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Neutron Scattering and Gamma-ray Absorption in Soil Moisture and Soil Density Determination

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A considerable number of direct/indirect, destructive/non-destructive methods for soil moisture determination are available.

a) The most accurate direct method is that of weighing a soil sample before and after oven-drying. The principle disadvantage, however, arises from the soil profile destruction. For long-range soil moisture surveys at a definite site the method is unfortunately of little use. In addition, a considerable waste of time during sampling and drying procedures should be taken into account.

b) Indirect methods, such as electrical and thermal conductivity, thermal diffusivity, dielectric constant, moisture

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tension a.o. are far from being satisfactory. All these methods, including the direct measuring method over block-embedded eletrodes (nylon, gypsum blocks) present, in general, considerable difficulties, particularly in calibration procedures. Calibration may be seriously affected by changes in soil texture, soil temperature, electrical contact resistence, salt-concentratiation and various chemical interactions between block-material, surrounding soil and soil water. The intensive use of fertilizer near the site under investigation, for example, will uncontrollably disturb the calibration of all methods stated above. Therefore calibration facilities are stable for short-term observations only.

c) Dealing with methods, found suitable up to a certain degree only, an ideal method for determining soil moisture in situ should at least match the following principles:

1) Highly sensitive equipment including long-term stable calibration facilities applyable to a comprehensive soil type spectrum.

2) Direct, non-destructive testing facilities.

Considering these principles, an approach to an ideal soil moisture determination, which avoids the principle disadvantages of early measuring techniques, will be the use of emanations from radioactive sources. The application of gamma rays in soil moisture survey is hardly of any use, as the absorption of solid material and water could not easily be discriminated. Alpha- and beta-rays are not applicable because of lack in range. Therefore much attention was paid to the emission of fast neutrons.

Neutrons (mass = 1.675×10^{-24} g) are uncharged subatomic particles of nearly the same mass as protons (mass = 1.673×10^{-24} g) and hydrogen nuclei (mass = 1.673×10^{-24} g). Fast neutrons, interacting with nuclei of atoms, may be captured (a), elastically (b) or inelastically (c) scattered.

a) If free neutrons are captured, the new-formed, usually unstable nuclei emit gamma-rays immediately following a (n, gamma) — process. In some cases they disintegrate with the emission of one or two light particles, commonly a proton (n, p-process), an alpha-particle (n, alpha-process) or two neutrons.

b) During inelastic neutron scattering the fast neutrons transfer a great part of their kinetic energy to the nuclei, raising them to a higher energy level. Immediately after the scattering the nuclei return to their original energy state, emitting gamma-rays.

c) Elastic fast neutron scattering (fig. 1) at nuclei of various elements is always accompanied by kinetic energy transfer to the collision partner. Maximum neutron energy loss depends on the mass number of the collided nucleus only, provided that direct impact is stated. The function can be formulated :

(1)
$$E\ (max) = \frac{4\ A}{(A - 1)^2} \times E_o$$

where A is the mass number of the collided nucleus and Eo the neutron energy level before scattering.
Considering all colision possibilities the neutron scattering angles must be taken into account, too.

Using the diffusion equation for epithermal neutrons the mean number of collisions required to slow fast neutrons to a thermal neutron level can be computed.

(2)
$$D\nabla^2 \Phi - N\delta \cdot \Phi - \frac{N \cdot \delta \cdot \xi}{\lg \frac{E_1}{E_2}} \cdot \Phi + S = 0$$

$$\nabla^2 \Phi - \left(\frac{1}{L^2} + \frac{1}{\tau} \right) \cdot \Phi + \frac{S}{D} = 0$$

Assuming a fast neutron energy of 1 MeV (million electron volt) and a thermal neutron energy level of 0.4 eV (electron volt), the values for hydrogen and oxigen are 17 and 136 respectively. (1 eV = 1.6×10^{-19} Amp x sec x 1 volt = 1.6×10^{-19} watt x sec = 1.6×10^{-12} erg; 1 watt x sec = 10^{7} erg).

During scattering the relative probalility that a neutron will interact with a nucleus is of high importance. The probability is formulated as Nuclear Cross Section, expressed in barns (1 barn = 10^{-24} cm^2 . The cross section depends primarily on neutron energy state.

Nuclear cross sections for fast and thermal neutrons interacting in neutron scattering at common soil elements were computed by Adair (1950). While most of the elements show no substantial variations of cross sections during scattering, the hydrogen cross section increases greatly (about 50 to 2) as the neutrons slow down.

While recognizing the outstanding features of hydrogen nuclei slowing down fast neutrons to thermal neutron level, the basis for soil moisture determination was found. As the slowing down length for hydrogen is very small in comparison to all other common soil elements, a thermal neutron detector mounted close to the source of fast neutrons will record rather exclusively hydrogen nuclei, i.e. soil water, water of the mineral fraction and vapor.

Unfortunately an important source of hydrogen nuclei in the soil is bound to organic matter, such as decomposition products and root-systems. In order to match this occasionally considerable part of total hydrogen content in routine soil moisture survey, special calibration practices must be used. In modification of the back-ground calibration for routine testings, however, arises a new field for detailed studies in evaporation, evapotranspiration, plant-water relationships and several other important and interesting subjects.

As stated above, gamma-ray application to the soil considering soil moisture testing procedures are hardly of any use, as absorption of solid material and water could not be easily discriminated. But on account of density determination hard gamma-rays have outstanding advantages in comparison to the early soil densitometry, provided that source-detector geometry is at a high standard.

Gamma-rays are electromagnetic waves of very short wavelenth. After collision of a gamma quanta with an atom in matter three different effects are possible (fig. 1) :

a) The photoelectric effect (fig. 1) arises at the absorption of a gamma quanta after collision with an atom, immediately followed by the emission of an photoelectron usually out of the atom's K-shell. The cross section at the interaction is a function of the atomic number and the initial gamma quanta energy. Mathematically formulated the nuclear cross section considering the photoelectric effect is

(3) $G\ (cm^2) = 1.0 \times 10^{-23} \times Z^5 \times E\ (MeV)^{-3.5}$

where Z is the atomic number and E the energy of the gamma quanta (photon). Considering the usually low atomic numbers of common soil elements, the photoelectric effect is of importance only below 100 KeV.

b) Pair production (fig. 1) appears when a gamma quanta of a definite energy interacts with the nuclear field of an atom, moderating the photon to an electron — positron pair. Following the Einstein mass energy ratio

$$E = m \times c^2$$

the energy — equilibrium of the pair production is formulated

(4) $Ee^+ + Ee^- = h \times v - 2m_oc^2$

where $2\ mo\ c^2$ equals 1.02 MeV, i.e. a gamma quanta transfers kinetic energy to the electron-positron pair above 1.02 MeV only. On the other hand the nuclear cross section necessary for pair production is proportional to the atom number squared (Z^2) In consequence, pair production with atoms of common soil elements of considerable low atom numbers gain importance above a photon energy of 10 MeV only.

c) If photon energy at a collision surpasses the energy of the K-shell electrons significantly, these electrons act like free electrons. This photon-electron interaction is called Compton-Effect ((fig. 1). After collision the photon energy E = h x v (formulated by Max Planck as hc/lambda) is partly transferred to the Compton electron (E = h (v — v'). In consequence, the energy of the scattered gamma quanta is

$$E' = h \times v' \quad \text{or} \quad E' = \frac{h \times v}{1 + \frac{h \times v}{m_o c^2} (1 - \cos O)} \qquad (5)$$

where h = 6.62517 x 10 erg x sec (Plancksches Wirkungs-quantum)

$$v = \frac{c}{\text{Lambda}} = \frac{2.99798 \times 10}{\text{wave length}}$$ cm/sec. O = the scattering angle, and

$m_o c^2 = 0.511$ MeV (based on the Einstein ratio).

In other words, the absorption probability of photons by Compton effect increases with rising atom number, but decreases with rising photon energy.

Basing on the theoretical approach, stated above, elements of low atomic number show dominantly absorption and scattering by Compton effect. The higher the density of the material, the greater the photon scattering and absorption. Up to some degree these two effects, scattering and absorption, tend to counterbalance. But by geometry arrangements of the source-detector equipment it is possible to suppress one of the effects. In our case the absorption of gamma quanta was chosen for the desitometry set., i.e. with increasing density the radiation density decreasses.

During a fourteen-month soil survey at different sites in the Manaus Region a portable, battery-fed rate meter LFC/S of the Nuclear Laboratory Prof. Berthold, Wildbad — Schwarzwald, Germany, was in action. (fig. 2)

The rate meter can be charged by different probes for soil moisture, soil density and general radiation determinations respectively.

The special steel manufatured soil moisture probe contains a 100 mCi 241 Am-Be (halflife over 400 years) fast neutron source (n.-gamma-process) emitting an insignificant gamma radiation, too, as well as a scintillation detector LB 6600 I (lithium cristal), sensitive for thermal neutrons only. The probe measures 540 mm by 36 mm in diameter and weighs 2.4 kg. The soil moisture probe container LB 7407 measures 370mm by 230mm in diameter and weighs 13 kg. (fig. 2). The special steel manufactured soil density probe works with a 3 mCi 137Cs (halflife 30 years) gamma rays source and a scintillation detector LB 6610 I for gamma quanta. Detector and source are separated by a lead shield. The probe measures 680 mm by 36 mm in diameter and weighs 3.6 kg. The soil density container LB 7408 has the same dimensions as the container LB 7407, but weighs 15 kg. (Fig. 2).

Soil moisture and density measurements were carried out in precision steel tubes measuring 150 to 300 cm at an inner diameter of 37 mm. The probes were moved from basis to top of the tubes always for 20 cm in 5-minute intervalls. In order to detect instability in the measuring system as well as anomalities in soil profiles the rate meter was operated with a recorder.

According to the experiences with the neutron-gamma equipment in field work and laboratory testing, the following conclusions may be justified :

1) The installation of special steel tubes into sandy soils did not show any difficulties, whereas the same procedures in

latosols and river plain soils of the Amazon were considerably troublesome. Up to a length of 1.50 m the tubes were driven into the soils, using a heavy plastic hammer and a protective steel cap. At greater lengths an auger was applied. Close contact between steel tube and soil was obtained by using auger blades of the same diameter as the tubes. To place steel tubes up to 2.50 m into site, about 15 minutes were spent, considering sandy material. The same procedure required in latosols and river plain soils up to 45 minutes each.

2) At least one assistant should be at disposal in the different field work facilities, especially on rough terrain or in dense forest. A team of three, including the scientist has proved best. (Fig. 3).

3) The steel-tube mounted probes are easily protected by a cover of plastic foils. In consequence, dowpours do not affect testing. This fact can be regarded a great advantage, compared with some early techniques, especially in wet front analysis a.o.. Recording facilities are of great help anyway.

4) The battery-fed rate meter LFS/C operates recording over a 10-hour period without interruption. Charging-up time for the two DEAC-batteries amounts to about 10 to 12 hours only, and can be carried out with a gasoline-fed, portable generator, i.e., field work is rather undisturbed by base-distance. This fact is of high importance in regions with low-level infrastructure.

5) The probes can be operated over a wide-spread testing spectrum with a considerable sensitivity. Used today in soil survey, they may be applied tomorrow in concrete testing for roads or air bases, in earth dam density determination as well as in snow-pack analysis for peak-discharge prediction in hydrology.

6) Neither temperature nor chemical influences on calibration were observed in the soils under investigation. But, publications dealing with the subject in semi-arid, irrigated regions of the near East, Egypt and Northern Africa report

considerable calibration difficulties in soil profiles affected by salinization or alkalization processes in consequence of the frequent moderation in the state of agregation.

7) Every 5 minutes the probes were lifted up 20 cm from base to top of the tubes. Soil moisture and density recording showed a remarkable deviation from calibration curve over a wide-spread soil spectrum in the upper 20 cm of the soil profiles. In consequence, top soil data, although of high importance in numerous soil-plant relationships, must be excluded from interpretation. Nevertheless, the upper soil layers can be investigated by surface probes with distinct geometry.

8) Studying soil moisture and soil density in a dense tropical forest is at first sight rather difficult on account of subsurface biomass, i.e. the root systems. But operating with a discrimination technique, the probes can be used in soil study and subsurface biomass determination respectively.

Summing up, the soil moisture and soil density equipment used for our purposes, acting under ordinary calibration only, showed some serious disadvantages, but operated at special calibration, proved satisfactory results.

The outstanding advantages of soil moisture determination by the Neutron Scattered Method and soil densitometry by the Gamma Ray Absorption Method can be marked in soil survey history as a real gain.

But at any time health hazard must be given the fullest attention. The interaction of neutrons and human tissue covers the neutron energy spectrum from 0.01 eV to 10 MeV. The energy transfer of fast neutrons in human tissue is mainly brought on by elastic neutron scattering at hydrogen-nuclei up to 90%. In consequence, neutron scattering at carbon, oxigen and nitrogen-nuclei is rather negligible. Thermal neutrons are incorporated by different reactions, too.

Considering our neutron equipment the 100 mCi 241 Am-Be source (100 mCi $= 3.7 \times 10^9$ d/sec) emits gamma rays of a low energy level and fast neutrons. By backscattering a considerable amount of thermal neutrons is to be expected, too.

Handling the soil moisture probe outside the container, a 0.29 mrem/h dose rate was recorded at a distance of one meter. With the source mounted on the container a 2.5 mrem/h dose rate is to be expected at the container surface, reducing the neutron hazard to 0.1 mrem/h at a 0.50 m distance. The low energetic gamma rays are shielded in the probe and can be neglected. (fig. 3)

Working with the soil density probe outside the lead container, the 3 mCi 137 Cs source (1 mCi = 3.7×10^7 d/sec) emits gamma-rays effecting a 1 mrem/h dose rate at a 1 meter distance. The dose rate at the container-surface with probe mounted, is at about 2.5 mrem/h. 0.50 m off from the container surface the dose rate amounted to 0.1 mrem/h. (fig. 3)

Under field conditions there is rather a hazard, as the soil mass acts as a satisfactory shield. Considering the principle radiation hazard regulations, the dose rate will remain well below the rem/year limit.

ABSTRACT.

A considerable number of direct/indirect, destructive/non-destructive methods for soil moisture determination are avaliable. But, all these techniques are found suitable up to a certain degree only.
Soil moisture determination in situ should at least match the following principles :

1) Highly sensitive equipment including long-term stable calibration facilities applyable to a comprehensive soil type spectrum.

2) Direct, non-destructive testing facilities.

An approach to these principles was found by recognizing the outstanding features of hydrogen nuclei slowing down fast neutrons to thermal neutron level.

For soil densitometry gamma rays were applied. Element of low atomic number show dominantly absorption and scattering by Compton effect. The higher the density of the material, the greater the photon scattering and absorption. By geometry arangements of the source-detector equipment one of these effects, tending to counterbalance, can be suppressed.

During a 14 month soil survey a portable, battery-fed rate meter LFC/S of the Nuclear Laboratory Prof. Berthold, Schwarzwald, Wildbad, Germany was in action. The rate meter was charged with a soil moisture probe (100 mCi 241Am-Be fast neutron source plus scintillation detector LB 6600I) or a soil density probe (3 mCi 137 Cs gamma source plus scintillation detector LB 6610 I) respectively.

Unfortunately an important source of hydrogen nuclei in the soil is bound to organic matter, such as decomposition products and root-systems. The serious disadvantage of the equipament could be matched by operating with special calibration practices, e.g. in modification of the background calibration for routine testings.

Considering the principle radiation hazard regulations, the dose rate of both probes will remain well below the critical level.

RESUMO

Existe um considerável número de métodos, diretos e indiretos, destrutivos e conservadores, para a determinação da humidade do solo. Todos aqueles métodos são adequados a diversas situações mas não atendem tôdas as necessidades da pesquisa.

A determinação da humidade do solo "in situ" deveria atender pelo menos a duas condições :

1 — Empregar equipamento de alta sensibilidade, com possibilidade de calibração estável a longo prazo, aplicável a um espectro satisfatório de tipos de solo.

2 — Utilizar método direto não destrutivo (conservador).

O reconhecimento da possibilidade de desaceleração de neutrons rápidos dos núcleos de hidrogênio até o nível de neutrons térmicos, permitiu o atendimento das condições supra.

Na determinação da densidade do solo, foram usados os raios gama. Elementos de baixo número atômico possue também capacidade dominante de absorção e dispersão pelo efeito de Comton. Quanto mais alta a densidade do material, maior a dispersão de fotons. Através de arranjos geométricos entre a fonte e o detector de raios gama, é possível suprimir um daqueles efeitos antagônicos.

Durante os 14 meses que durou o levantamento de solos realisado pelo Autor, foi usado um equipamento portátil LFC/S, alimentado a bateria do laboratório nuclear do Prof. Berthold, Sohwarzwald, Wilbad, Alemanha. Como fonte de neutrons acelerados foi usado 100 mCi 241 Am-Be e, como fonte de raios gama empregou-se 3 mCi 137 Cs. Para as determinações de humidade foi usada uma sonda contendo, além da fonte de neutrons, um detector de cintilação LB 6600I e para as determinações de densidade empregou-se uma sonda contendo, além da fonte de raios gama, um detector de cintilação LB 6610 I.

Uma importante fonte de núcleos de hidrogênio no solo é representada pela matéria orgânica. produtos de decomposição de raizes e detritos vegetais, etc.; a dificuldade resultante da presença daquele hidrogênio pode ser superada através de práticas especiais de calibração.

A dose de radiação proveniente de ambas as sondas situa-se bem abaixo do nível crítico admitido pelas exigências do contrôle dos riscos da radiação.

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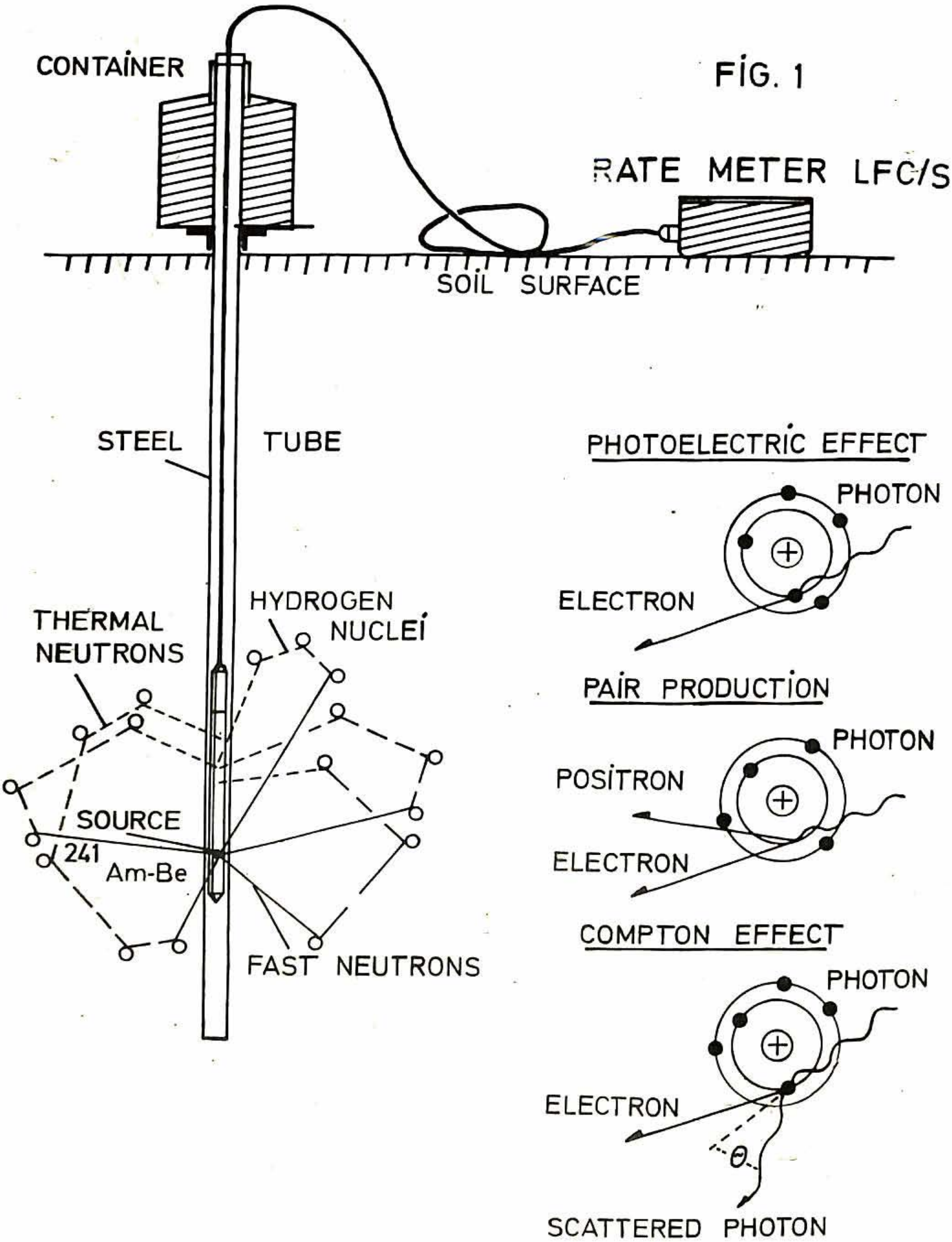
FIG. 1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SCATTERED PHOTON

FIG. 2

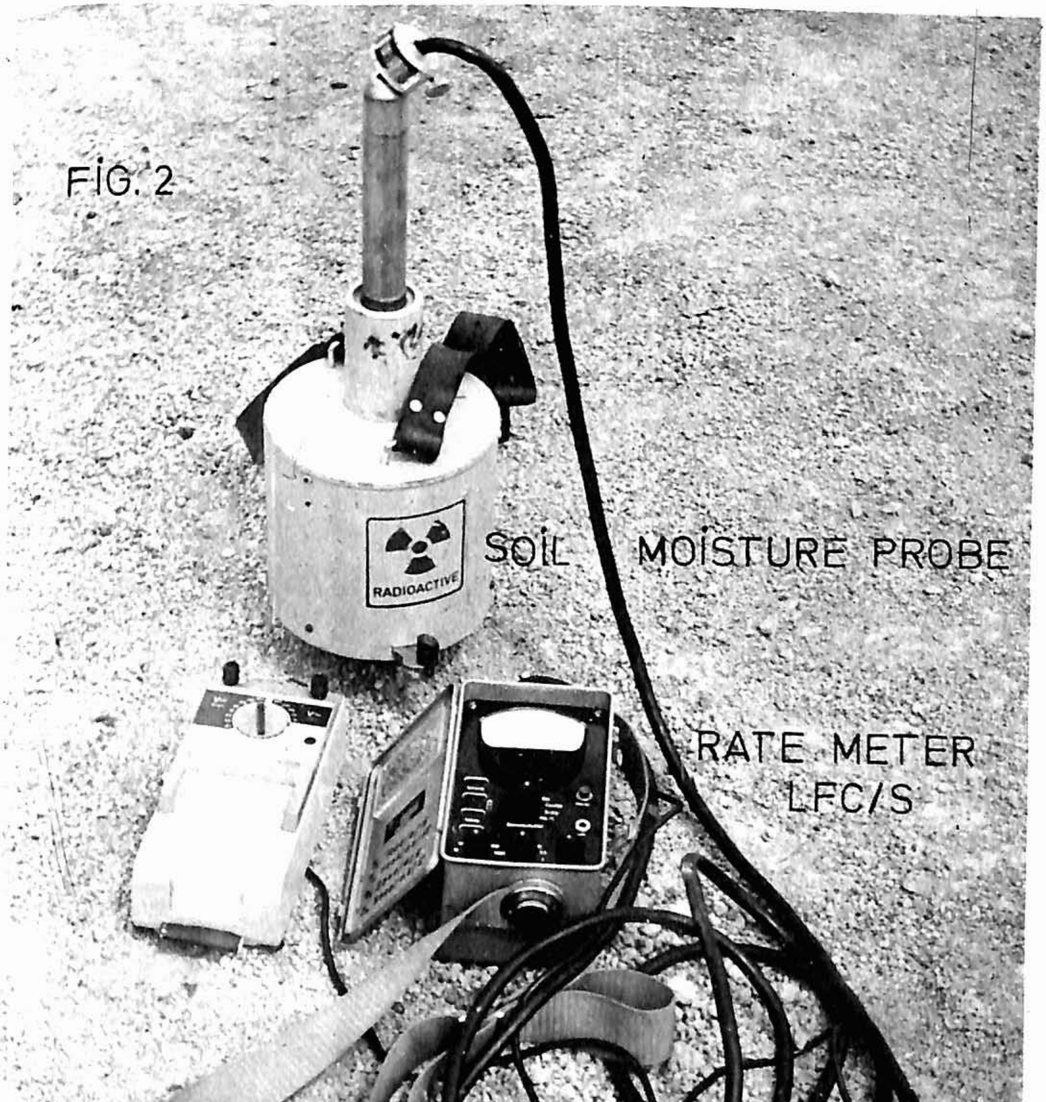

FIG. 3

NOTA

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