Designation: D6727/D6727M − 16

Standard Guide for
Conducting Borehole Geophysical Logging—Neutron[1]

This standard is issued under the fixed designation D6727/D6727M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This guide is focused on the general procedures necessary to conduct neutron or neutron porosity (hereafter referred to as neutron) logging of boreholes, wells, access tubes, caissons, or shafts (hereafter referred to as boreholes) as commonly applied to geologic, engineering, groundwater and environmental (hereafter referred to as geotechnical) explorations. Neutron soil moisture measurements made using neutron moisture gauges, are excluded. Neutron logging for minerals or petroleum applications is excluded, along with neutron activation logs where gamma spectral detectors are used to characterize the induced gamma activity of minerals exposed to neutron radiation.

1.2 This guide defines a neutron log as a record of the rate at which thermal and epithermal neutrons are scattered back to one or more detectors located on a probe adjacent to a neutron source.

1.2.1 Induction logs are treated quantitatively and should be interpreted with other logs and data whenever possible.

1.2.2 Neutron logs are commonly used to: (*1*) delineate lithology, and (*2*) indicate the water-filled porosity of formations (see Fig. 1).

1.3 This guide is restricted to neutron logging with nuclear counters consisting of scintillation detectors (crystals coupled with photomultiplier tubes), or to He^3-tube detectors with or without Cd foil covers or coatings to exclude thermalized neutrons.

1.4 This guide provides an overview of neutron logging including: (*1*) general procedures; (*2*) specific documentation; (*3*) calibration and standardization, and (*4*) log quality and interpretation.

1.5 To obtain additional information on neutron logs see References section in this guide.

1.6 This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This guide should not be used as a sole criterion for neutron logging and does not replace education, experience, and professional judgment. Neutron logging procedures should be adapted to meet the needs of a range of applications and stated in general terms so that flexibility or innovation are not suppressed. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged without consideration of a project's many unique aspects. The word standard in the title of this document means that the document has been approved through the ASTM consensus process.

1.7 *Units*—The values stated in either inch-pound units or SI units given in brackets are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be use independently of the other. Combining values from the two systems may result in non-conformance with the standard. Add if appropriate: "Reporting of test results in units other than SI shall not be regarded as nonconformance with this standard."

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use. The use of radioactive sources in neutron logging introduces significant safety issues related to the transportation and handling of neutron sources, and in procedures to ensure that sources are not lost or damaged during logging. There are different restrictions on the use of radioactive sources in logging in different states, and the Nuclear Regulatory Agency (NRC) maintains strict rules and regulations for the licensing of personnel authorized to conduct nuclear source logging.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

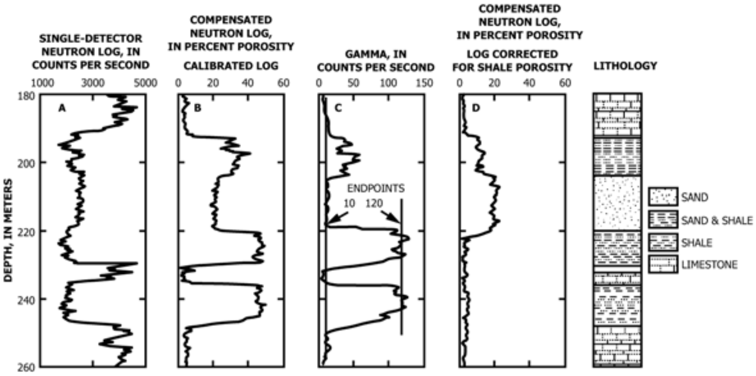
---

[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.01 on Surface and Subsurface Characterization.

Current edition approved Jan. 1, 2016. Published January 2016. Originally approved in 2001. Last previous edition approved in 2007 as D6727 – 01(2007). DOI: 10.1520/D6727_D6727M-16.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

***A Summary of Changes section appears at the end of this standard**



A–Single detector epithermal neutron log plotted in counts per second.
B–Dual-detector neutron log calibrated in limestone porosity units.
C–Gamma log showing maximum and minimum values used as endpoints for the gamma activity scale.
D–Dual detector neutron log plotted in porosity units corrected for the non-effective porosity of clay minerals using the equation:

$$N_c = N_0 - C_{sh} \cdot \Phi_{sh}$$

where:

N_c = corrected neutron log,
N_0 = original neutron log,
C_{sh} = computed shale fraction based upon the gamma log position between the endpoints of 10 and 120 cps, and
Φ_{sh} = estimate of shale non-effective porosity of about 40 % picked from intervals on the log where Φ_{sh} = 1.0.

FIG. 1 Typical Neutron Logs for a Sedimentary Rock Environment

D5088 Practice for Decontamination of Field Equipment Used at Waste Sites
D5608 Practices for Decontamination of Sampling and Non Sample Contacting Equipment Used at Low Level Radioactive Waste Sites
D5753 Guide for Planning and Conducting Borehole Geophysical Logging

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms in this standard, refer to Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *depth of exploration, n—in geophysics*, the radial distance from the measurement point to a point where the predominant measured response may be considered centered (not to be confused with depth below the surface).

3.2.2 *epithermal neutron, n*—neutron with kinetic energy somewhat greater than the kinetic energy associated with thermal lattice vibrations of the surrounding formation; such neutrons have been slowed enough by collisions with formation minerals to interact with the detector, but the population of epithermal neutrons is not strongly affected by absorption cross-sections of trace minerals in the geologic environment.

3.2.3 *neutron generator, n*—a device which includes a particle accelerator to generate a flux of high-energy neutrons, and which can be turned on and off through connection with an external power supply.

3.2.4 *neutron slowing distance, n*—the distance traveled by a neutron within a formation over the time required for the neutron to be slowed to half of its original velocity by repeated collisions with the atoms in the formation.

3.2.5 *thermalized neutron, n*—neutron that has been slowed to a kinetic energy approximately equal to that of the thermal kinetic energy of the surrounding formation.

3.2.6 *volume of exploration, n—in geophysics*, the volume, which is non-spherical and has gradation boundaries, that contributes 90 percent of the measured response and it determined by a combination of theoretical and empirical modeling.

4. Summary of Guide

4.1 This guide applies to borehole neutron logging.

4.2 This guide briefly describes the significance and use, apparatus, calibration and standardization, procedures, and reports for conducting borehole neutron logging.

5. Significance and Use

5.1 An appropriately developed, documented, and executed guide is essential for the proper collection and application of neutron logs.

5.2 The benefits of its use include improving selection of neutron logging methods and equipment; neutron log quality and reliability; usefulness of the neutron log data for subsequent display and interpretation.

5.3 This guide applies to commonly used neutron logging methods for geotechnical applications.

6. Interferences

6.1 Most extraneous effects on neutron logs are caused by logging too fast, instrument problems, borehole conditions, partially saturated formations, and geologic conditions.

6.2 Logging too fast can significantly degrade the quality of neutron logs, especially when neutron detectors are designed to exclude thermalized neutrons, resulting in relatively low counting rates. Neutron counts measured at a given depth need to be averaged over a time interval such that the natural statistical variation in the rate of neutron emission is negligible.

6.3 Instrument problems include electrical leakage of cable and grounding problems; degradation of detector efficiency attributed to loss of crystal transparency (fogging) or fractures or breaks in the crystal; and mechanical damage causing separation of crystal and photomultiplier tube.

6.4 Borehole conditions include changes in borehole diameter; borehole wall roughness whenever neutron logs are run decentralized; and steel casing or cement in the annulus around casing, and thickness of the annulus.

6.5 Geologic conditions include the presence of clay minerals with significant non- effective porosity (Fig. 2), and the presence of minerals such as chlorine with relatively large neutron absorption cross-sections.

6.6 Neutron log response is designed to measure water-filled pore spaces so that neutron logs do not measure unsaturated porosity.

7. Apparatus

7.1 A geophysical logging system has been described in the general guide (Section 6, Standard Guide D5753).

7.2 Neutron logs are collected with probes using He^3 detectors, which may be coated with Cd to exclude thermalized neutrons, or may be un-coated to detect both thermal and epithermal neutrons; neutron logs may occasionally be collected using detectors using lithium-iodide scintillation crystals coupled to photomultiplier tubes (Fig. 3).

7.2.1 A neutron shield is needed for the storage of the neutron source during transport to and from the logging site.

7.2.2 A secure storage facility is needed for neutron source during the time between logging projects when the source cannot be left in the shield in the logging truck.

7.2.3 Radiation monitoring equipment is needed for checking of radiation levels outside the neutron shield and in working areas during use of the neutron source to verify that radiation hazards do not exist.

7.3 Neutron logging probes generate neutron fluxes using a chemical radioactive source such as Ca^{252} or a combination of Am and Be; or by using a neutron generator.

7.4 Neutron probes generate nuclear counts as pulses of voltage that are amplified and clipped to a uniform amplitude.

7.4.1 Neutron probes used for geotechnical applications can be run centralized or decentralized (held against the side of the borehole); decentralized probes can be collimated (shielded on the side away from the borehole wall to reduce the influence of the borehole fluid column). However, collimation requires an impracticably heavy, large-diameter logging probe, and such probes are rarely used in geotechnical logging (Fig. 3C).

7.4.2 Neutron probes can have a single detector (Fig. 3A), or a pair of detectors located at different separations from the neutron source. When logging probes contain two detectors, the far detector is significantly larger than the near detector to compensate for the decreasing population of neutrons with distance from the neutron source, as indicated in Fig. 3B.

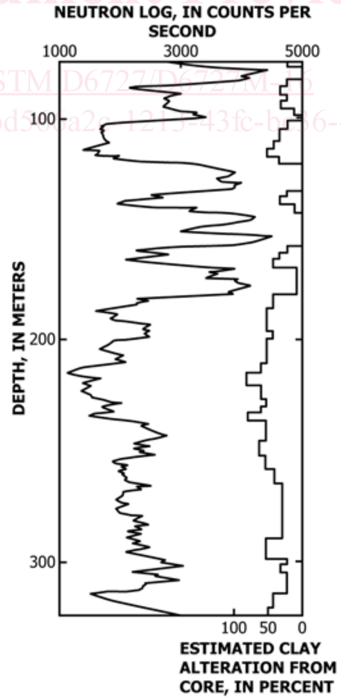
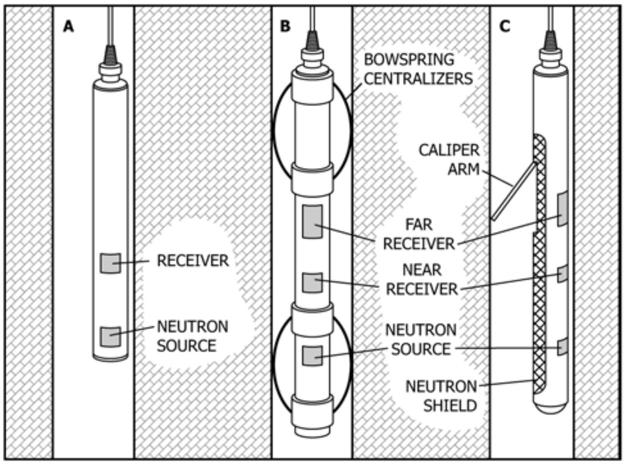


FIG. 2 Comparison of Single Detector Epithermal Neutron Log with Clay Mineral Fraction Determined Form Core Samples for a Borehole in Sedimentary Bedrock (from Keys, 1990)



A–Single detector run without centralization in a fluid-filled borehole.
B–Pair of detectors run with borehole centralization in a fluid-filled borehole.
C–Pair of detectors in a decentralized and collimated probe run in a fluid-filled borehole.

FIG. 3 Schematic Illustration of Neutron Logging Probes

7.4.3 Neutron probes are designed with source-to-receiver spacing such that measured neutron counts are proportional to the slowing down distance of the neutrons, which is assumed to be inversely proportional to the water-filled porosity of the formation.

7.5 The Volume of Exploration and Depth of Exploration are primarily determined by the moisture content of the material near the probe which controls the average distance a neutron can travel before being absorbed.

7.5.1 The Volume of Exploration for neutron logs is generally considered spherical with a radius of 1.5 to 2.5 ft [40 to 70 cm] from the midpoint between the neutron source and detector(s) in typical geological formations.

7.5.2 The Depth of Exploration for neutron logs is generally considered to be 1.5 to 2.5 ft [40 to 70 cm].

7.6 Vertical Resolution of neutron logs is determined by the size of the volume over which neutrons are scattered back towards the detector after being emitted by the source. In typical geological formations surrounding a fluid-filled borehole, this is a roughly spherical volume about 1 to 2 ft [30 to 60 cm] in diameter. Excessive logging speed can decrease vertical resolution.

7.7 Measurement Resolution of neutron probes is determined by the counting efficiency of the nuclear detector or detectors being used in the probe. Typical Measurement Resolution is 1 cps.

7.8 A variety of neutron logging equipment is available for geotechnical investigations. It is not practical to list all of the sources of potentially acceptable equipment.

8. Calibration and Standardization of Neutron Logs

8.1 *General:*

8.1.1 National Institute of Standards and Technology (NIST) calibration and standardization procedures do not exist for neutron logging.

8.1.2 Neutron logs can be used in a qualitative (for example, comparative) or quantitative (for example, estimating water-filled porosity) manner depending upon the project objectives.

8.1.3 Neutron calibration and standardization methods and frequency shall be sufficient to meet project objectives.

8.1.3.1 Calibration and standardization should be performed each time a neutron probe is suspected to be damaged, modified, repaired, and at periodic intervals.

8.2 Calibration is the process of establishing values for neutron response associated with specific values of water-filled porosity in the sampled volume and is accomplished with a representative physical model. Calibration data values related to the physical properties (for example, formation porosity) may be recorded in units (for example, cps), which can be converted to units of percent, water-saturated porosity.

8.2.1 Calibration is performed by recording neutron log response in cps recorded by one or a pair of detectors in boreholes centered within volumes containing a uniform, fully water-saturated medium of known porosity and mineral composition.

8.2.2 Calibration volumes should be designed to contain material as close as possible to that in the environment where the logs are to be obtained to allow for effects such as borehole diameter, formation density, and formation chemical composition.

8.2.3 Neutron log calibration is especially sensitive to borehole diameter in water-filled boreholes because the neutron flux from the logging probe interacts with water in the borehole as well as that in pore spaces; therefore, neutron log calibration is only accurate when applied to logs obtained in boreholes of nearly the same diameter as that of the calibration environment.

8.2.4 Neutron log calibration procedures depend upon whether single-detector or dual detector data are used.

8.2.4.1 Neutron log calibration fails above the water level where neutrons streaming along the air-filled annulus around the probe dominate the measured response of the equipment.

8.2.4.2 When counts from a single neutron detector are used, the measured counts are assumed to be inversely proportional to the logarithm of porosity.