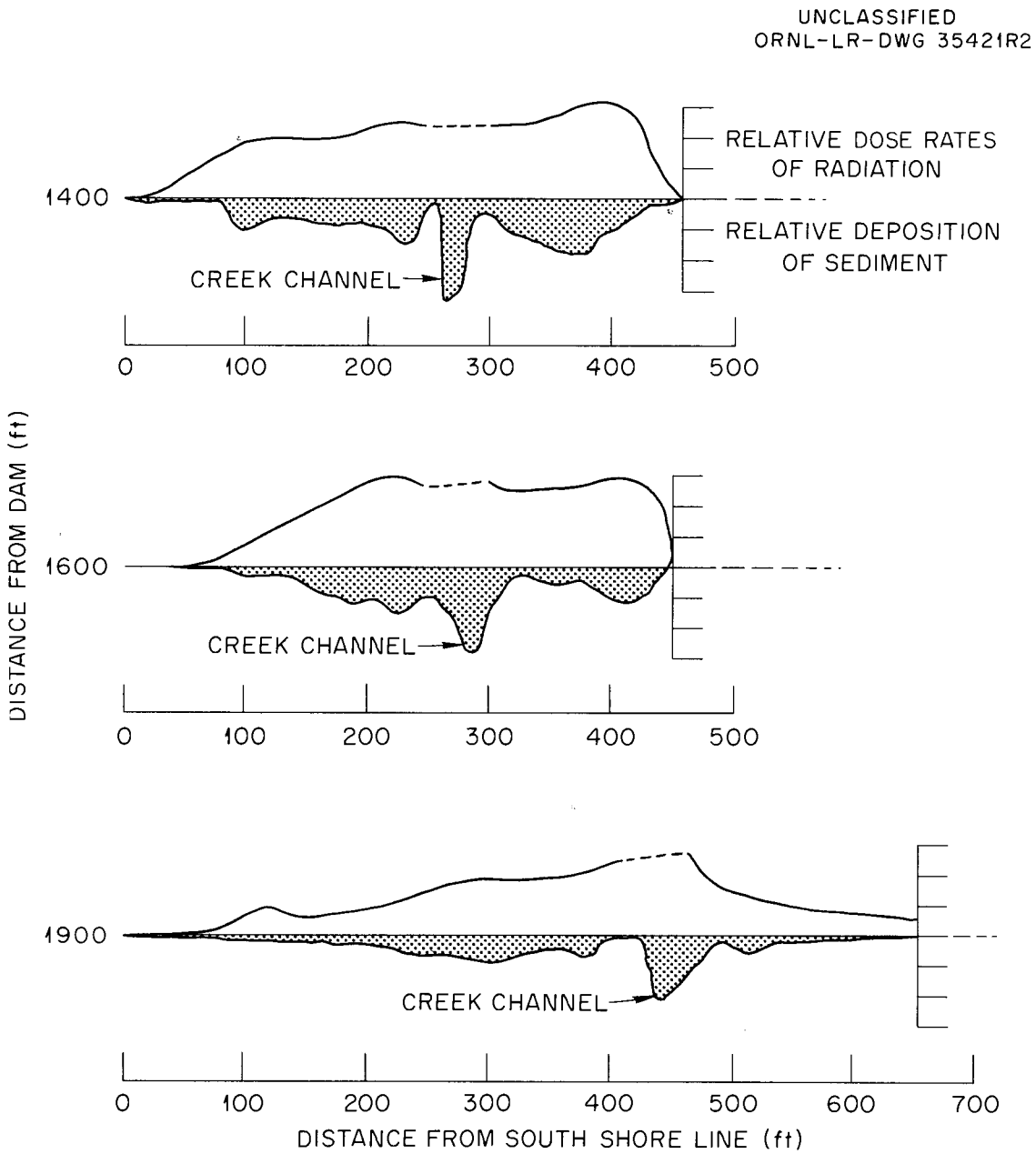

Fig. 10a. Sediment Deposit and Associated Radiation Field (White Oak Lake Bed).

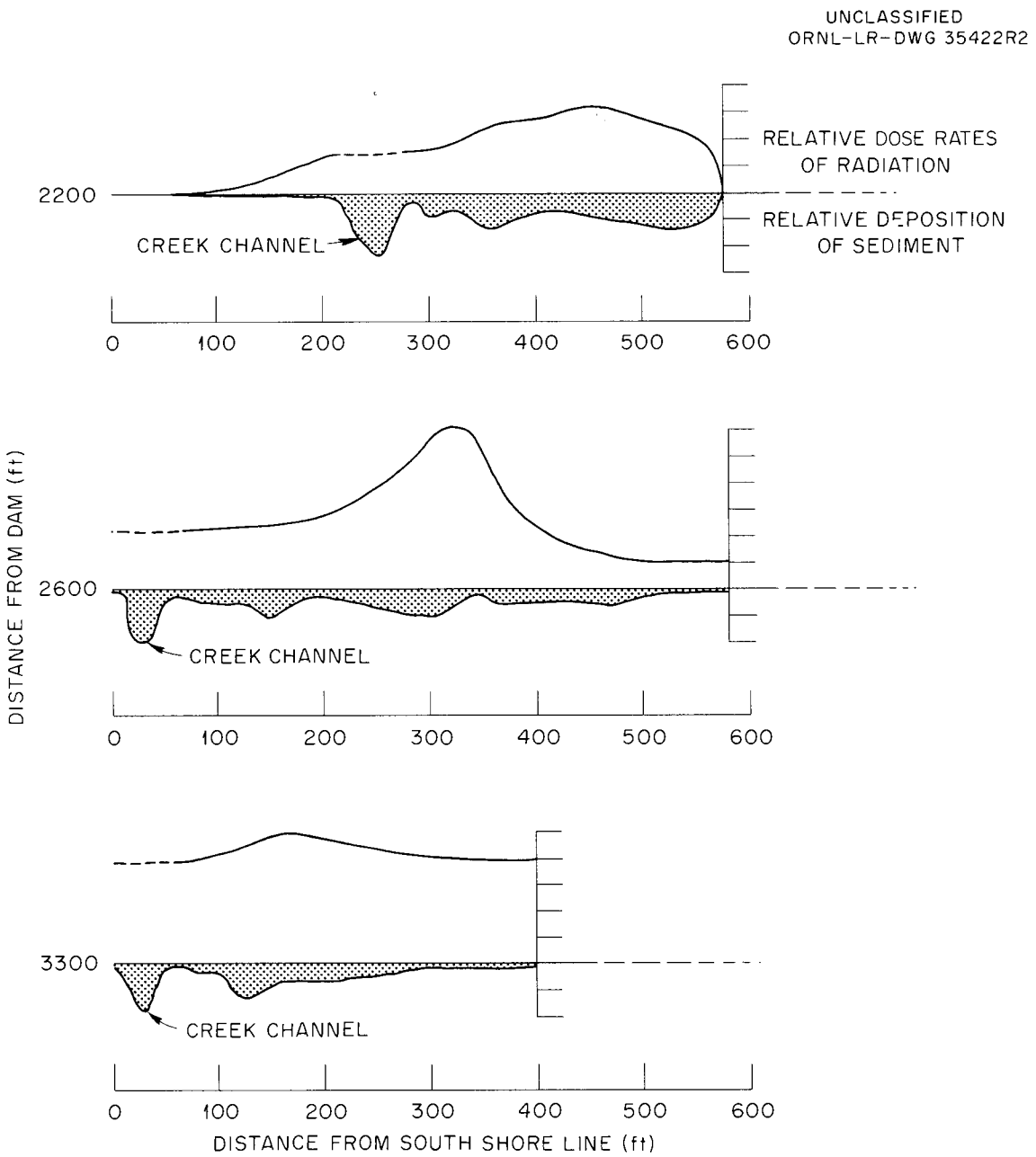

Fig. 10b. Sediment Deposit and Associated Radiation Field (White Oak Lake Bed).

when the lake was present.[23] In Figs. 10a and 10b the dose rate transects are plotted with the equivalent cross sections of sediment depositions. Two relationships between silt deposits and dose rates are indicated by these data. One is the positive correlation existing between the depth of silt deposited across the lake bed and the associated radiation. This correlation is denoted in each of the diagrams by the general similarity between the relative amounts of silt deposits and the relative radiation dose rates at various distances from the southern shore line. The other relationship is a negative correlation between the dose rates and the depth of silt deposited at varying distances from the dam. This relationship can be noted by comparing the diagrams at various distances from the White Oak Dam (Figs. 10a and 10b). At 3,300 ft from the dam only small depths of silt are present but rather high radiation dose rates. Conversely, at the 1,400 ft distance from the dam there are relatively large depths of silt, yet a less intense radiation field.

The radiation above the agricultural plot was found by film measurements to vary between 9 mr/hr and 17 mr/hr. The plot had been plowed recently before the measurements and was extremely rough; therefore, part of the variation noted was probably due to the difference in scattering of the gamma rays. The effect of plowing was evaluated by placing films over unplowed portions of the lake bed adjacent to the plowed area. These

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[23] A. S. Frye, Sediment Investigation of White Oak Creek and Lake, Roane County, Tennessee, TVA, Hydraulic Data Branch, Chattanooga (1953).

data indicated that dose rates above the agricultural plot had been decreased 25% as a result of the plowing.

The relative dose rates of the radiation at various heights above the lake bed are shown in Fig. 11. This graph is based on readings obtained from films placed on the observation pole at heights of 3 up to 15 meters. All the measurements at these heights were related to the average of the measurements taken with the ten films at ground level. The decrease in dose rate as a function of height is less over the lake bed than the gamma radiation above a fallout type contamination.[24] This dissimilarity in slopes is related to the differential distribution of the radionuclides in the examples. Fallout contamination is usually considered to be spread on top of the ground, thus forming a plane source, whereas the lake bed is more like a large volume source.

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[24] R. L. Mather, Residual Gamma Radiation Field from Induced Soil Activities, USNRDL-TR-240, 7 (April 9, 1958).

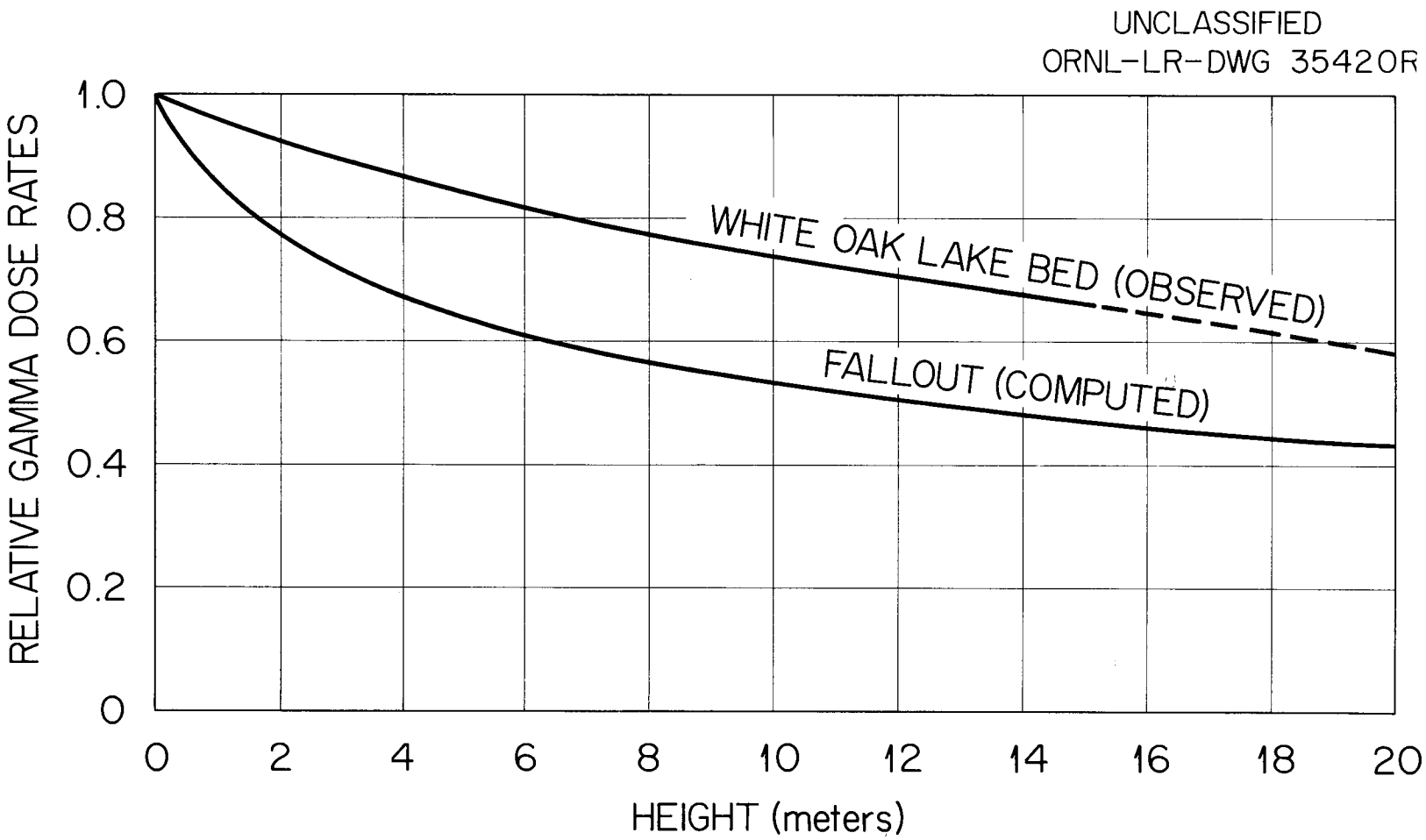

Fig. 11. Comparison of Gamma Radiation Intensity at Heights Above White Oak Lake Bed with That Above a Fallout-Type Source.

VI. DISCUSSION

The radiation field above the lake bed is closely related to the distribution of contaminating material. Consequently, the radiation field (Figs. 7, 8, 9) is an indication of the present distribution of radionuclides. Any alteration in the present distribution would, of course, be reflected by a change in the associated radiation field.

The original distribution of the radionuclides was a consequence of their absorption by sediment and organisms in the lake and the subsequent deposition of this contaminated material on the lake bottom. This deposition was controlled by several factors, including the varying current patterns and water levels of the lake. Cross sections of the sediment deposits (Figs. 10a and 10b) reveal the resultant deposition of sediment and thus the distribution of radionuclides on the lake bed. The increase of the dose rates compared to the depth of sediment toward the inlet of the lake indicates that sediment deposited here was contaminated to a greater degree than that deposited farther downstream. This higher degree of contaminatiom was partially the result of the sediment's being subjected to concentrations of radionuclides before their dilution by the lake water. Consequently, the probability that a particle of sediment or an organism would absorb the radionuclides is greater than at points downstream where the ratio of the radionuclide concentration in the water to the concentration of sediment and living organisms was less.

Draining the lake brought an end to the major influx of contaminating material. Since then some changes have been induced in the original distribution. These changes have resulted from a number of environmental factors whose effects are manifest in the present configuration of the radiation field. Portions of the lake bed have been and still are subject to erosion. This erosion removes the contaminants which are intermixed with the soil. The region of low dose rates along the southern shore line of the grid area (Fig. 7) is partially due to soil erosion of the upper layers of silt. The thin band of low dose rates along the north bank of the gridded area (Fig. 7) is also due in part to erosion. In this case uncontaminated soil from the area adjacent to the lake bed has been deposited over the contaminated soil, subsequently absorbing part of the radiation.

White Oak Creek, which flows through the area, is still used as a part of the Laboratory radioactive waste disposal system. During normal weather conditions the radionuclides deposited within the creek channel would have little effect upon the radiation field above the lake bed proper. However, at times of heavy rainfall the creek overflows, and may deposit some of the contaminated silt over the surrounding region. The high radiation dose rates at points near the creek (Fig. 7) are probably due in part to such phenomena.

Three radioactive waste pits[25] are located near the upper lake bed (Fig. 12). Some of the liquid radioactive waste stored in these pits seeps

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[25] K. E. Cowser and F. L. Parker, "Soil Disposal of Radioactive Wastes at ORNL: Criteria and Techniques of Site Selection and Monitoring," Health Physics 1, 152-163 (1958).

out into the surrounding region and follows a natural drainage line into the lake bed. The primary fission product in this moving material is Ru^{106} because all other radionuclides are absorbed or otherwise held up by the soil and rock formations surrounding the pits. It has been estimated that in 1957 approximately 200 curies of Ru^{106} were deposited in the lake bed, of which possibly 60 curies have moved into the creek.[26] The drainage seep containing the Ru^{106} enters the upper lake bed near the middle of the northern shore line (represented by the arrow in Fig. 12). From this point the material apparently spreads out over the lake surface in a fan-shaped pattern which is demarcated by the air dose rates of 30-45 mr/hr (Fig. 9). This portion of the bed is also characterized by a high water table resulting from the input of the drainage seep. Fluctuations of the dose rate measurements above this area are due to the effect of the unstable water level and the movement of Ru^{106}.

It is apparent that environmental factors have influenced the configuration of the radiation field above the lake bed. The loss of radionuclides by radioactive decay will also change the radiation field by lowering its dose rate. An estimate of the rate at which the dose rate will be lowered can be made if the concentration of nuclides now present and the contribution of each type to the total radiation field is known. This estimation was made by using a formula derived by Morgan.[27] The

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[26] K. E. Cowser et al., "Soil Disposal of Intermediate-Level Wastes," Health Physics Annual Progress Report, ORNL-2590, 15 (1958).

[27] K. Z. Morgan and H. M. Parker, Health Control and Nuclear Research, in preparation.

Fig. 12. Aerial View Showing Relative Location of ORNL Waste Disposal Pits (in Foreground) to White Oak Lake Bed.

formula was applied by utilizing the concentration of radionuclides contaminating the grid area (Fig. 3) and by considering this area to be a large volume source.

Two assumptions were made in order to facilitate the application of the formula. The first was that the grid area approximates an infinite 10-cm-thick slab source. The second assumption was that the nuclides are distributed throughout the slab in a uniform manner. These assumptions should not introduce significant errors as the grid area is large (10 acres) and the equation is solved for the average dose rate over the entire area.

The equation derived by Morgan for relating the expected dose rate of the radiation field to the amount of contamination is

$$D = \sum_{i = 1,2,3\ldots} \frac{2\pi}{u_i} N n_i G_i \left[1 - E_2 (u_i h_i) \right]. \qquad \text{Eq. 1}$$

In this equation D is the dose rate in roentgens per hour above an infinite slab source in which radionuclides ($i = 1,2,3\ldots$) are uniformly distributed to a depth h_i; u_i is the coefficient of absorption of the slab source with inverse centimeter units; N is the total concentration of radionuclides in millicuries per cubic centimeter units; n_i is the fraction of N of the ith nuclide; G_i is the dose rate in roentgens per hour at a distance of 1 cm in air from a one millicurie point source of nuclide i; and E_2 is an

E-function of the second order. The E_2 functions are related to first order exponential functions (E_1), a tabulated function,[28] by the formula

$$E_2(b) = e^{-b} - b\,E_1\,(b) \qquad \text{(ref. 29)} \qquad \text{Eq. 2}$$

Radionuclides considered in the evaluation of Eq. 1 were Cs^{137} - Ba^{137}, Ce^{144} - Ba^{137}, Ce^{144} - Pr^{144}, Co^{60} and the trivalent rare earths. These are the gamma emitters of sufficient concentration (Fig. 3) to make significant contributions to the radiation field. In the case of the trivalent rare earths it was assumed that each disintegration released a .76 Mev gamma ray. Essentially all beta particles would be absorbed by the soil; therefore, beta decays were not considered.

To solve this equation a number of variables must first be determined. Relating roentgens per hour to energy imparted by gamma rays in air, the solution of G_i becomes

$$G_i = 1.5 \times 10^{-5}\,(u - \sigma_s)_i \times E_i \qquad \text{Eq. 3}$$

In Eq. 3 $(u - \sigma_s)_i$ is the total coefficient of absorption of gamma rays by air minus the scattering coefficient, and E_i is the total gamma ray energy

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[28] National Bureau of Standards, Tables of Sine, Cosine, and Exponential Integrals, Vols. I and II, New York, 1940 (notation of E_1 in these tables is $E_1(X) = -E_1(-X)$).

[29] K. Z. Morgan and H. M. Parker, Health Control and Nuclear Research, in preparation.

released for each disintegration of nuclide i. Since $(u - \sigma_s)_i$ is approximately the same for all gamma ray energies used in this analysis, the constant value of 3.75×10^{-5} cm^{-1} was used. The determination of G_i then becomes

$$G_i = 5.63\ E_i \qquad \text{Eq. 4}$$

The product (Nn_i) is the concentration of isotope i in millicuries per cubic centimeter of soil. This variable was determined by assigning a typical density value to the soil of 1.6 g/cm^3 (ref. 30). The concentrations (C_i) which are in units of microcuries per 100 g of soil (Fig. 3) were then converted to units of millicuries per cubic centimeter by the relation

$$n_i N = \frac{Ci}{100} \times 10^{-3} \times 1.6 \qquad \text{Eq. 5}$$

Values for u_i were obtained by using the mass absorption coefficients of aluminum,[31] a substance similar in character to soil. These

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[30] T. L. Lyon, H. O. Buchman, and N. C. Brady, Nature and Properties of Soils, 5th ed., pp. 57, 63, Macmillan, New York, 1952.

[31] G. R. White, X-ray Attenuation Coefficients 10 Kev to 100 Mev, NBS Report No. 1003 (1952).

were converted to coefficients of absorption for soil by the relation

$$(u_i)\text{soil} = \left(\frac{u_i}{\rho}\right)\text{al}\ \rho\ \text{soil} \qquad \text{Eq. 6}$$

Once the proper values for the variables have been substituted into Eq. 1, the solution for D becomes 11 mr/hr. This value for D considers only direct unscattered radiation and thus is an underestimate of the actual radiation field. One method by which the scattered radiation may be included in the dose rate computation is to use absorption coefficients which do not include the scatter component. This has been done by again using the absorption coefficients of aluminum with u_i in Eq. 6 now being replaced by $(u - \sigma_s)_i$. After substitution of $(u - \sigma_s)_i$ for u_i in Eq. 1, the solution for D becomes 18 mr/hr. This is in favorable agreement with the average radiation field above the area of 16 mr/hr as determined with the ionization chamber.

The contributions of the various nuclides to the total radiation field were determined by the solution of Eq. 1. It was found that Cs^{137} contributed 46%; Co^{60} – 42%; TVRE – 11%; and Ce^{144} – less than 1%. The decline of the radiation field above the lake bed due to radioactive decay will be mainly controlled, therefore, by the 33 year half-life of Cs^{137} and the 5.3 year half-life of Co^{60}.

It is evident that both the configuration and the dose rate of the radiation field above the lake bed will vary in future years as the distribution and concentration of radionuclides change. Therefore, it is recommended that future determinations of the radiation field be made. These future investigations would be of value in fulfilling the function of

redefining the radiation field. Moreover, the data of a future survey, used in conjunction with physical and chemical measurements made during the interim, would provide a basis for evaluating, at least qualitatively, the role of environmental factors affecting the distribution and concentration of radionuclides.

APPENDIX I

Radiation Measurements Above White Oak Lake Bed (Grid Area)

The accompanying table lists the dose rates of the radiation field at each reference point in the ecology grid area as determined by various methods. All dose rates listed in the table are results of surveys taken between September 1 and December 20, 1958.

Listed in the first column of the table are the reference points of the grid. The grid forms a rectangular coordinate system using the numbers 1 through 31 and the letters A through Q.

The second, third, and fourth columns are the averages of four separate readings taken at each of three heights by the ionization chamber with the thin-walled chamber in place. The listed number represents the dose rates due to the total (beta and gamma) radiation field. There are no expressed units for these dose rates, but they are equal in magnitude to the number of milliroentgens per hour of gamma radiation causing the same instrument response.

The fifth column is the average of three surveys taken with the thick-walled chamber in place. These readings represent the gamma component of the total radiation and are in dose rate units of mr/hr.

The ionization chamber used in the surveys was not accurate in radiation fields of less than 10 mr/hr (units). Therefore, those listed readings of less than 10 mr/hr (units) may have large errors.

The last two columns list the radiation as detected by the film monitors. Since the films were used only to detect gamma rays, these readings also are listed in dose rates of milliroentgens per hour.

RADIATION MEASUREMENTS
WHITE OAK LAKE BED
(Grid Area)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-A	8 units*	8 units*	7 units*	- mr/hr	- mr/hr	9 mr/hr
2-A	3	3	4	-	-	-
3-A	2	2	2	-	-	3
4-A	2	2	3	-	-	-
5-A	2	2	2	-	-	6
6-A	3	2	3	-	-	-
7-A	3	3	5	-	-	5
8-A	4	5	6	-	-	-
9-A	7	6	5	-	-	8
10-A	6	5	6	-	-	-
11-A	5	6	7	-	-	7
12-A	7	7	8	-	-	-
13-A	9	9	7	-	-	9
14-A	7	7	8	-	-	-
15-A	9	9	9	-	-	9
16-A	10	9	8	-	-	-
17-A	8	8	4	-	-	7
18-A	4	4	4	-	-	-
19-A	5	5	4	-	-	7
20-A	1	1	1	-	-	-
21-A	2	2	1	-	-	5
22-A	1	1	1	-	-	-
23-A	1	1	1	-	-	3
24-A	1	1	1	-	-	-
25-A	2	2	1	-	-	4
26-A	1	0	1	-	-	-
27-A	-	-	-	-	-	3
28-A	2	2	0	-	-	-
29-A	0	0	0	-	1	3
30-A	0	0	0	-	-	-
31-A	-	-	-	-	-	-

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
Coordinate	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-B	8 units*	9 units*	10 units*	- mr/hr	- mr/hr	- mr/hr
2-B	5	5	6	-	9	7
3-B	5	4	4	-	-	-
4-B	4	3	3	-	6	6
5-B	3	3	3	-	-	-
6-B	1	1	2	-	6	6
7-B	3	3	3	-	-	-
8-B	7	6	6	-	8	7
9-B	9	9	8	-	-	-
10-B	9	7	7	-	9	9
11-B	6	5	5	-	-	-
12-B	7	7	7	-	8	8
13-B	8	8	8	-	-	-
14-B	7	6	7	-	8	8
15-B	4	5	5	-	-	-
16-B	10	10	9	-	9	10
17-B	10	10	10	-	-	-
18-B	11	11	10	-	9	9
19-B	8	9	9	-	-	-
20-B	1	1	2	-	6	4
21-B	10	10	8	-	-	-
22-B	2	1	2	-	6	3
23-B	1	1	1	-	-	-
24-B	0	1	1	-	4	4
25-B	6	6	4	-	-	-
26-B	2	3	2	-	4	5
27-B	0	1	1	-	-	-
28-B	4	3	3	-	5	3
29-B	10	10	9	-	-	-
30-B	2	2	3	-	6	3
31-B	1	1	1	-	-	-

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-C	21 units*	19 units*	16 units*	- mr/hr	- mr/hr	17 mr/hr
2-C	11	12	13	-	13	15
3-C	9	9	9	-	-	7
4-C	5	5	5	-	-	-
5-C	4	4	4	-	-	6
6-C	11	10	9	-	-	-
7-C	10	10	10	-	-	10
8-C	12	11	11	-	-	-
9-C	6	6	7	-	-	9
10-C	10	10	10	-	-	-
11-C	9	9	9	-	-	9
12-C	7	7	6	-	-	-
13-C	9	9	9	-	-	9
14-C	8	8	8	-	-	-
15-C	8	9	9	-	-	8
16-C	14	13	12	-	-	-
17-C	11	11	10	-	-	10
18-C	13	12	12	-	-	-
19-C	11	10	10	-	-	10
20-C	10	9	9	-	-	-
21-C	13	12	12	-	-	12
22-C	15	14	14	-	-	-
23-C	15	15	15	-	-	13
24-C	14	13	12	-	-	-
25-C	11	11	11	-	-	10
26-C	12	11	10	-	-	-
27-C	4	4	5	-	-	6
28-C	14	14	13	-	-	-
29-C	18	18	17	-	-	16
30-C	12	16	15	-	-	-
31-C	9	9	8	-	-	10

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
Coordinate	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-D	29 units*	28 units*	26 units*	- mr/hr	- mr/hr	30 mr/hr
2-D	-	-	-	-	-	-
3-D	27	26	24	-	-	-
4-D	11	10	10	10	10	11
5-D	9	9	8	-	-	-
6-D	13	12	11	11	11	10
7-D	16	15	15	-	-	-
8-D	15	14	14	14	13	13
9-D	13	13	13	-	-	-
10-D	11	11	11	10	10	11
11-D	10	10	10	-	-	-
12-D	10	9	8	9	10	10
13-D	8	7	7	-	-	-
14-D	11	11	11	-	-	10
15-D	14	13	12	-	-	-
16-D	17	16	15	15	15	14
17-D	18	17	16	-	-	-
18-D	15	15	15	14	13	13
19-D	17	15	15	-	-	-
20-D	18	17	16	16	13	14
21-D	20	20	19	-	-	-
22-D	20	19	18	16	14	17
23-D	20	19	18	-	-	-
24-D	18	17	16	16	14	15
25-D	20	20	19	-	-	-
26-D	21	20	19	17	15	21
27-D	19	19	18	-	-	-
28-D	16	15	14	13	12	13
29-D	20	20	18	-	-	-
30-D	20	20	18	16	14	16
31-D	13	12	11	-	-	-

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
Coordinate	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-E	30 units*	30 units*	27 units*	- mr/hr	- mr/hr	30 mr/hr
2-E	28	27	25	-	-	-
3-E	-	-	-	-	-	-
4-E	17	17	17	-	-	-
5-E	14	13	12	-	-	13
6-E	14	14	13	-	-	-
7-E	17	16	15	-	-	14
8-E	17	16	15	-	-	-
9-E	17	17	15	-	-	14
10-E	18	17	16	-	-	-
11-E	12	12	12	-	-	11
12-E	12	11	11	-	-	-
13-E	10	9	9	-	-	9
14-E	11	11	10	-	-	-
15-E	19	19	18	-	-	-
16-E	20	20	19	-	-	-
17-E	21	21	20	-	-	19
18-E	20	20	19	-	-	-
19-E	21	21	20	-	-	21
20-E	23	22	21	-	-	-
21-E	24	23	23	-	-	21
22-E	25	24	23	-	-	-
23-E	27	25	23	-	-	26
24-E	25	23	22	-	-	-
25-E	21	21	20	-	-	10
26-E	20	19	18	-	-	-
27-E	20	20	19	-	-	10
28-E	22	21	20	-	-	-
29-E	22	21	21	-	-	18
30-E	23	22	20	-	-	-
31-E	18	17	15	-	-	16

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-F	28 units*	27 units*	25 units*	- mr/hr	- mr/hr	- mr/hr
2-F	32	30	27	-	-	29
3-F	25	24	24	-	-	-
4-F	-	-	-	-	-	-
5-F	20	20	18	-	-	-
6-F	17	16	15	-	14	13
7-F	16	15	14	-	-	-
8-F	15	15	15	14	14	13
9-F	19	18	18	-	-	-
10-F	14	14	14	14	13	12
11-F	18	18	17	-	-	-
12-F	17	16	15	-	-	15
13-F	19	18	17	-	-	-
14-F	16	15	15	14	14	15
15-F	16	15	15	-	-	-
16-F	23	22	21	20	18	18
17-F	22	22	21	-	-	-
18-F	28	26	25	22	21	22
19-F	26	25	24	-	-	-
20-F	30	28	26	24	20	23
21-F	27	26	25	-	-	-
22-F	25	24	23	22	17	20
23-F	27	26	24	-	-	-
24-F	23	22	21	20	17	19
25-F	23	21	20	-	-	-
26-F	20	20	20	20	16	17
27-F	22	21	21	-	-	-
28-F	20	20	18	19	15	15
29-F	21	20	19	-	-	-
30-F	19	20	19	19	14	15
31-F	18	18	17	-	-	-

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-G	16 units*	15 units*	16 units*	- mr/hr	- mr/hr	10 mr/hr
2-G	22	21	20	-	-	-
3-G	25	23	22	-	-	23
4-G	25	25	23	-	-	-
5-G	-	-	-	-	-	-
6-G	22	22	20	-	-	-
7-G	17	15	15	-	-	14
8-G	15	14	14	-	-	-
9-G	19	17	17	-	-	15
10-G	20	19	18	-	-	-
11-G	19	19	18	-	-	15
12-G	18	18	17	-	-	-
13-G	17	16	16	-	-	17
14-G	21	20	19	-	-	-
15-G	21	20	19	-	-	16
16-G	23	23	21	-	-	-
17-G	24	23	22	-	-	22
18-G	24	23	21	-	-	-
19-G	24	23	21	-	-	24
20-G	28	26	24	-	-	-
21-G	27	25	23	-	-	20
22-G	22	20	19	-	-	-
23-G	20	19	18	-	-	19
24-G	17	17	16	-	-	-
25-G	19	19	17	-	-	17
26-G	24	22	21	-	-	-
27-G	23	21	21	-	-	18
28-G	20	19	18	-	-	-
29-G	22	21	20	-	-	18
30-G	19	19	18	-	-	-
31-G	18	18	17	-	-	16

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-H	29 units*	28 units*	26 units*	- mr/hr	- mr/hr	- mr/hr
2-H	18	19	17	12	12	10
3-H	18	18	18	-	-	-
4-H	18	16	16	14	14	16
5-H	14	14	13	-	-	-
6-H	-	-	-	-	-	-
7-H	22	22	20	-	-	-
8-H	19	18	17	14	16	15
9-H	20	19	18	-	-	-
10-H	17	17	15	14	14	14
11-H	20	19	18	-	-	-
12-H	17	17	16	14	16	14
13-H	21	20	19	-	-	-
14-H	23	22	21	-	-	20
15-H	22	21	20	-	-	-
16-H	21	20	19	16	16	18
17-H	20	20	19	-	-	-
18-H	19	18	18	15	13	15
19-H	24	20	19	-	-	-
20-H	-	-	-	-	-	-
21-H	-	-	-	-	-	-
22-H	-	-	-	-	-	-
23-H	-	-	-	-	-	-
24-H	19	17	15	-	-	-
25-H	18	16	15	-	-	-
26-H	19	17	16	14	14	15
27-H	21	20	19	-	-	-
28-H	26	24	22	18	16	16
29-H	25	25	24	-	-	-
30-H	26	24	22	21	-	19
31-H	22	21	20	-	-	-

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
Coordinate	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-I	31 units*	29 units*	27 units*	- mr/hr	- mr/hr	24 mr/hr
2-I	31	29	26	-	-	-
3-I	26	26	24	-	-	16
4-I	25	24	22	-	-	-
5-I	28	26	24	-	-	23
6-I	18	18	17	-	-	-
7-I	-	-	-	-	-	-
8-I	30	27	26	25	24	21
9-I	23	21	19	-	-	17
10-I	22	20	17	-	-	-
11-I	22	21	20	-	-	-
12-I	25	23	21	-	-	-
13-I	23	21	20	-	-	20
14-I	14	14	13	-	-	-
15-I	16	15	15	-	-	15
16-I	23	21	19	19	17	16
17-I	21	20	19	-	-	18
18-I	19	18	16	-	-	-
19-I	-	-	-	-	-	-
20-I	26	23	22	-	-	-
21-I	19	18	17	-	-	-
22-I	19	19	17	-	-	-
23-I	20	18	16	-	-	-
24-I	-	-	-	-	-	-
25-I	-	-	-	-	-	-
26-I	-	-	-	-	-	-
27-I	-	-	-	-	-	-
28-I	-	-	-	-	-	-
29-I	-	-	-	-	-	-
30-I	-	-	-	-	-	-
31-I	-	-	-	-	-	-

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-J	19 units*	19 units*	19 units*	- mr/hr	- mr/hr	- mr/hr
2-J	22	22	21	18	15	16
3-J	20	27	24	-	-	-
4-J	22	21	20	17	16	13
5-J	19	19	19	-	-	-
6-J	26	25	23	19	18	19
7-J	24	21	21	-	-	-
8-J	27	25	24	-	-	-
9-J	32	30	25	-	-	-
10-J	18	17	15	14	13	14
11-J	25	23	21	-	-	-
12-J	26	25	23	18	15	16
13-J	23	22	19	-	-	-
14-J	20	17	16	15	13	15
15-J	19	17	15	-	-	-
16-J	-	-	-	-	-	-
17-J	-	-	-	-	-	-
18-J	-	-	-	-	-	-
19-J	29	26	22	-	-	-
20-J	24	22	21	-	-	-
21-J	27	25	23	-	-	-
22-J	27	25	23	20	19	19
23-J	28	26	24	-	-	-
24-J	29	26	24	20	18	20
25-J	28	27	25	-	-	-
26-J	27	24	21	19	16	17
27-J	26	25	21	-	-	-
28-J	24	23	21	17	16	16
29-J	28	26	24	-	-	-
30-J	26	25	22	18	18	18
31-J	27	25	23	-	-	-

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-K	29 units*	27 units*	25 units*	- mr/hr	- mr/hr	23 mr/hr
2-K	28	27	26	-	-	-
3-K	28	26	24	-	-	20
4-K	22	22	21	-	-	-
5-K	26	24	22	-	-	21
6-K	11	11	13	-	-	-
7-K	14	15	15	-	-	10
8-K	29	26	21	-	-	-
9-K	-	-	-	-	-	-
10-K	-	-	-	-	-	-
11-K	43	38	30	-	-	25
12-K	-	-	-	-	-	-
13-K	26	22	20	-	-	-
14-K	-	-	-	-	-	-
15-K	-	-	-	-	-	-
16-K	20	18	15	-	-	-
17-K	23	20	18	-	-	17
18-K	28	28	24	-	-	-
19-K	29	27	24	-	-	28
20-K	28	26	23	-	-	-
21-K	29	27	25	-	-	30
22-K	30	27	27	-	-	-
23-K	31	29	27	-	-	21
24-K	31	29	28	-	-	-
25-K	31	29	28	-	-	28
26-K	31	30	28	-	-	-
27-K	32	31	28	-	-	29
28-K	31	29	27	-	-	-
29-K	29	28	26	-	-	28
30-K	27	26	25	-	-	-
31-K	26	26	26	-	-	26

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-L	37 units*	34 units*	30 units*	- mr/hr	- mr/hr	- mr/hr
2-L	30	29	27	24	17	17
3-L	32	30	27	-	-	-
4-L	27	26	25	25	17	18
5-L	23	23	22	-	-	-
6-L	17	16	13	12	14	13
7-L	13	12	11	-	-	-
8-L	20	17	15	16	10	16
9-L	20	18	15	-	-	-
10-L	10	10	10	10	9	8
11-L	11	10	10	-	-	-
12-L	14	13	12	11	9	8
13-L	12	11	10	-	-	-
14-L	10	9	9	10	9	8
15-L	20	20	19	-	-	-
16-L	20	20	19	18	16	17
17-L	15	14	14	-	-	-
18-L	22	21	19	-	-	16
19-L	25	23	22	-	-	-
20-L	24	23	21	19	18	17
21-L	17	16	16	-	-	-
22-L	20	19	19	18	17	16
23-L	22	22	22	-	-	-
24-L	25	25	23	20	18	19
25-L	25	23	22	-	-	-
26-L	25	24	24	22	21	19
27-L	25	25	23	-	-	-
28-L	25	24	24	-	-	19
29-L	24	24	24	-	-	-
30-L	25	25	24	22	19	19
31-L	25	25	23	-	-	-

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-M	23 units*	23 units*	23 units*	- mr/hr	- mr/hr	27 mr/hr
2-M	24	23	21	-	-	-
3-M	33	22	21	-	-	20
4-M	24	22	21	-	-	-
5-M	22	22	21	-	-	19
6-M	23	23	21	-	-	-
7-M	21	21	21	-	-	14
8-M	18	18	17	-	-	-
9-M	14	13	13	-	-	15
10-M	11	11	11	-	-	-
11-M	15	14	13	-	-	17
12-M	20	19	17	-	-	-
13-M	23	22	21	-	-	19
14-M	26	25	23	-	-	-
15-M	29	27	25	-	-	23
16-M	-	-	-	-	-	-
17-M	-	-	-	-	-	-
18-M	-	-	-	-	-	-
19-M	7	7	7	-	-	9
20-M	11	11	11	-	-	-
21-M	4	4	5	-	-	18
22-M	14	14	13	-	-	-
23-M	23	23	21	-	-	29
24-M	27	25	23	-	-	-
25-M	25	24	23	-	-	28
26-M	27	25	24	-	-	-
27-M	27	25	25	-	-	29
28-M	25	25	24	-	-	-
29-M	23	22	22	-	-	23
30-M	22	21	21	-	-	-
31-M	22	21	22	-	-	26

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
1-N	23 units*	22 units*	21 units*	- mr/hr	- mr/hr	- mr/hr
2-N	22	21	20	21	18	20
3-N	22	22	21	-	-	-
4-N	22	22	20	20	16	19
5-N	13	13	13	-	-	-
6-N	18	18	16	15	12	14
7-N	18	18	17	-	-	-
8-N	14	13	12	12	13	12
9-N	10	10	10	-	-	-
10-N	8	8	8	8	9	9
11-N	11	10	10	-	-	-
12-N	16	15	14	10	10	14
13-N	22	21	19	-	-	-
14-N	-	-	-	-	-	-
15-N	-	-	-	-	-	-
16-N	-	-	-	-	-	-
17-N	-	-	-	-	-	-
18-N	-	-	-	-	-	-
19-N	-	-	-	-	-	-
20-N	-	-	-	-	-	-
21-N	-	-	-	-	-	-
22-N	-	-	-	-	-	-
23-N	-	-	-	-	-	-
24-N	4	4	4	7	8	6
25-N	4	4	5	-	-	-
26-N	-	-	-	-	-	-
27-N	15	15	14	-	-	-
28-N	23	23	21	20	17	23
29-N	26	25	24	-	-	-
30-N	24	24	23	22	19	21
31-N	19	19	19	-	-	-

RADIATION MEASUREMENTS
WHITE OAK LAKE BED (contd.)

Coordinate	Ionization Chamber				Film	
	Thin Wall			Thick Wall		
	25 cm	50 cm	100 cm	100 cm	100 cm	5 cm
	(Height from ground surface)					
9-0	7 units*	7 units*	7 units*	- mr/hr	- mr/hr	- mr/hr
10-0	10	9	9	-	-	-
11-0	14	13	11	-	-	-
29-0	14	13	13	-	-	-
30-0	22	21	20	-	-	-
31-0	14	14	14	-	-	16
8-P	7	7	6	-	7	9
9-P	8	8	8	-	-	-
9-Q	10	8	7	-	-	-

*These readings have no expressed units but are dose rates being equal in magnitude to the milliroentgens per hour of gamma radiation causing the same instrument response.

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