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ABSTRACT:

For decades, measuring soil density and moisture content using nuclear gauges has been a well-accepted testing method for road and embankment construction. The ownership and use of nuclear gauges come with some regulatory burdens such as the need for licensing, special storage, transportation requirements, gauge operator training, and personal dosimetry. As a result, the industry has been searching for alternatives to nuclear gauges. So far, no such non-nuclear solution has been found.

Recently, in the United States, the Nuclear Regulatory Commission declared a nuclear gauge exempt from licensing due to its safe design and use of an extremely low-activity radioactive source. The availability of such an instrument allows many countries to accept a proven testing method where often little or no testing was completed. The outcome will be a longer lasting road foundations and safer embankments. We will present the technical aspects of this nuclear gauge and its performance.

New Low-Activity Nuclear Gauge for Soil Wet Density Measurement with Low Regulatory Burden

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1 INTRODUCTION

Soil compaction is essential to increase the load bearing capacity during construction of roads, airfields, building sites, embankments, and parking lots. Soil compaction is verified by measuring the soil density which is defined as mass per unit volume. The resulting density measurement is a measure of the degree of compaction. During the entire process of constructing the road foundation, dry density and moisture content of the compacted soil and aggregate base are monitored by the direct measurement of wet density and moisture content of soil.

Soil wet density can be measured by the direct determination of mass and volume of a sample. When using this measurement methods, soil mass is removed in the measurement area creating a small hole. Although the mass of the soil can be measured accurately, the volume measurement is challenging due to the irregular geometry of the excavated hole. Several methods based on this concept are used in the industry. They are the sand cone method (ASTM D1556), the rubber balloon method (ASTM D2167), and the drive cylinder method (ASTM D2937). Although these methods can be accurate, from early on, the construction industry understood the drawbacks of using these methods such as long measurement time and operator errors.

Nuclear techniques for soil density and moisture content measurements were introduced in the 1950s (Krueger 1950; Pieper 1949; Belcher and Cuykendal, 1950). Historically, this soil density measurement method is based on gamma-ray scattering and this moisture content measurement method is based on neutron scattering. Gauges based on nuclear techniques, which are called nuclear density gauges (NDG), have been in use worldwide as a soil compaction measuring device for over five decades. These gauges are widely used in the industry because of the ease of use, accuracy of density and moisture measurements, large measurement volume, and short measurement time. The accuracy of measuring density and moisture by NDGs has been well-established and in many places the nuclear techniques are used as the standard method for quality control or quality assurance (ASTM D6938-10).

The NDGs use radioisotope sources of gamma-rays and neutrons. The source activity or strength are less than 370 MBq (10 mCi) for density gauges and less than 1850 MBq (50 mCi) for combined density and moisture gauges. Although such levels of source activity is not high and gauge design provides adequate shielding from radiation for the gauge operator, regulatory agencies worldwide consider them as controlled devices. These regulations impose certain burdens for ownership and operation of nuclear gauges such as the need for licensing, special storage, transportation requirements, gauge operator training, and personal dosimetry. On account of these burdens, many non-nuclear technologies, based on soil electrical properties, stiffness, and modulus, have been evaluated as alternatives to the nuclear techniques but with limited success (Berney and Kyzar 2012; Mejias-Santiago et al. 2013; Rose 2013; Wen et al. 2015).

In order to lessen the regulatory burden for gauge users without sacrificing the accuracy and precision of the measurement, a new nuclear density gauge has been developed to be used in the United States and its territories with the expectation of the acceptance of its use by other countries in the near future. The new gauge uses a low-activity gamma-ray source of strength less than 3.7 MBq (0.1 mCi) and measures the soil wet density by the gamma-ray scattering method. The new low-activity nuclear density gauge (Low-activity NDG) is exempt from nuclear regulations in the United States and its territories. Furthermore, with the use of a reliable non-nuclear soil moisture measurement method, the Low-activity NDG can obtain the dry density of soil and perform measurements comparable to a traditional NDG.

This paper describes design features and the measurement properties of this new Low-activity NDG and presents the results of several field studies conducted in North Carolina, USA.

2 LOW-ACTIVITY NUCLEAR DENSITY GAUGE FOR SOIL WET DENSITY MEASUREMENT

2.1 General Description

The Low-activity NDG for soil wet density measurement (Figure 1 and 2) is based on the physics of gamma-ray interactions with matter. The primary interaction mechanism of gamma-rays with energies in the range from 0.1 to 2 MeV with atomic electrons of chemical elements in typical soils is Compton scattering. The Compton scattering rates depend on the density of electrons in the material and therefore depend directly on the bulk density of the material.

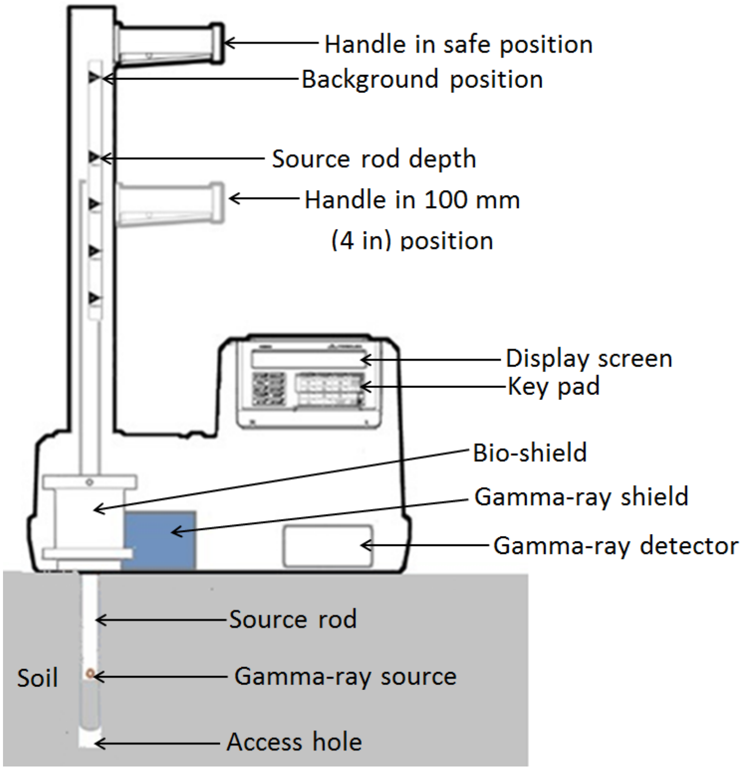

Figure 1. The Low-activity NDG for soil wet density measurement: Troxler Model 4590.

The gauge contains a radioisotope source of gamma-rays from a Cesium-137 source of primary energy of 0.662 MeV and an energy selective high efficiency gamma-ray detector. The gamma-rays traversing through the test sample that reach the detector having energies in the Compton range can be counted exclusively by the energy selective high efficiency detector. The scattered gamma-rays also scan a large volume of the sample enabling the estimation of densities of a heterogeneous material like soil. The instrumentation of this Low-activity NDG is similar to that of a laboratory nuclear density gauge for measuring bulk density of cylindrical compacted asphalt specimens, which is also exempt from regulations in the United States and its territories (Dep and Troxler 2000; Malpass and Khosla, 2001). Table 1 provides specifications and features of this Low-activity NDG and a conventional NDG for comparison.

The operation of the Low-activity NDG is similar to that of a conventional NDG except for one aspect, a short background count is required occasionally (Troxler and Dep 2009). The background count includes gamma-rays originated from the soil due to the natural radioactivity. For conventional NDGs, this background radiation is negligible when compared to the radiation from the gamma-ray source in the gauge. Since the Low-activity NDG uses nearly 1% of the source activity as that of a conventional NDG, the background radiation is measured and accounted for in the density determination. To measure the background radiation, a gamma-ray count is taken by placing the gamma-ray source in a special position where the source is still inside the gauge but is shielded by radiation shielding material in the tip of the source rod, bio-shield, and the extra shield between the bio-shield and the detector (Figure 1).

2.2 Measurement Process

The measurement process for the Low-activity NDG starts with the preparation of the test location by leveling the soil using the scraper plate, drilling a 16.5 mm (0.65 inch) diameter access hole about 50 mm (2 inches) deeper than the planned measurement depth, and then positioning the gauge directly on the soil. If this test is the first test for the day, the daily standard count (C_{std}) is taken first by taking two gamma-ray counts: one with the source at the safe position and the other with the source at the background position (Figure 1).

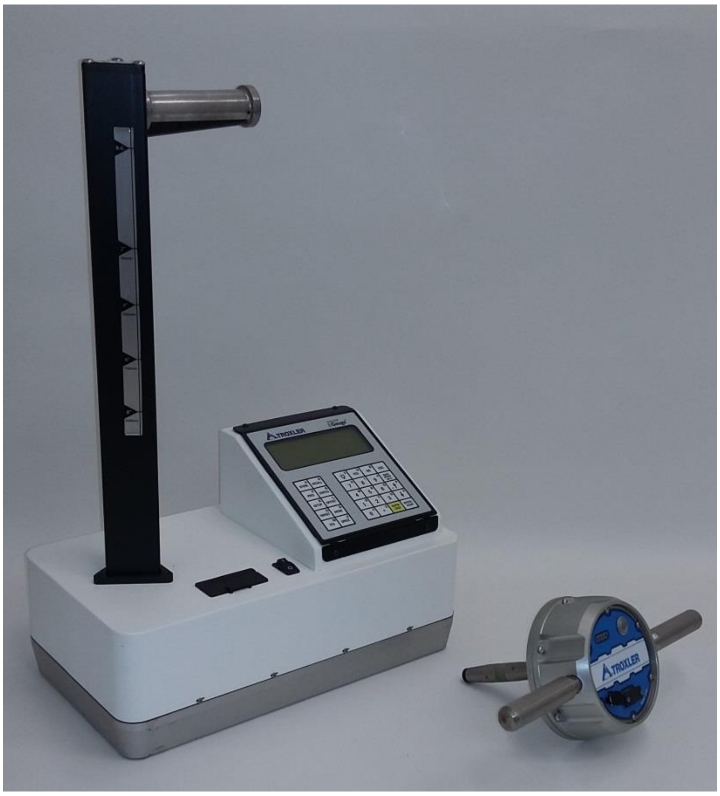

Figure 2. The Low-activity N for soil wet density measurement: Troxler Model 4590 (left) and the non-nuclear moisture probe: Troxler Model 6760 (right). The moisture probe communicates wirelessly with the gauge.

After accepting the standard count, the measurement is made by lowering the source rod to the desired depth *i* and taking the measurement count (C_{mi}) followed by moving the source rod up to the background position and taking the background count (C_b). The gamma-ray count-density relationship is given by

$$\frac{(C_{mi} - C_b)}{C_{std}} = A_i exp^{B_i \rho} + C_i \quad (1)$$

where A_i, B_i, and C_i are the calibration constants which are determined during the factory calibration of the gauge. The gauge computes the wet density ρ using the measured counts and the pre-determined constants.

2.3 Safety and Security Features

The Low-activity NDG comes with innovative safety features incorporating a very low activity or strength Cesium-137 gamma-ray source. The radiation shielding for the source during storage and transport reduces the annual radiation exposure to the gauge operator to be less than that of the natural terrestrial radiation- 0.12 mSievert (12 mrem) vs. 0.28 mSievert (28 mrem). The self- shielding source rod design eliminates the need for a spring loaded shutter mechanism as is used in the conventional NDGs. This also eliminates the need for cleaning of the shutter area due to accumulation of soil. The source rod removal requires a special proprietary tool. The source rod tower and bio-shield are ruggedized against accidental damage to the gauge in the field (Troxler Electronic Laboratories, 2016).

3 GAUGE MEASUREMENT PROPERTIES

3.1 Density Calibration

The wet density calibration procedure for the Low-activity NDG is similar to that of a conventional NDG. Since the gamma-ray source decays with time, the gauge response or the gamma-ray count decreases with time. Therefore, to eliminate the time dependence, the gauge count is standardized by dividing with a count that only depends on time (C_{std}). Since the Low-activity NDG uses a low strength gamma-ray source, gamma-rays detected other than that from the source traversing through the test sample, C_b, are also excluded.

The Low-activity NDG is calibrated using the same three density calibration standards in specially designed bays that are used to calibrate the conventional NDGs. These standards are made out of solely magnesium, combinations of magnesium and aluminum, and solely aluminum. They have different densities covering a density range from 1780 to 2690 kg/m^3 (111 to 168 lb/ft^3).

Table 1. Gauge properties for Low-activity NDG and a conventional nuclear density gauge

Property	Details	Low-Activity Nuclear Density Gauge (Troxler Model 4950)	Conventional Nuclear Density Gauge (Troxler Model 3440)[1]
Soil Property		Wet Density	Wet Density and Moisture
Technology	Measurement Method	Gamma-ray Compton Scattering	Gamma-ray Compton Scattering
	Gamma-ray Source	Cesium-137	Cesium-137
	Source Strength	3.33 MBq (0.09 mCi)	286 MBq (8 mCi)
	Detector	High Efficiency (solid phase)	Low detection efficiency (gas phase)
	Depth modes	Up to 200 mm (8 inch)	Up to 300 mm (12 inch)
	Analysis	Spectrometric	Counting
Accuracy & Precision of Wet Density Measurement		Meets Industry standard	Meets Industry standard
Security		Lower Activity Source Less risk	Higher Activity Source Greater risk
Safety	Radiation Dose	Lower doses 0.1 μSv/hr (0.01 mrem/hr) at 1 m	Higher doses 3 μSv/hr (0.3 mrem/hr) at 1 m
	Radiation safety Training requirement in US	Not Required	Required
Regulatory Burden	Burden	Very low	High
	Licensing in the US	Not Required	Required
	Shipping in the US: Type A packaging	Not Required	Required

[1]Troxler Electronic Laboratories (2015).

Calibrating the Low-activity NDG requires gamma-ray counts taken by placing the gauge on the three calibration standards for each measurement depth. For each calibration standard *i* of density ρ_i and the gamma-ray source at depth *j*, let the gamma-ray count be C_{mij}. Let C_{bi} be the gamma-ray count for the background. The calibration constants for the depth j, A_j, B_j, and C_j are determined using the measured counts and the densities of standards. Note that, when calibrating the new gauge, the count time is selected to minimize the natural error from randomness of radioactive decay of the source.

The calibration curves for the measurement depths 50 mm (2 in), 100 mm (4 in), 150 mm (6 in), and 200 mm (8 in) for a Troxler Model 4590 Low-activity NDG are shown in Figure 3. The figure also contains, for the same depths, the calibration curves for a Troxler Model 3440 conventional. For comparison purposes, curves for Model 3440 gauge was scaled so that both types of gauges have the same count ratio at the lowest density. The instrument sensitivity to soil density, the change in gauge count to the change in density as given by the slope of the curve, is slightly better for the Low-activity NDG especially at higher densities. The sensitivity at 2480 kg/m^3 (155 lb/ft^3) for the 150 mm (6 in) for Low-activity NDG is -0.00136 per kg/m^3 and for the conventional NDG is -0.00102 per kg/m^3.

3.2 Density Measurement Precision

The measurement precision is a measure of repeatability of a density measurement. The precision varies with measurement depth and density, and depends on the uncertainty of the measurement count and uncertainty of the background count. We have estimated the density measurement precision for the four depth modes 50 mm (2 in), 100 mm (4 in), 150 mm (6 in), and 200 mm (8 in) at the three calibration standard densities for the Low-activity NDG. The precision estimates were made using a Monte Carlo method allowing random variations for measurement count and background count using actual data collected from a gauge calibration. For these estimates, we have considered the variability of a 2 minute measurement count and a 1 minute background count for each depth mode. Figure 4 provides the results. The measurement precision at 2000 kg/m^3 (125 lb/ft^3) for the Low-activity NDG is 3 kg/m^3 (0.18 lb/ft^3) and for a conventional NDG, for 1 minute count, is 3.4 kg/m^3 (0.21 lb/ft^3) .

3.3 Density Measurement Precision: Repeatability and Reproducibility

For our preliminary study of determining the repeatability and reproducibility, we used four Troxler Model 4590 Low-activity NDGs. Three gauge operators conducted the test each operating a separate gauge. The fourth gauge was operated at different times by one of the same operators. We selected four test locations covering a 192 kg/m^3 (12 lb/ft^3) density range in a road construction project in Roxboro, NC. We selected the 150 mm (6 inch) depth mode of operation. For all measurements, a measurements count time of 2 minute and a background count time of 1 minute were used. On each test location, three measurements were obtained with each gauge. The repeatability of the measurement using the new nuclear gauge in the density range of 1955 to 2160 kg/m^3 (122 to 135 lb/ft^3) was (0.3 to 0.4 lb/ft^3) and the reproducibility was (0.5 to 0.6 lb/ft^3) (Table 2). For comparison purposes, Table 2 also shows the results of a more extensive test conducted for the conventional NDGs (ASTM D6938-10) where the measurement time of 1 minute, which is sufficient for the application, was used. The repeatability and reproducibility for the Low-activity NDG is similar to that for the conventional NDG.

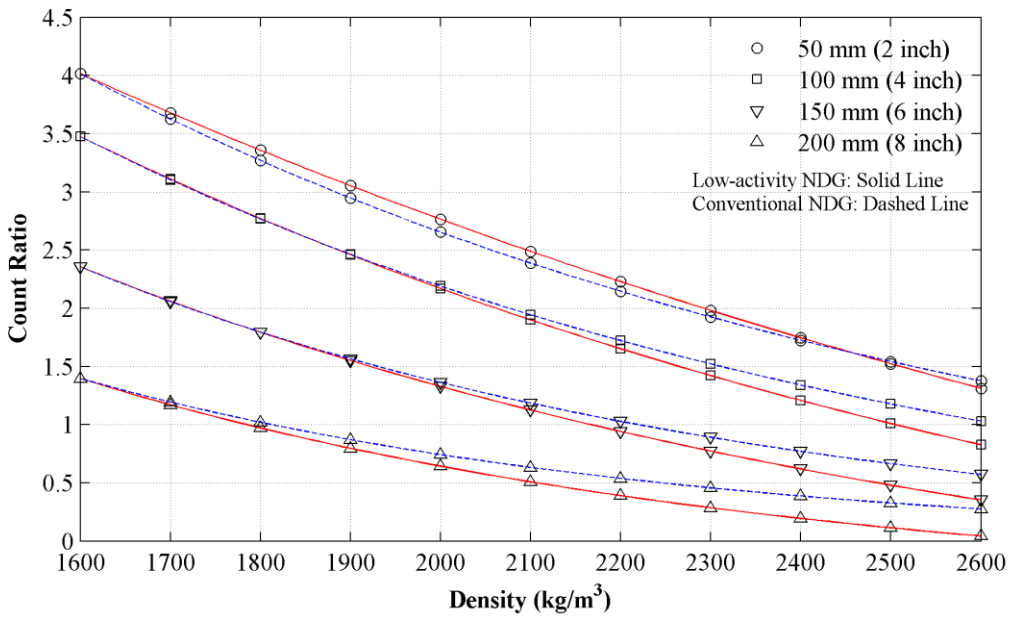

Figure 3. The wet density calibration curves for the Low-activity NDG (solid line) and a conventional nuclear density gauge Troxler Model 3440 (dashed line).

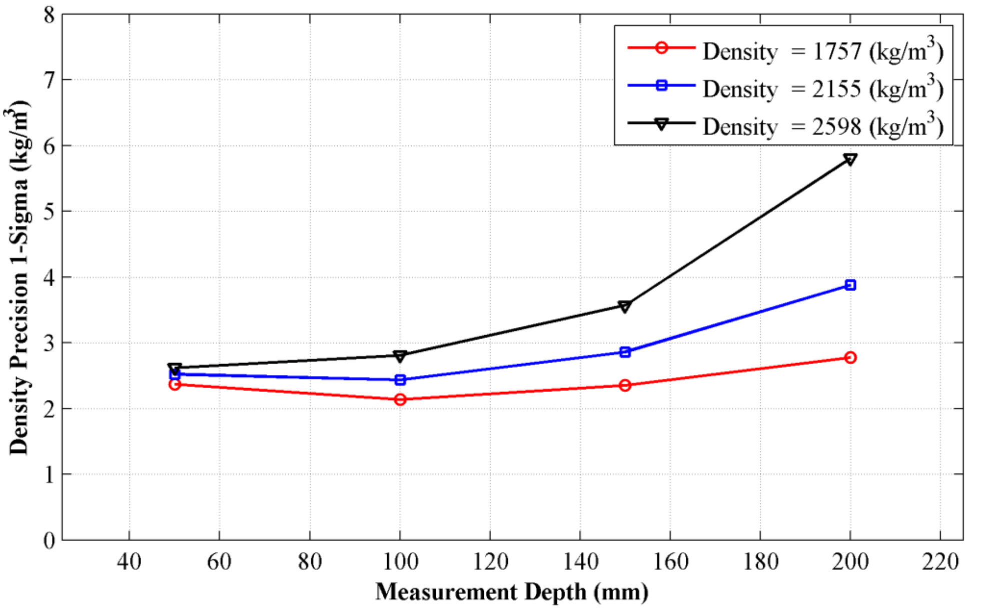

Figure 4. The Low-activity NDG density measurement precision for various measurement depths. Here, the precision is estimated for a measurement count time of 2 minutes and background count time of 1 minute.

For Low-activity NDG, the precision values estimated considering only the uncertainty of the gamma-ray counts from Poisson nature of radioactive decay as shown in Figure 4 was about 3 kg/m^3 (0.2 lb/ft^3) at 2162 kg/m^3 (135 lb/ft^3). This low value is expected since for this estimate gauge operator errors present in an actual measurement was not considered.

Table 2. The repeatability and reproducibility of wet density measurements[1] for Low-activity NDG and conventional nuclear density gauge

	Low-activity NDG (Troxler Model 4950)			Conventional Nuclear Density Gauge (Troxler Model 3440)
Test Location	1	2	3	Three locations (three soil types)
Average Density	1967 kg/m^3 (122.8 lb/ft^3)	2036 kg/m^3 (127.1 lb/ft^3)	2156 kg/m^3 (134.6 lb/ft^3)	1837-2084 kg/m^3 (114.7-130.1 lb/ft^3)
Repeatability at 1-σ	6.4 kg/m^3 (0.40 lb/ft^3)	7.0 kg/m^3 (0.44 lb/ft^3)	4.6 kg/m^3 (0.29 lb/ft^3)	4.2-7.4 kg/m^3 (0.26-0.46 lb/ft^3)
Reproducibility at 1-σ	8.7 kg/m^3 (0.54 lb/ft^3)	9.0 kg/m^3 (0.56 lb/ft^3)	9.3 kg/m^3 (0.58 lb/ft^3)	10.6-12.3 kg/m^3 (0.66-0.77 lb/ft^3)
Difference Between Two Test Results at 95% Limit for Repeatability	17.6 kg/m^3 (1.1 lb/ft^3)	19.2 kg/m^3 (1.2 lb/ft^3)	12.8 kg/m^3 (0.8 lb/ft^3)	11.2-20.8 kg/m^3 (0.7-1.3 lb/ft^3)
Difference Between Two Test Results at 95% Limit for Reproducibility	24.0 kg/m^3 (1.5 lb/ft^3)	25.6 kg/m^3 (1.6 lb/ft^3)	25.6 kg/m^3 (1.6 lb/ft^3)	30.4-33.6 kg/m^3 (1.9-2.1 lb/ft^3)

[1]The depth mode for both types of gauges is 150 mm (6 inch). The measurement time for Low-activity NDG is 3 minutes and for the conventional nuclear density gauge is 1 minute.

3.4 Source aging effect on density measurement precision

The gamma-ray source in the new gauge, Cesium-137, has a 30 year half-life. Since the gauge uses a low activity or strength source, the change in source activity with time due to natural radioactive decay can degrade the density measurement precision. The degradation of density precision was estimated by using a Monte Carlo method allowing the decrease in the source activity with time and the random variations for measurement count and background count using data collected for gauge calibration. The degradation of density measurement precision for the first ten years is shown in Figure 5 (left). The Low-activity NDG can hold the required density measurement precision for about 8 to 10 years after that it requires a gamma-ray source replacement. In addition, the source aging effect can add a significant bias to the density reading Figure 5 (right). To avoid addition of a bias to the density measurement, the gauge requires a calibration every 1 to 2 years.

3.5 Bias on density measurement due to variability in the background

In a given project, if the natural variability of the composition of the soil, for example the sand to clay ratio, is minimal, the magnitude of the background count remains a constant. However, due to the randomness in the radioactive decay process, the background count follows a Poisson distribution and a one-time determined background count can have a magnitude two standard deviation from the average count. Therefore, when using the background count measured at the first test site for all subsequent counts, a bias can be introduced to the density measurement.

When count time for the background is long enough to reduce the standard deviation, the uncertainty in the background count can be lowered thus reducing the possibility of a bias to the density value. We have estimated the density bias by using a Monte Carlo method allowing for the random variations for measurement count and background count using actual data collected from a gauge calibration. For this study, we have estimated the bias for measuring the density of a sample having a density of 2155 kg/m^3 (134.5 lb/ft^3) with a 2 minute measurement and 1 minute background count. The density bias estimate for 150 mm (6 inch) and 200 mm (8 inch) measurement depths was found to be than 8 kg/m^3 (0.5 lb/ft^3). Therefore, if the background count is measured at one test location and used for all subsequent measurements in that project, the bias in the density reading were small.

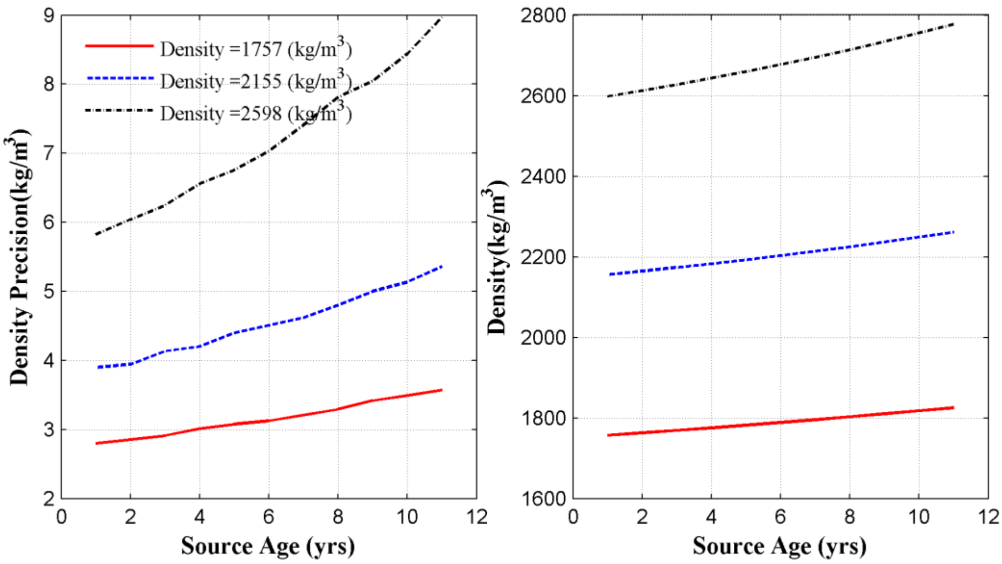

Figure 5. The gamma-ray source aging effect for the Low-activity NDG. Here, the source aging effect on precision and density are estimated for the 200 mm (8 inch) measurement depth and for a measurement count time of 2 minutes and background count time of 1 minute.

3.6 Field density measurement in comparison to a conventional gauge

Three Low-activity NDGs and one conventional NDG were used in a road construction project in Wayne County, North Carolina. Measurements were taken at four locations with each location wet density was determined for two depth modes 150 mm (6 in) and 200 mm (8 in). The results are shown in Figure 6. As expected, the three Low-activity NDGs showed good repeatability and reproducibility for wet density measurement with a range of 6 to 24 kg/m^3 (0.4 to 1.5 lb/ft^3) for the 150 mm (6 inch) measurement depth and 18 to 27 kg/m^3 (1.1 to 1.4 lb/ft^3) for the 200 mm (8 inch) measurement depth. The difference in the wet density values for the two types of nuclear gauges is less than 18 kg/m^3 (1.1 lb/ft^3) for both measurement depths.

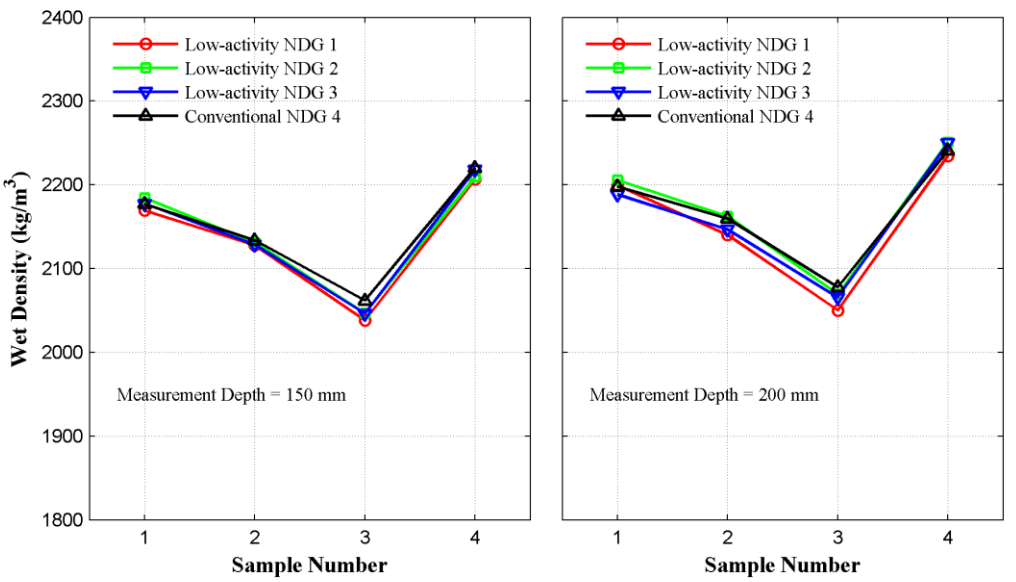

Figure 6. Low-activity NDG vs conventional nuclear density gauge density measurements for four test locations in a project. For the Low-activity NDG,, the count time for measurement is 2 minutes and for the background is 1 minute.

The gauge was tested at eight different road construction projects in North Carolina covering a wide range of soil types including aggregate base courses. One to two new nuclear gauges and one conventional gauge were used in density measurements done by multiple operators. Measurements were made at 6inch and 8inch depths. The new gauge measurement time was 2 minute with a one minute background count whereas the conventional gauge measurement time was 4 minutes. The results are shown in Figure 7 for 150 mm (6 inch) and Figure 8 for 200 mm (8 inch) measurements. For both depth modes, the new nuclear gauge showed a high correlation to conventional gauge measurements with a 95% reproducibility limit on the difference between two readings of about 38 kg/m^3 (2.4 b/ft^3). This proves to be close to the difference between two readings from two conventional gauges as stated for reproducibility in ASTM D6938-10.

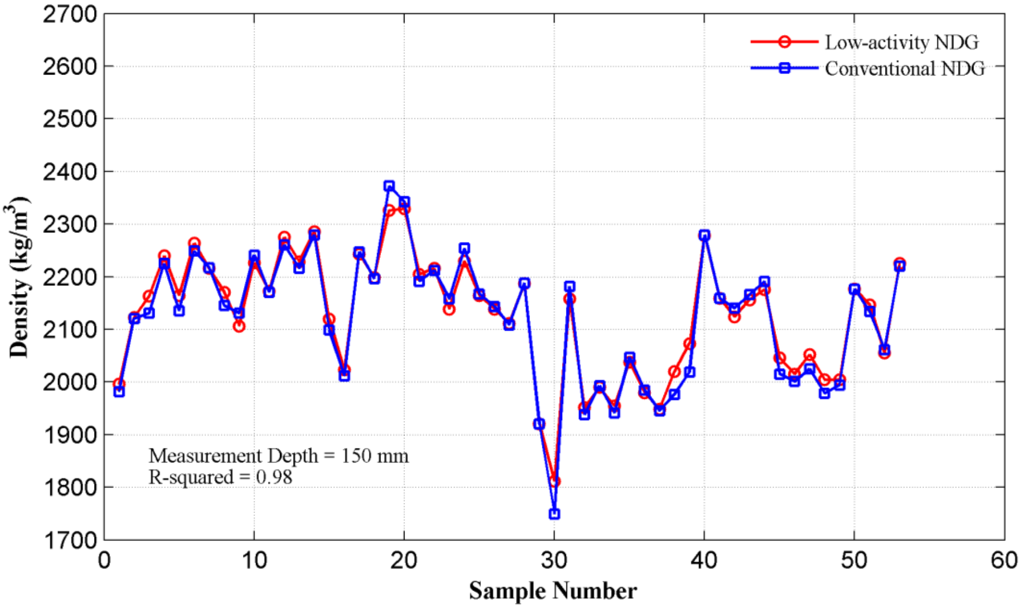

Figure 7. The Low-activity NDG and conventional nuclear density gauge density measurements for multiple locations in several projects. Here, the measurement depth is 150 mm (6 inches). For the Low-activity NDG, the measurement count time is 2 minutes and background count time is 1 minute.

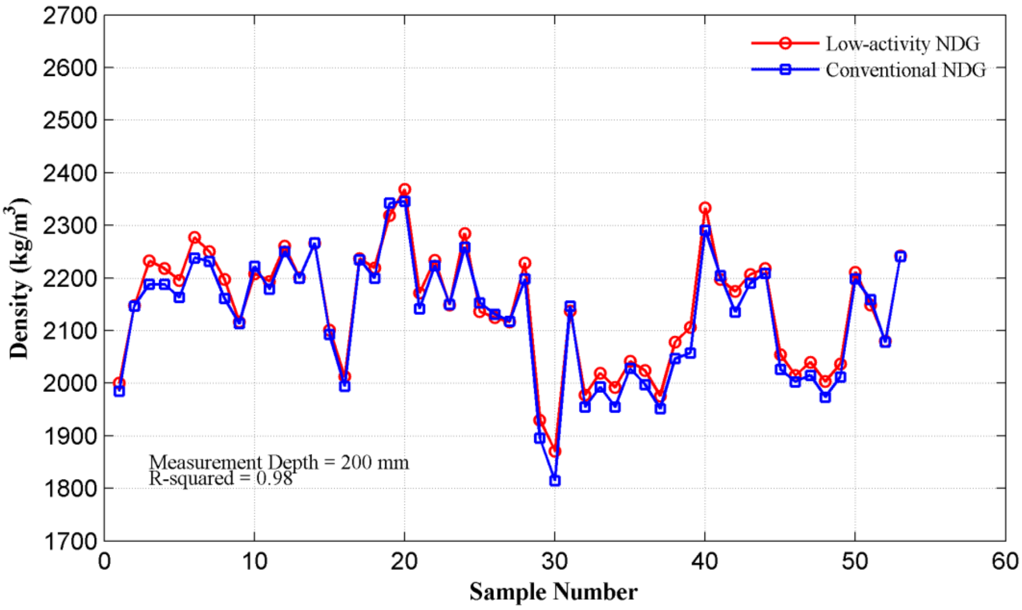

Figure 8. The Low-activity NDG and conventional nuclear density gauge density measurements for multiple locations in several projects. Here, the measurement depth is 200 mm (6 inches). For the Low-activity NDG, the measurement count time is 2 minutes and background count time is 1 minute.

4 SOIL DRY DENSITY MEASUREMENT

The Low-activity NDG only measures the soil wet density (WD). In order to determine the soil dry density (DD), it uses the moisture density (M) measured by a Troxler Model 6760 Moisture Probe. This probe uses electromagnetic technique for moisture measurement. The probe is inserted to the same access hole prepared for the Low-activity NDG when measuring the soil wet density. The dry density of soil is given by

$$DD = WD - M \qquad (2)$$

Table 3 provides the results for the road construction project in Wayne County, North Carolina. Also shown in the table are the results from a conventional NDG. The results show a good agreement of the dry density determined by the two types of nuclear gauges with a maximum difference of 10.4 kg/m^3 (0.65 lb/ft^3).

Table 3. Soil dry density measurement by Low-activity NDG and a non-nuclear moisture probe. For comparison, also included are the measurements using a conventional nuclear density gauge. Here, WD, M, and DD are soil wet density, moisture density, and dry density respectively.

	Conventional NDG			Low-activity NDG and Moisture Probe		
Sample	WD kg/m^3 (lb/ft^3)	M kg/m^3 (lb/ft^3)	DD kg/m^3 (lb/ft^3)	WD kg/m^3 (lb/ft^3)	M kg/m^3 (lb/ft^3)	DD kg/m^3 (lb/ft^3)
1	2177 (135.9)	170 (10.6)	2007 (125.3)	2177 (135.9)	180 (11.2)	1997 (124.6)
2	2134 (133.2)	186 (11.6)	1948 (121.6)	2147 (134.0)	189 (11.8)	1958 (122.2)
3	2061 (128.7)	155 (9.7)	1906 (119.0)	2055 (128.3)	149 (9.3)	1907 (119.0)
4	2220 (138.6)	191 (11.9)	2029 (126.7)	2225 (138.9)	184 (11.5)	2041 (127.4)

If the gauge operator wishes to use another method for measuring the moisture content of soil, this moisture value can be entered into the gauge using the gauge key pad. Then, the gauge can compute the soil dry density using the wet density determined by the gauge and the moisture content.

5 INTERNATIONAL REGULATIONS FOR NUCLEAR GAUGES

The conventional NDGs are used in most countries around the world with the requirement of a permit or license and other restrictions such as training, monitoring badges, shipping paperwork, etc. However, there are a few countries which will not allow these nuclear gauges inside their borders at all due to the activity of the sources. It is likely that the new Low-activity NDG will be allowed in these areas due to the extremely reduced activity or strength of the Cesium-137 gamma-ray source, elimination of the Americium-241-Beryllium neutron source from the gauge, and the innovative safety features incorporated to the gauge.

Troxler and our international partners are targeting some countries, which currently have similar regulations to the United States, as potentially open to the same exempt designation for the new Low-activity NDG as the United States. This would allow gauge use in those areas with no permit or license requirements. This will take some time and assistance from our partners located in those areas as well as from our friends in the construction industry. As advocates for proper quality control / quality assurance in the road building industry, we can see this opportunity to make it easier to perform the required density measurements. When little or no density and moisture testing is performed on a prepared roadbed, the life of the road is diminished. Great improvements in the quality of roads constructed around the world would result.

6 CONCLUSIONS

1) The measurement sensitivity of the Low-activity NDG is slightly better than a conventional NDG especially in the high density region and is acceptable for the soil compaction application.

2) The measurement precision for the Low-activity NDG when taking measurement counts for 2 minutes and a background count for 1 minute meets the industry requirement. However, the total measurement time for this gauge is longer than that for a conventional NDG: 3 minutes compared to 1 minute.

3) The repeatability and reproducibility of density measurement for the Low-activity NDG when taking measurements with measurement counts for 2 minutes and a background count for 1 minute is comparable to that of a conventional NDG using a count time of 1 minute.

4) The Low-activity NDG can hold the required density measurement precision for about 8 to 10 years after that it requires a gamma-ray source replacement. To avoid addition of a significant bias to the density measurement, the gauge requires a calibration every 1 to 2 years.

5) For a given project, when the soil type is not significantly changing, the measurement time can be shortened by taking the background count only at the first measurement location. The bias for density is small and can be ignored in this case. Whenever the accuracy of the density measurement is most essential, a separate background should be taken for each measurement.

6) The density measurements taken with the Low-activity NDG for 17 different sites at 150 mm (6 inch) and 200 mm (8 inch) depth agreed well with that of a conventional NDG. This high degree of correlation between the density values determined by the two types of gauges (R-squared is 0.98) is due to the fact that both type of nuclear gauges are based on the same measurement method- gamma-ray scattering. The small bias between the density values is due to the fact that both gauge types were calibrated on the same set of calibration standards.

7) The wet density measured using the Low-activity NDG together with the moisture content measured by other reliable methods should show sufficient accuracy for determining dry density for QC/QA purposes.

8) In the USA and its territories where the new Low-activity NDG is exempt from regulation, the gauge user has no additional regulatory burden in purchasing, storing, transporting to the test site, shipping the gauge to the manufacturer for calibration, and using the gauge in multiple states.

9) The new Low-activity NDG will allow reliable quality control of road foundations to be possible in parts of the world where it is currently not. Fewer, less restrictive regulations will make it easier to obtain and use the nuclear density measurement methods around the world extending the life and improving the safety of roads everywhere.

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