Scintillation Methods for the Determination of Density and Moisture Content of Soils and Similar Granular Systems

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Nuclear methods for moisture and density determinations in soils have reached a point of development that makes them valuable tools to the engineer and scientist. The paper first traces the history of the available techniques and discusses the underlying scientific principles as well as the characteristics of the various available probes and of their components. Subsequently, the principles and available methods of scintillation detection are described and are applied to the design of actual moisture and density probes. The performance of these probes in laboratory and extensive field tests are given and their advantages and shortcomings pointed out. Emphasis is placed on meeting the practical problems encountered in field conditions as they affect the operation of the probes and associated electronic equipment, the preparation of holes through various soil types, the readings obtained by the instruments used, and the calculation of results, so as to give the most accurate determinations of soil moisture and density.

● ALL physical properties of natural or disturbed soil systems, whether mechanical, thermal, electrical, acoustic or optical, are functions of:

1. The volume proportions of solid, liquid and gaseous phases of the soil;
2. The intrinsic properties of these phases at the environmental temperatures;
3. The spatial arrangement of these phases, and
4. The extent, geometry and physico-chemical character of the solid-liquid, solid-gas, gas-liquid and liquid-liquid interphases in the system.

In a specific natural soil system, factors 2, 3, and 4 are usually sufficiently constant that the physical property under consideration can be expressed in first approximation as a function of the phase composition which can be calculated from the density and moisture content of the soil and the specific gravities of its components. Knowledge of density and moisture content is, therefore, basic with respect to the understanding of any and every physical property of a soil system and also to the predicting of the variation of such properties as a result of weather, and seasonally induced variation in soil moisture and density. Obviously, there exists a definite need for simple, dependable and speedy methods of determining moisture contents and densities of soils in the field. The traditional methods are destructive, time consuming and cumbersome. Even the improved types of electric resistance blocks for moisture determination possess important limitations. References (45), (153) and (131) give comparisons of the advantages and limitations of different methods. The most promising methods for easy and speedy moisture and density determinations are those based on the use of nuclear radiation. They are: (a) determination of soil density from the absorption or scattering of Gamma rays (γ -ray densitometry), and (b) determination of moisture content by the neutron thermalizing technique (neutron hygrometry). Sufficient work has been done on and with these methods to know that they will keep their promise. On the other hand much work is still necessary to make these methods and the required equipment so simple, rugged and dependable that any workman can use it with a minimum of instruction and also with a minimum of radiation hazard. The purpose of the present work was to contribute to this development with special emphasis on the use of scintillation detection which, in addition to other advantages, permits the employment of low-intensity radiation sources.

HISTORICAL REVIEW

Initial research on the determination of soil density by gamma ray scattering was performed by Krueger (97) at Cornell University, whereas Pieper (118) and Yates (172) appear to have been the first to use the thermalizing of neutrons for measuring moisture content. Significant engineering research on the use of these methods for in situ determination of soil density and moisture content was performed by Belcher and his associates, also at Cornell University, in the course of a project sponsored by the Civil Aeronautics Administration, U. S. Department of Commerce. In their first published report of 1950, (7) Belcher and his co-workers demonstrated the great potentialities of their gamma-ray densitometer and their neutron hygrometer. The latter employed silver or rhodium foils whose activation by slow neutron bombardment was measured by means of a Geiger-Mueller tube. Previously, Berdan and Bernhard (11) at Rutgers University had demonstrated that soil density could be measured nondestructively by means of x-rays; however, the necessary equipment was rather bulky and the methodology, involved. In 1952, Belcher and his associates reported on an adaptation of the nuclear techniques to measure soil density and moisture content in thin surface layers (8). Probe modifications were reported in 1953 (33), the main one following an earlier design by Gardner and Kirkham (54) using a BF_3 continuous detecting device for slow neutrons. With the exception of Bernhard (13) and Timblin (154), all subsequent workers have used G-M tubes for the detector of the gamma ray densitometer (25, 75, 99, 58, 131, 165) and radioisotope cobalt 60 of varying intensities for the source. For neutron hygrometry either GM tubes in combination with neutron activated foils (7, 25, 144, 156) or BF_3-filled proportional counters have been used (154, 137, 162). Several investigators have used B^{10} lined BF_3-counters which have the advantages of greater stability, efficiency, smaller size and of operating at much lower voltages than BF_3-counters. However, these counters are expensive.

Earlier work on nuclear moisture meters made use of Po-Be sources, (7, 144, 156). Such sources are cheap, their chief asset, however, is low gamma radiation. Unfortunately, Po-Be has a half-life of a mere 140 days. Later, investigators used Ra-Be which has a half-life of 1,620 years; this source is fairly inexpensive but has the great disadvantage of very heavy gamma emission, (147, 163). One or two workers have used Ra D-Be sources which have low gamma emission and a half-life of 22 years; these sources, however, are expensive (37).

The moisture meter has come out so far only as a single probe instrument which contains both source and detector. The probes employing the foil-activation system are usually about 1 in. in diameter. The probes utilizing BF_3-counters are generally about 2 in. in diameter. The densitometers have generally been of the single probe type, employing a geometry involving gamma-ray scattering (9, 25, 76). Gamma-ray attenuating geometry, employing two parallel tubes, one containing the source, the other the detector, has been used by some workers (13, 131, 165). The former system is simpler for field measurements, although theoretically not quite so accurate and capable of narrow spatial resolution as the two-probe system. The only reported work using scintillation detection known to the authors is that of Bernhard and Chasek (13) at Rutgers University. These investigators used a 2 in. D x 1¾ in. NaI(Tl) crystal, with a photomultiplier tube that appears to be an RCA 931A type, though it is not reported as such in the paper. The tube was housed in a shield of the dimensions 5.25 in. dia. by 16 in. The two-probe geometry employing a 60 mc. cobalt 60 source was was used to measure densities of as great as 4-foot widths of soil, where the greater sensitivity of scintillation detection was used to advantage.

Several workers have used simple portable survey meters to measure the intensity of radiation picked up by the detector in the densitometer (131, 165). Others have employed absolute counting scalers (7, 33, 54, 75); Timblin (154) used a dosimeter. For measuring the radiation from slow neutron detection, some have used commercial or laboratory devised amplifiers and scalers (9, 54, 58, 72, 76, 78, 138, 146, 147, 156, 162).

Swanson (151) working with Van Bavel and Underwood developed an excellent stable and sensitive portable survey meter to handle pulses from a B^{10} lined BF_3 counter when activated by slow neutrons. Another portable instrument has been designed and further modified by Stone, et al (147). This instrument utilizes four cold cathode glow transfer

decade counter tubes.

THEORETICAL CONSIDERATIONS

Gamma Ray Densitometry

The scientific principles underlying gamma ray densitometry have been discussed by several investigators (6, 7, 25, 111). For detailed theoretical understanding, the reader is referred to the following references: (12, 41, 97, 111, 142). Only a cursory survey of the more important principles can be given here. There are three processes involved in the absorption of X- or γ-ray quanta. These are shown schematically in Figure 1. The total absorption coefficient μ is, therefore, the sum of the three absorption coefficients, corresponding to these three processes: the photoelectric effect μ_p, pair production μ_{pp}, and the Compton effect μ_C, so that:

$$\mu = N(\mu_p + \mu_{pp} + \mu_C) cm^{-1} \tag{1}$$

where N is the number of atoms per cm^3.

At energies above 0.3 Mev for the lighter elements, there is no absorption by the photo-electric process (hence $\mu_p = 0$), though this is the predominant mechanism of absorption at low energy levels below 0.1 Mev. Energy is not absorbed by pair production below 1.02 Mev, but is increasingly so with increasing energy. However, up to approximately 2.5 Mev, this mechanism is scarcely involved. The Compton effect remains nearly constant in absorbancy at energies from 0 to about 0.5 Mev; then it decreases gradually with increasing energy. In the range of energy of 0.35 to 2.5 Mev for the lighter elements, the Compton effect (μ_C) is almost the sole mechanism of absorption. This is clearly seen in Figure 1b which graphically shows the respective absorption coefficients for each of the three processes of γ-ray absorption by NaI(Tl) as a function of γ-ray energy. Hence, radioisotope Co60, which decays with the emission of gamma photons at 1.33 and 1.17 Mev, becomes an ideal source because its energy is almost solely absorbed by the Compton effect by elements found in the soil and because of its ready availability and low cost. For all practical purposes, Co60 may be considered essentially to decay mono-energetically with a mean energy of 1.25 Mev.

The fundamental equation governing the absorption of all monoenergetic radiation through homogenous media is the Bouguer-(Lambert)-Beer law:

$$\frac{I}{I_0} = e^{-\mu x} \tag{2}$$

where

I_0 = initial intensity of monoenergetic beam upon entering an absorbing medium.

I = intensity of the beam upon passing through a given thickness of the medium.

x = unit thickness of the path travelled by the beam.

μ = absorption coefficient of the medium.

Owing to the essentially monochromatic decay at 1.25 Mev of cobalt 60, and since only the Compton effect is instrumental in its absorption, Equation 2 becomes applicable without modification, when such a source is used to penetrate soil consisting almost entirely of the lighter elements.

The absorption coefficient due to the Compton effect is determined after Klein and Nishina (17) from two equations:

$$e^\mu = 2\pi r_0^2 \left[\frac{1+a}{a^2} \left\{ \frac{2(1+a)}{1+2a} - \frac{1}{a} \log_e (1+2a) \right\} \right.$$
$$\left. + \frac{1}{2a} \log_e (1+2a) - \frac{1-3a}{(1+2a)^2} \right] \tag{3}$$

(a) PAIR PRODUCTION
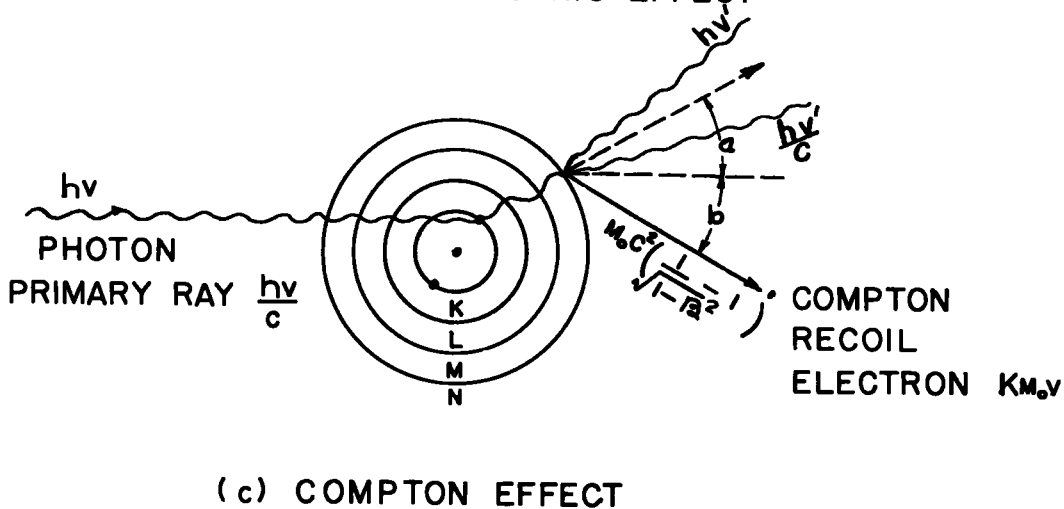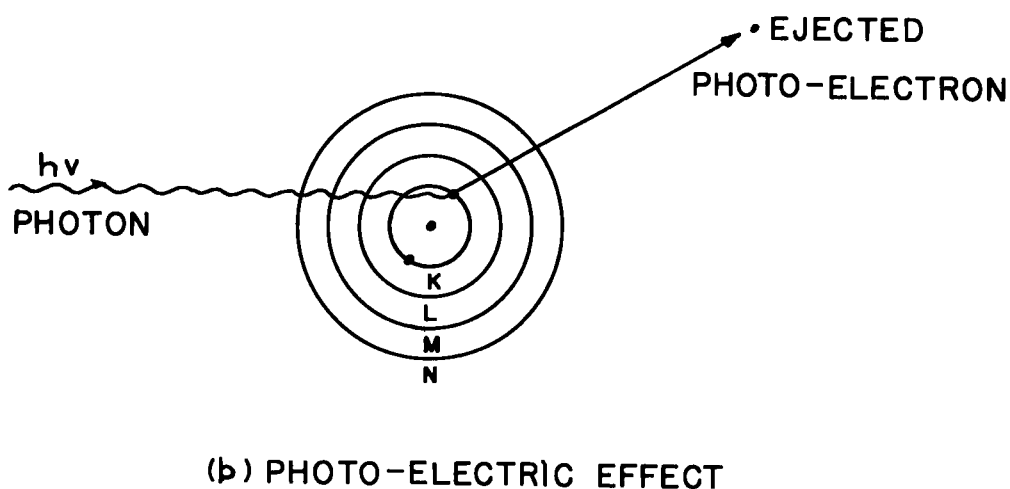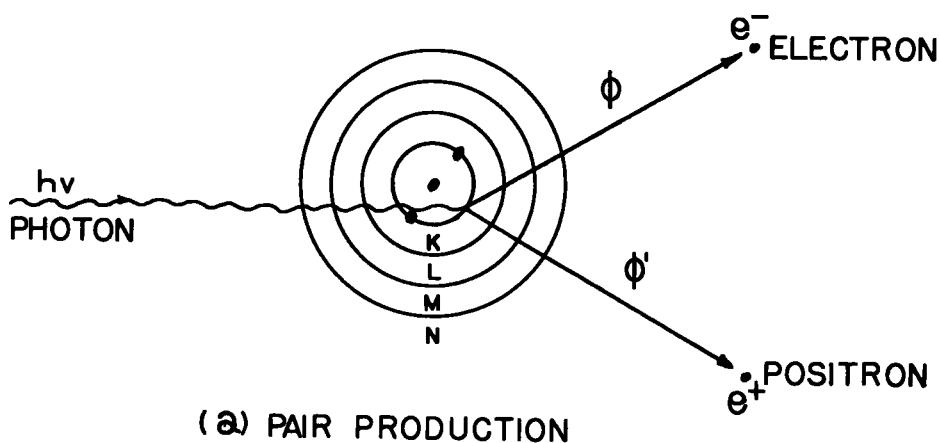
(b) PHOTO-ELECTRIC EFFECT

(c) COMPTON EFFECT

Figure 1 (a). Mechanisms of γ-ray absorption by matter.

and

$$e^{\mu s} = r_0^2 \left[\frac{1}{a^3} \log_e (1+2a) + \frac{2(1+a)(2a^2-2a-1)}{a^2(1+2a)^2} + \frac{8a^3}{3(1+2a)^3} \right] \qquad (4)$$

where e^{μ} = cross-section for number of photons scattered per electron of absorber,
1. e. the total energy removed from the initial beam per electron absorber;

$e^{\mu s}$ = cross-section for the energy retained by the scattered photons per electron absorber;

r_0 = radius of electron ($2 \cdot 8182 \times 10^{-13}$ cm);

$a = \dfrac{\text{photon energy of initial radiation source}}{\text{energy of electron}}$

$$\left(\text{i. e.}, \ a = \frac{1.25 \ \text{Mev}}{0.511 \ \text{Mev}} = 2.44 \right).$$

The cross-section for photon energy absorbed per absorber electron (e^{μ}), in collision with a photon of radiation is thus:

$$e^{\mu a} = e^{\mu} - e^{\mu s} \qquad (5)$$

Bernhard and Chasek (12) have calculated the values for these coefficients for radiation from Co60 from Equations 3 and 4:

$$e^{\mu} = 1.702 \times 10^{-25} \ \text{cm}^2/\text{electron}$$

and

$$e^{\mu s} = 1.27 \times 10^{-25} \ \text{cm}^2/\text{electron}$$

and therefore from Equation 5

$$e^{\mu a} = (1.70-1.27)10^{-25} \ 0.43 \times 10^{-25} \text{cm}^2/\text{electron}.$$

Davisson and Evans (41) give the relationships between μ, the linear absorption coefficient, and e^{μ} the total cross-section for ideal geometry as:

$$\mu = \rho N \frac{Z}{A} e^{\mu} \quad (\text{cm}^{-1}) \qquad (6)$$

where

ρ = density of the absorbing medium

Z = atomic number of absorber element (number of electrons)

A = atomic weight of absorber element

N = Avogadro's number = 6.02×10^{23}

In a fixed geometry e^{μ} is constant. $\frac{Z}{A}$ is approximately 0.5 for all light elements or their compounds up to a Z number of 30 in the periodic table. N is a constant. Hence, since all the factors on the right side of Equation 6 are constant except ρ, μ is proportional to ρ the density of an absorber such as soil (i. e., the electron density of the material).

In a geometry where photons are scattered within the solid angle which has its vertex at the point source and is subtended by the detector, the absorption coefficient, μ exp, varies with changing geometries, but within the following limits:

$$\left(\rho \frac{NZ}{A} \right) e^{\mu a} \leqq \mu \ \text{exp} \leqq \left(\rho \frac{NZ}{A} e^{\mu} \right) \qquad (7)$$

Using the previously calculated value of

$$e^{\mu a} = 0.43 \times 10^{-25} \text{cm}^2/\text{electron},$$

these limits can be calculated thus:

$$\frac{NZ}{A} \sigma = 6.02 \times 10^{23} \times 0.5 \ \rho = 3.01 \times 10^{23} \rho$$

Therefore

$$3.01 \times 10^{23}(0.43) \times 10^{-25} \rho \; \leqq \; \mu \exp \; \leqq \; 3.01 \times 10^{23}(1.70 \times 10^{-25}) \rho$$

or

$$0.0130 \, \rho \; \leqq \; \mu \exp \; \leqq \; 0.0512 \, \rho \; cm^{-1} \qquad (8)$$

ρ represents the wet bulk density of the absorbing material such as soil. Since the absorption coefficient, μ, for water has been calculated to be between 0.0632 cm^2/gm (12) and 0.055 cm^2/gm (165) and μ for soil by averaging all elements in proportion, to be between 0.056 cm^2/gm and 0.0512 cm^2/gm (12), it follows that the moisture content does not essentially change the absorption coefficient of wet soils.

In the single probe system, direct transmittancy principles do not apply. Gamma ray scatter is detected only, and this process is most difficult to define mathematically.

The density of the surrounding material and the source to detector geometry control the design of a gamma scattering densitometer probe. Though, as it has been indicated above, Compton scatter increases proportionately with electron density, it is also true that at high densities an increasing proportion of gamma rays are absorbed by the surrounding medium as its density increases. Hence, at considerably high densities, the number of scattered gamma photons is actually reduced.

For a probe with fixed distance between source and detector, the probability that a gamma ray emitted at the source will be scattered by an orbital electron of an atom of the surrounding medium and eventually reach the detector depends on the following:

Figure 1 (b). Absorption coefficients of Gamma Rays in NaI (Tl).

(1) The probability that the ray will be scattered rather than absorbed;

(2) The probability that the ray will reach a particular electron before being scattered by others;

(3) The probability that the electron will scatter the ray in the direction of the detector (see Figure 1),

(4) The probability that the scattered ray will reach the detector instead of being re-scattered or absorbed on its way.

Krueger (97) and Timblin (154) consider these probabilities to explain their results of obtaining a maximum number of counts recorded by the gamma-ray detector at a certain density, beyond which the counts decrease with increasing density. The density at which this maximum occurs changes with the distance between the source and detector. Hence, the expected range of density is an important consideration in fixing the geometry of a gamma scattering probe.

The absorption coefficient of the scattering medium for gamma rays definitely determines the number of scattered photons picked up by the detector, for any fixed geometry. Though the limits of the experimental absorption coefficients will approach the lower value of Equation 8 derived from the Klein-Nishina equations, no difference in μ has been substantiated for water and for soil solids. Hence, the scattering geometry works almost as predictably as the direct beam geometry, though for the former the predictions are based on empirical calibration alone. In spite of the possibility of calculating a count versus wet density curve for direct transmittancy geometries, owing to certain amount of scatter into the detector and aberrations of instrumentation, actual calibration curves should be obtained experimentally for greatest convenience and accuracy.

The chief disadvantage of the two-probe direct transmittancy geometry is that the distance between source and detector must be kept rigidly constant or measured precisely. A one percent error in the distance of the absorption path has been calculated to yield an error of 6.3 percent in the measured intensity of radiation I (refer to
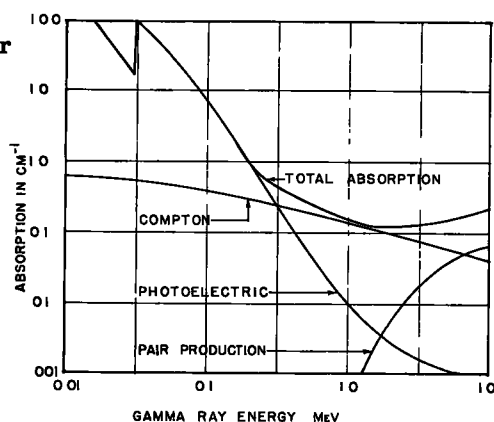
Equation 2) in an average reading of soil density measurement, in the set-up employed by Bernhard and Chasek (13). It is extremely difficult to make parallel holes to any great depth in the field and to maintain them equidistant throughout.

Basic Principles of Neutron Moderating Moisture Meter

For a thorough discussion of the theory governing the neutron scattering moisture meter, the reader is referred to the following works: (54, 166, 168, 172, 173, 96). Only the important fundamentals are reviewed here.

A mineral soil contains hydrogen mainly in three forms. Firstly, the soil minerals contain some hydrogen, but this amount is rather constant and its proportion by weight is negligible. Secondly, the organic matter in soils contains about 5 percent of hydrogen by weight. Since the organic matter content of most mineral top-soils ranges from 2 to 6 percent, and is fairly constant, at most 0.3 percent of the total weight of a mineral soil is contributed by the hydrogen content of its organic matter. Water, which contains 11 percent by weight of hydrogen and which is generally present in appreciable quantities, contains most of the hydrogen present in a mineral soil.

The fact that the hydrogen content of mineral soils, particularly of sub-soils, is almost entirely due to its moisture content, is utilized for moisture determination by means of the neutron scattering technique. Of all the soil elements, hydrogen is by far the most effective speed reducer (moderator) of fast neutrons, as its high ϵ value indicates. In addition, the large σ_s value for hydrogen indicates a greater probability of being struck by neutrons than exists for the other elements (see Table 1).

In order to utilize these properties of hydrogen and other elements for the design of a neutron scattering moisture meter, it is essential to understand a few basic principles. A neutron is a sub-atomic particle having no charge, but possessing approximately the same mass as the hydrogen nucleus (proton). Since the neutron has no charge, it does not have to overcome the Coulombic electrostatic barrier of repulsive forces in order to enter an atomic nucleus and thus possibly cause a nuclear reaction.

Figure 2. Slow neutron flux distribution about a point source of fast neutrons.

When neutrons strike atomic nuclei they are either captured or scattered. If the neutrons are captured, unstable nuclei of the struck atoms are usually formed. These nuclei either dissipate the extra energy gained by emitting gamma radiation, or disintegrate with the emission of one or more particles — usually a proton, an alpha particle or two neutrons. If the neutrons are scattered, the process may be "elastic" or "inelastic." If inelastic, the neutrons transfer enough of their kinetic energy to the nuclei to raise them to a higher energy state, from which they eventually rebound, emitting gamma rays as they do so. In neutron bombardment elastic collisions have a much higher probability of occurrence than inelastic scattering. Also, for light elements (A less than 60), elastic collisions are much more probable than capture.

In elastic collision, which is the most common neutron reaction in soil, the laws of conservation of energy and momentun apply (mass-energy equivalence). The neutron simply imparts to the nucleus some of its kinetic energy.

When a neutron collides elastically with a nucleus of mass number A, the average ratio of the neutron energy after collision (E_2) to that before collision (E_1), is for all angles of scattering,
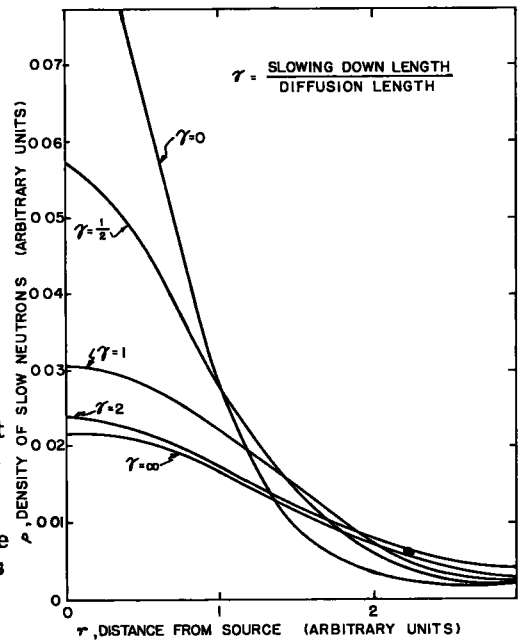
$$\xi = \log_e \frac{E_2}{E_1} = 1 - \frac{(A-1)^2}{2A} - \log_e \left(\frac{A+1}{A-1}\right) \tag{9}$$

The average energy E_n of a neutron after n collisions, have an original energy state E_0 is

$$E_n = E_0 \ e^{-n\epsilon} \tag{10}$$

From Equation 9 and known values of A, ϵ values can be calculated, as Adair (1) has already done. In Table 1 values for all abundant soil elements are listed. From the calculated values and Equation 10, the number of collisions required to slow neutrons to thermal velocities in the case of hydrogen, silicon, and oxygen may be computed; results of 17, 240, and 136, respectively, were obtained by Gardner and Kirkham (54) (assuming fast neutrons with energies E_0 of 1.0 Mev and slowed neutrons reduced to thermal energies E_n of 1/40ev). Accordingly, 14 times as many collisions are required in silicon as in hydrogen, and 8 times as many in oxygen as in hydrogen, to reduce the speed of fast neutrons to thermal velocities. This fact is essential for the successful function of the moisture meter, as it indicates that hydrogen is primarily responsible for the thermalizing of fast neutrons in a soil.

TABLE 1

VALUES OF ϵ AND σ_s FOR PRINCIPAL SOIL ELEMENTS

Elements	A	ϵ	Cross-Sections σ_s for Fast Neutrons at $\pm$2.5 Mev, in Barns[a]	Cross-Sections σ_s for Slow Neutrons at 1/40 Ev, in Barns[a]
H	1	1.000	2.55	47.5
C	12	0.162	1.60	4.6
N	14	0.145	1.0	13.0
O	16	0.128	1.5	4.2
Cl	17	0.113	2.7	40.0
Ti	22	0.068	4.4	3.0
Na	23	0.086	2.6	3.6
Mg	24	0.082	2.0	3.5
Al	27	0.075	2.5	1.6
Si	28	0.071	3.2	2.5
P	31	0.063	3.0	4.0
S	32	0.061	2.6	1 3
K	39	0.050	3.8	3.0
Ca	40	0.049	4.9	1.5
Mn	55	0.037	3.0	12.0
Fe	56	0.035	13.0	3.0

a A barn is the unit of measure of cross-sections equivalent to 10^{-24}cm^2. (Table taken from Gardner and Kirkham (54)).

Of further importance in the slowing of neutrons is the relative probability that a neutron will interact with an atom nucleus of a given element. This probability is expressed in the form of the nuclear cross-section σ_s (absorption number) in units of barns, one barn being equivalent to 10^{-24}cm^2. The numerical values for the neutron cross-sections depend primarily upon the kinetic energy of the neutrons, but for the lighter elements and with low neutron velocities they are also influenced markedly by interatomic forces. For a thorough understanding of known processes of scattering of slow neutrons by hydrogen molecules, the reader is referred to the recent work of Brimberg (24). For energies below a few Mev the scattering cross-section increases with decreasing neutron velocity for some of the lighter elements, particularly for hydrogen. In Table 1 average cross-sections are given for a number of elements for fast neutrons at approximately 215 Mev and for thermal neutrons at 1/40 ev. Of great

significance is the large increase in cross-section for hydrogen ($\frac{47.5}{2.55}$ = 18.6 times), attending the slow-down of fast neutrons to thermal velocities. For most other elements found in appreciable quantities in soil, the cross-sections remain much the same, with certain exceptions such as Cl, N, and Mn. Hydrogen is most effective in slowing fast neutrons both because of its high ϵ, and its large σ_S value. The former indicates the extent to which neutrons lose energy upon striking a hydrogen nucleus, while the latter indicates the probability of a nucleus being struck. When neutrons reach thermal energies, they come to thermal equilibrium with the surrounding atoms and cease to lose energy. They now scatter, in accordance with simple diffusion laws, until they are captured.

Mathematical Formulation

Certain peculiar characteristics of fast neutron emission, collision, and capture, that affect radically the design of a nuclear moisture meter are worthy of consideration through mathematical formulation of the rate processes and reactions involved.

Gardner and Kirkham (54) give essentially the following theoretical discussion: If

ρ (r) = density of slow neutrons per unit volume in a volume element located at a distance r from the source of fast neutrons;

t = the time elapsed, and T = the mean life time of a neutron (T is also the inverse of the probability of capture per unit time);

D = the diffusion coefficient, as ordinarily defined for gas; and

Q = the rate per unit volume at which thermal neutrons are created; then, from basic three dimensional diffusion theory, the equation of continuity is:

$$\partial \rho / \partial t = D \nabla^2 - (\rho/T) + Q \qquad (11)$$

The term on the left hand side of the equation is the time rate of variation of the density of slow neutrons in the volume element. The first term on the right represents the rate of increase of slow neutron-density in the volume element due to diffusion, and includes ∇, the Laplacian operator. The second term on the right represents the rate at which the slow neutrons disappear because of capture, and the last term Q represents the rate at which slow neutrons are created by the slowing of fast ones.

Since equilibrium is reached almost instantaneously, the primary assumption is: $\partial \rho / \partial t = 0$.

The diffusion length, L, is now introduced. This length is equal to $\frac{1}{6}$ the average distance from the point of origin to the point of capture of the thermal neutrons. The length includes also the distance traveled before capture and after being slowed to thermal velocities. In terms of D and T,

$$L^2 = DT$$

Hence, Equation 11 can now be written as

$$\nabla^2 \rho - \rho / L^2 = - (T/L^2) \; Q \qquad (12)$$

Q is usually calculated by means of the "Age theory" described by Marshak (109). According to this theory, Q satisfies the partial differential equation

$$\partial Q / \partial \theta = \nabla^2 Q + s \delta (\theta) \qquad (13)$$

in which θ is the "symbolic age," s is a function dependent on the shape of the fast neutron source, and δ is the Dirac δ- function. Physically, Q has the dimension of L^2. The Dirac δ- function is defined by the parameters δ (r) = 0 if r $\neq$ 0; and by $\int \delta$ (r) dr = 1, if the range of integration includes r = 0.

It is essential to obtain the boundary conditions in order to solve Equations 10 and 11, which is difficult to do. The diffusion length L has been defined above. The slowing-down length is defined as the average distance a neutron must travel in a medium before

it is slowed down to thermal velocity. The solution of interest here is the one for a point source of fast neutrons in an infinite, homogeneous, spherical medium. Wallace (166) presents the following solution in terms of the exponential function:

$$exp = e^x \text{ which is the error function;}$$

$$erf\ x = (2/\pi^{1/2}) \int_0^x e^{-y^2}\ dy;$$

and a quantity γ which is the ratio of the slowing down length to the diffusion length. Using the quantities A, B, C, D, for abbreviation, as defined below, Wallace (167) expresses the neutron density ρ (r) at a distance r from a point source of monoenergetic fast neutrons as:

$$\rho\ (r) = \frac{(exp\ \gamma^2)\ (1+\ \gamma^2)}{(8\pi r)\ (AB-CD)} \tag{14}$$

where:

$$A = exp\left[-r(1+\ \gamma^2)^{1/2}\right]$$

$$B = 1 - erf\left[\gamma - \frac{(r)}{2\gamma}\ (1+\ \gamma^2)^{1/2}\right]$$

$$C = exp\left[r(1+\ \gamma^2)^{1/2}\right]$$

$$D = 1 - erf\left[\gamma + \frac{(r)}{2\gamma}\ (1+\ \gamma^2)^{1/2}\right]$$

The significance of Equation 14 may be brought out by plotting the density ρ (r) of the slowed neutrons against the distance r from the source for several values of γ. This is done in Fig. 2 which is redrawn after Gardner and Kirkham (54), using arbitrary units. It can be seen that as γ approaches 0, the density of slowed neutrons is very large near the source (r = 0); while, if γ approaches ∞, the density of slowed neutrons will be small near the source. At a great distance from the source, ρ (r) is smaller for a small γ than for a larger γ. Also to be observed is that at distances far from the source, the percent of differences in ρ (r) are small, regardless of how large the differences are in γ.

It is now possible to apple the information given in Table 1 to the design of a neutron scattering moisture meter. First, because of the large ϵ and σ_s for hydrogen we would obviously expect the slowing-down length to be much smaller for hydrogen than for other common soil elements. For hydrogen, therefore, we would find the value of γ in Fig. 2 to be very small. Hence, if a counter to detect slow neutrons is placed near a source of fast neutrons, the total counts that it registers will be a function almost entirely of the amount of hydrogen present. As we have seen before, almost all the hydrogen in a normal mineral soil is contained in its moisture. Other elements in the soil contribute very little to the total slow neutron flux count, owing primarily to their considerably smaller ϵ and σ_s values. However, if the detecting counter were placed at an increasing distance from the fast neutron souce, the proportion of slow neutron counts registered due to hydrogen would be progressively less, the other elements accounting for progressively greater percentages of the count, as is evident from Equation 14 and Fig. 2.

Whitehouse and Graham (169) have shown that slow neutron density is greatest in the immediate vicinity of the source and rapidly approaches zero within 30 cm of water as shown in Fig. 3a. As a matter of fact, integration of the curve in Fig. 3a, showed that 95 percent of all the slow neutrons counted while a detector was extended along a radius from the source was contained within a sphere of water 15 cm in radius. This fact was pointed out by Van Bavel et al. (162), who have termed this the sphere of influence. Assuming that the volume of the sphere of influence is equal to that volume of soil that contains the same number of protons as a water sphere of 15 cm radius, these workers

determined the radii of the spheres of influence of soils with varying moisture contents, as given in Fig. 3 (b). The relationship used to calculate the spheres of influence as a function of the moisture content is given below:

$$R = 15 \sqrt[3]{100/\text{moisture content in percent by volume}}$$

This consideration ignores the effective cross-sections for neutrons of other elements in soils which become of increasing significance as the material contributing to the scattered neutrons detected grows in volume. However, with the geometry of their probe, Van Bavel and co-workers found that the sphere of influence ranged between 30 cm in diameter for water and 75 cm for dry soil. This indicates that the effect of elements other than hydrogen is actually not appreciable. From the considerations presented, it becomes obvious that the sphere of influence is not affected by the size of the source but by the geometry of the system and the moisture content of the soil under test. An important fact brought out by Van Bavel and co-workers is that the lower sensitivity at higher moisture contents reported by several other investigators could be explained by the decrease in size of the sphere of influence so that part of the sensitive portion of the long BF$_3$
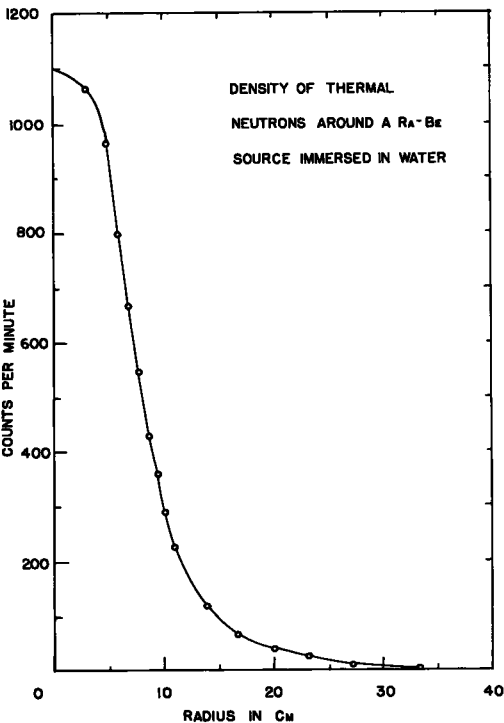

Figure 3 (a). Density of thermal neutrons around a RaBe source immersed in water.

tubes used fell outside this sphere. In order to obtain linear response the detector must be located wholly within the sphere of influence. Hence, the factors which chiefly determine the size of sample and the shape of the moisture content versus count curve are the size of the detector tube, the geometry of the source-detector system and the hydrogen content of the moderator material under test. For the first two factors involved, scintillation detection offers great advantages over BF$_3$ tubes, and is, in addition, much more sensitive.

METHODS OF RADIATION DETECTION

Several different techniques of detecting radiation have been devised. Only a brief discussion of these devices is appropriate here, in order to indicate how scintillation methods compare with other methods of radiation detection that could be used in these nuclear instruments.

Ion Chamber Counters

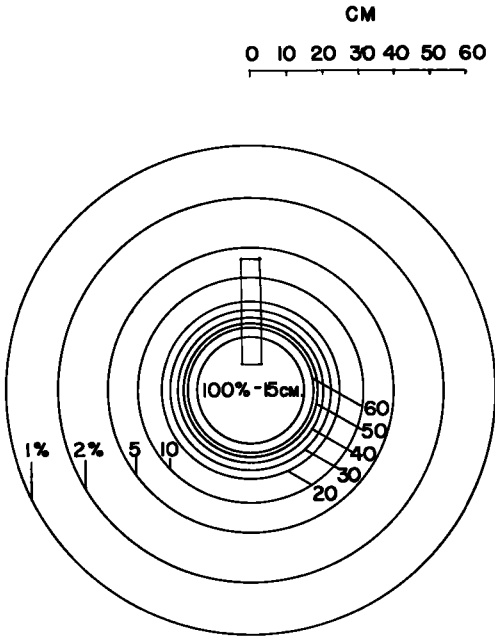An ion chamber counter consists of a metal cylinder containing a gas or vapor

Figure 3 (b). "Sphere of Influence" for a RaBe source surrounded by soil of varying moisture content in volume percent.

generally at atmospheric pressure. A metal rod which is insulated from the cylinder is held parallel to the axis of the cylinder. When any radiation capable of ionizing the gas enters the chamber through its thin window, it ionizes the gas. Because there is a small potential set across the chamber and the rod, the ions flow towards the opposite polarities and produce a faint ionization current which can be measured by an electrometer. Gamma rays can readily be detected by such counters. However, neutrons do not directly cause ionization as they have no charge. Hence, the chamber has to be lined with Lithium foil or a powder containing Boron. Neutrons passing through the foil generate α-particles by the n-α reaction, and these alpha particles cause the gas to ionize. The ion chamber is bulky and is capable of giving only a rate of radiation on an electrometer, being incapable of resolving individual pulses that follow closely upon each other. However, Koontz and Hall (89) devised a gas counter capable of being used as an ionization chamber or as a proportional counter which gives individual pulses that are proportional to the intensity of the primary ionization caused by an incident radiation photon.
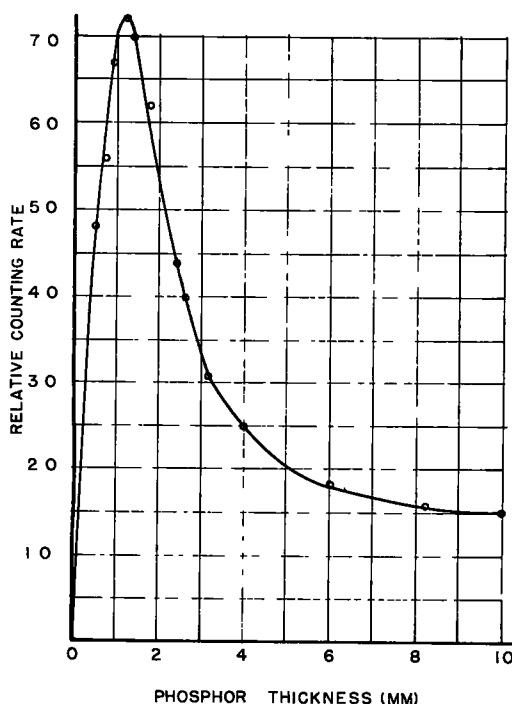

Figure 4. Relative efficiency of Neutron Phosphor vs. Phosphor thickness.

Proportional Counters

These counters are basically the same as an ionization chamber except that a higher potential electric field exists between the wall and the central rod. In operation, the primary ions that are produced upon radiation striking an atom of the gas in the chamber are accelerated by the high potential to cause secondary ions, and these in turn cause tertiary ionization, and so on, so that a sizable current is produced momentarily at the electrodes; this current, however, is still proportional to the primary ionization charge. The chief disadvantage of this system, though of more general use than the simple ionization chamber, is its long resolving time, so that at fast counting rates the pulses tend "to pile up" upon each other. These counters are also generally rather large.

Geiger Mueller Counters

These detectors depend on much the same ionization principle, but have been developed to a far greater extent so that there are several kinds, shapes and sizes of such tubes. In a Geiger-Mueller detector, the potential between the outer wall and the concentric thin wire along the axis of the gas cylinder is considerable. At the potential of operation, the primary ions produced by radiation are highly accelerated, causing a great many rapid secondary ionizations so that a large short-lived pulse is produced at the electrodes. The pulse so produced is not proportional in magnitude to the charge of the primary ionization event, tending to be fairly the same size irrespective of the original charge causing the cascade of ions. The chief advantages of this system are its versatility, its dependability, small size and convenience in use, and, above all, its stability in the region of its exciting potential plateau. The sensitivity of such tubes is very constant in spite of fluctuations of applied voltage within the plateau range. Such tubes are capable of fairly high counting rates as there are built-in mechanisms for suddenly quenching the pulse produced by the cascade of ionization sequences, after it registers a charge at the electrodes.

The efficiency of most gas filled counters is excellent for alpha and beta particles, but because of the low density of gas, it is poor for detecting gamma radiation. Uncharged particles, such as neutrons, cannot be detected directly by such counters. However, polar radiation can be produced by neutron bombardment of certain materials and this radiation can be detected. Of particular interest here is the detection of slow neutrons. As early as 1935 Locher (107) suggested that silver be used as the cathode shell in a G-M counter for slow neutron detection, noting that silver has a very high absorption cross-section of 600 barns for slow neutrons of 0.025 ev. The silver cathode would give off finite β radiation upon activation by slow neutron absorption. Belcher, Cuykendall and Sack (7) used a silver foil wrapped around a G-M tube to detect slow neutrons successfully in a soil-moisture probe.

Boron Trifluoride Counters

BF_3 counters deserve special attention here because they are the best means available for the detection of slow neutrons other than scintillation techniques. BF_3 tubes operate in the "proportional counter range." Such a counter consists of a cylinder with a central wire, filled with BF_3 at a certain pressure, generally between 2 - 140 cm of mercury. Ever since Korff and Danforth (91) devised the first BF_3 tube, it has been developed in a great variety of types, being the chief method of slow neutron detection until the recent development of scintillation detection systems for the same purpose. Ordinary BF_3 counters are large, operate at high voltages of 2,500 to 4,000 volts and have poor detection efficiency of generally below 3 percent.

Fowler and Tunnicliffe (53) used $B^{10}F_3$ fill at a pressure of 60 cm mercury, claiming a 60 - 100 percent efficiency for this counter. However, the tube deteriorated rapidly, becoming useless within half a year. Tongiorgi, et al. (159) used $B^{10}F_3$ at a higher pressure (101 cm of mercury) which, operating at 3,500 volts, was 9 - 33 percent efficient in detection, and did not deteriorate. More recent developments have led to B^{10}-lined BF_3-filled counters that are of high efficienty (10-40 percent), stable, small, long-lived and capable of operation at much lower voltages (600-1,500 v. D. C.) Such tubes have few disadvantages as compared to a scintillation system. However, such a B^{10}-lined tube is expensive, has longer pulse rise and fall times and often, a long "dead" time; also upon reduction in size there is considerable loss in sensitivity. For a thorough understanding of gas counters the reader is referred to Korff (92), Curran and Craggs (38), and Rossi and Straub (130).

Other Methods

There are other methods of radiation detection which could possibly be applied for the indicated purposes. One method consists of lining with Boron several warm junctions of thermocouples. The fission products due to the slow neutron bombardment of Boron cause the junctions to warm up, their temperature being indicative of the rate of slow neutron bombardment at each junction. Thermopiles are quite expensive, but their chief drawback is insensitivity.

Another method which has been used for a long time is by photographic technique. A photographic emulsion could be loaded with lithium, boron or $LiBO_3$ to obtain neutron tracks. These methods are capable of a high degree of resolution and great sensitivity. However, although rapid optical densitometric scanning methods are now available, the methods require too much technical skill and are too slow compared to gas and scintillation detection systems.

Scintillation Detection Methods

Owing to the rapid development of photomultiplier tubes and of better "phosphors, " scintillation detection systems are progressively displacing other radiation detection methods. Before considering the scintillation counter as a whole, the theory of phosphors will be discussed.

A "phosphor" is a liquid or solid that upon excitation by radiation of one sort or another gives a high fluorescent yield on its surface. For separate detection of each

E: INCIDENT RADIATION QUANTUM

POLISHED ALUMINUM
REFLECTING CONTAINER

PHOSPHOR

CRYSTAL

SCINTILLATION

FLUID OPTIC SEAL
(DOW-CORNING D-C 200 SILICONE)

INTERNAL CONDUCTIVE COATING

SEMI-TRANSPARENT
PHOTOCATHODE

PHOTOMULTIPLIER
TUBE

INCIDENT LIGHT PHOTON

GRILL

ACCELERATING ELECTRODE

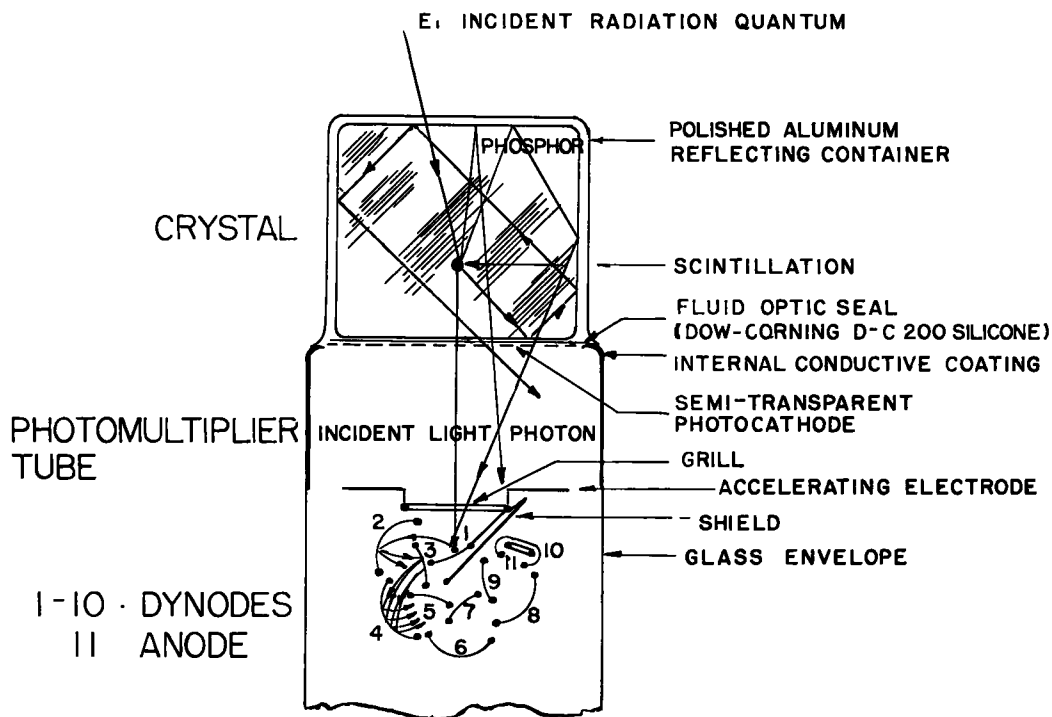SHIELD

GLASS ENVELOPE

I-IO · DYNODES
II ANODE

Figure 5. Schematic operation of a Scintillation System using RCA photomultiplier tube
types such as 6199 and 5819.

photon or particle that causes emission of fluorescent light, this emission must be of
very short duration, in the order of microseconds or fractions of microseconds. Hence
the term "phosphor" is actually a misnomer, for sustained phosphorescence upon exci-
tation is certainly undesirable in a scintillation detector. Both inorganic and organic
phosphors with excellent scintillation properties have been developed.

The action mechanisms of organic phosphors differ from those of inorganic ones.
Only inorganic phosphors were employed in the present investigation; however, because
of the growing importance of organic phosphors and for purposes of comparison, their
functioning is discussed briefly in the following.

Upon excitation of a fluorescent organic molecule by absorption of ionizing radiation
the molecule radiates at a higher energy level and with increased interatomic distances.
The excess energy of the excited state can be dissipated in one or several of the follow-
ing ways: (a) resultant chemical dissociation; (b) transfer of energy to different vibra-
tional states with resultant marked change in molecular configuration; (c) transfer by a
resonant process (in condensed organic crystals) termed "exciton migration" by Bowen
et al. (23). The exciton is capable of transfer from molecule to molecule in a system,
similar to electron migration in the conduction band of an inorganic crystal, until it is
eventually quenched or yields fluorescent lumination; (these processes are fully dis-
cussed by Botden (21), Reid (125), Kallman and Furst (84); (d) direct return of the
molecule from the excited state to the original ground level with subsequent emission
of light quanta.

Substances that tend to dissociate chemically, have close coupling between the elec-
tronic and vibrational states of its molecules, or have sinks that absorb energy without
yielding luminescence, are not useful as luminescent organic phosphors. High lumi-
nescent yield efficiency is to be expected only from such organic molecules in which
excitation is not accompanied by marked configurational distortions, and where exciton
transfer leads to fluorescent yield. Such organic molecules are found chiefly among
the pure and substituted aromatic hydrocarbons such as the benzene ring derivatives
and similar substances containing six π-electrons shared between the carbon atoms
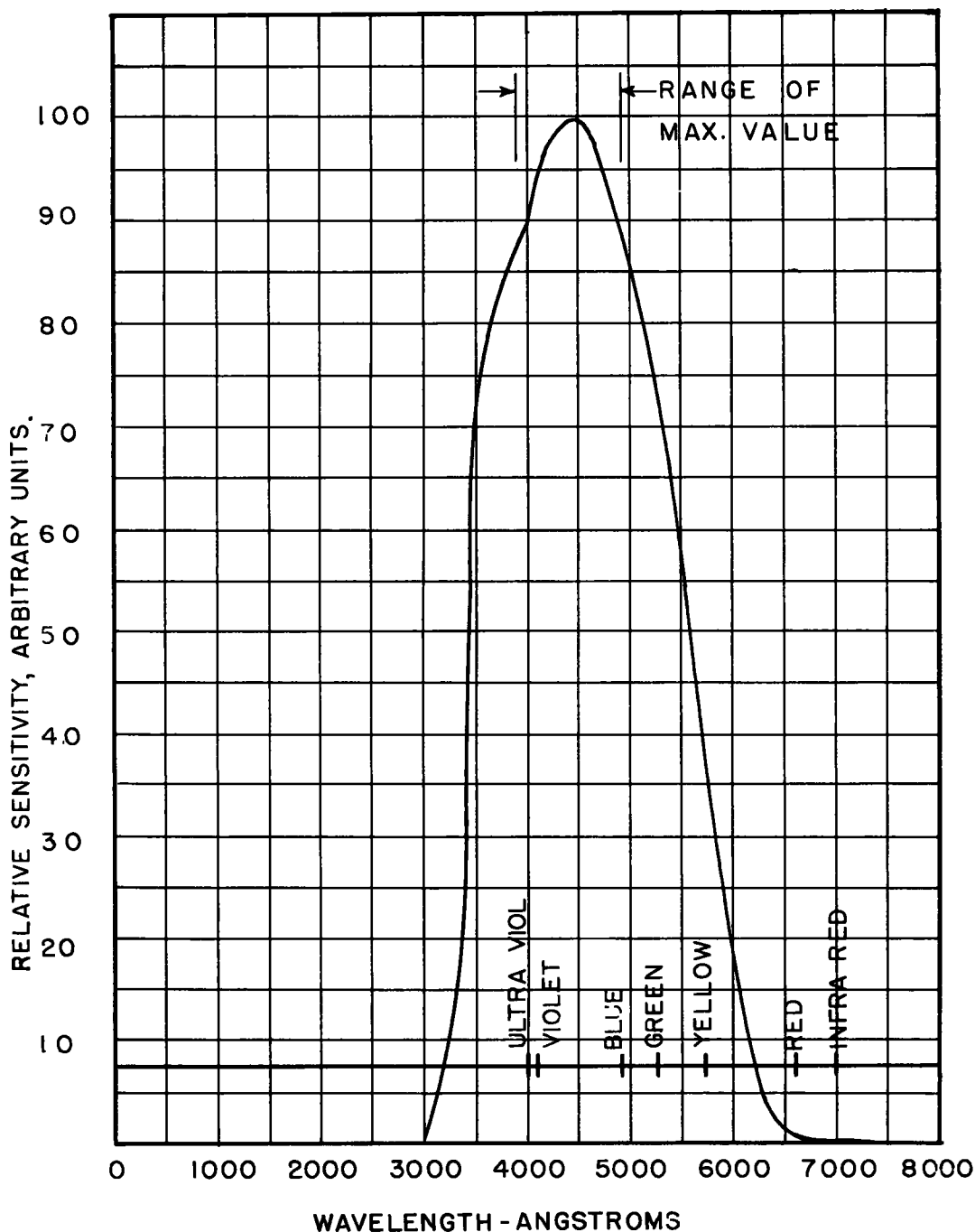
72

Figure 6. Spectral sensitivity of Type S-11 response for photomultiplier tubes
shown in Table 3.

to form molecular orbitals in conjugated double bond structures. Judicious solute-solvent proportional mixing of various materials can yield organic phosphors of vastly different properties with respect to the extent of exciton migration, number of quench or fluorescent yield centers, and wave lengths of absorption and emission spectra of the phosphors.

Figure 7. Scintillation density probe using K-1382 photomultiplier tube, 1 in. in diameter.

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Organic phosphors have the great advantage of very short decay times, in the order of 10^{-8} sec; they are generally highly transparent to their own fluorescent emission, can readily be grown in large single crystals and, because of their high hydrogen content, are efficient when used for fast neutron detection by proton recoil within the phosphor itself. Organic phosphors are poor for gamma detection at most energies because of their low density and low Z values. They also have lower conversion efficiency and pulse-height aplitudes as compared with the more widely used inorganic phosphors.

Inorganic Phosphors

Most of the inorganic phosphors are impurity activated. There exist certain similarities of their action mechanisms to those of mixed organic phosphors. A single atom or molecule has its electronic energy states in a series of discrete levels. Upon agitation by mutual interaction between atoms the outer energy levels of electrons in an inorganic crystal lattice line up to form series of continuous "allowed" energy bands
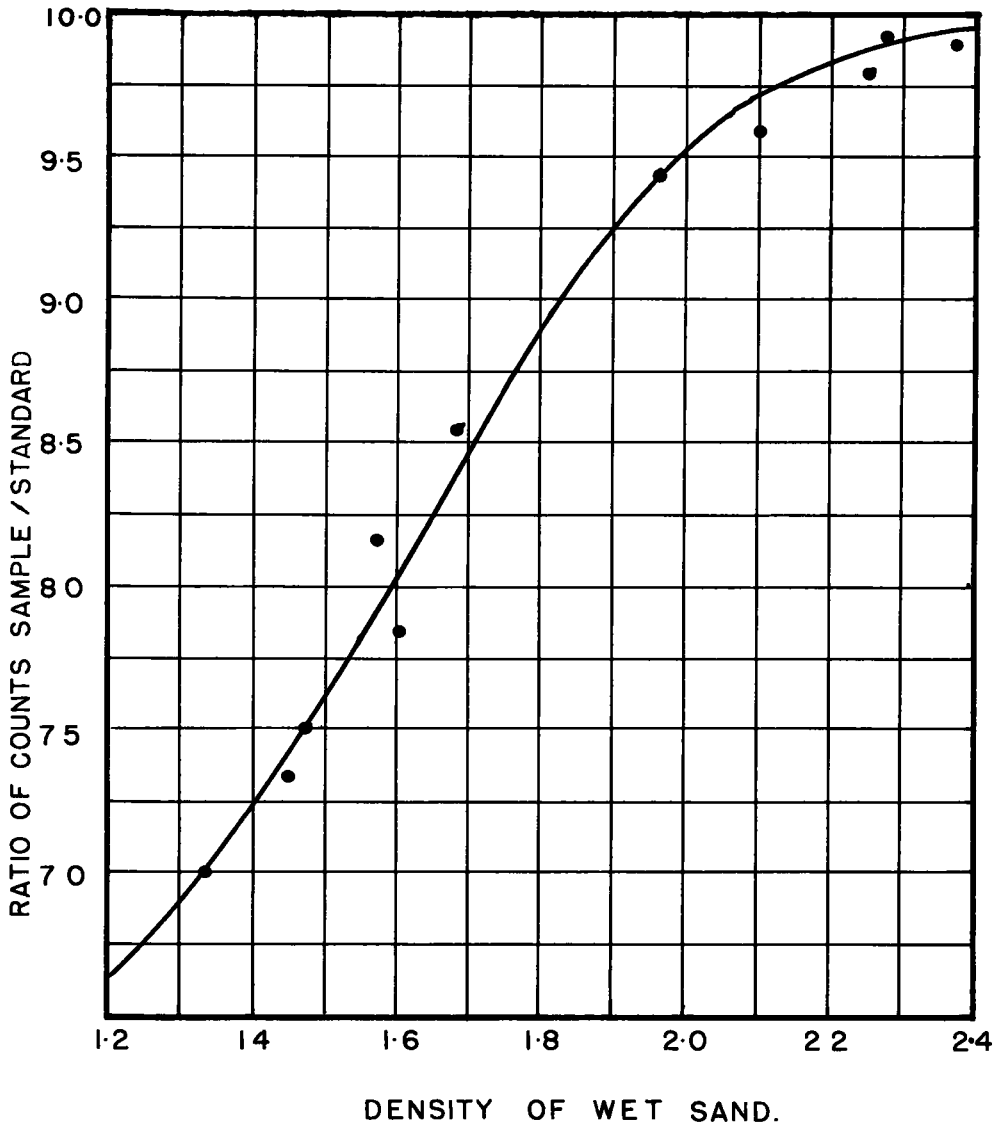

Figure 8. Counts/density curve for 1-in. diameter density probe using K-1382 photomultiplier.

separated by "forbidden" bands. The inner electronic levels remain essentially un-perturbed maintaining their normal character. In the normal state, lower energy bands are filled with electrons, whereas the higher ones remain empty. Electrons can move freely through the dimensions of the crystal in their own respective bands without ad-ditional activation energy. Movement of electrons in a filled band causes no electrical conduction since equal numbers are forced to move in opposite directions. By the ab-sorption of energy quanta, electrons in a filled band may rise into the empty bands, leaving positive holes in the filled bands. Conductivity then occurs owing to the motion of both the excited electrons and the positive holes. This is a model of an insulator with perfect crystal lattice. Actual phosphor crystals have lattice defects which cause variations in the energy bands that produce local electronic energy levels within the normally forbidden band. If such levels are vacant, electrons may be drawn into these centers. There are three main types of centers: (a) Quench centers in which excita-tion energy is changed into thermal energy and lost without radiation; (b) luminescence centers in which the excited electron returns to the ground state causing emission of a light quantum; (c) electron traps, wherein electrons are captured under emission of thermal radiation. This thermal energy may raise electrons to an excited state from which they may return to the conduction band, or fall to the ground state by radiation-less transitions through metastable levels of the impurity center.

For a phosphor to be an efficient scintillator, luminescence centers must predomi-nate. This is guaranteed by activating the phosphor with small quantities of ionic im-purities that are evenly distributed throughout the crystal lattice. These impurity ions cause additional levels of energy which form luminescence centers and markedly affect the energy band system. The efficiency of phosphors depends also on the wave length of the absorbed photons. Irradiation of a phospor at the fundamental absorption band of its matrix lattice has a low quantum efficiency (generally 20 percent or less) be-cause of competitive capture of excited electrons by luminescence and quenching cen-ters. Incorporation of an activator produces new optical absorption bands of longer wave length which are added to the fundamental absorption bands. These represent additional electronic levels formed by the activator luminescence centers between the conduction band and the ground state. Irradiation of a phosphor at its activator band wave lengths could yield quantum efficiencies of 100 percent if the absorbed energy passed completely into an excited level of luminescent centers and provided that no electrons migrated through the conduction band to be captured by quenching centers. The properties and functioning of certain phosphors used in the present investigation will now be discussed.

Sodium Iodide

Thallium-activated sodium iodide is one of the best and most widely used scintilla-tion phosphors. It is one of a group of alkali halide phosphors whose action mechanisms differ slightly from the general behavior of inorganic phosphors that has been discussed above. In impurity activated alkali halide phosphors, there are metastable levels es-tablished at luminescence centers formed by the impurity ions. These metastable levels operate somewhat like electron traps as they capture electrons and do not permit elec-tronic transition to the ground state. However, by absorption of thermal energy, the electron in a metastable state can be raised to an excited level which has an allowed transition to the ground state yielding emission of a light quantum. This accounts for the generally longer decay times of such phosphors $(\sim 10^{-3}$ sec); however, this phos-phorescence has not restricted the use of NaI (T1).

Only the Zn S phosphor and its relatives have a higher energy conversion efficiency than NaI(T1), variously estimated as between 8 - 11 percent for the latter phosphor. The fluorescent emission spectrum of NaI(T1) has a mean wavelength of 4,100 $\overset{\circ}{A}$ with a width of 850 $\overset{\circ}{A}$ to half of the maximum intensity. This makes it ideal for most photo-multipliers with typical S-11 spectral response. It is also highly transparent to its own emitted light radiation as absorption occurs only below 3,000 $\overset{\circ}{A}$. The actual decay time of NaI(T1) is 2.5×10^{-7} sec at room temperature; it increases with increasing tem-perature. Crystals of NaI(T1) can be made in large sizes; it has a high specific gravity

of 3.67, and contains iodine with a high Z number of 53. Hence, NaI(Tl) is particularly useful as a general γ and X-ray detector.

Figure 1 (b) shows the absorption coefficients of the three quantum absorption processes as a function of γ ray energy. It is to be noted that the total absorption coefficient is only negligibly greater than that due to Compton scatter at energies of 1 to 1.4 Mev (as from Co^{60}). This also serves to illustrate that only the absorption coefficient μ_c, due to the Compton effect, is instrumental in the functioning of the soil densitometer. Therefore, Na(Tl) is the logical choice of a phosphor for use with a scintillation detection type densitometer.

Lithium Iodide

For the efficient detection of thermal neutrons LiI(Tl) or LiI(Sn) crystals have been employed to a considerable extent since Hofstadter, et al., proved their usefulness (67, 14, 134). This alkali halide phosphor demonstrates another mechanism by which scintillation systems supercede other detection techniques. The compound that constitutes the crystal matrix contains a highly absorbing element for a certain type of radiation only. In a LiI crystal, containing natural lithium with 7.4 percent Li^6, the extremely high (900 barns) absorption cross-section for thermal neutrons is effectively utilized. The detection method is based on the Li^6 (n, α) H^3 reaction which yields product nuclei (α-particle and triton) with a total energy of 4.79 Mev. Hence, a detected slow neutron yields a constant amplitude scintillation pulse, entirely independent of the energy of the incident neutron; the latter can readily be detected against a γ-ray background.

Recently, europium has been used and found to be a more efficient activator for LiI crystals. LiI(Eu) has a density of about 4.1 gm/cm^3 and a decay time of 2×10^{-6} sec. LiI(Eu) is transparent to its own fluorescence; its emission spectrum is in the blue region. The LiI crystals are deliquescent similar to those of NaI and, hence, require hermetic sealing against moisture. The conversion efficiency of LiI phosphors is about 1 percent. Thermal neutrons have hitherto been very difficult to detect with greater efficiency than by means of LiI crystals. Intensive research has now borne fruit in the recent development of a much sought for high efficiency slow neutron detector.

Boron - Plastic - Zinc Sulphide Phosphor

Several investigators have sought for an efficient thermal neutron detector which utilizes the (n, α) reaction within a crystal by detecting the alpha particle produced. There are several ways to do this and through ingenious and persevering research a number of superior detectors have been developed. The most promising methods have been studied and evaluated by Dooley (42) after exhaustive research on slow neutron detectors. The fundamental reaction utilized in most slow neutron detectors is: $_5B^{10} + _0n^1 \longrightarrow _3Li^7 + _2He^4$, wherein a boron^{10} nucleus captures a slow neutron with the resultant ejection of an alpha-particle which is then detected by one of several means. The most efficient way of α detection is by the use of Zn S (Ag); hence, this compound is incorporated somehow into one containing B^{10}

If natural boron containing 19 percent B^{10} is used, compounds containing the highest proportions by weight of boron should preferably be employed if practical. The compounds must be transparent and colorless, such as BN, B_2O_3 and $H_3B O_3$. BN has the highest weight percentage of boron, and also has a suitable emission wave-length for use with photomultipliers (100). However, BN is refractory and does not melt below the sublimation temperature of Zn S (Ag). This makes it impossible to combine the two essential compounds. B_2O_3, with 33.1 percent by weight of boron, and a melting temperature of 580 deg C appears as the next best choice. However, B_2O_3 even at temperatures of 1,000 deg C is highly viscous which prevents uniform combination. Good emission efficiency of phosphors requires a substantial energy transfer. In vitreous B_2O_3 systems, having little energy transfer, lower conversion efficiencies must be expected, particularly because only that energy will yield light which is transferred directly to a luminescence center from the excited state. Hence, Dooley (42) observes that B_2O_3 systems are the lowest in the efficiency scale, and gives, in order of ascending

efficiency: vitreous organo-boron compounds containing conjugated multiple bonds, crystalline organo-boron compounds, and ionic boron compounds.

Kasha (86), Kallman (83) and Dooley (42) worked a great deal with Anthracene - $B_2 O_3$ systems, but did not produce a totally satisfactory detector in spite of exhaustive theoretical calculation, and explanation of the physical mechanisms involved. A brief resume is included here, because a highly efficient slow neutron detector operating on similar principles, devised by Sun, Malmberg and Pecjak (149) has been used most successfully in investigations here.

Fields of slow neutrons are generally found where fast neutrons and gamma emission is also present if not prolific. Hence, a most essential feature in a slow neutron detector is its selective detection in order to prevent γ and fast neutron detection. If systems are found wherein the quenching curve falls off sharply to 0 beyond 5 or 10 ev, neutrons with energies above this would remain undetected. Plastic and organic crystals have ratios of conversion efficiencies for γ and for α, $E_\gamma : E_\alpha$, in the order of 50:1 and 15:1 respectively, whereas inorganic crystals have ratios of merely 0.5:1 to 5:1. Hence the higher the proportion of inorganic crystals in the phosphor the smaller will be the proportion of counts attributable to gamma rays. The size of the phosphor must be calculated so as to adequately absorb a maximum percentage of neutrons and yet a minimum number of γ photons. However, there are further factors such as optical density to be considered particularly in multi-crystalline phosphors. The Boron compound - Zn S (Ag) type of detector operates in the following three distinct stages of events, each event having its own probability of occurrence:

1. A slow neutron is captured by a B10 nucleus within the material of the phosphor;
2. The resultant alpha particle from the B10 (n, α) Li^7 reaction reaches a Zn S (Ag) granule with sufficient energy to cause scintillation;
3. The fluorescence from the point of scintillation reaches the photocathode of a photomultiplier with adequate energy to be converted into a photoelectron.

The over-all efficiency of the scintillator is then the product of the probabilities of an event occurring in each of these three successive stages.

The thickness of a phosphor with fixed composition and density determines the probability of occurrence of event 1. As shown previously in the theory of the operation of the neutron thermalizing probe, thermal neutrons have Maxwellian distribution in matter until captured. For neutrons with a maximum energy between 0.025 and 0.05 ev, neutron absorption by a thickness d of a material is:

$$\frac{I_d}{I_0} = e^{-n \ s(E)d}$$

where

I_d = neutron flux on penetrating a thickness d of target

I_0 = neutron flux incident on target

$s(E)$ = total neutron cross-section in cm^2

n = number of target nuclei/cm^3

E = energy of neutrons

From the equation, given above, the percentage of neutrons absorbed can be worked out as a function of phosphor thickness. Table 2 gives the results of Dooley's calculations using a $B_2 O_3$ - ZnS (Ag) phosphor with a molecular weight of 69.6, and assuming a 600 barn value for the cross-section of natural boron for slow neutrons possessing an energy of 0.0388 ev.

Table 2 shows that optimum thickness, as far as absorption percentage is concerned, is in the range of 0.2 to 0.25 cm for such a phosphor. Increase in thickness beyond 0.25 cm does not give any significant increase in absorption. Therefore, it would be injudicious to increase the probability of occurrence of event 1 by increasing the depth of a fixed composition phosphor beyond a certain optimum value, for with increasing depth the decrease in the probability of event 3 occurring becomes increasingly greater than the increase in the probability of event 1 occurring.

It is possible to increase the probability of occurrence of event 2 by increasing the proportion of ZnS(Ag); this, however, would be at the expense of the probability for neutron capture as there would then necessarily be fewer B^{10} nuclei. Further, the greater the quantity of ZnS(Ag) the less transparent is the detector with a consequent reduction in the probable occurrence of event 3; also the phosphor's sensitivity to γ-radiation would be greater. It is possible to calculate the proportions of the mixture so that the probability of event 2 occurring is optimized. This is dependent on the density of the phosphor, the path length of the radiation penetration and the minimum residual energy threshold of the luminescent center.

TABLE 2

PERCENTAGE OF ABSORPTION OF SLOW NEUTRONS WITH CHANGE IN
B_2O_3 - ZnS(Ag) PHOSPHOR THICKNESS (AFTER J. A. DOOLEY)[a]

Thickness of Phosphor in cm	0.366	0.242	0.121	0.073	0.036	0.005
n s(E). d	6.95	4.605	2.3	1.39	0.69	0.10
Percent n Absorption	99.9	99.0	90	75	50	10

[a] Reference (42).

Because of the high specific ionization caused by α-particles, the incident path of an alpha particle within the phosphor may be considered to excite an unbroken cylindrical volume to the α-range R_1. The excited volume V_1 would then be $\pi r_1^2 R_1$, if r_1 is the radius of the mean range of secondary electrons. Normal ionizing radiation may be considered to have N primary collisions in its range R, each with a volume V of a sphere at the center of which there is the greatest concentration of secondary ionization and other energy transfer. The energy transfer process is best described by a quenching curve which has the excitation energy in the material plotted against the distance from the primary ionization. The "energy threshold" is defined as the lowest energy which, when transferred to a luminescent center, will emit a photon of light. The farthest intersection of the plotted quenching curve with the horizontal threshold level defines, therefore, the parameter r, the effective radius of the excitation sphere.

Within an average excitation sphere or cylinder as in the case of an α-ionization path, there is a number or fraction, m, of luminescent centers. Of these, only a fraction, f, will be energized and will emit fluorescence. Hence, the total number of luminescent photons produced by an excitation sphere is proportional to N m f. In terms of density of active centers per unit volume, designated by n, the photons emitted would be proportional to N V n f. The excitation sphere volume could be used just as effectively as the more indirect probability sphere concept to determine the optimizing of the proportions of luminescent center producing material and the primary ionization producing substance. Homogeneous distribution of these materials, and particularly the size of the ZnS(Ag) crystals used, can affect considerably the working properties of the phosphor.

Figure 4 redrawn from Sun, Malmberg and Pecjak (149) shows the relative efficiency as a function of phosphor thickness of the excellent phosphor they developed. It is to be noted that beyond a 1.2 mm thickness, with a ZnS(Ag): "Boron Plastic" ratio of 2.0, owing to the greatly decreased probability of scintillations reaching the photocathode primarily, the efficiency of the phosphor drops off sharply, in spite of the increasing probability of higher neutron capture. The efficiency of the phosphor having a corrugated surface and using a 1:2 Boron Plastic to ZnS(Ag) mixture is 33 percent. Gamma rays contributed only one percent of the total count in an experiment of counting slow neutrons from a Po-Be fast neutron source surrounded by a paraffin moderator. ZnS(Ag) is the best alpha detector known; it is capable of 100 percent detection at proper thicknesses. Beyond a thickness of 25 mg/cm^2 ZnS(Ag) crystals become opaque and are therefore quite useless as phosphors. However, for α-particles that can be stopped

completely within 10 mg/cm², the phosphor is transparent enough for efficient detection. It has a conversion efficiency of 28 percent, the highest of any phosphor known. Its emission spectrum spreads from 4,000 - 6,000 Å with the maximum at 4,500 Å. The decay time of ZnS(Ag) is longer then 10^{-5} sec which is unfortunate, but its other properties more than make up for this deficiency.

Scintillation Detection

Visual scintillation detection was introduced in 1903 by Crookes and Regener, who used an activated ZnS screen and a microscope for detecting α -particles. During the 1930's, visual scintillation detection became obsolete as a result of the development of the gas ion detector which produces an electric pulse upon the passage of an ionizing particle, and of electronic circuits for amplifying, measuring and counting such pulses. In 1944, Curran and Baker first devised a photomultiplier system; their work, however, was not declassified until 1947. Since then, highly efficient photomultiplier tubes, sensitive to very low light intensities, and various types of scintillation crystals have been developed and scintillation counting is rapidly replacing the use of gas counters. This is particularly true where resolving times in the range of fractions of micro-seconds are needed, where the amplitude of the signal pulse has to be linear to the energy of the particles or photons detected or where rapid counting, great sensitivity and selectivity is required. Great strides were made by such investigators as Kallmann (83), Reynolds (126), Bowen (23), Broser (26), Taylor (152), and Hofstadter (67) in the development of phosphors that are sensitive to several types of radiation and efficient in producing light scintillations upon ionization taking place within them.

The fundamental processes involved in scintillation detection may best be understood by periodic reference to Fig. 5. Birks (16) gives the operation of the counter in the following five distinct consecutive steps, of which the first three have been treated somewhat in the theory of phosphors:

(1) The incident photon with energy E_1 impinges upon the phosphor. This photon energy is either partially or wholly absorbed in the ionization and excitation of molecules of the phosphor;

(2) Upon reversion to the ground state of electrons within the phosphor that have been excited by this energy, photons in the visible spectrum are produced which radiate in all directions;

(3) These photons are transmitted in and from the crystal to the cathode of the photomultiplier tube;

(4) The photons are partially absorbed at the photocathode of the photomultiplier tube and this causes the emission of electrons;

(5) The electron multiplication process within the photomultiplier tube now takes place in successive dynode stages to give a pulse large enough to activate the electronic amplifying, measuring and counting circuits.

At each stage certain factors enter which affect the nature of the output pulse from the photomultiplier. Some of these must be dealt with in order to better understand the functioning of the scintillation system, so that it may judiciously be adapted to suit the purpose at hand.

Absorption of the incident radiation. If E_1 is the energy of the incident particle and A the fraction of its energy absorbed by the phosphor, then E_1A, the energy expended, will logically be greater with an increase in the size of the crystal phosphor (see Table 2) and with a smaller maximum range r of the particle within the phosphor. Thus A = 1, if the thickness d of a phosphor is greater then r of a heavy particle entering normally into the phosphor and traveling in a straight line.

The magnitude of r is dependent on the nature and energy of the incident radiation, and the absorptivity of the phosphor which is a function of the atomic number, mass and density of its constituent elements.

Each incident charged particle will cause ionization of the phosphor material, if it is fully or even partially absorbed within the phosphor. Thus, charged particles are capable of one hundred percent detection efficiency. Uncharged particles such as γ-ray quanta and neutrons do not ionize directly. Hence, for the detection of such particles

or quanta, it is necessary to have their energy absorbed by some particles within the phosphor which then produce secondary particles capable of ionization. This ionization caused by secondary particles gives rise to scintillations which can be picked up by the photo-cathode. Only a fraction f of the incident uncharged particles or quanta produces secondary ionizing particles, with a corresponding reduction of detection efficiency. The fraction f may be calculated from the expression:

$$f = 1 - e^{-\mu x} \tag{15}$$

where:

x = the thickness of the phosphor, and

μ = absorption coefficient of the phosphor for the incident radiation.

For X- or γ-ray quanta the principles discussed earlier, based on Equation 1, will determine the total absorption coefficient. Cobalt 60 sources are invariably used here; the incident radiation of 1.25 Mev energy will almost totally be absorbed by μ_c the absorption coefficient due to the Compton effect. In Compton scattering, the electrons are produced by quanta of energy distributed from O to a maximum E_c, which may be computed from the equation:

$$E_c = \frac{E_1}{1 + m_0 c^2 / 2EI} \tag{16}$$

The rest-energy of the electron $m_0 c^2 = 0.511$ Mev, hence for $E_1 = 1.25$ Mev:

$$E_c = \frac{1.25}{1 + \left(\dfrac{0.511}{2.50}\right)} = 1.06 \text{ Mev.}$$

The remnant of the incident energy, in the form of the scattered quantum (see Fig. 1), generally escapes from the phosphor. Fast neutrons are best detected by the ionizing recoil protons produced upon elastic collision with H nuclei. Hence, several efficient organic phosphors have been developed for fast neutron detection because of their high percentage of hydrogen and their good transparency. Slow neutron detection is more complicated and generally involves several special techniques, including nuclear reactions. In such techniques, the fraction f of neutrons detected will depend upon σ, the slow neutron capture cross-section of the phosphor, and N , its areal density. Hence, Equation 15 may be written:

$$f = 1 - e^{N\sigma} \tag{17}$$

The energy of the secondary ionizing particles produced is generally independent of that of the incident neutron, often exceeding it considerably. Thus we observe that a phosphor containing lithium, detects slow neutrons by the $_3Li^6(n, \alpha)_1H^3$ reaction, and the combined energy of the α-particle and triton yield 4.8 Mev.

Photon emission. If E_1 is the energy of the radiation incident on the phosphor and E_1A is the energy that is dissipated within it (i.e., absorbed by the phosphor), then E_1A is converted by the phosphor with an efficiency C_{1p} into p photons with an average energy E_p, as expressed below:

$$p = \frac{E_1 A C_{1p}}{E_p} \tag{18}$$

This photon emission is not instantaneous. The decay rate of photon emission is generally exponential. If the initial intensity is I_0 and the decay period t_0, the luminescent intensity I, after a time t, is given as

$$I = I_0 e^{-t/t_0}. \tag{19}$$

Hence, the number of photons emitted in a time interval t is

$$p_t = p(1-e^{-t/t_0}) \tag{20}$$

The shorter decay period t_0 of a phosphor makes it capable of better time resolution which is a much sought for feature in phosphors as it determines its capacity of counting closely time-spaced scintillations; i.e., there is a smaller probability that two pulses which follow within a long decay period be counted as one.

Transmission of photons to photocathode. In order to reduce the number of scintillation photons absorbed with the phosphor, μ the optical absorption coefficient of the phosphor with respect to its own fluorescence radiation should be low. Hence if T_p is the transparency and x the light path length, T_p should be as near unity as possible, since

$$T_p = e^{-\mu x} \tag{21}$$

The absorption coefficient μ varies with the wave length of the luminescence of the phosphor. For clear single crystal phosphors, T_p approaches unity; for this reason, they can be used effectively in great thicknesses as in the case of NaI and of good organic phosphors. In the multi-crystalline phosphors such as ZnS, where μ is great, only limited thicknesses can be used. The light path x is almost invariably greater than the distance from the point of photon origin to the photocathode, as most of the light is reflected internally before impinging on the photo-cathode.

Only a fraction G of the photons p produced per scintillation fall on the photocathode. G is dependent upon the optical geometry of the system and is chiefly affected by the solid angle subtended by the point of scintillation at the photocathode and the reflecting surfaces of the phosphor (see Fig. 5). The number of photons p' ($< p$) that impinge upon the photocathode is:

$$p' = T_p G_p \tag{22}$$

Conversion of photons to photoelectrons. This and subsequent steps occur in the photomultiplier tube. The process of producing electrons by irradiation of metals with light, the so-called photo-electric effect, was first discovered by Hertz in 1887 and qualitatively explained by Hallwachs in 1888. Lenard in 1900 elucidated experimentally the relationships existing between the frequency of the impinging light and the speed of the released electrons and between the intensity of the light and the number of electrons. He also showed the influence of the irradiated material on the speed of the electrons. In 1905, Einstein explained Lenard's experimental results by means of Planck's concept of the energy quantum. The latter equals $h\nu$ for radiation of frequency ν. Einstein's explanation of the photo-electric effect is that the entire energy of an incident photon is transferred to a single electron in the metal it strikes, so that when the electron comes out of the surface of the metal it has a kinetic energy given by:

$$\tfrac{1}{2} mv^2 = h\nu - p \tag{23}$$

This phenomenon is basic in the conversion of light scintillations, produced within the crystal by radiation, into photo-electric current upon striking the photosensitive metal of the photocathode. Photons incident upon the photocathode are converted into photoelectrons with an efficiency $C_{pe} f(\nu_p)$, where C_{pe} is the photo-electric conversion efficiency of the photocathode material (number of electrons/incident photon) at its optimum frequency, and where $f(\nu) \leq 1$ is the relative response at frequency ν. C_{pe} is dependent on the optical absorption capacity of the cathode material for incident light and upon its photo-electric properties. The factor $f(\nu)$ is also dependent on the nature of the photocathode material, but its value is often sharply cut off at short wavelengths because of the glass or quartz photomultiplier envelope.

Thermionic emission of electrons from the photocathode provides the main source of undesirable dark noise pulses above which the amplitude of the signal n, caused by scintillation is to be measured or counted. The number of thermionic electrons N_e generated per second by the photocathode depends on the "thermionic work-function" of the cathode material, and is proportional to the area a, of the cathode, from which the electrons are collected and multiplied by successive dynode stages. N_e is temper-

ature dependent and is given by:

$$N_e = aT^2 e^{-b/T} \qquad (24)$$

where

T = temperature in $^{\circ}$K

b = a function of the photocathode material

Upon cooling the photocathode, the number, not the amplitude, of the dark current pulses is reduced greatly. Theoretically, it should be possible to detect all signals with a signal to noise ratio, n - 1; in practice, at room temperature, n must be at least 3 - 5 for ready detection against the background dark noise. Other potential causes of dark noise are:

(1) If, in the detection of intense and penetrating radiation such as γ radiation or neutrons, these radiations are not fully absorbed by the crystal detector and reach the cathode, they are capable of producing direct emission of electrons from the photocathode and dynodes;

(2) Ionization of residual gas in the phototubes causes the acceleration of positive ion feedback towards the cathode with a consequent release of secondary electrons;

(3) Direct ohmic loss over and through internal insulators;

(4) The intense electrical fields that exist around each dynode may be concentrated at sharp points and edges, causing spurious field emission.

The electron multiplication process. This process upon which the photomultiplier operation so greatly depends is based on the phenomenon of secondary emission first discovered in 1935. This phenomenon takes place when an electron strikes a metal surface with sufficient velocity to cause ejection of one or more electrons from its surface. A typical photomultiplier tube is shown schematically in Fig. 5. When a photon of light is converted into a photoelectron by the photocathode, it is accelerated and focused towards the first dynode which upon being struck ejects a few electrons. These secondary electrons are focused and accelerated towards the second dynode by virtue of its shape and its higher potential. Each electron causes the ejection of three or four others through secondary emission. Hence, if the multiplication factor is R per dynode and if there are m dynode stages, each at a higher potential than the preceding one, the number of electrons emitted by the last one would be R^m. However, collecting of the electrons particularly in the latter dynode states is not one hundred percent efficient. Hence, if C is the collection efficiency, the over-all gain M of the tube is:

$$M = CR^m \qquad (25)$$

Both the dark noise and the photoelectrons are proportionally multiplied at each dynode.

The electron multiplication factor R depends on the C of the preceding dynode and on the secondary emission characteristics of the dynode material. R increases greatly with increase in accelerating voltage that is applied between dynode stages. M, the over-all gain, varies as a high power (~ 7) of the voltage applied between the photocathode and the anode of the tube. Thus the high voltage supply should be stabilized to ± 0.1 percent. The dynodes also contribute somewhat to the over-all dark noise of the tube, as generally they are made of the same material. However, owing to fewer multiplication stages ahead, the stages nearer the collector plate contribute successively less towards over-all noise. The best all around material used in the construction of photocathodes and dynodes is antimony-cesium which is generally surface-deposited on nickel. Silver-magnesium is used in some tubes in spite of its lower photoelectric and secondary emission factors, because of its considerably lower thermionic emission.

Considering all steps involved in the scintillation process, Birks (16) gives the number of electrons, n, produced at the photocathode by an incident radiation photon of energy E, as:

$$n = \frac{E_i A C_{ip} T_p G C_{pe} f(\nu_p)}{E_p} \qquad (26)$$

If n is multiplied by the gain factor M of the photomultiplier and e, the electronic

charge, the total charge Q of the signal pulse is:

$$Q = n e M \qquad (27)$$

This charge, when fed to a suitable capacitor, will build up a potential difference whose value can be measured by electronic circuits. These circuits generally produce a pulse of a given amplitude upon the capacitor being charged by the stream of electrons from the output of the photomultiplier. These pulses are then either amplified or counted directly, or integrated with a time constant to give a rate of counts.

DESIGN OF SCINTILLATION DENSITY AND MOISTURE PROBES

The size, geometry and components of scintillation detection type density and moisture probes are primarily dependent on the type of photomultiplier tube selected. It is imperative that the choice available in types and operating characteristics of photomultiplier tubes be examined closely in order to arrive at a judicious selection for the purpose at hand.

There are two general types of photomultiplier tubes: the focused and the unfocused types. Of the unfocused types there are two kinds of dynode structures: the longitudinal venetian blind type developed and described by Sommer and Turk (143), and the box and grid type described by Linden (106). These types of tubes are manufactured by the Electric and Musical Industries Ltd. of Britain and the Du Mont Company in the United States. The Radio Corporation of America and Mazda manufacture the circular electrostatically focused type, an example of which is shown schematically in Figure 5. These types, described by Engstrom (49), have no accelerator grids; they use the dynode structure invented by Rajchman (122). The first Zworykin multiplier used crossed electric and magnetic fields that direct electrons to strike the dynode surface at an area where the electric field repels the electrons (174). Both focused and unfocused photomultiplier types now achieve this by purely electrostatic means.

Most photomultiplier tubes use Sb-Cs for photocathode and dynode surfaces which is generally deposited on nickel. The photo-electric conversion efficiency of antimony-cesium laminae is generally getween 0.15 to 0.25 electrons/photon; its thermionic emission is as low as 1,000 electrons/cm^2/sec at 30 C. This corresponds to a dark current of approximately 1.6×10^{-16} amps/cm^2. When housed in a glass envelope, a photocathode with Sb-Cs has a spectral response of the general type S-4, with a maximum in the region of 4,200 Å and a spectral range covering 6,500-3,000 Å.

A great variety of photomultiplier tube types is available today and better tubes are constantly being developed. It should be noted that characteristics specified for any tube type are average specifications. In practice, because of factors too difficult to control in manufacturing, such tube characteristics as over-all gain and luminous sensitivity may vary considerably from reported characteristic average specifications.

In our investigations here, it was first thought necessary to limit the probe diameter to 1 inch. This limited early choice of photomultipliers to a few recently developed 3/4-inch tube types which proved to have abnormal variation from tube to tube. Only the Du Mont K-1303 3/4-inch 6-stage tube was available and proved before 1956. Since then Du Mont has made two other 3/4-inch diameter photomultipliers available, whereas RCA has developed one with the laboratory developmental number type C 7204. Some of the noteworthy characteristics of these tubes are compared in Table 3 against larger ones of recognized stability and dependability.

Work was first performed with a probe manufactured by National Radiac, Newark, New Jersey, modified to make a densitometer and a hygrometer. The probe employed a Du Mont K-1303 tube which has a low gain of only 3,000 at 1,200 volts. Hence, a pre-amplifier which uses sub-miniature tubes with a gain of 75 was used within the probe in bullet-type construction. The pulse amplitude was found far too low to operate a scaler. Upon using a wide band amplifier with a gain exceeding 1,000, the pulses operated a one volt input scaler. It was found that the pre-amplifier was the cause of a host of difficulties. It made necessary the use of large capacity batteries. Because of a total plate dissipation and filament heat of approximately 5 watts at recommended voltages, the whole probe warmed up considerably causing excessive thermionic emission from the

K-1303 photomultiplier. Operating voltages were reduced to a minimum for the reduction of dark noise, but this merely reduced the magnitude of the problem. Isolation of the photomultiplier from the pre-amplifier was the logical answer, which would perhaps have been worthwhile if the pulse coming from the pre-amplifier had been capable of being counted by any of the portable meters that were available in the laboratory. The pre-amplifier supply voltages were found to require a high degree of regulation, as both the signal and noise components decreased materially, the latter proportionately more so, upon a slight reduction of voltage. Cooling techniques in the field appeared unfeasible and, because of other deficiencies mentioned above, the system was rejected.

TABLE 3

CHARACTERISTICS OF SELECTED PHOTOMULTIPLIER TUBES

Tube Type	Du Mont K 1303	Du Mont K 1193	Du Mont K 1382	RCA CT 204	RCA 6199	RCA 6655	RCA 6810-A
Cathode Area (sq in.)	Ca. 0.2	Ca. 0.2	Ca. 0.2	0.2(Circ)	1.2(Circ)	2.2(Circ)	2.2(Circ)
Cathode Luminous Sensitivity[1] (μa/lumen)	-	50	50	40	45	50	60
Equivalent Anode-Dark-Current Input (Lumen)[2]	-	7×10^{-8}	7×10^{-8}	2.5×10^{-9}	8×10^{-10}	8.5×10^{-10}	5×10^{-10}
Max. Anode Current (ma)	1.0	5.0	1.0	0.4	0.75	0.75	2.0
Spectral Response[3]	S-11	S-11	S-11	S-11	S-11	S-11	S-11
Over-all Operating Voltage	1,200	1,150	1,150	1,000	1,000	1,000	2,000
Number of Stages	6	10	10	9	10	10	14
Over-all Gain	3×10^3	1.5×10^5	3×10^5	2×10^5	6×10^5	5×10^5	12.5×10^6
Length of Tube (in.)	2½"	4⅞"	4⅞"	4"	4⁹⁄₁₆"	5⅝"	7½"
Diameter of Tube (in.)	¾"	¾"	¾"	¾"	1⁹⁄₁₆"	2¼"	2⅜"

[1] The cathode luminous sensitivity is the current leaving the photocathode divided by the incident light flux.

[2] The equivalent anode-dark-current input is the quotient of the anode dark current and the luminous sensitivity.

[3] The S-11 type spectral response curve common to all these photomultipliers is given in Figure 6. Maximum response is at a wavelength of $4,400 \pm 500$Å.

The newly developed ¾ inch diameter ten-stage K-1382 Du Mont photomultiplier seemed to be the next logical choice. The over-all gain claimed for this tube is 3×10^5, other characteristics being given in Table 3. The probes developed using this tube are shown in Figures 7 and 9.

The voltage divider made in bullet-type construction, utilized 22 meg resistors in

series, so that with a 1,100 v.d.c. drop between anode and cathode, the supply voltage per dynode stage and that between the last dynode and anode was 105 v.d.c., and the supply voltage between the cathode and first dynode was 210 v.d.c. Only 6 feet of RG-59 U coaxial cable was used. The details of construction for each probe are otherwise self-apparent in the Figures 7 and 9.

The geometry for the densitometer is quite the same as for Belcher's densitometer using a G-M detector. The distance from source to detector was kept at $6\frac{1}{4}$ inches which gave a count versus density curve that was fairly straight but tended to flatten out markedly beyond a density of 2.1 (Figure 8). This curve was obtained using one type of sand which was compacted to different densities and contained varied amounts of moisture. The sand was contained in a cylinder (24 in. diameter x 3 feet) which had a steel access tube of $1\frac{1}{32}$ in. inside diameter and $\frac{1}{32}$ in. wall thickness, inserted centrally along its longitudinal axis. At low densities, it is known that the limits of the cylinder being only 12 inches in radius fell short of that of the "sphere of influence" of the densitometer. For this reason the slight leveling off of the counts/density curve, observed at low densities, would probably have been more marked if the diameter of the sample cylinder had been as great as 3 feet. The apparent center of the densitometer was determined by having a highly densified layer sandwiched between two layers of low but equal density. At the depth at which maximum counts were obtained, the apparent center was assumed to be located. This was $1\frac{1}{2}$ inches below the lower end of the sodium iodide crystal, but as Timblin has demonstrated (154) this center should shift considerably with the density of the medium under test. However, no attempts were made to determine the change of center with density variation, nor to improve further or test the probe for reasons that are reported later.

The moisture probe using the K-1382 photomultiplier is shown in Figure 9. No calibration curve was made on this probe owing to the poor results that were indicated by the preliminary trial. Only a discrimination bias curve deduced from plotting the number of counts detected versus the level of setting of an integral discriminator was obtained, using a 5 mc Ra D Be source in the geometry shown in Figure 9. The maximum number of counts attributable to slow neutrons was in the order of 20 c.p.s. only, and noise pulses could not be reduced to below 15 percent of the total count. The reasons for the poor sensitivity and what appeared to be serious signal differentiation were not investigated thoroughly to the point of correction. Possible reasons for the deficiencies noted are listed below, for which the probe was checked:

(1) The LiI(Eu) crystal used was small ($\frac{5}{8}$ in. diameter x 1 in.), had internal refractive surfaces along cleavage lines, and appeared to be cracked and discolored; hence the capacity and efficiency of detection were very low. It was not possible to obtain another crystal for a long time.

(2) The crystal was manufactured with a projecting flange that was meant to slip smoothly over the glass envelope of the photomultiplier to cover the end window. Unfortunately, the diameter of the photomultiplier was approximately $\frac{1}{32}$ in. greater than the inside diameter of the slit-side flange. Hence, to slip the phosphor on it was necessary to flare the flange outwards, which resulted in a tendency for the phosphor to be pushed away from the photomultiplier. It was not possible to bring the surface of the crystal closer than $\frac{1}{32}$ in. to that of the photomultiplier face. There was no way conceivable in which the crystal could be made to fit properly without damaging the phosphor which is highly shock sensitive, and tends to crack easily. Hence, silicone optical coupling fluid, Dow-Corning DC 200, was filled in between the crystal and the photomultiplier surfaces. Such a poor optical connection could have caused excessive reflective surface, and considerable light absorption with the consequence of serious output pulse differentiation. A wad of glass wool was used to keep the crystal pressed against the photomultiplier so that a constant distance between the surfaces of "contact" would be maintained. During tests, it was noted that there was a definite decrease in both number of pulses and their height when the crystal pulled away slightly from the photomultiplier.

(3) Only a 6-ft. length of RG-59 U coaxial cable was used, as the pulses were attenuated too much by longer cable lengths to be detected by the scaler after even a gain factor of about 5,000, using a pre-amplifier and high-gain wide band amplifier. A shorter cable

gave better results and less differentiation, but made the probe practically useless. Placing various sized capacitances in series with the signal lead indicated an improvement with larger capacitance. However, it appeared that only an impractically large sized capacitor of perhaps 5 μf would be adequate, which was not available to take 1,200 working volts d. c. It appeared that a great amount of the differentiation of pulses was caused by improper cable impedance and capacitor matching.

(4) The high gain amplifier used tended to be noisy at high gains. Since the actual counting of pulses could only be done using this amplifier at high gain settings, it is possible that noise due to the amplifier was somewhat responsible for the poor results obtained.

Lacking a portable pre-amplifier-cathode follower circuit design for this system, which was obviously indicated, and noting that a high gain amplifier was essential to obtain meaningful results, development of the probes using the K-1382 photomultiplier was temporarily suspended until time and equipment became available to make the system operate satisfactorily in the field.

Efforts were next directed along the development of 2-in. diameter probes owing to the failure of the $\frac{3}{4}$-in. diameter photomultiplier systems. From a practical viewpoint this was justified because of the limitation to a minimum of 2-in. diameter of available power drilling and coring rigs. Upon examination of the sizes of the larger photomultiplier tubes, it was noted that the most tried and proved ones were larger than 2 in. in diameter, such as the RCA 5819 and 6655. A comparatively little known photomultiplier, the RCA 6199 with a gain as high as those mentioned above but only $1\frac{7}{16}$ in. in diameter, seemed to be a logical choice.

In development, two or three sets of density and moisture probes were tried, with two types of voltage divider circuitry. The voltage divider circuits common to both types of probes will be dealt with first. A rather nonconventional system was used so that only a single coaxial cable would be needed between the amplifier-counter and the probe. This circuit design is given in Fig. 10. One watt, 22 megohm resistors were used to drop the potential across each dynode, two such resistors being used to cause twice this voltage drop between the first dynode and the photocathode. The hi-cap 100$\mu\mu$f capacitors used for filtering out any positive ion feed-back due to excessive space-charge effects or satellite after-pulses, had a rated capacity of 600 working volts d. c. each, and hence were arranged in steps across dynodes not to exceed this voltage drop. There is no load resistor across which the signal pulse appears, as there is in a conventional circuit, the impedance of the cable being used for this purpose instead. The blocking condenser which builds up the signal charge had values of 0. 01 to 0. 05 μf, depending upon the length of the cable and the size voltage input of the pulse required to operate the various ratemeters and counting meters in the laboratory. Cable lengths used varied from 4 to 18 ft of RG-59 U coaxial cable with an impedance of 73 ohms/ft and a capacitance of 21 $\mu\mu$f,/ft. This same cable was also used to feed the high voltage with the positive center wire leading to the anode collector, and the shielding as the return from the photocathode. The signal pulse collected at the anode is, therefore, also conveyed by the center wire which feeds the voltage divider circuit. Because the applied voltage is steady D. C., the signal pulses remain unaffected by such a system, except that a blocking capacitor of adequate working voltage must be employed so that no high voltage appears across the signal receiving circuit. "Glass-mike" blocking condensers with rated working voltages of greater than 3,000 V. D. C. were used for this purpose.

Because of slight signal pulse differentiation and quite severe drifts in readings with a slight change in high voltage, stable circuits along the lines suggested by Sherr and Gerhart (141) were tried out. The most successful of these circuits using RCA 6199 photomultiplier tubes is shown in Figure 11. This method of stabilizing the pulse height of a focused type photomultiplier tube consists of fixing the voltage of an interior dynode near the anode collector of the dynode structure by means of a battery. The battery voltage is varied between 90 and 120 volts and fixed at the most suitable potential for stabilization. Each individual photomultiplier tube has a different optimum voltage for stabilization. The resistance, R , between the two dynodes on either side of the interior dynode was set as follows: At a fixed supply voltage between cathode and anode,
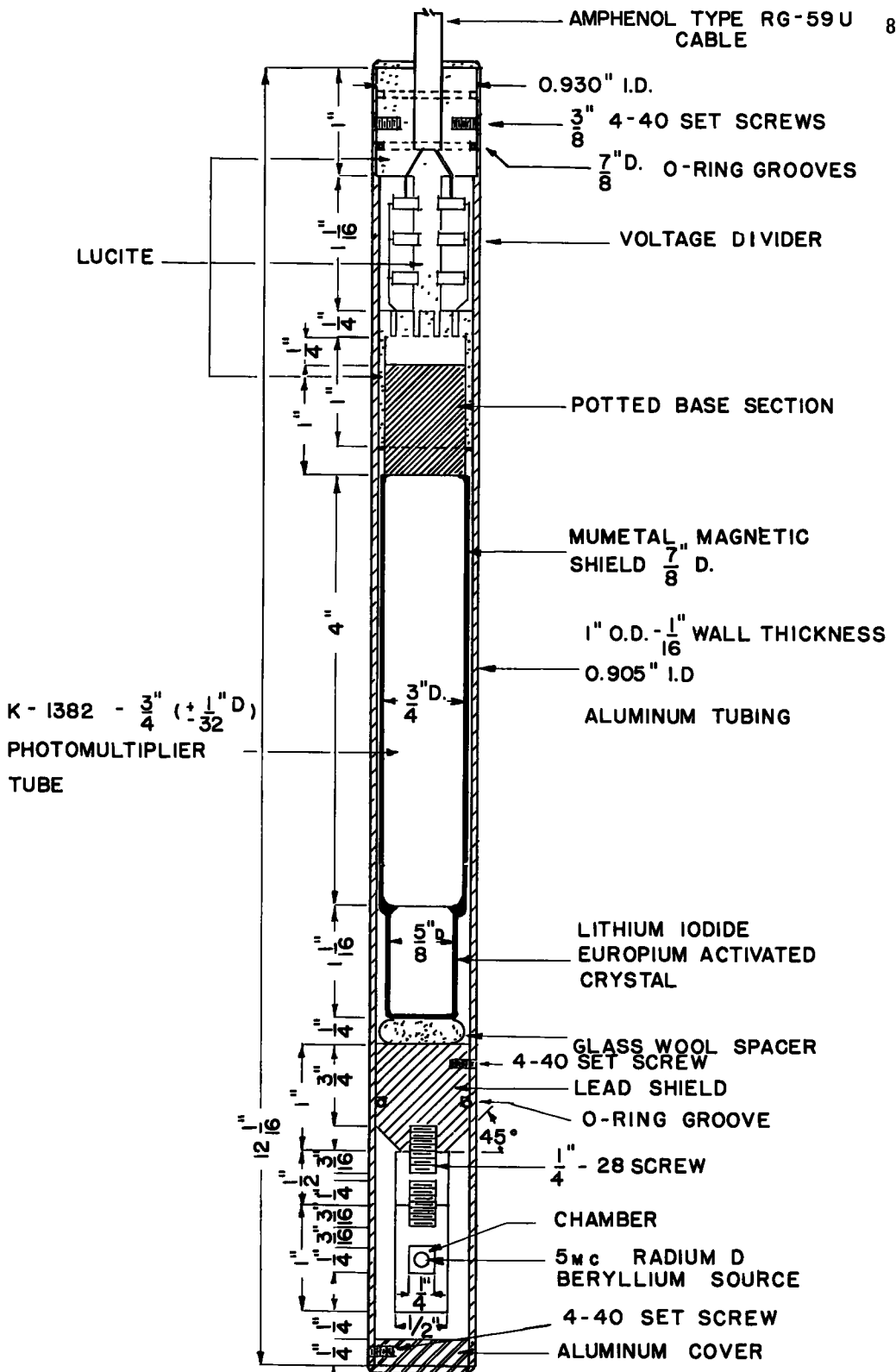
Figure 9. Scintillation moisture content probe using K-1382 photomultiplier tube, 1 in. in diameter.
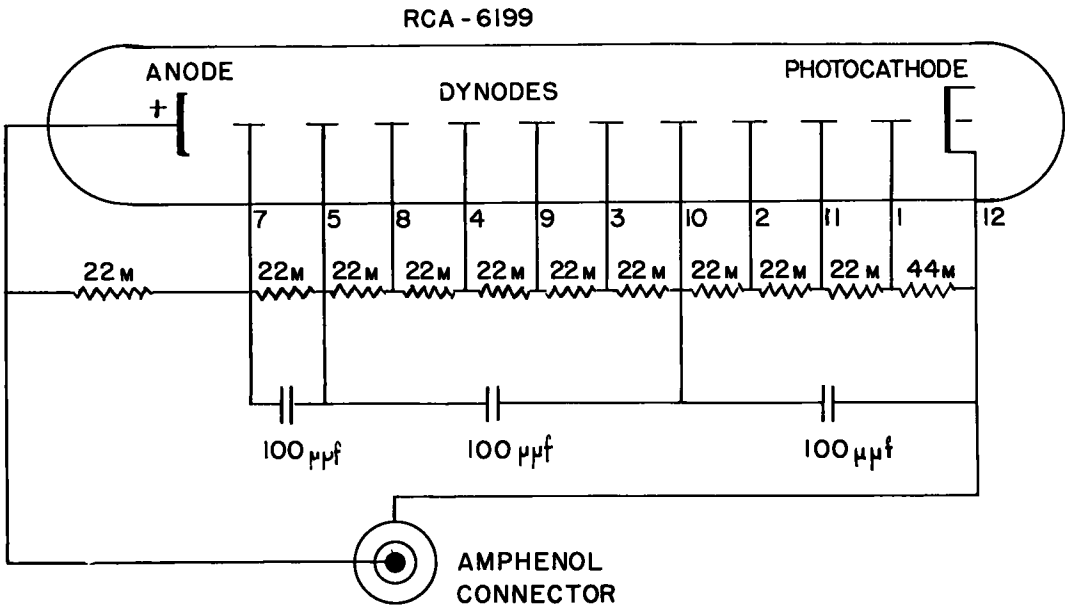
RCA - 6199

Figure 10. Voltage divider circuit for probes using 6199 photomultiplier tube.

the value of this resistance was varied between 20 and 100 meg using a decade resistance box. The output pulses were observed on an oscilloscope for pulse height. The pulse height was plotted against the resistance, as given in Figure 12, and the value R is fixed at half the peak pulse height on the descending side of the curve. Stabilization of pulse amplitude occurs only for over-all supply voltages that are beyond 1,075 volts, the plateau being maintained to 1,300 volts and perhaps beyond. The gain reduction is in the order of 20 to 25 percent.
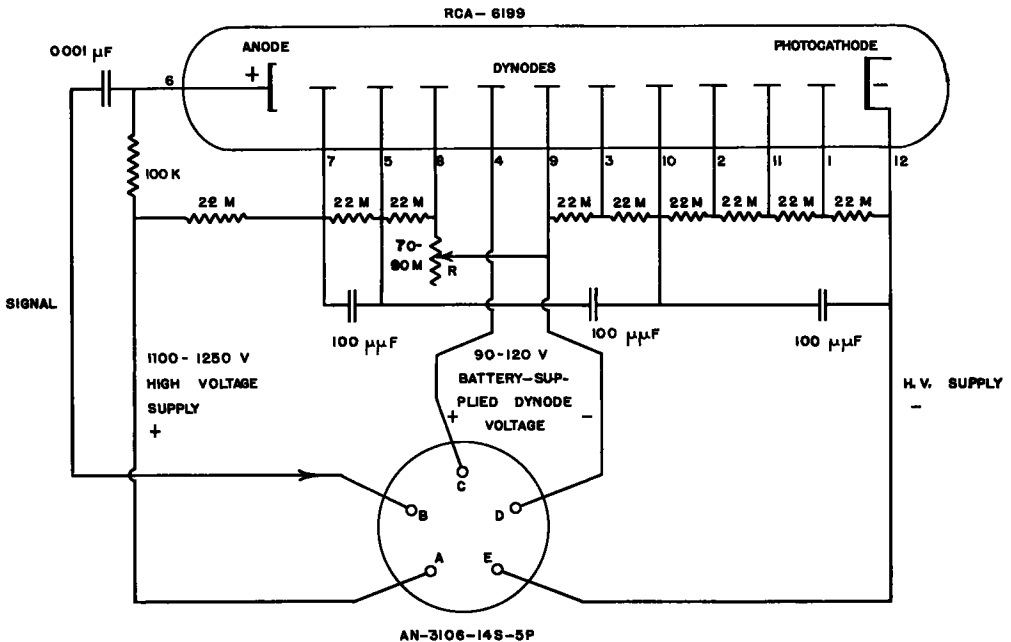
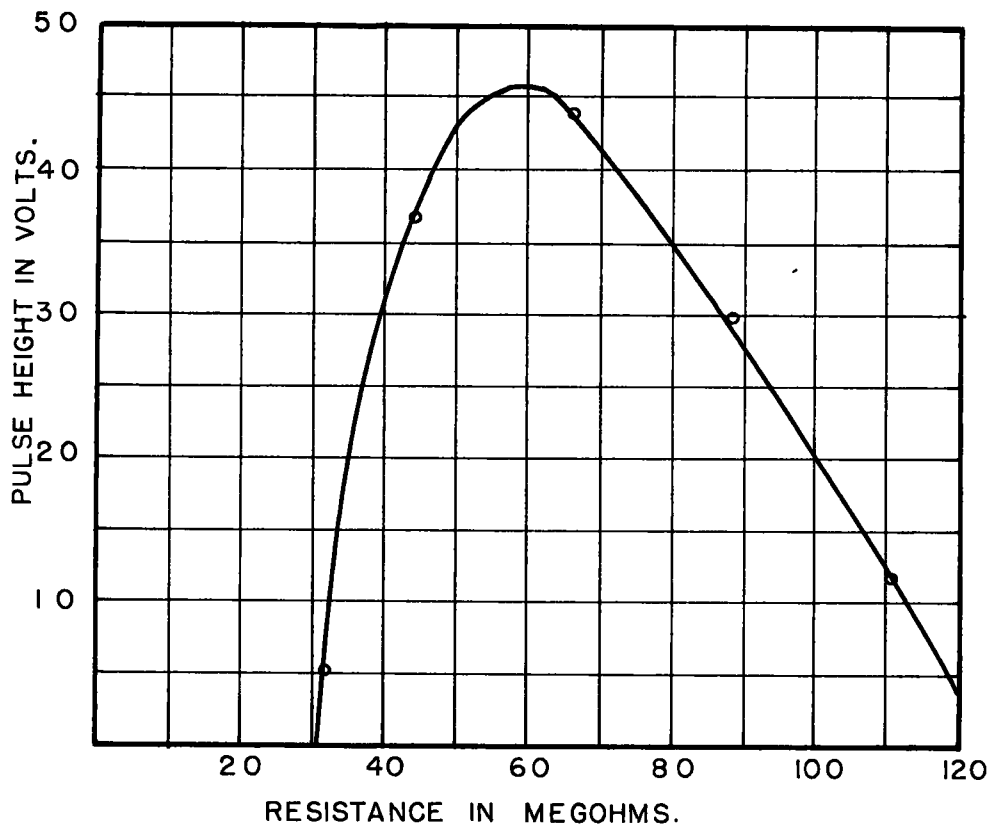Figure 11. Stable circuit for probes using 6199 photomultiplier.

Figure 12. Pulse height response to varying resistance in stabilized type circuit.

It was found that this system of stabilization was far better than the other suggested by Sherr and Gerhart. Apparently, the dynode structure of the 6,199 tube is much the same as that of the 5,819 tube since similar results were obtained throughout. The pulse differentiation was eliminated by the use of the stabilized voltage divider circuit. However, counting rate drifts were still apparent. In the laboratory, it was found that a line voltage regulator eliminated most of the drift. By careful testing, the discrimi-nator circuits of both laboratory instruments and the portable meters were found to be the chief cause of count instability. Since, by matching cable impedance with the block-ing capacitor value, it was possible to reduce the differentiation of the signal, the sta-bilized voltage divider circuit was not used in the field, as it necessitated battery packs, a five-wire cable with three connectors at the instrument end, and because its gain was considerably lower permitting the use of shorter cable lengths than for the simple coax-ial cable system.

CONSTRUCTION OF 2-INCH DIAMETER DENSITY PROBES

Three density probes were tried out having an outside diameter of 2 in. The source used in each case was 1 mc (nominal) Co^{60}, hermetically steel encapsulated. The RCA 6,199 fitted with a 1 in. diameter x 1 in. Na(T1) crystal was used in each of the two scintillation probes. The manner of assembling the scintillation detector systems used in the probes is now described. A 12-pin mica impregnated non-hygroscopic bakelite socket is fixed onto a machined lucite reel as shown in Figure 13. The components for the voltage divider and the amphenol connector for the high voltage power supply are then mounted on the reel, and wired according to the circuits shown in Figures 10 or 11. In assembling the photomultiplier tube with the phosphor, the facing surfaces of both are first thoroughly cleaned and polished using silicone treated tissue paper. For
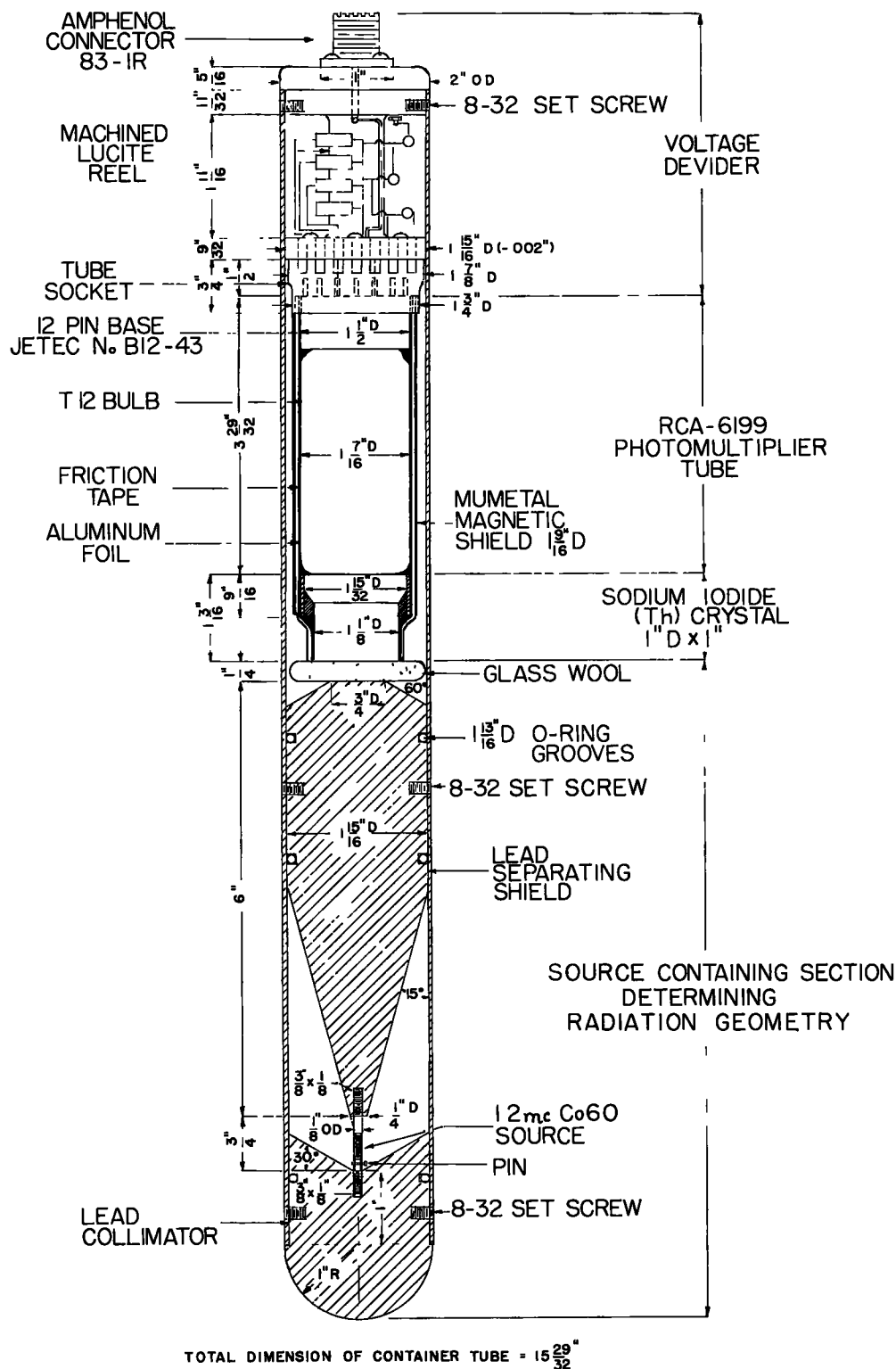
AMPHENOL CONNECTOR 83-IR

MACHINED LUCITE REEL

TUBE SOCKET

12 PIN BASE JETEC No B12-43

T 12 BULB

FRICTION TAPE

ALUMINUM FOIL

LEAD COLLIMATOR

8-32 SET SCREW

VOLTAGE DEVIDER

RCA-6199 PHOTOMULTIPLIER TUBE

MUMETAL MAGNETIC SHIELD $1\frac{9}{16}$"D

SODIUM IODIDE (Th) CRYSTAL 1"D x 1"

GLASS WOOL

$1\frac{13}{16}$"D O-RING GROOVES

8-32 SET SCREW

LEAD SEPARATING SHIELD

SOURCE CONTAINING SECTION DETERMINING RADIATION GEOMETRY

12 mc Co60 SOURCE

PIN

8-32 SET SCREW

2" OD

TOTAL DIMENSION OF CONTAINER TUBE = $15\frac{29}{32}$"

Figure 13. Scintillation density probe using RCA 6199 photomultiplier tube, 2 in. in diameter.

optical coupling, either white vaseline (petroleum jelly) or preferably silicone fluid, Dow-Corning DC-200 or any other optical cementing agent, is applied and spread evenly on both surfaces. The crystal is worked in carefully avoiding the inclusion of air bubbles and pressed as close to the photomultiplier face as possible; the excess fluid is then wiped off. Aluminum foil that is wide enough to cover the crystal and run up to half the length of the photomultiplier tube is wrapped closely around the tube and crys-
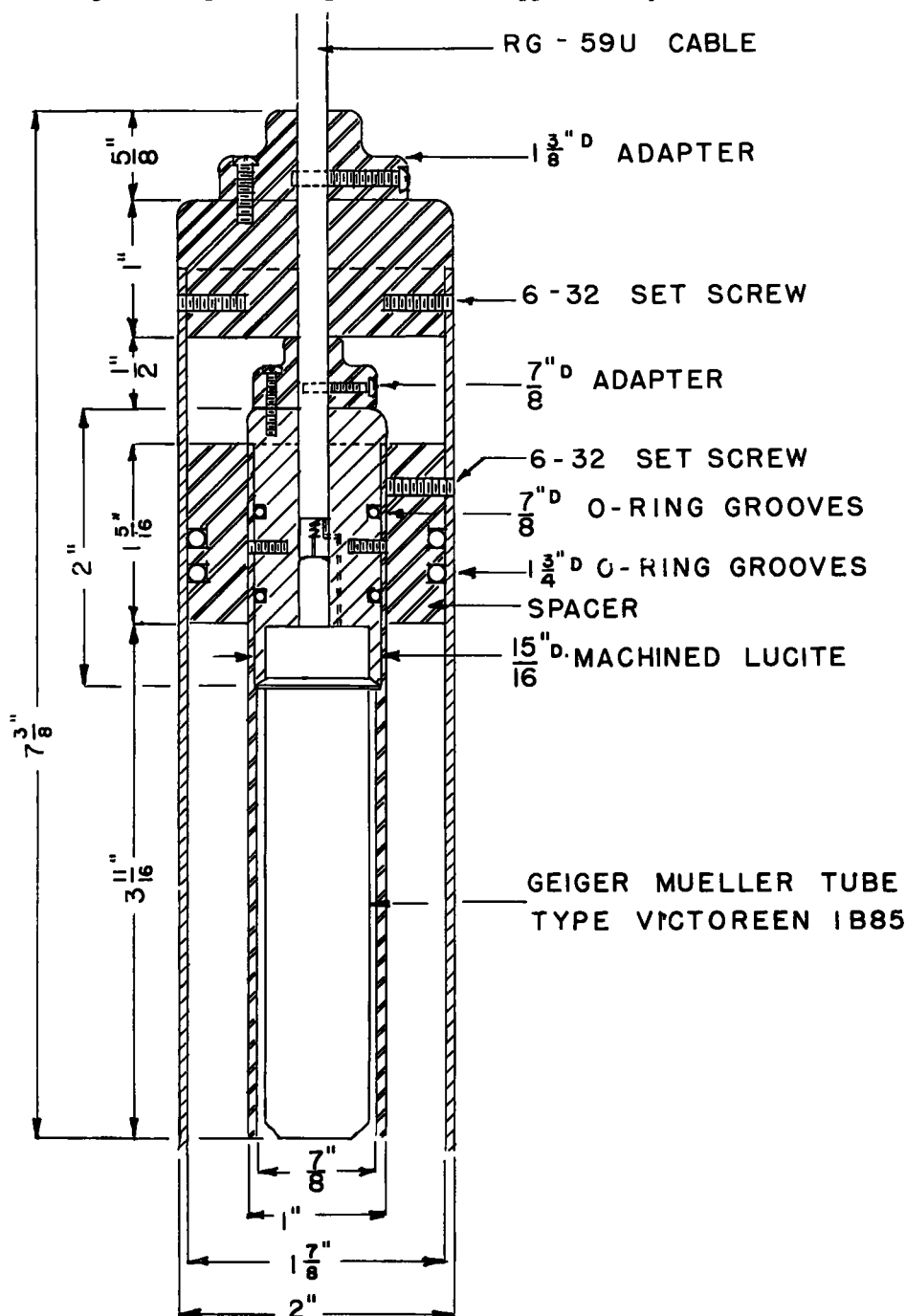
Figure 14. Geiger-Mueller detector adapted for 2-in. diameter density probe.
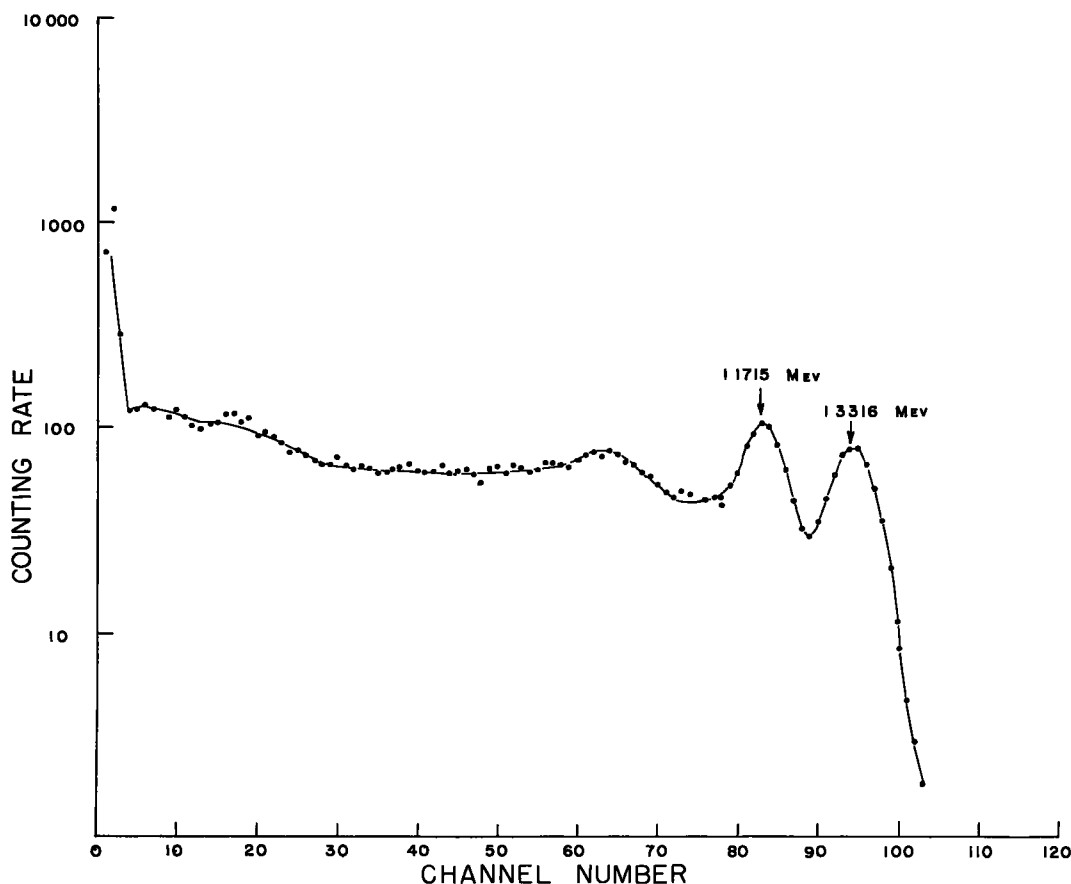
Figure 15. Gamma Ray Spectrum of Cobalt 60.

tal. Black plastic electrical tape is then wrapped around the tube beginning from the opaque base, covering the lower glass envelope of the photomultiplier, progressing to the end of the envelope on top of the aluminum foil and finally binding the phosphor closely onto the end of the photomultiplier tube. This is to make certain that there is no possibility for light leakage into the tube. At the middle and at the base end of the photomultiplier, the diameter of the wrapped tape is built up so as just to permit a double mumetal magnetic shield to be drawn up tight over on top of the tape until it is flush with the base. A few wraps of tape are used to bind the magnetic shield onto the base of the photomultiplier after its pins are snugly fitted into the base.

The voltage divider reel, the photomultiplier tube and the crystal, which are the working components of the scintillation detection system thus become a single detachable unit. Two 8-32 set screws through the brass tube containing the probe into the lucite are all that are used to hold the scintillation head in the probe.

The source, which is a 0.5 cm long solid Co^{60} wire, is encapsulated in a steel cylinder with a diameter of 1.27 mm. A steel machine screw is drilled concentrically to a depth of $1\frac{1}{4}$ in. using a $\frac{1}{16}$ in. drill bit. A $\frac{1}{16}$ in. hole is also drilled transversely through the screw, $\frac{1}{2}$ in. from the open end. A lead collimator and separating shields are turned according to the dimensions in Figure 13 and threads are tapped both in the concave center of the collimator and at the apex of the 75 deg angled cone of each separating shield. The source is inserted in the center core of the steel screw, and a pin is used to secure it in place. Depending on the probe geometry, either a long or short separating shield and a collimator are then screwed in so as to form one unit. The source containing unit is slid up the brass containing-tube sandwiching a wad of Fiberglas between the top of the shield and the phosphor. The Fiberglas wad acts both to keep
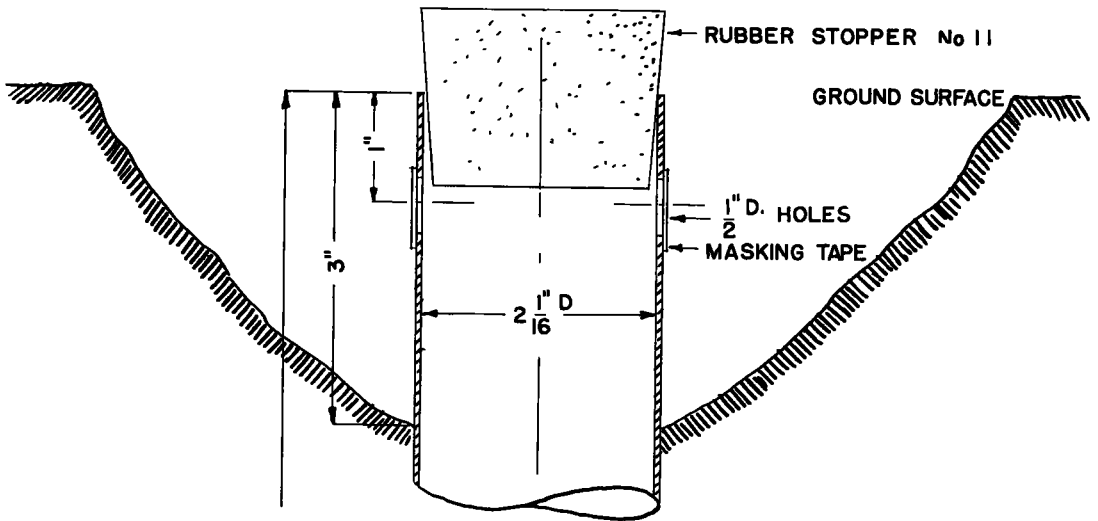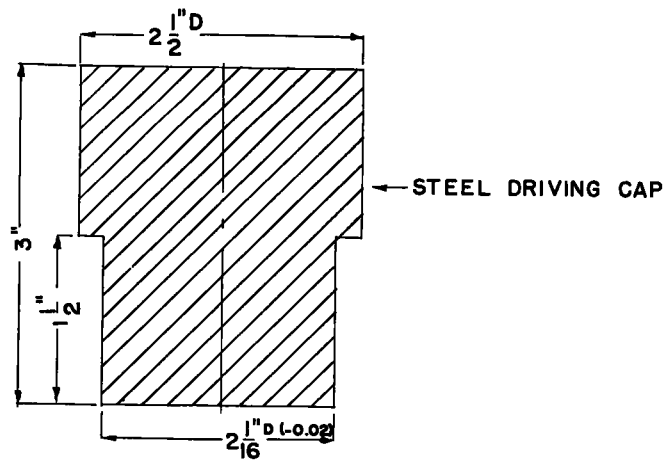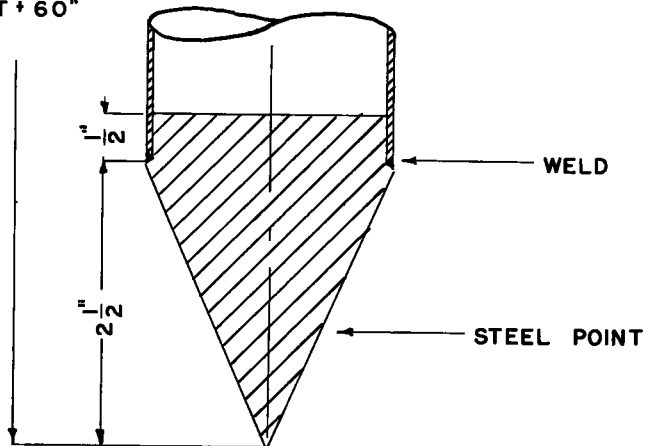
Figure 16.   Access tube for field measurements.

the phosphor pressed against the face of the photomultiplier and to dampen shocks suffered by the scintillation head unit. Set screws are used to keep the source holding unit in a rigid fixed geometry with respect to the phosphor detector.

Two types of density probes using scintillation were tried out in the field. The only difference between these two probes was that whereas the distance between the source and phosphor was 7 in. in the earlier one, as shown in Fig. 13, it was only $5\frac{3}{4}$ in. in the latter. Fig. 14 shows the detector head of a third probe, not using scintillation, but adapting a 1-in. Geiger-Mueller detection head system for the 2-in. diameter probe. The source holding unit had exactly the same shape as for the short scintillation probe which is the same shape as for the long probe, but with the separating shield cut at the top so that the source to detector distance is $5\frac{3}{4}$ in.

Operation of Density Probes

The scintillation detection system was very sensitive, being 20 to 40 times more sensitive than the Geiger-Mueller system used. Hence the 1 mc source was unnecessarily large, 0.1 mc being more than adequate for the purpose at hand. Since the most reliable equipment was confined to the laboratory, spectral emission curves and preliminary calibration were first performed with such equipment. However, the laboratory and equipment had only a binary scaler with a scale of 64 which was incapable of registering counts in excess of 200 cps. At low discriminator settings, the counting rate with the probe in use was in excess of 5,000 cps. Hence, at first, a great mistake was made in trying to reduce sufficiently the number of counts detected by raising the discriminator level. As may be observed from the spectral emission of Co^{60}, shown in Fig. 15, this could only be accomplished by raising the level so high as to cut out all pulses beyond that for the higher energy peak of Co^{60} at 1.33 Mev. Since only about 3 percent of the total detected counts were needed, this meant setting the discriminator at the lower end of the steep descent from the 1.33 Mev. peak. Obviously, at this setting any slight drift in the discriminator would give drastic count variation. Much time and work was wasted until the cause for this drastic variability was ascertained. Two scalers were later used in series, with discriminator setting set low in order to include most of the spectral range of γ-ray scatter impinging on the crystal. Hence, high enough counting rates could be registered so as to have the discriminator set at the relatively flat region of the spectral detection curve, where discriminator instability was not hypercritical.

The probe, with 7 in. distance separating the source from the detector, was designed so as to obtain as deep a sample as possible, yet one which would also extend the greatest distance horizontally. At a density of 1.8 g/cm^3, the shape of the sample was estimated to be that of a rotation ellipsoid with a vertical diameter of about 12 in. and a horizontal diameter of about 24 in. with the apparent center located about $1\frac{1}{2}$ in. from the bottom of the phosphor. The probe was specifically designed to meet the exigencies of a practical job in which it was sought to obtain greatest accuracy at low densities. The job consisted of measuring the density and moisture content to find the thermal resistivity of soil under city pavements which were to entrench high tension cable lines. The job was performed in collaboration with the Public Service Company of New Jersey, whereby this probe was thoroughly tried out in the field.

Calibration of the early 2-in. diameter long probe was performed as follows: Sand was wetted and densitied to different degrees in an aluminum cylinder (3 ft. in diameter and 4 ft. high) in layers not less than 1 ft. deep. The center was then augered out and a steel access pipe ($2\frac{3}{16}$ in. outside diameter and $\frac{7}{16}$ in. thick) inserted which was capped at the bottom end. The dimensions and construction of the access pipe are shown in Fig. 16. The calibration cylinder as used during calibration is drawn in Fig. 17. Immediately after the access tube was inserted, readings were made both for the density and moisture content using the 2-in. diameter probes. When the laboratory equipment was used, two one-minute-absolute-count readings were made using an electric elapsed-time timer, for each depth for each probe. Depth intervals at which readings were taken were 3 in. during all calibration work.

Upon cessation of readings by the nuclear meters, a Coile-type core sampler equipped with a drop hammer was used to take two or three undisturbed 3-in. diameter x 3-in.

cylindrical samples from each depth, spaced at even radial intervals. Hence, an average density for each 3-in. layer was easily deduced, as well as for 12-in. and deeper layers. This enabled both the calibration of the probes against the densities and moisture contents as determined by the air pycnometer or by core drying, and also the estimation of the vertical extent to which soil contributed to the counts for varying densities and moisture contents. The calibration curve obtained for the density is shown in Fig. 18.

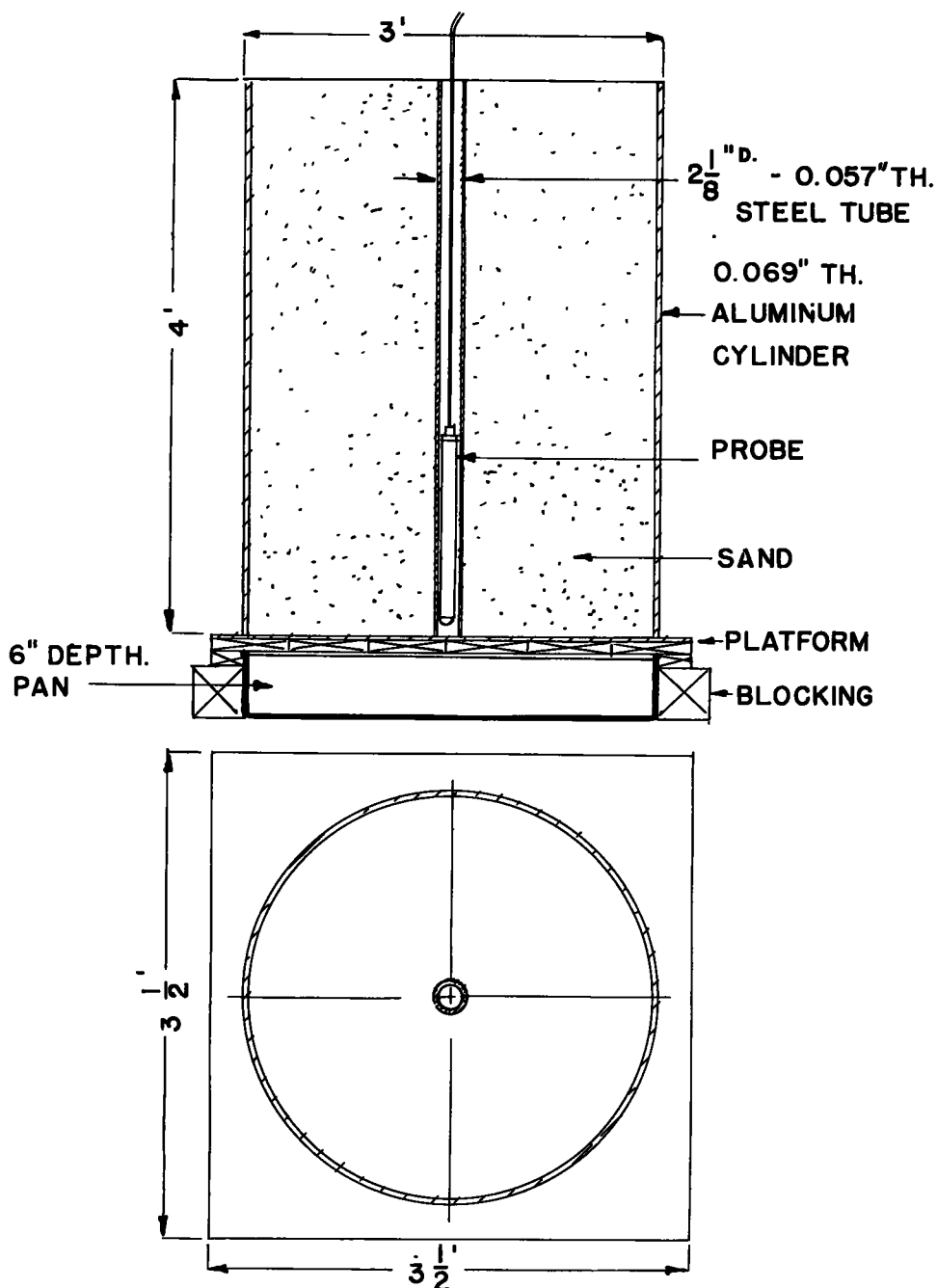Unfortunately, high densities could not be obtained by such a technique of calibration.

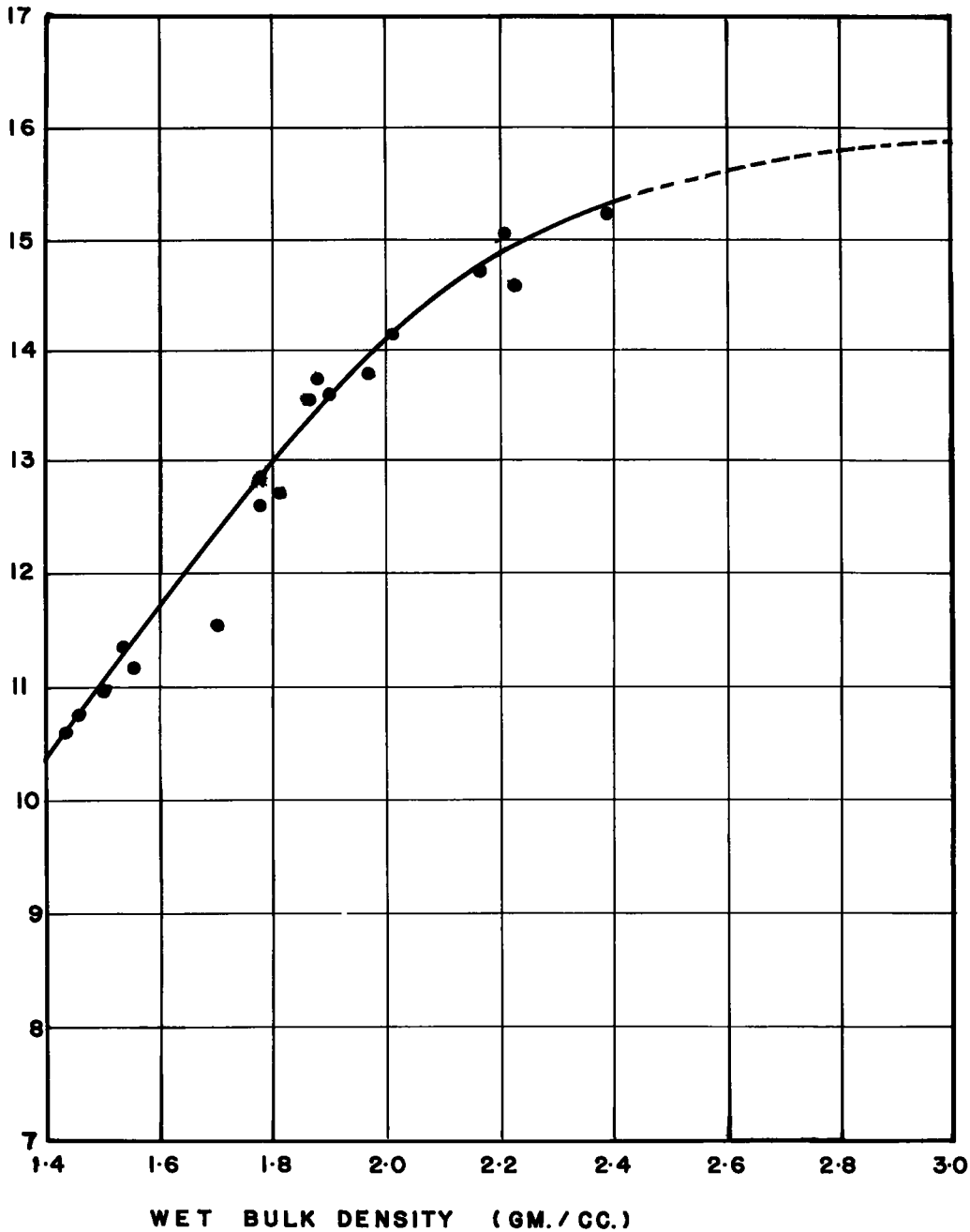Figure 17. Equipment for laboratory testing and calibration of probes.

Figure 18. Calibration curve for densitometer using RCA-6199 NaI(Tl) and 7-in. source-detector spacing.

Hence, natural soil was used in situ, to obtain a few points on the higher end of the density curve. The use of the Coile sampler was not only laborious but yielded very few undisturbed samples on stony field soils, particularly where the density was high. It was hoped to complete the density curve up to high limits at the job site with the use of mechanically powered coring rigs, but several factors prevented this. Hence, the dotted curve in Fig. 18 represents projection beyond actual calibration limits of density. From this curve it is apparent that the probe geometry caused good linear response of counts up to a wet density of 2.0, beyond which there is a decided flattening of response. For the purpose for which this probe was applied, this was no real handicap, as the low densities of soil cause poor thermal conductivity, the detection and possible amelior-

Figure 19. Calibration curve for 2-in. diameter Geiger-Mueller probe with 5-3/4" source to detector spacing.

ation of which was the main purpose of the field work. However, this flattening is a serious drawback to the general use of the probe. Hence, another probe, similar in construction but with only $5\frac{3}{4}$ in. between source and detector, was made to give good linearity throughout the medium to high density range in soils. Time has prevented the making of a good calibration curve for this probe, but enough work has been done here to assure good sensitivity of the probe to beyond a density of 3.0 gm/cm^3 although from theory and the experience of Belcher (9) and Timblin (154), one should expect a flattening of response at low densities.
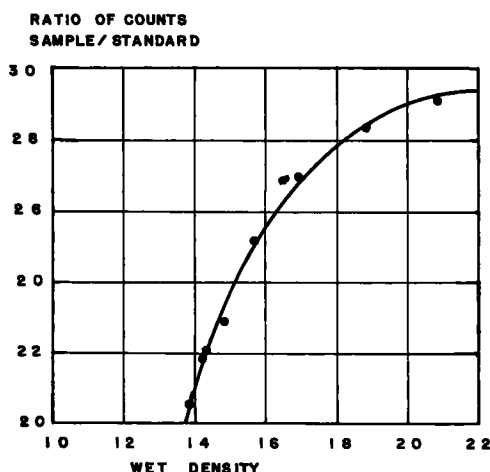
For the 1-in. diameter Geiger-Mueller detection system adapted to the 2-in. diameter probe with $5\frac{3}{4}$-in. distance between source and the end of the Geiger-Mueller tube, the preliminary calibration curve is as given in Fig. 19. As only a few points make up this curve it is not very reliable but adequately serves to indicate the nature of its response to density change in the range covering 1.4 - 2.2 gm/cm^3. This calibration curve was obtained by taking 4-in. diameter x 6-in. cylindrical samples contained in a thin-wall sampler with lining, or 3-in. diameter x 16-in. Shelby samples from an adjacent parallel hole within 3 ft. from the hole made to take the nuclear measurements. Selected sites that appeared to offer great variation in density and moisture content were explored through 6-ft. or 10-ft. profiles, using a motor-operated hydraulic-feed coring rig to obtain undisturbed samples and make $2\frac{3}{8}$-in. holes to receive the closed-end access tubes in preparation for the reception of the density and moisture probes. The precautions required to prepare such holes will be discussed later.

The size of sample that the Geiger-Mueller 2-in. densitometer resolves in its use was not determined precisely. However, from the determination of the center of this sample, which is approximately 1 in. below the bottom of the detector tube at densities of about 2.0 g/cm^3, and from noting at what distance boundaries have no effect on readings, it was deduced to be a rotation elipsoid with 10 in. as the vertical diameter and 20 in. as the horizontal diameter. As others (9, 33, 41, 76, 154) have pointed out previously, the size of the sample varies with the density of the material under test. For very dense material (3.0 g/cm^2), the size and shape of the sample would be much nearer a sphere in shape, with perhaps 8 in. as the vertical diameter and 12 in. as the horizontal one. Upon use in low-density material approaching 1.0 g/cm^3, the vertical diameter of the sample elipsoid would perhaps be about 12 in., whereas the horizontal one would have stretched to near 28 in. Lack of labor and time has prevented the actual determination of the change of sample size and shape with variation in density, but the figures given are approximations which should certainly be within $\pm$ 10 percent of the actual values.
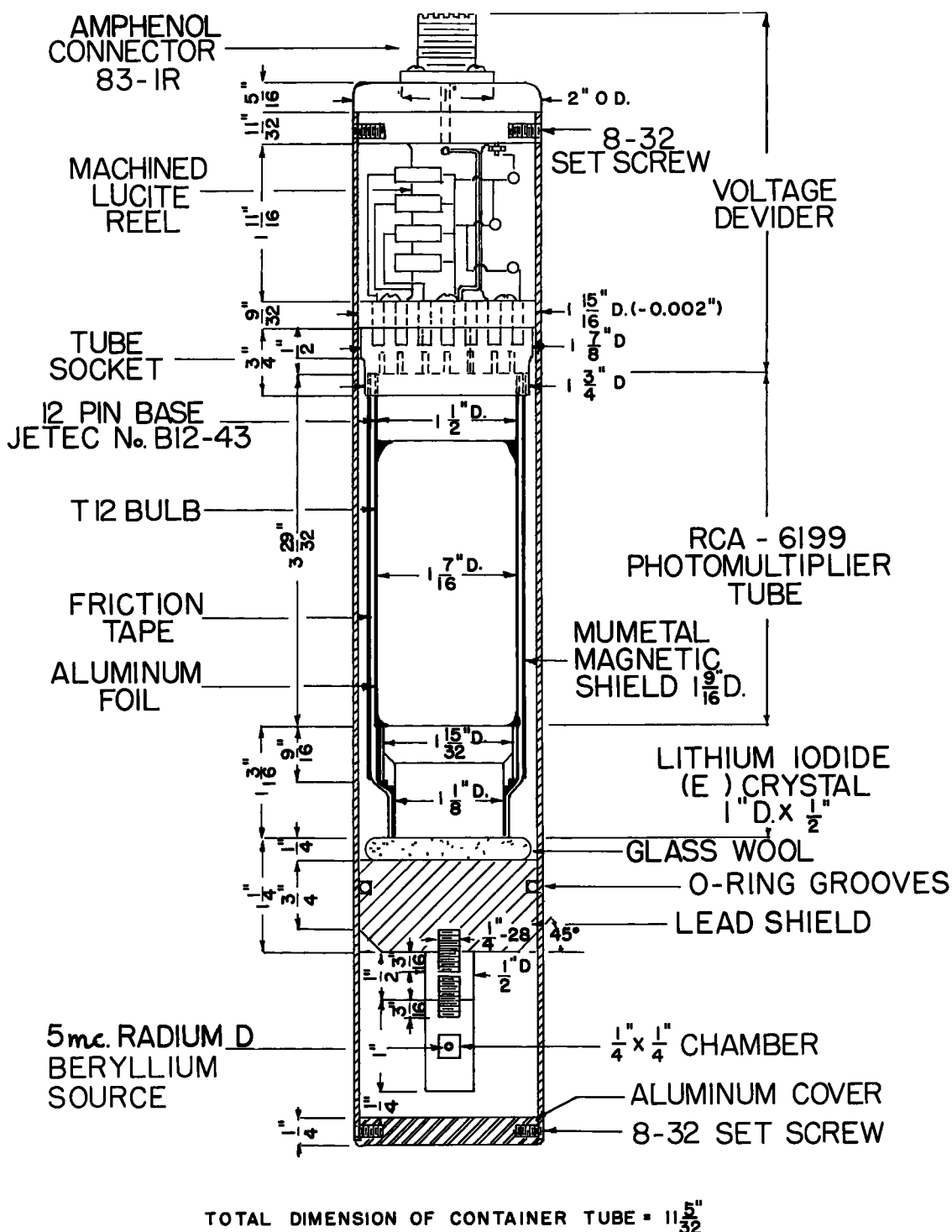
Figure 20. Scintillation moisture content probe using RCS-6199 photomultiplier tube LiI(Eu) phosphor and RaDBe source, 2 in. in diameter.

Appraisal of 2-in. Diameter Density Probes

The sensitivity of the 1-in. diameter x 1-in. NaI(T1) crystal and RCA-6199 detection system was about 25 times that of the Geiger-Mueller probe. Hence, a system using the thinnest NaI(T1) phosphor available and a Co^{60} source of very low intensity, such as 0.1 mc, would still yield a greater number of counts than the G-M system. From the viewpoint of universal use, this is a great asset as it would virtually eliminate the radiation hazard. The scintillation probe could cost as little as $85.00 competing well with the very low cost of $40.00 for the parts for a G-M probe.

In operation, the probe using the source-detector distance of 7 in. is definitely lacking in sensitivity at high densities, and is not recommended for general use. The Geiger-Mueller probe, already tried out for over a thousand determinations in the field, gives good linear response throughout the density range likely to be encountered in soil testing. Owing to its low sensitivity, the probe gives a reading error of about 1.0 percent owing to statistical counting of random counts over one minute. It was found that probably due to humidity and temperature change during prolonged use, the sensitivity of the probe would vary as much as 25 percent. In use with the UAC 522 the accuracy that would be expected for density determinations is $\pm$ 1.5 percent. The even sized pulses from a G-M tube, and the broad counts versus high voltage plateau, makes it unnecessary for the G-M detection system to use a precision meter with discriminator, and a highly regulated high voltage supply, reducing both the necessity for complicated electronic circuitry and the cost for meters.

With respect to linearity of response throughout the density range, there is no reason why the scintillation density probe with the source-detector distance of $5\frac{3}{4}$ in. should not be much the same as the Geiger-Mueller system with the same spacing. There are,
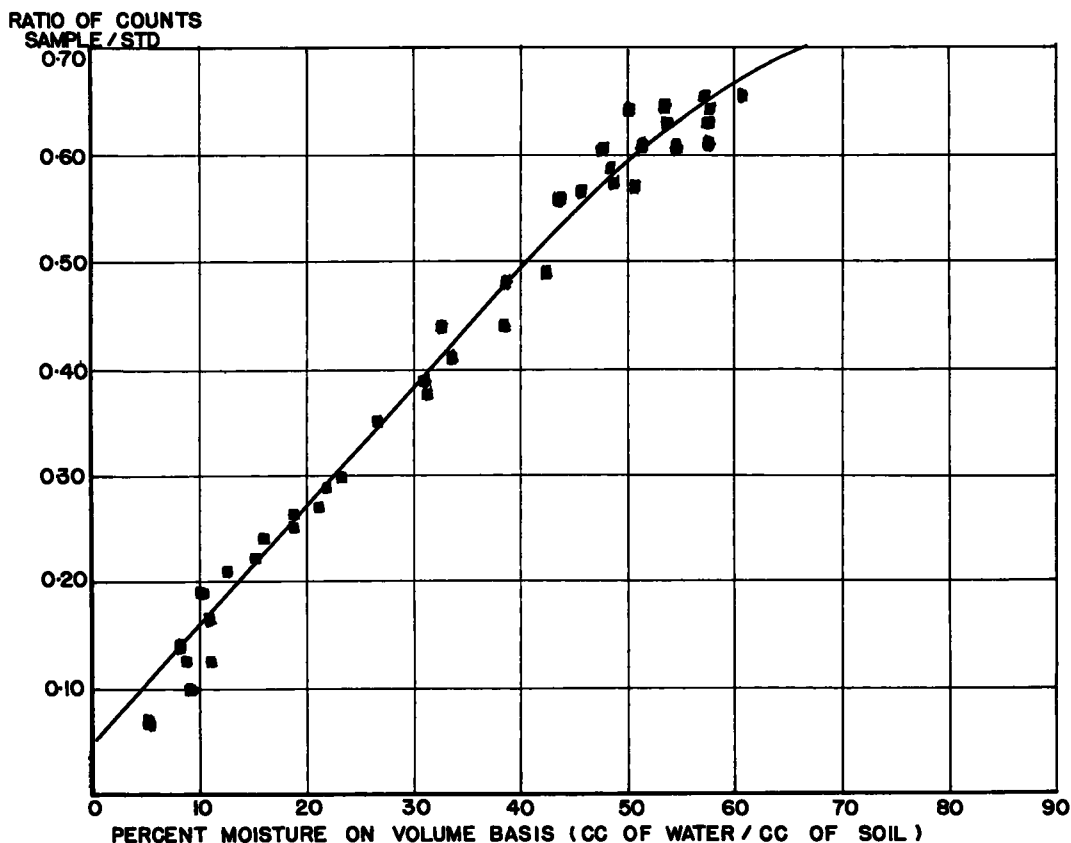

Figure 21. Calibration curve for hygrometer using RCA-6199, LiI(Eu) and 5 mc RaDBe source.

however, still certain problems inherent in scintillation detection, of γ photons in particular, that makes it potentially a less accurate system, unless highly stable electronic amplification and counting systems are made available for field use. The first fact to be recognized is that because the scattering type single probe densitometer works on Compton scatter, the energies of scattered γ photons would cover an entire range starting at 1. 06 Mev, down to 0 for a Co^{60} source. Because of the linear response of intensity of illumination to the energy of the γ photon absorbed by a NaI(Tl) phosphor, there would be a continuous spread in the amplitude of pulses as picked up, amplified
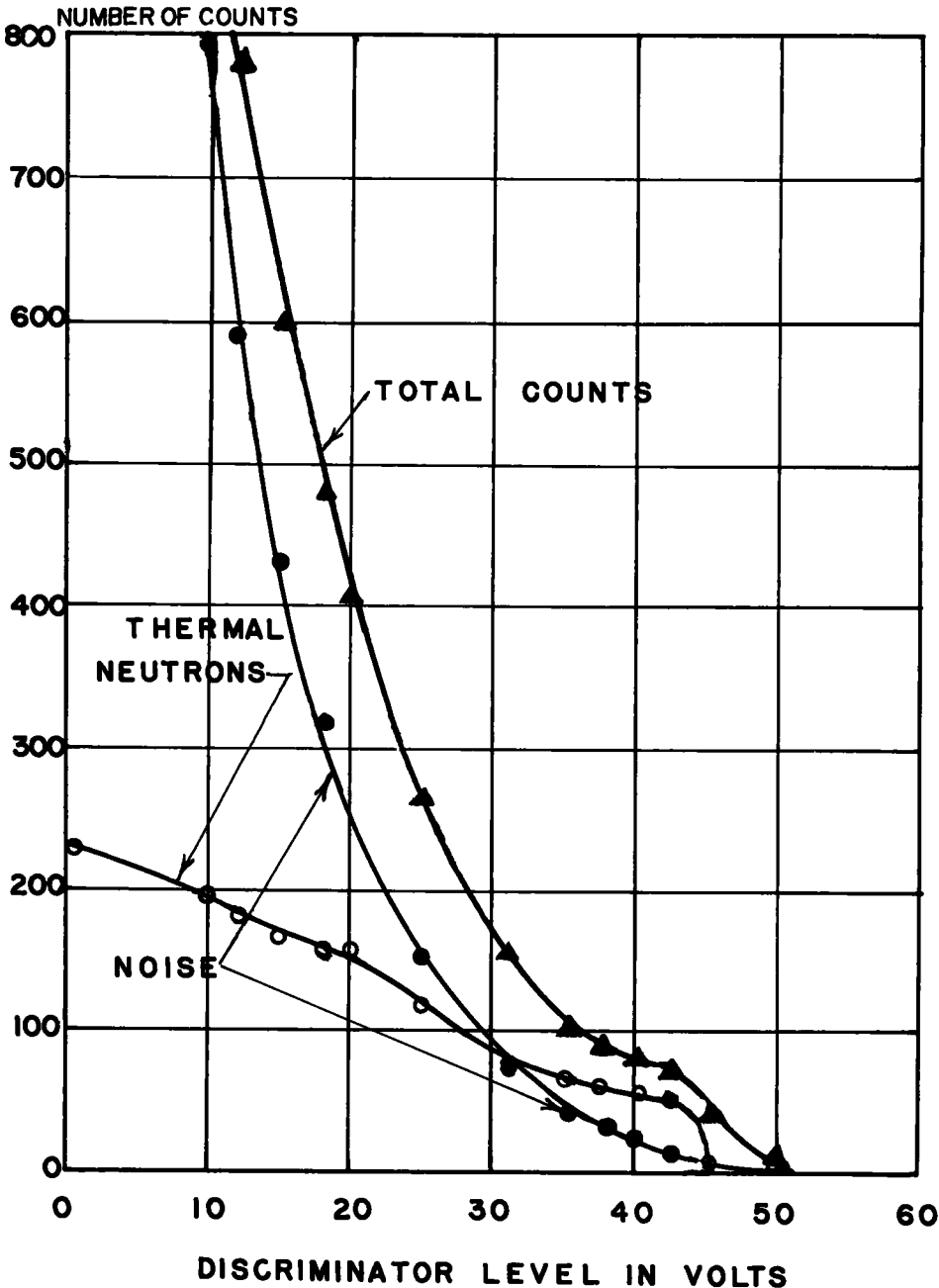

Figure 22. Discrimination bias curve for LiI (Eu) phosphor, RCA-6199 Probe.
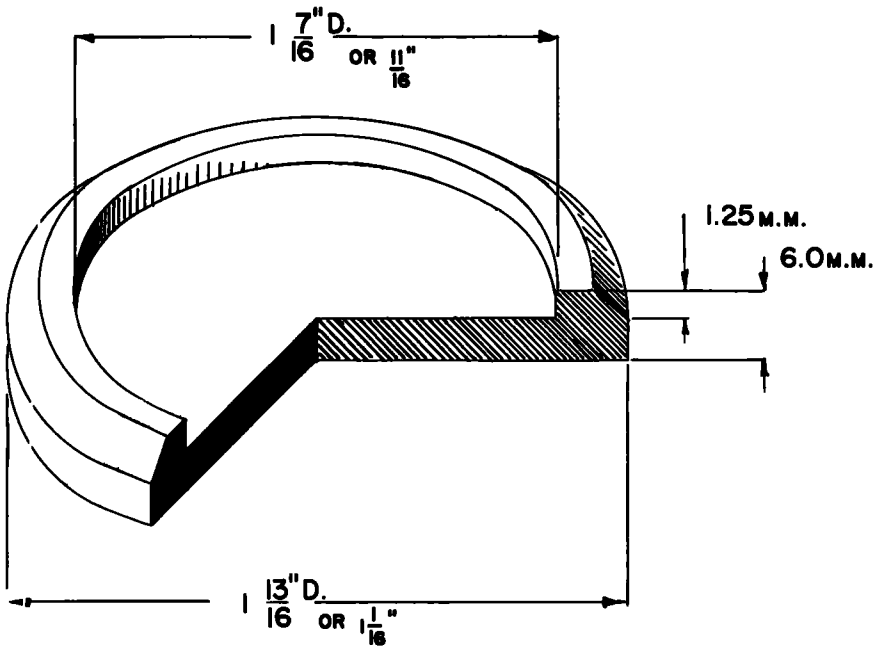
Figure 23 (a). Metal mold for neutron phosphor.
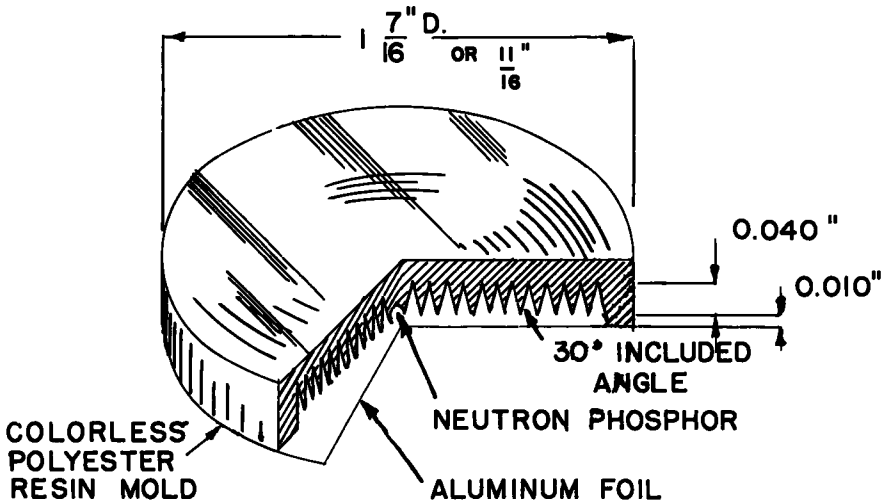
Figure 23 (b). BP-ZnS(Ag) Moisture type slow-neutron scintillator.

and delivered as the output of the photomultiplier. This enforces a severe demand for a strictly stable discriminator level in counting detected pulses by such a system. This need becomes even greater if, because of several reflective surfaces in the crystal and because of poor matching of cable impedance to handle the signal charge, each pulse is considerably differentiated. The demands are such that, at present, they can only be met adequately by large line operated instruments (with voltage regulators) employing highly stabilized vacuum tube discriminator circuits. None of the instruments made in this laboratory for field use, or even a precision rate-meter commercially manufactured,

AMPHENOL CONNECTOR 83-IR

MACHINED LUCITE REEL

TUBE SOCKET

12 PIN BASE JETEC NO B12-43

T12 BULB

FRICTION TAPE

ALUMINUM FOIL

OPTICAL COUPLING FLUID DC-200

$\frac{1}{4}$" 28 SCREW

SEALED STEEL CONTAINER

$\frac{5}{8}$"

$\frac{1}{16}$"

2" O.D.

8-32 SET SCREW

$\frac{1}{8}$" X 1$\frac{15}{16}$" O-RING

1$\frac{15}{16}$" D. (-·002")

1$\frac{7}{8}$" D.

1$\frac{3}{8}$" D.

1$\frac{1}{2}$"

1$\frac{7}{16}$"

MUMETAL MAGNETIC SHIELD 1$\frac{9}{16}$" D

1$\frac{7}{16}$" D X 1·2 MM BORON PLASTIC ZnS(Ag) PHOSPHOR

O-RING

LEAD SEPARATOR

RADIUM BERYLLIUM SOURCE 3-10 MC.

ALUMINUM CAP

8-32 SET SCREW

VOLTAGE DIVIDER

RCA-6199 PHOTO-MULTIPLIER
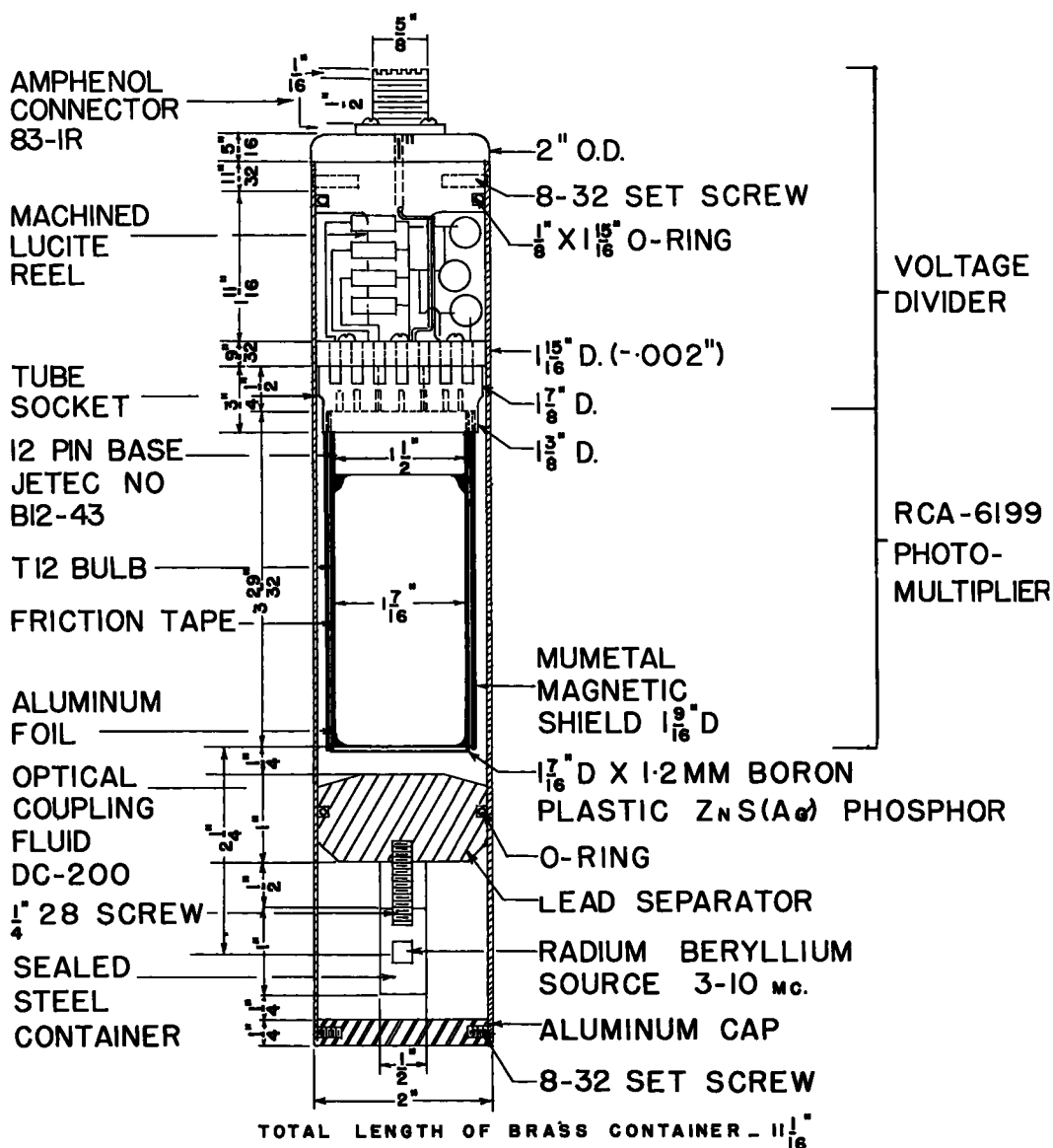
TOTAL LENGTH OF BRASS CONTAINER - 11$\frac{1}{16}$"

Figure 24. Scintillation moisture probe using RCA-6199, BP-ZnS(Ag) phosphor and RaBe source, 2 in. in diameter.

had adequate stabilization of discriminator circuits to give satisfactorily accurate readings. Since the amplitude of the signal is increased with an increase in the potential supplied between anode and photocathode, a highly stabilized high voltage supply also becomes a necessity. Though it is possible, with the use of a portable generating plant, good voltage regulators and line-operated vacuum tube circuits, to satisfy these stringent requirements in the field, such instrumentation is unwieldly and expensive. The accuracy to be expected from the over-all system can be no better than that made possible by the least accurate component, which in the case of the scintillation sensitometer is that determined by the discriminator and high-voltage stability of the equipment used.

The equipment used both for calibration and actual field tests was a newly developed transistorized precision ratemeter manufactured as Model 522 B by the Universal Atomics Division of Universal Transistor Products Corporation. The over-all excellence of

this very light (10½ lb) portable instrument which has features such as a well regulated transistorized power supply capable of varying the voltage from 800 - 1,300 v. d. c., an 11-transistor amplifier, a discriminator circuit, 6 ranges covering 0 - 10,000 cps, an oscillator operating at 1,500 cps for calibrating the instrument internally, four time constants (1 second, 5 seconds, 20 seconds and 120 seconds), and an accuracy of ± 2 percent at full scale deflection, made it the selected choice for use in the field. An appraisal of the functioning of this meter is dealt with later. It is sufficient to report here that the meter lacked adequate discriminator stability and was also somewhat deficient in high voltage stability, particularly at temperatures above 85 or 90 deg F. The accuracy obtained with the use of this meter in over 1,000 determinations averaged about ± 5 percent over the entire range of densities encountered on the field when employed with the scintillation type densitometer. With the Geiger-Mueller probe, density could be determined with an accuracy approaching ± 1.5 percent. The instability of the discriminator level and that of the high voltage supply scarcely affects the G-M system as a constant amplitude pulse is produced along the broad high voltage plateau beyond the Geiger threshold level of the tube.

Design of 2-in. Diameter Moisture Probes

Fig. 20 shows the earlier model of the 2-in. diameter moisture probe. The scintillation detection head is assembled in the same manner as described for that used in the densitometer. The only difference is that a 1-in. diameter x ½-in. LiI(Eu) crystal is used instead of the NaI(T1) phosphor. It would have been preferable to have used a 1-in. diameter x 1-in. LiI(Eu) phosphor but at the time of need this size was not procurable. The geometry arrived at first, shown in Fig. 20, was a compromise between greatest efficiency and greatest sample size. Owing to a fairly high rate of γ emission from the 5 mc RaDBe source used, and a considerable sensitivity of the LiI(Eu) phosphor to γ photons, the 1-in. lead shield was found necessary to reduce the background count. As has been previously discussed in the theory of the moisture probe utilizing the thermalizing of fast neutrons, the source to detector distance should not exceed 15 cms at the greatest distance of the sensitive portion of the detector from the source. This imposed the maximum limit for the distance between source and detector. The source was tried at distances of 15 cms to 5 cms from the farthest end of the LiI(Eu) crystal, while the probe was immersed in a bucket of paraffin with a 2-in. hole in its center for its reception. The source to detector distance which was decided upon for the probe was 8.0 cm. (from the farther end of the phosphor). This was fixed as such because there was an attempt to increase the size of sample to be more in keeping with that of the density measurement. However, the greater the source to detector distance, the less accurate were the readings owing to the lower count rates particularly for dry soils. The distance decided upon would give statistical accuracies of 1-min. readings of approximately ± 1.5 percent at a moisture content of 5 percent by volume, and about ± 0.9 percent for 100 percent water owing to the random nature of radioactive emission alone. A larger source or a larger phosphor could possibly have permitted a full 15 cm source to detector geometry which would have given the greatest depth of vertical resolution of which the instrument is theoretically capable. The assembly of the moisture probe is self-evident from Fig. 20. Because of the sensitivity of LiI(Eu) to γ photons, a low γ emission rate 5 mc RaDBe source had to be used for the fast neutron source. The source is contained in a hermetically sealed cylinder ½-in. diameter by 1 in.

The size of sample of water that this probe measures was found to be less than a 10-in. diameter sphere with the center approximately at the bottom of the crystal. In air-dry sand the size of sample was about 16 in. in depth and about 24 in. in diameter, with its center being approximately 1 in. below the bottom of the LiI(Eu) phosphor. Figure 21 gives the calibration curve for this probe.

The spectral detection curve, as determined by plotting the counting rate against the level of discriminator bias, gives important information which must be obtained so that the level, at which the discriminator is fixed, is judiciously selected to give maximum accuracy and stability. Fig. 22 shows the discrimination bias curve of the LiI(Eu)

phosphor detecting emission from a 5 mc RaDBe source in the geometry of the probe as shown in Fig. 20, while the probe is in a paraffin bucket. Noise and unwanted radiation counts grow in geometric proportion in their contribution to the total count as the discriminator level is reduced. At increasing threshold levels of the discriminator, an increasing proportion of the total counts is contributed by the 4.8 Mev energy pulses of
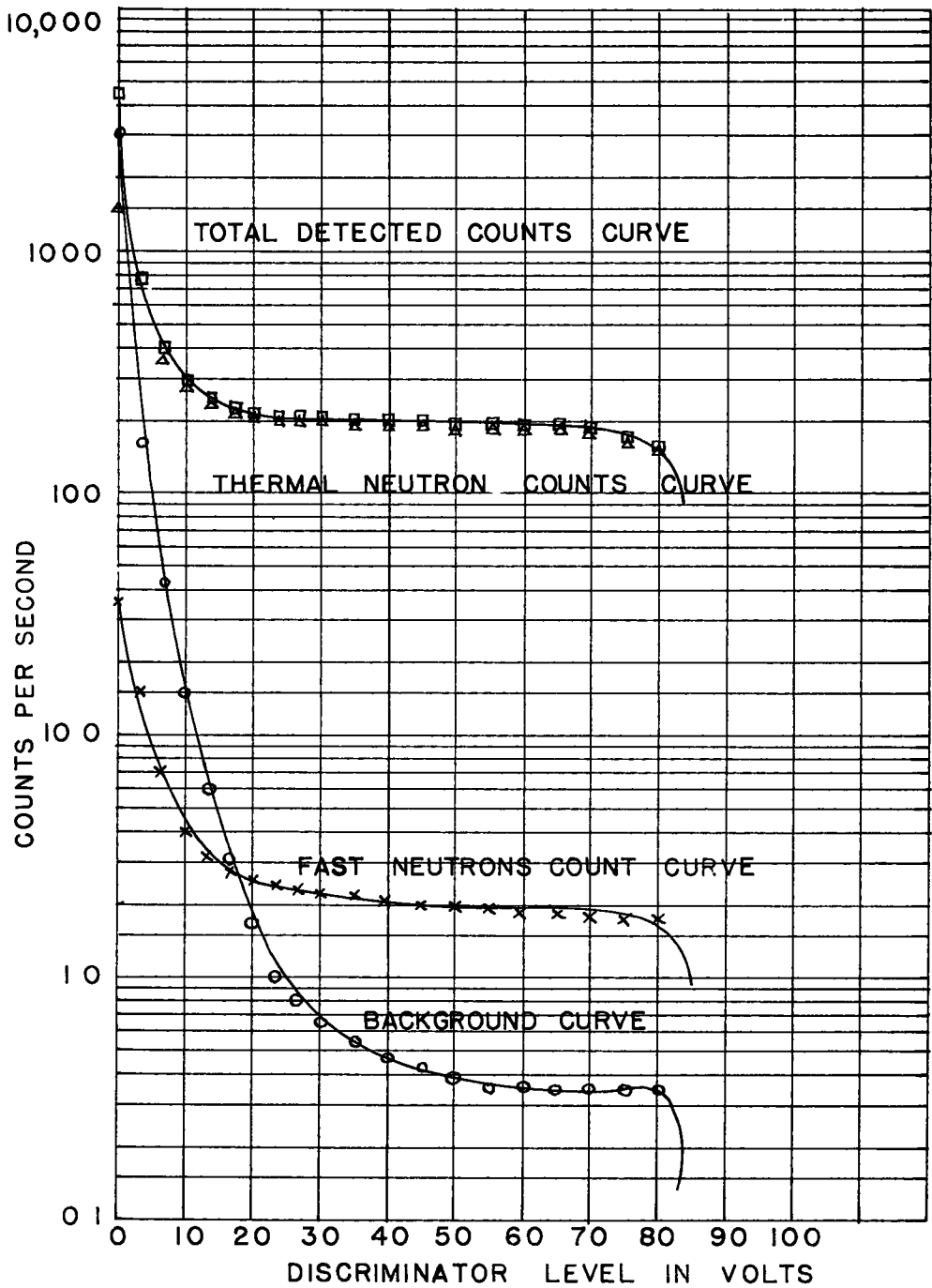

Figure 25. Total spectral detection curve and its components for BP-ZnS(Ag)-RCA-6199 moist probe in 10-in. diameter paraffin standard.

the total product nuclei in the Li^6 (n, α) triton reaction. The number of the counts deriving from the detected thermal neutrons diminishes steadily as the discriminator level is raised, but that of the counts due to extraneous radiation decrease at a more rapid rate. The counts due to unwanted radiation were determined by merely suspending the probe in air in the middle of a room at least four feet from any solid surface. Those attributed to thermalized neutrons were the difference between the total count of each discriminator setting and those due to unwanted radiation.

The discriminator level could be fixed at any height that would yield a high proportion of counts due to thermalized neutrons as compared with "noise" pulses of the total count. However, it must be ascertained then that the pulses due to unwanted radiation will be the same under all test conditions as it is for the standard.

Figure 26. Calibration curve for BP-ZnS (Ag)-RCA-6199 moisture probe.

If this could be ascertained definitely, then a smaller LiI(Eu) crystal and/or a smaller source could be used successfully in the probe. Because of the number of variables that would need to be "controlled" in order to ascertain that the noise counts remain constant in all test conditions, the labor and technical difficulties to be tackled would make this an expensive, time-consuming proposition. Theoretically, it could hardly be expected that the noise counts would remain constant, for the following reasons:

1. Because RaDBe emits considerable γ radiation with energies of up to 2 Mev. the process of Compton scatter will be involved and hence there will be a steady increase in γ photons detected with greater electron density per cm^3 of the test material for threshold setting up to and below this energy level.

2. The density of protons as compared with electron density should by theory affect the total absorption coefficient composed of the three processes involved in γ radiation absorption. This is particularly true because a significant percentage of radiation will be absorbed by pair production.

3. The natural background count composed of radiation from outer space and from the earth is likely to change because of cosmic ray shower intensity and radiation from the earth changing upon penetration of the earth's surface to shallow depths.

For these reasons, it was decided to play safe by using a sufficiently high discrimination level to reduce the background noise to a very small fraction of the total count, and yet yield a reasonably high rate of counts due to thermalized neutrons. In the paraffin standard, the noise count was 2 cps when the standard total count registered 62 cps, giving a signal to noise ratio of 30:1. Even a 50 percent variation in noise counts would scarcely affect the number of counts attributed to signal pulses. At this level, the discriminator setting is still well on the plateau, being considerably lower than the knee of the curve. It must be specified here that these measurements were performed using the simple voltage divider circuit, as shown in Fig. 10, and 12 ft of RG-59 U coaxial cable, as this was the actual system to be used in the field. However, laboratory counting instruments with stabilized high voltage supply and preamplifier and amplifiers were used to obtain such data for the sake of accuracy. It must also be indicated here that from results obtained later using the stabilized voltage divider circuitry shown in Fig. 11, the plateau was much more flat with a much pronounced 4.8 Mev equivalent signal that cut off quite sharply beyond this value of discrimination of the pulse height. However, no spectral detection curve was made for this system as it was never used in the field.

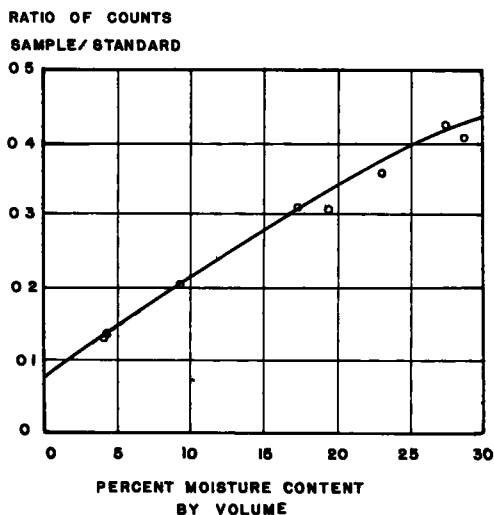This probe gave more accurate results than its scintillation density probe counterpart.
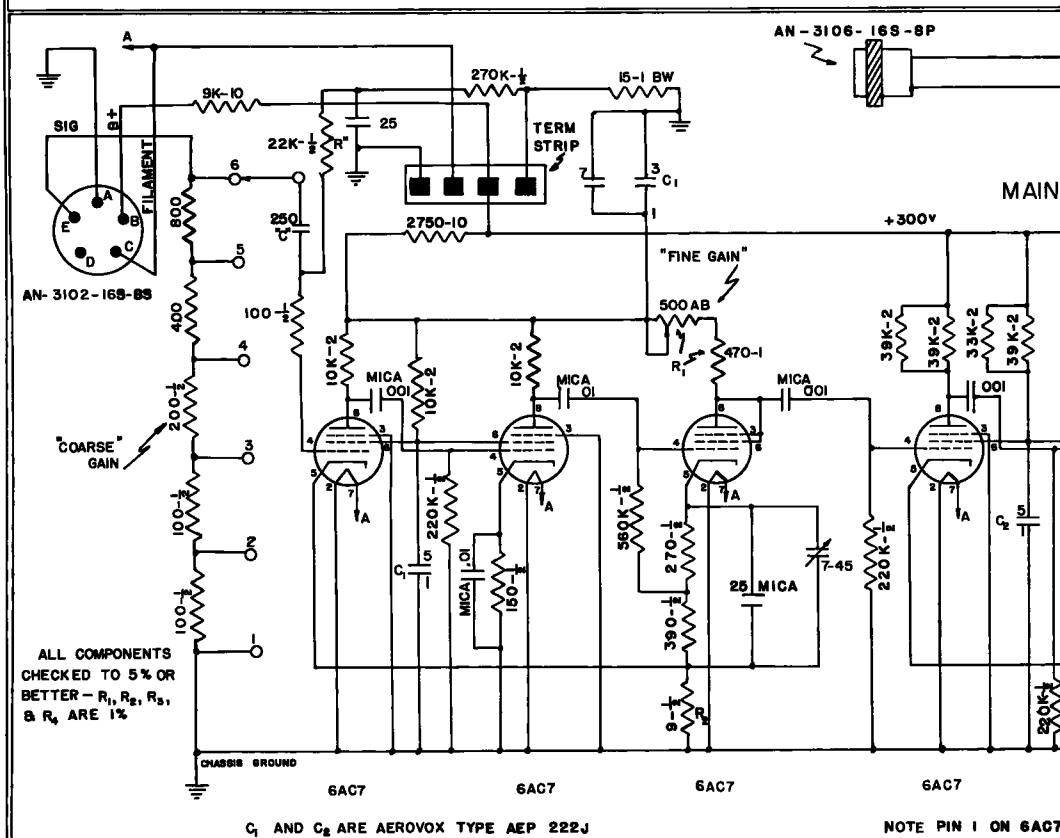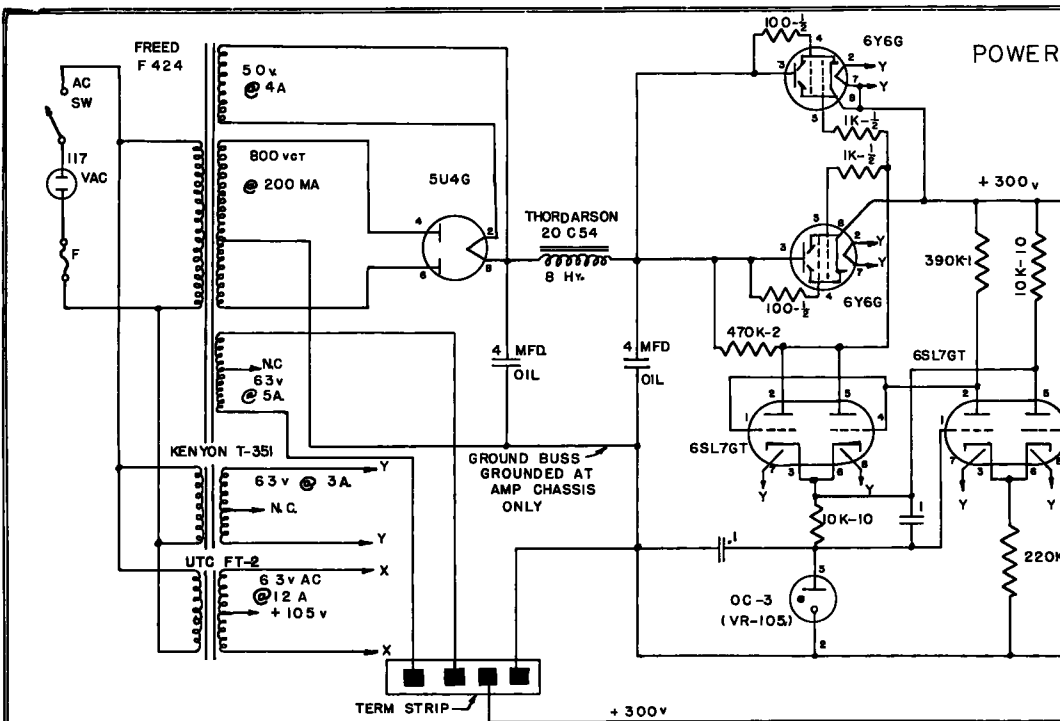
Figure 27. Laboratory meter set up for measuring

SUPPLY

PRE-AMPLIFIER

SIGNAL INPUT
83-1R

TUBES—ALL 6AK5's

+100v

10 MFD
450 V

150K-1   2.2M-1

10K-1   30K-1   10K-1

ERIE BUTTON   ERIE BUTTON

500   500

220

50K WW

VOLTAGE ADJ SDA

1M-1

4 MFD OIL

82K-1

75 MEG SS WHITE

1M-1   450   1M-1   500   400   4-30

1500   50

GROUND   B+

SIG   E   A   B   D   C

NC

AN-3102-16S-8P

FILAMENTS

IN "E" CONNECTED WITH RG-591U

PRE-AMP CABLE

SHIELDED JACKET

AN-3106-16S-8S

TO OBTAIN A GAIN OF 10,000 THE
RATIO $\frac{R_1}{R_2}$ = 106 ; $\frac{R_3}{R_4}$ = 105

AMPLIFIER

7.5K-10W   KOOLOHM

7   3   C₂

01 MICA   OUTPUT   83-1R

.01 MICA   5-1

4-20   10K-2   R₃

220   220

01 MICA   OUTPUT   83-1R

100-1   R₄

10K-2   10K-2

TIME	"R"	"C"
μ SEC.	OHMS	μμ F
10	20K	500
5	20K	250
2	20K	100
1	10K	100
.5	5K	100
.2	2K	100
1	2K	50

VALUES FOR "R" AND "C"
FOR CLIPPING TIMES

6AG7   6AC7   6AC7- 6AC7

AND PIN 3 ON 6AG7 GROUNDED

501 AMPLIFIER - PRE-AMP & P S

DATE 7-26-49

ELECTRONIC SHOP NO 1046

and counting signal pulses from various probes.

The calibration curve which was obtained by taking moisture content determinations at the same time the density determinations were made in cylinders as shown in Fig. 17. Exactly the same procedure was used for obtaining this calibration curve as described for obtaining the density curve, employing the aluminum cylinders and one type of sand only. The accuracy during calibration was $\pm$ 2. 1 percent as measured against "undisturbed" 3-in. diameter by 3-in. core samples. The accuracy obtained in the field with over a 1, 000 field measurements was $\pm$ 3 percent for the entire range on the average. In all cases the U. A. C. #522 B meter was used; this meter, chiefly because of its discriminator level instability, was the main limiting factor in the degree of accuracy with which moisture content could be determined. This instability, in its effect on the accuracy of results obtained from the moisture probe, was much less as compared to the serious degree of inaccuracy such instability caused on the density readings. This is because of the much smaller effect on the readings for the moisture probe for a certain shift in discrimination level as is evident from a comparison of the spectral detection curves of the moisture probe to the density probe.

The accuracy of the LiI(Eu) - RCA-6199 scintillation detection system was still unsatisfactory and it had the serious objection that an expensive RaDBe source was essential to be used in conjunction with it. Hofstadter (70), Draper (44), and Sun and Shoup (148) had used compressed multicrystalline B_2O_3 phosphors and Koski (94), Bube (31), Keepin (87) and Dooley (42) had tried several boron containing ZnS phosphors for the detection of slow neutrons; but none of these seemed to offer the promise of being better than the LiI(Eu) system when employed in the probe. However, in the latter half of 1956, Sun, Malmberg and Pecjak (149) produced a Boron Plastic-ZnS(Ag) crystal with a very high thermal neutron efficiency which was practically insensitive to γ radiation. It held potential superiority in several respects for the purposes at hand to be tried in the moisture probe, over all other slow neutron scintillation detectors, for reasons which have been reported previously. This crystal was tried out. The manner of making these crystals is given in the paper by the above named authors (149). The metal mold used to cast the crystal and the crystal itself is shown in Figures 23a and 23b. Very recently, Nuclear Enterprises, Canada, have begun to manufacture these crystals commercially.
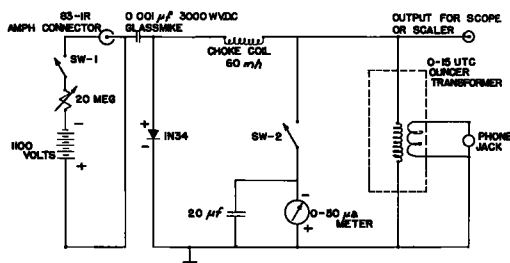

Figure 28. Modified circuit for scintillation counter used with RCA-6199 probes.

Fig. 24 shows the probe developed using the BP-ZnS(Ag) type of crystal. The only basic changes from the former is the replacing of the LiI(Eu) crystal with the $1\frac{7}{16}$-in. diameter x 1. 2 mm thick BP-ZnS(Ag) containing probe, and the geometry which had to be fixed more precisely, using the distance versus slow neutron density detected with the probe in a 10-in. diameter bucket of paraffin. The shape and size of the sample could not be changed appreciably owing to the more critical effect of distance on the slow neutrons detected. A RaBe source of as low an intensity as 3 mc could have been used. However, a 10 mc RaBe source was used because the actual efficiency of the probe could not be predicted before trial. A 5 mc RaBe source used in conjunction with this BP-ZnS(Ag) crystal in the same geometry as shown in Fig. 24 would give 50 percent more thermal neutrons detected than the probe using the 1-in. diameter by $\frac{1}{2}$ in. LiI(Eu) crystal with a 5 mc RaDBe source in the geometry of Fig. 20. In cost, the latter source is three times as expensive, at least, for an equivalent fast neutron output. Further, RaBe has a half-life of about 1, 620 years, as opposed to 22 years for RaDBe.

The BP-ZnS(Ag) phosphor is estimated to commercially cost approximately half the cost of LiI(Eu) phosphor for equivalent sensitivity.

The total spectral detection curve for the BP-ZnS(Ag) phosphor, RCA-6199 moisture probe is given in Fig. 25. This is broken down into these constituent curves: The dark noise and γ radiation detected versus discriminator level is given as one curve, whereas the counts due to thermal neutron and fast neutron detection versus discriminator level is given by the other curves. Because of the significant fast neutron detection, which cannot be fully excluded by raising the discriminator level, it should be noted that as high as 5 percent of the total count could be due to all unwanted pulses in dry soils, whereas in the paraffin standard the contribution by noise pulses was only 1.2 percent of the total count. The discriminator level should be set at any level along the plateau for the detection of slow neutron curve which is beyond the flex-point of the γ- and-background count curve.

A calibration curve for this probe has been made using the same procedure as for the G-M 2-in. diameter probe. Since only a few points have been obtained, this curve as shown in Fig. 26 is only tentative. It, however, serves to indicate the good response through a wide range of moisture content.

Appraisal of 2-in. Diameter Moisture Probes

The BP-ZnS(Ag) phosphor, RCA-6199 probe is a radical improvement over the probe using the LiI(Eu) phosphor. Because of its relatively flat plateau, discriminator drift barely affects the accuracy of the probe, it being capable of giving an over-all accuracy of each reading of $\pm$ 0.8 percent. This represents a potential accuracy of $\pm$ 0.5 percent of moisture content by volume, as compared to $\pm$ 3.0 percent actual accuracy for the LiI(Eu) probe, using the UAC-522 B portable meter. The sensitivity of the BP-ZnS(Ag) phosphor is more than three times that of the LiI(Eu) phosphor as used in their respective probes. In cost, the BP-ZnS(Ag) system is far less expensive. For equivalent sensitivity a probe containing a 1-in. diameter x 1 in. LiI(Eu) phosphor, RCA-6199, and a 5 mc RaDBe source would total approximately $550, whereas one containing a 3 mc RaBe source, BP-ZnS(Ag) phosphor, and a RCA-6199 would cost about half this amount. It should be noted that this latter probe alone is considerably less expensive than a BF_3 or B^{10} enriched BF^3 type system. Theoretically, the BP-ZnS(Ag) should yield the most nearly linear response of counts to increase of proton density per cm^3 (moisture content by volume), because the detection is in a very small volume of phosphor. The BP-ZnS(Ag) containing probe should also be capable of giving the most narrow depth resolution of samples.

The size of the sample resolved by the BP-ZnS(Ag), RCA-6199 probe has as yet not been determined. It is certain that it does not exceed a 10-in. diameter sphere of water, and that the depth is less than that resolved by the LiI(Eu) containing probe. The center of this sphere has not yet been determined accurately, but appears to be approximately 1 in. below the phosphor. A probe containing the BP-ZnS(Ag) has already been tried in the field yielding over 1,000 readings with trouble-free performance. The reliability of determinations obtained has not been calculated statistically as yet, because of the lack of a better calibration curve. However, from its comparative freedom from drift and the much greater reproducibility of its readings indicating a potential $\pm$ 0.5 percent accuracy, this is certain to be the most accurate one so far developed and proved here.

COUNTERS, METERS AND OTHER ELECTRONIC EQUIPMENT USED IN CONJUNCTION WITH PROBES

Jordon and Bell (82), Elmore and Sands(48), Gillespie (57), Lewis and Wells (104), Dow (43), Stone (147), Underwood, et al (158) and Bousquet (22) have given details, circuitry, and comparison of operation of several types of absolute counting and rate-meter instruments that could be modified for use with the scintillation probes at hand. Counters and associated electronic equipment used with each type of probe deserve the greatest attention, as they generally are the weakest links as far as accuracy and dependability are concerned, particularly when made small and self-contained for the

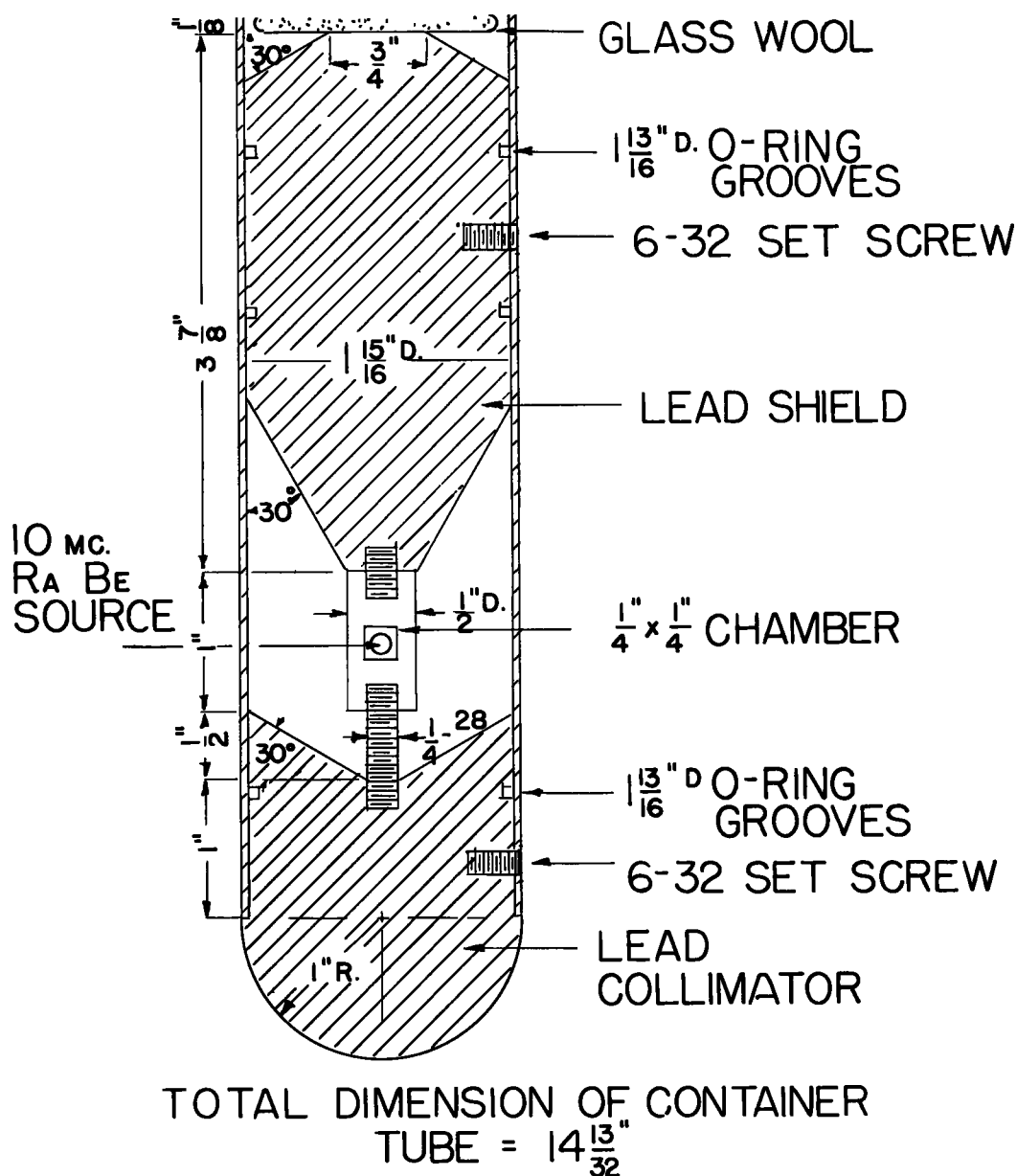Figure 29. Portable cold cathode glow transfer decade counter circuit.

Figure 30. Scintillation moisture-density probe bottom phosphor, for use with RCA-6199 photomultiplier tube, and LiI(Eu) phosphor, 2 in. in diameter.

sake of portability and in field usage. Work along this phase of developing adequate portable instrumentation for scintillation probes has been limited owing to the lack of time, funds and sufficient technical knowledge. It is certain that scintillation moisture and density probes will prove superior to other types if highly stable electronic circuits can be made into portable units. A brief review of the developments along this line follows, showing what difficulties were encountered in each of the electronic systems employed:

Laboratory Systems

Most of the equipment used in the laboratory was borrowed with the kind permission

of personnel authorizing such loans, from the Palmer Physical Laboratories and the Cosmic Ray Laboratory of Princeton University. Unfortunately, most of the borrowed equipment had been shelved for a long time, was in disrepair, and had various circuits modified without recording the modifications. It was a time consuming task to get into satisfactory operation a system such as shown in Fig. 27. We are indebted to the Electronics Shop of Palmer Physical Laboratories for the use of these circuits and for their equipment. Minor modifications were found necessary at the signal input end to accept the signals from the various types of probes while under test in development.

In operation, the preamplifier shown in Fig. 27 caused severe oscillation when used with the RCA-6199 probes. A two-tube (6AK5's) cathode follower with no gain was used instead, whenever work on spectral curves was involved, or whenever used for analyzing certain characteristics in a scope. The fast oscilloscope used was a Tectronix Model 511, with a 5-in. diameter tube. If the pulse was sufficiently large, and no special observations other than counts were to be made, the output of the probe was connected directly to the wide band high-gain main amplifier, with its gain setting set adequately high. Constant care had to be taken to avoid noise developing. It was found that dust constantly caused noise at switch terminals and connectors, and at times the only way to get rid of the noise was by replacing these parts.

Generally, the above equipment worked satisfactorily, but the gain factor of the preamplifier and amplifier varied significantly with a variation in line voltage. A line voltage regulator was found to be essential. The output from the amplifier was led to the input of a binary scaler with a scale of 64, which had a pulse-height discriminator. The discriminator level fluctuated significantly, and lacked adequate stability in use with most of the probes. Whenever our equipment was deemed inadequate, work was performed in the Palmer Physics Laboratories. The lack of drifts and fluctuations with the use of superior equipment soon established the components at fault. To demonstrate that highly stable electronic circuits are what is lacking, prolonged stability tests were performed with both the Physics Department equipment, and the laboratory system used chiefly in the investigations as described above. The average deviation from the mean for a series of replicated readings for the scintillation on type γ-ray densitometer probe was 3.2 percent and 0.9 percent for each one minute readings, for the laboratory system used here and for the system used in the Physics Department, respectively. The expected mean deviation owing to the random occurrence of radioactive disintegrations for the above experiment was 0.93 percent. This demonstrates that even the 2-in. diameter γ-ray density probe was inherently an excellent instrument if there was no limitation to the excellence of associated electronic equipment.

Portable Systems

However, the aim of these investigations was to develop adequate portable field instruments, which made it quite unfeasible to consider such elaborate lab. equipment for anything other than testing. Much work had been done previously with portable equipment suitable for detecting pulses from Geiger-Mueller and BF^3 tubes (151, 147, 158, 162). The much more stringent requirements for stability and handling very fast pulses with a wide continuous spread in amplitude in the case of scintillation detection systems makes it a very difficult task to produce adequately stable battery-operated electronic equipment which is truly portable. Stable circuits can best be obtained by the use of a greater number of vacuum tubes which makes the instruments larger, and also necessitates larger battery power supplies. However, the shrinkage of battery voltage upon prolonged use and with a decrease of temperature is sufficient to affect the operation of scintillation detection systems unless adequate circuitry is designed to take care of such voltage supply deficiencies. For the high voltage supply to the dynodes of a photomultiplier, even though the battery drain is negligible, the fluctuation of voltage with temperature variation encountered in the field is sufficient to affect the accuracy of readings. With these general remarks in mind, which applied to most of the instruments worked with here, further problems involved in each instrument will be discussed as each is considered.

Charge Multiplying Meter

Sherr (140) had developed a unique simple α -particle scintillation counter using no vacuum tubes, which was insensitive to γ radiation. Employing an RCA-931A photomultiplier tube and a ZnS(Ag) phosphor dusted onto it, Sherr obtained excellent results, the meter being adequate for strong sources. A similar instrument adapted to the RCA-6199 was made here, the circuit for which is given in Figure 28. Except for the 20 megohm potentiometer used to vary the high voltage supplied between the photocathode and anode of the 6199 tube, the components operated satisfactorily. The potentiometer was inadequately insulated for use with such high voltages, and it was not replaced by another because of the ease of varying the supply voltage by connecting the necessary number of batteries in series. There was distinct audible differentiation when the instrument was used with a 6-ft RG-59 U cable, the RCA-6199 tube with a H. V. supply of 1, 100 volts and a LiI(Eu) phosphor. In essence, the α -triton product nuclei in the $_3Li^6(n \alpha)_1H_3$ reaction gave distinct clicks, against the γ background which was a hiss. There was no noticeable change in this characteristic differentiation when the detection was of slow neutrons and γ radiation from RaDBe or RaBe sources. However, the meter movement using a 5 mc RaDBe in the LiI(Eu)-RCA-6199 probe in its paraffin standard was only up to 10 μ a (20 percent of scale in 50 μ a meter). Greater sensitivity by a factor of 5 or 10 times was called for so that a longer cable length could be used. The meter was laid by until either a more efficient nuclear detection system was obtained, or some simple electronic means could be found to increase the charge-multiplying gain factor from 12 to 60 or 100. Lack of opportunity has prevented the trying out of the BP-ZnS(Ag), RCA-6199 system on this meter. It is confidently felt that the use of the RCA 6810-A photomultiplier in conjunction with the BP-Zn(Ag) phosphor would give the desired gain to obtain full scale deflection. However, the dependability of the instrument in field use must be proved. This line of development is in our plans, as it is felt that not only would the cost of instrumentation be reduced very materially but, also, that there is greater likelihood for more accurate, stable, fool-proof, simple operation of such an instrument over the elaborate portable electronic instrumentation otherwise deemed essential in association with scintillation probes. In the projected future development, a 3-in. diameter moisture probe is planned, with a transistorized high voltage supply capable of regulation within 0. 05 percent and variable between 1, 800-2, 300 volts. The cost for parts for such an instrument would be under $100.

Portable Slow Neutron Flux Meter

A slow neutron ratemeter had been specifically designed by R. W. Swanson (151) by modifying a circuit given by Rohr, et al (129), to count slow neutrons detected by a B^{-10} coated proportional counter. Before proceeding further with the description of this instrument, it appears appropriate here to give a brief description of the general mode of operation of ratemeter or counter circuits used for handling pulses from radiation detectors.

Either a negative or positive pulse of a fairly even amplitude (as in G-M counters) or of variable amplitudes (as in scintillation detectors) is impressed across a load resistance through a blocking capacitor that prevents d. c. high voltage from appearing on the amplifier circuits. The signal pulse is generally lead to the control grid of a Class A₁ type amplifier tube which amplifies and usually inverts it so that the signal appears across the plate load resistor of the next Class A₁ amplifier stage where it is further amplified and reinverted. Depending on the amplification gain required the signal goes through as many similar stages of amplification to obtain this gain. In the circuit of the amplification stages, the amplitude range of the input pulse that is to be accepted is determined by components involved in the circuitry. For constant amplitude pulses only a narrow range is adequate, where for scintillation detection, if the entire spectral range of detection is desired, wide band linear amplification is essential. If a variable potentiometer with the right range in value is installed to control the grid bias of a certain stage of amplification, the width of the amplitude of pulses accepted can be affected by changing the threshold lower level of the pulses to be accepted by the circuit,

and in effect this becomes a simple pulse height discriminator.

In a ratemeter, the pulses coming from the last amplification stage are shaped so that irrespective of the amplitude of the input pulse to the first amplifier stage, a proper amplitude pulse is put out so as to "trigger" a multivibrator circuit. A resistor-capacitor coupling causes the multivibrator to oscillate at a specific rate which determines the time base of the multivibrator circuit. During one such period, the multivibrator remains in its unstable state thus averaging the charge accumulated within this period. If this charge is permitted to flow through a meter, the input pulse rate remaining constant, the longer the time base, the greater will be the average current flowing through the meter. Hence, for various scale ranges, a fixed resistance can be coupled by switching with a series of capacitors in steps of varying values (or vice versa), so that a steady signal input rate would yield varying meter needle deflections for each of the ranges. Meters also could be made to have several "time constants." The time constant of a meter is the period of time which it takes for the meter needle to deflect from 0 to half scale of the value of the current flowing through the meter. This feature of ratemeters is very useful as it makes possible the dampening of fluctuations of statistical variation inherent in the rate of radiation detected, so that more accurate readings could be obtained directly from the meter, as time permits.

The ratemeter made here, followed Swanson's basic circuit. It employed three stages of amplification using 1L4 tubes. It was modified to accept both positive and negative pulses by switching in a phase transformer when the input pulses were positive. The non-overload feature of the Swanson circuit was modified in an attempt to take in as wide a band of pulses as possible. The discriminator bias placed on the control grid of the second amplifier tube was modified to give a complete range of discrimination by using a precision vernier potentiometer so that γ -radiation and background could be obtained if wanted, and also all pulses below any desired level blocked out if necessary. The discriminated pulse was amplified further in the third amplification stage which is then fed to the multivibrator circuit which integrates the pulse on a time base selected by switching in a suitable value resistance (potentiometer) coupled with a capacitor on the range selection switch. There are four such pairs of "RC" couplings to give four scale ranges, potentiometers being used so that the time base could be slightly altered to give correct meter deflection from range to range. The single time constant employed in the meter is 12. 5 secs.

It was found that careful component lay-out plans were necessary to install parts in close proximity to others involved in a circuit, to prevent a high noise level. Each tube is electrostatically shielded. Further, the first two stages of amplification should have been shielded effectively from the rest of the circuitry, and Underwood, et al (158) recommended the amplifier-discriminator unit to be shielded by housing this stage in an inner chassis. Such care in shielding was not maintained in constructing the instrument used here, though it is felt that such care was warranted.

This meter worked adequately for handling the pulses from both the moisture and density probes employing the RCA-6199 directly. Of all the meters used here, this had the greatest stability giving identical readings every time for the same rate of radiation. Certain difficulties were encountered which still remain unsolved owing chiefly to a lack of time to work out the problems. First, it appears that the tampering with the non-everload circuitry did not yield the desired results, and was probably the cause of oscillation at high counting rates because of pile-up of pulses. The chief difficulty was that with the scintillation probes, the meter ranges scarcely operated. It was at first deduced that the long time bases used were to blame; therefore, smaller values of resistor-capacitor couplings in the range switch were tried out. Though the performance improved somewhat, the ranges still did not spread enough to the required extent. It appeared that the circuitry was inadequate to handle the pulses from scintillation systems. Lacking the technical knowledge and time to correct for these deficiencies, and the exigencies of other competing investigations to be performed, forced a temporary shelving of this meter. However, because of the excellent stability and over-all simplicity of this meter, it is planned to work out the difficulties of the circuits so as to satisfactorily measure the output from scintillation probes.

Cold Cathode Glow-Transfer Type Counter

Stone, et al (147) had developed an absolute counting portable, battery operated meter employing four GS10C cold cathode glow transfer tubes. The authors are greatly indebted to Mr. Stone for the generous help he has given in making available his circuits and modifications thereof. The first instrument that was made according to the circuit employing four GS10C tubes worked well, handling pulses from either the 2-in. diameter density or moisture probe directly without any amplification. The pulses are fed to the univibrator circuit of the first (units) stage, which consists of the first two sub-miniature CK-6088 tubes. Each pulse fed to the univibrator, triggers the electronic decade counter which is visibly indicated by the transfer of a "glow" to the next pin. Upon completing 10 counts, a pulse is transferred to the univibrator circuit of the "tens" stage, and so on, for the "hundreds" and "thousands" stages. In effect, this becomes an electronic absolute counter which replaces a mechanical counter that requires considerably more power for its operation and, of course, is not capable of registering such high counting rates. The limitation of the GS10C tube was its long dead time of 300 microseconds, it being capable of handling counting rates from 0 - 4,000 cps. The density probe using the NaI(Tl)-RCA-6199 system gave a higher count than this at low discriminator settings. Owing to the great potential value of a good portable, battery operated instrument, it was decided to modify this instrument by replacing the bulky batteries with a transistorized high voltage power supply, and to include a modified circuit that Stone had kindly made available through personal correspondence, which substituted a GC10D tube for the "units" stage GS10C tube. This "dekatron" tube has a dead time of only 50 microseconds and is capable of counting up to 20,000 cps.

The modified circuit employed is given in Fig. 29. The transistorized high voltage power supply operated satisfactorily, being highly stable. However, the counting meter ceased to operate properly. At first, excessive oscillation appeared across the signal input. By reassembling parts and employing shielding, the oscillation was reduced so that it could be discriminated against. However, this height of discrimination also cut out most of the γ counts from the NaI(Tl)-RCA-6199 probe. It appeared that the GC10D tube circuitry was at fault, or else the tube itself was not stable. After a few attempts at rectifying the difficulty, the meter had to be temporarily shelved in favor of exerting more effort on the development and testing of the probes. Two features of such absolute counting meters are potentially poor. The first is that readings must be taken in the field with a stopwatch. For a two-minute reading even a one second error in timing would give a 0.9 percent error in counts. The other is, since calibration of the probe has to be done constantly against a standard, great difficulty would be encountered if the standard was to be brought to a specific count rate each time by adjusting the discriminator control. It is desirable from the standpoint of greater accuracy to use a fixed count, rather than having a variable count for the standard, as will be pointed out later. However, if time is not the greatest priority, such a portable absolute counting meter is potentially capable of greater accuracy than a ratemeter having the same stability of the discriminator circuit contained in the absolute count meter. For a thorough comparison of counting rate meters and scalers the reader is referred to Bousquet (22).

Transistorized Model UAC-522 B Precision Ratemeter

The recent development of a very light, portable precision ratemeter for use with scintillation probes announced by the Universal Atomics Division of the Universal Transistor Products Corporation appeared to be the answer to our need by the way of a precision, portable, battery-operated, stable field instrument. With the general failure of our laboratory portable meters to operate as desired, this newly developed commercial meter was invested in as a dire necessity. This meter has been the only one in systematic use throughout field trials for all probes developed here up to date.

This meter consists of a 14-transistor circuit. There are several amplifier stages so that as low an input as 0.015 volts will give a meter response. The instrument also

has the following features which make it highly commendable:

(1) Six range scales covering 0 - 10, 000 cps.

(2) An internal pulse generator working at 1, 500 cps for on-the-spot calibration.

(3) It has either 110 volts 60 cps AC line operation, or battery operation. Power for battery operation is supplied by six $1\frac{1}{2}$-volt nickel-cadmium cells that are capable of operating the instrument for 50 hours without recharging. These cells are recharge-able 200 times, and hence are capable of operating for 10, 000 hours. Also, a $22\frac{1}{2}$-volt battery, and a mercury primary cell are used.

(4) It has four time constants—1 sec, 5 sec, 20 sec and 120 sec—which permit both rapid meter response to counting rate and very steady needle response for greater accuracy of readings.

(5) It weighs only $10\frac{1}{2}$ lb.

The features that were found somewhat lacking were:

(1) The accuracy was $\pm$ 2 percent of full scale on all ranges but this dropped off considerably, being $\pm$ 4 percent at about 60 percent of full range around which most readings were obtained. A larger dial meter should overcome this defect considerably.

(2) The transistorized regulated high voltage power supply capable of continuous variation from 700 volts to 1, 300 volts, although of compact size and novel circuitry, lacked somewhat in stability. In the field, not only was it found that the high voltage dropped steadily, though only slightly, on constant operation but, also, there were at times small fluctuations. The reported drift of $\pm$ 0. 1 percent in any 8-hour period during operation on batteries was either exceeded, or was sufficient to materially af-fect the accuracy of the instrument.

(3) The discriminator circuit was found to be too unstable for the purposes employed here. In spite of a precision vernier potentiometer installed later, the variability of the discriminator level on the field was found to be the chief cause of inaccurate read-ings. This was particularly true when temperature variation during the day was con-siderable, and when the air temperature rose above 85 deg F. Perhaps the replace-ment of germanium transistors by silicon transistors on this circuit would adequately take care of the problem.

The meter operated satisfactorily in general, except for the foregoing defects. At times, however, for no apparent reason, the meter would fluctuate excessively. Also, on occasion, the switching from one scale to another would render as high as 20 per-cent error in reading a constant counting rate on one scale as compared to the other. An improved instrument of this type, which satisfactorily overcomes the above men-tioned difficulties, appears to be just the instrument required for use in conjunction with scintillation moisture and density probes in the field.

Scope of Future Development of Instrumentation

From the foregoing, it is clear that the electronic-transistor industry is quite capable of developing instruments commercially which could satisfy the stringent re-quirements for use of scintillation probes in conjunction with highly stable portable, precision ratemeters. It is merely a matter of demand to justify the expense of fur-ther development. The cost of an adequately stable transistorized precision ratemeter such as an improved UAC 522 B in the respects indicated should not be over $850. If such a meter were developed and if it were capable of giving consistently dependable, accurate results, its versatility would render it the most desirable meter for use with either scintillation, BF_3 or Geiger-Mueller counters.

However, there is a great deal to be said in favor of simple instruments which can operate without the use of transistors and electronic tubes. With the recent develop-ment of the RCA-6810 photomultiplier (see Table 3), it is possible to obtain such a high gain of linear amplification by the tube itself ($12. 5 \times 10^6$) that it obviates the neces-sity of complex wide band fast pulse linear amplifier circuits. It appears feasible to eliminate electron tube circuits altogether, if such a circuit as shown in Fig. 28 could be modified to function satisfactorily with the RCA-6810. Not only would this reduce the cost of instrumentation very materially, but it should be capable of rendering more de-

pendable, accurate and stable results. Research along these lines is at present underway. The greater sensitivity of the 6,810 tube should enable the use of smaller intensity sources, further reducing the cost of instrumentation, and potential radiation hazard.

The most apparent need for increasing the versatility of these probes so that they are capable of probing to any desired depth is for a preamplifier to be constructed within the probe itself. This would also add to the accuracy and dependability of results obtained. The probes using the 6199 operate satisfactorily to probe depths up to 10 ft using 12-ft RG-59 U cable lengths. Upon further increase in length the pulses are attenuated so that increasingly fewer counts cause a registry on the ratemeter. By raising the high voltage supply to the limit for the photomultiplier tube and reducing the discriminator level to block out only unwanted pulses, it is possible to use up to 20 ft. of cable length with the probes developed here, employing the simple circuit with the 6199 photomultiplier tubes. However, the accuracy of the system becomes poorer, and the system becomes considerably more temperamental.

What is required is a preamplifier-cathode follower for each probe. With the use of electron tubes, it would become necessary to thermally isolate the preamplifier from the rest of the probe as heat flow by conduction is otherwise likely to affect the thermionic emission rate of the photomultiplier tube. It is possible to fit a battery supply in a 2-in. diameter or larger probe, but not in a 1 in. diameter one, so as to simplify wiring, if electronic tubes are used. A two-tube circuit should be adequate, but even for two sub-miniature tubes, the battery drain for heater and plate supplies would be as much as 5 watts.

Transistors offer the best means for use in preamplifier-cathode follower circuits for scintillation probes as small as 1 in. in diameter. The best arrangement would be to house all the circuit components and battery supplies along with the voltage divider in a longer length of tube, in "bullet-type" construction. For a 2- or 3-in. diameter probe it may be possible to use a transistorized high voltage supply within the probe itself, operated from a single D-type cell, and so further simplify the wiring. If the scintillation system probes are to operate more satisfactorily, and at greater depths, the development of suitable preamplifier-cathode follower circuits is a prime necessity, and hence deserves priority in attention.

Future Development of Probes

The direction of future research is towards the making of the following instruments:

(a) Moisture density scintillation probes equipped with preamplifier-cathode followers that are 1 in. in diameter. The moisture probe will employ the Boron Plastic-ZnS(Ag) type crystal.

(b) A moisture-density probe using a 10 mc RaBe source, RCA-6199 and a LiI(Eu) crystal with a source to crystal distance of approximately 14 cm. In theory, there is little reason why such a probe should not function adequately to give accurate moisture and density determinations. Such a probe has already been constructed here as in Fig. 30. A highly stable electronic system must, however, be used in conjunction with such a probe if accurate readings are to be obtained. No practical work has so far been done in testing the feasibility of this probe.

(c) An attenuating geometry densitometer using Co^{60} as a source and one of the photomultipliers with its end facing the source, to make laboratory determinations of wet density of core samples, blocks, cubes and for special studies where strict localization of the volume measured is imperative.

(d) A fast neutron attenuating hygrometer utilizing in end-to-end geometry a fast neutron source and a suitable photomultiplier across a specific "cell-depth" in which the sample of uniform dimensions is placed. The phosphor to be used for such a probe should be such as Hornyak (77) and Harding (63) have employed using ZnS(Ag), or a plastic scintillator such as Harris (64) has described for fast neutron detection.

Probes such as described in (c) and (d) should predictably become regular laboratory equipment for routine soils and materials testing in a few years. The research scientists, such nuclear probes would make possible non-destructive measurements of water movements under various types of potentials, and the continuous measurement of density

by non-destructive means, to enable certain types of investigations which had hitherto been beyond the realm of possibility.

Procedure for Obtaining In Situ Measurements of Soil Density and Moisture Content

It must be recognized that notwithstanding the potential accuracy of instruments used in any measurement, the manner in which such measurements are performed eventually determines the actual accuracy obtained with the method employed. The importance of using the best procedures to obtain accurate results with the scintillation and other probes cannot be overemphasized.

During extensive job use of the instruments, mainly underneath city streets, much was learned with respect to the type of drilling operations necessary to prepare the hole to receive the access tube into which the probes were inserted while taking readings. Certain recommendations are therefore specified in Appendix 1 that should be adhered to if significant inaccuracies arising from improperly made holds are to be avoided. Specifications are given for the making of holes to accept the $2\frac{3}{16}$-in. outside diameter access tube used for the reception of 2-in. diameter probes.

Besides making holes correctly in the field, it is imperative that readings be taken carefully and in a certain manner dependent chiefly on the nature of the meters being used. Standards that double as shields should always be set off the ground on a stool during calibration. It must be remembered that no electronic precision equipment can be expected to remain stable until it has been "warmed up" for over an hour before any readings are taken. Portable, battery-powered equipment needs constant battery checking and replacing if not up to par. Because of expected drift, calibration against the standard must be resorted to preferably at constant intervals of time, and readings must be taken in a specific manner to enable easy calculation in order to eliminate the error in counts due to drift and to obtain the greatest statistical accuracy of each reading in the time available. Hence, a step-by-step procedure is outlined in Appendix 2, to act as a guide in obtaining accurate readings in the shortest possible time, with the meters and probes at hand.

The manner of calculating results particularly in systems which tend to drift considerably during use, is very important if error introduced due to drift is to be kept at a minimum. Unless a system is very stable so that a constant value can be obtained in counts for each standard of each method of measurement, it is not recommended that calibration curves using counts versus density or moisture content be drawn. It is essential that the ratio of counts for the measurement to counts for the standard be obtained for each type of determination (moisture or density) and that this ratio is plotted against moisture content or wet density. Further, if the signal to noise ratio changes considerably in the range of drift encountered, it is important that another manner of calculating the sample to standard ratio of counts becomes necessary. To clarify the significance of correct procedures in calculating actual dry density and moisture contents from the readings obtained using the nuclear probes on the field, an actual datasheet from the routine data obtained on the job, and various methods of calculation with their expected accuracies, are given in Appendix 3.

SUMMARY AND CONCLUSIONS

The development of nuclear techniques for soil densitometry and hygrometry has been traced historically and the scientific principles underlying these techniques have been presented. The potential advantages of scintillation detection have been pointed out and the principles on which such detection is based have been discussed in detail together with the functioning and characteristics of the components of scintillation detection systems.

The actual construction and performance of nuclear moisture and density probes developed in this work have been reported. The evaluation of each probe system is summarized below:

(1) 1-in. diameter, National Radiac probes using a Du Mont K-1303 tube with interchangeable crystals ($\frac{5}{8}$ in. diameter x 1 in. NaI(Tl), and $\frac{5}{8}$ in. x 1 in. LiI(Eu)). The

output from the preamplifier had to be highly amplified (x 1000) in order to operate a 1-volt input laboratory scaler. The two-tube preamplifier located in the scintillation probe caused excessive thermionic emission from the K-1303 photomultiplier because of the heat dissipated at the plates and heaters of the electron tubes and conducted to the photomultiplier. The supply voltages not only to the photomultiplier but also to the preamplifier had to be highly regulated in order to obtain any reasonable readings. The heating-up problem, the need for a high degree of regulation of voltage supplies and the need for a high factor of amplification were some of the important reasons for rejecting the probes using the K-1303 tube from further testing.

(2) 1-in. diameter probes utilizing the ten-stage $\frac{3}{4}$ in. diameter K-1382 photomultiplier were constructed. The density probe had more than adequate sensitivity using a $\frac{5}{8}$ in. diameter x 1 in. NaI(T1) phosphor with a 1 mc nominal Co^{60} source. A calibration curve was obtained for the density probe using laboratory instrumentation because of the necessity of a high gain amplifier to obtain counts. The curve tended to flatten out at low densities and was markedly flattened out at densities beyond 2.1 g/cm^3. A moisture probe using a $\frac{5}{8}$ in. diameter x 1 in. LiI(Eu) phosphor with a 5 mc RaDBe source did not operate satisfactorily because of serious signal differentiation. The LiI(Eu) crystal was internally defective in appearance and did not fit properly onto the photomultiplier. The sensitivity of the system was very low, and the noise level too high. Because of the need for a very high gain factor of amplification to be used to obtain counts, the poor sensitivity and high noise level, no further work was performed with this probe. The 1 in. diameter probes employing the K-1382 were confined to laboratory use because of the lack of an adequate preamplifier-cathode follower circuit designed for them. Further work on these probes was temporarily suspended.

(3) 2-in. diameter probes using RCA-6199 photomultipliers were next developed. These photomultipliers were tried with a stabilized voltage divider circuit which operated as desired, as well as with a simple nonconventional voltage divider which conveyed the signal pulse on the same wire as the positive high voltage supply. The latter simple voltage divider system was found to be much more convenient, and hence was used throughout field trials. After each probe was tested for its characteristics with respect to spectral detection, signal to noise ratio, sensitivity and over-all stability with the laboratory equipment, it was invariably calibrated and used on the field employing the Universal Atomics Corporation 522B transistorized precision ratemeter. Hence, all reported results on the following probes were obtained using this equipment for calibration and for field determinations. Three 2-in. diameter density probes were developed, and two of these were thoroughly proved on the field. Two moisture determining probes 2 in. in diameter were also made. The evaluation of each of these probes follow:

(a) The 2-in. diameter density probe using 1.2 mc Co^{60}, a NaI(T1) phosphor and an RCA-6199, with a source to phosphor distance of 7 in. was first made. The design was specially adapted to the purpose of obtaining as large as possible a soil volume sampled for each determination, and for greater accuracy at low densities. The counts response to increase in density flattened out considerably at high densities beyond 2.0, though actual calibration points could not be obtained for the range of density above 2.4. In the laboratory, using highly stabilized electronic circuitry, the probe was capable of yielding an accuracy of density readings in the linear part of the curve of ± 1.2 percent. However, in the field, using the UAC 522 B meter which had considerable drift in its discriminator circuit, the actual accuracy of the density determinations was in the order of ± 4.3 percent on the average, being as high as ± 8 percent at a wet density of 2.8. The sensitivity of the scintillation system was about 25 times as great as that for the probe using the Geiger-Mueller detector.

(b) A density probe using the same components as the one above, but with a source to detector distance of only $5\frac{3}{4}$ in. was next constructed. This probe has only been tested incompletely, but preliminary results indicate a much more linear response of counts to density change. While the average accuracy of this probe cannot be expected to be much better than that for the longer one, if used with the same meters, it will be more uniform throughout the density range. If a highly stable portable precision meter

is used, this latter probe should be capable of rendering density readings with an accuracy approaching 1 percent. It is evident that the use of these scintillation probes impose severe requirements upon the associated electronic equipment, for it is the accuracy of the latter that limits the over-all accuracy of the system.

(c) The 1 in. diameter Geiger-Mueller density probe was adapted to one of 2 in. in diameter; a distance of $5\frac{3}{4}$ in. was between the end of the tube and the 1 mc nominal intensity source. This density probe gave good linear response to density change from 1.0 to 3.0 gms/cm^3 in a preliminary calibration, with an expected accuracy of $\pm$ 1.5 percent. Although more than 1,000 field determinations have been made, the actual accuracy in field use cannot be calculated until a good calibration curve is made. The advantage of this probe over the scintillation density probe is that a simple precision meter is more than adequate to obtain as accurate a reading that the probe will permit. Though lacking in sensitivity, the Geiger-Mueller system is really no handicap because an inexpensive 1 mc Co^{60} source is adequate for all practical purposes. It must here be mentioned that for undetermined causes the sensitivity of the system sometimes fluctuated as much as 25 percent in the field, while used over prolonged periods. Temperature and perhaps humidity appeared to have considerable effect on the sensitivity of the Geiger-Mueller tube.

(d) The 2-in. diameter moisture probe using a 5 mc RaDBe source, an RCA-6199 tube and a LiI(Eu) phosphor - this probe gave an accuracy of $\pm$ 3 percent over extensive field measurements where actual moisture content samples were determined by other means also. The apparent inaccuracy of the determinations was due at least as much to the inaccuracy of the other means of moisture measurement against which the nuclear method was evaluated. Owing chiefly to the characteristics of the RCA-6199-LiI(Eu) detector, it is necessary to use highly stable electronic instruments in conjunction with this probe. With good stable meters this probe should be capable of giving moisture contents with about 1 percent accuracy. However, it lacks sensitivity so that the statistical error in counts becomes considerable at low moisture contents. A 1 in. diameter by 1 in. LiI(Eu) crystal should replace the 1 in. diameter x $\frac{1}{2}$ in. phosphor which was used in the tests. With the use of LiI(Eu), a great disadvantage in terms of cost is the necessity of a RaDBe source and also of highly stable electronic meters.

(e) A 2-in. diameter probe using a 10 mc RaBe source, a RCA-6199 photomultiplier, and a $1\frac{7}{16}$-in. diameter by 1.2 mm thick BP-ZnS (Ag) phosphor proved to be a highly significant improvement over any moisture probes known to have been developed so far by anyone. Because of its characteristics of detection, this probe employing the BP-ZnS(Ag) phosphor can be used with a meter having only moderately stringent requirements for stability of electronic circuitry. A potential accuracy of the probe based on the range of counts corresponding to a range of moisture content and the reading accuracy of the UAC-522 B meter is in the order of $\pm$ 0.5 percent of moisture content as an average for the entire range coverage of 0 to 100 percent water by volume. The sensitivity of this probe was three times as great as that using the LiI(Eu) phosphor; in cost, it should be just about half as expensive if used with a 5 mc RaBe source. Further, the cost of electronic meters used in conjunction with this probe would also be considerably less.

As far as ruggedness and dependability of the scintillation type probes are concerned, they have proved themselves very satisfactory in extensive use under rugged field conditions. In fact, what is most susceptible to changes under atmospheric conditions, jolting, dust and water, is the electronic equipment used with these probes. All the probes using scintillation detection are capable of giving more accurate results if used with highly stable precision meters. The 2-in. diameter scintillation probes can be used to probe any depth to which a sealed end $2\frac{3}{16}$-in. outside diameter x $\frac{1}{16}$ in. wall thickness access tube can be installed. In fact, it is possible to completely seal the probe against water and air and to take readings in unprotected holes, but this is risky not only because of the possibility of leaks, but because of overburden accumulating on top of the probe which may even cause the total loss of the probe by preventing its extraction.

The need for a cathode follower-preamplifier is indicated for probing to depths beyond 15 ft. The importance of the limitation of accuracy imposed by inadequately stable

and precise electronic instrumentation has been pointed out. Other sources that lead to inaccuracy, such as the manner of preparing holes to receive the probes, the manner of taking readings and calibrating, and the manner of obtaining results by calculation have been indicated, and instructions have been given so as to prevent such causes of error entering into the determinations made. An over-all evaluation of scintillation detection as used in nuclear probes for the measurement of the moisture content and density of soils and similar porous granular systems has been indicated, so that it may be compared with other radiation detection systems that have so far been almost exclusively for these purposes.

ACKNOWLEDGMENTS

Appendix A

SPECIFICATIONS FOR THE PREPARATION OF HOLES MADE IN SOIL TO RECEIVE 2-INCH DIAMETER PROBES

Equipment

Minimum requirements for the drilling equipment on the job are as follows:

If only soil of various types, not containing too many stones, rock layers or bedrock is to be tested for moisture and density, and if power equipment is not available, a complete hand operated soil sampling kit is recommended. Such a kit should have at least the following tools: a $2\frac{1}{4}$ inch diameter twist auger, a $2\frac{1}{4}$ inch spiral auger, a $2\frac{1}{4}$ inch O. D. $\pm\frac{1}{8}$ inch core barrel, and rod extension capable of augering or boring 6 inches beyond the greatest depth at which measurements are to be taken. Two Stillson wrenches, a sledge hammer, a rod puller and interchangeable open, saw-tooth shoes, and basket shoes are necessary accessories.

To handle any type of soil, where rock layers, scattered boulders or stones, and bedrock has to be penetrated, it is essential to use motorized equipment for which specifications are given below:

(i) A motor-driven drilling rig possessing preferably an infinitely variable hydraulic feed;

(ii) A motor-driven cathead winch capable of operating a 350-lb. drop hammer. Together with this a derrick or a hydraulic hoist with a sheave wheel at the top of the mast

is required for working the hammer and extracting the driving rods from the ground. It should have a capacity of at least 1,000 lb.

(iii) A power-driven pump capable of pumping clean water (for the coring of rock and concrete) and aquagel dispersions (necessary for driving in soil where no casing is used). The pump must also be usable for jetting and pumping water from the bore hole.

(iv) Accessory equipment such as various driving and coring rods and tubes, coring bits, driving caps, adaptors and fittings, rope, auger flights, water hose, Stillson wrenches, hammers, shovels, hacksaw blades, crayon, etc.

(v) Special equipment required for the different conditions that are described further on.

Drilling Procedures

1. Rock or Similar Solid Material

(a) Solid Rock or pavement from the surface down.

The access hole should be made with the coring equipment using water to cool the coring bit and wash away the fines. The runoff water should be diverted to a distance at least 8 to 10 ft. from the hole in order to prevent excessive seepage into the test location. The coring bit should be such that it provides a hole $2\frac{3}{16}$ to $2\frac{7}{8}$ inches in diameter. After completion of the hole the water in the hole should be pumped out or taken out by some other means.

(b) When drilling through pavements or layered surface rocks, drilling should be stopped about 1 in. from the bottom of the rock bed or pavement. The hole should then be pumped and mopped dry. The last in. or so of rock or pavement should be punched through or cored dry using low speed rotation to prevent excessive heating of the cutting edges. The boring of the soil underneath the hard surface rock or pavement should then proceed in accordance with the applicable section of soft soil boring.

(c) Rock at some depth beneath the ground surface.

The drilling through the overlying material should proceed according to the applicable section below, until the surface of the rock is encountered. The walls of the hole in the soil should be made impermeable to water by circulating a heavy suspension of aquagel for some time throughout the depth of the hole. After this precaution the coring of the rock should proceed as described for rock on ground surface under section 1 (a) or 1 (b).

(d) Boulders and Stones in the Soil:

Soft boulders and stones are rocks or gravel material that can be penetrated by soil boring equipment without any noticeable deformation of the driving shoe. Hard boulders and stones are rocks or gravel material which do not fall in the above class.

Large stones with lateral dimensions greater than 4 in. are referred to as boulders.

Small rocks less than 4 in. in lateral dimensions are referred to as stones or gravel if the dimensions are between 0.2 and 2 cm.

(i) Soft boulders and stones are treated like soil and should be bored as specified below under soils.

(ii) Large hard boulders should be bored as specified under 1 (c) (rock at some depth beneath the ground surface).

(iii) Small hard stones, gravel or hard rocky material. If possible, boring in all material containing boulders and especially small hard stones should be avoided because the boulders or stones are apt to deflect the drilling rods from its straight path, resulting in a poor hole. If avoiding these materials is unfeasible, the following procedure should be followed. The hole should be driven past the obstruction by means of a $2\frac{7}{8}$ in. diameter penetration cone made of hardened steel. After passing the boulder or stone the normal boring procedure should be resumed.

In case of slumping of gravel or pebbles into the hole, the $2\frac{3}{16}$ in. O.D. access tube should be driven in along with the penetration cone tip, in order to prevent the falling in of coarse gravel or stones from the sides to the bottom of the hole as the drilling proceeds.

(e) Rubble fill or other material of similar nature should be treated as boulders in the soil.

2. Soil and Similar Material

For the present purpose soil is defined as any type of material the effective grain sizes of which are less than 2 mm in diameter.

(a) Cohesive soils—any soil material that will maintain an unlined $2\frac{7}{8}$ in. diameter hole without closing in for at least an hour. This includes partially saturated sands and silts, clayey sands, clayey silts, dry clays, stiff moist and saturated clays or any combination thereof in a state which conforms to the requirement set in the previous sentence.

The access hole should be made in such soil by either pushing (hydraulically) or hammering into the ground (with 350 lb hammer dropping 12 inches) an open end ($2\frac{7}{8}$ in. outside diameter $\frac{7}{16}$ in. wall thickness) flush coupled drive pipe 5 ft long. This tube may be obtained by cutting the female thread off from one end of an N-size drive pipe and bevelling the wall to a 45 deg bevel. After each 2 ft penetration the tube should be withdrawn from the soil and the recovered spoil cleaned out before the next 2 ft is driven. After the desired depth has been reached the driving tube should be withdrawn and the $2\frac{3}{16}$ in. outside diameter $\frac{7}{16}$ in. wall thickness, closed-end access tube, drawn in Figure 16, be installed immediately. No water should be used at any time during this operation.

(b) Non-cohesive Soils—any soil material that will slump into the hole upon extraction of the driving tube specified under (a). Such material embraces loose, dry, or saturated sands or silts without any clay as a binder.

(i) An open-ended access tube should be driven into the soil together with a driving tube which fits inside the access pipe. The driving tube should be 2 in. in diameter by $\frac{3}{16}$ in. wall thickness and about 5 ft long with an internal 30 deg bevel at the cutting end. An E-size drive pipe with the female thread cut off at one end and provided with an internal bevel may be used. The inside driving tube should be driven first, 2 ft or less at a time. The access tube should then be driven (or pushed) around the driving tube to the same depth or, if the driving of the access tube is too difficult, then the driving tube should be withdrawn while the outer access tube is being pushed down.

(ii) In cases where it is impossible to extract any soil by means of the inner driving tube, the access tube should be driven open ended and the material inside this tube washed out by means of an aquagel suspension. Finger bits may be used but the bottom of the access tube should never be less than 6 in. below the soil elevation inside the tube where it is being washed out.

(iii) Under saturated conditions where the material tends to flow into the tube from the bottom the same procedure as described under (ii) should be followed.

When the required depth has been reached the bottom of the access tube should be sealed off and all water (if any) inside the tube should be taken out.

(c) Very soft clays, muds, peat, muck and related materials. This condition will be encountered when a clay soil exceeds its liquid limit and seems to behave more like a liquid or where a great percentage of the soil is organic material derived from plants, etc. in various stages of decomposition.

The $2\frac{3}{16}$ in. O. D. access tube should be provided with a welded penetration cone tip as shown in Fig. 16 and should be pushed (hydraulically) into the soil by means of a 2-in. diameter rod fitting into the tube and pushing the penetration cone end.

(d) In unusually hard soil (clay pan, hard pan, etc.) or where the depth of the hole is such that soil friction around the periphery of the $2\frac{7}{8}$ in. driving tube becomes excessive and limits its effectiveness, washboring with finger bits or fish-tail bits may be used without a casing. The equipment used should be such as to provide a $2\frac{3}{16}$ to $2\frac{7}{8}$ in. diameter hole and the boring fluid must be a thick suspension of aquagel to minimize the effects of change in moisture content of the surrounding soil.

Suggested Procedure to be Followed in Borings

A (1) If rock is encountered on the surface, it must be decided whether the rock is layered or continuous throughout the depth. With concrete pavements or other paving this is easily recognized. With layered rock the method employed should be that specified under 1 (b).

(2) If there is uncertainty about the extent of the rock it may be bored as solid rock throughout the depth specified under 1 (a). If the rock is found to be layered a new hole location should be selected close to the previous one and the borings should proceed as given in 1 (b).

(3) If a hard rock is encountered at some depth below the surface of the soil, a general knowledge of the area in which the hole is situated may give an indication whether or not solid rock may be expected at the depth to be probed. In case of boulders the response of the driving rod to driving (number of blows vs. penetration) and examination of the cutting edge of the driving tube will disclose whether the boulder is small or large. After the nature of the obstacle is determined the driving should proceed according to the applicable specification.

(4) If it is established that the resistance to driving is caused by stones the penetration cone should be driven. If the material slumps into the hole after extraction of the driving cone the access tube with the penetration cone end should be used.

B (1) In soils the driving usually will start out according to specification 2 (a) except where conditions at the surface point out clearly the unfeasibility of this operation – that is, where dry loose sand or silt, saturated loose sand or silt, very wet and fluid clay or soft peat is encountered on the ground surface.

Notice should be taken of the amount of material extracted from the driving tube using the method as specified in 2 (a) and also of the nature of the material and its position in the tube, i. e., whether the tube is filled right up to the cutting edge or not. The number of blows per 6 or 12-inch penetration will indicate the resistance to driving and can be correlated to the nature of the material found at that depth in the driving tube.

(2) If more material is taken out of the driving tube than the distance penetrated, sloughing of the walls of the hole is indicated and procedures as specified under section 2 (b) (i) should be followed. When it is impossible to extract any material by means of the driving tube driven according to specifications 2 (a) or 2 (b) (i), then the driving should be by using the wash boring method as set forth in specification 2 (b) (ii).

(3) Very little resistance to penetration, immediate closing up of the hole when the driving tube is withdrawn and varying amounts of material recovery in the driving tube indicate the material for which the driving procedure is specified under section 2 (c). The access tube should be installed following this method.

(4) If the resistance to penetration is excessive (greater than for well compacted sand near the surface of the ground) and the material recovered by the driving tube still indicates that no rock or boulders have been encountered, then the procedure set forth under specification 2 (d) should be adopted for installing the access tube.

Whether boring through rock or soil, upon striking particularly obstinate obstructions such as hard boulders that tend to bend the drive pipe or are quite unyielding, the most practical and time saving measure is generally to move a few feet away, and core a new hole, using the information gathered from the last hole to attempt to forestall complications such as pebbles dropping to the bottom of the hole being bored.

Boring Log. The boring log should contain the following information:
1. Number and location of the hole.
2. General information such as: date, time of starting the drilling of the hole, the weather, a short description of the site where the hole is located (general topography; whether it is in a paved area, woodland, grassland or cultivated land, etc.), the state of the ground surface whether rock, pavement, sod, dry clear ground, marshy or peat.
3. The actual depth from the surface at which each sample is judged to have been extracted, and the depths at which marked changes in the nature of the profile are encountered. Also the depth of the water table if any.
4. The number of blows (if driven by hammer) per foot of penetration.
5. The amount of recovery in the driving tube.

| Excessive - - - | more material in driving tube than would normally be found for a 2-foot penetration indicating slumping in of the walls, or the inclusion of spoil unrecovered by the previous sample. |
| Full - - - | if it is the total normal recovery of a 2-foot penetration. Driving tube filled up to the cutting edge. |

Partial or None - - - less material than would normally be found for 2 foot pene-
tration. The driving tube empty or just partially filled,
in which case the amount filled should be specified in inches.

6. The nature of the material at every foot of depth of the hole. Textural classifi-
cation such as sand, silt, clay, silty sand, clayey silt, peat, etc., its color if distinc-
tive; structural classification given as loose, dense, very dense, hard, soft, very soft.

7. Remarks. This column must contain the method used for making the hole and at
which depth the procedure was changed when necessary. Also the condition of the driv-
ing tube edge must be stated if it has been deformed. The response of the driving
tube to driving should be noted if it deviates from the normal. Any additional informa-
tion relevant to the boring of the hole at the specified depth should be given such as
the moisture conditions of the soil – (dry, moist, wet, saturated).

Appendix B

PROCEDURE FOR TAKING READINGS IN THE FIELD FOR MEASUREMENTS
AND FOR CALIBRATION

(i) Turn on the power supply switches for all equipment employing electronic tubes
or transistors in their circuitry, and keep the instrument in stand-by operation con-
dition for at least one hour before readings are to be taken. Always keep electronic
instruments and the nuclear probes as sheltered as possible from direct sun, strong
winds, rain and dust.

(ii) "Zero" the instrument. Check all the batteries, replacing any that are out of
condition.

(iii) If the instrument is equipped with an internal calibrator, calibrate the meter
precisely.

(iv) Set the high voltage at the approximate optimum operating voltage for the probe
to be used.

(v) Connect the cable from the probe to the input connector of the meter, being
careful not to touch the chassis while making this connection, if there is no high volt-
age switch that can be turned off.

(vi) Insert the probe in the standard which should preferably always remain in its
shield-standard when not taking field measurements. It is essential that the probe in
its standard is placed on a stool at least two feet off the ground, and at a distance
greater than the safe distance to the nearest personnel attending the meter. Make
certain that no radiation from the other probe or from other sources can affect the
readings.

(vii) Make certain that adequate safety precautions are taken, according to USAEC
regulations, monitoring if necessary, cordoning off the radiation area if in a place
frequented by the public.

(viii) Set the discriminator level so that the setting is on the flattest part of the
spectral detection curve well beyond the flex point for the noise pulse curve (see
Figure 22).

(ix) The discriminator should be fixed at the setting that yields as accurately as
possible the "constant" count aimed for, for the particular probe in its standard.

(x) Once the discriminator level is set, twice the number of readings that time
permits for the taking of each actual field reading should be taken for the calibration
standard.

(xi) The access tube having been previously installed in accordance with the spec-
ifications given in Appendix A, the probe should be removed from the standard, kept
at arm's length, quickly but gently inserted into the access tube and clamped so that
the apparent center of the prove is held at the level at which the first measurement is
desired.

(xii) If a ratemeter is used: The time constant should at first be switched to the
smallest period the meter has, so that the response in counts takes place as soon as
possible. (If there is only a single time constant, there should be a waiting period of
5 to 8 times this period, before a reading is taken.) The highest time constant should

then be switched to (unless this period is very long, such as 2 minutes in the case of the UAC 522), a 10- to 20-second time constant being most practical.

(xiii) The accuracy of most meters being greatest at full scale deflection, the range selector must be switched so that the readings obtained register as near full scale as possible.

(xiv) The first reading should be taken soon after it is observed that the meter needle is fluctuating both up and down.

(xv) A minimum of two readings should be taken for each depth. Between the readings there should be a time lapse at least as long as the time constant used. If it is known that the system tends to drift, two readings for each depth should be taken as the probe is dropped at regular time and depth intervals, and as it is pulled up again. This procedure helps to cancel errors due to slight drifts.

(xvi) If the meter is known to be very stable in operation, two readings taken at each depth should suffice to give highly accurate readings, and it should not be necessary to recalibrate the instrument throughout all the depth readings for a shallow hole.

(xvii) If the meter is known to drift considerably with time while the counting rate is constant, the probe should be pulled out when it reaches the bottom of the hole and a set of counts taken in the calibration standard before proceeding further with testing. The readings should then be resumed starting from the lowest depth. At the end of the last reading for the location closest to the top of the hole, the probe should be recalibrated. The time of initial, intermediary and end calibration should be recorded. The readings for each depth should be systematically timed so that they are obtained at fairly constant time intervals.

(xviii) If a stable absolute counting meter is employed, two one-minute readings should be adequate for each depth, the readings being permitted to be started immediately upon placing the probe at the depth desired. Longer readings should be taken if less than 10,000 counts per minute are obtained, so that at least this number of counts registers on the meters. (This is generally preferable to timing 10,000 counts with a stop-watch on the field, as precision in such timing is lacking owing to inadequate physical response to such rapid sensory stimuli.)

(xix) The depth interval recommended for continuous profile analysis is 6 to 12 inches using the 2-inch diameter probes developed here.

(xx) After readings are completed with one probe, it should be removed to a sufficient distance from the other probe which is now placed on the stool for making the calibration of the standard.

(xxi) The meter should be "zeroed" again, and internally recalibrated. (This procedure is often repeated as necessary during readings.) The high voltage should be reset at the optimum for the new probe. The same procedure using the second probe (either moisture or density) should be followed as outlined above.

(xxii) The data should be recorded as in the data sheet presented in Appendix C, which is taken from an actual set of readings obtained using the LiI(Eu)-6199 moisture probe and the NaI(Tl)-6199 density probe. These probes were used in conjunction with the UAC-522 B meter which had considerable drift.

Appendix C

CALCULATIONS OF MOISTURE CONTENT AND DENSITY FROM DATA

DATA SHEET

LOCATION __Newark, N. J. McClellan St.__   DATE ___5-13-57___

SITE OF   REPORT __Linden-Bergen Line__
TEST HOLE __Intersection McClellan-__

__Freylinghusen Ave.__

INSTRUMENT ___UAC-522 B___

PROBES __2" D., 6199-NaI(Tl), 7" Geom.__

__(Fig. 13)__

__2" D., 6199-LiI(Eu)__

__(Fig. 20)__

SOIL PROFILE	HOR. SURFACE	DEPTH
Black top surfacing		0-8"
Base - sub-base and sub-grade		8-15"
Red-Brown clay	"B₁"	15-56"
Light-Brown sandy	"B₂"	56-60"
Purple-Red decomposed shale	"C"	60-72"

REMARKS

After rain on previous day. Humid,
warming up. Sunny. Typical soil
conditions of area.

MOISTURE STANDARDS

SETTINGS		REP. NO.	START	INTER.	END
HIGH VOLTAGE	1145	1	58.0	58.8	62.0
		2	58.0	59.1	59.0
DISCRIMINATOR	27	3	58.0	59.0	61.0
		4	58.0	59.1	60.0
TIME CONSTANT	20	5	58.0	59.0	61.0
		6	58.0	58.9	56.0
		7	57.7	58.8	60.0
		8	58.0	58.8	60.0
		AVG.	58.0	58.9	59.9
		TIME	10:20	10:27	10:33

MOISTURE READINGS

DEPTH	1	2	3	4	AVG.	STD.	RATIO	moist %
24"	30.0	30.0	32.0	33.0	31.2	59.5	0.532	44.0
36"	22.0	23.5	24.0	23.0	23.1	59.1	0.394	31.0
48"	22.0	20.5	21.5	22.0	21.5	58.6	0.366	27.8
60"	19.8	19.0	18.5	18.6	19.0	58.2	0.326	24.0

DENSITY STANDARDS

SETTINGS		REP. NO.	START	INTER.	END
HIGH VOLTAGE	1150	1	200	203	203
		2	200	202	203
DISCRIMINATOR	20	3	197	204	205
		4	202	205	208
TIME CONSTANT	20.5	5	202	204	208
		6	200	204	210
		7	201	205	209
		8	200	203	210
		AVG.	200.3	203.8	207.0
		TIME	10:47	10:51	10:55

DENSITY READINGS

DEPTH	1	2	3	4	AVG.	STD.	RATIO	WET DENSITY
24"	2900	2850	2850	2900	2870	205.8	14.0	1.92
36"	2850	2850	2800	2850	2840	204.5	13.9	1.91
48"	2800	2800	2800	2800	2800	203.1	13.8	1.90
60"	3000	2950	2950	2950	2960	201.7	14.7	2.16

The foregoing is a recommended style for a data-sheet to obtain moisture and density determinations of soil using nuclear methods.

In these tests, a set of four replicate readings were taken, beginning from the lowest depth. It is clear from the data on the initial, intermediate, and final calibration standard readings that both the moisture and density readings increased at a fairly steady drift rate. Hence, the total disparity in each standard reading should be divided by the number of readings plus one, to obtain the drift per reading. Thus, the standard for each reading is much more accurately obtained instead of merely using the average of the initial and final readings for each measurement.

The dry density D_b is obtained merely by multiplying D_{bw} the wet density by 100, subtracting x, the percent moisture content by volume, and dividing the whole by 100:

i.e.
$$D_b = \frac{D_{bw} \times 100 - x}{100}$$

The values obtained for the more accurate method of calculating the dry density using the moisture content and density readings by accounting for the drift of the meter, is given below:

Results

Depth	Dry Density
24"	1.48
36"	1.60
48"	1.62
60"	1.92

The columns listing the percent moisture and the wet density are simply obtained from the calibration curves given in Figures 21 and 18 respectively.

It is to be noted that if the signal to noise ratio is significantly different for the initial and final standard readings during a test, more accurate results will be obtained by determining the proportion of noise and deducting the noise counts from each reading as well as from the standard. Such signal/noise ratios are obtained by making counts versus discriminator bias curves as in Figures 22 and 25.

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