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Continuous Monitoring of Coal by a Neutron Moisture Meter

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Continuous Monitoring of Coal by a Neutron Moisture Meter

By A. W. Hall, J. L. Konchesky, and R. F. Stewart
Morgantown Energy Research Center, Morgantown, W. Va.

UNITED STATES DEPARTMENT OF THE INTERIOR
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CONTINUOUS MONITORING OF COAL BY A NEUTRON MOISTURE METER

by

A. W. Hall,[1] J. L. Konchesky,[2] and R. F. Stewart[3]

ABSTRACT

A nuclear method was developed for continuously and automatically determining the moisture content of coal flowing through a bin. Fast neutrons from a 1 curie americium-beryllium source penetrate the coal, are thermalized (slowed down) by hydrogen in the moisture, and are counted by a thermal neutron detector. The difference between the number of these thermal neutrons and those thermalized by dry coal (in a reference drum) is a measure of the moisture content of the coal. A materials handling system was developed and in tests at a commercial coal preparation plant, moisture in coal was monitored continuously within 0.2 percent of values determined by conventional means. The meter responded rapidly to change in moisture content, making it adaptable to automatic process control, and was operated for 1 year without malfunction or recalibration. Shielding of the source by the coal kept the neutron flux level at the bin wall less than 1 milliroentgen per hour, a safe level for personnel.

INTRODUCTION

Continuous, rapid methods are needed for measuring the moisture content of tonnage streams of coal. Conventional analytical methods are laborious and time consuming, and the results often are not available until after the coal has been shipped or burned. Continuous methods would facilitate production of specification fuels, reduce transportation costs, and effect more efficient utilization.

Researchers have had only limited success in developing methods for continuously determining the moisture content of bulk quantities of coal and other solids. Moisture values determined by methods based on dielectric constants, electrical resistance, and electrical conductivity can be misleading owing to bulk density changes, temperature variations, electrode wear, electrical noise generated from intermittent contact of probes with the

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[1]Research chemist.
[2]Chemical research engineer.
[3]Research supervisor.

material, and from variation in inorganic salts content (8).[4] Also, these methods are restricted to use with fine, uniformly sized particles, since only the surface moisture, not the moisture in the capillaries, is measured. Other methods, such as nuclear magnetic resonance and microwave transmission, are unsuitable for process control. The former is restricted to small, constant-weight samples (7); the latter is sensitive to changes in bulk density (8), which varies with moisture content, ash content, particle size, compaction, and other variables.

Ray (7) reviewed various methods for determining the moisture content of coal and other solid materials and concluded that continuous measurement probably cannot be achieved, but that automatic periodic measurements might be possible. Coal preparation plants typically produce more than 1,000 tons per hour, hence a compromise is necessary between measurement of the entire production stream and an elaborate sampling method that eventually produces a small sample but of questionable representation. The ideal method must measure a representative sample without changing the properties of the material, including moisture content, by crushing and drying during sampling. It must also respond rapidly, be insensitive to certain variables, and not require frequent calibration.

These specifications were objectives of the Bureau of Mines in the development of a nuclear-type meter (12-13). A pilot-scale system was designed to compensate for bulk density changes of the coal and was fitted with a moisture meter that had shown promise in laboratory tests. In pilot-plant runs with a variety of coals containing 1 to 12 percent moisture, a precision of better than 0.2 percent moisture was achieved, with this precision virtually unaffected by ash variation between 5 and 15 percent. Subsequently, improved material handling equipment was developed and tests of the meter were conducted at the Robena Coal Preparation Plant of the U.S. Steel Corp., near Uniontown, Pa. (3). This report describes the equipment, procedure, and the performance of the meter under industrial conditions.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the cooperation and assistance of officials and employees of the Robena Coal Preparation Plant, U.S. Steel Corp., Uniontown, Pa.

NEUTRON THERMALIZATION PRINCIPLE

The neutron method for determining the moisture content of coal is based on the slowing down or energy loss (thermalization) of fast (high energy) neutrons by elastic collisions with the hydrogen nuclei. Fast neutrons have approximately the same mass as hydrogen atoms and interact with nuclei of the latter in billiard-ball-type collisons. The average energy lost by each neutron is transmitted to the hydrogen nuclei or the nuclei of other elements and is expressed by the formula (1):

[4] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

$$\left(\frac{\Delta E}{E}\right) = \frac{2A}{(A+1)^2}$$

where ΔE is the energy lost by the neutron in one collision with the nucleus, E is the energy of the neutron prior to collision, and A is the mass number of the nucleus which slows down the neutron. For hydrogen, A = 1, each neutron that collides with a hydrogen nucleus loses on the average one-half of its energy.

Hydrogen slows down neutrons more effectively than any other of the common elements. The other major elements (carbon and oxygen) present in coal have a large scattering effect but little effect in thermalizing neutrons (10). This scattering effect tends to confine the neutrons to the vicinity of the gage until the hydrogen has reduced the neutrons to thermal energies. Many other elements are present in the ash, but not in sufficient quantity to have a significant effect. Thus, when fast neutrons are projected into a material the number of thermal neutrons produced depends primarily on the quantity of hydrogen present (9).

Thermal neutrons are produced from the bound hydrogen and moisture in coal. However, the bound hydrogen content of coals from a particular mine generally does not vary more than 0.1 percent, on a moisture-ash-free basis, so suitable calibration curves can be plotted for each type coal to account for the number of slow neutrons thermalized by bound hydrogen.

The gage is not capable of serving as an analytical instrument to determine the absolute moisture content of a variety of coals nor is it suitable for blends of different bound hydrogen contents mixed in uncertain ratios. However, the neutron moisture meter is adaptable for process control and the size of the sample monitored makes the results more representative than those from conventional methods. It can be used with any coal of any size and moisture content provided that the fuel can be made to flow uniformly through a bin.

In the application of this technique, a small radioactive source and a boron-lined proportional detector sensitive only to slow (thermal) neutrons are located in the center of a 40-inch-diameter test bin through which the coal is passed. A second source and detector are located in a 40-inch-diameter hermetically sealed reference drum (fig. 1) containing the same type coal dried to less than 1 percent total moisture. Fast neutrons from the sources penetrate the coal and are thermalized by hydrogen atoms. One-curie quantities of the radioactive material constitute virtually point sources (due to the small volume) that emit radiation equally in all directions, thereby producing a flux of thermal neutrons that effectively measure a 36-inch sphere (approximately 700 pounds) of coal. Figure 2 shows how a fast neutron (energy >0.500 MeV) from the source successively strikes hydrogen nuclei and is slowed (illustrated by increasing wavelength) to thermal energies (0.025 eV) and counted by a detector. A change in moisture content of the coal passing through the bin proportionately changes the hydrogen concentration and the number of thermal neutrons. The difference between the number of the thermal neutrons and number of thermal neutrons from the dry coal in the reference drum is a measure of the moisture content of the coal.

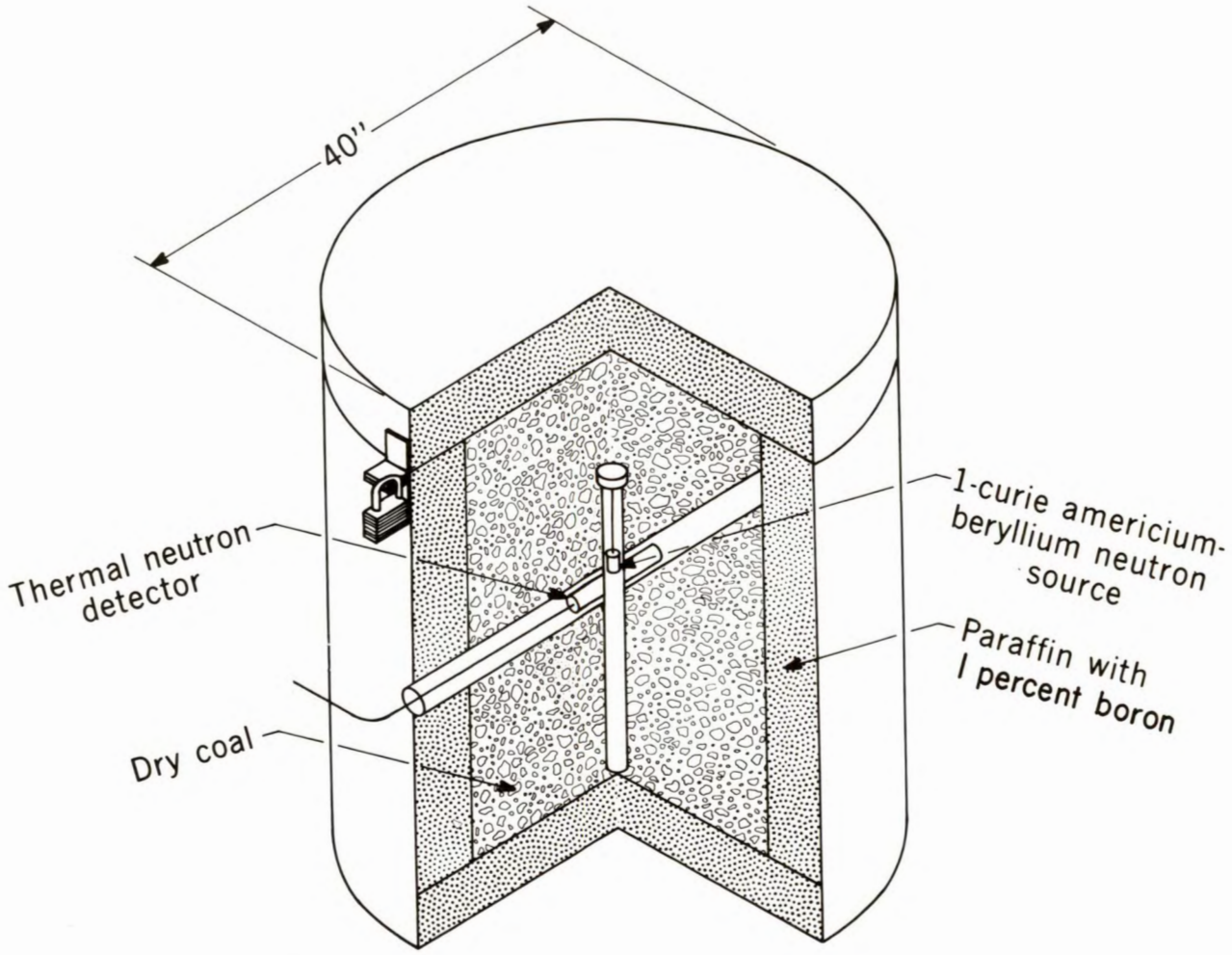


FIGURE 1. - Reference drum of dry coal for neutron moisture meter.

SELECTION OF NEUTRON SOURCE AND DETECTOR

Matched, 1-curie americium-beryllium sources were chosen as the most suitable for the application. Americium-241 has a half-life of 458 years and a virtually constant emission rate of 2.2×10^6 neutrons per second per curie (2), which is sufficient for a statistical measurement of ±0.2 percent moisture and still in compliance with health physics requirements. Shielding of the source by the coal kept the neutron flux level at the bin wall below 1-milliroentgen per hour, a safe level for personnel, and the source could be retracted and stored in a wax drum for plant shutdown or repairs. The sources used were 0.75-inch diameter by 1.5 inches long, doubly encapsulated in stainless steel, and each contained 0.30 gram of americium and 5.5 grams of beryllium. Average neutron energy was about 5 MeV (6).

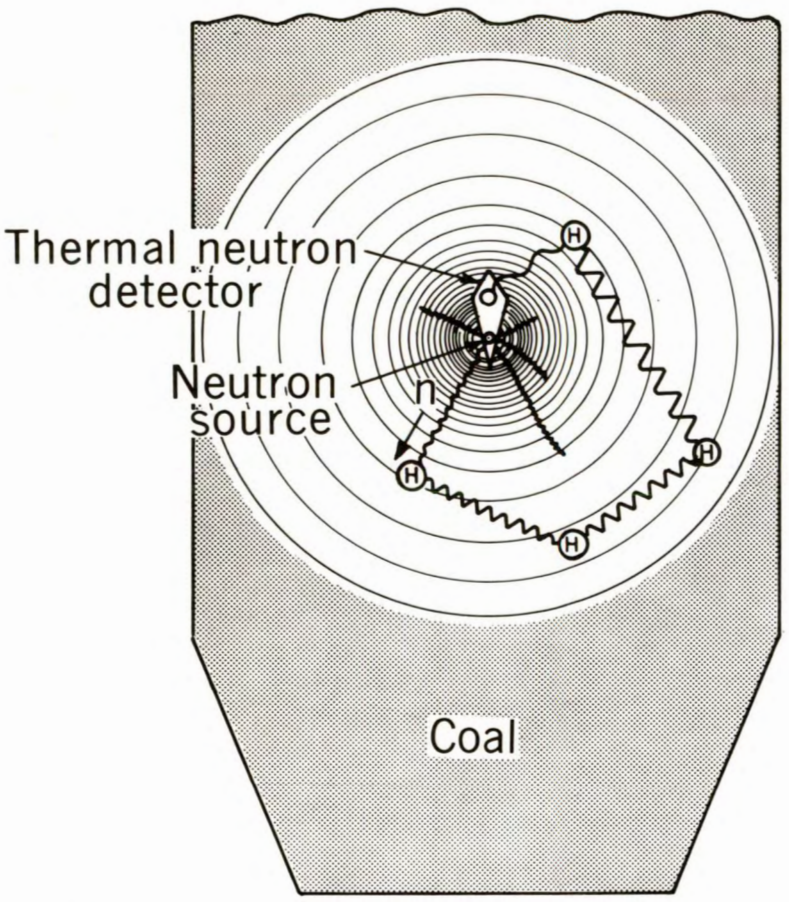


FIGURE 2. - Thermalization of high energy neutrons by hydrogen produces a sphere of thermal neutrons in the coal.

Two matched, boron-lined thermal neutron detectors, with similar plateau slope, plateau length, and count rate at a common operating voltage, manufactured by General Electric Co.,[5] 3 inches in diameter by 15 inches long, were selected which discriminated between the thermal neutrons and the gamma radiation emitted from the neutron sources. Also, these detectors were relatively unaffected by temperature variations and vibration and suffered negligible deterioration from exposure to constant high radiation fluxes.

ELECTRONIC INSTRUMENTATION

Determination of the difference in total hydrogen content of wet and dry samples of coal calls for a highly precise measurement of the difference between two large numbers. A 1-percent change in 200,000 counts per minute rate results from a 1-weight-percent change in water content of coal containing about 7 percent moisture; therefore, the moisture meter must be precise to 400 counts per minute to determine moisture to ±0.2 percent. This requires electronic instrumentation with high sensitivity and extreme stability, which is beyond the capability of conventional instrumentation, particularly when subjected to the environment of coal preparation plants. An electronic system was developed in which two similar scalers measure the difference between the number of neutrons thermalized by the coal being analyzed and the number of neutrons thermalized by dry coal in a reference drum. The difference is directly proportional to the moisture content of the coal and is recorded on a strip chart.

[5]Reference to a specific company is intended to facilitate understanding and does not imply endorsement by the Bureau of Mines.

For a count rate of 200,000 counts per minute for each system (reference and measuring), a 1-percent change in count (2,000 counts per minute) corresponds to approximately a 1-percent change in moisture. The instrument was designed to be stable to within ±0.1 percent of the count, or in the case above, ±200 counts. The statistical error (one standard deviation) for a 1-minute counting period is 630 counts, or 0.3 percent moisture. The total error (measuring and instrument) would be 0.3 percent for a 1-minute moisture measurement. However, the minimum effective counting time for a given sample passing through the measuring section is 6 minutes and the instrument has a response time constant of 1 minute. This means that the statistical error of the measurement would be 0.12 percent and the total error of the moisture measurement, including instrument error, would be 0.16 percent.

To increase the stability of the moisture meter counting system, two identical amplifier-discriminator sections were incorporated and were time-shared by the reference and measuring detectors. This multiplexing technique effectively minimized drift effects normally associated with the high gain amplifiers and discriminators by permitting all system voltage amplification to be placed within the commutated sections. Switching was accomplished by means of high quality reed relays at a rate of one alteration per second. The instrument was installed in a room separate from the facility housing the test bin, thereby reducing the effects of dust, moisture, and temperature on the electronic components. Use of time-shared dual system resulted in high precision and reliability approaching the statistical error of 0.12 percent. Test of the instrument resulted in a total error of moisture measurement of less than 0.2 percent.

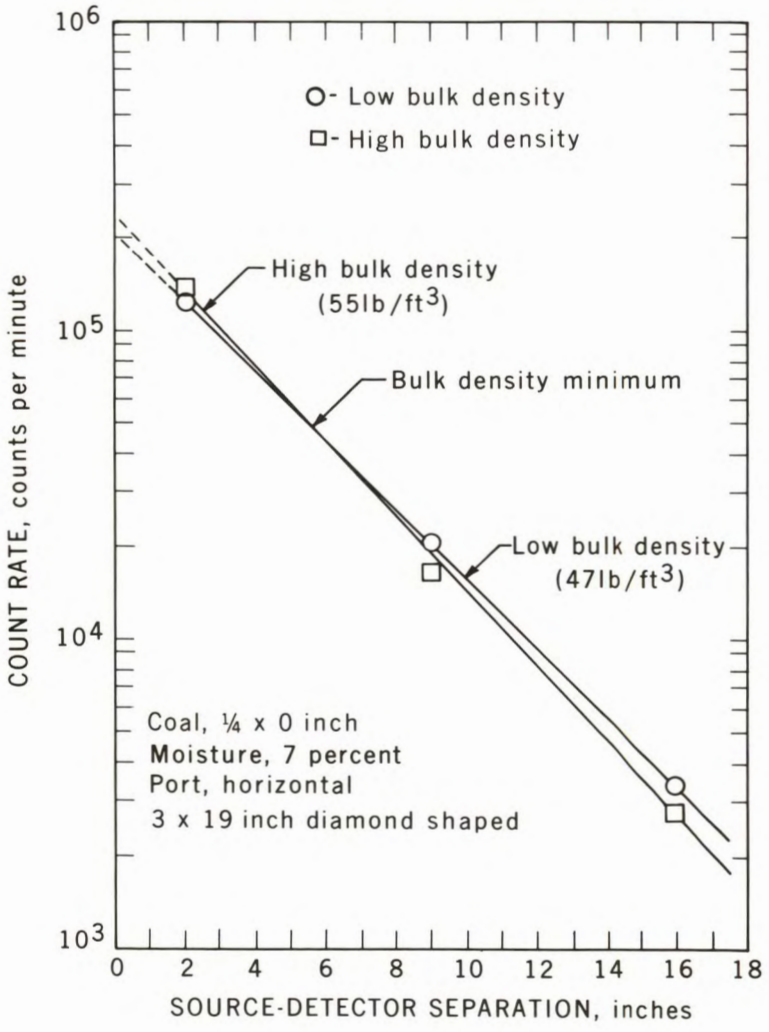


FIGURE 3. - Optimum distance between source and detector.

BULK DENSITY COMPENSATION

Variation in response of the moisture meter to changes in bulk density of

the coal (which in turn varies with moisture and ash content, particle size, and compaction) (11) was compensated by spacing the source and the detector so as to achieve an optimum separation distance. This is the distance that gives the minimum error in moisture content measurement from variation in bulk density of the coal. Figure 3 illustrates how the optimum separation distance was determined for the horizontal, 19-inch-high, 3-inch-wide diamond-shaped port that was used in the test bin. Moisture meter count rate is plotted against source-detector separation distances for batches of the same coal compacted to bulk densities of 47 and 55 lb/cu ft--approximately the extremes encountered in a coal preparation plant. Optimum separation distance--about 6 inches--is indicated by the intersection of the lines representing the two densities. Use of the 6-inch separation distance gives moisture meter measurements virtually independent of bulk density variations for this port. For each different port configuration, a new optimum separation distance must be determined.

Minimizing of the effect of bulk density variation on moisture measurements is also assisted by locating the test section at least 1-1/2 vessel diameters below the surface of the coal where the vertical bulk density gradient is slight. This reduces in the measuring region the effects of variables such as moisture and particle size on the bulk density, giving increased reliability of the bulk density compensation method. The validity of bulk density compensation was confirmed by a bulk density gage that consisted of a 17-curie cesium-137 gamma ray source on one side of the bin and an ionization detector on the opposite side. (Calibration tests of the gage showed an average bulk density reproducibility better than 0.15 lb/cu ft in a chart recorder range of 47 to 55 lb/cu ft.) The bulk density in the pilot-scale tests did not vary more than ±0.5 pound per cubic foot, indicating that the density remained fairly constant in the test zone.

FIELD TESTS

The neutron moisture meter was field tested at the Robena Coal Preparation Plant, U.S. Steel Corp., in southwestern Pennsylvania (fig. 4). Figure 5 is a schematic diagram of the major components of the test system. A representative batch of coal comprising about 500 pounds per cut is extracted from the production stream every 65 seconds by the primary sampler and crushed to 1/4-by-0-inch. This coal goes through a secondary sampler on to a conveyor, through the test bin, and back to the main product belt. (The secondary sampler removes coal at 80-second intervals for analysis by conventional methods for comparison with the nuclear results.) The main coal stream from the secondary sampler passes into the test bin and enters a particle distributor (4-5)--a coal chute with a discharge that oscillates radially as it rotates about the center of the test bin--that minimizes horizontal particle-size segregation. The distributor continuously spreads the coal particles, maintaining a smooth bed surface and keeping the flow of coal around the source-detector port representative of the production stream. The diamond-shaped port, shown in figure 6, contains the centrally located neutron source and thermal neutron detector. A vibrating hopper at the bottom keeps the coal flowing uniformly through the test bin.

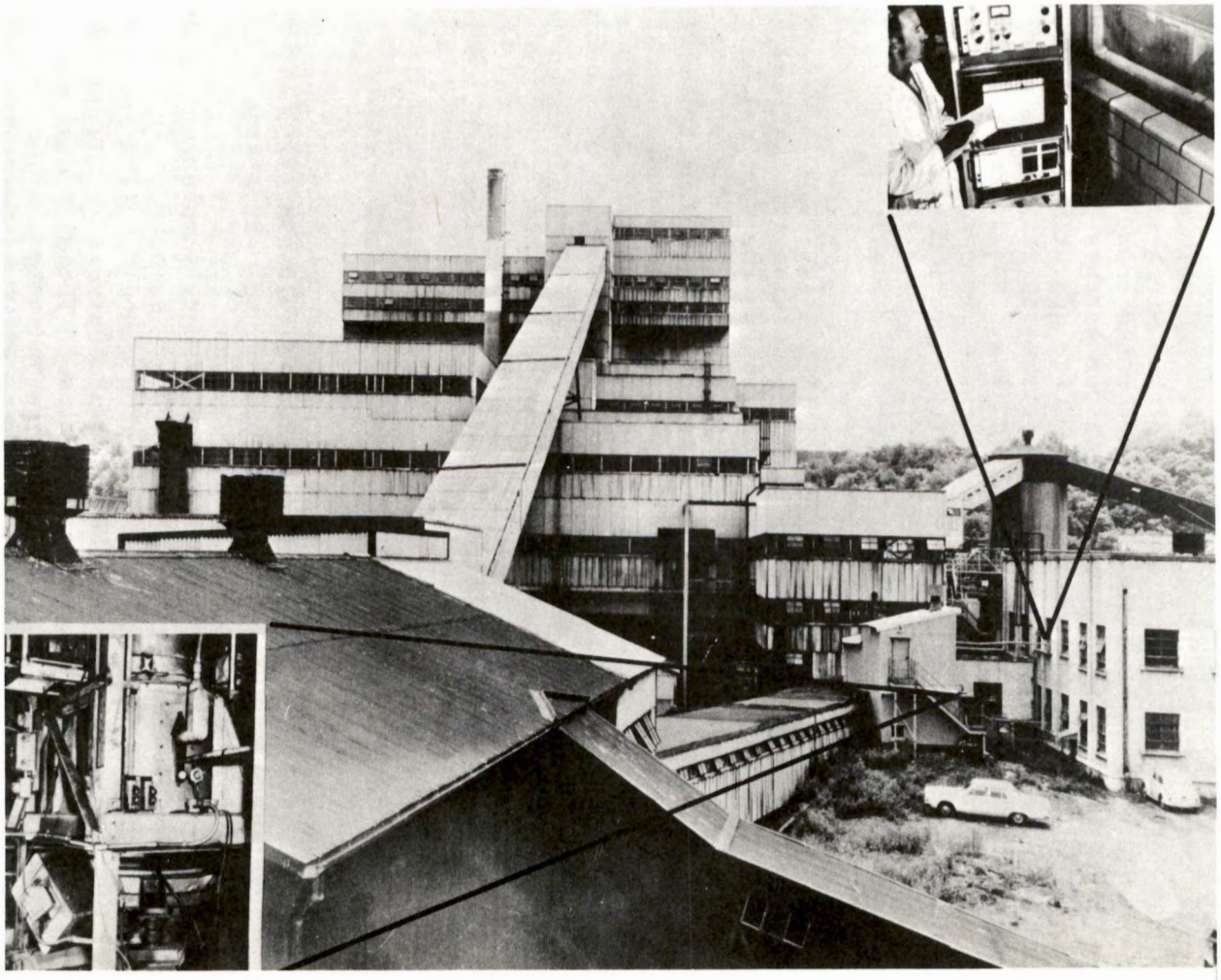


FIGURE 4. - Robena coal preparation plant with locations of moisture meter test section and instrumentation.

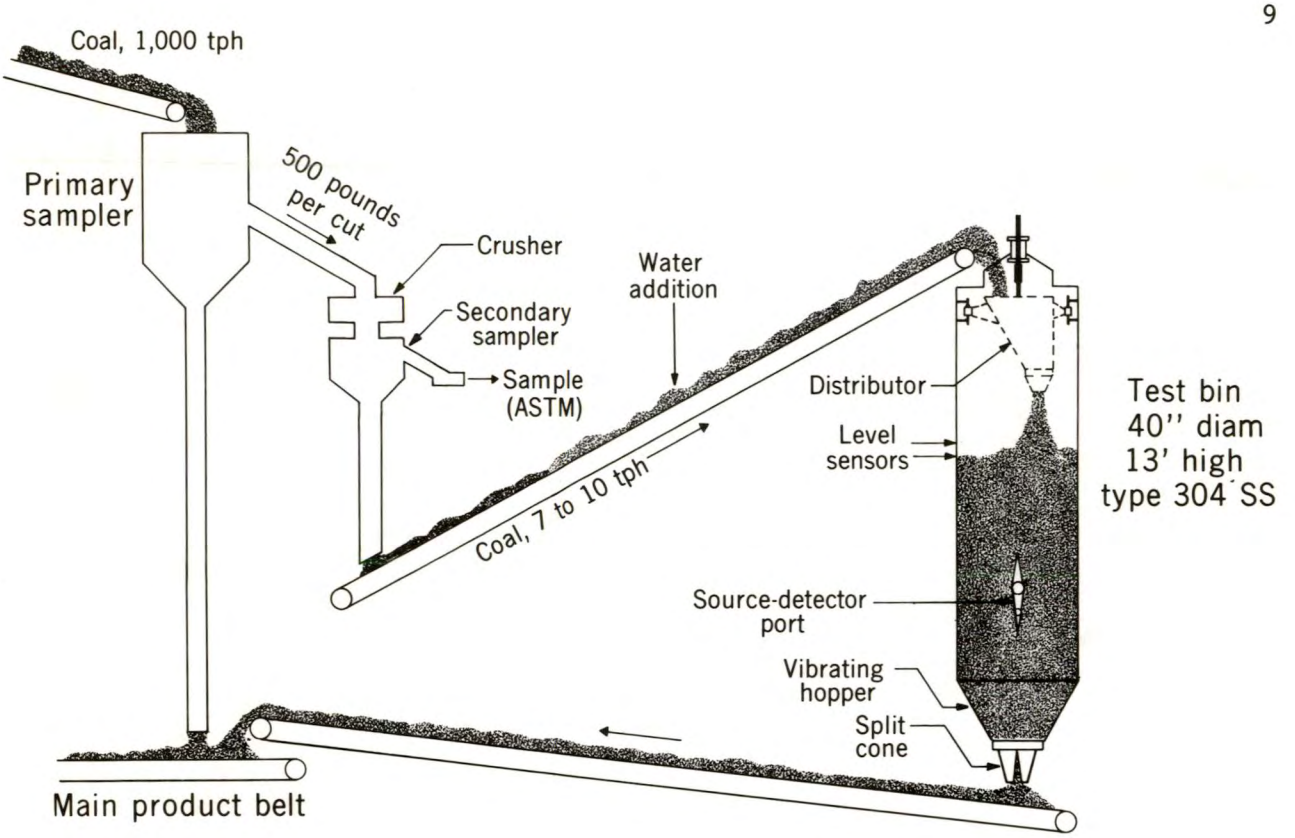


FIGURE 5. - Moisture meter installation at coal preparation plant.

An automatically controlled truncated split cone (fig. 7)--8 inches in diameter opened and 3-1/4 inches in diameter closed--maintains continuous flow and a constant coalbed level of 9 feet ±1 inch, even though the flow rate fluctuates between 7 and 10 tph. The cone is controlled automatically by two level sensors spaced 1 inch apart vertically and located 9 feet above the bottom of the bin. The sensors transmit an electrical pulse to a solenoid that actuates an air-driven piston on the two segments of the cone. When the surface of the coalbed rises until the coal covers the top sensor the cone opens, increasing the discharge rate and dropping the bed surface; when the surface drops below the bottom sensor, the split cone closes, decreasing the discharge rate and raising the bed level. Uniform flow is necessary to establish the time between sampling for conventional analysis and moisture determination by the nuclear method, thus permitting a valid comparison of values.

The moisture meter was calibrated by means of values determined by ASTM analysis of more than 1,200 samples and known moisture increases from periodic addition of small amounts of water to the coal entering the test bin. Figure 8 is the calibration curve. For the upper portion of the calibration curve (values greater than 7 percent moisture, ASTM), the average standard deviation of meter values from actual moisture values is 0.18 percent. The data points that deviate more than 0.2 percent from actual values in the lower part of the curve (less than 7 percent moisture) resulted from formation of voids in the test section during the last portion of moisture additions.

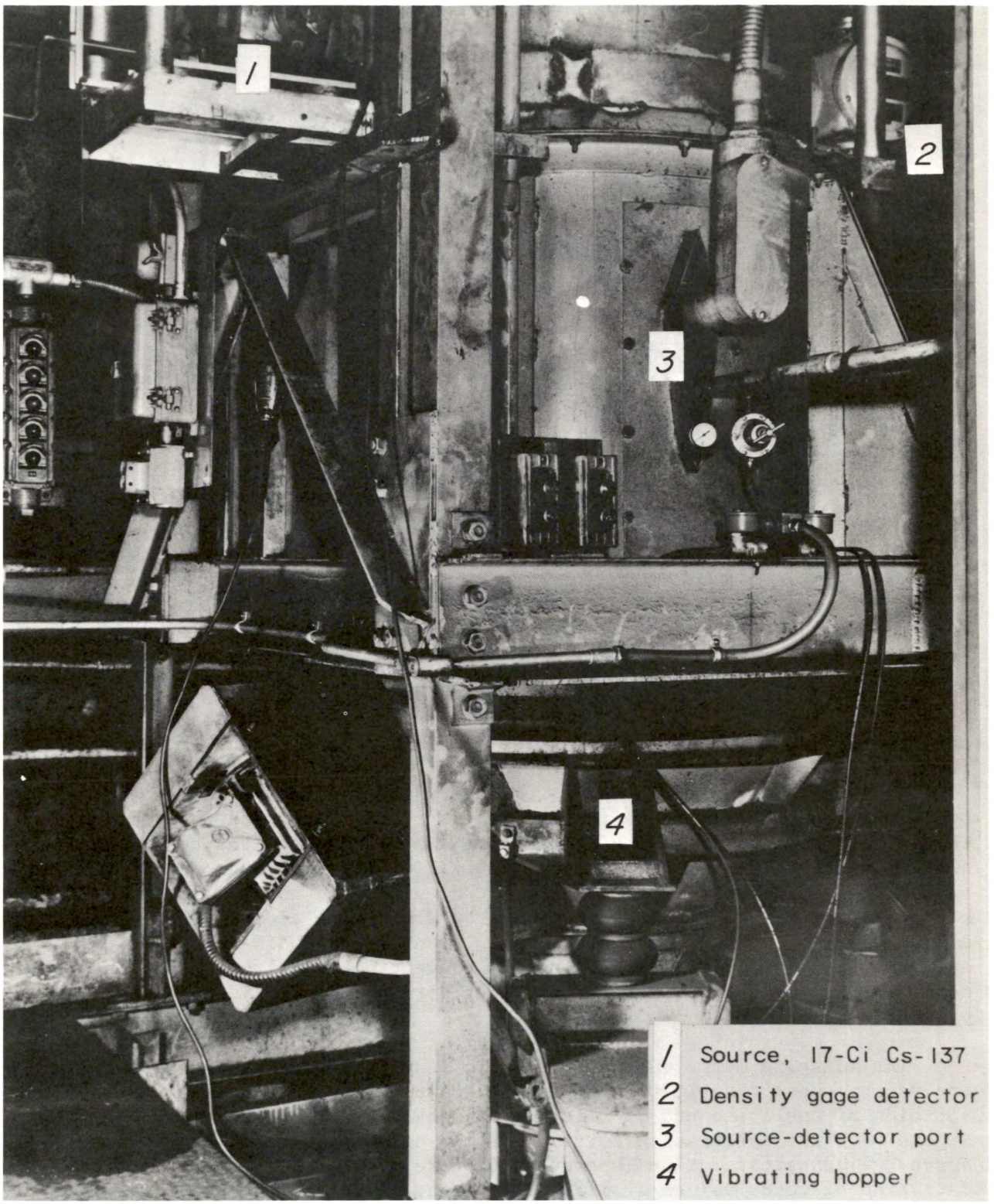


FIGURE 6. - Moisture meter test section.

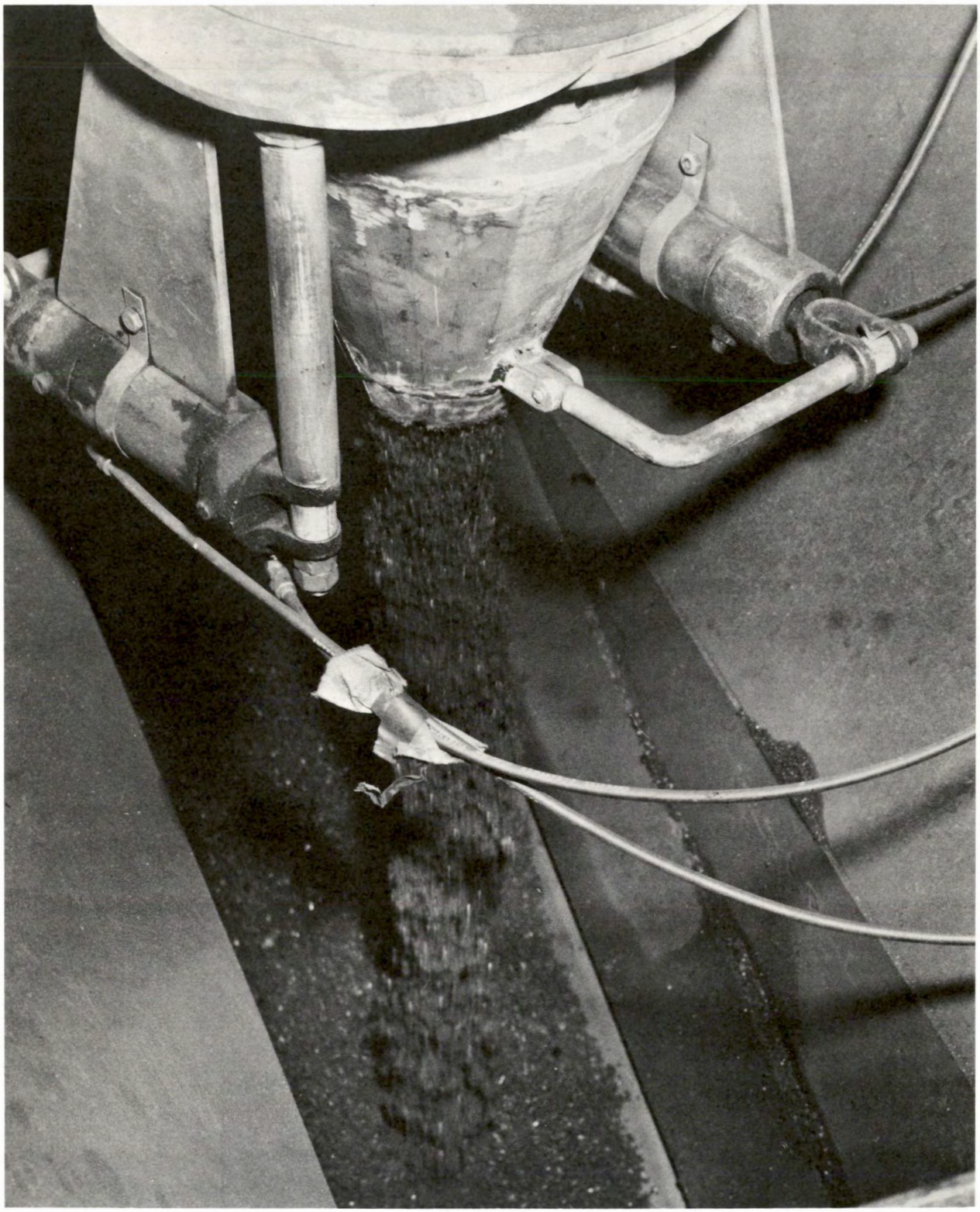


FIGURE 7. - Split cone.

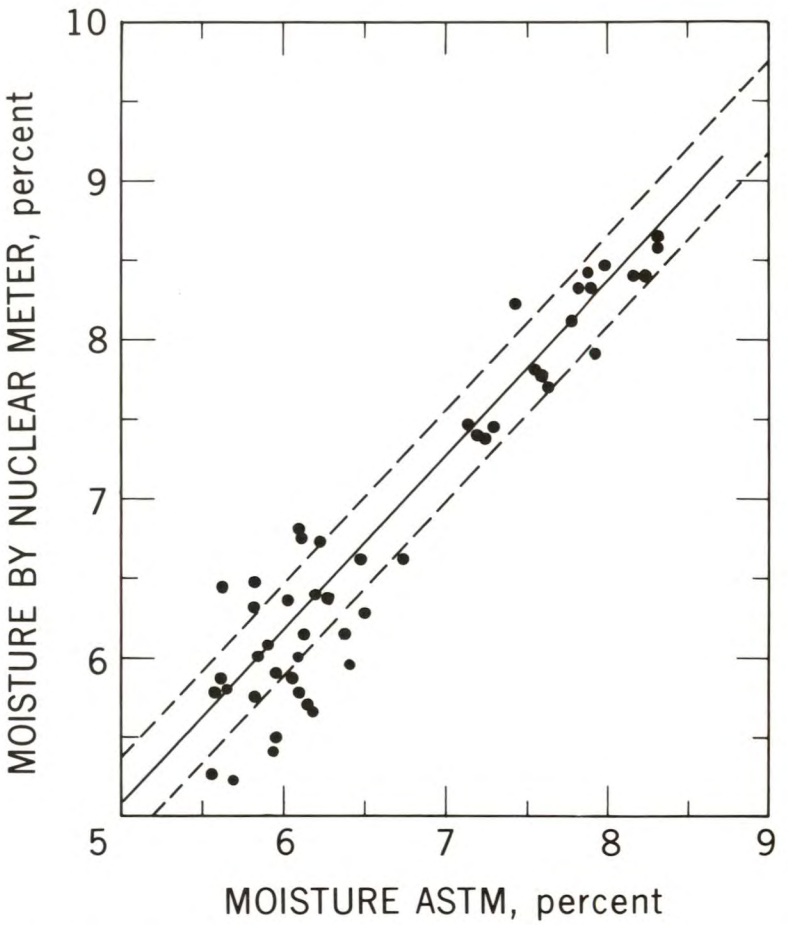


FIGURE 8. - Calibration curve for neutron moisture meter.

Figure 9 is a reproduction of a chart that compares moisture meter values with those determined by ASTM procedure. The left side of the strip chart shows ASTM moisture analysis of samples collected every 80 seconds. The peaks and shaded areas on the right hand side show the magnitude of response and sensitivity of the gage to moisture change.

The jagged line is a 50-second rapid response recording that shows moisture change with considerable statistical error, but indicates a sharp rise and fall during water additions; the heavier, smoother line is a 10-minute response recording that shows a slower rise and fall after a response delay. The rapid response is more difficult to evaluate but more sensitive to small moisture changes, whereas the slower response is easier to read but not as sensitive to moisture change. Any intermediate response time can be preset on the meter.

The chart recording also indicates that the excess moisture in the fine wet coal during the last portion of water addition caused caking, uneven flow, and formation of voids. This is indicated by sharp dips (low values) on the chart following the end of the moisture addition response at 20 minutes and successive dips between 120 and 140 minutes. Conventional ASTM moisture analyses of coal samples showed the average moisture content to be 6 percent; the meter shows it to range from 4.8 to 7.2 percent.

In order to show the meter was sensitive to moderate increases in moisture, water was added after coal passed through the secondary sampler at rates of 3, 4, 5, and 6 pounds per minute for 12-minute periods to increase the moisture content, respectively, to 1.20, 1.59, 1.98, and 2.37 percent above the average moisture level (determined subsequently by chemical analysis). For each of 18 periods of moisture increase, table 1, the meter showed a proportionate increase for the correct time intervals.

TABLE 1. - Comparison of moisture content increase with values obtained by moisture meter

Moisture increase, percent	Increase by moisture meter,[1] percent	Difference
1.20	1.07	-0.13
1.20	0.98	-.22
1.20	1.15	-.05
1.59	1.47	-.12
1.59	1.53	-.06
1.59	1.49	-.10
1.59	1.54	-.05
1.59	1.65	.06
1.98	2.15	.17
1.98	2.04	.06
1.98	2.44	.46
1.98	1.69	-.29
1.98	2.20	.22
1.98	1.89	-.09
1.98	1.93	-.05
2.37	2.30	-.07
2.37	2.22	-.15
2.37	2.07	-.30

[1] Recorded increase above the initial moisture value determined by ASTM analysis.

In 15 of the 18 tests, the difference between known values and meter values did not exceed 0.22 percent. Meter values in the other three tests differed as much as 0.46 percent from the known values, possibly because of errors in moisture addition or fluctuations in coal flow rate.

Time averaging is necessary to effect a closer agreement between actual and meter values. The graph in figure 10 compares moisture meter results with those by conventional analysis derived from a statistical evaluation of continuous and incremental methods of analysis. The ASTM values vary by as much as 1.7 percent from corresponding chart values. However, integrated average values from the meter more closely approach the cumulative average of ASTM analyses with increase in number of samples averaged, as is indicated in the table of figure 10. For 12 samples, this average difference approaches the precision of the moisture meter, 0.2 percent. Increasing the number of samples averaged and comparison with a longer section of chart recording reduces the average difference between them to 0.1 percent, the approximate accuracy of chemical analysis.

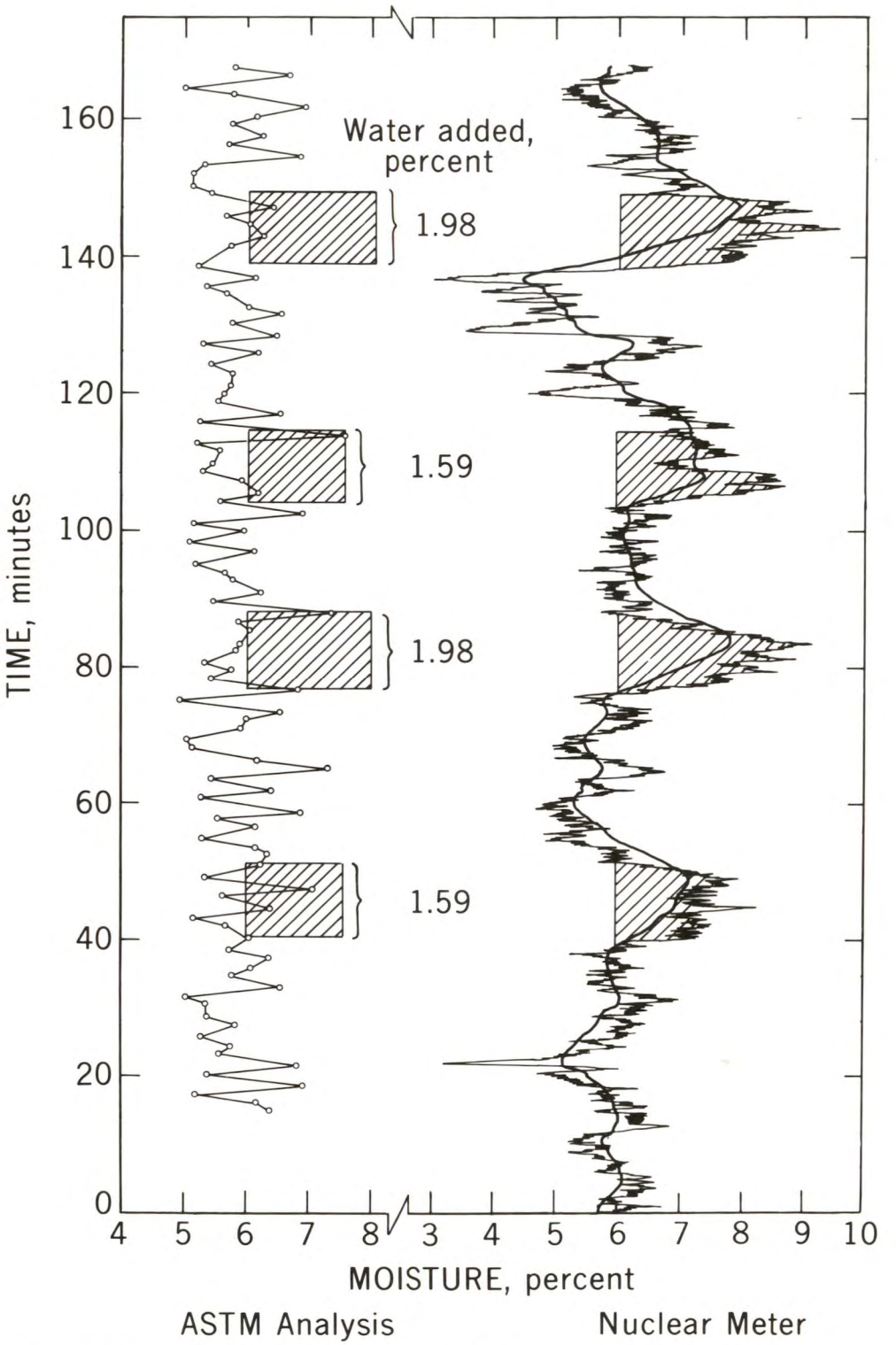
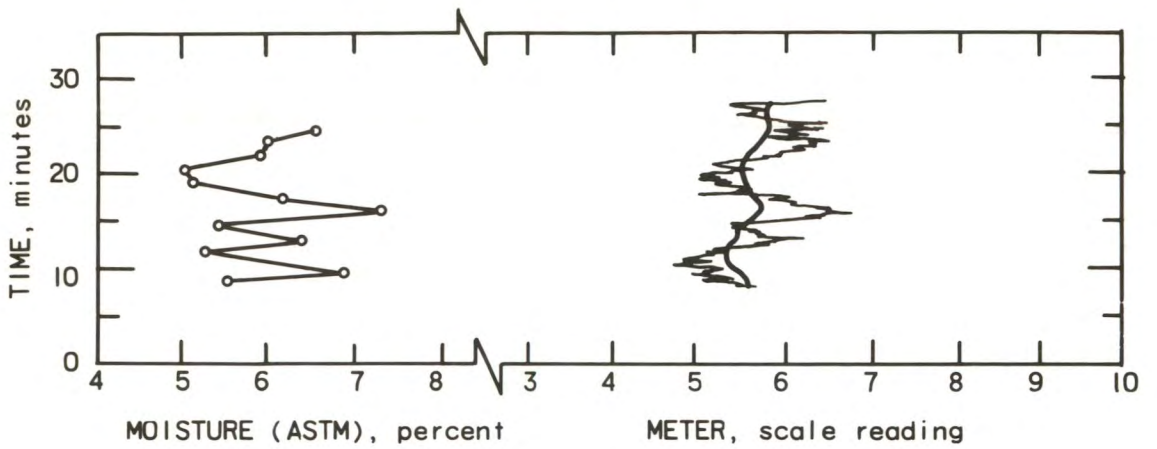


FIGURE 9. - Comparison of moisture (ASTM) analysis of samples collected at 80-second intervals with neutron meter recording.



Sample No.	ASTM moisture, percent		Meter reading (50-second response), percent		Difference between average ASTM and moisture meter values, percent
	Individual sample	Cumulative average	Chart value	Integrated average	
1	5.53	---	5.25	5.20	---
2	6.87	6.20	5.15	5.20	1.00
3	5.27	5.89	5.35	5.50	.39
4	6.40	6.02	5.80	5.46	.56
5	5.43	5.90	5.50	5.34	.36
6	7.31	6.14	6.65	5.45	.59
7	6.19	6.14	6.15	5.70	.44
8	5.11	6.01	5.30	5.69	.32
9	5.05	5.91	5.50	5.63	.28
10	5.90	5.91	5.90	5.63	.28
11	6.00	5.91	6.40	5.72	.19
12	6.56	5.97	6.20	5.77	.20
Av	5.97	----	5.76	----	----

FIGURE 10. - Comparison of incremental sampling and analysis with neutron moisture recordings.

SUMMARY

A neutron moisture meter for coal was developed and operated satisfactorily and reliably in a commercial coal-preparation plant for 12 months without requiring recalibration. Moisture values determined by the meter were within 0.2 percent of ASTM values for 1/4-by-0-inch Pittsburgh-seam bituminous coals containing 4 to 10 percent moisture and 5 to 7 percent ash. Previous tests of the meter in a pilot-plant system had shown that various coals containing moisture and ash in the 1- to 12-percent and 5-to 15-percent ranges, respectively, could be monitored with the same precision.

Bulk density variations encountered in the commercial plant did not have an adverse effect on the measurements. This is because bulk density compensation was not required beyond that obtained by the 6-inch source-detector separation, and the test section was located 1-1/2 vessel diameters below the surface of the coal where the bulk density gradient is essentially constant. However, if the bulk density changes are greater than 47 to 55 pounds per cubic foot, that is, with certain pulverized coals or unwashed strip mine coals, additional bulk density compensation may be required to achieve sufficient accuracy in moisture determination.

Shielding of the source by the coal kept the neutron flux level at the hopper face less than 1.0 mr/hr, a safe level for personnel, and the source could be retracted and stored in a wax storage drum for plant shutdown or repairs.

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