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A laboratory study of nuclear moisture-density gage parameters is reported. Commercial gages were studied to determine the capabilities of present day gages. A research gage was fabricated with a system of precision modular instruments for radiation analysis and measurement and variable gage parameters. Gage geometry, configuration and components could be varied simultaneously or independently. The following gage parameters were investigated:

Source-detector
a. Separation
b. Collimation
c. Selection
d. Shielding
Gamma Photon Energy Discrimination
Gage Configuration

These parameters were evaluated by gage response to changes in moisture, density, soil mineral composition, surface irregularities, temperature and influence by nearby objects.

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Improved Performance Criteria For Use In Nuclear Gage Specifications

75-21

FINAL REPORT
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a. Separation
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Gage Configuration

These parameters were evaluated by gage response to changes in moisture, density, soil mineral composition, surface irregularities, temperature and influence by near-by objects.

The objective was to develop the criteria necessary to write efficient "state-of-the-art" specifications for nuclear-moisture density measurement gages for use in highway compaction control.

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TRANSPORTATION LABORATORY

May 1975

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Mr. R. J. Datel
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research report titled:

IMPROVED PERFORMANCE CRITERIA FOR USE IN

NUCLEAR GAGE SPECIFICATIONS

Study made by . . . . . Geotechnical Branch

Under the Supervision of . . . . . Raymond A. Forsyth

Principal Investigator . . . . . Joseph B. Hannon
and
Jerry C. Chang

Co-Investigators . . . . . Ellsworth L. Chan
and
Frank C. Champion

Data Analyzed and Report
Prepared By . . . . . Frank C. Champion

Very truly yours,

GEORGE A. HILL
Chief, Office of Transportation Laboratory

Attachment

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Recognition is extended to Ellsworth Chan and David Castanon for their participation in the Laboratory and analysis portion of the program. Donald L. Durr served as principal investigator during the earlier part of this project.

This is a final report on work done under the HPR Work Program as Item No. F-4-24 in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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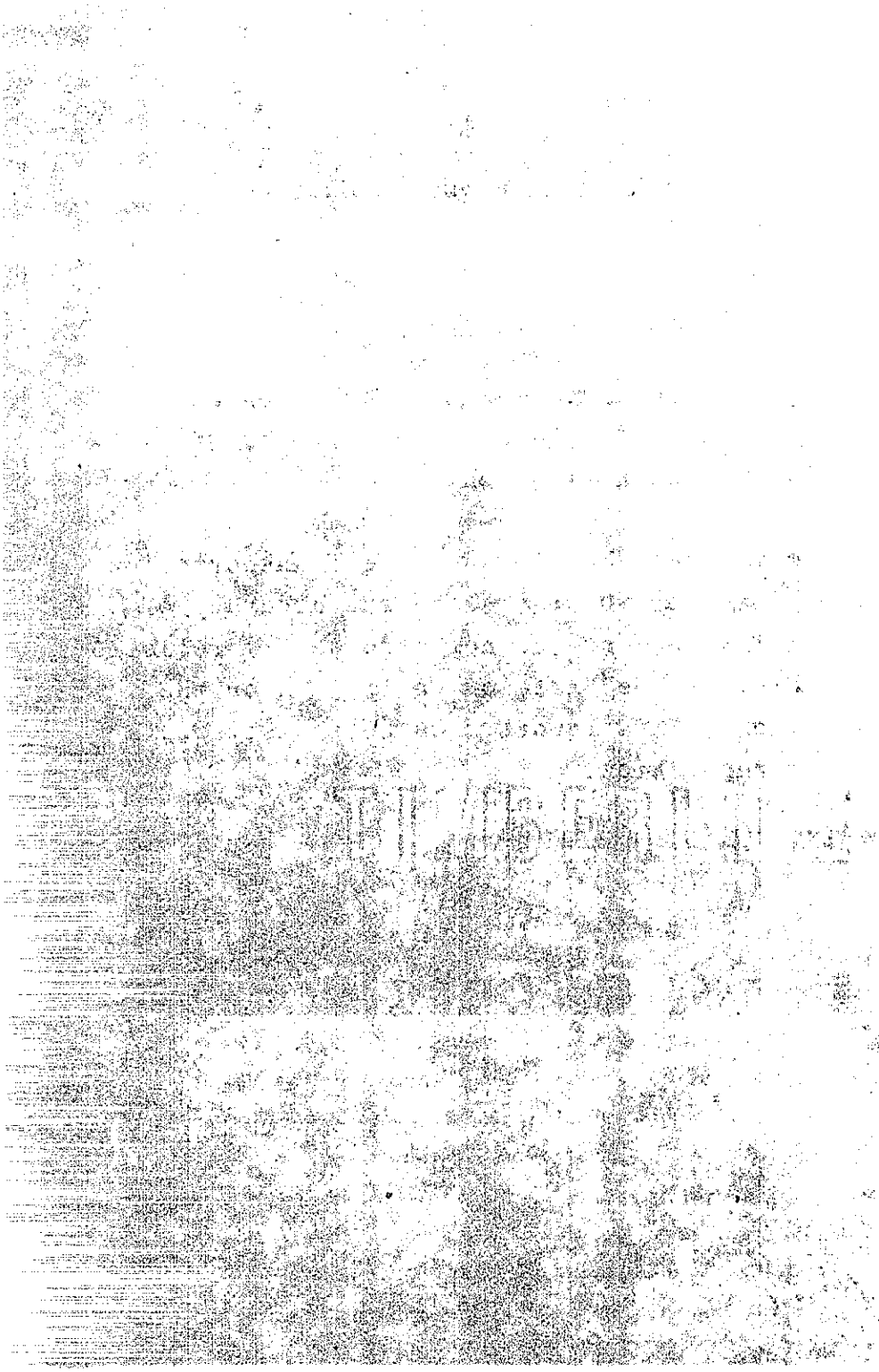

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INTRODUCTION

In 1969, the California Department of Transportation initiated a program to investigate nuclear moisture-density gage parameters prompted by an inadequate knowledge in certain areas of nuclear gage design. As a result of this deficiency, our nuclear gage specifications did not realistically reflect current state-of-the-art concepts.

At the inception of this project, the California Department of Transportation was heavily committed to the use of nuclear moisture-density gages. Approximately 80 nuclear moisture-density gages had been purchased during the 1966-67 and 1967-68 fiscal years. Forty-one were purchased during the following fiscal year. As indicated by the number purchased, reliance on nuclear gage measurements for earthwork control progressively increased. Therefore, valid gage specifications were of utmost importance.

In order to create effective state-of-the-art specifications, it was necessary to understand the gage parameters and their inter-relationships. The inter-relationships are generally complex, and the variation of one parameter usually affects other gage parameters.

A list of the basic gage parameters investigated are:

a) Source-detector separation
b) Source and/or detector collimation
c) Radioisotope selection
d) Primary shielding
e) Energy discrimination
f) Detector selection

The measure of each parameter's influence was determined by our definition of the gage performance criteria listed below:

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a) Sensitivity Response Ratio
b) Chemical Sensitivity
c) Surface Texture Sensitivity
d) Count Rate
e) Electronic Stability

The Performance and Parameter terms are defined in the Glossary of Terms.

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CONCLUSIONS

1. It is possible to increase gage sensitivity to density and moisture by about 20% above California's present 1972 nuclear moisture-density procurement specification standards. However, this may not be practical when all gage parameters are considered.

2. Although gage performance is significantly influenced by the amount and configuration of shielding material and source detector separation, these parameters should remain under the manufacturers control and need not be specified since they are adequately controlled by gage performance specifications.

3. The density portion of the gage can be successfully isolated from non-density sensitive backscatter radiation by proper shielding of the source and detector. This will reduce the influence of radiation backscattered from nearby objects to negligible levels.

4. Gage requirements of California's 1972 nuclear gage specifications for density measurements could be improved such that a reduction in the error due to soil composition of at least 20% would result.

5. Source collimation reduces gage sensitivity to surface irregularities and increases the depth of sampling influence. No advantage is gained by source collimation when utilizing the transmission mode of testing.

6. Source detector separation is not a factor in chemical composition sensitivity.

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7. The performance of the backscatter gage can be increased to meet or exceed most of the performance potentials of the transmission gages on todays market.

8. An evaluation of Cesium 137, Cobalt 60 and Radium 226 for density determination indicated Cesium 137 to be the preferable source.

9. An evaluation of Americium Beryllium and Radium Beryllium sources for moisture determination indicated Americium Beryllium to be the preferable source.

10. The platinum lined, halogen quinched, Geiger Muller detector is the most suitable for density determination of those detectors on the market today.

11. The boron trifloride gas-filled detectors appear to be the most suitable for neutron moisture gages.

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IMPLEMENTATION

The findings of this study have been successfully incorporated into our procurement specifications for nuclear gages. A copy of these specifications are appended. The gages received under these specifications have demonstrated improved capabilities over previous gages. We will continue to incorporate these findings into the specifications for the procurement of nuclear gages to be purchased in the future.

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PRELIMINARY CONSIDERATIONS

The primary goal of this research project was to develop the criteria to write explicit "State-of-the-Art" specifications for the Nuclear Gages which are used to measure moisture content and density of compacted soils involved in highway construction. Our past experience indicated that the research project should address itself to the following questions:

1. How much can conventional nuclear gage specifications, concerning gage sensitivity to changes in moisture content and density, be raised above our present standards?

2. Can our gage specifications, concerning measurement deviations caused by soil composition, be improved?

3. What basic arrangement of source-detector shielding and separation offer greater advantages than the arrangements presently specified?

4. Can attenuated radiation, returning to the gage from nearby objects, be prevented from influencing gage measurements?

5. What are the basic design criteria for current commercial gamma and neutron detectors, which ensure optimum performance?

6. Which radioisotopes, of those currently employed, are the best for nuclear gage applications?

7. Can the performance of the portable backscatter gage be perfected to a level which will provide satisfactory use as a compaction control device for construction soils?

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DENSITY DETERMINATION

Source Evaluation

The determination of density by nuclear testing is based upon the attenuation of gamma photons by matter and the detection of the attenuation gamma photons. A gamma photon, which has no charge or mass, has the ability to penetrate deeply into matter. As the gamma photon penetrates into matter it collides with and gives up energy to the atoms of the matter through which it is passing. The denser the material through which the photon passes the more atoms per unit volume and the greater the probability of collision. Therefore, as the density of the test material is increased the detector count rate will decrease and thus provide an indication of density.

The following discussion will elaborate on nuclear gage parameters and their inter-relationship.

Out of the hundreds of radioisotopes (over 1300 have been identified) only a few are suitable for use in nuclear density gages. Each radioisotope can be identified by its own peculiar radioactive characteristics. Radioisotopes vary by their rate of decay and the type and energy of their emissions.

Cesium 137 (Cs-137), Cobalt 60 (Co-60) and Radium 226 (Ra-226) are the three most commonly used sources for this purpose. These three radioisotopes were evaluated to determine which is the most suitable for hand portable nuclear density gages. The evaluation was based on both performance and the following nuclear characteristics:

1. Source half life
2. Gamma Photon Energy
3. Shielding requirements

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a. Half Life

The half life of a source is defined as the time required for a radioactive material to loose 50 percent of its activity by decay.

Each radio nuclide has a unique half life. Half lives vary from a fraction of a second to billions of years. The half life is a measure of the rate of decay of a radioisotope. For instance, a fast decaying radioisotope (half life of one month) will be reduced in activity fifty percent for each month that passes. For our application we require a radioisotope with a long half life to avoid the necessity of frequent recalibration of the gage. As an example, a nuclear gage using a radioisotope with a half life of one year will have lost half of its activity in one year and therefore the initial count rate will have been reduced by 50 percent. As is readily apparent this would necessitate recalibration of the gage several times a year which is undesirable.

b. Gamma Photon Energy

Gamma photons or "rays" as they are commonly referred to are utilized for density determination. A gamma photon has no charge or mass which give it the ability to penetrate deeply into matter. It is this characteristic that makes it so useful for determining density. The depth of penetration of the photon into matter is a function of photon energy and the density of the matter. As the photon travels through matter it collides with the atoms of the matter through which it is traveling and is randomly scattered about. Eventually the photon will have transferred all of its energy to the atoms with which it has collided and cease to exist.

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The denser the material the more atoms per unit volume and the greater the probability of collision. Therefore, as the density of the test material is increased the detected count rate will decrease thus providing an indication of density.

Gamma photons differ only as to the energy they possess. When evaluating a source you are choosing gamma photon energy or energies as the case may be. The behavior of gamma photons as they travel through matter is a function of this energy. Gamma energy is disipated in three ways, compton scatter, photoelectric absorption and pair production. At high energies (2.0 Mev and above) pair production is the dominant reaction. Below 2.0 Mev and above 0.1 Mev compton scatter is the dominant reaction. Below 0.1 Mev photoelectric absorption predominates. The photoelectric absorption and pair production reactions both are undesirable for density determination.

c. Compton Scatter

Compton scattering is an elastic scattering of the photon upon collision with an electron. The electron will gain energy from the collision and the photon will continue on with a reduced energy. The reaction is with electrons and not the nucleus of the atom, therefore, the mineral composition of the test material has no affect.

d. Photoelectric Absorption

Photoelectric absorption is the process by which a gamma photon collides with an electron and pulls the electron out of its atomic orbit giving the ion pair all of its energy. This reaction is most apt to occur below 0.1 Mev energy. The probability of this happening is also dependent upon the chemical

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composition of the material. Therefore, low gamma energy sources and detection of gamma photon energies below 0.1 Mev should be avoided as they will result in a chemical sensitive density indication.

e. Shielding Requirements

The amount, configuration and placement of the shielding in a hand portable density gage is one of the major design parameters to be considered. If it were not for the weight factor no problem would exist. There are two primary purposes for adding shielding to a gage; the health safety requirements imposed for personal protection and isolation of the detector from nondensity sensitive radiation.

By law sufficient shielding must be used to adequately protect personnel. Federal and state regulations define the acceptable limits of external radiation. These limits must be met. The shielding provided to meet safety standards can also be used to help isolate the detector from nondensity sensitive radiation. The shielding that is added to improve gage performance will be referred to as "primary shielding".

f. Radium (Ra-226)

Ra-226 has a half life of 1620 years, thus eliminating the problem of correcting for changes in source activity. The gamma yield from Ra 226 and the associated daughter radiations is high. The gamma energies emitted range from 0.047 to 2.4 Mev. A major percentage of gamma energy emitted is at or below the 0.4 Mev range. The lower energies are undesirable because of the photoelectric soil compositional effects. The higher energies are also undesirable because of the increased shielding

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requirements and subsequent weight and bulk problems. A short performance evaluation program bore the aforementioned facts out. Ra 226 proved to be the least desirable radioisotope of the three evaluated for density determination.

g. Cobalt (Co-60)

Cobalt-60 was evaluated for use as a gamma source for hand portable nuclear density gages. Co-60 is an excellent high gamma yield source. The principal gamma energies emitted are 1.173 and 1.332 Mev. Two gamma photons are yielded per decay event. Of the three radioisotopes considered cobalt had the highest average gamma photon energy. This fact, coupled with the high photon yield provides an outstanding high count rate and excellent soil penetration characteristics. On a curie for curie basis, Cobalt 60 out performed both Cs-137 and Ra-226 when evaluating count rate and depth of penetration. Cobalt yields gamma energies well above 0.1 Mev and is, therefore, an excellent source to use to minimize soil composition induced errors by photoelectric absorption.

High energy gamma photons require increased source-detector separation to optimize gage parameters for maximum performance, this in turn yields an increased sample size.

On the negative side the higher energy gamma photons necessitate increased dimensional requirements, which add to the bulk of the portable unit. Additional shielding is required for personnel protection. The backscatter mode requires isolation of the detector from nondensity sensitive radiation. Additional shielding requirements increase the weight of the gage.

The half life of Co-60 is 5.3 years which necessitates frequent corrections for source activity changes.

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h. Cesium (Cs-137)

Cesium 137 provides a high yield of gamma radiation. The principal gamma energy emitted is 0.662 Mev. Cesium requires approximately half the shielding that cobalt and radium require which reduces the required weight and bulk of the gage. The lower energy requires less source detector separation to optimize gage performance. The reduced source detector separation results in a smaller backscatter mode sample which is not desirable but the reduced dimensions make the unit easier to seat on the soil surface which is an important factor. The half life of Cs-137 is approximately 30 years, therefore, recalibration due to source activity change need only be done on an annual basis.

Strictly on a performance basis cobalt proved to be slightly superior to cesium but on an overall evaluation between the two sources cesium is the best overall source for hand portable density gages when weight, bulk and half life are taken into account.

Gamma Detector Evaluation

For gamma detection two types of detectors were evaluated. These were the Geiger-Mueller (G.M.) detector and the Scintillation detector.

a. Geiger-Mueller Detector

Three types of Geiger-Mueller detectors of the steel cathode type were evaluated. Two of these had a lining on the inside wall of the cathode which gave performance that was definitely superior to the unlined detector. The two types of linings were platinum

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and tantalum. Increased performance due to the lining material was immediately evident. The linings increased the count rate and decreased the sensitivity to changes in soil composition. The tantalum detectors were unstable when subjected to surface temperatures of 300¼ Fahrenheit. The platinum detector gave a slightly lower count rate than the tantalum detector but was not affected by 300¼ surface temperatures.

Platinum-lined detector sensitivity response ratios in excess of 1.8 were obtained for the backscatter mode and ratios exceeding 3.0 were obtained for the direct transmission mode. At the same time the chemical composition was less than 2.0 lbs when tested on silica and calcium standards. The high performance was obtained with 9" source detector separation in the backscatter mode and 15" source detector separation in the transmission mode. The source used for this evaluation was Cs-137. The majority of commercial gages on the market today are now using the platinum lined G-M Detectors.

b. Scintillation Detector

The advantages of using a scintillation detector are high gamma detection efficiency and a pulse output which is proportional to the incident gamma photon energy absorbed by the crystal. The probability of an incident gamma photon producing a reaction within the crystal is very high. The proportional pulse output makes it possible to use electronic energy discrimination to improve gage performance.

The disadvantages are temperature and shock sensitivity. The temperature sensitivity can be compensated for by electronic adjustment, but this is not practical for portable gages.

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The scintillation detector used for this study was a 1.5" diameter by 1.5" thick thallium activated sodium iodide crystal optically coupled to a photo-multiplier tube. This was used in conjunction with a single-channel analyzer for energy discrimination.

Backscatter Mode Parameters

a. Source-Detector Separation

The source and detector geometry is one of the most important single factors to consider in gage design. For the backscatter mode refer to Figure 1. The ability of a gage to identify changes in density increases as the source and detector are separated until an optimum separation distance is reached. The point of optimum separation will vary as the other gage parameters are varied. The type and strength of the gamma source, amount and placement of primary shielding, source and detector collimation, detector type, and the selection of detected gamma energies, play an active part in determining the optimum separation distance.

As the source and detector are separated the following occurs:

1. The count rate decreases

2. The average mean gamma energy detected remains constant

3. Gage response to density changes increases

4. Sensitivity to chemical composition remains unchanged

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The optimum source-detector separation, as noted above, is a function of the initial gamma photon energy emitted by the radioisotope. Higher initial photon energies require greater source-detector separations to maximize density sensitivity. The optimum separation, which produces greatest density sensitivity, is also governed by the count rate of the interval of detected energies. The count rate decreases as the source-detector separation increases, provided the energy interval remains constant. Assuming that the energy interval detected was carefully selected for minimum chemical composition error, the optimum source-detector separation may have to be compromised to maintain a count rate that is statistically reliable.

Source detector separation has little effect on chemical composition sensitivity in either backscatter or transmission modes. The mean detected energy remains the same regardless of source detector separation. Chemical composition error is primarily a function of the detected gamma photon energy distribution and the unattenuated gamma energies of the source selected.

Table 1 demonstrates that although increasing the source-detector separation decreases the detected count rate the accumulation percentage of the total count rate from each energy level does not change. Therefore source detector separation is not a factor in chemical composition sensitivity.

Table 2 is a summary of experimental results using a 3 mc Co-60 source and a sodium iodide crystal scintillation detector system. Even though three different detected energy intervals and three different source collimation positions were used, detected energy interval and collimation position for each condition in Table 2 are constant with the source-detector separation being varied. As the source-detector separation is increased within each condition, the Sensitivity Response increases.

Gage sensitivity to surface texture and the physical geometry and location of the source and detector are two additional areas of

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investigation not attempted. The backscatter gage sensitivity to surface texture will probably change with source-detector separation. The physical geometry and location of the source and detector should decrease the number of surface attenuated emission being detected. The depth of soil influencing the density measurement was not investigated as a function of source-detector separation. However, due to the random collisions between gamma photons and soil minerals, our first hypothesis would be to expect no change in measurement as a result of depth.

b. Source Collimation

A noncollimated gamma source is usually located as close to the bottom of the gage as physically possible. A collimated source has been drawn up into a cavity in the lead shielding. Source collimation restricts the number and direction of the gamma photons entering the attenuating soil being tested.

Collimation of the gamma source affects the following measures of gage performance:

1. Density sensitivity
2. Sensitivity to Surface Texture
3. Chemical composition sensitivity
4. Depth influence gradient
5. Sensitivity to air gaps at gage-soil interface

As the collimation restrictions increase, gage sensitivity to density changes also increase. The apparent reason for this phenomenon is due to the reduced detection of attenuated photons coming from the soil-gage interface. Source collimation greatly reduces the incidence angle and refraction angle involved with the first gamma-soil collisions at the soil-gage interface. Little or no collimation increases the refraction angles, thus directing a larger number of photons towards the gamma detector. The effects

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of source collimation are much more noticeable when an air gap between the soil surface and gage bottom exists. In this case, an absence of collimation greatly increases the detection of the photon interacting with the soil surface, and reduces the gage response to soil density. As a direct result of the air-gap collimation experiments as reported by Chan, et.al.(2), the reduction of gage sensitivity, caused by soil surface texture, appears to decrease with the introduction of source collimation. Surface texture, as well as source collimation decide the direction of all photon-soil surface collisions.

As the source is collimated the error due to chemical sensitivity is decreased. The average mean energy detected is increased with increased collimation. Figure 2 is a typical plot of the accumulative percentage of the total count rate detected versus energy. Increased source collimation demonstrates less low energy radiation detected and reduces the chemical composition sensitivity.

Source collimation was observed to influence the number of attenuated photons detected from each successive increment of soil depth beneath the backscatter gage. This depth influence was determined with a collimated and a noncollimated backscatter gage, designed for laboratory use. The gage parameters of both gages were optimized prior to the depth influence experiments. The collimated gage had the source elevated 0.5 inches above the gage bottom or gage-test surface interface.

Magnesium plates, 0.5 inches thick, served as the test medium. Each gage was positioned on the plate and the count rate recorded. In singular fashion, an additional plate was placed on top of the preceeding one to increase the total magnesium thickness, and the

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count rate again was recorded. The experiment with each gage was terminated when the recorded count rate appeared to remain constant as the total magnesium thickness increased. Analysis of the data collected during the experiment is presented in Table 3, which shows the influence of each additional plate as a percent of the constant count rate when the test was completed. Table 4 indicates the accumulated percentages. Table 3 clearly shows that the collimated gage derives nearly equal influence from each 0.5 inch plate, up to a total depth of 2.5 inches. The uncollimated gage exhibited a definite decrease in influence over the same range of thicknesses. Table 4 reveals that 80 percent of the constant count rate is derived from approximately 3.2 inches and 1.7 inches of magnesium beneath the collimated and uncollimated gages respectively. Note also, that the collimated gage secured 10 percent of its constant count rate from depths greater than 4 inches, where as the uncollimated gage derived about 1 percent beyond 4 inches.

In the study of source collimation, an attempt was made to define and understand its important functions. It is believed that the principle reason for source collimation is the angular restriction of unattenuated emissions entering the test medium, and also, the reduction of surface attenuated radiation traveling in the general direction of the gamma detector. Surface attenuated radiation is very insensitive to soil density, and mainly governed by the surface texture of the soil and improper seating of the backscatter gage, causing air-gaps between the gage bottom and soil surface.

A desireable backscatter gage provides maximum radiation intensity entering the soil, and limits the direction of gamma-soil collisions at the soil surface. As the source is collimated, the radiation intensity decreases by the inverse square of the collimated distance away from the soil surface. Therefore, a compromise

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between maximum intensity and angle restriction must be reached. The most common method of producing a collimated source of radiation is by placing the source in the cavity of a lead housing. The shape and size of the cavity opening will govern the limitations of the compromise mentioned above.

Figure 4 illustrates a backscatter gage configuration consisting of the gamma source, collimator housing, and detector with shielding. The distance "h" represents the vertical distance from the center of the source to the bottom of the collimator. The distance "X" represents the horizontal distance from the center of the source to the left side of the collimator cavity. The figure shows the source in three positions within the cavity. The angles $\emptyset_1$, $\emptyset_2$, and $\emptyset_3$ represent the maximum restriction angle that causes gage measurements to be very sensitive to soil surface conditions, and results in the detection of radiation from shallow depths.

The optimum vertical source collimation required for a given gage design depends upon:

1. The horizontal source position within the collimator cavity.

2. The energy spectrum of the gamma source.

3. The amount and configuration of the lead collimator housing, and the shielding between the source and detector.

4. The intended gage use.

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The horizontal source position within the cavity determines the maximum path of radiation having the greatest probability of being directed towards the gamma detector. As the source is moved horizontally to the left within the cavity, less vertical collimation is required to maintain the same restriction angle (Figure 4).

The gamma source energy spectrum can also have an effect on the optimum collimation height. High energy sources, such as cobalt, require greater collimation heights and primary shielding to entirely absorb the gamma energy directed towards the wall vicinity of the cavity opening. At low collimation levels, a larger number of wall-attenuated photons, emerging from the gage bottom, can migrate to the detector. Possibly a textured sleeve of tungsten could be inserted to line the cavity wall to suppress the gamma migration.

The thickness and configuration of lead shielding between the source and detector determines the amount of direct photon migration included in the total density gage measurement, (Figure 5). Sufficient primary lead shielding, to prevent direct photon migration, must be provided to make source collimation effective. Under inadequate shielding conditions, direct photon migration will dominate the detector count rate and overshadow any change in soil density sensitivity produced by source collimation. In fact, the absence of shielding between the source and detector, would virtually eliminate density sensitivity.

Source collimation, as previously discussed, determines the number of attenuated photons being detected from various depths beneath the backscatter gage. Our experiments show that increased collimation yields detection of attenuated photons from greater depths. Therefore, the backscatter gage collimation design should be adjusted to reflect the soil density of the desired soil layer thickness beneath the gage.

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The design of the source housing and collimation cavity appears to have been overlooked by most gage manufacturers and researchers. The major objection to common cylindrical cavity source collimators is the significant decrease in count rate, which in some instances is statistically undesirable. Most of these count rate deficiencies however, can be overcome by proper design of the collimator cavity. The cavity opening should be designed to expose a maximum soil surface to a maximum gamma intensity, in a direction favorable to the density sensitivity of the gage. The cavity walls should be designed to control the amount of direct and indirect photon migration toward the detector.

c. Detector Collimation

The features of the detector housing and collimator cavity shape are similar, if not identical, to those of the source collimator-housing. The primary duty of the detector housing is to protect against direct and indirect photon migration. Detector collimation, as recorded by our experiments, was not beneficial to the density sensitivity of the gage. Collimation heights extending one inch above the gage bottom slightly decreased density sensitivity. This occurrence verified our expectations. Assuming that the number of direct and indirect photon migrations detected remained unchanged, the act of detector collimation reduced the number of detectable photons emerging from the soil beneath the detector. As a result, the detected ratio of soil attenuated photons to migration photons was decreased; thus effecting gage sensitivity to soil density changes. Our laboratory results must, however, be based on the size and shape of the detector collimator-housing. A vertical wall (Figure 5) helped oppose indirect photon migrations coming from the soil surface and gage bottom. Beveling this wall towards the source would have induced more migration detection. In this case, some detector collimation could possibly correct the beveled wall effects. Therefore, the primary

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advantage of detector collimation is supression of detecting soil-gage interface photons, and directional selection of photons aimed at the detector. Statistical count rates will, as mentioned in our discussion of source collimation, require a compromise between beneficial and detrimental detector collimation effects.

d. Primary Shielding

When lead shielding between the source and detector is completely removed, little or no density sensitivity will occur. In this case, the majority of the detected radiation has not entered the soil and therefore cannot be an indication of soil density attenuation. Once primary shielding is placed between the source and detector, the detected radiation is now more density sensitive, and is composed of more attenuated radiation returning from the soil. If the detector is properly shielded to eliminate all direct radiation, as illustrated in Figure 5, the backscatter gage response to soil density will greatly improve.

Table 5 contains data obtained using a three millicurie source of Cobalt-60 and a sodium iodide crystal detector. The table demonstrates the importance of providing sufficient primary shielding. Listed in the table are four conditions of primary shielding thickness versus three energy threshold levels. For each condition four values are listed. The first value is the count rate for a 60-second count period. The second value listed just beneath the count is the square root of the count rate. The third value is the percentage that condition four is of each of the other three conditions. The fourth value is a precision value which denotes the maximum precision to be expected for each condition. The precision factor is discussed in further detail later in this report.

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On examination of Table 5 many factors become apparent. These factors are discussed in the following paragraphs.

An examination of the count rate for each energy level shows condition four to yield a count which is considerably less than condition one. From this it can be concluded a preponderance of the condition one count is composed of nondensity sensitive radiation. As the lower discrimator energy level is raised, this condition is increased.

Upon examination of the square root of the count rate, it can be seen that the lower energy threshold level of the condition four value is approximately half that of condition 1. The higher energy threshold level condition (0.445 Mev) is less than one-fourth the condition one value.

To understand the significance of this value it must be remembered that although a radioisotope disintegration is of a random nature, if sufficient count is obtained the true mean rate of disintegration can be predicted to various levels of confidence. Sixty-eight percent of the time the indicated count can be expected to be within plus or minus one standard deviation of the true count. The standard deviation is calculated by taking the square root of the indicated count rate. From this and further examination of Table 5 it can be concluded that increased shielding increases gage precision. The precise amount for these conditions is listed as a precision value in units of pounds per cubic foot.

This is the upper limit of precision to be expected for a confidence level of 68 percent and is based solely on nuclear statistics. Electronic, chemical and mathematical errors are factors which can expand upon this error.

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The third value listed is a percentage. This is the percent of count that condition four is of the other three conditions. If it is assumed condition four is composed of 100 percent density sensitive radiation, or nearly so, then it can be seen that condition one is composed of predominantly nondensity sensitive radiation. It can also be concluded that as the lower energy threshold is raised the percentage of density sensitive radiation is decreased and that more primary shielding is necessary.

If the count rate for 0.227 Mev or 0.445 Mev is subtracted from the representive count rate for 0.090 Mev then the results divided by the 0.090 Mev value with the resultant multiplied times 100 then the percentage of the low energy between these two ranges is obtained. Upon examination of this percentage it can be observed that the percentage of lower energy radiation is increased, therefore, more composition error can be expected.

Direct Transmission Parameters

The parameters involved in the transmission mode, in many respects, are the same as those mentioned in our discussion of the backscatter mode. Other parameters, common to both modes of gage operation, will be discussed following this presentation.

Our study is limited to only one method of transmission gage operation. The transmission gage design currently used by our Department places the gamma source in the compacted soil and locates the detector on the soil surface, at a constant distance from the source. All comments in our discussion of the transmission mode will be exclusively devoted to this particular transmission configuration.

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a. Source-detector Separation

Source-Detector Separation is determined by measuring the shortest distance between the source and the center point of the gamma detector. Figure 3 illustrates the basic transmission gage in the operating position. Varying either the horizontal separation or transmission depth will alter gage performance significantly. The experimental results seem to support the same conclusion stated for the backscatter gage. As the gamma source and detector are separated, gage sensitivity to distinguish soil density differences improves.

b. Source and Detector Collimation

Source and detector collimation do not appear to be applicable to the transmission mode of operation. These conclusions are intuitively derived by the visual interpretation of Figure 3. Due to source positioning during the test, collimation would not have the same physical meaning as it does for the backscatter mode. In this case, the effect of raising the source towards the soil surface has the same effect as the source being at the surface, or the gage in the backscatter mode. Transmission response to soil density decreases as the gamma source approaches the soil surface.

Gamma photons, emanating from the source when using transmission mode, penetrate the soil in all directions, and randomly collide with the soil elements which determine their direction of migration. A portion of the omnidirectional emissions, initially migrating away from the direction of the detector, will be attenuated towards the detector. Some of these photons finally penetrate and activate the detector. Many of these detected photons probably possess very low gamma energies which are subject to photoelectric absorption by the soil elements. Detection of these photons have a potential for inducing chemical sensitivity or gage error.

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Experiments were not conducted to explore this potential or compensate for the presence of photons by detector adjustments. Future research could probe this subject by designing some sort of source cavity in the transmission rod to limit the omnidirectional emissions entering the soil.

We do not anticipate any improvement in transmission gage response by employing detector collimation. Since the gamma source is buried in the soil, the amount of indirect radiation migrating along the gage-soil interface is probably minimal; thus reducing the need for detector cavity design and collimation to restrict photon access to the detector. Detector collimation may be necessary, however, when shallow transmission depths are employed, which intuitively would increase indirect radiation migration.

c. Primary Shielding

Shielding requirements, to ensure optimum performance of the transmission gage, are not as stringent as those applied to the backscatter gage. Minimum shielding, to protect the gage operator and satisfy health safety requirements, must be provided within the gage body, in order to store and transport the portable gage. In addition to this basic requirement, some form of shielding should be provided in the transmission rod above the gamma source to prevent emission migration up to the soil-gage interface where some emissions could penetrate and activate the detector. This form of indirect migration would reduce gage sensitivity.

Backscatter Radiation From Nearby Objects

Of the total cloud of radiation emanating from the source only a fraction of a percent (less than 0.01%) will be detected by the detector. The radiation emanates from the source uniformly in all directions. As the radiation travels through the test

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material it is randomly scattered and absorbed by the test media and the environment. That radiation initially traveling in the direction of the detector is the most apt to be detected.

Surrounding all nuclear gages there is a volume of influence which is made up of the cloud of radiation emanating from the source. An object within this volume will alter the detected count rate by absorbing and/or scattering the radiation. This volume of influence includes not only the test material but the environment about the gage, including the gage itself. Therefore any object within the test volume of influence and foreign to the normal test environment can change the detected count and yield an erroneous test count. This is true whether the object is above or below the test surface or both.

This environmental volume of influence can be reduced to negligible levels by providing adequate shielding about the source and detector. The mode of operation (direct transmission or backscatter) and gage configuration determines how and when the shielding should be placed.

In the backscatter mode shielding should be placed about both the source and detector. Shielding is placed about the source to absorb radiation not traveling toward the test material. Shielding is placed about the detector to absorb radiation coming from other than the test material. Weight is a major factor governing the amount of shielding used.

In the transmission mode either the source or detector is placed in the test material. The other component remains in the gage. Adequate shielding of the component remaining in the gage will reduce errors caused by foreign objects to a negligible level.

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As said before these errors can be reduced to negligible levels but not eliminated completely. Therefore, it is always good practice to provide as much space about the gage as possible. A minimum of ten inches of clear space about the detector is a good rule to follow.

In Highway Research Report No. CA-DOT-TL-2130-1-73-41 entitled "Structure Backfill Testing", part of the conclusion of that report stated that field and laboratory studies showed no discernable wall effect if the density test was performed such that the source detector rod axis is kept parallel to and about 5 inches or more from the wall.

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MOISTURE DETERMINATION

Introduction

A nuclear moisture gage measures the water content of a soil by first irradiating the soil with fast neutrons and then detecting the neutrons that have been thermalized by the soil. The number of thermalized neutrons detected is very nearly proportional to the water content of the soil. Most soils contain little hydrogen except that present as part of the free water molecules. Hydrogen is the major contributor to the thermalization of fast neutrons. The mass of hydrogen and that of a neutron being nearly equal, when the two collide the hydrogen nucleus will absorb nearly half the energy of the neutron. As the mass of the atoms is increased the energy lost in collision with a neutron is decreased. For this reason hydrogen is the most efficient atom for thermalizing neutrons.

The probability that a nuclear reaction will occur between a neutron and any particular atom is referred to as the "neutron cross section", the measure of which is barns. One barn is equal to 10^{-24} square centimeters. The neutron cross section for the hydrogen in water is high when compared to other atoms commonly found in soils. For a more detailed description of moisture theory refer to California Department of Transportation Research Report titled "Improved Nuclear Gage Development", by Chan, et. al.

Sensitivity Response

a. Measures of Performance

Moisture sensitivity is a measure of gage performance and can be defined as the ability of a gage to determine small incremental changes in moisture content. The sensitivity response ratio

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is one measure of this ability. It is obtained by dividing the moisture count at 20 pounds moisture by the moisture count obtained at 5 pounds moisture. A second measure of gage performance is a precision value which is obtained by dividing the square root of the count at 15 pounds moisture by the slope of the calibration curve. This value indicates the expected variation based on nuclear decay statistics and does not include electronic stability or other sources of error.

b. Source Detector Separation

As the source and detector are separated the sensitivity response ratio and the precision value depreciate. For hand portable nuclear gages optimum source detector separation occurs when there is little source detector separation.

Collimation of the source and/or the detector degrades gage performance, but only to a limited extent. As an example, 1/2-inch collimation of the lithium iodide crystal produces a change in the precision value of 1.5%. A 1/4-inch collimation of both the source and the lithium detector produced a 6% drop in the sensitivity response ratio and a 10% reduction in the precision value.

c. Energy Discrimination

Energy discrimination can be used to improve gage performance. This discrimination can be accomplished electronically or mechanically by physically filtering out the lower energy neutrons by using a material with a high absorption cross section for thermal neutrons. By reducing the percentage of detected low energy neutrons the sensitivity response ratio can be increased and the precision value reduced.

Moisture-Soil Composition Effect

Nuclear moisture gages are subject to error due to neutron capture. The capture cross section for neutrons is a function of the neutron energy and varies with the element involved.

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The neutron capture cross section is a measure of the probability that a particular nuclear reaction will occur. The unit of measurement is barns. Most soils are composed of elements which possess low capture cross sections and compositional errors due to neutron capture are negligible. Occasionally materials are encountered which contain elements of high capture cross sections for neutrons. Errors produced by neutron capture result in erroneously low moisture indication. In these cases special calibrations are necessary if accurate nuclear soil moisture determinations are to be made. This compositional effect can be minimized but not eliminated if the low energy neutrons are not counted. Our work has borne this fact out.

Another source of error in nuclear moisture determinations is hydrogen in the soil not as free moisture but chemically bound. At the present time we have found no way to reduce error attributed to hydrogen as part of the soil structure. When this type of soil is encountered a special calibration must be used.

At the present time California's nuclear gage specifications contain no provisions to limit soil moisture determination compositional errors.

Two methods can be used to discriminate the lower energy neutrons; electronic discrimation and/or a system of filters.

Neutron detectors are proportional counters. The output pulse is proportional to the detected neutron energy. With this type of detector electrical discrimination may be used to count only detected neutrons which produce a pulse exceeding a selected amplitude. In this manner the low energy neutrons are not counted and compositional errors are reduced.

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Most neutron detectors detect only very low energy neutrons (thermal neutrons) or neutrons in the region up to 10 EV (epithermal neutrons). Some manufacturers use a system of neutron moderation and absorption about the detector to improve detector efficiency and also reduce compositional errors. This can be accomplished by using a system of polyethylene to both thermalize neutrons that are above thermal energies plus filter out the lower energy thermal neutrons. Cadmium by itself, or a system of cadmium and polyethylene combined has also been used successfully to improve gage performance.

Neutron Detector Evaluation

Five neutron detectors were evaluated. They consisted of two basic detector types, namely the proportional counter and the scintillation detector. Four proportional counter designs and one Lithium iodide scintillation crystal were examined. Two boron trifloride gas filled detectors, one helium detector, three gas filled detectors and one boron lined, carbon dioxide and argon gas filled detector were evaluated by laboratory experiments.

This will be a brief discussion of the neutron detector characteristics. For a detailed discussion refer to the neutron detector evaluation section of the California Department of Transportation Research Report titled, "Improved Nuclear Gage Development", by Chan, et.al.

a. Boron Trifloride Detector

At the present time the boron trifloride detector appears to be the most logical choice of detector for the nuclear moisture units. This detector has an extremely long flat high voltage plateau. The sensitivity to thermal neutrons is good and the detector can be operated with no apparent detrimental effects

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at high temperatures. The first detector tested remained stable up to 250°F and the second one remained stable to 300°F and was not tested beyond that temperature. The neutron gamma pulse height ratio is good at approximately 30 to 1. This detector showed no improvement for compositional error due to neutron absorption.

Table 6 is a listing of neutron detector specifications and characteristics.

b. Helium (He_3) Detector

The helium (He_3) detector demonstrated the highest neutron sensitivity of the proportional-counters tested. The detectors evaluated had a gas fill pressure of two atmospheres which make them sensitive to neutrons in the thermal range. The manufacturer's literature indicates at higher gas fill pressures the detectors are sensitive to neutrons with energies in the intermediate range. The use of these detectors could possibly reduce the error caused by neutron absorption. The high voltage plateau is short and steep. The neutron gamma pulse height ratio is approximately 10 to 1. Under normal operating conditions the overall performance of this detector was superior to those tested. At extreme operating temperatures (above 250°F) these detectors became unstable and when cooled did not return to the original operating condition.

For this reason we do not recommend use of the He_3 detector at the present time. One gage manufacturer has produced gages with these detectors but has since discontinued their use due to the instability problem associated with high temperature operation.

c. Boron Lined Detector

The boron lined detector demonstrated the lowest neutron

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sensitivity but the highest neutron gamma pulse height ratio. The plateau length was between 200 and 250 volts with moderately steep slope. The output pulse was of sufficient amplitude to eliminate the need for the use of a preamplifier. This detector produced the lowest compositional errors due to neutron capture. The low neutron sensitivity makes this detector undesirable for the portable nuclear gages.

d. Lithium Iodide Detector

The Lithium Iodide detector was used more as a research tool than actually evaluated for use in hand portable nuclear gages. The advantages of this type of detector is high thermal neutron count efficiency and the ability to detect neutrons in the intermediate neutron range. This detector demonstrated to be the least sensitive to the chemical composition of the material. The disadvantages are higher expense, it is relatively fragile and is temperature sensitive; all of which make it impractical for use in portable units.

e. Moisture Detector Shielding

Unlike the density detectors it is not necessary to place shielding about neutron detectors. Lead will reduce the gamma background count but is a very poor moderator of neutrons. Ra-Be and Am-Be emit fast neutrons only which must be moderated to be detected by proportional counters or scintillation crystals. They detect only very slow and thermal neutrons. Therefore, lead shielding about the detector is not necessary unless the source produces an excessively high gamma background count.

Some gage manufacturers place a shield of high hydrogen content about the detector. The purpose of the shield is to improve the detectors efficiency by:

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1. Detecting thermal neutrons which initially passed through the detector undetected.

2. The thermalization and detection of neutrons slightly above the detection threshold of the detector.

On the negative side the additional hydrogen raises the background neutron count. The overall effect is to improve the gage performance by increasing the neutron detection rate and decreasing the soil compositional errors by including the detection of higher energy neutrons which have a smaller cross-section for neutron capture.

Cadmium foil can be placed around the detector sides and top to reduce the detection of nonmoisture thermalized neutrons. These are neutrons that have been thermalized by the material of the gage or objects in the immediate environment about the gage. Cadmium has an extremely high capture cross section for thermal neutrons.

Our work has shown that if a material with a high hydrogen content such as polyethylene plastic is used as a detector housing, the effect can increase detector efficiency. With a dry soil the intensity of thermal neutrons about the moisture detector is much less than the intensity of thermal neutrons about the detector when a wet soil is tested. It follows that the number of nonmoisture sensitive neutrons detected due to the addition of polyethylene to the gage should remain essentially constant with changes in moisture content. However, as the soil moisture content about the gage increases the intensity of the thermal neutrons about the detector will increase also, and the increased number of neutrons detected due to the addition of the polyethylene should increase proportionally thereby increasing the efficiency of the detector. The high hydrogen content material has several effects:

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1. It redirects some thermal neutrons which have initially passed through the detector undetected.

2. It rediverts and causes to be detected some thermal neutrons which have missed the detector initially.

3. It will thermalize, redirect and cause to be detected some neutrons which were initially at energies above the detection threshold. (Detection of these higher energy neutrons can reduce soil compositional error.)

Of course, one disadvantage is that the polyethylene will also cause to be detected some neutrons which are not moisture sensitive. However, if the overall effect is to increase the detector efficiency then the detection of these nondensity sensitive neutrons cannot be considered detrimental. That is, if the sensitivity response ratio is increased and the gage precision is improved the addition is beneficial.

Our work has shown that a filter system composed of an outer shield of cadmium foil to absorb thermal neutrons and an inner layer of polyethylene to thermalize intermediate energy neutrons will decrease the error caused by thermal neutron absorption. Also a filter of polyethylene by itself will also decrease this error but in both cases the sensitivity response ratio and gage precision are adversely affected and the dry moisture count is increased considerably.

Neutron Source Evaluation

Our evaluation of radioisotopes for moisture determination was restricted to two sources, radium beryllium and americium beryllium. These are two of the most commonly used sources for moisture determination. Our purpose was to determine which was

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the most suitable source for a nuclear-moisture gage combination. Table 7 lists some of the more important properties of both sources. Plutonium beryllium is also a commonly used moisture source and for this reason it is included in the table although it was not a part of this study.

a. Radium 226 Beryllium

As can be seen from Table 7 radium beryllium has both an excellent neutron yield and a long half life. The major disadvantage of this source stems not from the neutron yield but from the spectrum of gamma energies emmitted. A radium 226 source with all daughter radiations grown in emits fourteen distinct levels of gamma energy ranging from 0.047 to 2.42 Mev. The higher gamma energies require increased shielding and the associated weight increases. A radium beryllium source also produces photo neutrons with a maximum neutron energy of 0.7 Mev. These low energy neutrons result in degraded moisture performance. Another negative factor is the production of radioactive radon gas which present a potential health hazard should a capsule become ruptured.

b. Americium 241 Beryllium

Americium 241 has a low yield of gamma photons, the majority of which are below 0.1 Mev. Maximum gamma photon energy is 0.77 Mev which is well below the photon energy level required to produce photo-neutrons. The half life of Americium (458 years) while only one-third that of radium 226 is more than adequate to provide the long term stability requirements. The neutron yield of Americium is approximately one-seventh that of radium, but sufficient quantities can be obtained without detrimental effects by increasing the source size to provide sufficient neutron intensity while not producing excessive gamma background or shielding problems.

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SUMMARY OF RESEARCH OBJECTIVES AND CONCLUSIONS

A summary of the conclusions derived from the research, to date will be discussed in the numerical order listed by the research objectives.

1. Gage sensitivity to soil moisture content and soil density can be improved significantly. Table 8 lists the sensitivity specifications used by the California Department of Transportation in the past, and also indicates a practical upper limit obtainable through research gage design.

This project has also demonstrated that the practical upper limit shown in Table 8 can be exceeded by possibly compromising other gage performance parameters.

2. Deviation of density measurements or measurment error, caused by soil composition, can be substantially reduced by monitoring a selected range of soil attenuated photons, in addition to proper design of other gage parameters. The practice of selected photon energy detection, commonly known as "Energy Discrimination", showed that 1972 specification requirements could be tightened by at least twenty percent. Table 9 lists the density deviations, defined and referred to as "Chemical Sensitivity" in pounds per cubic foot, as revealed by research and as stated by specifications.

Specifications defining Chemical Sensitivity for moisture measurements have not been established by the California Department of Transportation. The necessity of establishing this criteria has not been justified, due to a heavy reliance upon the wet density procedure to determine relative compaction.

3. Presently, there are no specifications directly relating to source-detector shielding or separation arrangements. These parameters have been controlled indirectly by gage performance

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specifications. The shielding surrounding both source and detector directly affect the performance of the nuclear density and moisture gages. Maximum shielding will result in best gage performance. However, shielding as well as separation have been limited by weight and size requirements imposed by present specifications. In general, increased source-detector separation results in greater density gage sensitivity, where as decreased source detector separation yields greater moisture gage sensitivity. The precise placement, configuration, and shielding design of the nuclear gage should remain at the manufacturer's discretion.

4. The density gage can be successfully isolated from radiation scattered by nearby objects above the soil surface. Shielding on top and sides of the source and detector will reduce to negligible levels this form of scattered radiation.

Methods of reducing moisture measurement error by detecting gamma and thermalized neutrons created within the gage body have not been investigated. This amount of radiation is extremely large, due to the location of the neutron detector adjacent to the neutron-gamma source. This effect has been present in all commercial gages which have been examined to date. The errors introduced in moisture measurements are significant, ranging up to 30 percent of the detected count rate. One manufacturer has placed a polyethylene shield, covered with cadmium foil, on top of the thermal neutron detector. This approach appears successful in reducing moisture gage errors.

5. Detector performance criteria of two basic detector types was evaluated. The gas-filled tube and the crystal scintillator types were examined. Scintillator detectors were found superior in performance, to the gas-filled detector but could not withstand the temperature and handling abuse during field use without special design precautions. Research emphasis was placed on investigating commercially available Geiger-Mueller gamma detectors and gas-filled thermoneutron detectors (proportional counters).

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Three Geiger-Mueller detectors commonly used in density gage instrumentation were evaluated. These were tantalum lined platinum lined and unlined detectors. A platinum lined detector performed excellently and remained stable at high operating temperatures. A tantalum lined detector performed equally well, but could not tolerate temperature extremes. An unlined detector proved to be inferior to the lined detectors and was not considered for further investigation.

The platinum lined, halogen quenched Geiger-Mueller detector was found to be the most suitable gamma detector for portable nuclear density gages.

Several proportional counters were considered during our investigations. Two Boron Trifloride detectors, one Helium 3 detector, and one Boron Lined detector, filled with a mixture of carbon-dioxide and argon, were tested in the Laboratory. The Boron Trifloride detectors appear to be superior for thermoneutron moisture gage use based on low operating voltage, plateau length, neutron to gamma pulse height ratio, temperature sensitivity, and plateau slope.

6. Cesium-137, Cobalt-60, and Radium-226 were the three gamma sources examined in the course of this project. Selection of the most suitable gamma source was based on several considerations. Most important among the factors considered were shielding, related to gage weight and size, gamma yield and predominant initial photon energy, chemical sensitivity caused by photoelectric absorption, and gamma photon penetration effects on thermoneutron detector performance. The best overall gamma source to employ was found to be Cesium-137.

Americium-beryllium and Radium-beryllium were evaluated for moisture gage use. Criteria similar to those mentioned in our discussion of the gamma source were applied to the neutron source study. The

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fast neutron source selected must be compatible with a Cesium-137 gamma source placed in the same vicinity of the dual purpose moisture-density gage. Self absorption and emission of low energy gamma photons were considered. These emissions could prove detrimental to density gage performance. The possibility of gamma-neutron reactions were also studied. Low neutron energies derived from these reactions may hinder moisture gage response.

This evaluation demonstrated that Americium-beryllium is the preferred neutron source for nuclear moisture determination use. Radium-beryllium was rejected as a neutron source on the basis of the detrimental effect it had on the density system of the dual gage, the shielding requirements, and the influence of gamma-neutron reactions.

8. The performance of the backscatter gage can be improved substantially to a level which will meet or exceed most of the performance parameters displayed by the transmission gages found on the market today. The areas where the backscatter mode can not compete with the transmission mode are depth of the density test and sensitivity to surface roughness. The backscatter gage is limited to less than four inches of compacted soil beneath the gage. Secondly, the test surface must be plane and relatively smooth, to provide intimate contact area along the soil-gage interface. Although proper backscatter design can reduce surface sensitivity, and increase the effective test depth, we cannot foresee the backscatter gage being equivalent to the transmission gage in these areas.

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TYPICAL COMMERCIAL GAGE CONFIGURATION

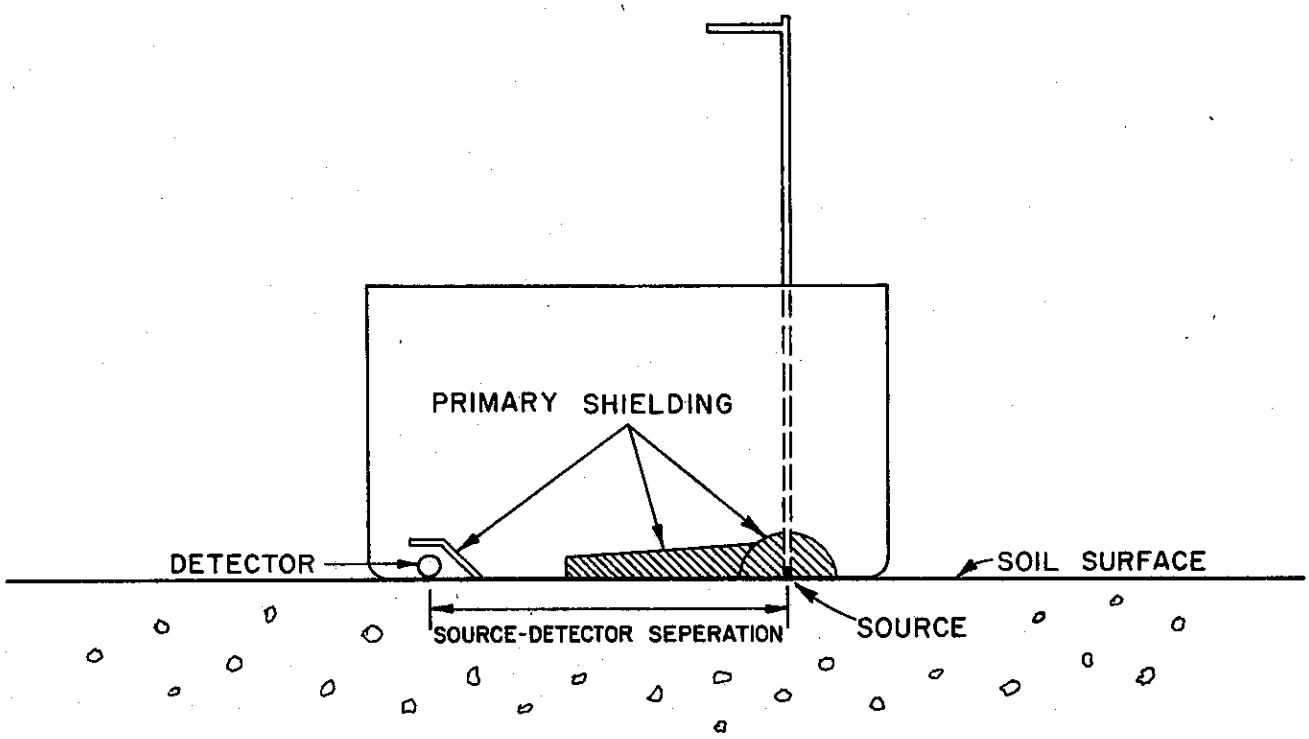

Fig. 1 BACKSCATTER MODE

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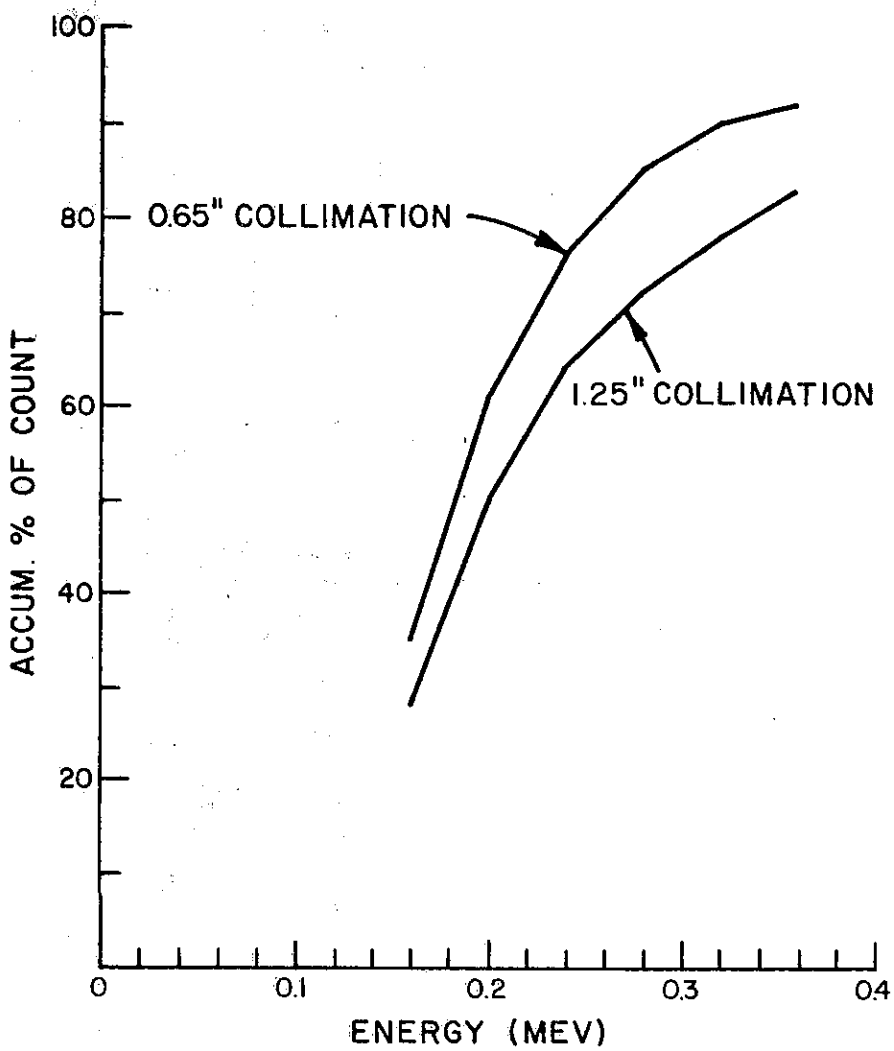
Figure 2

TYPICAL CURVE DEMONSTRATING THE EFFECT OF INCREASED SOURCE COLLIMATION



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TYPICAL COMMERCIAL GAGE CONFIGURATION

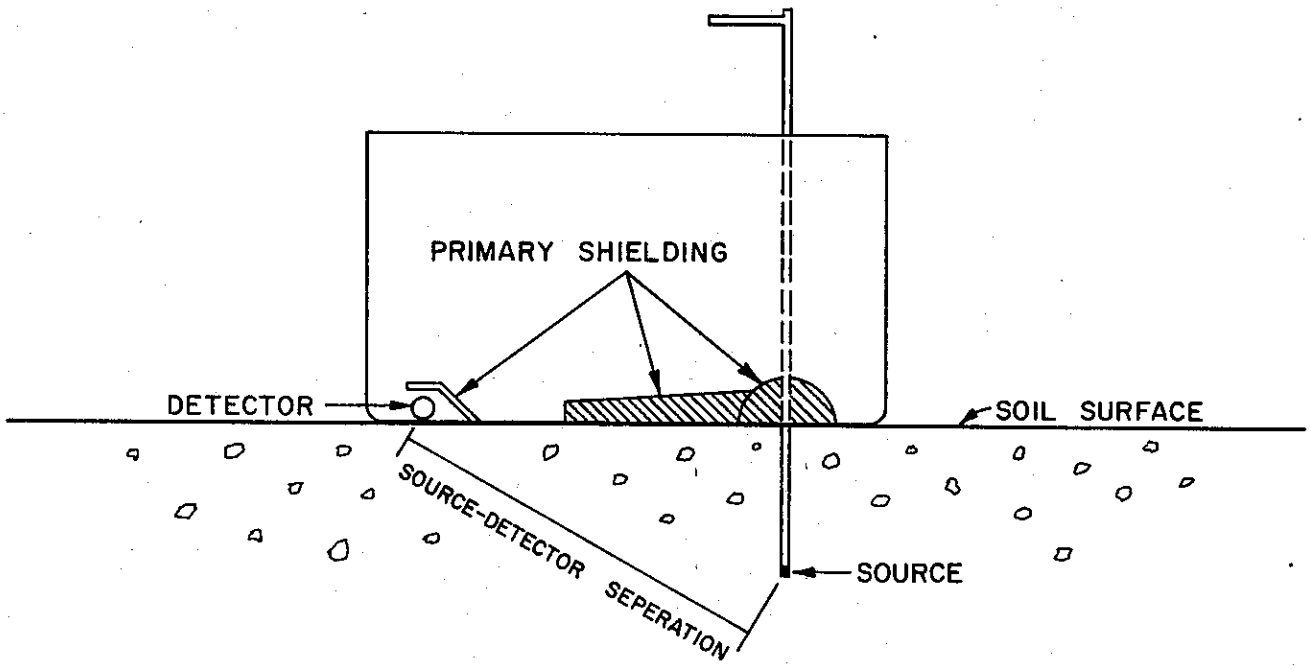

Fig. 3 TRANSMISSION MODE

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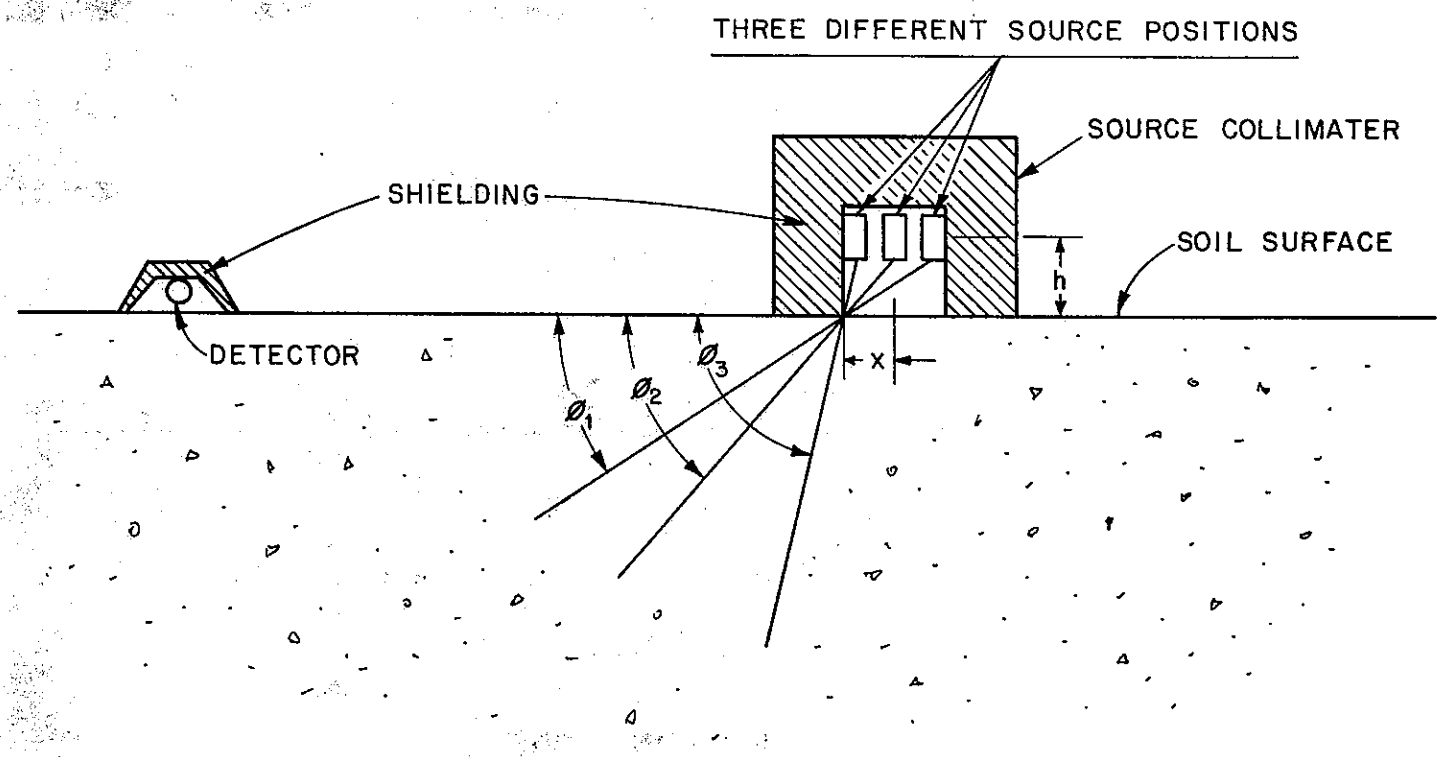

Fig. 4 SOURCE COLLIMATOR DEMONSTRATING VARYING HORIZONTAL GAMMA SOURCE POSITIONS

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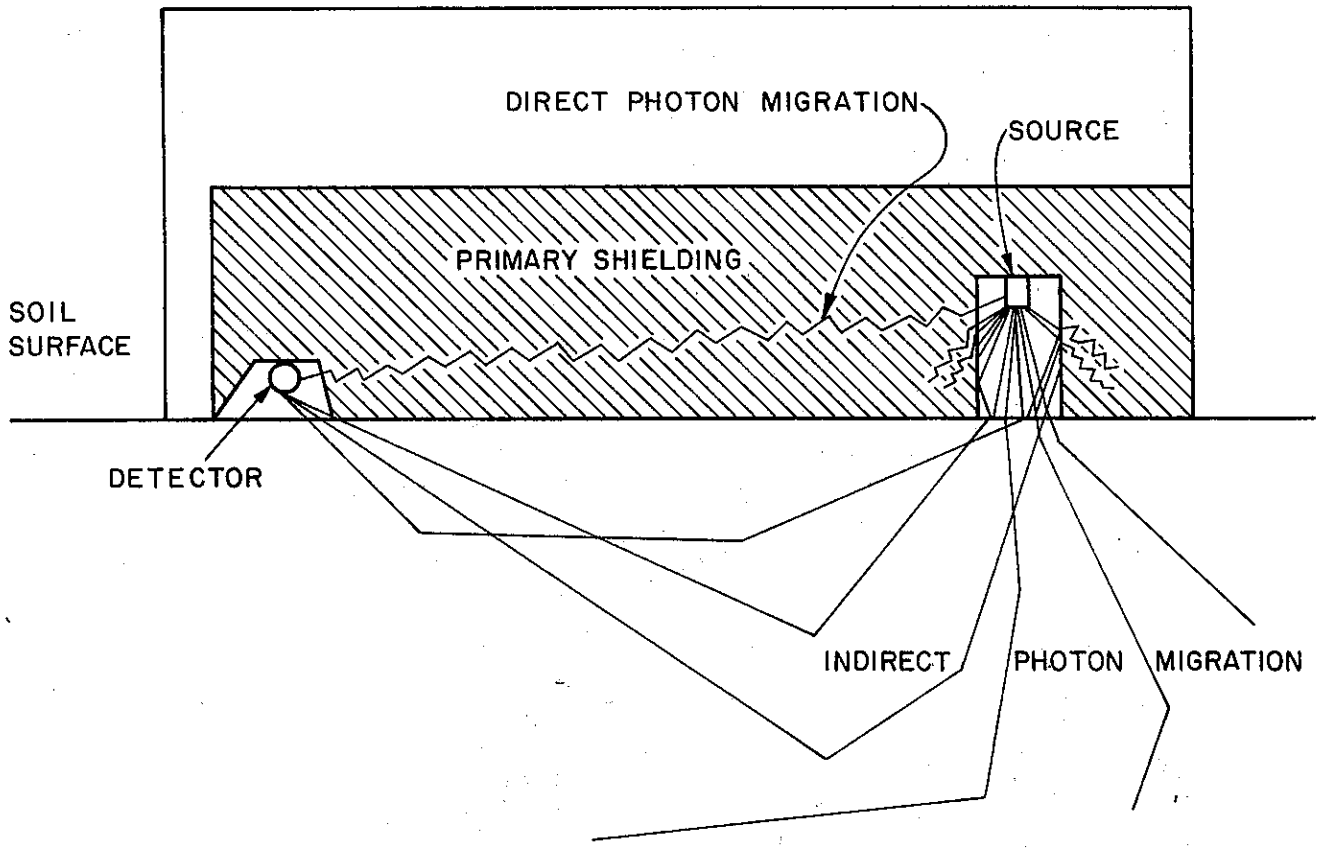

Fig. 5 EXPERIMENTAL GAGE
DEMONSTRATING PHOTON MIGRATION TO DETECTOR

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EFFECT OF SOURCE-DETECTOR SEPARATION ON PERCENT OF DETECTED COUNT FROM DIFFERENT ENERGY LEVELS

TABLE 1

Energy (Mev)	9.3" Source-Detector Separation Count	%	Acc. %	13.0" Source-Detector Separation Count	%	Acc. %
.02	975	1.4	1	274	1.7	2
.04	1379	1.9	3	329	2.0	4
.06	1921	2.7	6	410	2.5	6
.08	3771	5.3	11	819	5.0	11
.10	6873	9.7	21	1599	9.8	21
.12	7116	10.0	31	1592	9.8	31
.14	7025	9.9	41	1621	9.9	41
.16	6523	9.2	50	1486	9.1	50
.18	5624	7.9	58	1368	8.4	58
.20	5325	7.5	66	1204	7.4	66
.22	4809	6.8	72	1020	6.3	72
.24	4280	6.0	78	947	5.8	78
.26	3749	5.3	84	843	5.2	83
.28	3175	4.5	88	704	4.3	87
.30	2776	3.9	92	613	3.8	91
.32	2173	3.1	95	514	3.2	94
.34	1619	2.6	97	406	2.5	97
.36	1165	1.6	99	313	1.9	98
.38	795	1.1	100	239	1.5	100
Total	71073			16301		

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SENSITIVITY RESPONSE TO CHANGES IN SOURCE DETECTOR SEPARATION UNDER VARIABLE CONDITIONS

TABLE 2

Condition	Energy Interval (Volts)	Source Colimation (Inches)	Sensitivity Response (Ratio)	Source Detector Separation (Inches)
I	0.35 to 2.0	0.65	2.15	15
			1.97	14
			1.89	13
			1.71	11-3/8
			1.58	10-1/4
II	0.5 to 2.0	0.65	2.07	15
			1.86	13
			1.67	11-3/8
			1.54	10-1/4
III	0.5 to 2.0	1.0	2.12	15
			1.93	13
			1.59	10-1/4
IV	0.5 to 10.0	0.65	1.76	12
			1.67	11-38
			1.55	10-1/4

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TABLE 3

INFLUENCE OF DEPTH INTERVAL ON % OF TEST COUNT
FOR COLLIMATED AND UNCOLLIMATED NUCLEAR GAGES

Source Collimation Height	Depth Interval* 0.0" to 0.5"	0.5" to 1.0"	1.0" to 1.5"	1.5" to 2.0"	2.0" to 2.5"	2.5" to 3.0"	3.0" to 3.5"	3.5" to 4.0"	>4"
0	31	27	17	10	8	4	1	1	1.0
1/2"	12	15	15	15	13	8	6	6	10.0

TABLE 4

INFLUENCE OF DEPTH ON ACCUMULATIVE % OF COUNT
FOR COLLIMATED AND UNCOLLIMATED NUCLEAR GAGES

Source Collimation Height	Depth* 0.5"	1.0"	1.5"	2.0"	2.5"	3.0"	3.5"	4.0"	>4
0	31	58	75	85	93	97	98	99	1
1/2"	12	27	42	57	70	78	84	90	10

*Magnesium Plate Thickness

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TABLE 5

INFLUENCE OF PRIMARY SHIELDING ON NUCLEAR GAGE COUNT AND PRECISION

Energy Threshold (MEV)	Values	Primary Shielding Conditions (Inches of Lead) Cond. 1 1.4"	Cond. 2 3.4"	Cond. 3 5.4"	Cond. 4 7.4"
0.090	Count	245423	78346	67662	66722
	$\sqrt{\text{Count}}$	495	280	260	258
	%	27	85	99	100
	Precision	$\pm$.29 lb/ft^3	$\pm$.16 lb/ft^3	$\pm$.15 lb/ft^3	$\pm$.15 lb/ft^3
0.227	Count	162413	35053	27528	26533
	$\sqrt{\text{Count}}$	403	187	166	163
	%	16	76	96	100
	Precision	$\pm$.73 lb/ft^3	$\pm$.39 lb/ft^3	$\pm$.30 lb/ft^3	$\pm$.30 lb/ft^3
0.445	Count	87881	10290	5442	4542
	$\sqrt{\text{Count}}$	296	101	74	67
	%	5	44	83	100
	Precision	$\pm$4.4 lb/ft^3	$\pm$1.5 lb/ft^3	$\pm$1.1 lb/ft^3	$\pm$.99 lb/ft^3

Note: 3 MC Cobalt-60 Source

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TABLE 6

NEUTRON DETECTOR SPECIFICATIONS

Neutron Detector Type	Boron Trifloride #1	Boron Trifloride #2	Boron Lined	Helium Three	Lithium Iodide Crystal
Diameter	1"	2"	1"	1"	1.5" D. x 3 mm Thick
Sensitive Length	8"	8"	4"	6"	- - - - - - -
Plateau Length	1150 V	250 V	50 to 100 V	50 to 200 V	No Plateau
Plateau Slope	<.02%/Volt	.004%/Volt	0.1%/Volt	<.250%/Volt	Approx. 0.2%/Volt
Max. Operating Voltage	3000 V	2000 V	2000 V	2000 V	1500 V
Max. Operating Temperature	150° C	120° C	200° C	120° C	120° C
Neutron Sensitivity s/n/cm^2-sec.	4	Not known	1	8	Not known
Neutron Gamma Ratio	30:1	20:1	40:1	10:1	9:1
Composition Error	7.0 lbs	7.0 lbs	4.0 lbs	7 lbs	2.2 lbs
Gas Fill Pressure	40 cm hg	Not known	1 cm hg CO_2 19 cm hg Argon	152 cm hg	- - - - -
Gas Fill Type	BF_3	BF_3	CO_2 Argon	He_3	- - - - -

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TABLE 7

NUCLEAR SOURCE PROPERTIES

	Source		
	Radium-Beryllium	Americium-Beryllium	Plutonium-Beryllium
Half Life	1620Y	458Y	24360Y
Gamma Neutron Theoretical Yield per 10^6 Disintigrations	550	74±2	60±2
Practical Yield Neutron/Sec/Curie	1.0-1.5 x 10^7	2.2 x 10^6	1.8 x 10^6
Max. Neutron E (Mev)	13.08	11.0	10.74
Average Neutron Energy (Mev)	3.9	- - -	4.5
Average Alpha Energy (Mev)	- - -	5.47	5.14
Maximum Gamma Energy (Mev)	2.42	0.722	0.72
Major Alpha Energy and Occurance	4.78 95% 4.60 6%	5.49 85% 5.44 13%	5.16 88% 5.11 11%

TABLE 8

SENSITIVITY SPECIFICATIONS

Specification Period	1969	1970	1972	Practical Upper Limit
Moisture Sensitivity Response Ratio (Backscatter)	≥3.0	≥3.0	≥3.0	≥3.7
Density Sensitivity Response Ratio 8" Transmission Mode	≥1.9	≥1.9	≥2.0	≥2.5
Backscatter Mode	≥1.3	≥1.3	≥1.5	≥1.8

TABLE 9

CHEMICAL SENSITIVITY SPECIFICATION (lb/ft^3)

Specification Period	1969	1970	1972	Practical Upper Limit
Chemical Sensitivity 8" Transmission Mode	≤4	≤3.0	≤2.5	≤1.5
Backscatter Mode	≤6	≤4.0	≤2.5	≤2.0

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GLOSSARY OF TERMS

This glossary is provided to define terms as they are used in this report.

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Absorption: The process by which radiation imparts some or all of its energy to any material through which it passes. (See Compton Effect, Photoelectric Effect, and Pair Production.)

Attenuation: The process by which a beam of radiation is reduced in intensity when passing through some material. It is the combination of absorption and scattering processes and leads to a decrease in flux density of the beam when projected through matter.

Background Count: Count arising from any source other than the one directly under consideration. This may include but is not limited to; electronic noise, cosmic radiation and radiation from other sources in the area.

Backscatter Mode: The determination of moisture or density by the detection of backscattered radiation. (See Figure 1).

Backscatter Radiation: Radiation that has been scattered by collisions through angles of greater than 90° with respect to the original direction of motion.

Barn: Unit expressing the probability of a specific nuclear reaction, in terms of neutron cross-sectional area. Numerically, it is 10^{-24} cm^2.

Cathode: Negative electrode; electrode to which positive ions are attracted.

Chemical Sensitivity: The sensitivity of a gage to the mineral composition of a soil. The measure of which is the maximum deviation in pounds per cubic foot produced between two sets of calibration standards, one set being predominantly siliceous and the other calcareous. This is over a range of 100 to 160 pounds per cubic foot.

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Compton Effect: An attenuation process observed for x-ray or gamma radiation in which an incident photon interacts with an orbital electron of an atom to produce a recoil electron and a scattered photon of energy less than the incident photon.

Count: (Radiation Measurements) The external indication of a device designed to enumerate ionizing events. It may refer to a single detected event or to the total number registered in a given period of time.

Counter,Geiger-Mueller: A gas filled counting tube with a cylindrical outer shell (cathode) and an axial wire electrode (anode). Used for detecting the presence of cosmic rays or radioactive substances by means of the ionizing particles that penetrate its envelope and set up momentary current pulsations in the gas.

Counter, Scintillation: The combination of phosphor, photo-multiplier tube, and associated circuits for counting light emissions produced in the phosphors.

Count Rate: The number of detected events per unit of time.

Cross Section, Capture: The probability that a nucleus will capture an incident particle. The unit of cross section is commonly the barn (10^{-24} cm^2).

Cross Section, Nuclear: The probability that a certain reaction between a nucleus and an incident particle or photon will occur. It is expressed as the effective "area" the nucleus presents for the reaction.

Curie: The basic unit to describe the intensity of radio-activity in a sample of material. The curie is equal to 37 billion disintegrations per second. A curie is also a quantity of any nuclide having 1 curie of radioactivity.

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Density Sensitivity: Density sensitivity is a measure of the ability of a gage to detect small incremental changes in density. A measure of density sensitivity is the sensitivity response ratio (S.R. Ratio). The sensitivity response ratio definition is included in the Glossary of Terms.

Detector: Material or a device that is sensitive to radiation and can produce a response signal suitable for measurement or analysis. A radiation detection instrument.

Detector Collimation: The act of physically selecting gamma photons to be detected by chamber design and positioning within the chamber.

Direct Radiation: That portion of the detected radiation which has penetrated the primary shielding.

Depth Influence Gradient: The depth of influence gradient is the measurement of the gage influence to each increment of depth expressed as a percent of the total change in count as determined by placing 0.5-inch thick magnesium plates on a concrete standard of approximately 150 lbs. per cu. ft. density.

Electron Volt: A unit of energy equivalent to the energy gained by an electron in passing through a potential difference of one volt. Larger multiple units of the electron volt are frequently used: KeV for thousand or kilo electron volts; MeV for million or mega electron volts. (Abbreviated: eV, 1 eV = 1.6×10^{-12} erg.)

Electronic Stability: Freedom from electronic drift or the generation of extraneous counts by the electronic system.

Energy Discrimination: The process by which a band of energies is selected by rejection of those falling outside this band. This can be accomplished electronically or by the use of filters.

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Epithermal Neutron: A neutron in the intermediate neutron energy range between 0.5 eV and 100,000 eV.

Fast Neutron: Neutrons at energies between 10 keV and 20 MeV.

Gamma Ray: High-energy, short-wave length electromagnetic radiation. Gamma rays are very penetrating and are best stopped or shielded against by dense materials such as lead. Gamma rays have no mass or charge and exist only as photons of energy.

Half-life, Radioactive: Time required for a radio-active substance to lose 50 percent of its activity by decay. Each radionuclide has a unique half-life.

Moisture Sensitivity: Moisture sensitivity is a measure of the ability of a gage to respond to variations in moisture. This is measured by the moisture sensitivity response ratio which is calculated by dividing the moisture calibration count at 20 lbs. of water per cubic foot by the count at 5 lbs. water per cubic foot.

Neutron: An uncharged elementary particle with a mass slightly greater than that of a proton. A free neutron is unstable and decays with a half-life of about 13 minutes into an electron, proton and a neutrino.

Neutron-Gamma Pulse Height Ratio: The neutron gamma pulse height ratio is the ratio of the observed mean neutron pulse height to the observed maximum gamma pulse height.

Pair Production: An absorption process of X-ray and gamma radiation in which the incident photon is annihilated in the vicinity of the nucleus of the absorbing atom, with subsequent production of an electron and positron pair. This reaction only occurs for incident photon energies exceeding 1.02 MeV.

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Photon: The carrier of a quantum of electromagnetic energy. Photons have an effective momentum but no mass or electrical charge.

Photoelectric Effect: Process by which a photon ejects an electron from an atom. All the energy of the photon is absorbed in ejecting the electron and in imparting kinetic energy to it.

Plateau: As applied to radiation detector chambers, the level portion of the counting rate-voltage curve where changes in operating voltage introduce minimum changes in the counting rate.

Primary Shielding: Primary Shielding is that shielding which is placed between the source and detector for the purpose of isolating the detector from nondensity sensitive radiation.

Proportional Counter: A gas-filled radiation detection device; the pulse produced is proportional to the number of ions formed in the gas by the primary ionizing particle. Normally used for thermal neutron detection.

Radioisotope: A radioactive isotope. An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation.

Sensitivity Response Ratio (Density): The ratio of the count at 110 lb. per cubic foot density divided by the count at 140 pounds per cubic foot. This count is determined from the gage density calibration.

Sensitivity Response (Moisture): The ratio of the count at 20 pounds per cubic foot moisture divided by the count at 5 pounds per cubic foot moisture. This count is determined from the gage moisture calibration.

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Scintillation Counter: An instrument that detects and measures ionizing radiation by counting the light flashes (scintillations) caused by radiation impinging on certain materials (Phosphors).

Source Collimation: Collimation of the source is defined as the positioning of the source within its protective lead shield to produce a beam of radiation traveling in a desired direction and absorbing radiation traveling in other than the desired direction.

Source Detector Separation: The horizontal separation between the center of the source capsule and the longitudinal axis of the detector.

Surface Texture Sensitivity: This is the sensitivity to the surface texture. It is measured by the deviation produced in pounds per cubic foot between a specified air gap condition and the flush condition.

Thermal Neutron: Neutrons in thermal equilibrium with their surroundings. In the report all neutrons with energies less than 0.5 eV will be considered in the thermal energy range.

Transmission Mode: The determination of density by providing a direct path from the source to the detector through the material being tested (see Figure 3).

Tube, Photomultiplier: An electron multiplier tube in which the electrons initiating the cascade originate by photoelectric emission.

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APPENDIX A

California Department of Transportation
Specifications for Nuclear Density-Moisture Gage

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SPECIFICATIONS FOR NUCLEAR DENSITY-MOISTURE GAGE

September 1973

I. GENERAL

The portable nuclear density-moisture surface gage shall be suitable for determining density and moisture of soils, aggregates, treated bases, and the density of asphalt pavements. It shall be capable of determining density in two operating modes. These modes shall be direct transmission of gamma radiation, and backscatter of gamma radiation. The gage shall determine moisture by detecting backscattered thermalized neutrons.

The gage shall be a single unit, self-contained and consist of a radioactive source, radiation detectors, power supplies, counting circuits, timing circuits, data display, and related electronic components.

The gage shall be dustproof, moisture proof, shock resistant, and electronically stable. The gage shall operate reliably, accurately, and with negligible drift, in all three operating modes, over an ambient temperature range of 32°F to 145°F and with the probe on, or in, material whose internal and surface temperature will range between 32°F and 300°F.

The radioactive source shall be in the transmission rod and the radiation detector(s) in the case.

The gage shall weigh not more than forty (40) pounds and have outside dimensions not to exceed seventeen (17) inches in length, ten (10) inches in width and twenty-two (22) inches in height.

All above specified dimensions apply to the gages with any appurtenant lid or cover in place and closed. The dimensions include the carrying handle and any exterior tube positioning brackets with the tubes in place.

All electronic circuitry, radiation detectors and batteries shall be so arranged as to be easily removable from the case without removing, unshielding, or in any way disturbing the source.

All electronic circuitry shall be of solid state, mechanically sound, modular construction. The circuitry shall be mounted on G-10 epoxy glass plug-in circuit boards. The manufacturer shall provide sufficient "burn-in" time for electronic subassemblies to assure himself that premature failure or change

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in electrical characteristics of a component is only a remote possibility. The length of "burn-in" time shall conform to current instrumentation industry practice and in no case shall be less than fifty (50) hours total.

An exterior service access opening shall be provided in the gage case to permit the use of an external test meter to check the output of the primary voltage supplies while the circuitry is in operation. High voltage adjustment controls to obtain plateau curves for the gamma and neutron detectors shall be adjustable by means of the service access opening. The intent is that the external test meter connection facilities, and the high voltage adjustment controls will be affixed to the electronic circuitry chassis in such a way as to be removable from the case as part of the chassis for bench testing and adjustment, as well as to be reachable through the access opening for field testing and adjustment without removal of the electronic chassis from the case. A dust and moisture proof cover plate to be provided for the service access opening shall be secured in place by means of machine screws rather than sheet metal screws.

Exception to the external test meter connection facilities may be taken, provided the manufacturer supplies a suitable extender board as a part of the gage purchase price. The use of such a board shall be evaluated, on an actual gage, by the purchaser to determine whether or not the exception will be allowed. A bidder may also take exception to the provision of high voltage adjustment controls provided the detectors meet the requirements set forth in Section II of these specifications.

Design of the probe, scaler, and control panel shall reflect consideration of the human operator and the manner in which he functions as the user of the gage.

II. GAGE SYSTEM

The radioactive source, to be placed in the ground for operation in the direct transmission mode shall be contained in a transmission rod either 5/8 $\pm$ 1/64 inch in outside diameter or 3/4 $\pm$ 1/64 inch in outside diameter. The tube shall be made of non-corrosive material having a minimum hardness of 60 as rated on the Rockwell B scale. The tube shall be strong enough to resist bending in normal hard usage and the outside surface shall be smooth and true. Permanent markings, referenced to the center of a radioactive source within the rod, shall be provided on the outside surface of the rod (or guide rod) at one (1) inch intervals to denote, from two (2) to eight (8) inches, the depth, below ground, of the transmission readings.

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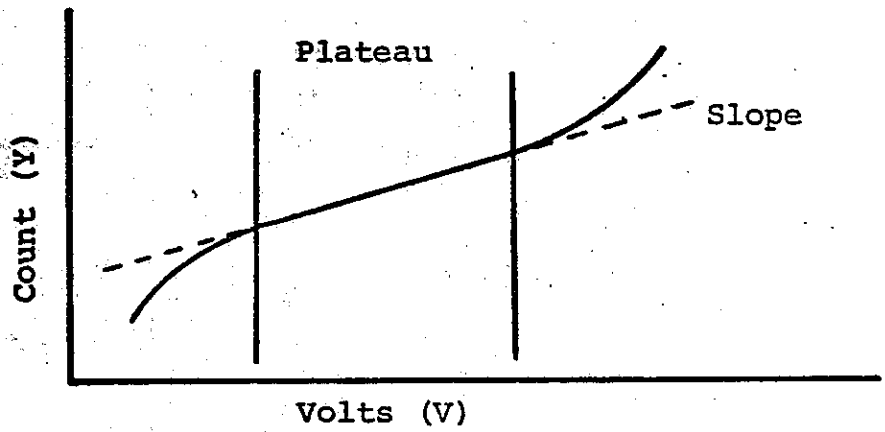
Any gamma detector used in the gage shall be of the halogen quenched, platinum cathode, Geiger-Mueller type. The operational response curve of any gamma detector used in the gage shall exhibit a well defined plateau with respect to applied voltage when used on a density standard weighing between 100 and 140 lbs. per cu. ft. The plateau shall have a minimum length of two hundred and fifty (250) volts and shall have a slope of five (5) percent, or less, per one hundred (100) volt change. The slope percentage shall be based on the following relationship:



$$\text{Slope} = \frac{Y_2 - Y_1}{\left(\frac{Y_2+Y_1}{2}\right)\ (V_2-V_1)}\ (10^4) = \%/100 \text{ volts}$$

Y = Counts
V = Volts

The operating voltage, for the gamma detector, shall be set by the manufacturer at a point in the plateau about one-third (1/3) of the length of the plateau from the lower end. In the event the manufacturer elects to provide a fixed high voltage supply, rather than the specified variable supply, he shall provide a certificate stating that the detector characteristics, during the life of the detector, will not change the plateau to the extent that a change in operating voltage would be required. Additionally, in this case, he shall provide normally priced supply of replacement detectors with plateau ranges which essentially duplicate that of the original detector, for a minimum 5-year period subsequent to the date of delivery of the gage.

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Except as provided below, a separate high voltage plateau adjustment shall be provided for each radiation detector. The intent is that each detector should operate within its plateau voltage.

Exception to a separate adjustment will be allowed if the manufacturer will certify that his detectors are of such standard manufacture that required operating voltage for replacement detectors will not change significantly for a 5-year period. The intent is that tube replacement can be made, and optimum performance obtained, without modification of the unit. Recalibration with tube replacement is satisfactory.

The detector(s) shall be easy to remove from the gage case and any detector(s) shall be connected to other circuitry by means of male and female connectors at the base of the detector.

A guide for the transmission rod shall be provided to hold the rod so that the long axis of the rod coincides with a plumb line when the gage is placed on a level surface. The guide shall be sturdy and shall provide positive mechanical indexing for the rod at all marked depths. The guide shall be so designed, that once the rod is indexed, the source-detector geometry cannot be altered by rocking or sliding of the rod with respect to the guide. When the source rod is in the 8-inch transmission position, a 20-pound force applied perpendicular to the end of the rod in one direction, then applied at 180° in the opposite direction shall not cause more than .125 inch differential movement. The gage will be held rigidly in place during this test.

A satisfactory method shall be provided for visually indexing the rod with respect to rotation, about its long axis, within the guide. Positive mechanical indexing shall also be provided for the rod when the backscatter mode is used. Also, design of the rod and the bracket shall be such that soiling of the rod resulting from normal usage neither causes sticking nor necessitates frequent cleaning. One hundred (100) tests will be performed in the 8-inch direct transmission mode in any soil type (at any moisture) used for highway construction and no excessive sticking of the rod shall occur. The transmission rod will not be wiped by the operator during these tests. A self cleaning unit shall be a part of the gage. In addition, the bracket shall be easy to clean and shall protect both ends of the inserted portion of the transmission rod from mechanical damage or contamination with soil or asphalt. In the event that a guide for the rod for the backscatter mode is built into, rather than affixed to, the case, it shall be in the form of a sheath which is easily cleaned and whose opening does not communicate, in any way, with the interior of the gage case.

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The isotopes in the radioactive source shall consist of between eight (8) to ten (10) millicuries of Cesium^{137} and fifty (50) millicuries of Americium^{241} Beryllium. The source shall be doubly encapsulated in stainless steel, and shall be so contained in the gage system case that it may readily be exposed while taking readings and contained within shielding when not in use. The source shall be positively positioned and secured within the transmission rod and designed so that no movement of the rod (source) occurs about its longitudinal axis. The operation and design of the source-shielding complex shall be such that emitted radiation, with the source in any exposed position, does not vary from one time to another. The radiation levels shall not exceed 10 mrem/hr at a distance of 6 inches from the top and sides of the gage while in the normal backscatter operating position on the surface of compacted soil weighing 150 pounds per cubic foot. The gamma and neutron radiation levels shall not exceed 50 mrem/hr at a distance of 6 inches from the bottom of the gage while in the safe or shielded position.

The gage shall be equipped with a keyed locking device to prevent accidental unshielding of the source.

In the event that the handle used for carrying the probe also serves to unshield the source, the handle shall be designed so as to not only be stable while carrying, but also to prevent accidental unshielding of the source.

The detector for thermalized neutrons for moisture determination shall be a Boron Triflouride tube(s).

III. POWER SOURCES

The gage shall be capable of operation from its own self-contained power pack, and 115 ± 10 volt, 60 Hz alternating current. The self-contained power pack shall be composed of nickel-cadmium batteries. These batteries shall be sealed and leakproof. The batteries used in the power pack shall have sufficient ampere-hour capacity, based on a ten (10) hour discharge rate to properly operate the gage as discussed below.

The gage shall be equipped with a charging circuit capable of recharging the power pack at a rate equal to the battery manufacturer's recommendations. The charging circuit shall operate whenever the gage is connected to the 115 ± 10 volt, 60 Hz alternating current and shall be so designed as to automatically prevent overcharging the internal power pack. The combination of current drain and battery capacity shall be such that, beginning with a full charge, the gage can be operated continuously

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for 400 count-read cycles spaced over 16 hours; and the power pack can then be brought back to full charge within an 8-hour charge period with the charger operating on a 115 ± 10 volt 60 Hz A.C. supply. A count-read cycle, for the purposes of this paragraph, shall consist of a one (1) minute count followed by a five (5) second display period.

The gage shall have a device to automatically turn off the gage when the battery drops to below a satisfactory operating level. Individual batteries in a pack, may be soldered together, but a battery pack consisting of two or more batteries shall have plug in leads to facilitate easy replacement in the field.

The battery condition shall be visually indicated on the scaler control panel. It may be a go no-go indicator and shall be operated by a switch. A continuous indicator so long as the gage is turned on is acceptable.

All voltage supplies shall be highly regulated and shall produce sufficient power to satisfy all demands of the gage. All high voltage supplies, regardless of the basic power source used and with the gage in operation, shall supply, at any setting of the high voltage adjustment controls, a voltage which will remain constant, with respect to time, within ± 1/2 percent between 32 to 145 F.

The gage shall be equipped with an automatic electronic timer. The frequency base for the timer shall be either a crystal or a tuning fork oscillator. The timer shall be preset to sixty (60) seconds ± one (1) second and that time interval shall be repeatable within ± 0.03 second over operating temperature ranges specified in Section I. A check circuit shall be provided to verify timer accuracy and counting function. It shall be selectable by means of a switch and shall count pulses or multiples thereof from some standard frequency base such as a crystal, tuning fork oscillator, or 60 Hz A.C. The check function shall provide not less than 3600 pulses per minute.

The gage shall be capable of counting zero to 99,999 counts per minute. The resolution time shall be two micro-seconds or less. Display of count shall be electronic and shall be made automatically at the end of the counting interval. The display shall continue for some minimum length of time not less than 10 seconds for an in line digital display. If the count is not displayed automatically, a visual signal shall indicate the end of the counting cycle and the display shall be selectable for a period not less than 1-1/2 minutes. Electronic circuitry in the scaler shall be refined such that spurious counts are not generated. Count shall

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be displayed to, at least, the nearest ten (10) counts. Units shall be counted but need not be displayed provided that accuracy requirements, stated elsewhere in these specifications, are met.

IV. PERFORMANCE CRITERIA

Each gage must satisfy the performance criteria listed below when tested in the manner prescribed by these specifications. All references to the capacity of the gages to determine density or moisture are made in terms of a set of calibration density and moisture standards maintained by the California Division of Highways. These calibration blocks are located at the Transportation Laboratory at 5900 Folsom Boulevard, Sacramento, California. The term, "Reference calibration curve," will mean a calibration curve established using these standards.

The reference moisture and density calibration curves will be established by taking at least four one-minute readings on each standard. The mean value of a set of these readings will be used to determine each point on the reference calibration curve. The calibration curves for either transmission or backscatter density will consist of three semi-logarithmic regressions. One regression will represent standards high in calcium, the second will represent standards high in silica and the third will represent an average of all standards. Unless otherwise specified, the third, or average, regression line will be the one used to determine specification compliance. The calibration for moisture will be a linear curve based on data between approximately 0 and 25 pounds of water per cubic foot.

EFFECTS OF DROPPING

The gage will be dropped on its bottom surface from a height of 6 inches on a 1-inch diameter steel ball bearing placed on a concrete floor. The ball bearing is placed randomly so that contact is made on any bottom point of the gage. The gage shall operate correctly after 2 drops in all modes of operation. The average of four one-minute counts shall not deviate more than $\pm$ 1 pcf in density and moisture as compared to tests performed before the drops. Tests before and after will be performed on the same standard. There shall be no cracking or distortion of the case.

The gage will also be dropped from a height of 10 inches onto a asphalt concrete surfacing weighing approximately 140 pcf. The same performance criterias stated in the preceding paragraph shall apply.

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SENSITIVITY TO VIBRATION

The gage will be fastened securely to a vibrating table for a period of twenty (20) to twenty-four (24) hours. The vibrating table will have a frequency of 12.5 ± 0.1 vibrations per second and an amplitude of 0.1 ± 0.01 inch. The equipment shall operate correctly after this period of vibration in all modes of operation. The average of four one-minute counts shall not deviate more than ± 1 pcf in density and moisture as compared to tests before vibration. Tests before and after will be performed on the same standard.

EFFECT OF MOISTURE

The gage will be placed in a warm (100° to 105°F) dry environment for one or more hours then transferred to a moist room having 100% humidity and a temperature 30°F less than the dry room, for one hour. The gage will be covered to prevent water from dripping directly upon the units. After three dry-moist cycles, the average of four one-minute counts shall not deviate more than ± 1 pcf in density and moisture from tests performed at room temperature (70° to 75°F). Tests shall be performed on the same standard.

EFFECT OF AMBIENT TEMPERATURE

At an ambient temperature of between 60° and 70°F; the average of four one-minute readings in the eight in. transmission position on a density standard of between 120 and 140 lbs per cu ft, and the average of four one-minute readings on a moisture standard of between 10 and 20 lbs per cut ft, will be determined. The gage will then be placed in a heat controlled room or oven at 145° ± 5°F for two (2) hours and the readings repeated. Count ratios will be determined based on a standard count between 60 and 70°F.

These count ratios must not indicate a shift of more than ± 1 lb per cu ft density or moisture from the reading on the same standards at an ambient temperature of between 60° and 70°F, as determined by the reference calibration curves for the gage.

The same tests shall be performed with the gage temperature being lowered from ambient temperature between 60° and 70°F to 35°F ± 3°F. The drop to 35°F shall be performed in a cold box set to 35°F. The same specification of ± 1 lb per cu ft density or moisture will apply at the ambient and 35°F temperature.

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EFFECT OF HOT SUBSTRATE

The average of four one-minute readings in the backscatter position will be taken on an aluminum standard with the gage and standard at 60° - 70°F. The standard will then be heated until the internal temperature is 300°F. At this point, the gage will be placed on the standard for 10 minutes and the readings will be repeated as above. The average of these counts must not indicate a shift of more than ± 1 lb per cu ft density from the reading on the same standards at the temperature of between 60° and 70°F, as determined by the reference calibration curves for the gage. The tests at 300°F shall be completed in 15 minutes.

STABILITY WITH TIME

The daily and day-to-day random variation in indicated density of an arbitrary standard of between 120 and 140 lbs per cu ft density, when measured by an average of four one-minute counts in the eight in. transmission position, shall not vary more than ± 0.8 lb per cu ft. The daily and day-to-day random variation in indicated moisture of an arbitrary standard of between 10 and 20 lbs per cu ft moisture when measured by an average of four one-minute counts shall not vary more than ± 0.8 lb per cu ft.

In either moisture or density, a systematic variation or drift greater than that permissible for normal aging of detector tubes shall not be permitted.

EFFECT OF CHEMICAL COMPOSITION

The California Division of Highways has a set of three high silica and a set of three high calcium density calibration standards. A separate reference calibration curve shall be determined for the silica and calcium standards at the eight in. transmission position. These curves will be a semi-logarithmic regression. The spread between the curves shall not be greater than two and one half (2.5) lbs per cu ft when measured at any point between 100 and 160 lbs per cu ft. In the backscatter density mode the spread between these reference calibration curves, for the same range of densities, shall not be greater than two and one half (2.5) lbs per cu ft.

MINIMUM ONE-MINUTE COUNT-DENSITY

When the gage is used in the transmission position at a depth of eight (8) inches there shall be not less than 11,000 counts per minute indicated at a soil density of 140 lbs per cu ft. This shall be a count of the actual detector discharges, and not electronically or otherwise multiplied. When the gage is used in the backscatter position on a similar density standard, it shall have not less than 10,000 counts per minute without multiplication.

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MINIMUM ONE-MINUTE MOISTURE COUNT

When the gage is used to determine the water content of a 10 lb per cu ft moisture standard, there shall be a minimum count of not less than 1600 counts per minute. This shall be a count of the actual detector tube discharges and not electronically or otherwise multiplied. There shall be not more than 500 moisture counts per minute when the gage is suspended in air.

PERMISSIBLE VARIATION IN DENSITY DETERMINATION

When determining density in the eight (8) in. transmission position of a standardization block of between 110 and 140 lb per cu ft density, the average of a set of two readings shall constitute a density determination. In a set of ten such density determinations, no more than 3 shall indicate a density variation greater than $\pm$ 0.3 lb per cu ft as determined by the reference calibration curve.

When used in the backscatter position, no more than 3 in a set of ten such density determinations shall indicate a density variation greater than $\pm$ 0.8 lb per cu ft.

PERMISSIBLE VARIATION IN MOISTURE DETERMINATION

When determining moisture on a standardization block of between 10 and 20 lbs per cu ft moisture, the average of a set of two readings shall constitute a moisture determination. In a set of ten such moisture determinations, not more than 3 shall indicate a moisture variation greater than 0.3 lb per cu ft as determined by the reference calibration curve.

SENSITIVITY RATIO-DENSITY

The count (or count ratio) of the reference density calibration curve for the eight in. transmission position at 110 lbs per cu ft density shall be equal to or greater than 2.0 times the count (or count ratio) at 140 lbs per cu ft density. This ratio shall be equal to or greater than 1.5 when used in the backscatter position.

SENSITIVITY RATIO-MOISTURE

The count (or count ratio)of the reference moisture calibration curve at 20 lb per cu ft moisture shall be greater than 3.0 times the count (or count ratio) at 5 lb per cu ft moisture.

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V. ACCESSORIES

A permanent shipping container constructed of metal or wood shall be furnished for the gage. When wood is used it shall be 1/2" thickness grade AB exterior plywood with all joints glued and with glued interior corner chamfer strips. Shock absorbing mounting for the gage shall be provided within the container. Exterior corners shall be protected by metal corners. The container lid shall be hinged and provided with locking hasps accepting 3/8" shank padlocks and a folding chest handle equal to Stanley No. 1205K size 3-1/2" shall be attached to the container. All exterior surfaces of the containers shall be protected with two (2) coats of first quality exterior paint or enamel. All containers shall be constructed and labeled to comply with all applicable State and Federal regulations. With the gage in the shipping container, the radiation level must not exceed 10 mrem/hr at any point on the top, sides or bottom surfaces and must not exceed 0.5 mrem/hr at 3 feet from the top, sides or bottom surfaces.

The following accessory items shall be furnished for each gage and included with the respective gage in the shipping container.

1. The gage shall be provided with a single standard to obtain nuclear counts in density and moisture in such a manner that the respective detectors are used in each measurement within the range of normal operation. This standard shall remain stable with time and be so constructed that the source and detector tubes can be repeatedly placed at the same identical position with respect to the surface of the standard.

2. A power cable for battery charging of sufficient cross-section to prevent voltage drop shall be supplied for connection to the 110-130 volt power source. This cable shall have a minimum length of 8 feet. One end shall have the standard 3-prong male plug for connection to standard outlet and the other end shall have a weatherproof connector for connection to the gage.

3. Operation and maintenance manuals in booklet form shall be provided. Operating and troubleshooting procedures for the gage shall be detailed. A block diagram shall be provided for each circuit module, and one block diagram shall show the intermodular relationships. Complete schematic diagrams for all circuitry shall be provided. The schematics shall include wave form diagrams sufficient to analyze performance. the wave form diagrams shall show wave shape and list nominal amplitude and pulse width. All components in the schematics shall be identified and referenced to a complete parts list. The parts list shall show at least two sources

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for commercial components or parts, except standard hardware items. Exception to the two sources can be taken for specialized parts fabricated in the manufacturer's plant or by other vendors for the manufacturer.

4. The vendor shall designate by name, address, telephone number and air freight shipping point, the service facility to which the gage and/or components thereof are to be shipped for repairs, replacements or servicing required during the warranty period. This information may appear in the operation or maintenance manual, in separate shipping instructions, or on a plate attached to the shipping container.

5. Wipe test results, as specified by the State and/or Federal regulating agencies, shall be provided for the radioactive source in each gage.

6. Copies of any calibration curves worked up by the manufacturer during the course of his gage preparation and testing shall be provided. It is not intended that the vendor submit complete calibration curves for the gages since this will be done by the purchaser.

VI. DELIVERY, SERVICE AND WARRANTY

The vendor shall be responsible for delivery of the gages to the customer's dock at 5900 Folsom Boulevard, Sacramento, California. The manufacturer shall staff and maintain permanent facilities within the State of California. These facilities shall provide complete maintenance and repair services for the nuclear gages purchased as a result of his successful bid.

Each complete gage and each component thereof including cables, cable connecting devices and batteries shall be warranted for a period of one (1) year from the date of the acceptance of the gage by the State of California. If a gage fails to function properly during the warranty period the manufacturer shall assume full liability for restoring the complete gage including connecting cables, cable connectors and batteries to proper working order without cost to the State of California. The manufacturer shall assume all transportation charges and incidental expenses involved in the shipment of gages and/or components under warranty from a shipping point selected by the State of California to the service facility designated by the manufacturer and the return of the shipped items to the point of origin. Transportation shall be via air freight whenever feasible. The total time lapse that a gage and/or components reach and leave the manufacturer's facility shall not exceed eight (8) calendar days. The warranty shall be voided by

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physical damage, modification, alteration, abuse or misuse of a gage beyond normal service usage in field and laboratory applications outlined in appropriate test methods and procedures of the State of California.

VII. VENDOR'S BID PROPOSAL

Schematic drawings of the gage are to be submitted with the bid. These drawings must show the arrangement of the components, the size of the case, the source strength, the model number, the size and type detectors used, and the estimated radiation level six inches from all sides and the bottom of the case. Prototype gages may be submitted for inspection and the vendor may use the State's calibration blocks for checking compliance with specification. Other pertinent information concerning the gage shall also be presented by the bidder. All data will remain confidential and will be used to determine if the bid is acceptable to the State. The acceptance of the design portrayed in the drawings and data submitted for bid purposes will not relieve the manufacturer of the full responsibility for furnishing a gage which shall meet these specifications and all requirements of the California Department of Public Health, California Administrative Code, Title 17 and all other pertinent rules, regulations, or orders in effect in California. The manufacturer shall also assume all responsibility for obtaining approval for the use of the gage(s) in California.

In the event that the California Division of Highways might wish to purchase complete sets of plug-in circuit boards or modules for gage maintenance, the vendor shall supply, in his bid proposal, a price list for all the modules in the gage he proposes to supply. These module prices will not be a consideration in bid evaluation.

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