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Test Apparatus for Measuring Sound Power Levels of Drills

By William W. Aljoe, Robert R. Stein,
and Roy C. Bartholomae

UNITED STATES DEPARTMENT OF THE INTERIOR
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David S. Brown, Acting Director

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm	cubic foot per minute	in/s	inch per second
dB	decibel	Kb	kilo byte
dBA	decibel, A-weighted	kHz	kilohertz
ft	foot	lbf	pound (force)
ft^2	square foot	Mb	megabyte
ft^3	cubic foot	min	minute
ft/min	foot per minute	pct	percent
gpm	gallon per minute	psi	pound (force) per square inch
h/d	hour per day	s	second
Hz	Hertz	V	volt
in	inch		

TEST APPARATUS FOR MEASURING SOUND POWER LEVELS OF DRILLS

By William W. Aljoe,[1] Robert R. Stein,[1] and Roy C. Bartholomae[2]

ABSTRACT

This Bureau of Mines report describes in detail the design and operation of a test apparatus for measuring the sound power levels of drills used by the mining industry. The two major components of the test apparatus are a computer-controlled automated drill test fixture (ADTF) and a large (45,000-ft^3) reverberation chamber that houses the ADTF. Design specifications and performance capabilities of the ADTF and the reverberation room are given. Initial test results for three types of drills--a pneumatic percussion drill, a hydraulic percussion drill, and a pneumatic rotary drill--are given to illustrate the types of experiments that can be conducted with the test appartus.

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[1] Mining engineer.
[2] Supervisory electrical engineer.
Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

Percussion drills used in the mining industry produce noise that can cause exposures of 10 to 20 times the limits allowed by Federal noise regulations. Typical noise levels experienced by percussion drill operators are 110 to 120 dBA. Approximately 60,000 percussion drills are being used in the mining industry (1),[3] and many more are used in the construction industry. Given the severity of the percussion drill noise problem, it is not surprising that considerable efforts have been made toward its control.

The primary noise-generating mechanism in all percussion drills is the repeated hammering action of an oscillating steel piston on the end of a long, slender striking bar (drill rod). This action causes vibration of both the drill rod and the cylindrical piston housing, thereby producing drill rod noise and drill body noise. On pneumatic drills, the high-pressure air used to oscillate the piston is exhausted to the atmosphere through ports in the drill body, thus producing air exhaust noise. Figure 1 depicts these three major noise sources on a typical hand-held pneumatic (stoper) drill. Figure 2 shows the various noise sources associated with a typical machine-mounted (jumbo) drill; however, the drill body, drill rod, and air exhaust are still by far the most serious noise sources on the drill.

Numerous attempts have been made in the past by the Bureau of Mines and other researchers to control percussion drill noise through the use of retrofit noise control treatments (2-6) and new drill design features (7-10). These attempts have been moderately successful, resulting in noise reductions of up to 15 dBA at the drill operator position. Unfortunately, some of the noise-controlled drills were rather impractical from an operation standpoint (e.g., reduced drilling rates, muffler freezing, excessive weight and bulk).

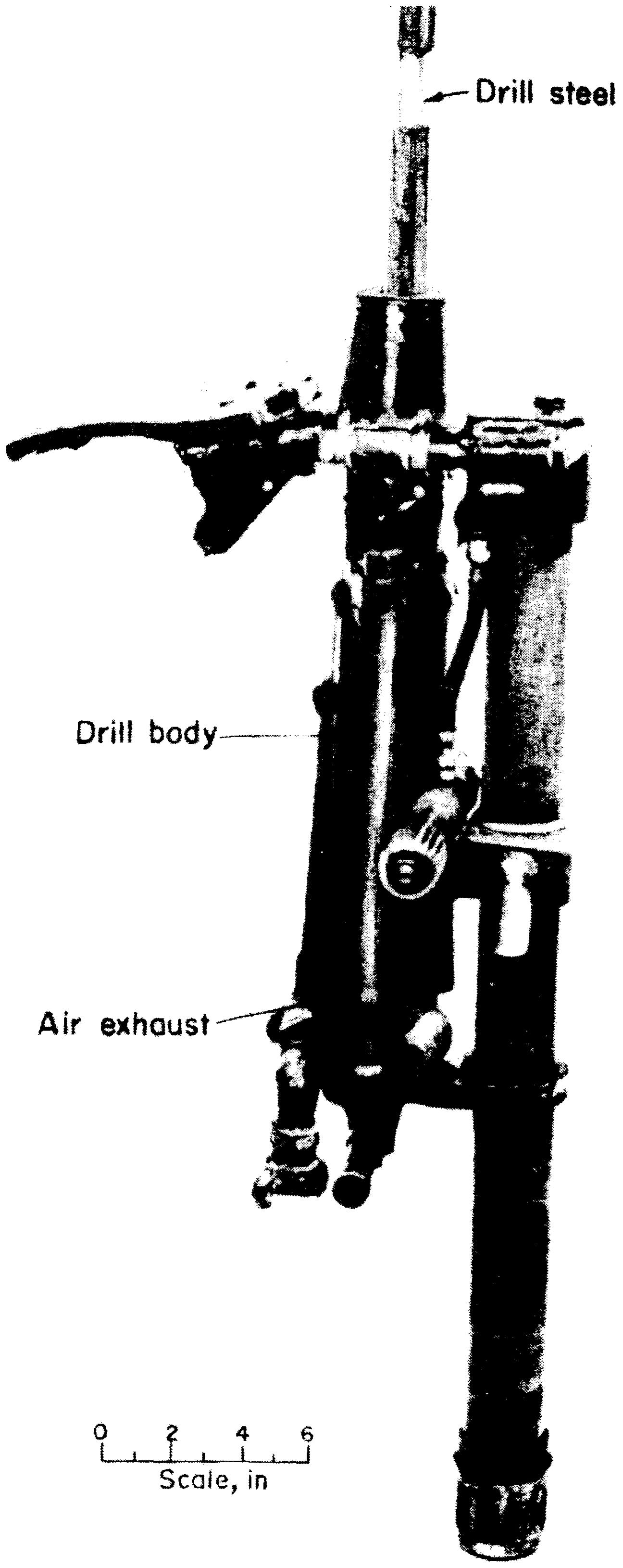

FIGURE 1.—Noise sources on typical hand-held percussion drill.

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

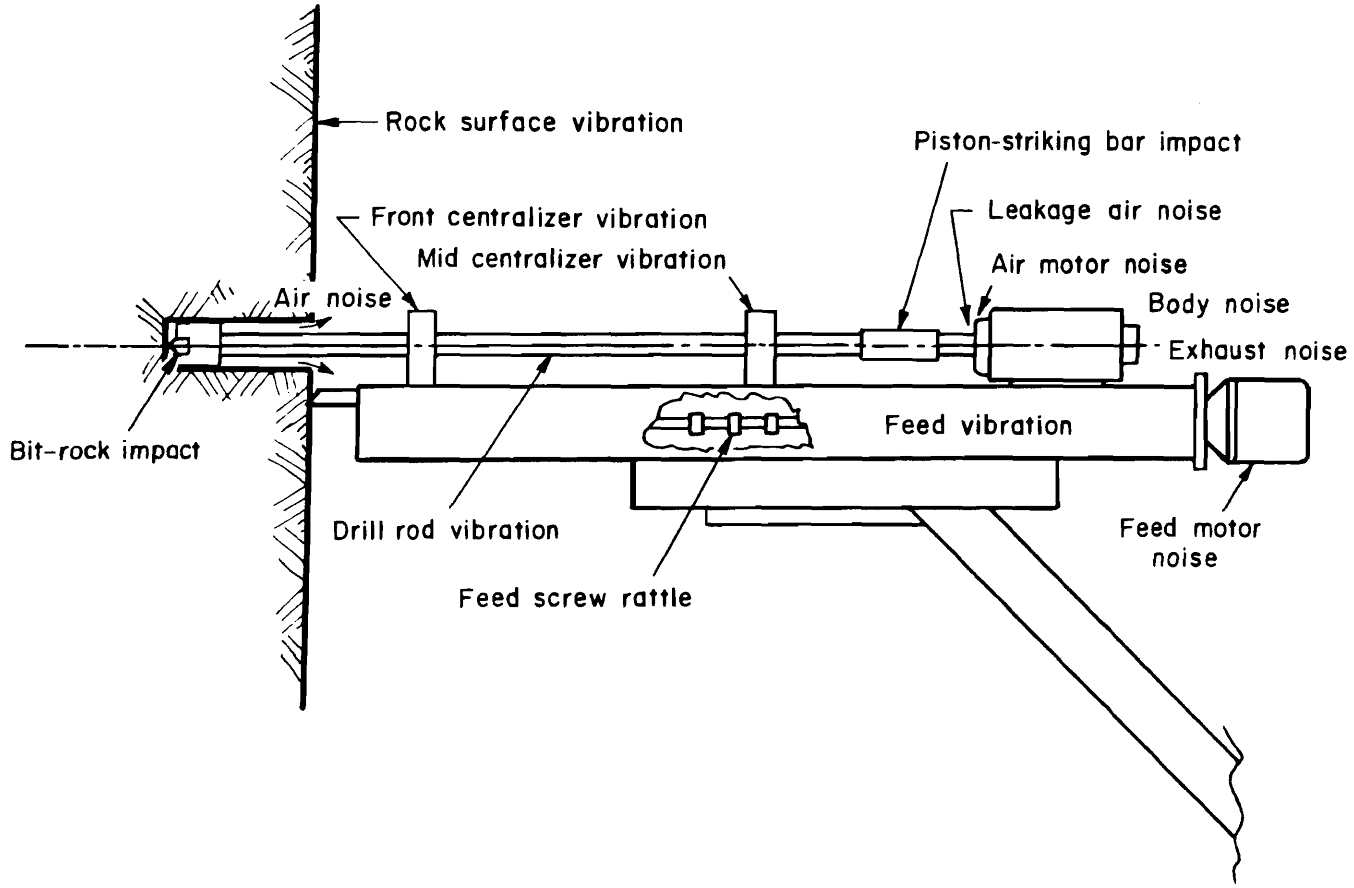

FIGURE 2.—Noise sources on typical jumbo-mounted percussion drill.

Furthermore, in most cases the quieted noise levels were still above 100 dBA; operator exposure would have to be limited to only 2 h/d to maintain compliance with Federal noise regulations.

To date, the most effective means of protecting the percussion drill operator from noise overexposure has been to isolate him or her from the noise source by using an acoustical cab. Noise reductions of up to 20 dBA have been achieved through this technique, and in several cases the noise level measured inside the cab was below 90 dBA (6). Acoustical cabs can be applied most successfully to machine-mounted drills that are used in areas of unrestricted headroom or where remote control of drill positioning and operation is employed. However, many mining situations require the use of small hand-held drills because of space limitations; this precludes the use of acoustical cabs. In fact, the hand-held percussion drill remains the bulwark of many underground ore mining operations because of its compactness, flexibility, reliability, and low cost. Space limitations and interference with drill operation (e.g., operator vision) also discourage the use of acoustical cabs on many types of jumbo-mounted drills.

Considering the high-energy nature of percussion drilling, the limited success of previous efforts to control drill noise at its source, and the limited practical application of acoustical cabs, it is doubtful that the majority of percussion drill operators will work in a nonhazardous noise environment in the near future. If the mining industry continues to use percussion drills, even quieted models, as it has in the past, it is reasonable to assume that numerous noise overexposures will occur in the years to come.

Despite the severity of the percussion drill noise problem and the fact that all percussion drills are inherently noisy, it is important to note that some drills generate more noise than others. Operator exposure to noise can be reduced by choosing a less noisy drill or drilling system. Factors that can affect the noise produced by a drill include the source of power (air or hydraulic), input energy, degree of wear and leakage, drill rod size and type, hammer and shank configuration, means of drill steel rotation (rifle bar or independent), and location of the operator with respect to the drill. The application and effectiveness of noise control techniques are greatly affected by these differences.

An in-depth understanding of drill design characteristics and their effect on noise is an important part of any effort to reduce the noise problem. The Bureau of Mines, while continuing in this endeavor, does not possess the funding or drill design expertise to embark on a program to develop a drill or drilling system that can solve the problem completely. However, with the aid of the test apparatus described in this report, it is possible for the Bureau to significantly enhance the body of knowledge on the subject of drilling noise. For example, the test apparatus can provide valuable but heretofore unavailable quantitative information on the sound power levels produced by different types and models of drills. Noise variations resulting from differences in drill operating parameters can also be investigated and quantified.

TEST SYSTEM CONSIDERATIONS

To conduct thorough, systematic studies of drill noise, the researcher needs (1) control of the parameters that affect drill performance, (2) control of the acoustical environment in which the drill operates, and (3) a comprehensive, well-organized data collection and analysis system. The Bureau's test apparatus fulfills all three of these requirements.

CONTROL OF DRILL OPERATING PARAMETERS

The operation of a percussion drill is affected by many parameters such as the composition of the drilling medium, sharpness of the bit, type of bit used, length and type of drill rod, number of rod sections, drill feed force, supply pressure to the drill, wear condition of the drill, and hole flushing medium. Under actual drilling conditions in the field, control of all these parameters is a very difficult and sometimes impossible task. In short, it can be said that no two holes drilled in the field are ever exactly the same.

In the laboratory, however, it is possible to control these parameters such that any drilled hole is repeatable. More importantly, it is possible to selectively change only one parameter from hole to hole to determine its effect on noise and penetration rate. The computer controlled automated drill test fixture (ADTF) facilitates this process by automatically maintaining the supply pressure, rotation flow, and feed force specified by the user. These parameters can also be changed by the user during the course of a test if desired. The ADTF also allows the user to select an exact hole location (following a preprogrammed pattern), hole depth, and drill power source (air or hydraulic) for each test.

The ADTF achieves this control through the use of standard, commercially-available hardware such as pressure, flow, and position transducers, a programmable process controller, and a desktop microcomputer. Software designed specifically for the purpose of drill test provides the user with continuous on-line information and interactive capability via the computer's cathode ray tube and keyboard. Safety is ensured by the presence of several types of automatic and user-initiated shutdown modes.

By conducting drill noise tests in the laboratory, it is also possible to exercise almost complete control of the drilling medium, bit type and sharpness, drill rod length and type, and hole 'ushing medium. These parameters can .most never be changed or controlled in the field due to local geology, blasthole size requirements, and other production considerations. The capability of providing a relatively homogeneous drilling medium (precast concrete or precut granite) is particularly advantageous when assessing the effect of other drilling parameters on drill penetration rate.

CONTROL OF THE ACOUSTICAL ENVIRONMENT

The acoustical environment of an operating mine is rarely consistent because the extent of the mine and the location of the noise sources change almost daily as mining progresses.

Irregular reflecting surfaces are often present, and extraneous noise sources (other pieces of mining equipment) add to the difficulty of measuring the noise produced by a drill. Microphone location is another important factor to consider when measuring drill noise in the field because the sound pressure can vary greatly from point to point within the area of interest. Measurement of drill noise in the laboratory allows for control of some of these variables, but the experimental environment must be chosen carefully to assure that useful noise information is obtained in a practical and cost-effective manner.

The two fundamental properties that define the noise-radiating capability of a sound source are its sound power and directional characteristics. Sound power is a measure of the rate at which acoustical energy is emitted by a noise source; it is usually expressed as sound power level, in decibels (dB), by the formula

$$PWL = 10 \log (W_{act}/W_{ref}),$$

where PWL = sound power level, dB,

W_{act} = actual sound power, w,

and W_{ref} = reference sound power, 10^{-12} w.

The most important distinction between sound power level and sound pressure level, the quantity most commonly associated with noise, is that sound power is a fundamental property of the noise source itself. Conversely, the sound pressure level is dependent on the distance from the noise source, the direction from the source, and the acoustical properties of the environment in which it is measured. The relationship between sound pressure and sound power levels can be quantified (11):

$$SPL = PWL + 10 \log [(Q/4\alpha r^2)+(4/\alpha S)] + 10,$$

where SPL = sound pressure level at any given point in an environment, dB,

PWL = sound power level of noise source, dB,

Q = directivity factor (dimensionless) of the source, whose value is dependent on the angle from the acoustical center of the source to the measurement point,

r = distance from the source, ft,

α = average absorption coefficient (dimensionless) of the acoustical environment, including its boundaries and objects located within it,

and S = total surface area, ft^2, of all reflecting surfaces within the environment.

For the drill noise research program envisioned by the Bureau of Mines, sound power is the quantity of greatest interest because (1) it allows direct noise comparisons to be made among different types and models of drills, and (2) it can be used to predict the sound pressure levels that will occur in other environments, given their acoustical characteristics.

The directional property of a sound source describes its tendency to radiate more noise in one direction than in others. Directional properties are usually displayed in a graphical form called a radiation pattern (fig. 3), showing sound pressure level at a fixed distance from the source as a function of angle. It should be noted that figure 3 is for illustrative purposes only; the sound pressure levels in the figure do not correspond to measured values for an actual drill.

From a purely diagnostic standpoint, the most complete characterization of any noise source can be obtained by isolating it in an anechoic (free field) environment, i.e., one in which no reflections

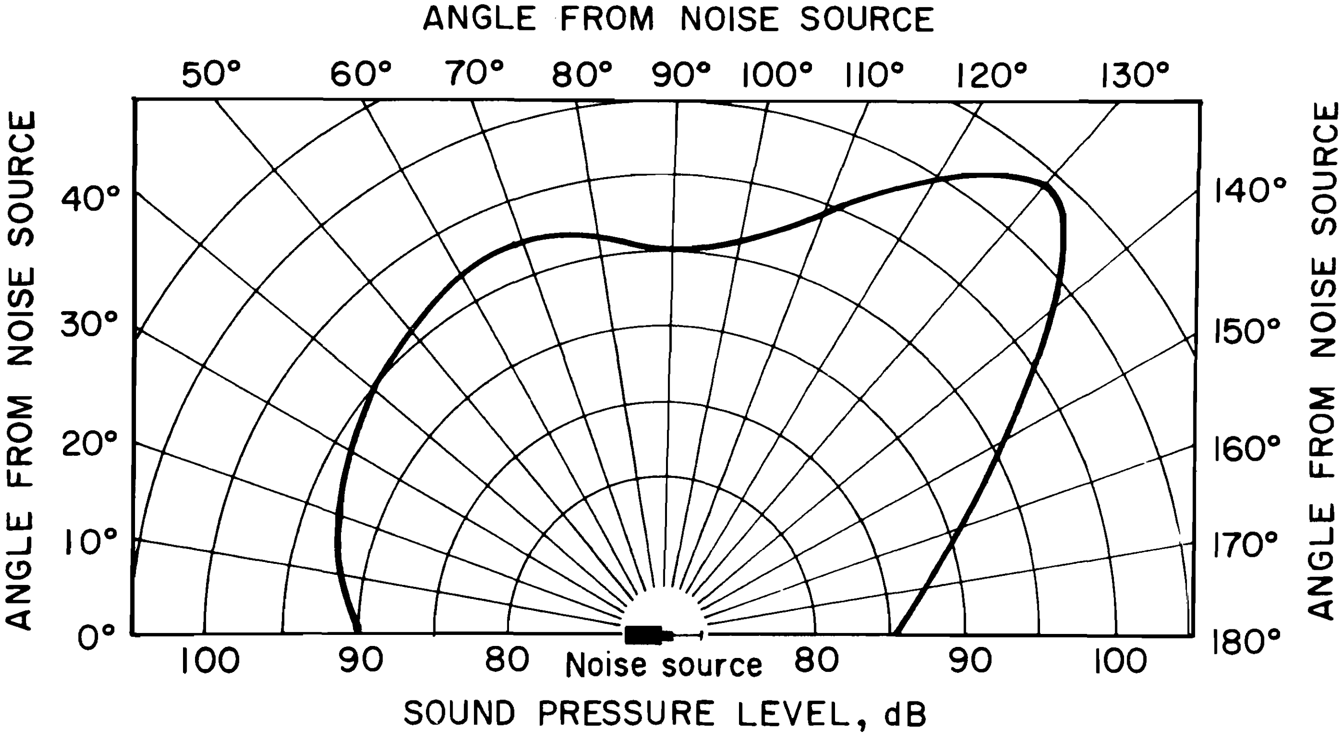

FIGURE 3.—Typical noise radiation pattern.

occur and no other noise sources are present. By measuring the sound pressure at numerous points on a series of imaginary spheres located at various radial distances from the geometric center of the noise source, it is possible to determine both the sound power and the directional properties of the source. Unfortunately, this experimental approach could not be pursued by the Bureau of Mines because it would have been prohibitively expensive, time consuming, and impractical.

In terms of cost, practicality, and the ability to obtain useful information on drill noise, the Bureau of Mines determined that the reverberant environment was the best environment to choose. An important feature of a perfectly reverberant environment is that the sound pressure levels at all points are the same due to the multitude of sound reflections that occur at its boundaries (walls). If only one dominant sound source is present in the environment, its sound power level can be calculated easily by comparing the measured sound pressure levels to those produced by a reference source of known sound power. Most importantly, it was possible to construct, at a reasonable cost, a reverberant environment (reverberation chamber) capable of housing a full-sized drill test fixture. In addition, the instrumentation needed to automatically calculate drill sound power levels was affordable, the test procedures involved with this setup were relatively simple, and useful results could be obtained within a reasonable time frame.

The greatest disadvantage of testing drills in a reverberant environment is the inability to determine the directional nature of the noise source. The lack of directional information makes it more difficult to assess the relative noise contributions of the drill rod, drill body, and air exhaust. Also, potential noise reductions that could result from the judicious selection of the drill operator position or the insertion of partial acoustical barriers between the drill and the operator cannot be detected. This disadvantage can be overcome by conducting supplemental tests in a semifree field (outdoors) with drills that exhibit particularly strong directivity patterns.

DATA COLLECTION AND ANALYSIS

Collection of drilling data in the field usually requires substantial human effort such as constant visual monitoring of pressure gauges, flowmeters, stopwatches, etc. Noise monitoring in the field is often performed only with handheld sound level meters. Extensive, careful notes must be maintained to make sure the data are recorded completely and correctly. Even when data are recorded electronically (strip chart recorders, data loggers, or magnetic tape), considerable human intervention is needed to assemble and correlate the data for later analysis.

The computer-controlled ADTF is the ideal means for simplifying the task of data collection and analysis. Signals from permanently installed transducers for flow, pressure, and position are converted by the ADTF software into standard units (cfm, psi, etc.) and are recorded on a floppy disk at 4-s intervals. Sound power levels are recorded at 18-s intervals, and a continuous record of time elapsed during the test allows for automatic correlation of all test parameters. All other information pertinent to the test (drill type, hole size and location, drill rod and bit type, etc.) is also recorded on disk, and the computer assigns a specific test number to the entire block of test data. This greatly facilitates posttest analysis and comparisons among different tests.

SYSTEM DESCRIPTION

The drill noise test apparatus consists of eight distinct components, shown schematically in figure 4:

1. A microcomputer (IBM model PC-XT,[4] referred to as the XT) with hard-disk storage of menu-driven programs for drill operation and data analysis.
2. A programmable process controller (Westinghouse PC-700, referred to as the PC) with control cards for input, output, and high-speed counting functions.
3. A 15-ft-long by 9-ft-wide by 6-ft-high drill test rig consisting of (a) a rubber-tired carriage, (b) a pivoting boom with two 10-ft-long feed channels, (c) the drills themselves, and (d) the hydraulic and pneumatic control valves and transducers. Figures 5-8 show several views of the drill test rig and drilling medium. The valves and transducers (fig. 8) are designed to meet the capacities of the hydraulic and pneumatic power sources listed in items 6 and 7 below.
4. Valve driver cards (manufactured by Ledex, Inc., and referred to as the Ledex drivers) needed to operate some of the larger hydraulic control valves that require a 24-V input potential.

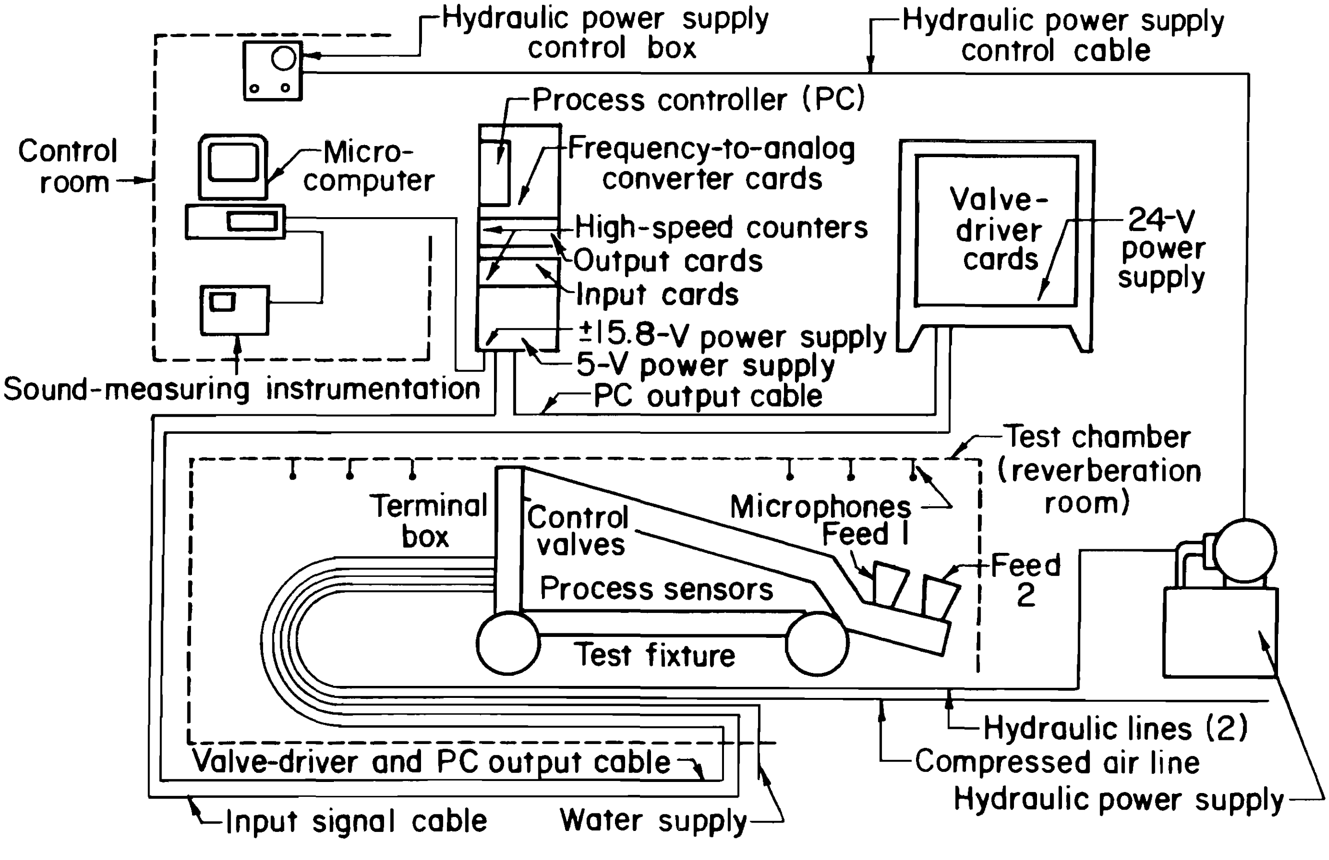

FIGURE 4.—Components of automated drill test fixture and control system.

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[4] Reference to specific products does not imply endorsement by the Bureau of Mines.

5. A sound measurement system consisting of an array of microphones suspended from the ceiling of the reverberation room and instrumentation to calculate sound power levels. Figure 7 shows some of the sound measuring instrumentation in the control room adjacent to the reverberation chamber.

6. A remotely controlled hyraulic power source capable of providing up to 35 gpm of flow at 5,000-psi pressure. This is sufficient to operate most currently available hydraulic percussion drills.

7. A compressed air source capable of providing 1,200 cfm of flow at 100-psi pressure. This is sufficient to operate most currently available pneumatic drills with the exception of down-the-hole drills.

8. A flushing water source for dust suppression.

The first four components combine to form the automated drill test fixture (ADTF); the other four provide vital support functions and are accessed by the ADTF during its operation. The drilling rig and microphones are located inside the reverberation chamber, the XT and sound measuring instrumentation are located inside the control room adjacent to the chamber, and the PC and valve drivers are located in cabinets immediately outside both the test chamber and control room. The hydraulic power pack and air compressor are located remotely so that their noise contribution to the test chamber is minimal.

All eight components are required for the operation of pneumatic drills, and all but the air compressor are required for hydraulic drills. Although two drills can be mounted on the ADTF at once, only one drill at a time can be operated. The advantage of having two feeds is that a pneumatic and hydraulic drill can operate in consecutive tests without having to dismantle and reconnect numerous fluid supply connections. Both percussive-rotary and all-rotary drills can be tested on the ADTF using the same test program and procedures.

The primary drilling medium consists of two 6- by 6- by 12-ft concrete blocks (compressive strength approx. 6,000 psi) inserted into the chamber wall; see figures 5 and 6. Provision has also been made to drill into granite or another drilling medium either by replacing the concrete or by inserting the medium into the wall between the two concrete blocks. All drilling takes place in the horizontal direction, with a maximum depth of 12 ft governed by the confines of the building in which the reverberation chamber is housed.

The reverberation chamber and sound measurement system meet the criteria of ANSI S1.31-1980, "Precision Methods for the Determination of Sound Power Levels of Broad-Band Noise Sources in Reverberation Rooms." The chamber itself is 60 ft long by 34 ft wide by 22 ft high and is constructed of filled concrete block with nonabsorptive paint covering its interior surfaces. Exhaust fans and floor drains provide a clean working environment with consistent acoustical properties. The sound measurement system consists of (1) an array of 20 randomly spaced microphones positioned at 9 to 11 ft above the chamber floor, (2) two 8-channel multiplexers (Bruel & Kjaer model 2811) to provide access to 16 of the 20 microphones during any single test, and (3) a Bruel & Kjaer model 7507 sound power calculator. Alternatively, if sound pressure rather than sound power were the desired quantity, a Bruel & Kjaer model 2131 digital frequency analyzer could serve as the third component of the sound measuring system. This system was qualified using the test procedures in section 8 of the ANSI S1.31-1980.

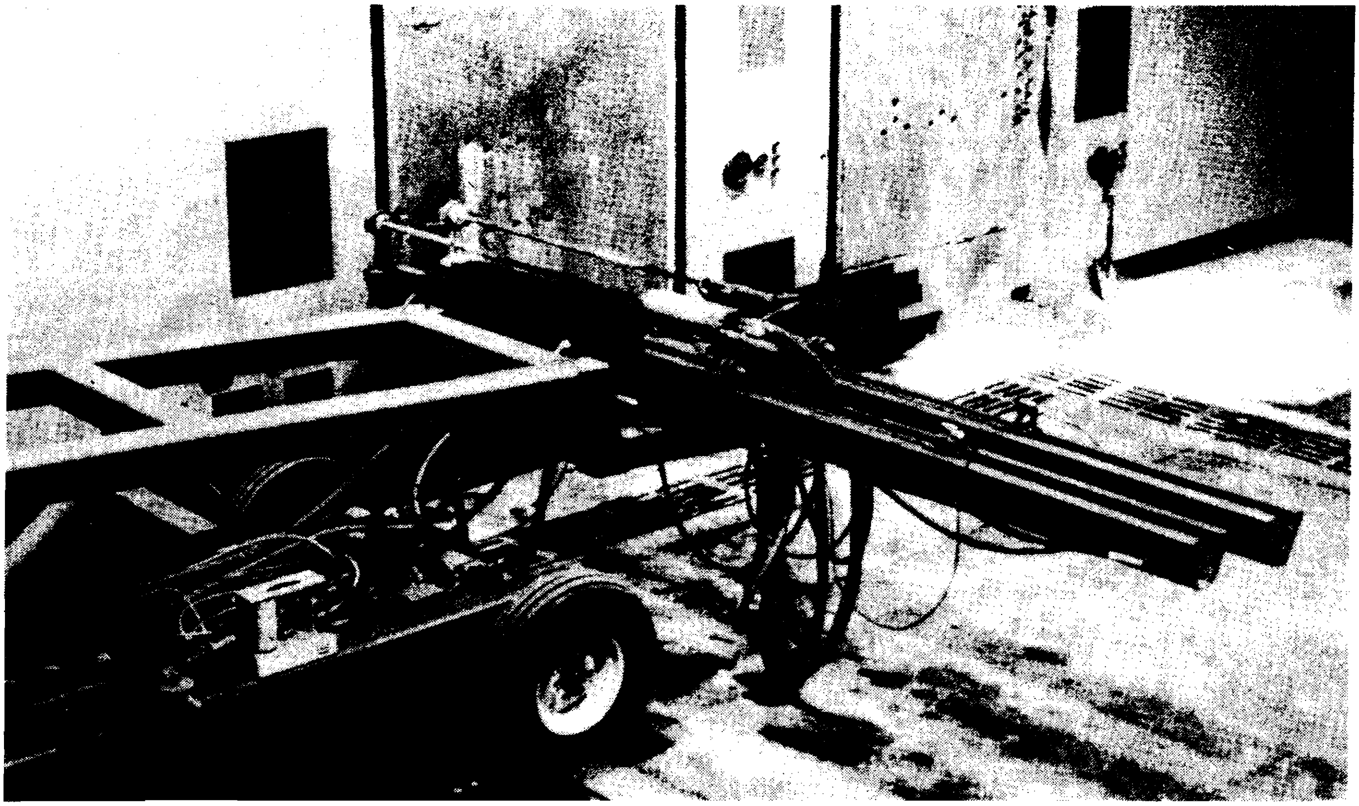


FIGURE 5.—Drill test rig in reverberation chamber, top view.

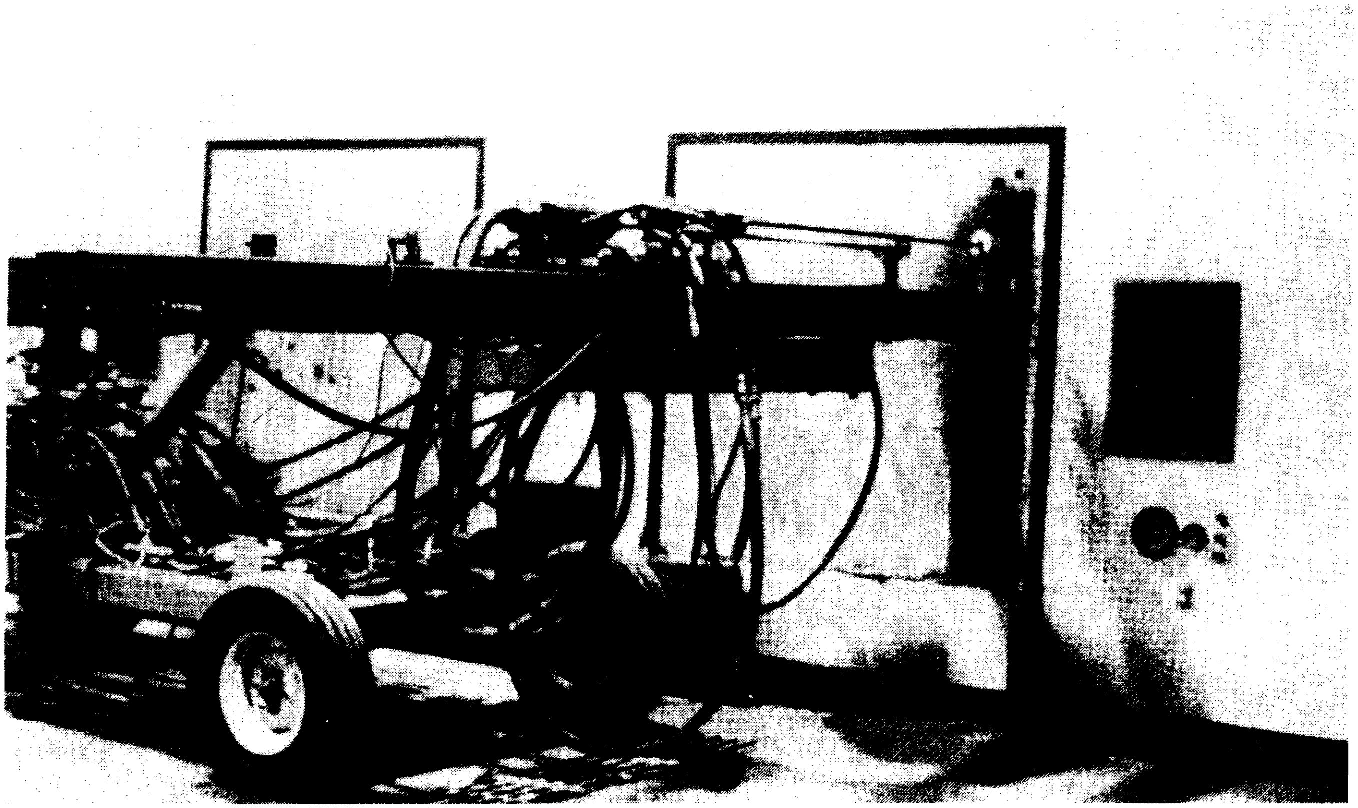


FIGURE 6.—Drill test rig in reverberation chamber, profile view

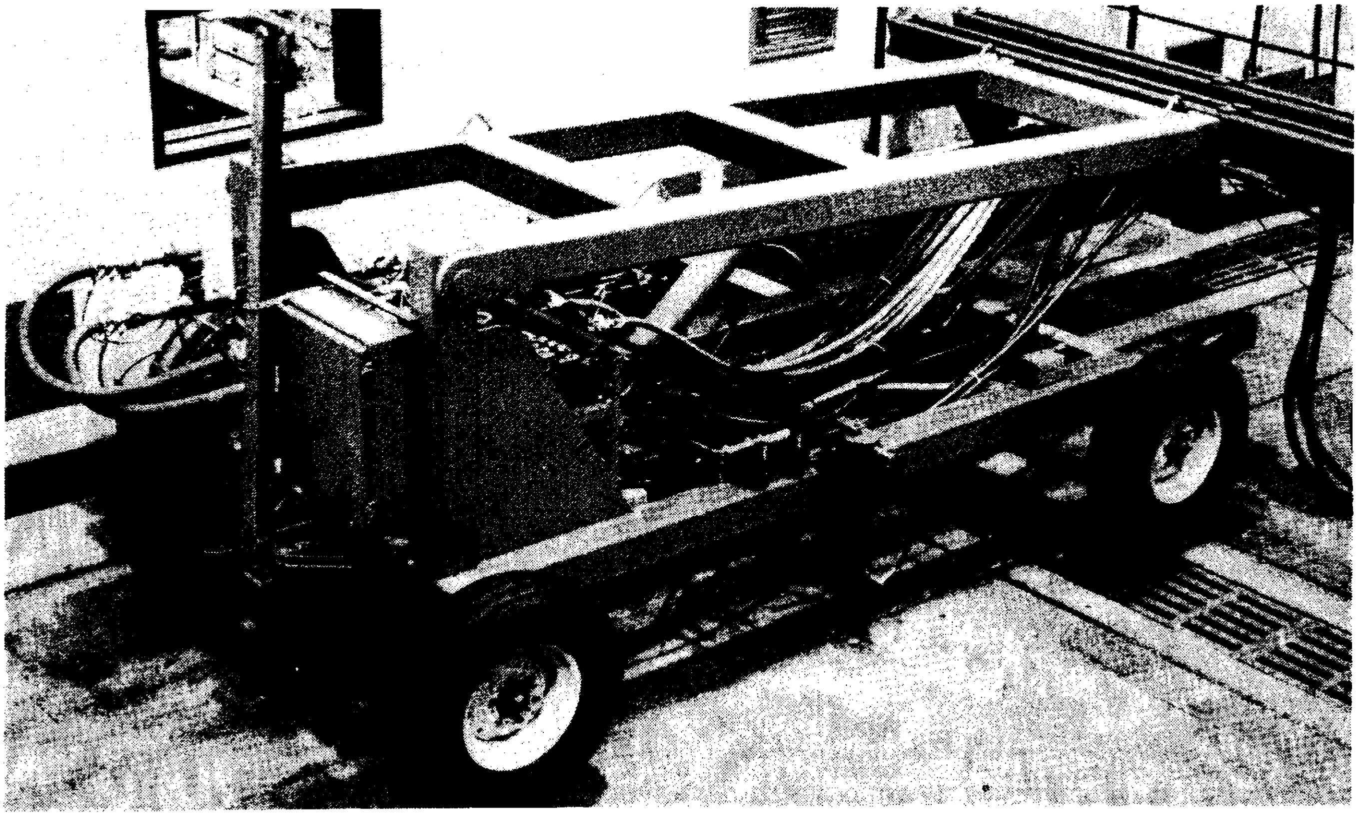


FIGURE 7.—Drill test rig in reverberation chamber, rear view showing control room.

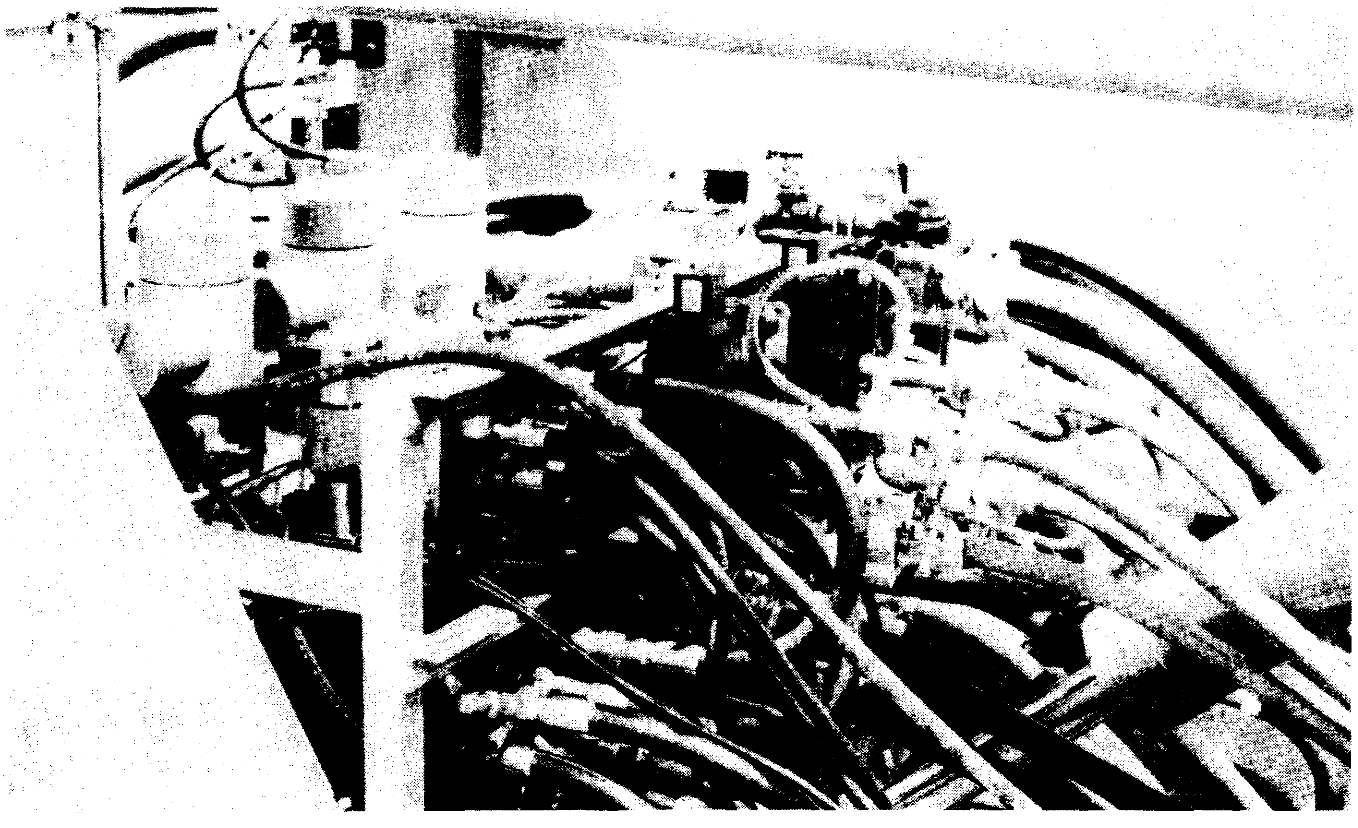


FIGURE 8.—Drill test rig in reverberation chamber, control valves and process sensors.

SYSTEM OPERATION

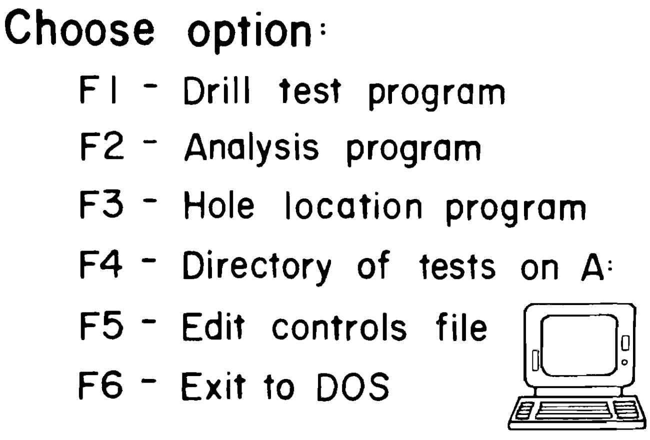
The operator activates the drill test system by turning on the process controller (PC), the sound power measurement system, and the microcomputer (XT). Turning on the XT with no floppy disk in place automatically loads the disk operating system (DOS) from the hard disk. At the DOS prompt, the operator loads the drill test software and is presented with the menu shown in figure 9.[5] The function keys F1 through F6 on the XT keyboard are used to access the various options. The three major elements of the drill test software--the drill test program, analysis program, and hole location program--are described in this section.

DRILL TEST PROGRAM

Test Sequence

Prior to running a drill noise test, the operator starts the hydraulic power pack and air compressor (if required) and adjusts them to operating pressures that are at least as great as those that will be required for the test. A typical drill noise test sequence follows:

1. The test operator loads the drill test program (F1 in figure 9) and enters descriptive information and control parameters (set points) into the XT.
2. The drill test program checks the input values and, if consistent with system limitations, loads them into the PC along with a command word to start the test.
3. The PC moves the drilling rig to the selected hole location, locks the carriage, and pauses for an operator command to proceed. When this command is issued, the PC starts the drilling process, and the sound measurement system is activated. Throughout the test, the PC handles the task of reading the pressure and flow transducers, comparing their values to those of the set points, and opening or closing valves to maintain the set points as closely as possible.
4. When the feed thrust reaches the set point, the XT starts to collect information from the PC at intervals specified by the test operator. It continues to do so until the hole depth reaches the set point or the operator terminates the test. At this point the XT instructs the PC to stop drilling and retract the drill; the sound measurment system is also deactivated, and the data are written to a file on a floppy disk in the A: disk drive unless the operator decides the test was invalid.
5. When the drill reaches its original, completely retracted position, the system waits for a new test command to be entered into the XT.
6. The operator either analyzes data from the test just completed or enters new data for another test. If no other tests are needed but data analysis is desired for one or more previous tests, the operator exits the drill test program, enters the data analysis program (F2 in figure 9), and calls in the desired test numbers. Pressing the F4 key allows the operator to check the directory of the disk in the A: drive.
7. If no subsequent tests or data analyses are desired, the operator issues a command that moves the rig to a home position (conveniently located to permit drill maintenance or removal), exits the drill test program, and shuts down the ADTF and power sources.



Choose option:

F1 - Drill test program

F2 - Analysis program

F3 - Hole location program

F4 - Directory of tests on A:

F5 - Edit controls file

F6 - Exit to DOS

FIGURE 9.—Drill test software program selection menu.

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[5] Throughout this report, graphs and menus such as figure 9 have been modified slightly to conform to Bureau of Mines publication standards.

Data Input and Startup Procedure

Data input begins when the operator enters the drill test program and is presented with the menu shown in figure 10. The circled numbers in figure 10 denote the fields in which test data are entered by the operator, as described below:

Fields 1, 4, 5, 6, and 9 are text entries for documentation purposes; they facilitate later analysis but do not directly impact the test itself.

Field 2, entered as P or H, identifies whether the drill to be tested is pneumatic or hydraulic. Field 3, entered as 1 or 2, identifies the feed channel on which the test drill is mounted. This information allows the appropriate set of control cards in the PC to be activated during the test.

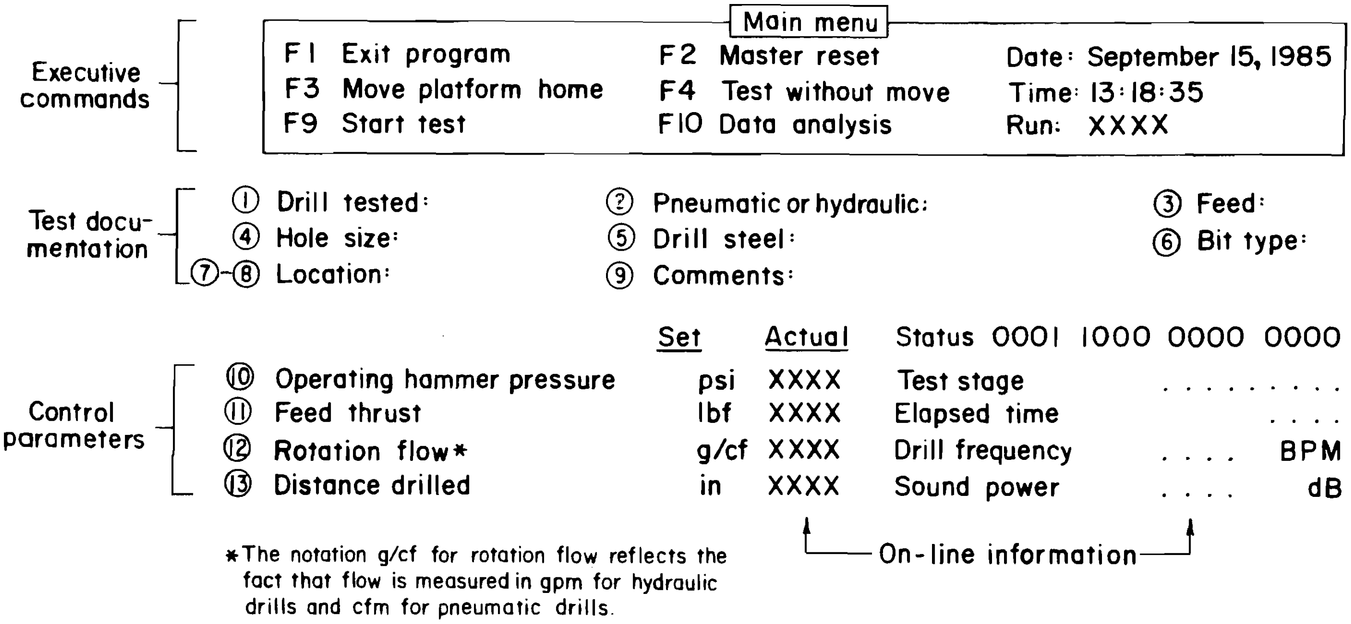
Fields 7 and 8, respectively, specify the vertical (rows A through N) and horizontal (columns 1 through 36) hole location. Field 3 is also important in this regard because, for the same hole ation on the wall, the actual amount carriage and boom movement is different for each feed. The operation of the hole location program is discussed in more detail later in this report.

Fields 10, 11, 12, and 13 are the main control parameters governing the operation of the drill during the test. Input values are assigned the units shown in figure 10. In the case of field 12, rotation flow, the units depend on field 2; gpm is assumed for hydraulic drills and cfm for pneumatic drills. Table 1 lists the maximum allowable values of these parameters and the accuracies achieved by the ADTF control system.

After all data have been entered, the operator presses the F9 function key (fig. 10) to continue the test. The program checks the input values for conformance with the above requirements, issues an error message if this is not the case, and allows the operator to correct the erroneous data. If the inputs are valid, the program loads the input values into

TABLE 1. - Maximum values and accuracy of ADTF control parameters

Parameter	Maximum value	Accuracy pct
Hammer pressure (hydraulic).	5,000 psi	5
Hammer pressure (pneumatic).	350 psi	5
Feed Thrust........	12,000 lbf	4
Rotation flow (hydraulic).	50 gpm	5
Rotation flow (pneumatic).	1,000 cfm	2
Distance drilled...	144 in	3



*The notation g/cf for rotation flow reflects the fact that flow is measured in gpm for hydraulic drills and cfm for pneumatic drills.

FIGURE 10.—Main data input menu for drill test program.

the PC, issues a "Ready" message, and prompts the operator to press F9 again. The drilling rig then moves out to the specified hole location, locks itself into place with two clamping cylinders, and pauses. The hole location is then checked visually and, if satisfactory, the operator presses F9 a third time to start the drilling process. At any time during the startup procedure or drilling process, the operator can press the [Esc] key, standard on all IBM and IBM-compatible personal computer keyboards, to halt the test and enter new input data into the main menu. A closed-circuit television system enables the operator to monitor the entire sequence from the safety of the control room and allows him or her to terminate the test quickly should problems occur.

Data Collection and Display

As soon as the drill test program checks the data input values and finds them to be valid, it opens a file on the XT floppy disk and writes the input data to the file. These drill test files are named "TEST____.DAT", with the blank corresponding to the sequential test number assigned by the drill test program. This four-digit test number is then displayed on the XT video monitor ("Run" in figure 10) and is used for all subsequent data retrieval and analysis.

After drilling has begun, control of the test is maintained by the process controller (PC). As soon as the feed thrust reaches its set point, the XT collects data by reading the PC and the sound measuring instrumentation at specified intervals and writing this information to the floppy disk file. The optimum sampling interval for data collected from the PC was found to be 4 s. Shorter intervals are possible but would result in rapid exhaustion of floppy disk space; longer intervals could result in the loss of important test data. The sampling interval for sound power data was chosen to be 18 s. This interval allows the multiplexer to scan 16 microphones for 1 s each and gives the sound power calculator ample time to perform its computations and store the data. These intervals, along with the maximum control parameter values listed in table 1, can be changed easily by the test operator. The F5 "Edit conrols file" key in figure 9 provides the operator with a menu that enables these changes to be made from the XT keyboard. Selected information is also displayed on the XT video monitor, as shown in figure 10. The data displayed immediately to the right of fields 10 through 13 allow the operator to compare the actual values of the control parameters with those of the set points. The lower right section of figure 10 contains the following information:

Status word.--This 16-digit binary number contains information pertinent to the movement and locking of the drill test rig. It changes during the drill movement sequence, with each digit either identifying the status of a particular hardware component critical to this process (e.g., limit switches open or closed, input parameters valid or not) or issuing a command to proceed to the next step in the movement cycle (e.g., move carriage and boom to set point, lock carriage). The status word is a valuable troubleshooting aid if the drill rig either fails to move on command or moves incorrectly.

Test stage.--A string of text characters written to the display on the basis of the status word. The four test stages are collaring (drill rig moving to set point and drill operating before feed thrust reaches set point), testing (data being collected), retracting, and moving home.

Elapsed time.--The PC timer starts when the feed thrust reaches the set point and ends when the prescribed drill depth is reached. This provides the time base essential for all posttest analysis.

Drill frequency.--For percussion drills, the number of blows per minute (BPM) can be used to determine if the drill is operating correctly and can also affect the noise frequency spectrum. Drill frequency information is supplied to the PC via an accelerometer mounted on the drilling rig and appropriate signal conditioning equipment.

Overall sound power.--The XT reads this value directly from the Bruel & Kjaer sound power calculator every 18 s, then resets the 7507 and the multiplexers for another sample. The PC is not involved in this process. The sound power levels displayed in figure 10 are linear (unweighted) values. Although A-weighted overall sound power levels would be more desirable from a perceptual standpoint, they cannot be obtained directly owing to the recording and calculating techniques used by the 7507.[6] A-weighted levels can be obtained, however, through posttest analysis of the linear data.

Although the XT serves primarily as a data collector during a normal test, the operator can also enter commands in midtest through the XT keyboard. Most importantly, the operator can terminate a test at any time. It is also possible to change one or more of the control parameters in fields 10 through 13 by typing new values in the appropriate field(s) and pressing the F9 key. The program responds with a message "New Parameters Sent" on the monitor, and the XT records the values and the time they were sent. This capability is especially advantageous because it minimizes the number of holes needed to establish the optimum set of operating parameters (i.e., the set that yields the maximum penetration rate) for a particular drill.

A typical drill test requires approximately 1,000 bytes of floppy disk space per foot of hole. Therefore, data from at least 30 tests (all 12-ft holes) can be contained on a single 360-kb floppy disk. Larger numbers of tests with shallower hole depths can also be retained on a single disk. Data collection and analysis is discussed later in this report.

Control Subsystems

As described above, the ADTF consists of four major elements--the IBM-XT microcomputer, Westinghouse PC-700 process controller, Ledex valve drivers, and the various transducers and control valves on the drilling rig. This section describes how these elements function as a unit to provide the required control of the drilling process.

IBM-XT Microcomputer

The IBM-XT is a standard model with a 360-kb floppy disk drive, a 10-Mb hard disk drive, a 256-kb random access memory (RAM), and a serial port for communications with the PC-700. All the drill test software is permanently installed on the hard disk. Other add-on cards are installed for (1) a color monitor and graphics printer, (2) programming the PC-700, (3) interfacing with the Bruel & Kjaer sound measuring instrumentation, and (4) a real-time clock and calendar function.

Westinghouse PC-700 Process Controller

The PC-700 has a 4,136-kb memory and can address 32 analog inputs, 32 analog outputs, 256 discrete inputs, and 256 discrete outputs. The ADTF system uses 14 analog inputs, 12 analog outputs, 4 discrete inputs, and 16 discrete outputs. The drill operating information is passed to and from the PC via analog input cards, two analog output cards, one discrete input card, one discrete output card, and four high-speed counter cards. Four frequency-to-analog converter cards are also located in the PC-700 cabinet; although these are not addressed directly by the PC, they are essential for PC control of flow-based processes. Power is supplied by three sources--a 5-V supply for the high-speed counters, a 15.8-V supply for the input and output cards, and a 5-V supply for the frequency-to-analog converters.

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[6] The A-weighting process simulates the response of the human ear to sounds of various frequencies. The 7507 can record the desired 1/3-octave band sound power levels only in the linear mode, so the subsequent calculation of the overall ound power level yields a linear value.

All inputs such as transducer signals and control set points from the XT are converted to digital values and stored in selected memory cells called holding registers. During operation, the PC achieves process control by comparing the actual values in the holding registers with those of their corresponding set points. Based on the difference between the actual and set point values, the PC program writes digital values to its output registers, which in turn activate the appropriate valves, valve drivers, or counters on the drill test rig. Also contained in the holding registers are values that control the rates at which the output registers are changed; this allows smoother operation of the drills and drilling rig.

Drill Rig Positioning Control

The control elements for carriage and boom movement are shown in figure 11. During initial startup, the PC moves the carriage and boom to the zero position, where the limit switches on the drilling rig are closed mechanically. Closure of the limit switches resets the PC's high-speed counters with actual values of zero and reference values corresponding to the set points previously entered into the XT. Based on the PC's comparison between the information provided by the position transducer (100 counts per inch input to the high-speed counter) and the count corresponding to the set point, the carriage smoothly accelerates to its maximum speed, then decelerates as it approaches the set point position. After this position is reached, the PC nulls the Ledex driver card (input to Ledex of 4 V), thus closing the hydraulic control valve, and locks out the high-speed counter to make sure it does not change during the test. The above sequence is then repeated for the boom. After a test is completed and a new hole location is selected, the carriage and boom move to the new position without moving to the zero position.

Carriage Lock Control

The carriage lock-unlock system, shown in figure 12, is somewhat simpler than the positioning system in that the PC issues only an on-off command to the hydraulic control valve. The two horizontal locking cylinders in the carriage guide rail and the vertical foot jack (fig. 7) are connected in parallel to extend and retract simultaneously. Prior to a carriage move, the PC sets the appropriate bits in the discrete output

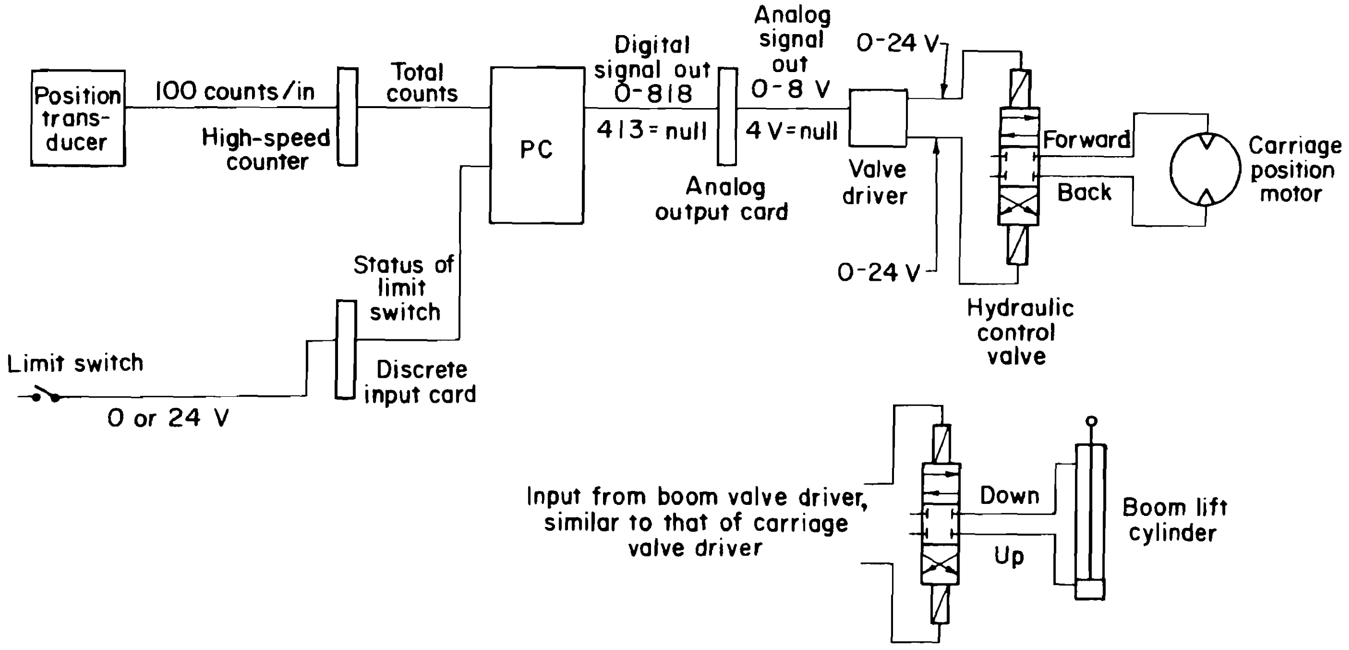


FIGURE 11.—Drill rig carriage and boom positioning system.

card to activate the "unlock" side of the hydraulic valve and deactivate the "lock" side. The reverse takes place after the carriage and boom have reached their set points, thereby locking the rig in place for the test. A timer loop in the PC program delays execution of further steps until the locking or unlocking process is completed.

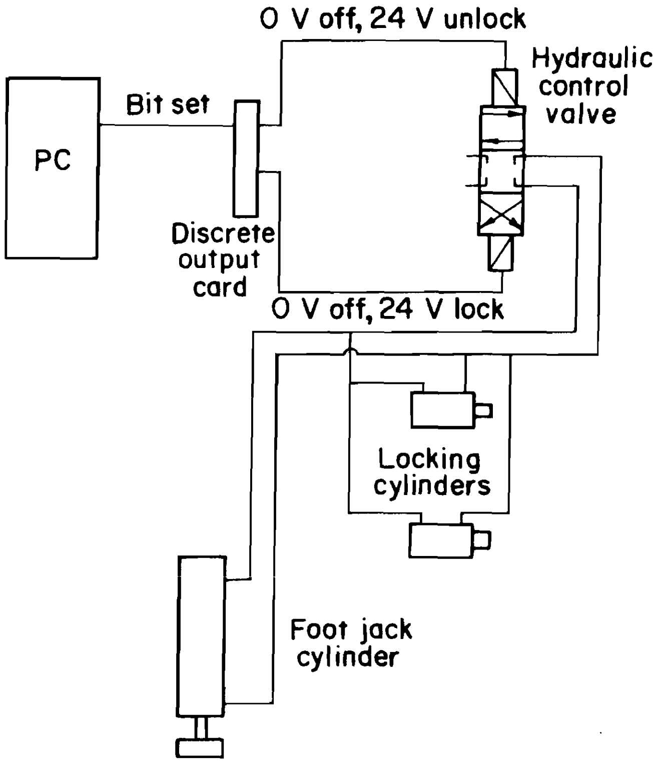


FIGURE 12.—Drill carriage lock system.

Feed Thrust and Hole Depth Control

The feed thrust and hole depth are controlled by the pressure and flow, respectively, of hydraulic oil in the feed cylinder. The upper portion of figure 13 diagrams the feed thrust control, and the lower part describes the depth control.

Since the area of the feed cylinder piston is fixed, the feed thrust is proportional to the hydraulic pressure on the larger (head) side of the piston. The pressure transducer in figure 13 sends a voltage signal to an analog input card, which in turn assigns a digital value to a holding register in the PC. During drilling, the PC program compares this value to the set point and, depending on whether the pressure needs to be increased or decreased, assigns an appropriate digital value to an analog output card. The voltage at the output card is sent to the Ledex driver, which increases or decreases the current to the "Forward" side of the hydraulic control valve. This side of the valve then opens or closes to increase or decrease the pressure on the head side of the piston. The digital output of the PC is constrained within a relatively narrow range during the drilling mode to prevent the feed

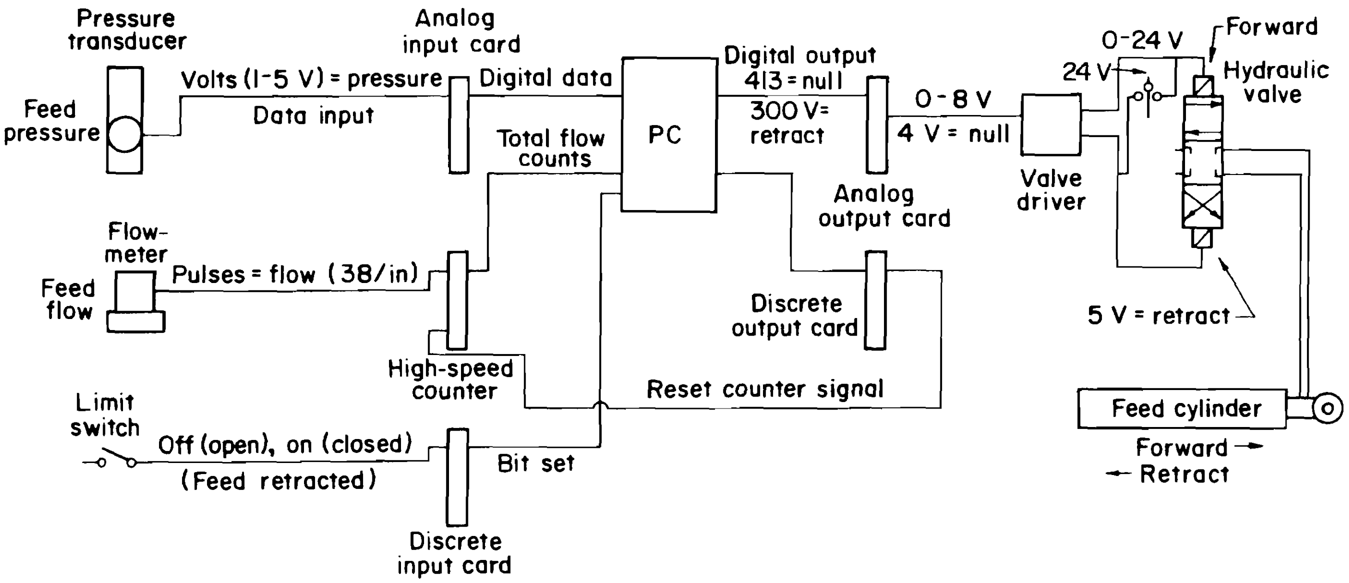


FIGURE 13.—Feed thrust and hole depth control system.

from lurching forward at the start of drilling, when the actual and set point pressures are far apart. A dead band around the set point is also included to prevent the feed pressure from oscillating rapidly when the actual and set point pressures are very close but not identical.

Hole depth is measured and controlled by the flow of hydraulic oil through a positive-displacement flowmeter in the line leading to the head side of the feed cylinder. This flowmeter generates 38 voltage pulses per inch of feed travel, which are transmitted to the high-speed counter. The counter tallies the pulses and assigns the total count during a test to a PC holding register for comparison with the count corresponding to the drill depth set point. A normal test ends when the two counts are equal; at this point the XT commands the PC to stop drilling and retract the feed.

To initiate the retraction phase, the PC sends a digital value of 300 to the analog output card, which then sends an input voltage of 3 V to the Ledex driver. The subsequent Ledex output is 5 V to the "Retract" side of the hydraulic control valve. This causes oil to flow to the rod side of the feed piston at a slow, constant rate to retract the drill. When the drill reaches the fully retracted position, the limit switch on the feed (fig. 6) closes mechanically. The PC then sends a null value (413) to the analog output card, thus stopping the feed, and sends a discrete output to the high-speed counter to zero the actual count for the next test.

Drill Hammer Control

Two different types of drill hammer control systems are shown in figure 14; the top portion describes the analog control system for hydraulic drills, and the lower part shows the discrete control system for pneumatic drills. The two systems are similar in that pressure is used as the process control variable, with flow being recorded in the PC for informational purposes only. However, the method for controlling pressure is somewhat different, as described below.

Pressure control for hydraulic hammers involves the same basic sequence as feed thrust control. Voltage from a pressure transducer is converted to a digital signal and compared to the set point in the PC, which assigns an output that eventually results in the opening or closing of a hydraulic valve. In the case of hammer pressure, only one side of the valve is activated because a reverse hammer function is not required. As with feed pressure, the PC's digital output range is limited to prevent hammer pressure surges, and a dead band around the set point is included.

Pressure control for pneumatic hammers includes the same type of analog input and PC comparisons as for hydraulic hammers, but the output involves three discrete control circuits. One circuit serves only to turn the main air supply valve on or off, as determined by the pneumatic-hydraulic choice entered into the XT (field 2 of figure 10). The other two circuits operate the pilot valve that controls the pressure-regulating valve (figure 14). After the PC compares the actual pressure to the set point, it opens one side of the pilot valve and closes the other. If the actual pressure is less than the set point, the PC opens the side that increases the pressure in the regulating valve. If the actual pressure is greater than the set point, the PC opens the opposite side of the pilot valve, reducing the pressure in the regulating valve. Reaction time of this system is very rapid and a dead band is included, so the amount of air vented to the atmosphere is minimal.

Drill Rod Rotation Control

Drill rod rotation control (fig. 15) is very similar to hammer control for pneumatic and hydraulic drills, as can be seen by comparing figures 14 and 15. The major difference is that flow rather than pressure serves as the process control variable, with pressure being recorded for informational purposes only. Flow is the preferred control variable for rotation because the load on the rotation motor varies considerably during the course of a test (collaring, drilling,

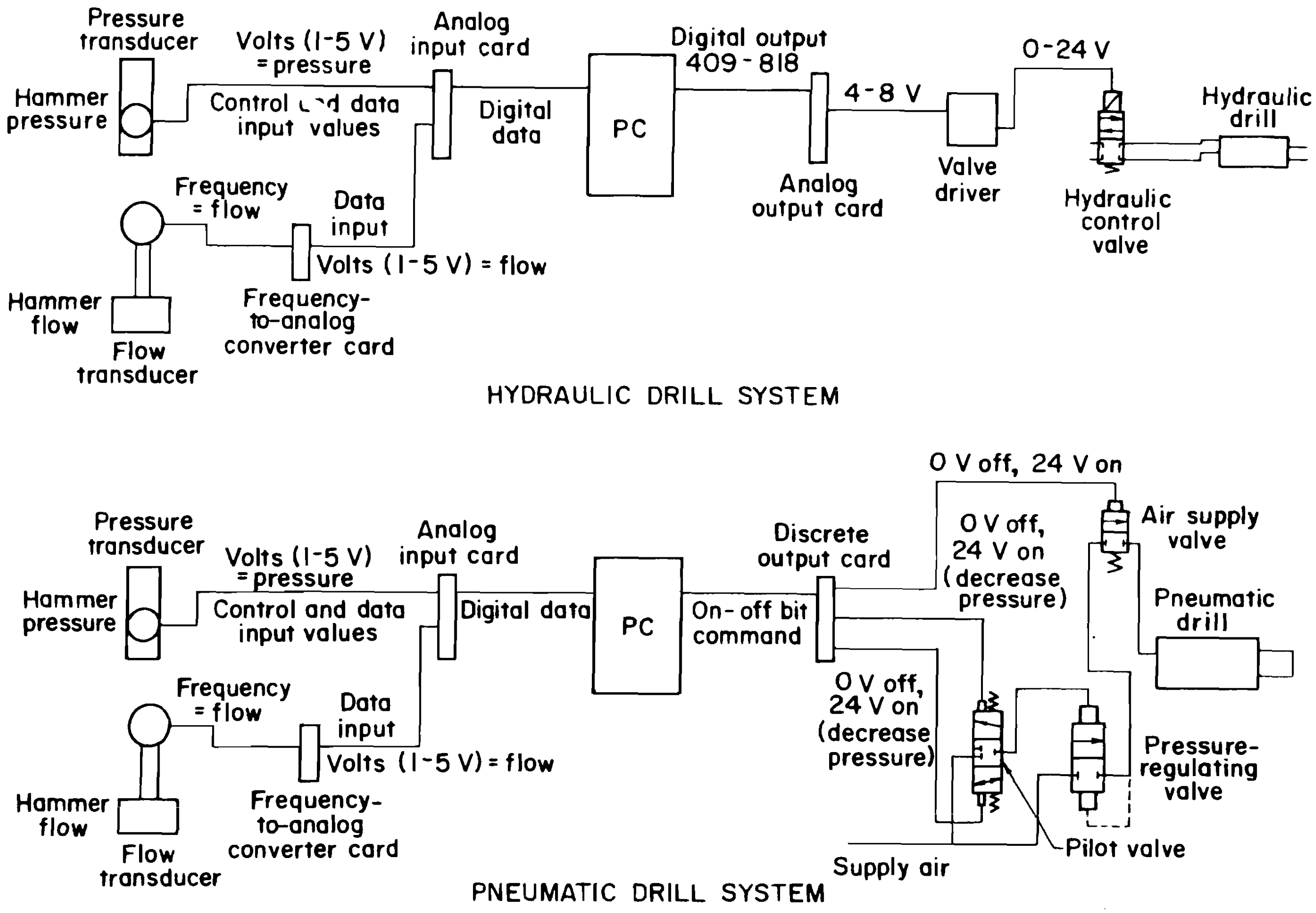


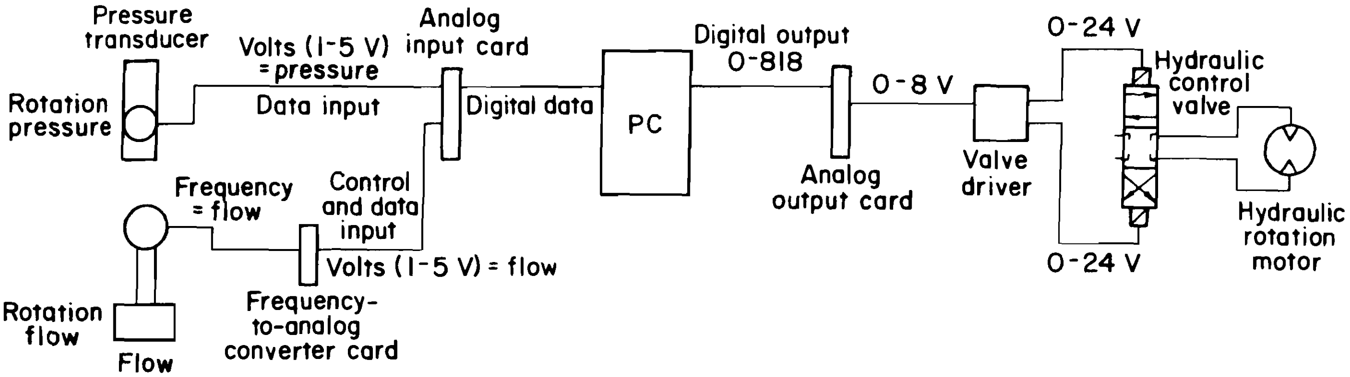
FIGURE 14.—Drill hammer control system.

and retracting modes). Flow changes resulting from motor load changes are much smaller in magnitude than the associated pressure fluctuations, thus making a flow-based control system more desirable.

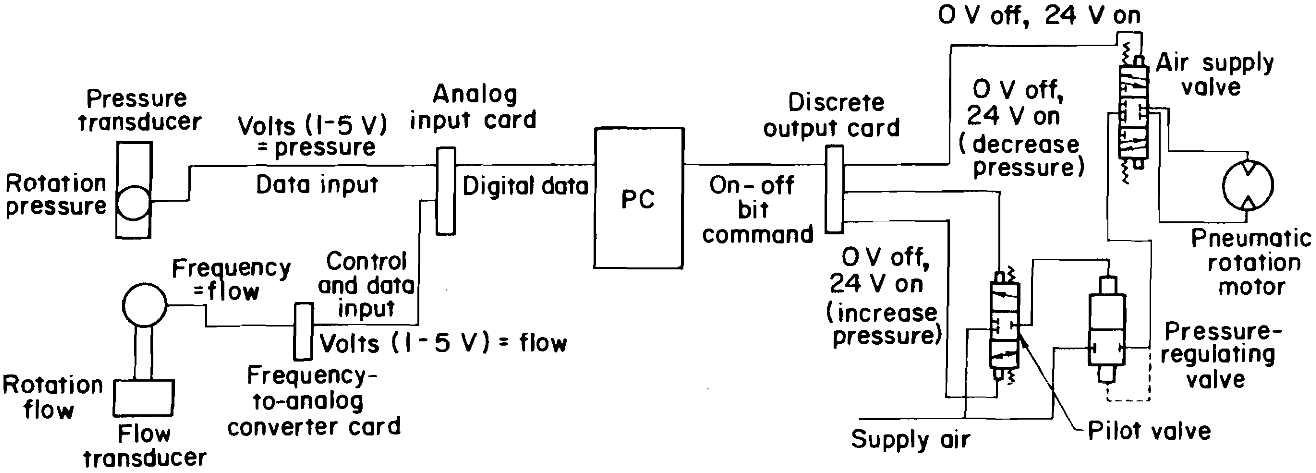
Input signals are generated in the form of voltage pulses from turbine flowmeters, converted to analog signals by the frequency-to-analog cards, and sent to the PC via analog input cards. Output signals are generated by the PC based on the difference between the actual flows and the set points. For hydraulic rotation, the "Forward" side of the rotation valve is opened or closed proportionally via the Ledex driver to increase or decrease rotation flow. For pneumatic rotation, the pilot valve pressure regulating system described for pneumatic hammers is employed; in this case flow control is achieved through pressure changes.

Another difference between the hammer and rotation control systems is that reverse rotation is possible, although forward and reverse rotation cannot be achieved during the same drill test. Reverse rotation can be obtained simply by reversing the hose connections to the rotation motor.

Rotation flow is also monitored by the XT to serve as a safety shutdown during the drilling and retracting phases of a test. A rotation flow of zero indicates a stuck bit, which could cause damage to the bit, drill rod, and perhaps the drill itself. If the flow goes to zero during the drilling phase, the test is aborted and the retraction phase initiated. If the flow remains zero (unsuccessful retraction), the PC goes into a null state to allow the stuck bit to be freed by hand.



HYDRAULIC DRILL SYSTEM



PNEUMATIC DRILL SYSTEM

FIGURE 15.—*Drill rod rotation control system.*

Flushing Water Control

Flushing water is controlled by a simple on-off command from the PC. When the test operator issues the final "Start Test" command through the XT keyboard (see "Data Input and Startup Procedure"), the PC activates a discrete output that opens the water valve completely. Water continues to flow to the drill until the feed limit switch is closed following drill retraction. Flushing water pressure is measured and recorded, but not controlled, by the PC and XT during the test. A manually operated pressure-reducing valve is used to adjust water pressure.

Other Drill Test Commands

The drill test program software permits several other operator command choices from the main test menu, as shown in the "Executive commands" box at the top of figure 10:

Exit program (F1).--This results in the display of the higher level option menu of figure 9.

Master reset (F2).--This nulls the PC holding registers that had previously contained set points or test data and changes the status word to that shown in figure 10. Resumption of testing after a "Master reset" command results in the same sequence as the initial startup in that the drill carriage and boom move to the home position before moving out to the selected hole location.

Move platform home (F3).--Moving the drilling rig to its home position places it close to the zero position, thereby shortening the initial startup process for the next test session. The home position is also the most convenient one for drill rig maintenance; therefore, this command is usually issued at the end of a drill test session or when a substantial amount of mechanical work (e.g., changing drills) needs to be performed on the drilling rig.

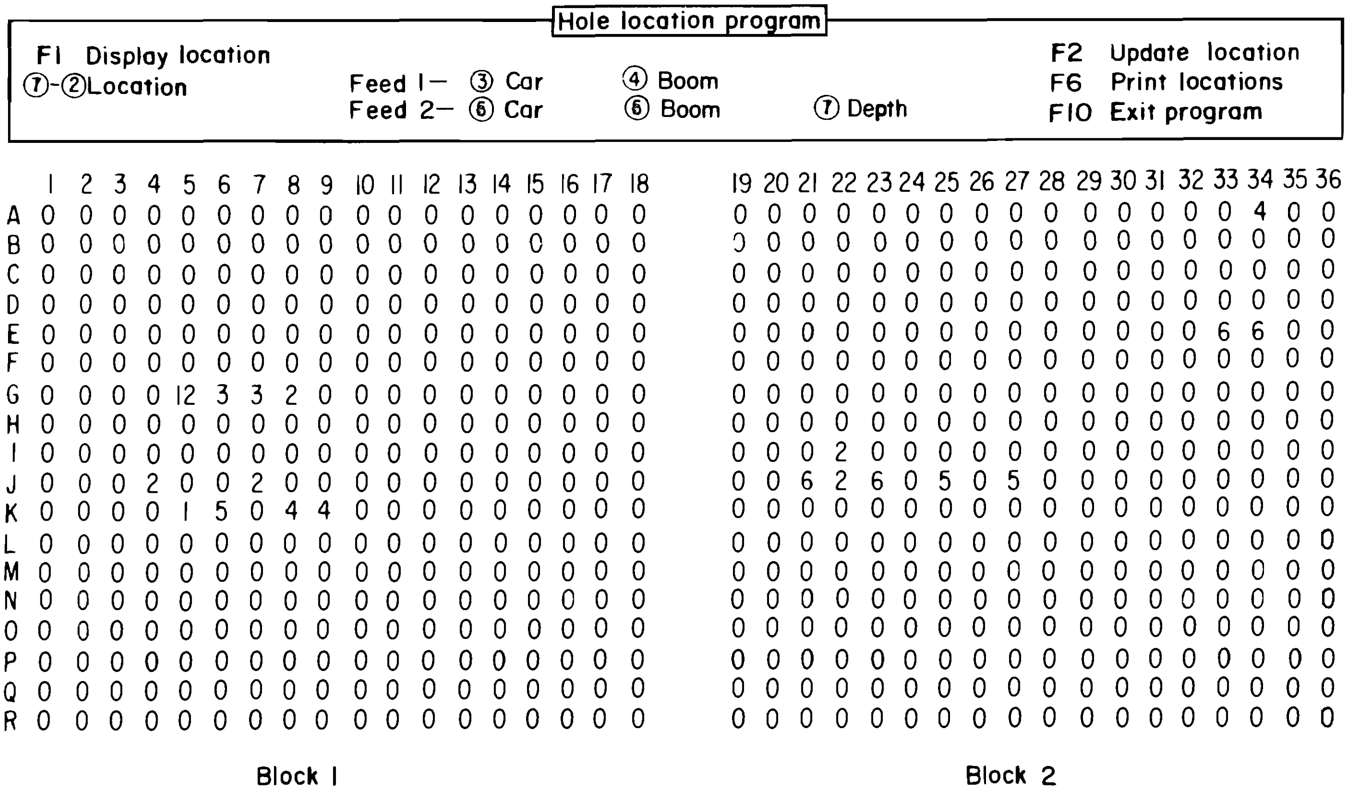
Test without move (F4).--This command starts the drilling process without moving the carriage or boom. It is used most often when a successful move has been completed but the maximum hole depth has not been reached. For example, the operator may notice a problem (e.g., stuck drill bit, leaking hose, etc.) and terminate the test before the hole is completed. The "Test without move" command enables the test to be restarted (with a new test number) after the problem has been corrected without going through the time-consuming move process.

HOLE LOCATION PROGRAM

The hole location program is a very convenient means for managing the locations and depths of all holes drilled by the ADTF. It can be accessed directly by the test operator to change the actual position of any row or column assignment in the hole location grid, or to change the depth (from the program's standpoint) of any hole on the existing grid. It is also addressed during the startup phase of the drill test program to prevent the use of a hole location that has already been drilled to the maximum depth of 12 ft. These three functions of the hole location program are described below.

Selection of Hole Position

The test operator gains direct access to the hole location program by choosing option F3 in the menu of figure 9, which results in the display of figure 16, the hole location grid. The vertical hole



```
                                   Hole location program
 F1  Display location                                                          F2   Update location
 ⑦-②Location              Feed 1— ③ Car    ④ Boom                             F6   Print locations
                           Feed 2— ⑥ Car    ⑥ Boom          ⑦ Depth            F10  Exit program

    1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18     19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
A   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  4  0  0
B   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
C   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
D   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
E   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  6  6  0  0
F   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
G   0  0  0  0 12  3  3  2  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
H   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
I   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  2  0  0  0  0  0  0  0  0  0  0  0  0  0  0
J   0  0  0  2  0  0  2  0  0  0  0  0  0  0  0  0  0  0      0  0  6  2  6  0  5  0  5  0  0  0  0  0  0  0  0  0
K   0  0  0  0  1  5  0  4  4  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
L   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
M   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
N   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
O   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
P   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
Q   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
R   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0      0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0

                        Block 1                                                     Block 2
```

FIGURE 16.—Data input menu for hole location program.

positions (hole rows) are denoted by the letters A through R; the horizontal positions are given by columns 1 through 18 (left-side concrete block) and 19 through 36 (right-side block). Operator control of hole position is achieved by entering information in the circled fields 1 through 6 in figure 16. Fields 1 and 2 are the row and column assignments, respectively, of the hole to be considered. Fields 3 through 6 contain the desired number of counts (38 counts per inch) to be issued by the position transducers en route from the home position to the hole. Fields 3 and 4 are the carriage and boom counts for feed 1, while fields 5 and 6 are for feed 2. These data are then placed into the appropriate PC holding registers by pressing the "Update location" (F2) key. A current listing of the counts for each hole location can be obtained by pressing either F1 (output to video monitor) or F6 (output to printer).

The entire hole location grid was preprogrammed in this manner to remain within the confines of the two existing concrete blocks. Spacing between adjacent rows and columns was set at 4 in, and the pattern was staggered by 2 in (i.e., even-numbered columns were shifted 2 in downward from odd-numbered columns) to provide an actual hole spacing of about 4.5 in. Under normal circumstances, the test operator would have no reason to change the preprogrammed hole positions. However, an important exception occurs when considering the use of drilling media other than the concrete blocks. For example, a granite test block was inserted into the wall between the concrete blocks, and previously unused hole locations around the perimeter of the concrete blocks were utilized to establish a hole pattern on the granite block. The only constraints on hole position are the physical travel limits of the carriage and boom.

Validation of Input Data

At the end of each drill test, the drill test program automatically enters the hole depth (in feet) into the hole location program. If the operator subsequently specifies a hole location that has already been drilled to the maximum depth (e.g., location G-5 in figure 16) or asks for a depth that would exceed the maximum at that location (e.g., a 7-ft hole at location J-21), the drill test program issues an error message. Testing cannot proceed until the error is corrected by specifying either another hole location or a shallower hole depth.

Selection of Hole Depth

During the initial programming of the hole location grid, the depth of each hole was set to zero via field 7 of figure 16. Subsequent drill tests resulted in the assignment of actual hole depths to various locations. In some cases, however, it is desirable for the operator to arbitrarily assign hole depths through the hole location program. For example, a very large drill hole at a particular location may interfere with adjacent holes if the holes are not perfectly straight; damage to the drill rod or drill could result if the holes intersect within the block. Therefore, even though the actual depths of the adjacent holes are zero, the operator may wish to enter a depth of 12 ft into the hole location program (field 7 of figure 16). This will cause an error message to appear if the operator tries to select these holes for drill tests. The hole depth selection feature also allows easy reinitialization after the concrete blocks are replaced.

DATA ANALYSIS PROGRAM

The drill test software possesses very powerful analytical capabilities. Any drilling parameter stored to disk can be studied and compared graphically to any other variable. The data analysis program can be called in from the overall software menu (fig. 9) or the main drill test menu (fig. 10) for simultaneous analysis of any two tests. The data recorded to disk can also be converted easily to commercially available spreadsheet files (Lotus 1-2-3) for subsequent analysis using the spreadsheet software.

Direct Data Analysis and Graphics

Test Selection

Recall that all test data are stored on floppy disks in files named "TEST____.DAT," with the blanks corresponding to the four-digit test number assigned by the XT. When data analysis is desired, the test operator first makes sure the correct test numbers are available on the floppy disk by selecting option F4, "Directory of tests on A:" from the overall software menu shown in figure 9. The operator then chooses the data analysis program (F2), which results in the display of the menu in figure 17. The test or tests to be analyzed are selected by entering the four-digit test number(s) in fields 1 and 2 of figure 17 and pressing the F9 "Retrieve tests(s)" key. Note in figure 17 that tests 0178 and 0293 have been selected. Test 0178 is that of a small, muffled pneumatic percussion drill; test 0293 is that of a small, all-rotary pneumatic drill. These two tests will be used below to illustrate the basic graphics capability of the data analysis program. Further comparisons between the two drills are contained in the section of this report entitled "Initial Test Results."

Raw Data Retrieval

The "List test" and "Print test" options in figure 17 (function keys F7 and F8) are used to retrieve all the data recorded during a given test. "List test" displays the data only on the XT video monitor; "Print test" also provides a hard copy of this information. Figure 18 shows the data recorded for the first 45 s of test 0293. Descriptive information is given at the beginning of the test file, and the entry of new test parameter values is documented at 15.7 and 26.3 s. The top row of figure 18 shows all the drilling parameters recorded during the test and the units in which they are given. Sound power information is given at 18.1 and 36.2 s; the first 21 values in the string correspond to the twenty-one 1/3-octave bands comprising the 100- to 10,000-Hz frequency range, and the final value is the overall (unweighted) sound power level. Note that in this particular test, the values for hammer pressure and drill blow frequency appear as dummy values of 1.0 and 0.0, respectively, because of the all-rotary operating mode of the tested drill.

The ability to scan the entire set of test data in this manner helps the test operator in several ways: (1) Graphs

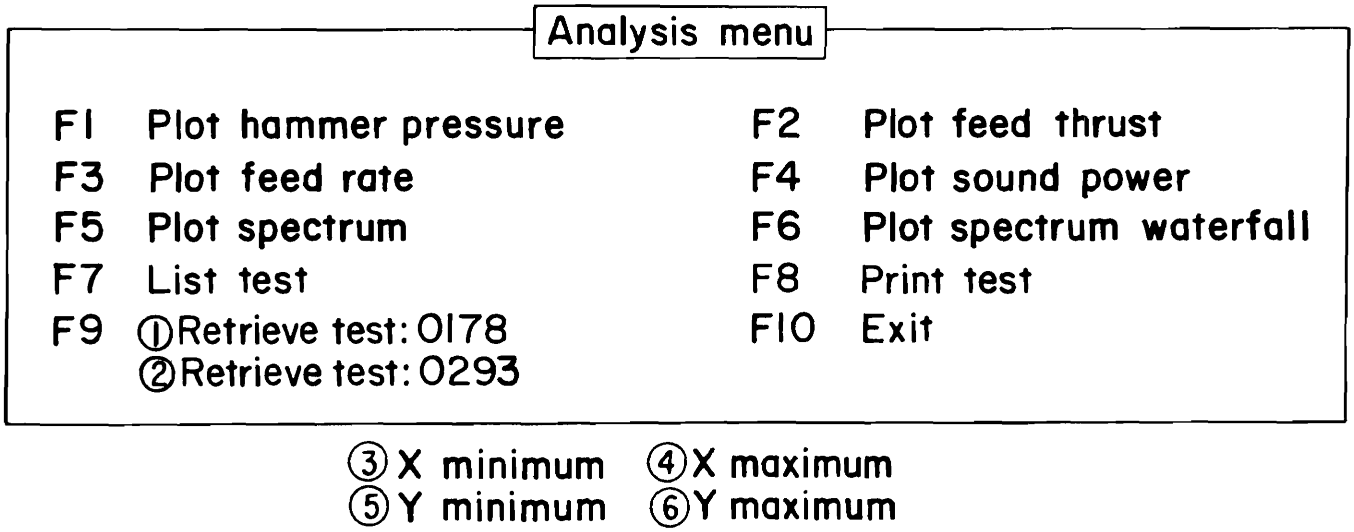
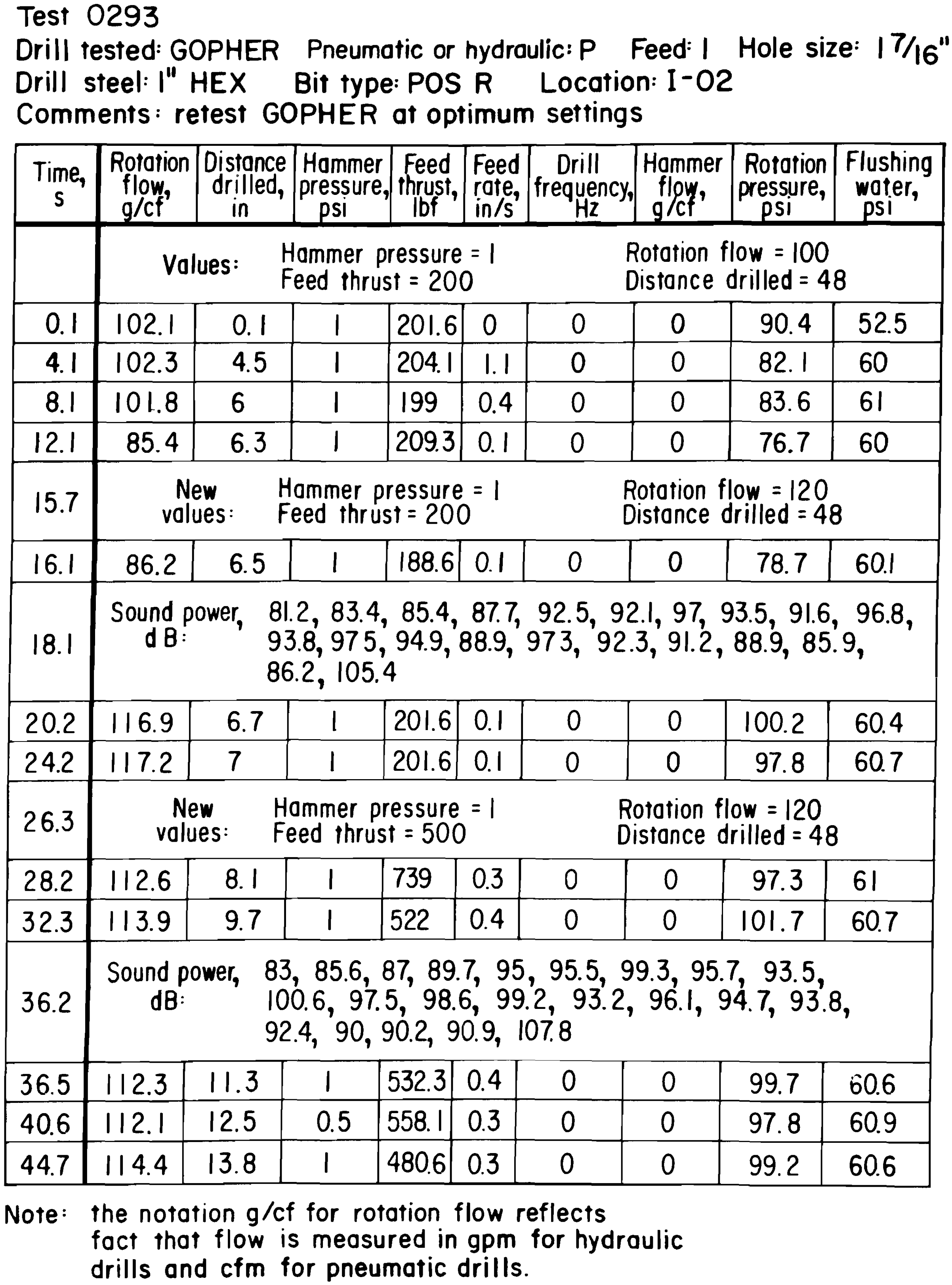


FIGURE 17.—Data input menu for analysis program.



Test 0293
Drill tested: GOPHER Pneumatic or hydraulic: P Feed: I Hole size: $1\frac{7}{16}$"
Drill steel: I" HEX Bit type: POS R Location: I-02
Comments: retest GOPHER at optimum settings

Time, s	Rotation flow, g/cf	Distance drilled, in	Hammer pressure, psi	Feed thrust, lbf	Feed rate, in/s	Drill frequency, Hz	Hammer flow, g/cf	Rotation pressure, psi	Flushing water, psi
	Values: Hammer pressure = I Feed thrust = 200 Rotation flow = 100 Distance drilled = 48								
0.1	102.1	0.1	I	201.6	0	0	0	90.4	52.5
4.1	102.3	4.5	I	204.1	1.1	0	0	82.1	60
8.1	101.8	6	I	199	0.4	0	0	83.6	61
12.1	85.4	6.3	I	209.3	0.1	0	0	76.7	60
15.7	New values: Hammer pressure = I Feed thrust = 200 Rotation flow = 120 Distance drilled = 48								
16.1	86.2	6.5	I	188.6	0.1	0	0	78.7	60.1
18.1	Sound power, dB: 81.2, 83.4, 85.4, 87.7, 92.5, 92.1, 97, 93.5, 91.6, 96.8, 93.8, 97.5, 94.9, 88.9, 97.3, 92.3, 91.2, 88.9, 85.9, 86.2, 105.4								
20.2	116.9	6.7	I	201.6	0.1	0	0	100.2	60.4
24.2	117.2	7	I	201.6	0.1	0	0	97.8	60.7
26.3	New values: Hammer pressure = I Feed thrust = 500 Rotation flow = 120 Distance drilled = 48								
28.2	112.6	8.1	I	739	0.3	0	0	97.3	61
32.3	113.9	9.7	I	522	0.4	0	0	101.7	60.7
36.2	Sound power, dB: 83, 85.6, 87, 89.7, 95, 95.5, 99.3, 95.7, 93.5, 100.6, 97.5, 98.6, 99.2, 93.2, 96.1, 94.7, 93.8, 92.4, 90, 90.2, 90.9, 107.8								
36.5	112.3	11.3	I	532.3	0.4	0	0	99.7	60.6
40.6	112.1	12.5	0.5	558.1	0.3	0	0	97.8	60.9
44.7	114.4	13.8	I	480.6	0.3	0	0	99.2	60.6

Note: the notation g/cf for rotation flow reflects fact that flow is measured in gpm for hydraulic drills and cfm for pneumatic drills.

FIGURE 18.—Printout of drill test data.

generated by the software are more easily interpreted with the availability of hard numbers, especially when input parameters are changed during a test, (2) particularly interesting portions of a test can be isolated for more detailed analysis, and (3) data anomalies that sometimes occur at the start of a test are easier to identify.

Basic System Graphics

The function keys F1 through F6 in figure 17 are used to display graphs on the XT video monitor; hard copies are obtained easily by pressing the "Print screen" key of the XT keyboard when the graph is displayed. Function keys F1 through F4 provide graphs that utilize the indicated test parameter as the dependent (Y-axis) variable and elapsed time as the independent (X-axis) variable. Function key F5 plots the 1/3-octave band sound power levels versus frequency, and F6 provides a simulated three-dimensional graph with frequency as the X-axis, 1/3-octave band sound power level as the Y-axis, and time as the Z-axis. Figures 19 and 20 are examples of these graphs for tests 0178 and 0293.

Fields 3 through 6 in figure 17 are used by the test operator to define the range of values to be displayed on the X- and Y-axes of each graph. These values are entered before pressing the function key for the desired graph. If these fields are left blank, the range is determined by the actual minimum and maximum values contained in the data. In figures 19 and 20, ranges were selected such that all test data would be displayed on easily readable axes. For example, the total elapsed time in each test was slightly greater than 150 s;

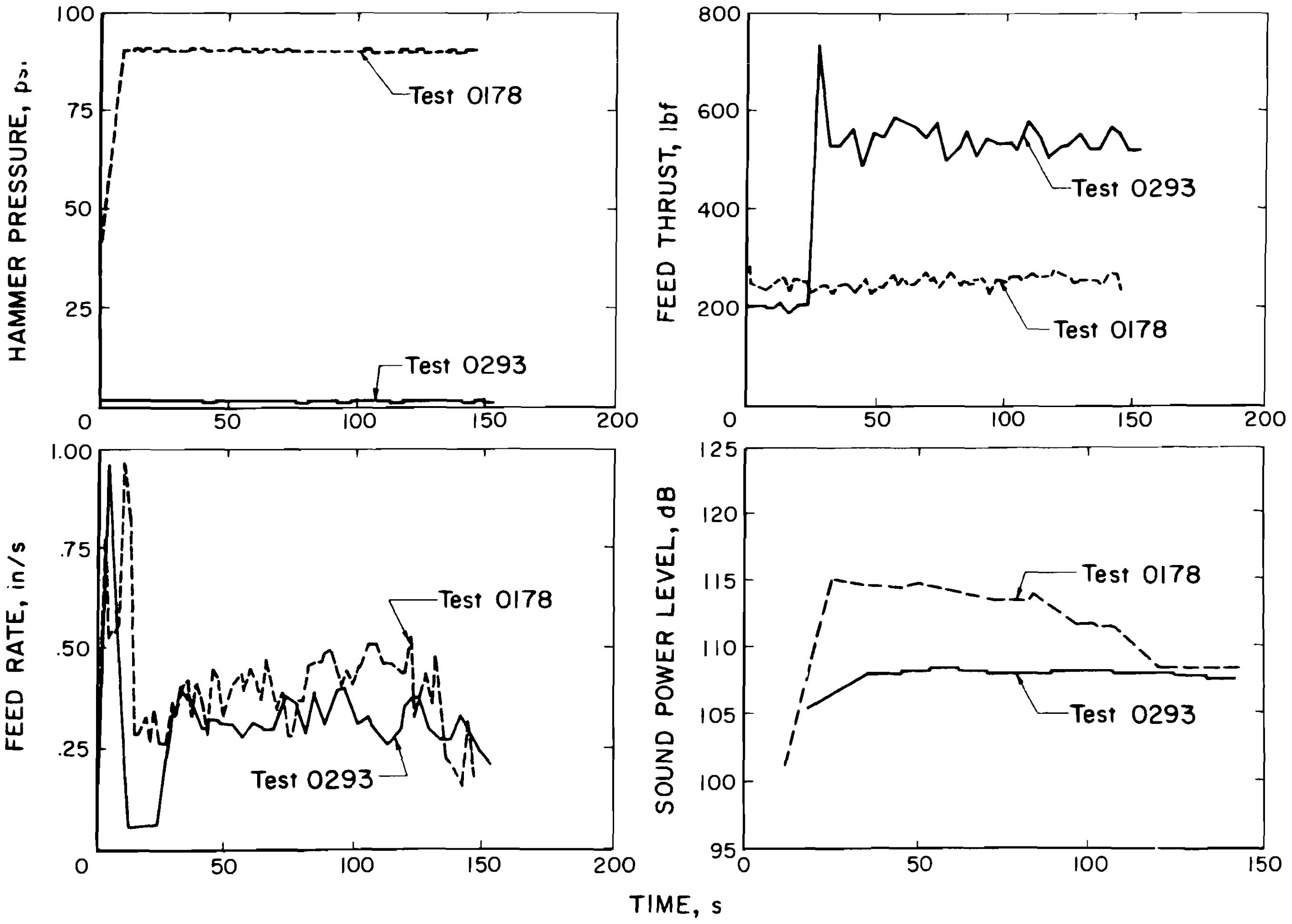


FIGURE 19.—Graphs of hammer pressure, feed thrust, feed rate, and sound power versus elapsed time.

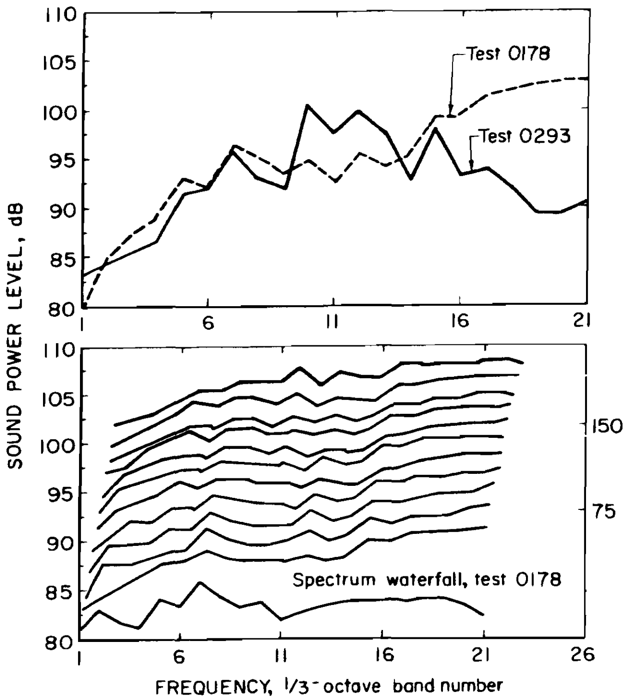


FIGURE 20.—Sound power spectrum and spectrum waterfall graphs.

therefore, the "Xmax" (field 4) value in the time-based graphs was set at 200 s so that values of 50, 100, and 150 s would occur at the three computer-generated subdivisions. Maximum and minimum values for all the other parameters were chosen in the same manner.

Hammer pressure (fig. 19).--Hammer pressure for test 0178 (pneumatic percussion drill) was set at 90 psi; the ADTF achieved this pressure shortly after startup and maintained it very consistently throughout the test. Hammer pressure for test 0273 was set at a nominal value of 1 psi (rotary drill).

Feed thrust (fig. 19).--Feed thrust in test 0178 was set at 240 lbf and remained there throughout the test. Feed thrust in test 0293 was initially set at 200 lbf; after the hole was collared, thrust was increased to 500 lbf. Except for the brief spike that occurred as the ADTF adjusted to the higher set point, feed thrusts remained fairly close to the set point values.

Feed rate (fig. 19).--The abnormally high feed rate at the start of each test corresponds to the forward movement of the drill before the bit contacts the concrete. After collaring, both drills achieved a fairly steady feed rate of 0.3 to 0.5 in/s, although the percussion drill was somewhat faster. In test 0293, an abnormally low feed rate occurred during collaring because of the low feed thrust; this rose markedly when the feed thrust was increased.

Sound power (fig. 19).--Sound power of the rotary drill (test 0293) was very consistent at 105 to 107 dB through the test. Sound power of the percussion drill (test 0178) was around 115 dB at the start of the test, but decreased as the drill rod entered the hole. This effect did not occur in test 0293 because the drill rod is not a major contributor to rotary drill noise.

Spectrum (fig. 20).--The 1/3-octave band sound power levels in these two tests were very similar at low frequencies. The major difference between the two spectra occurred at higher frequencies, where the drill rod noise of the percussion drill was more prominent.

Note in figure 20 that frequency data are reported in "band number" rather than Hertz because this is the way the sound power calculator reports frequency data to the XT. In this case, band 1 corresponds to 100 Hz and band 21 corresponds to 10,000 Hz. However, since Hertz is the universally accepted unit of frequency measurement, the use of band number in graphs represents a major deficiency of the basic system graphics. Two other limitations of the basic system graphics for sound power spectra are that (1) only the final sample recorded during the test is graphed when the F5 key in figure 17 is pressed and (2) the overall sound power level cannot be plotted on the same graph as the 1/3-octave band data. As discussed in the next section, all three of these problems can be resolved by using electronic spreadsheets to look at frequency data.

Spectrum waterfall (fig. 20).--This shows how the noise frequency spectrum varies during a test. It can provide useful qualitative information with regard to frequency shifts during the course of the test, but it is of little value for quantitative comparisons. Owing to the complexity of the spectrum waterfall graph, it can be displayed for only one test at a time.

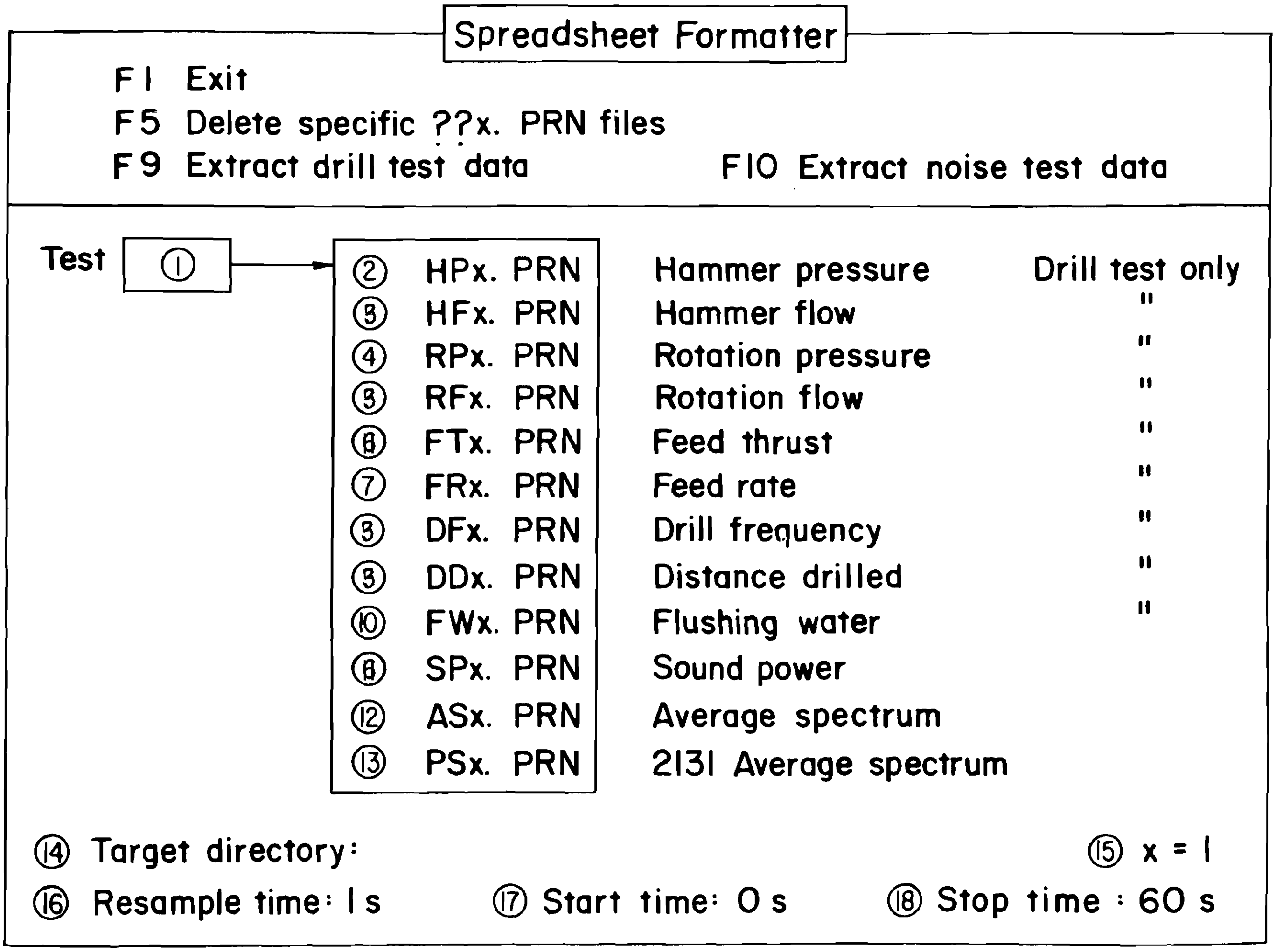
Expanded Data Analysis Through Spreadsheets

Given the limitations of the basic system graphics, a method for obtaining a more complete data analysis was desired. The most effective approach was to convert the test data files to electronic spreadsheet files. Lotus 1-2-3 was chosen as the spreadsheet program because of its ready availability and compatibility with the IBM-XT. To avoid the manual entry of test data into the spreadsheet files, special software was written to convert the individual parameters of the "TEST____.DAT" files into a format that could be read by the lotus program's "File Import" function. For convenience, the Lotus Formatter program and the standard Lotus 1-2-3 software are contained on the hard disk.

File Conversion Procedure

The step-by-step procedure for converting the "TEST____.DAT" files to Lotus 1-2-3 files is described below:

1. The test operator loads the Lotus Spreadsheet Formatter program into the XT, which results in the display of the menu shown in figure 21.
2. The four-digit test number of the test to be formatted is entered into field 1 of figure 21.
3. The parameters to be formatted are selected by placing any nonzero



Spreadsheet Formatter

F1 Exit
F5 Delete specific ??x. PRN files
F9 Extract drill test data
F10 Extract noise test data

Test ①

②	HPx. PRN	Hammer pressure	Drill test only
③	HFx. PRN	Hammer flow	"
④	RPx. PRN	Rotation pressure	"
⑤	RFx. PRN	Rotation flow	"
⑥	FTx. PRN	Feed thrust	"
⑦	FRx. PRN	Feed rate	"
⑧	DFx. PRN	Drill frequency	"
⑨	DDx. PRN	Distance drilled	"
⑩	FWx. PRN	Flushing water	"
⑪	SPx. PRN	Sound power	
⑫	ASx. PRN	Average spectrum	
⑬	PSx. PRN	2131 Average spectrum	

⑭ Target directory:
⑮ x = 1
⑯ Resample time: 1 s
⑰ Start time: 0 s
⑱ Stop time : 60 s

FIGURE 21.—Data input menu for Spreadsheet Formatter program.

character in fields 2 through 13. The general names of the files to be created by the Lotus Formatter (see item 5 below for specific file names) are shown immediately to the right of fields 2 through 13, and the parameter names are displayed on the right of the file names.

4. The disk drive to which the formatted files will be written is entered into field 14. The hard disk (c): is the default drive.

5. The specific names of the files to be created by the Lotus Formatter are chosen by entering any of the numbers 1 through 9 into field 15. For example, if nonzero characters were entered in fields 2 and 9 and the default value of 1 were left in field 15, the two files created would have the names "HP1.PRN" and "DD1.PRN." Up to nine Lotus-formatted files for each parameter can thus be contained on any one output target (floppy or hard disk), and almost an unlimited number of such files can be maintained by renaming the files after they are formatted.

6. The amount of drill test data to be formatted is chosen by entering the appropriate values in fields 16, 17, and 18. Since the Lotus Formatter program uses the "Elapsed Time" parameter as a key, field 17 (Start time) and field 18 (Stop time) determine the portion of the test to be formatted. The default values of 0.0 and 60.0 s are shown in figure 21. Field 16 (Resample time), specifies the interval at which the Lotus Formatter program will recheck the "TEST____.DAT" file for new data. When the default value of 1.0 s is shown in figure 21, the program interpolates between the actual values recorded at 4- or 18-s intervals.

7. When all selections in fields 1 through 17 have been made, the F9 key is pressed to perform the file conversions. Confirmation messages and/or error messages appear at this time, including an option to overwrite any "xxx.PRN" files that are already located on the target directory. Pressing F5 rather than F9 deletes from the target directory any files whose names are the same as those of the "marked" files.

8. The operator exits the Lotus Formatter program, enters Lotus 1-2-3, and calls in a special worksheet file that contains A-weighting correction factors, convenient column headings, and appropriate axis labels for later graphs. This serves as a template worksheet to which the formatted drill test files will be imported.

9. The cursor is moved to the area of the worksheet in which the test data are to appear, and the "File Import" procedure of Lotus 1-2-3 is used to call in the formatted files. This procedure is repeated for each "xxx.PRN" file created in steps 1 through 7 above.

10. The standard Lotus 1-2-3 file manipulation and graphics options are utilized to perform the desired analyses. Examples of the use of Lotus graphics are given in the section of this report entitled "Initial Test Results."

Note that fields 2 through 11 correspond to the drilling parameters listed in figure 18. Fields 12 and 13 are special parameters that are created by the Lotus Formatter software prior to conversion. The "Average spectrum" (field 12) consists of the logarithmic average of the sound power levels in each of the twenty-one 1/3-octave bands, with the number of samples determined by the specified start and stop times. For example, the default values of 0.0 and 60.0 s would result in the averaging of three sound power values per frequency band (data at 18, 36, and 54 s). Field 13 is analagous to field 12 except that the Lotus Formatter looks for sound pressure data recorded from the Bruel & Kjaer model 2131 digital frequency analyzer.

Advantages of Spreadsheet Analysis

Multivariable Comparisons

The basic system graphics package can only plot drilling parameters versus time. With spreadsheet analysis, any two parameters in a given test can be compared against each other. The most frequent use of this capability would be the comparison of sound power and hole depth.

Also, if one or more drilling parameters are changed during the test, the effect of these changes on all other parameters can be displayed graphically.

Multitest Comparisons

The Lotus 1-2-3 graphics package can display the results of up to six tests on the same graph, versus only two for the basic system graphics package. Parametric studies (where only one variable is changed from test to test, to observe its effect on other variables) are therefore much easier to perform. This capability also facilitates comparisons among several different types and models of drills.

Frequency Analysis

As mentioned above, the limited frequency analysis capability of the basic system graphics package is one of its greatest deficiencies. Spreadsheet analysis overcomes these deficiencies in the following ways:

1. The average frequency spectrum from any portion of the test can be obtained by judicious selection of the start and stop times in the Lotus Formatter program (fields 17 and 18 in figure 21). In this manner a two-dimensional "spectrum waterfall" can be created to observe how the spectra change during the course of a test.

2. A-weighting of the 1/3-octave band noise levels can be performed quickly and easily. An overall A-weighted level for each spectrum can then be calculated and displayed on the same graph as the 1/3-octave band data.

3. Frequency rather than band number can be displayed as the X-axis of all graphs.

Analysis of Other Noise Tests

Since the Lotus Formatter can operate on any data file created by the sound measuring instrumentation, it can be used to analyze noise information from any test conducted in the reverberation chamber. A separate noise test program allows this instrumentation to be activated through the XT, and causes it to write the noise data to disk with a file name of "NOIS .DAT". The Lotus Formatter program can then be used to convert the data to a "xxx.PRN" file. The same 10-step procedure described above is used instead of the F9 "Extract drill test data" command. As noted in figure 21, drilling parameters cannot be converted using the F10 command. One of the most common uses of the noise test program is to read the room correction factors from the Bruel & Kjaer 7507 sound power calculator. Knowledge of these room correction factors allows the sound pressure levels to be calculated from the sound power levels using the Lotus software.

INITIAL TEST RESULTS

To further demonstrate the abilities of the automated drill test fixture, some observations of the initial test data are included. Three types of drills were tested to help assure that the test fixture was capable of performing as specified. A pneumatic percussion drill, a hydraulic percussion drill, and a pneumatic rotary drill were all run in the concrete test medium to compare performance against the manufacturers' published data and to measure their sound power levels in an operating situation. All three drills are of the small "hand-held" class for which noise control technology has been difficult to implement.

The general test scheme involves finding the set of operating parameters that results in the optimum penetration rate for the drill being tested and measuring the sound power level under these conditions. However, drills designed to operate in soft rock perform better in the concrete test medium than those designed to drill hard rock. Therefore, it is possible that the penetration rates presented here could be different if the drills were tested in a hard drilling medium.

Several points should be noted about the test data. Most importantly, the number of tests to date is too small to generate statistically valid results concerning the behavior of the drills under differing operating conditions. Second, the primary purpose of these tests has simply been to verify the capabilities of the ADTF in terms of process control, data collection, and test analysis; however, operation of the test fixture has still yielded some interesting information. The confirmation of the contribution of the drill steel to the overall noise level in percussion drills is one factor that can be noted from the available data.

PNEUMATIC VERSUS HYDRAULIC PERCUSSION DRILLS

The drill used for the tests of pneumatic percussion drill was a Technological Enterprises QHR drill, a quieted pneumatic drill developed under contract with the Bureau of Mines (9-10). Its valveless design, independent rotation, and integral muffler make the QHR drill one of the quietest in its class. A Tamrock HH-50 was chosen to represent hydraulically powered percussion drills. This drill also has independent rotation and is capable of accommodating either water or air flushing, as is the QHR. The sound power spectra of these two drills are shown together in figure 22.

The QHR and the HH-50 are in approximately the same weight and power-output class and give a fairly good comparison between the two different power sources. During the tests chosen for comparison, the QHR drilled at a rate of 1.95 ft/min under an average thrust of 245 lbf and the HH-50 drilled at a rate of 2.20 ft/min under an average thrust of 277 lbf. Although they are not typically used for concrete drilling, button bits were used to maintain bit consistency during testing.

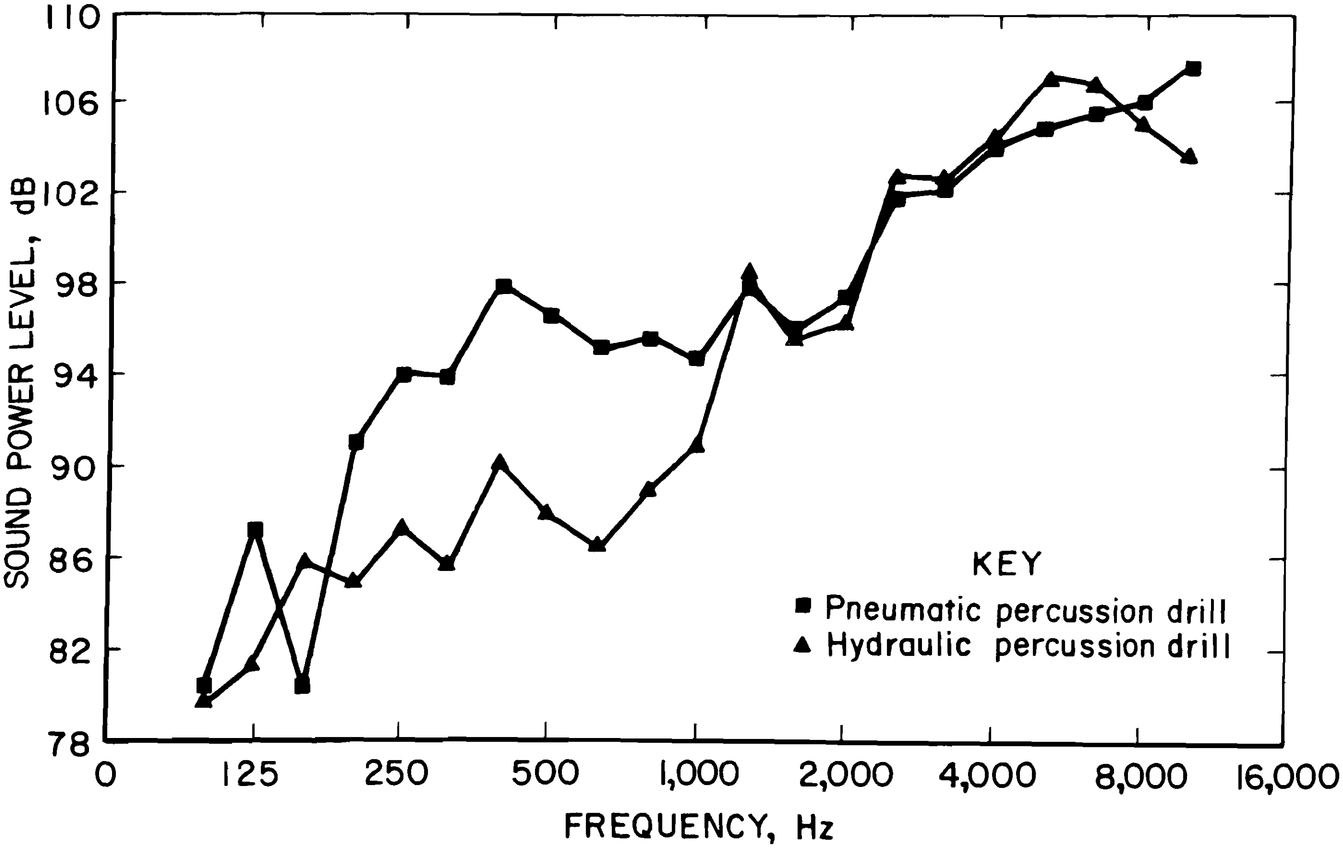


FIGURE 22.—Average frequency spectra: pneumatic and hydraulic percussion drills.

It can be noted in figure 22 that the drills differ significantly in sound power output between 160 and 1,250 Hz. This area is dominated by the noise produced by the exhaust of the pneumatic drill. The difference would be even larger if the pneumatic drill were not muffled. At 1,000 Hz and above, the two drills produce approximately the same power spectrum. This is to be expected as the noise in this frequency range is characteristic of the drill body and drill steel.

The sound power output at 1,250 to 8,000 Hz is largely a product of the exposed drill steel. In particular, the spectra from 1,250 to 4,000 Hz are almost identical. This is not surprising because the two drills operate at about the same frequency and the length of the steel in both tests was the same. This noise is not produced solely by the drill itself, and in operating situations it is inseparable from the drill body noise.

In the future, when tests for actual drill sound power output are performed, the drill steel noise will be eliminated by removing the steel from the test. This will be accomplished by using a "dead block." The dead block is simply a device that can absorb and dissipate the energy produced by the drill, usually in the form of heat. The drill will be coupled to the dead block by a very short section of steel that will be acoustically isolated from the test environment. For the present, however, the dead block is not being used so the effect of the drill steel can be observed as it occurs in the actual operation of the drill.

Research by Hawkes (12) shows that noise produced by the drill steel is caused primarily by bending waves in the steel. These bending waves occur at many frequencies above a critical frequency and are calculated by the formula

$$f_B = \frac{n^2 \quad DC_s}{8 \ L^2} \ [1-1.2(nD/L)^2],$$

where f_B = bending wave frequency, Hz,

n = mode number (1 for first critical frequency),

D = drill steel diameter, in,

L = drill steel length, in,

and C_s = speed of sound in drill steel, 2×10^5 in/s.

These bending wave frequencies are spaced sufficiently close together to produce noise in all 1/3-octave bands above the initial frequency.

Note in the above equation that the bending wave frequencies are directly related to the length of the drill steel; the longer the steel, the lower the first critical frequency. The drill steel used in the tests of the percussion drills was 10 ft in length, resulting in a first critical frequency of approximately 5 Hz, well below the 1/3-octave band centered at 31.5 Hz. The contribution to the overall noise level occurs in all bands measured but is considerably larger at frequencies above 2,000 Hz (fig. 23). This is of particular importance up to 4,000 Hz because of the potential effects on hearing loss. The noise levels drop over the course of a test due to the entrance of the drill steel into the hole. The section of steel that has penetrated is shielded from the test environment, and the overall contributution of the steel is thus reduced.

This type of information is particularly useful when designing noise controls for drills or when attempting to develop noise-controlled operating procedures. The time effects would be difficult to observe with traditional data collection methods but are easily noted by the regularly spaced intervals of data provided by the test fixture's data collection system.

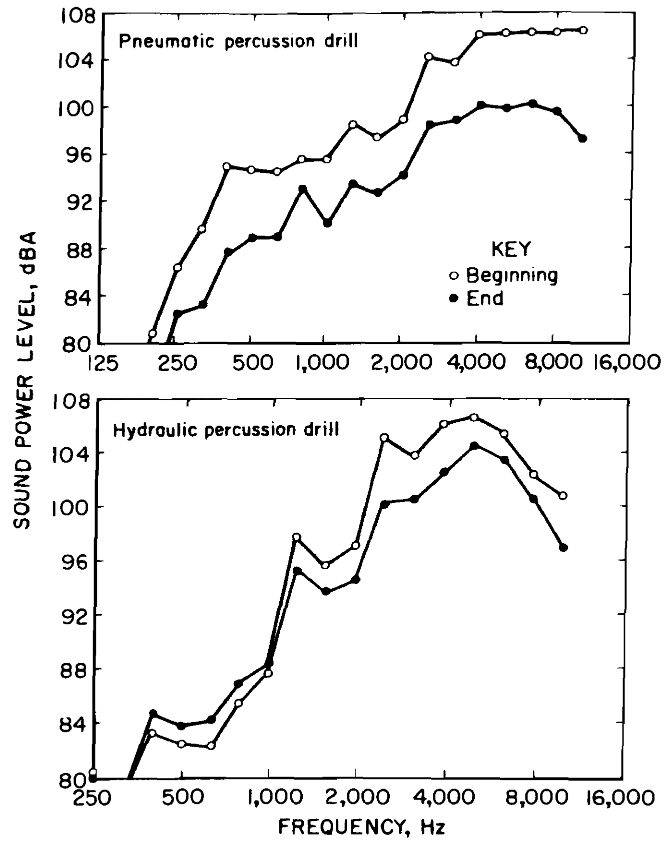


FIGURE 23.—Frequency spectra for percussion drills, beginning versus end of hole.

ROTARY VERSUS PERCUSSION DRILLS

A pneumatic rotary drill, the ALMINCO Gopher, was also tested on the drill test fixture. The intended uses of the Gopher are roughly the same as for the two percussion drills; however, rotary drills operate at higher thrust levels than percussion drills. This fact, combined with the different control demands of a rotary drill, allowed the test fixture to be operated over a greater range of thrust values than when testing percussion drills alone. The Gopher drilled at a rate of 1.57 ft/min under an average thrust of 521 lbf during the test selected for comparison. The data retrieved from the tests of the rotary drill provide some interesting contrasts to both of the percussion drills.

The sound power spectrum of the rotary drill is similar to that of the pneumatic percussion drill from the standpoint of the pneumatic exhaust, but it differs from those of the percussion drills in the relatively minor contribution of drill steel noise. These observations are evident in figure 24. The portion of the spectrum from 200 Hz to 1 kHz is greater in level for the two pneumatically powered drills than for the hydraulically powered drill. The greater contribution by the drill steel of the percussion drills can be seen at 2 kHz and above. The absence of drill steel noise is also shown in the sound power levels taken at intervals during the test. The overall levels for the rotary drill differ by less than 1 dB from beginning to end, and the average spectra are approximately the same (fig. 25), indicating that noise radiated from the rotary steel is not a major contributor to the overall noise level.

Another good example of the types of phenomena that can be observed is illustrated by the shape of the average test spectra (fig. 24). A potential problem with the rotary drill is revealed near the center of the graph. It can be noted from the graph that the portion of the spectrum from which a majority of the noise is produced is in a relatively small range that differs from the predominant noise of the percussion drills. The span of frequencies in the 1/3-octave bands centered from 800 to 1,600 Hz contains over half of the total sound energy. These frequencies overlap the range of human speech. Hearing loss at these frequencies greatly impacts functional hearing ability. Based on the observation of overall levels alone, or even individual narrow band spectra produced from recordings of field test, one may conclude that the rotary drill is less of a noise problem than the percussion drills; however, by examining the operation of the drill more closely, it can be seen that a more thorough investigation of the sources is necessary.

The positive side to this particular observation is that the peak noise produced by the rotary drill has more potential solutions than the noise produced by the percussion drills. The frequency range of the noise, along with information about the operating principles of the drill, suggests that the noise arises from the gear motor that drives the

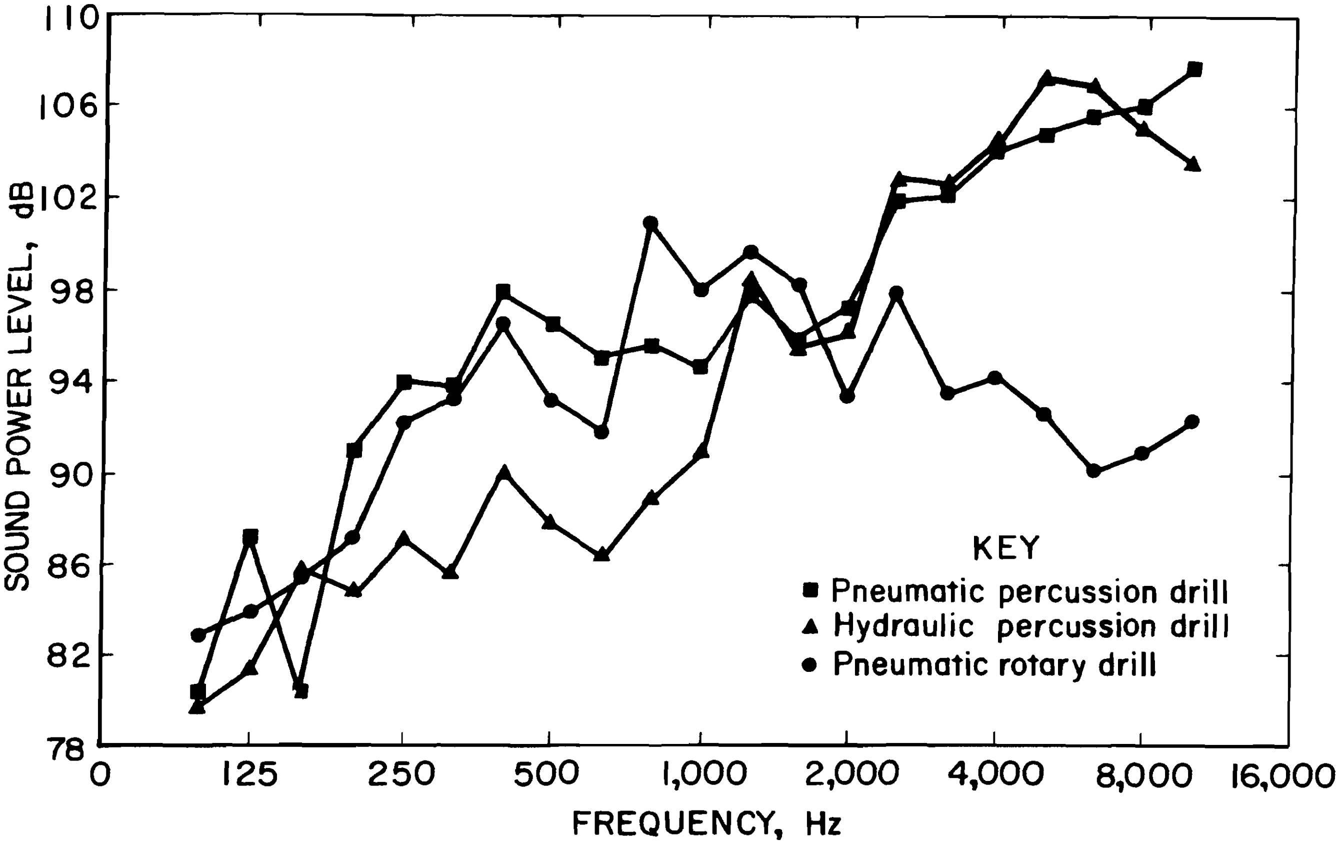


FIGURE 24.—Average frequency spectra: pneumatic and hydraulic percussion drills, pneumatic rotary drill.

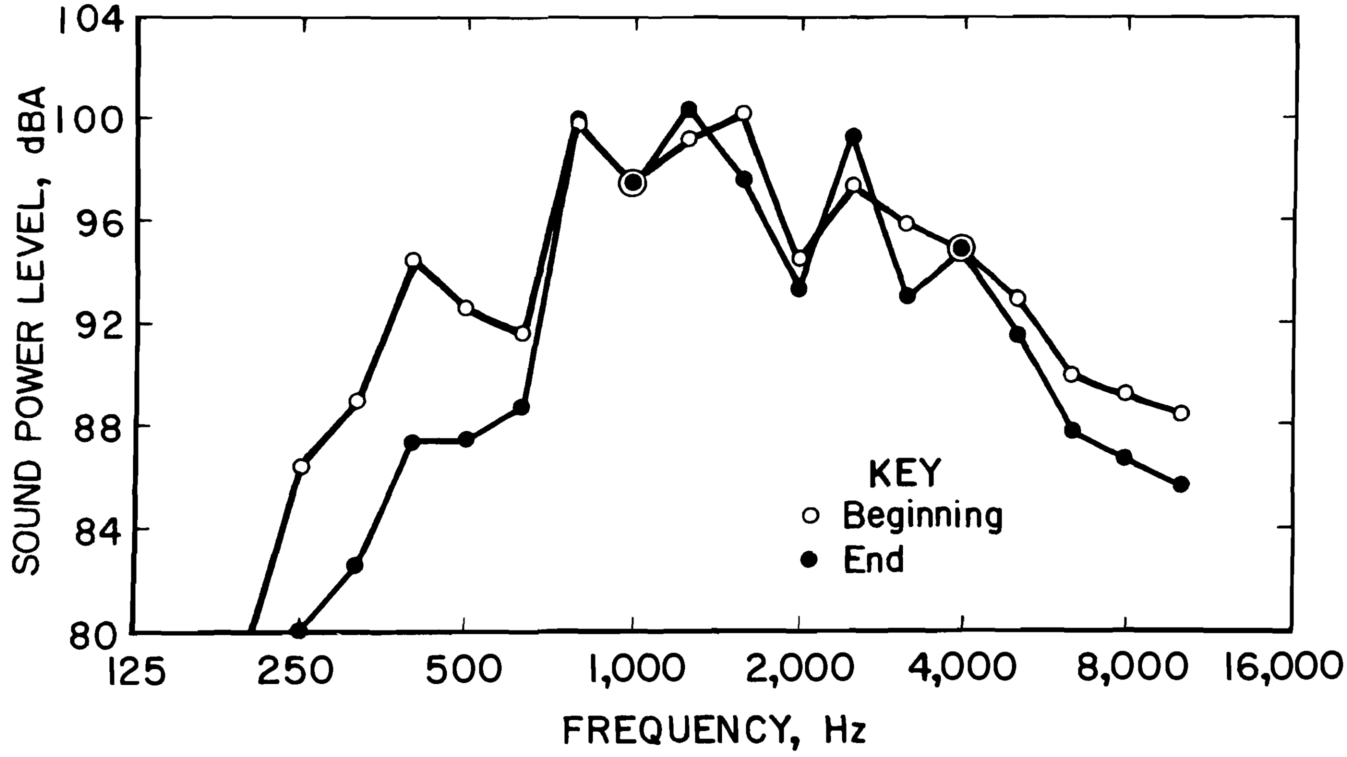


FIGURE 25.—Frequency spectra for pneumatic rotary drill: beginning versus end.

drill. This type of noise can sometimes be attenuated by redesigning the rotors and reduction gears to shift the frequency into a more tolerable range.

It should be pointed out again that these are merely observations of selected test data and are in no way statistically representative of the way the drills behave, especially in terms of penetration rate.

DISCUSSION

The automated drill test fixture is a very powerful tool for studying the noise characteristics and operational performance of percussion and rotary drills. The unique feature of the ADTF is that it is housed within a large reverberation chamber to allow the easy calculation of drill sound power levels. Sound power data are not usually provided by drill manufacturers, so the ADTF can supply drill users with information that has previously been unavailable. If noise is a consideration when selecting a drilling system, this information can be very valuable.

The ability to achieve control over all important drill operating parameters is a key advantage of the ADTF. Test conditions can thus be reproduced exactly or changed to study the effect of one or more parameters on the overall performance of the drill. Diagnostic work of this type can provide useful information on drill penetration rate as well as noise. The ability to change drilling media is very important when examining drill penetration rate. Each drill must be tested in the medium for which it was designed (soft, medium, or hard rock) in order to make valid comparisons of drill penetration.

Initial tests conducted with the ADTF confirmed that it is capable of achieving the desired process control and data recording functions. The data analysis software greatly facilitated the interpretation of these initial tests. General observations were made with respect to the noise produced by pneumatic percussion, hydraulic percussion, and pneumatic rotary drills. A much more extensive testing program with each of these drills must be conducted before definitive comparisons can be made.

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