MEMORANDUM REPORT

NOVEMBER 1979

NATURAL GAMMA RAY/ NEUTRON POROSITY LOGGING

SOUTH FLORIDA WATER MANAGEMENT DISTRICT

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NATURAL GAMMA RAY/NEUTRON POROSITY LOGGING

by

Michael P. Brown
and
Steven Anderson
Groundwater Division
Resource Planning Department
South Florida Water Management District
West Palm Beach, Florida 33402

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NUCLEAR LOGGING

Introduction

Nuclear logging, also known as radiation logging, comprises methods of measuring the intensity of either induced or natural radiations emitted by the formation. Nuclear logs have a fundamental advantage over most other logs - they can be made in either cased or open holes filled with any type of fluid. Four major types of nuclear logging are employed in groundwater resources investigations:

(1) Natural Gamma Ray

(2) Neutron Gamma

(3) Neutron Porosity

(4) Gamma Gamma Density

Our discussion will be restricted to natural gamma ray and neutron porosity logging.

Natural Gamma Ray Logs

All substances are assemblages of atoms. Each atom comprises a nucleus, made up of neutrons and protons packed together with electrons revolving around the nucleus. The arrangement of neutrons and protons in the atoms of certain elements is unstable, occasionally a natural rearrangement occurs during which protons and neutrons are ejected from the nucleus and energy is emitted in the form of gamma rays. Virtually all rocks contain radioactive elements, commonly uranium, thorium and potassium.

Mechanical and chemical erosion (weathering), principally of igneous rocks, forms the major portion of sedimentary clastic formations (e.g., sandstones and shales). These acidic rocks originally contain the major portion of the earth's potassium and a large fraction of the uranium.

In south Florida, carbonate rocks were developed by either direct precipitation from sea water, or from calcareous marine skeletal matter. Pure carbonate sediments have low radioactivity. When magnesium ions in migrating groundwaters cause dolomitization, slightly higher radioactive levels are often observed. Also, phosphorites abundant in south Florida's Miocene and younger sediments have high radioactivity.

Figure 1 shows the level of radiation normally associated with various rock types. The length of the line denotes the intensity range in API Gamma Ray Units. The vertical width of the line increases with the frequency of occurrence. Figure 2 shows assorted gamma ray responses "idealized" for different lithologies.

The primary application to date of the natural gamma ray log is: (1) lithology identification and stratigraphic correlation; (2) as an index to permeability in clay formations; and (3) for use in monitoring changes in well screens due to plugging.

Natural Gamma Ray Equipment Description

The SFWMD Groundwater Division's Research Geophysical Logger utilizes a Gearhart-Owen 1-11/16 inch O.D., gamma ray, casing collar locator (ccl), Neutron Porosity Tool. The electronics are all solid state and most of the circuit functions are performed by high temperature rated integrated circuits mounted in field replaceable modules. The detector is a high sensitivity scintillation type with a sodium iodide crystal emitting light pulses optically coupled to a photomultiplier tube where a pulse of electrical current amplified about 1 X 10^6 times, is produced. This pulse is sent to the surface equipment (ratemeter module) where the pulses are integrated over a preset time constant and a DC-voltage output is used to drive the recorder pen to reflect the formation's natural gamma radiation intensity in counts per second (cps).

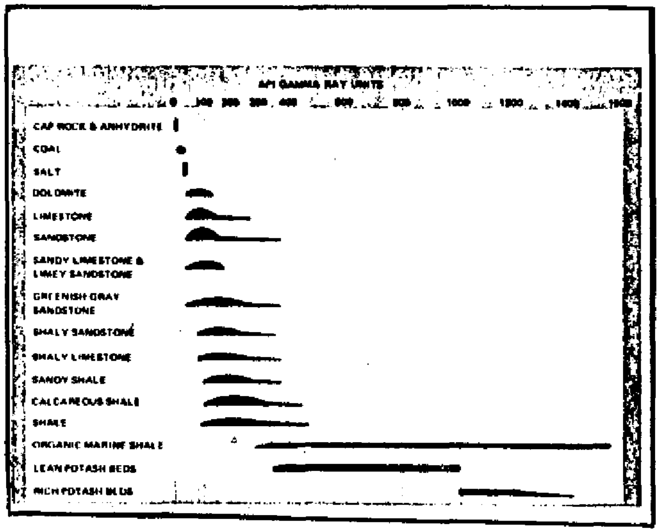

Figure 1 - Typical Levels of Gamma Radiation Associated with Various Rock
types (taken from Dresser Atlas, 1974).

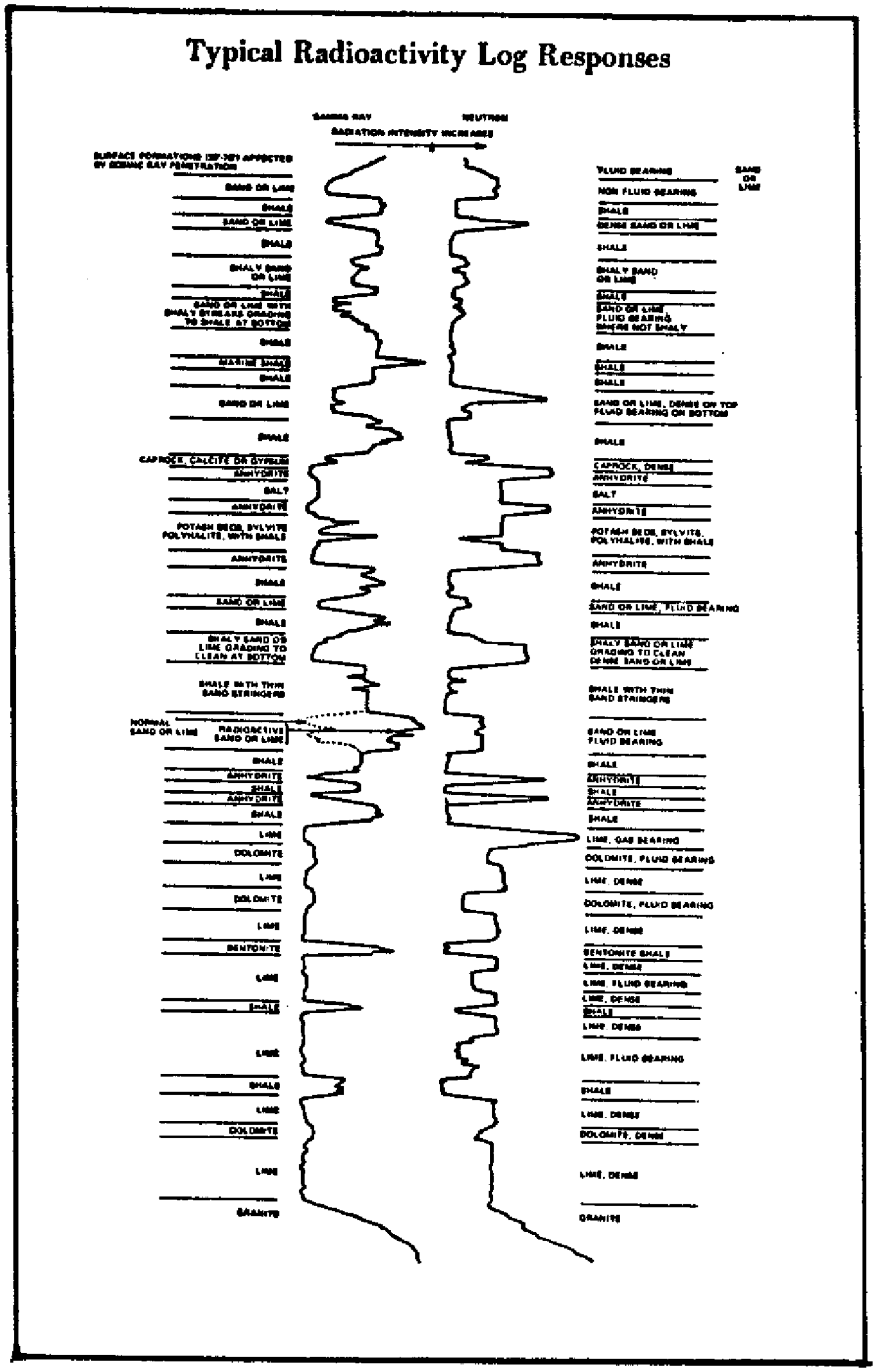

Figure 2 - Typical Gamma and Neutron Responses for Different Lithologies (taken from Dresser Atlas, 1974).

Gamma Ray Calibration Principles

The purpose of calibration is simply to adjust the recorded tool response (counts per second) in terms of "API Gamma Ray Units". The API Gamma Ray unit is an industry standard, which has been set up in order to standardize logs obtained by different logging instruments, relating the logs to a standard environment. The standard environment is the gamma ray test pit at the University of Houston. We will discuss the API test pit later.

Field calibration of the gamma ray tool is accomplished by the use of a Gearhart-Owen Gamma Ray calibrator, factory adjusted, to give a response equivalent to 100 API units. The gamma ray calibrator provides a spacing of 48 inches between a Cs^{137} 100 curie source and the detector (Figure 3) which increases the count rate by 100 API units. Recorded with all gamma ray logs for calibration purposes is gamma background (detector 20' from any source and 5' above land surface on time drive) and background plus source standard (Figure 4). The difference between background and background plus source standard equals 100 API gamma ray units.

Neutron Porosity Logs

The neutron porosity log is often a standard counterpart of the natural gamma ray log. Neutron logs respond to the fundamental formation property of hydrogen richness. Upon entering the borehole with the neutron source bombarding the formation, neutrons undergo a continuous de-energizing process. This energy reduction occurs when neutrons emitted from the source collide with nucleus of borehole and formation elements. A neutron loses some of its total kinetic energy each time it is involved in either an elastic or inelastic collision. Energy loses are a function of the angle of collision and the relative mass of the struck nucleus. Since hydrogen atoms are both relatively abundant and nearly equal in mass to the neutron, they are

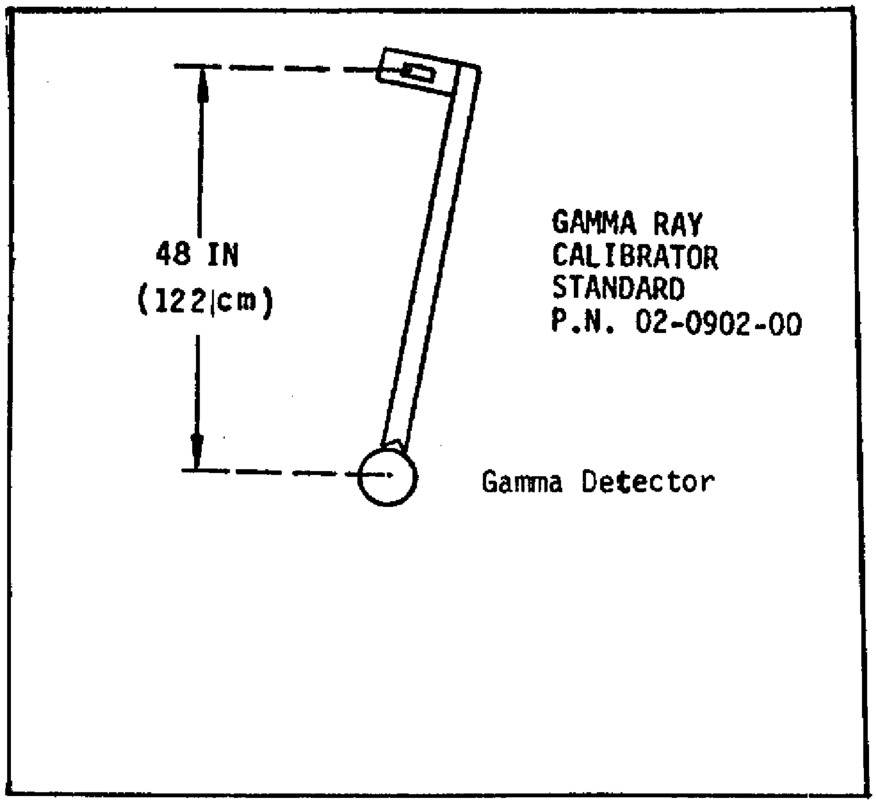

Figure 3 - Setup for the Gamma Ray Calibrator (taken from G.O.I., 1978).

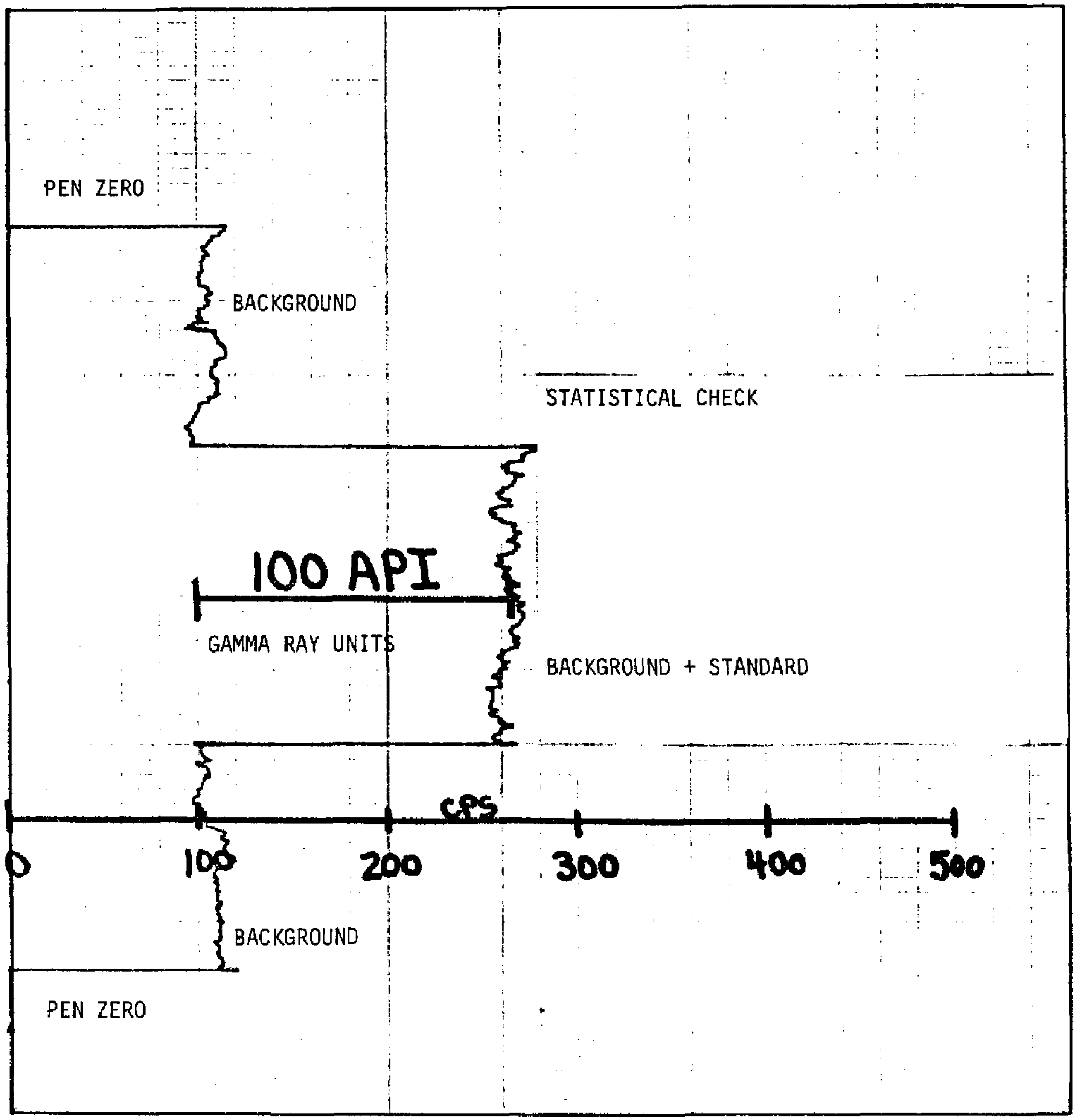

Figure 4 - Standard Field Calibration Recording.

primarily responsible for reducing high energy neutrons to their thermal state. If all of the formations's hydrogen is contained in the form of liquids (H_2O), and if these liquids completely occupy the total pore volume, hydrogen richness is an index to porosity.

The primary application of the neutron porosity log is for: (1) lithologic identification and stratigraphic correlation, (2) porosity or total water content of the formation which may include pore water between mineral grains, bound or absorbed water in clay, or even crystallization water in gypsum.

Neutron Porosity Equipment Description

The Groundwater Division's neutron porosity tool is connected to the natural gamma ray tool enabling the two surveys to be made simultaneously. The source for the neutron tool is a 3 curie $Am_{241}Be$ with a neutron emission of about 10×10^6 per second at 4.5 Mev. The detector is spaced 13.0 inches from the source and is a He^3 filled type which responds only to thermal neutrons and is relatively insensitive to gamma radiation. As with the gamma ray tool, the pulse is sent to the surface equipment where the pulses are integrated over a preset time constant. The DC voltage output is used to drive the recorder pen reflecting the formation's porosity by the relation:

$$\text{uncorrected porosity} \propto \frac{1}{\text{intensity (cps)}}$$

Neutron Porosity Calibration Principles

The neutron porosity calibration procedures are similar to the gamma ray calibration. API units have been adopted by the industry to calibrate the neutron tool. As discussed previously, API calibration is based on the tool response in a controlled logging environment which is the neutron calibration test pit maintained by the University of Houston, Texas.

The Division's neutron tool is calibrated in the field with a secondary standard which was calibrated against the tool response in the API neutron calibration test pit, University of Houston. The neutron field calibrator consists of a plastic sleeve 26 inches long having a 8.5 inch O.D. and a 5.5 inch I.D. The field calibrator is placed over the tool as shown in Figure 5; this will provide a known response equivalent to 1000 API neutron units at 19% limestone porosity. On all neutron logs calibration curves are provided with the 1000 API neutron unit response and 0 API response. A linear function is assumed in this procedure.

Nuclear Logging Statistical Variations

The nature of radioactive emissions are quite random, thus a count rate (cps) measurement of the occurrences will always be less than 100% accurate. These time variations in emission account for the "statistical nature" of radioactive logs. In both gamma ray and neutron logging an averaging (time constant) circuit is used to minimize statistical fluctuations by increasing the overall "response time" and to limit the rate at which the system can make accurate measurements.

A statistical check will demonstrate the magnitude of statistical variations that can be expected on a particular log (Figure 4). This type of check is recorded for a time span at which the sonde remains stationary with all dial settings (t.c., c/s, sen., etc.) at the same setting as when the log was run.

API Calibration Test Pits

In order to provide standard units for natural gamma-ray and neutron porosity measurements, the American Petroleum Institute (API) in 1948 adopted the terms "API Gamma-Ray Unit" and "API Neutron Unit". This recommended practice is the result of a conclusion reached by a large segment of the

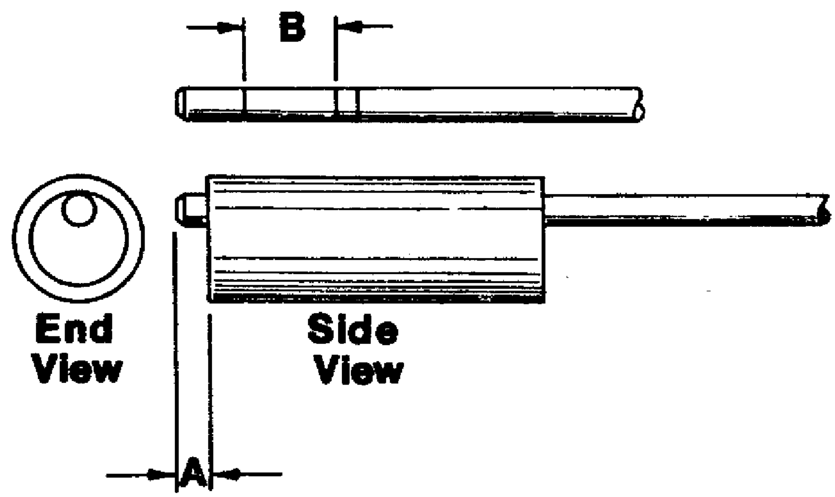

Figure 5 - Standard neutron porosity field calibrator (modified from GOI, 1977).

oil industry. The recommended practice was proposed to provide the basis for standardizing nuclear log units for presentation, including means for reporting adequately and uniformly the data that should accompany each log to facilitate correct interpretation and use.

The API nuclear calibration facility is located on the campus of the University of Houston, Houston, Texas. Operation of the facility is a function of the University, and funds for operation and maintenance are obtained from fees paid by users of the facility to the University.

Natural Gamma Ray API Test Pit Calibration Procedures

In order to provide a standard unit for gamma ray log measurements, the API has adopted the term "API Gamma Ray Unit". One API Gamma-Ray Unit is defined as 1/200 of the difference in log deflection between the zones of low and high radiation in the gamma-ray calibration pit.

The design of the gamma-ray calibration pit is shown in Figure 6. This pit is 4 ft. in diameter, 25 ft. deep, and is filled with three 8 ft. thick zones of concrete. Five and one-half inch casing extends through the 3 concrete sections and 15 ft. below the bottom of the pit. The top and bottom concrete zones in the pit are of very low-radioactivity concrete equal in radiation to approximately twice that of an average scale.

The calibration procedures include:

(1) A record of calibration using the field calibrator before and after calibration runs in the pit.

(2) Two decentralized runs of the gamma-ray logging tool made in the pit from top to bottom.

(3) The logging tool is stopped for a reading opposite the center of the radioactive-concrete section.

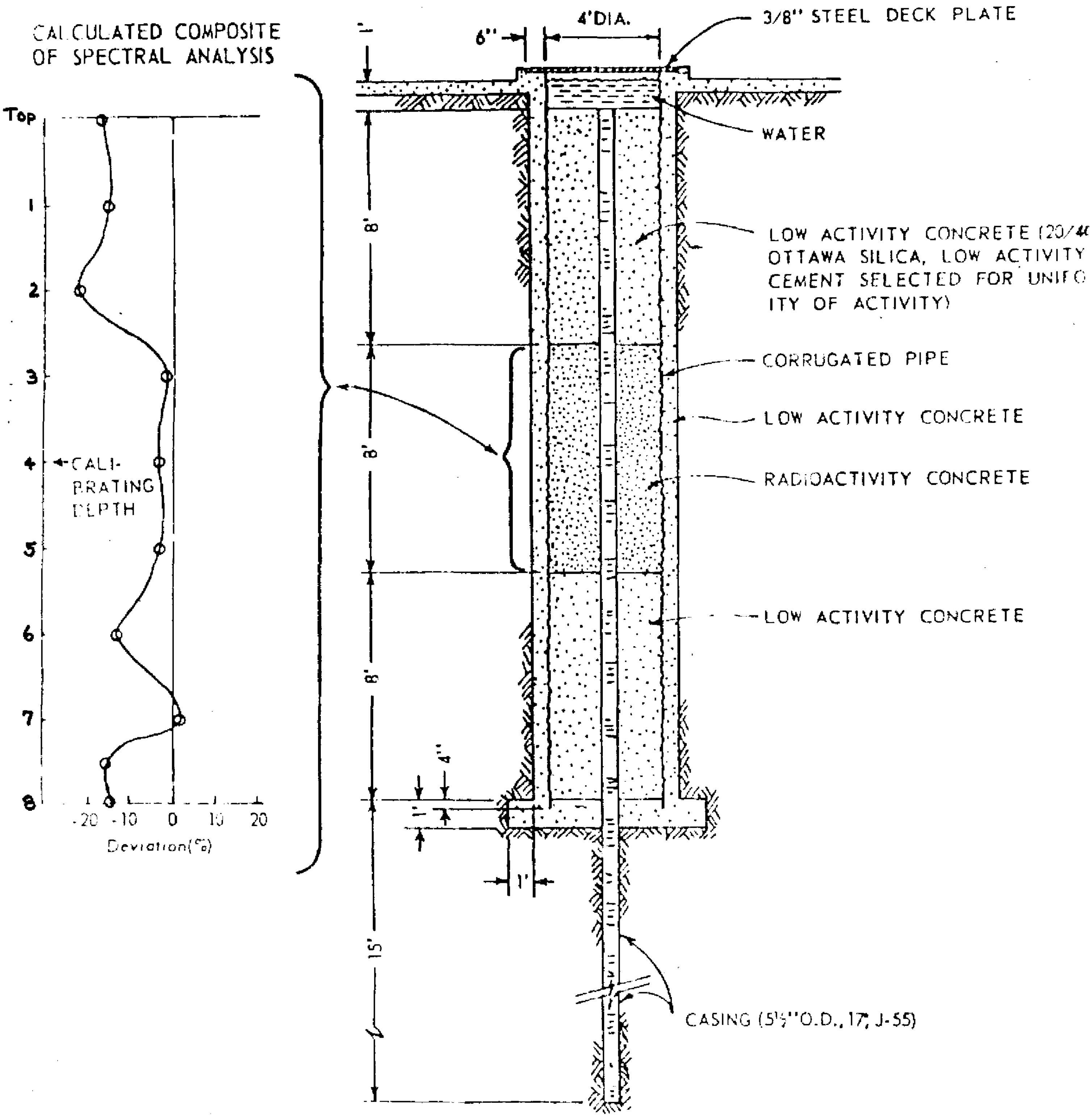

Figure 6 - Gamma Ray Calibration Pit (taken from API, 1971)

Neutron Porosity API Test Pit Calibration Procedures

As with the natural gamma-ray standard unit, the API has also adopted the term "API Neutron Unit". One API Nuetron Unit is defined as 1/1,000 of the difference between instrument zero and log deflection opposite the 6 ft. zone of Indiana limestone in the neutron calibration pit.

Since there are differences in the responses of various neutron porosity logging tools in different ranges of porosity, two additional limestone zones having differing porosities are included in the neutron calibration pit. The three limestone zones provide an accurate means for comparing neutron logs made with different tools through the entire range of porosity.

Design details of the neutron calibration pit are shown in Figure 7. This pit is 6 ft. in diameter and 24 ft. deep, with three 6 ft. thick limestone zones of varying porosity. The limestone blocks are regular octagons 1 ft. thick and 5 ft. across, with a 7 7/8 inch hole in the center. The limestone blocks are saturated with water and the pit is kept filled with water at all times. There is a 6 ft. water shield above the limestone blocks.

The limestone blocks from bottom to top are:

(1) Austin limestone having an average porosity of 26 percent.

(2) Indiana limestone having an average porosity of 19 percent.

(3) And the top zone, Carthage marble having an average porosity of 1.9 percent.

The center limestone block (Indiana limestone) was used to establish the API Neutron Unit and is used for calibrating logging tools in these units.

The calibration record for the neutron log is similar to the gamma ray log and includes a record of calibration using the logging company's field calibrator before and after the tool is run in the neutron calibration pit. Two runs are made in the pit with the tool decentralized. Each run is made

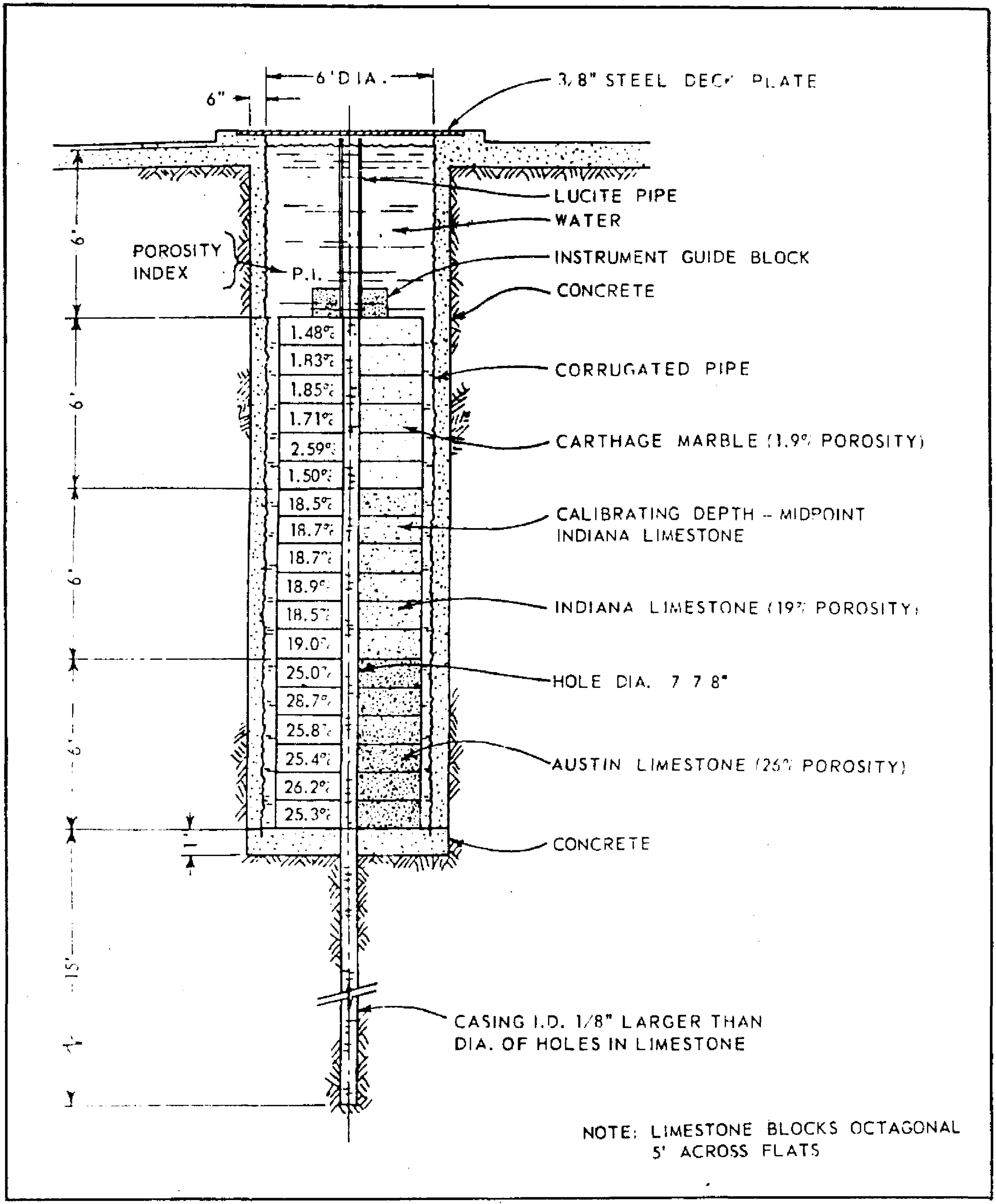

Figure 7 - Neutron Log Calibration Pit (taken from API, 1971)

from the bottom of the pit to the top and includes a recording of instrument zero, the three zones of limestone blocks, the water shield and a second instrument zero. During the calibration run, when the tool is opposite the center of the Indiana limestone zone it should be stopped for a calibration reading.

Calibration Results

The following figures show results for the natural gamma ray and neutron porosity tests runs in the API test pits at the University of Houston. These surveys were made on June 6, 1979 by logging operators, Michael P. Brown and Steven Anderson assisted by Herman D. Collette, Research and Development, Gearhart-Owen Industries. These runs were made under the guidelines described in "Recommended Practice for Standard Calibration and Format for Nuclear Logs", 1974. Two line speeds of 10'/min. and 25' min. were chosen to produce logs that best resemble line speeds used under field conditions.

Figures 8 and 9 show natural gamma ray test runs at line speeds of 25'/min. and 10'/min. respectively. Both runs were made at a time constant of 3. As can be observed in these figures, the deflection starting at approximately 7 ft. is caused by the high radioactive concrete. The difference between the low radioactive concrete baseline and the high radioactive concrete baseline equals 200 API gamma ray units. The API scale at the top of the log was produced using this method. The cps scale is our internal calibration. Run #1 (Figure 8) has an average 1.20 cps/API where Run #2 (Figure 9) has a 1.17 cps/API, a difference of .03 cps/API or a 2.5% change between the two runs.

Figure 10 shows natural gamma ray calibration using the GOI field calibrator. Results show the difference between background and background plus standard equal to 100 API units having a 1.48 cps/API. The difference

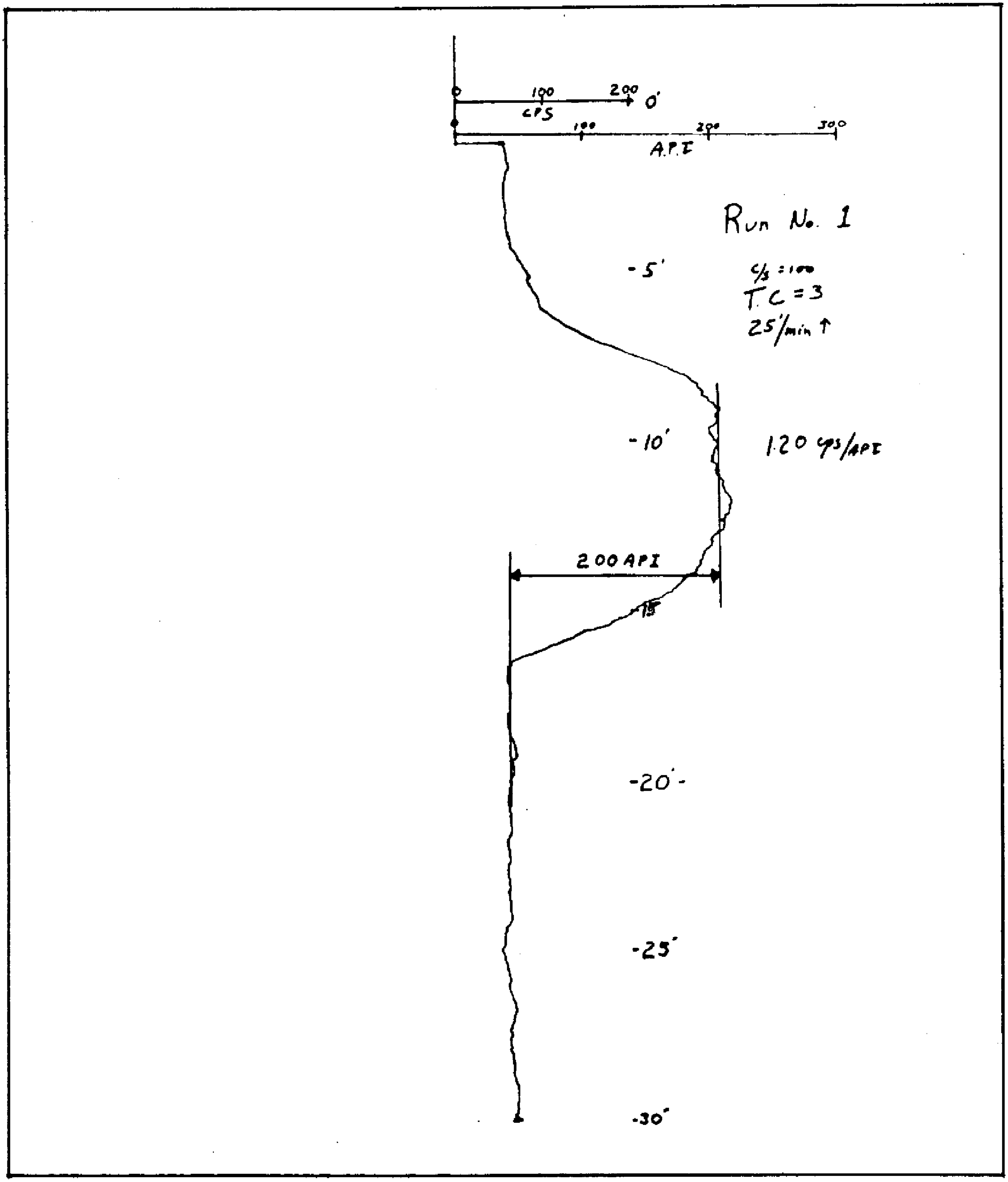

Figure 8 - Natural gamma ray Run #1 in the gamma ray API Test Pit, University of Houston.

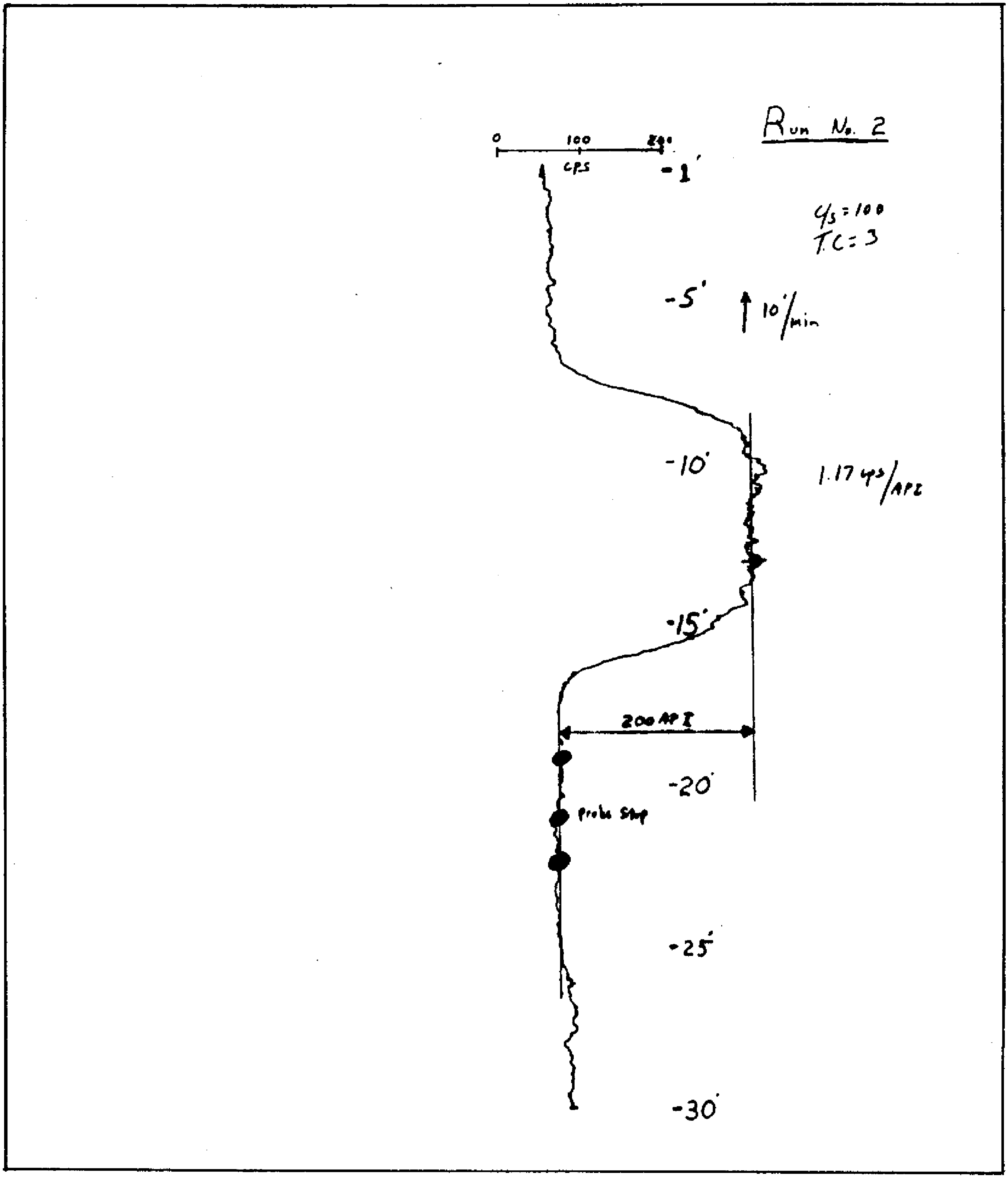

Figure 9 - Natural gamma ray Run #2 in the gamma ray API Test Pit, University of Houston.

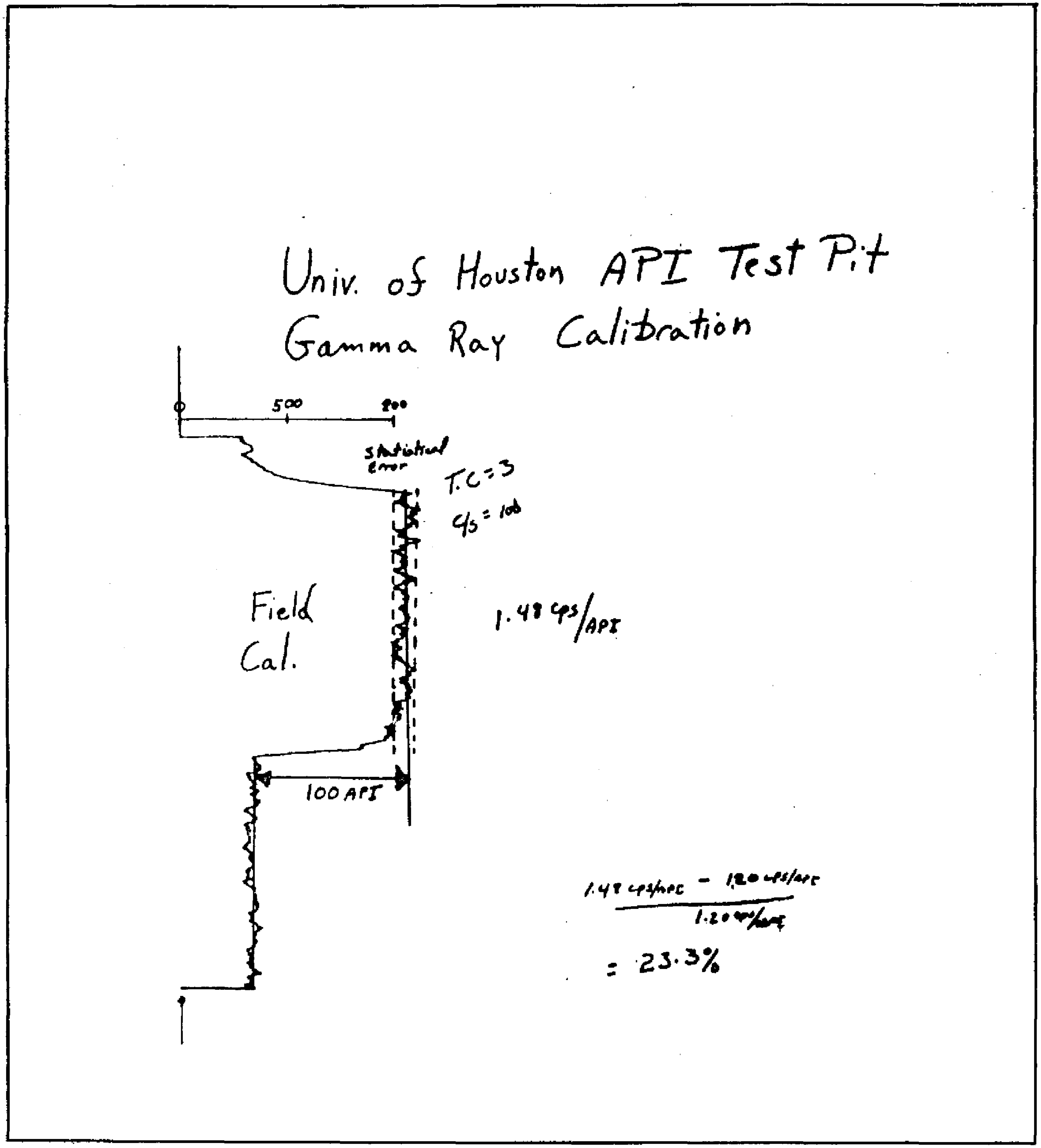

Figure 10 - Natural gamma ray calibration using the GOI gamma ray field calibrator.

between the field calibrator calibration and test pit calibration is 22.3%. This is not very significant considering a specified GOI calibration error for this equipment of 25% (personal communication, GOI, 1979). Also, knowing the difference between the two calibrations a user can correct logs to the correct test pit API unit. This type of correction would only serve a purpose if a comparison or correlation is required between this equipment's tool response and that of another type of calibrated equipment.

Figure 11 and 12 present neutron porosity test runs at line speeds of 25'/min. and 10'/min. logged at time constants of 2 and 3 respectively. These surveys reflect deflections controlled by porosities of the different test pit borehole media as described earlier (remember, porosity is inversely proportional to intensity). Figure 13 shows neutron intensities with the sonde held stationary at the center of each media during which the chart recorder was set in time drive. As can be observed, the Indian limestone at 15' gives a neutron response of 1.60 API/cps. Figure 14 shows the calibration using the GOI field calibrator. The response for this calibration is 1.67 API/cps having a difference between the test pit calibration and field calibrator calibration of .07 API/cps or a 4.3% change.

Figure 15 shows the type neutron log response for a GOI 1-1 1/16" decentralized tool. Superimposed on this curve are the points measured in the different porosity media of the test pit. As can be observed from this figure, the data collected during the neutron test runs in the API calibration pit are essentially the same as shown on the type curve.

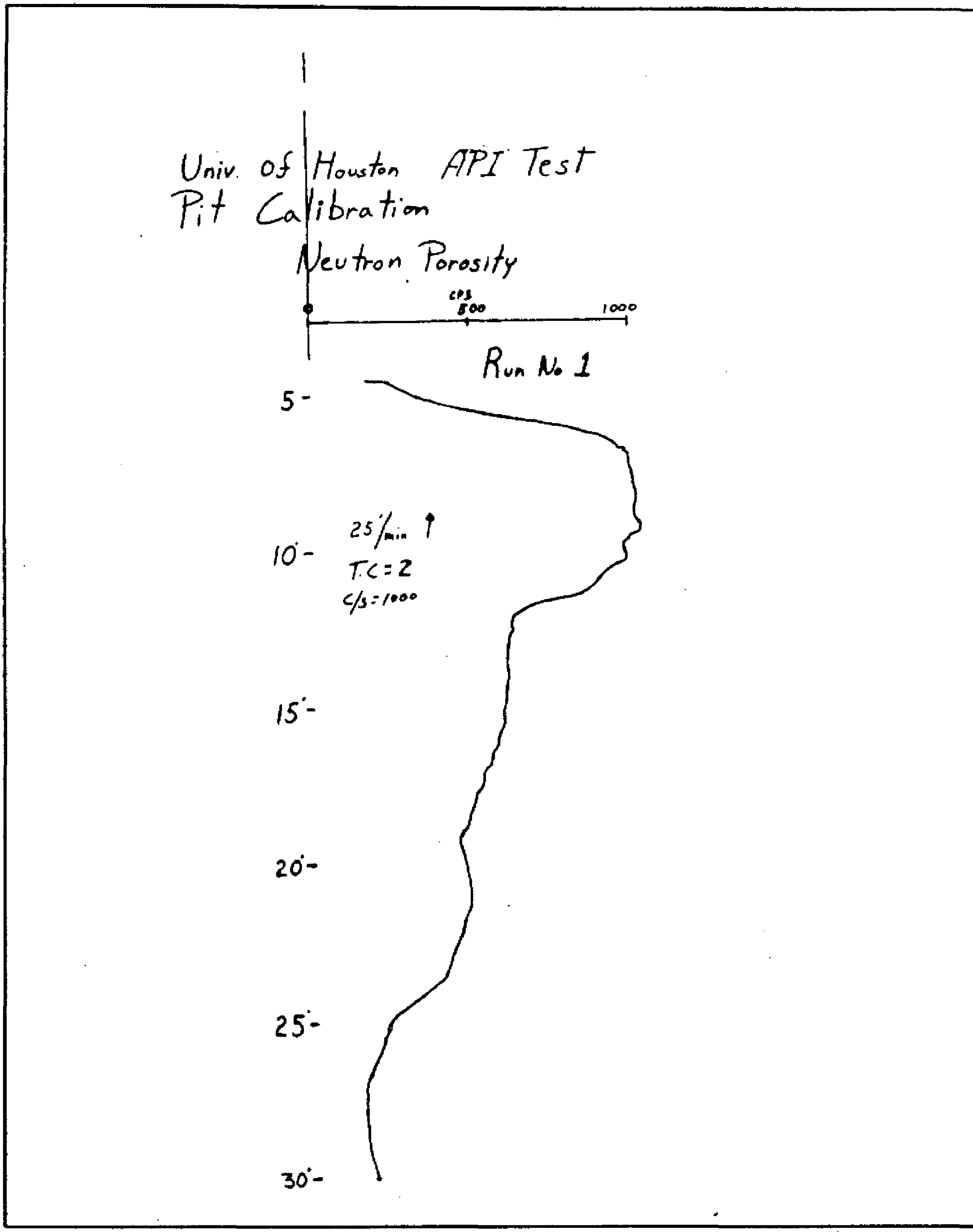

Figure 11 - Neutron porosity test Run #1 in the API Test Pit.

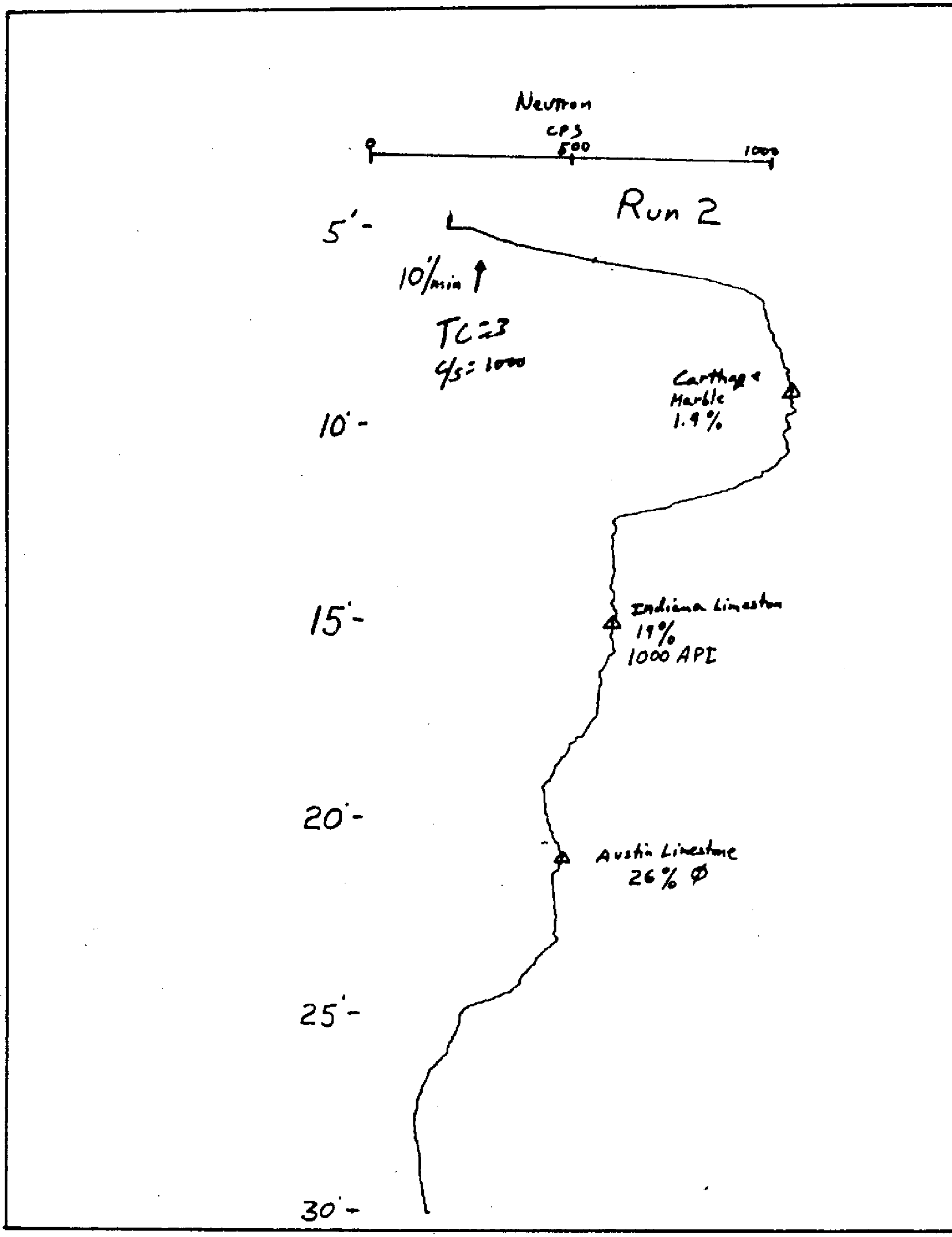

Figure 12 - Neutron pososity test Run #2 in the API Test Pit.

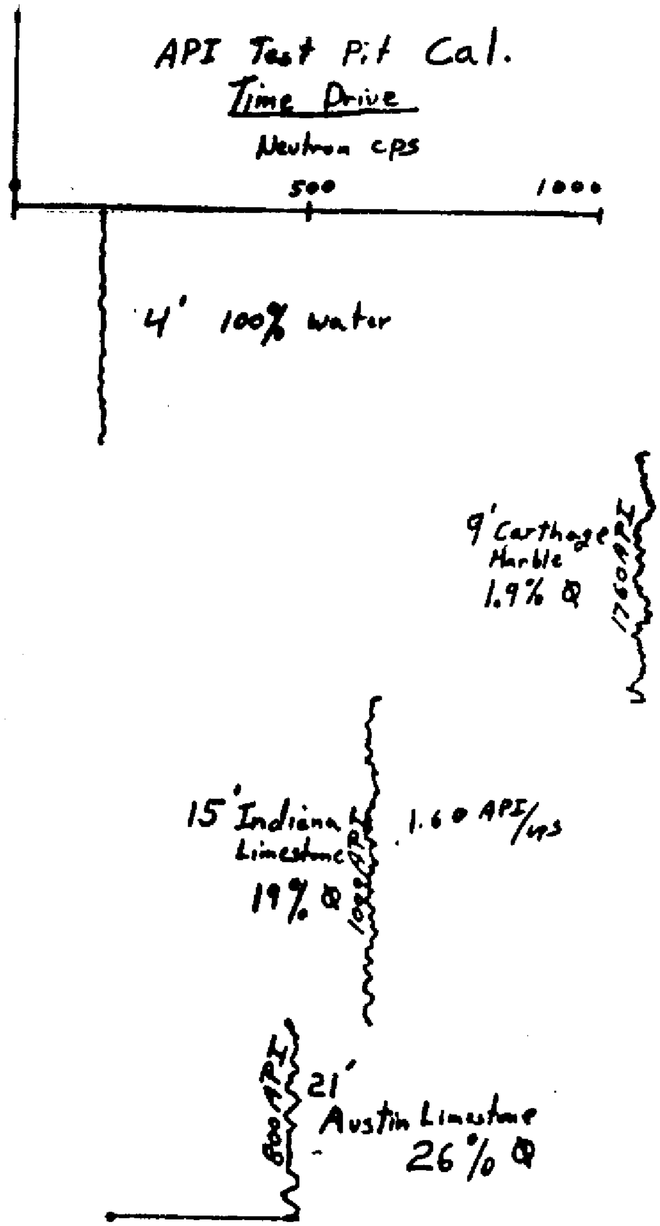

Figure 13 - Neutron porosity responses with the probe stationary at the center of each test pit media.

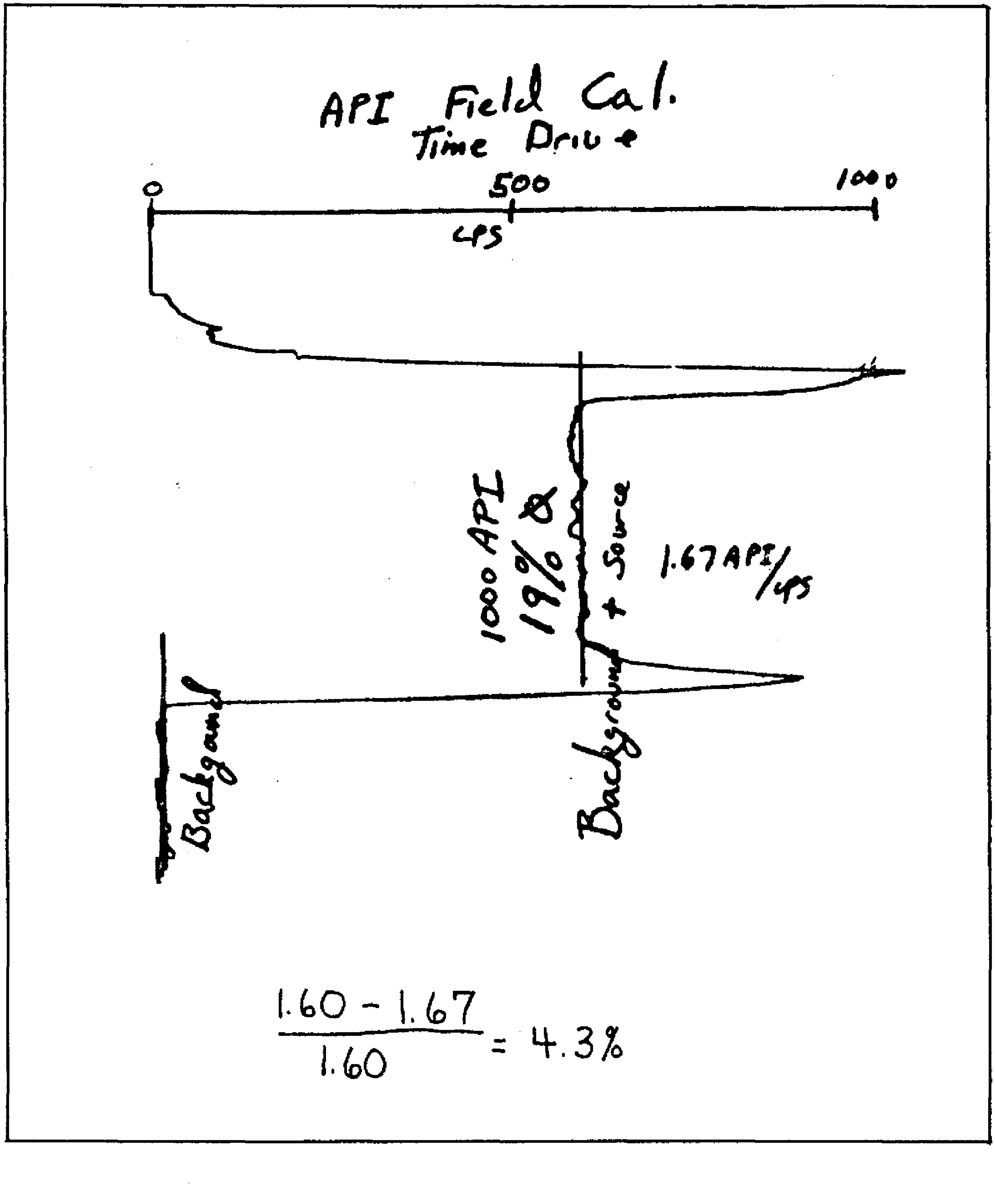

Figure 14 - Neutron porosity calibration using the GOI field calibrator.

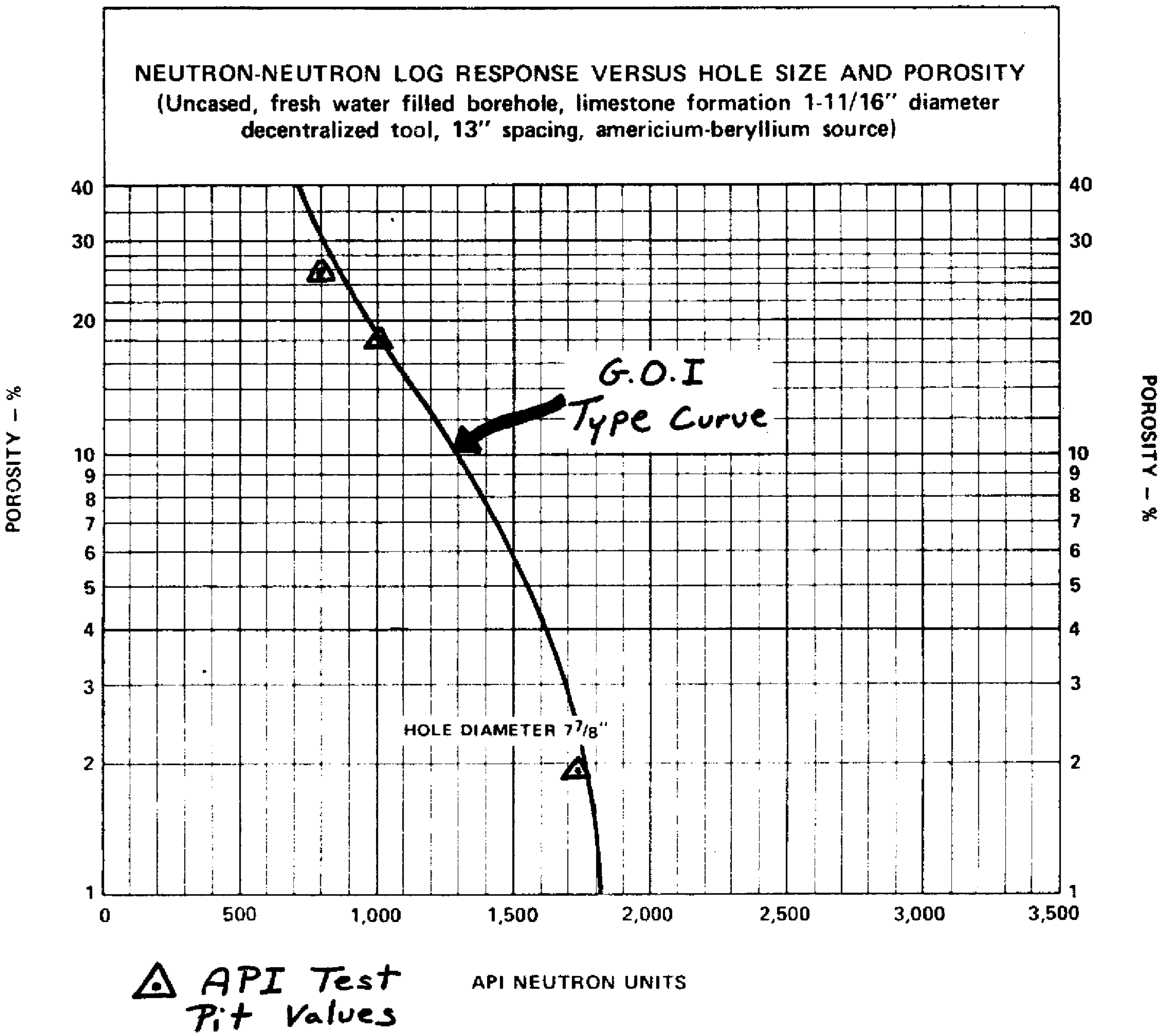

Figure 15 - Type neutron log response with API Test Pit measurements superimposed on curve (modified from GOI, 1977).

SELECTED REFERENCES

American Petroleum Institute, 1971. Recommended Practice for Standard Calibration and Format for Nuclear Logs, API, RP 33, 3rd Edition, 13A.

Dresser Atlas, 1974. Log Review 1, Dresser Industries, Inc., pp. 8-1 through 8-21.

Gearhart-Owen Industries, Inc., 1977. Formation Evaluation Data Handbook, Gearhart-Owen Second Edition, Ft. Worth, Texas, 240 p.

Gearhart-Owen Industries, Inc., 1977. Gamma Neutron System, Gearhart-Owen, Fort Worth, Texas.

Guyod, H., 1972. Application of Borehole Geophysics to the Investigation and Development of Groundwater Resources, Water Resources Bulletin, Vol. 8, No. 1, pp. 161-174.

Hilchie, D. W., 1978. Applied Openhole Log Interpretation for Interpretation for Geologists and Engineers, Douglas W. Hilchie Inc., Golden, Colorado.

Keys, W. S., MacCary, L. M., 1971. Application of Borehole Geophysics to Water Resources Investigations, U. S. Geological Survey, Technical Water Resources Investigations, Book 2, Chap. E1, 126 pp.