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TILTMETER INSTRUMENTATION FOR DEEP HOLE OPERATION

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13. ABSTRACT

Extensive field tests with the first deep-hole tiltmeter system (DBT-1) have been completed and a second system (DBT-2) is being made ready for tests at the shallow test borehole at Bedford, Massachusetts. Problems encountered with cable generated noise and drift have been resolved by using a chain-type cable decoupler and a four-point contact holelock modification. Several improvements have been made on the DBT-2 control electronics and the downhole electronics of the DBT-1 was rebuilt to become identical with the improved downhole electronics of the DBT-2 system. The pressure casing of the second downhole package was fabricated of Armco type 22-13-5 stainless alloy (Monel K-500 was used in the No. 1 unit) and both holelocks are made of type 316 stainless steel. Two lengths of 7-conductor, armored cable (316 stainless armor) have been ordered and received from the Vector Cable Co. They are 2300 and 5300 ft. long, wound on a special tandem reel built by the mobile Drilling Unit of the Army Corps of Engineers for a modified power winch supplied by them. These items are presently at the Stone Canyon, California test site where the above Unit is drilling two 2000 ft. boreholes for the tilt and strain experiment.

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SEMI-ANNUAL TECHNICAL REPORT

15 December 1971 through 14 June 1972

TILTMETER INSTRUMENTATION FOR DEEP HOLE OPERATION

Sponsored by

Advanced Research Projects Agency

ARPA Order No. 1584

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Arthur D. Little, Inc.

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IDENTIFICATION

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Telephone No.:	(617) 8645770

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I. SUMMARY

Extensive field tests with the first deep-hole tiltmeter system (DBT-1) have been completed and a second system (DBT-2) is being made ready for tests at the shallow test borehole at Bedford, Massachusetts. Problems encountered with cable generated noise and drift have been resolved by using a chain-type cable decoupler and a four-point contact holelock modification. Several improvements have been made on the DBT-2 control electronics and the downhole electronics of the DBT-1 was rebuilt to become identical with the improved downhole electronics of the DBT-2 system. The pressure casing of the second downhole package was fabricated of Armco type 22-13-5 stainless alloy (Monel K-500 was used in the No. 1 unit) and both holelocks are made of type 316 stainless steel. Two lengths of 7-conductor, armored cable (316 stainless armor) have been ordered and received from the Vector Cable Co. They are 2300 and 5300 ft. long, wound on a special tandem reel built by the Mobile Drilling Unit of the Army Corps of Engineers for a modified power winch supplied by them. These items are presently at the Stone Canyon, California test site where the above Unit is drilling two 2000 ft. boreholes for the tilt and strain experiment.

II. FIELD EXPERIMENTS

In the period from December 15 through April 27, 1972, field experiments with the first deep hole tiltmeter system (DBT-1) have been completed at the Bedford, Massachusetts test site. A total of 5800 hours of continuous operation has been accumulated with DBT-1 since the downhole package was placed in the test borehole.

The experience gained in these tests lead to various changes that have been incorporated in the second system (DBT-2) which was in the design and construction stage during that time. The principal conclusions derived from the field tests are summarized below.

- Temperature inversion generates convective instability in the borehole which causes swaying of the armored cable, which inturn transmits tilt noise to the downhole package.

- Convective instability can be eliminated by increasing viscosity of the well fluid.

- Downhole package can be effectively decoupled from the cable noise by inserting a highly compliant section (chain and limp cable) between it and the armor termination.

- The observed tilt drift results from slow movement (settling) of the holelock of the downhole package in the casing. This can be eliminated by providing a four-point contact of the casing wall.

- The two confined-ring teflon seals used in the downhole package are perfectly leak tight, both at high temperatures and pressures as well as at temperatures well below the lowest expected use conditions.

- The digital electronics, both in the downhole and uphole units tend to become unreliable at temperatures near and below the freezing point; line transients also tend to cause the electronics to malfunction. The causes of these conditions have been located and eliminated.

- Automatic data acquisition on punched tape was found most useful and convenient for further processing. However, recording at fixed sampling intervals is a severe drawback when random events (e.g. seismic) are of interest.

In addition to the conclusions from the field tests stated above, other developments contributed to further modifications in the systems. Some of the more important developments that occurred in the program are listed below.

- The decision to make the first application of the two deep hole tiltmeter systems at the Stone Canyon site at San Andreas fault.

- Limited availability of wells suitable for tiltmeter emplacement in oil fields--possibly one well only in the Los Angeles area.

- Change in well use plans: only plugged wells or wells cemented at the bottom would be used. Such wells can be bailed and refilled with inert or inhibited fluids, thus reducing the severity of corrosion.

- Change in the scope of the present program including reduction of the number of deep hole tiltmeter systems from three to two.

- Availability of the equipment and personnel of the Army Corps of Engineers Drilling Unit at the Stone Canyon site.

Based on all considerations stated above the following changes have been made.

(1) Tilt sensors for the second downhole unit have been modified to have greater sensitivity required for measurement of small tectonic tilt changes.

(2) Data acquisition system was modified to allow continuous analog recording of at least one tilt channel along with digital sampling of all channels at predetermined intervals.

(3) The case of the downhole package of the DBT-2 unit was made of stainless steel rather than Monel.

(4) Both downhole cases have been provided with inserts for four-point contact with the well casing when locked in position.

(5) Two downhole cables, 2300 and 5300 ft. long have been ordered with stainless steel armor.

(6) Placement of the downhole packages at Stone Canyon will be made with the assistance of the Corps of Engineers crew and using the rig, winch and other equipment.

(7) Orientation of the downhole packages is to be determined using a borehole TV camera supplied and operated by the Corps of Engineers.

Details of the work performed are given in the following sections.

III. MECHANICAL MODIFICATIONS

A. MATERIAL

At the inception of this program, the intended use of the instrument in any existing borehole with unknown chemical conditions demanded the use of the most corrosion resistant material for the pressure casings that also possessed the requisite strength for operating perssures of 5000 psi. Monel K-500 served the purpose adequately. Obtaining the material and processing by machining and heat treating proved to be a laborious task. When the requirements were relaxed with regard to the corrosive environment a different material was considered. The Armco alloy type 22-13-5 was chosen because of its corrosion resistance. In this respect it is better than type 316 stainless and more importantly, its yield strength ($\sim$ 65,000 psi, annealed) is approximately twice that of 316 stainless. While this is less than the yield strength of the heat treated Monel K-500, the strength of 22-13-5 is adequate for the operating pressure of 5000 psi with a safety factor of 1.85.

B. DESIGN CHANGES

The new material was available only in solid bar form so the design was changed to reflect a one-piece construction rather than a two-piece welded construction. The strength performance was not affected in any way by either construction method since the weld or transition was located at a thick wall where lower stresses are developed.

The only other change in the DBT-2 pressure casing construction was the elimination of the purge and vent holes which were provided in the DBT-1 unit. Condensation proved not to be a problem and the elimination of two seals enhances the reliability of the system.

The first holelock purchased for development work was a modified standard Teledyne Geotech holelock wherein the wall thicknesses and collar diameters were enlarged to accommodate our particular design requirements. The material was nickel plated tool steel. For field use of DBT-1 and -2, two stainless steel (316) holelocks were purchased, identical in design to the development model. Only the locking cam was made of 17-4 PH steel as a compromise to the conflicting requirements of high strength (and hardness) of the teeth and corrosion resistance.

As a result of the tests at Bedford, it was determined that a four-point contact was necessary for the holelock to maintain a stable position inside the well casing. Consequently the "as-received" modified holelocks are to be modified further by the installation of three ball-ended buttons on the side of the holelock opposite the cam. With the cam these buttons create the four-point match with the inner diameter of the casing. Two of these buttons are to be located in the upper collar at ±45° opposite the centerline of the cam and one in the lower collar, directly opposite the cam.

The stainless holelock (Serial No. 062) with four-point contact, the 22-13-5 Armco pressure case and the DBT-2 tiltmeter with electronics will be trial tested in the 100 ft. test hole in Bedford, Massachusetts.

C. CABLE ROTATION

The series of Bedford tests indicated a definite need for mechanical decoupling to prevent downhole cable motion of whatever cause, from perturbing the tiltmeter.

Also anticipated was the need to accommodate the unlaying (twist) of the cable due to the unloading of the instrument weight from the cable after the instrument was locked to the hole casing. The chain and limp cable arrangement developed earlier (Figure 1) was also expected to provide this torsional decoupling. Vector Cable Co. was asked to perform rotation and elongation tests on a sample 25 ft. of cable cut from our order of stainless cable. The tests showed that there would be between 12 and 19 degrees of rotation per 25 ft. of cable due to unloading, independent of the total cable length suspended from the ground. The 10 ft. of chain used in the present setup will accommodate the worst case of ten full turns that will be experienced for 5000 ft. of the longest cable. The elongation data will determine the exact process of cable payout, after locking is completed, to account for both twist and elongation. The downhole cable end connector was specified to Vector Co. to allow the 10 ft. of chain to be connected to the armored termination, 10 ft. below which is the electrical termination. Thus the armored or load carrying connections and electrical connections are independent in function and separated in space.

Mr. Charles Thurber reviewed our design approach and pursuant to his recommendations, two modifications to the instrument top split ring will be effected. One involved cutting a tapered thread and groove to allow recovery with common fishing tools if the instrument was lost down hole. The second requires a "weak link" to exist in the chain assembly at its lowest part to insure that the load carrying structure will break so as to leave no chain or armored cable in the hole. Thus the instrument becomes "clean" and easier to recover. The "weak link" will be provided by reducing the cross section of one of each of the last links of the pair of chains. These links are made of 318 in. rod and the reduced cross section will have a load capacity equal to about 10 times the instrument weight, which is approximately 400 pounds. The total original breaking strength of the pair of chains is about 20,000 pounds and the ultimate strength of the armored cable is 18,000 pounds. The spread of loads will be sufficiently large to insure that the "weak links" will break first.

FIGURE 1 VIEW OF CHAIN-TYPE CABLE DECOUP[illegible]

IV. INSTRUMENTATION

A. TILTMETERS

A total of three downhole tiltmeter assemblies have been completed. All of them are essentially of the same type and construction as described in our first Annual Technical Report of June 14, 1971. Each unit contains two tilt sensors, mounted orthogonally in gimbals that can be leveled by remotely controlled motors over a range of ±7°. Auxiliary circuits, control relays, limit switches, end-of-range level indicators and thermistor sensors are also included in the assemblies. Minor changes in the mechanical support structure have been made in units No. 2 and 3, but the principal dimensions and electrical parameters were maintained so that all three assemblies are interchangeable.

Since only two complete DBT systems have been built, one of the three tiltmeter assemblies will serve as a spare. The physical configuration of the new assemblies (No. 2 and 3) is shown in Figure 2. Tilt sensors in the No. 2 and 3 units were built so as to have inherently higher sensitivity than those in the original No. 1 unit. After the completion of field tests the sensitivity of the No. 1 units was increased somewhat by a change in the preamplifier circuits.

Summary of the calibration results made on the three tiltmeter assemblies (at 22°C) is given in Table I. Since the sensitivity of the tilt sensors varies with temperature, the complete assemblies, No. 1 and 2, were recalibrated over a temperature range from 20° to 75°C. The results are shown in Figure 3. At the same time we measured the shift of the instrument zero as a function of temperature over the same range. The results are plotted in Figure 4.

B. ELECTRONICS

The uphole control electronics of the DBT-2 System differs somewhat from the No. 1 unit and therefore it is reviewed here breifly. The block diagram of the entire system is shown in Figures 5 and 6. These figures apply to both systems DBT-1 and DBT-2, except where indicated. Unit No. 2 allows selection of either tiltmeter axis to be read out analog fashion on a chart recorder during the time between automatic printout and punching of the data at selected intervals. No. 1 does not have this capability. Both units can monitor any one data channel analog fashion at the sacrifice of automatic printing and punching of data at aslected time intervals. The layout of the control panel of the No. 2 unit, which differs slightly from the first unit, is shown in Figure 7. The digital clock and digital voltmeter (DVM) are of a different type than in the No. 1 unit. They both use solid state digital displays rather than neon

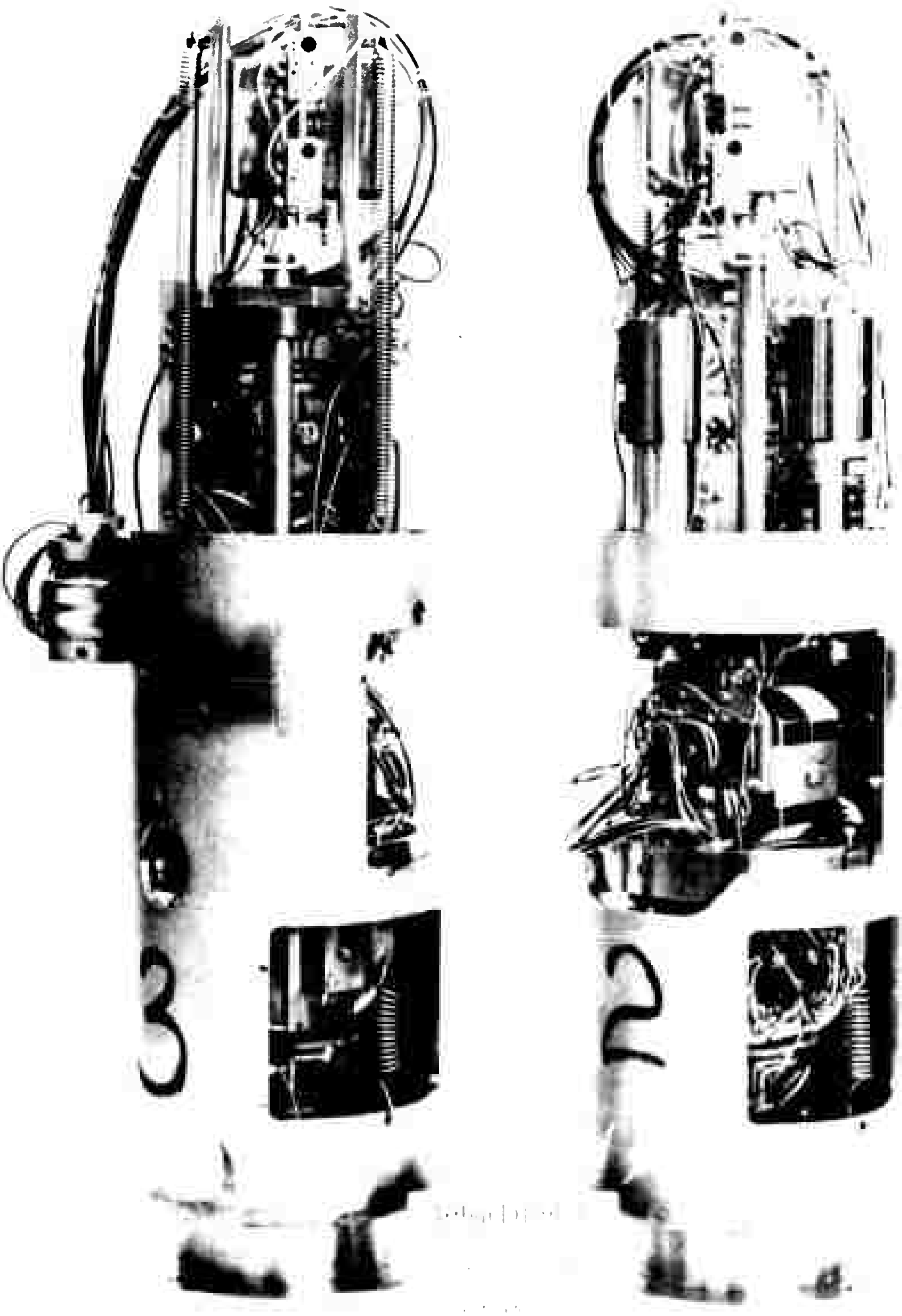

FIGURE 2 VIEW OF DOWNHOLE TILTMETER ASSEMBLIES NO. 2 AND 3

TABLE I

Summary of Electrical Parameters
of Tiltmeters Used in Downhole
Units Nos. 1, 2 and 3 (at 22 °C)

Unit No.	Sensitivity (mv/μrad)	Range (stop to stop, μrad)	Offset Voltage* (volts)
X-1	8.10	-770 to 810	+2.753
Y-1	11.0	-740 to 500	-3.276
X-2	14.0	-320 to 220	+0.325
Y-2	17.5	-570 to 200	-2.808
X-3	12.7	-340 to 400	-0.674
Y-3	12.6	-440 to 300	+2.213

* This is a voltage used for checkout purposes with the "Lamp-Off" command.

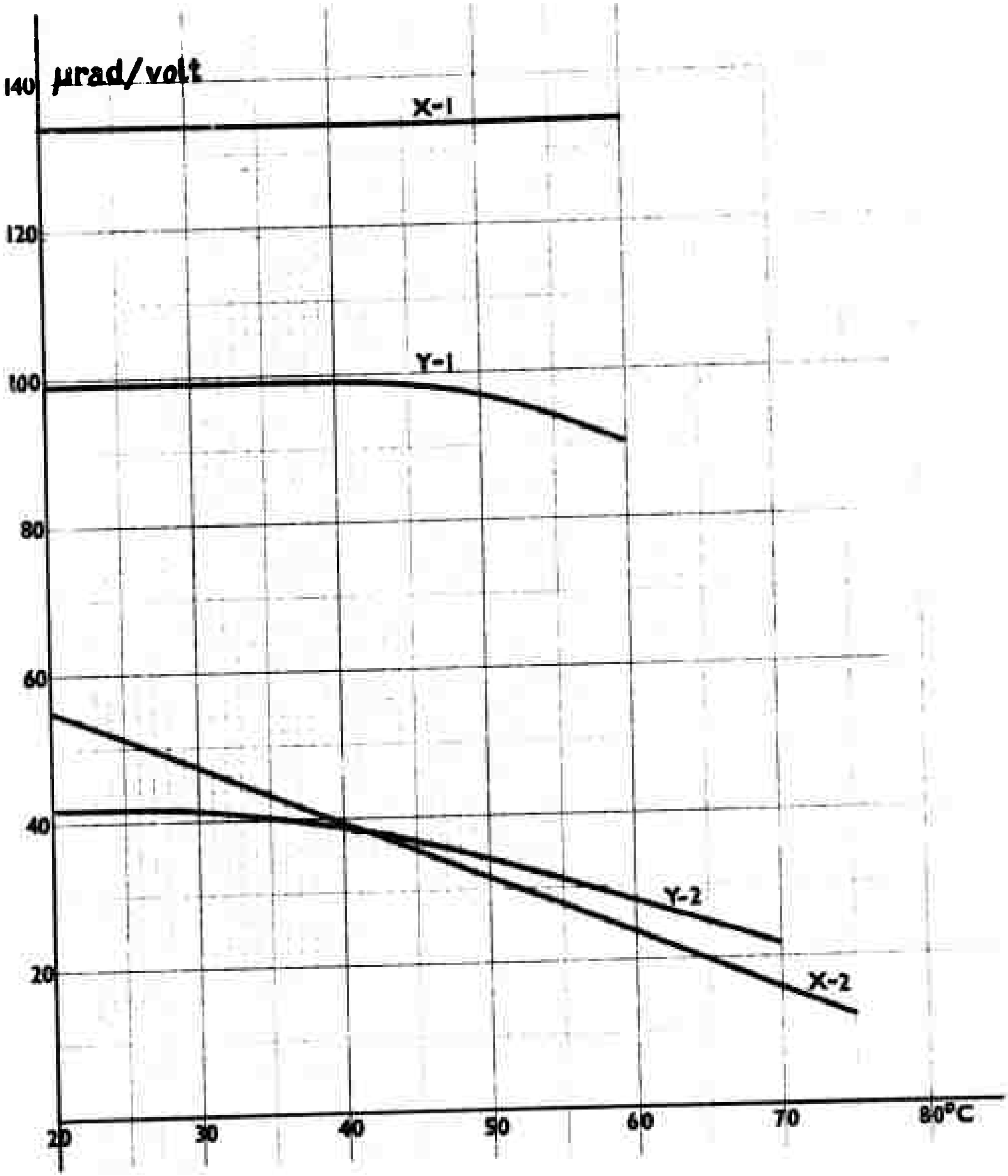

FIGURE 3 TILT CALIBRATION CONSTANTS OF COMPLETE UNITS NO. 1 AND 2 AT ELEVATED TEMPERATURES

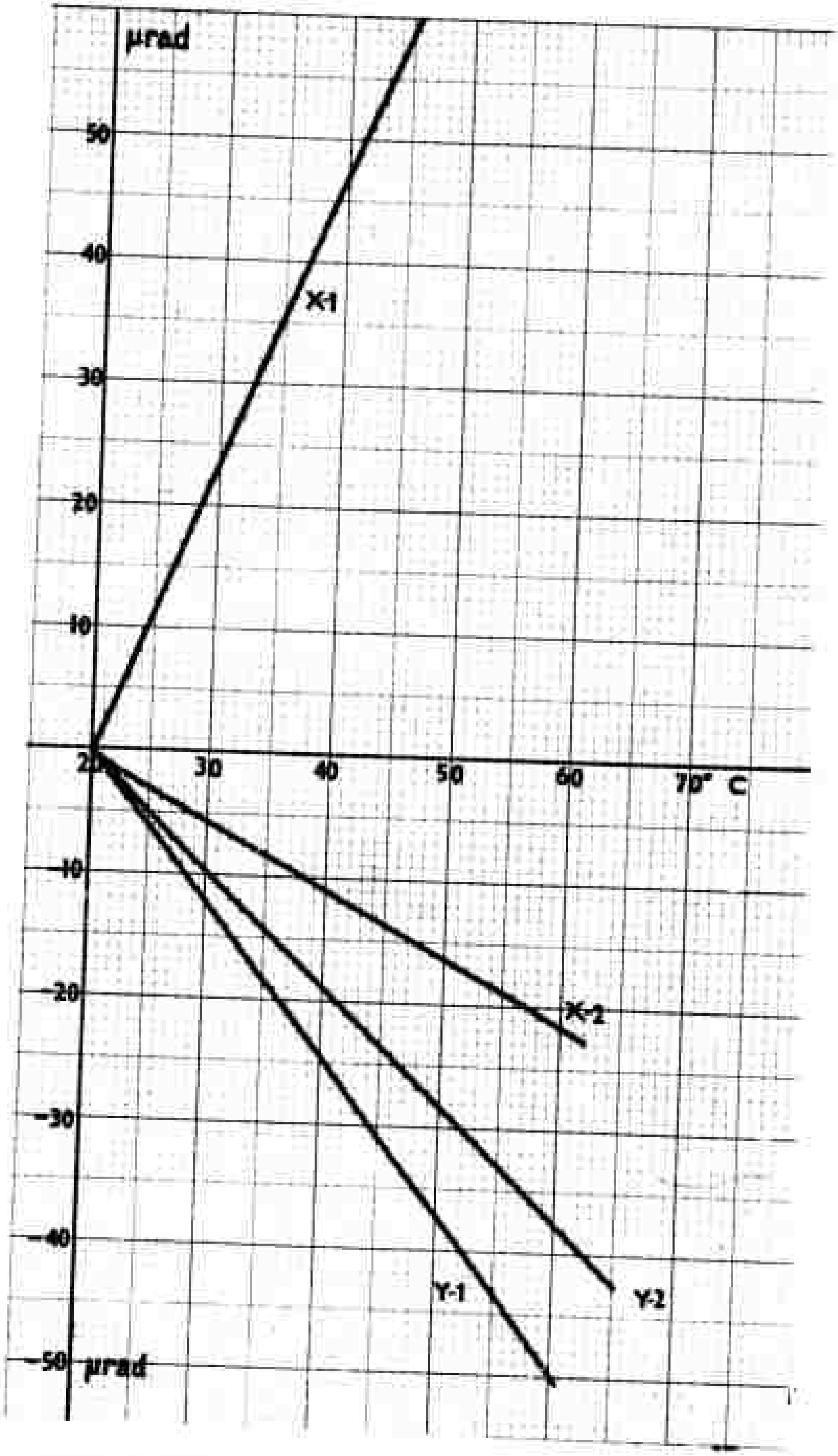

FIGURE 4 APPARENT ZERO SHIFT OF UNITS NO. 1 AND 2 AS A FUNCTION OF TEMPERATURE

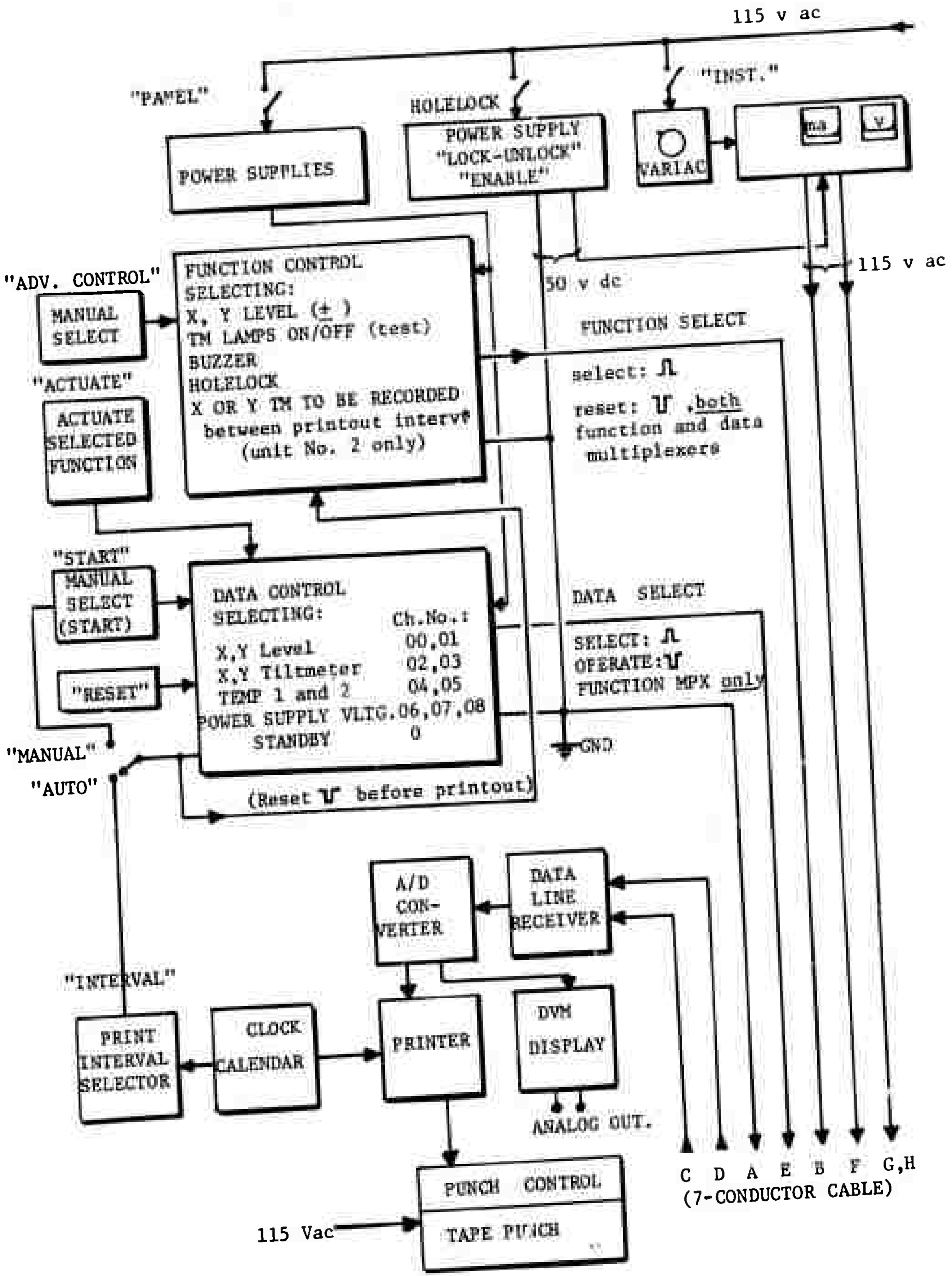

FIGURE 5 CONTROL PANEL - No. 2

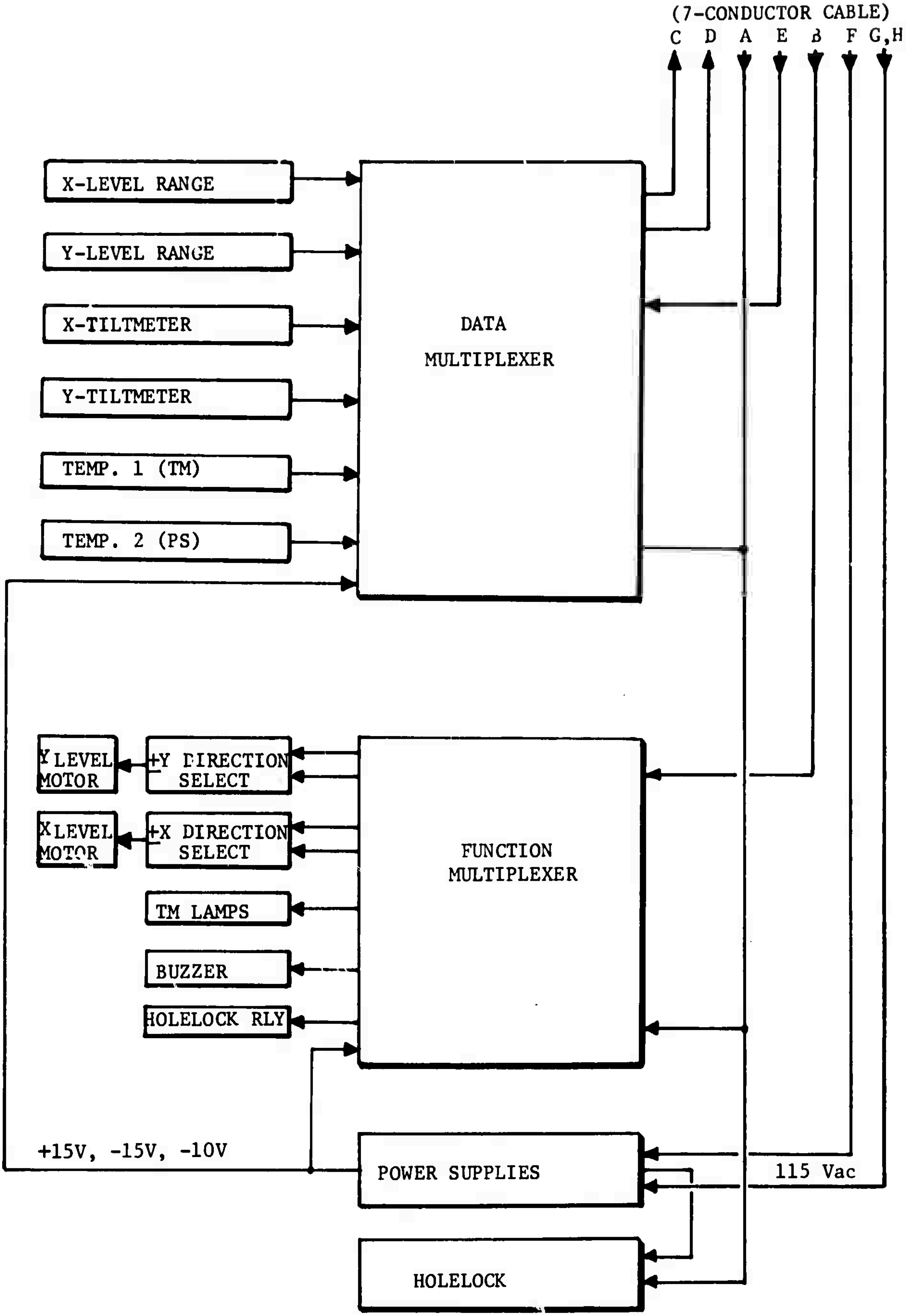

FIGURE 6 DOWNHOLE ELECTRONICS - No. 2

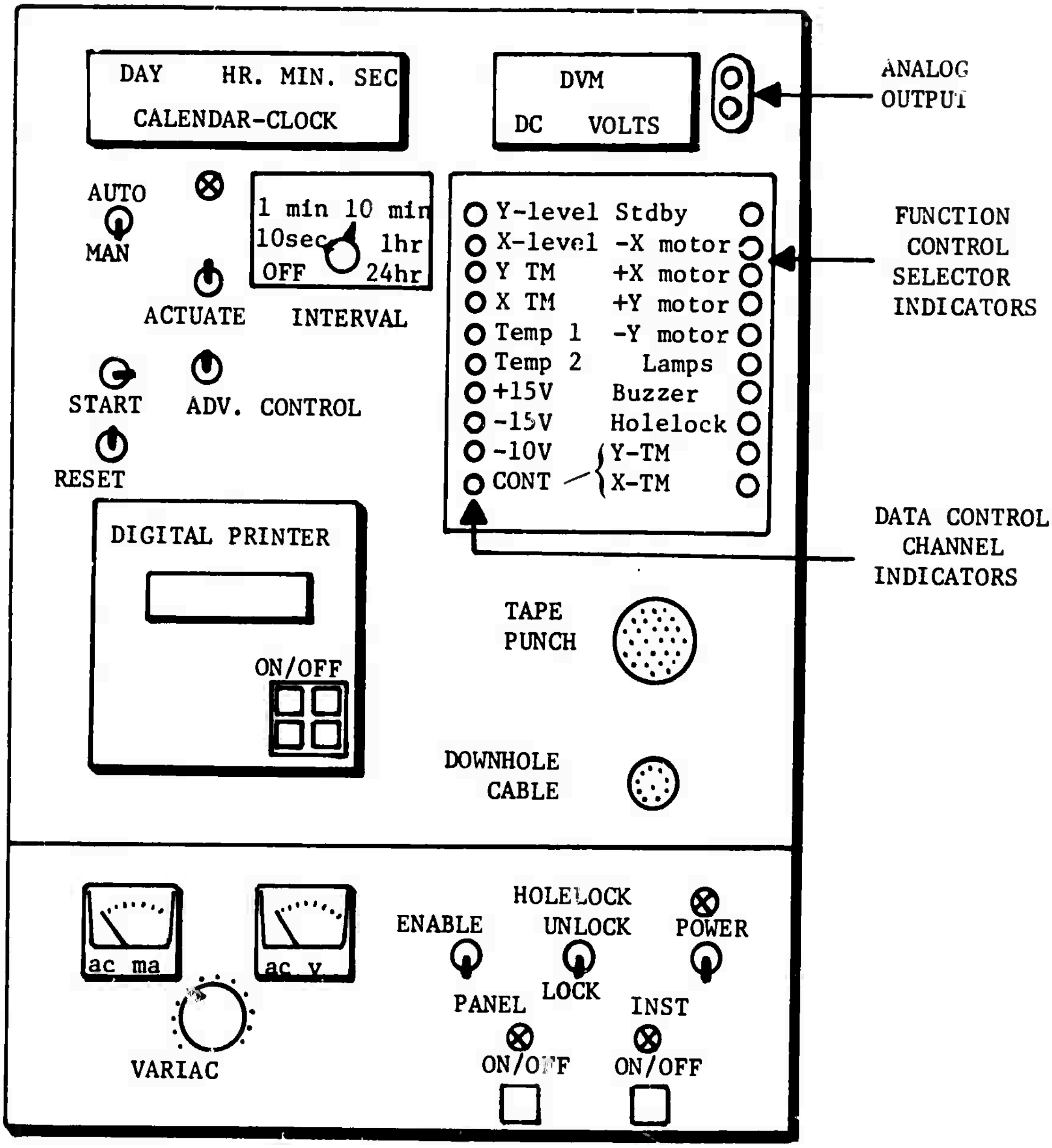

FIGURE 7 DBT-2 CONTROL PANEL

(Nixie) tubes and the clock can be read and set from the front. These new components are believed to be more reliable than those of the No. 1 unit.

There are two modes of operation of the system, automatic and manual. When AUTO-MAN switch is switched to automatic, the printout cycle is initiated by an output from the digital clock at intervals selected by the readout INTERVAL selector switch. When the automatic cycle is initiated, the counters controlling the data multiplexers and control selection are "cleared"; the printer advances paper three or four lines and a "trigger" pulse is transmitted to the analog-to-digital (A/D) converter which initiates an internal digitizing cycle. At the end of the digitizing cycle the A/D converter transmits the "End of Conversion" (EOC) pulse to the data control card which transmits a "hold" signal to the digital clock and the A/D converter and a "print" signal to the printer and at the same time advances the data multiplexer counters in the panel and in the downhole package by one step. When the printer has printed one line it advances the paper and transmits the "End of Print" (EOP) pulse to the data control card which begins the A/D cycle again. When the last channel is selected the EOP pulse is blocked and the next A/D cycle is not begun until a new sequence is originated by the clock or by the START switch (manually). Note that at the end of the automatic sequence the display is switched to channel 09. Operating the RESET switch resets the data and the function control counters.

Channel 09 is not connected in unit No. 1. In unit No. 2 channel 09 connects to either X or Y tiltmeters as selected by the function control for analog recording. Channel 09 is the "home" or standby position for the automatic cycle.

When AUTO-MAN switch is switched to the manual mode, actuating the START switch advances the data control counter. Thus, any of the data channels can be monitored continuously. In this mode the INTERVAL selector switch must be in the "OFF" position and the multiplexers must be started from the "home" position which is accomplished by operating momentarily the reset switch. When AUTO-MAN switch is in the manual position and INTERVAL switch is not in the "OFF" position the system will print the displayed data and advance the data counter one channel at each selected time interval.

The function control system permits the following operations under the control of the panel operator:

1. remote level in direction +Y
2. remote level in direction -Y
3. remote level in direction -X
4. remote level in direction +X
5. turn off tiltmeter lamps
6. turn on buzzer (vibrator)

7. operate relay to connect holelock

*8. connect Y-tiltmeter for analog recording between print intervals

*9. connect X-tiltmeter for analog recording between print intervals

(* The last two operations are provided in the No. 2 unit only.)

Each triggered automatic cycle of the data control system "clears" the function control counters in the panel and downhole circuits so that no function is selected. The purpose of this is to reduce the likelihood of accidental operation of any of the downhole functions. The control function counters are advanced by means of the ADVANCE switch. The selected function is operated by OPERATE in No. 1 unit and ACTUATE in the No. 2 unit.

The holelock activation system has a separate power supply (50 V dc) for the holelock motor and a series of interlocking controls which were originally provided as a security against accidental lock release. We found in actual use that the risk of accidental unlocking is negligible since the downhole package, once locked in position is mechanically jammed in the borehole and cannot be released except by pulling on the cable.

The following paragraph describes the sequence of events required to operate the holelock when the downhole package is placed in the borehole.

i. set AUTO-MAN switch on "Manual"

ii. turn holelock POWER switch on

iii. operate RESET switch momentarily to reset counters

iv. operate START to advance the function control indicators to holelock

v. select LOCK position on LOCK-UNLOCK switch

vi. operate the function by ACTUATE switch

vii. turn on the holelock ENABLE switch. In this position the ac milliammeter will be indicating the holelock motor current (approx. 40 ma). The operation takes approximately 11(eleven) minutes to complete. At the end of this period the motor opens a limit switch and the current drops to zero.

viii. turn off holelock ENABLE switch and the POWER switch

ix. reset counters with RESET switch and start normal operation of the system.

The control panel circuits can be energized without applying power to the downhole package but not vice-versa (switches PANEL and INST). A.C. power at 117v is provided to the package via a Variac to permit partial compensation for line voltage drop whenever a very long cable is used between the panel and the downhole package. The a.c. voltage on the line is indicated on a panel meter. Since the cable used (Vector, type 7-46NT) has a resistance of 10 ohms per 1000 ft. for each conductor and the downhole package draws a current of 0.150 amps the voltage drop to be made up by the variac is approximately 3 volts for each 1000 ft. of cable length. In addition, the voltage regulators in the downhole package will tolerate a very wide range of a.c. input voltage. The outputs of the three voltage regulators at +15v, -15v, and -10v are printed out during each print-out cycle to indicate the conditions of the regulators and are also useful as references to check the operation of the entire data multiplexing system at each printout cycle.

The downhole electronics assemblies of the DBT-1 and DBT-2 systems are nearly identical and interchangeable. Assembly No. 1 was rebuilt after the tests at Bedford were completed using printed circuit boards of the same layout as in No. 2 unit; only the downhole power supply subassembly of the No. 1 unit remains of the original perforated board construction. The p.c. board construction is believed to be more reliable and simplifies replacement of subassemblies if necessary.

The terminals marked on unit No. 2 ANALOG OUT are provided for connecting an external recorder for continuous recording of the X or Y tiltmeter data as described earlier. These terminals are parallel to the input of the digital voltmeter and thus the voltage indicated by the DVM is equal to that at the terminals. This voltage is indicated on the display in volts with the sign and decimal point shown. The printout indicates the sign also, but the decimal point is not printed. Thus, for example a voltage indicated as +5.431 (volts) is printed out as +05431 vdc.

In the No. 1 control panel the situation is somewhat different: a voltage of +5.431 volts is displayed by the DVM as +5431 (no decimal point shown) and it is printed out as +05.431 vdc (decimal point shown). However, the voltage actually appearing at the ANALOG OUTPUT terminals is one-tenth of the DVM voltage, i.e., +0.5431 volts.

Caution is to be exercised in connecting the external recorder, lest any spurious voltage, ac or dc (higher than approximately 10 volts) be accidentally applied to the terminals. While the DVM itself is protected against overvoltage (up to 500v) the instrument amplifier (Burr-Brown, Mod. No.3165/25) which feeds it is not protected and can be easily damaged by overvoltage.

V. WORK IN PROGRESS

The complete second system (DBT-2) is being made ready for tests in the 100 ft. borehole at Bedford, Massachusetts. These tests are expected to continue through July 1972. After their completion both systems (DBT-1 and DBT-2) will be packed and crated for shipment to the site at Stone Canyon, California.

At the present time one hole is being drilled at that site by the Drilling Unit of the Army Corps of Engineers of Mobile, Alabama and another hole will be drilled at the same site after completion of the first hole. The first hole is intended for permanent emplacement of a deep-hole strainmeter presently under development by the Develco Corp. Since this instrument will not be ready until late 1972 one of the ADL deep-hole tiltmeter systems will be placed in hole No. 1 and left there as long as possible. The other ADL tiltmeter system will be placed in hole No. 2 and left there indefinitely. Thus, for some period of time two deep-hole tiltmeter systems will be operated simultaneously in two boreholes adjacent to each other.

Eventually, when the No. 1 borehole is called for to be occupied by the Develco strainmeter, the ADL deep-hole package will be removed from it and the tiltmeter system will become available for use at another test site, possibly in one of the oil fields in the Los Angeles area.

The placement of the ADL deep-hole tiltmeter packages in the holes at Stone Canyon will be made by the personnel of the Corps of Engineers Drilling Unit, making use of their drilling rig and a specially modified winch. Plans for this operation have been developed in discussions with Mr. David Childers of the Mobile Drilling Unit and are being carried out by his successor, Mr. Charles Cox, of the same office.

According to present estimates the first hole at Stone Canyon will be completed (with a 9 5/8 in. I.D. casing) early in August, 1972 and the ADL system will be installed some time later that month.

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