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DEVELOPMENT OF A THROUGH-THE-EARTH MONITOR SYSTEM

Contract H0177098
Arthur D. Little, Inc.

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16. Abstract

The object of this program was to design and build a self-contained system for remote monitoring of the atmosphere in mines. The system developed uses the mine pager phone line as the primary communication channel and also has the capability of using 208 Hz in the ELF band for wireless transmission through the earth. The depth for through-the-earth transmission is expected to be about 80 to 90 meters in high conductivity soil and is limited by the noise level in the ELF band-pass filters. The underground components of the TEM System are energized by mine power through a battery charger - storage battery power supply. In the event of mine power failure the battery capacity is more than sufficient for one week's operation with interrogations every four hours.

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FOREWORD

This report was prepared by Arthur D. Little, Inc., Cambridge, MA 02140 under USBM Contract Number H0177098. This contract was initiated under the Coal Mine Health and Safety Program. It was administered under the technical direction of the Pittsburgh Mining and Safety Center with Mr. Harry Dobroski as the Technical Project Officer. Mr. Doyne W. Teets was the Contract Administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period October 1977 to December 1980. This report was submitted by the authors in December 1980.

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INTRODUCTION

The objective of this program was to obtain a self-contained monitor data transmission system that uses existing mine wiring as the primary means of data transmission, but which can also transmit directly through the earth. This objective was attained in a three-phase program:

Phase I - Establish System Functional Requirements and Select Sensors

Phase II - Detailed Engineering Design

Phase III - System Fabrication and Performance Evaluation

The resulting Through-the-Earth Monitor System (TEMS) has a total capacity of 1,000 addresses and is under control of a central unit at which commands are dispatched and responses received. The TEMS, as delivered, has a single remote unit with sensors for fire, methane, and air flow.

PHASE I - ESTABLISH SYSTEM FUNCTIONAL REQUIREMENTS AND SELECT SENSORS

The primary design goal for the Through-the-Earth Monitor System was to provide a means to monitor from a surface station carbon monoxide, methane, and air flow at various places in a mine. Existing mine wiring, when available, was to be used for data transmission with direct signal transmission through the earth to be used otherwise. The wireline transmission scheme developed for the Visual Display and Control System (VDCS), phase inversion modulation of a 16 KHz carrier, was retained for the TEMS wireline mode. Other features of the VDCS were also retained, including the addressing and command formats and the data transmission protocol, so that both TEMS and VDCS remote units can be addressed by the TEMS control unit. Through-the-Earth communication is provided by an ELF data link. Unlike the VDCS remote units, the TEMS remote units are powered by a rechargeable battery which is kept charged by 115V ac or 270V dc mine power, when available.

Remote Unit Operating Modes

The following remote unit operating specifications were defined for the four combinations of wireline communication and mine power availability. It should be pointed out that different monitor units in the system can be in different modes at any given time.

Mode 1

Wireline communication and mine power are both available to the remote unit. This is the normal mode of operation. TEMS remote monitor units are fully powered-up continuously. They can be interrogated at any time, either manually or automatically (see below) and will send back their instrument readings immediately.

Mode 2

Wireline communication is available, but mine power is out at a given unit. That unit goes into a low power mode where only the front end of the communication circuits is active. When that unit is interrogated, it signals the surface that it has been powered-down, after which it goes into a four minute sensor warm-up cycle. After five minutes, the surface control unit will automatically re-interrogate it. After transmitting its instrument readings, it returns to the low power state until the next interrogation.

Mode 3

Wireline communication has been lost, but mine power is on at the remote unit. Communication is provided by the ELF channel which may require, because of the relatively short communication range of the ELF channel, that the control console and ELF antennas be moved to a surface location directly above the remote unit. Except for a signalling rate approximately twenty times slower, operation is the same as Mode 1.

Mode 4

Neither mine power nor wireline communication is available. ELF communication is used as in Mode 3, but the remote unit goes into a low power state between interrogations, as in Mode 2.

System Operating Modes

The TEM system was specificed to have three operating modes - Keyboard, Automatic, and Test. In the Keyboard mode, remote units are interrogated by manually entering addresses and commands on the console keyboard. Instrument readings are reported by NORMAL/ERROR LEDs on the console and printed reports on the TTY. Monitored variables outside a preselected range trigger an audible alarm. Supervisory verification of communications link integrity is provided and indicated as in the VDCS (1). In the Automatic mode, TEMS monitor units are interrogated automatically every five minutes according to a polling list in the controller memory. In both Keyboard and Automatic modes, CURRENT, OLD, and ERROR lists are maintained as in the VDCS. In addition, the TEMS maintains an ALARM list of all monitor units which have experienced alarm conditions. There is also a Test mode which permits various types of system diagnostics in the field. These modes are described in detail in the VDCS/TEMS Technical Manual (2).

Sensor Evaluation and Selection

After reviewing the state-of-the-art of carbon monoxide, methane, and air velocity sensors, J-Tec Associates, Inc. of Cedar Rapids, Iowa was selected on the following basis:

- Single source of supply for all three sensor types;
- Units are available and meet all performance requirements;
- Units operate at 12V dc and consume little power; and
- Units have been demonstrated in the field.

The VM-101 methane sensor detects methane concentrations in the 0 to 4% range and creates a 0 to 5V dc output directly proportional to methane concentration. The VA-216 air draft sensor converts air speed in the range of 50 to 1,500 feet/minute to a 0 to 5V dc output signal. Both of these units were designed and have been certified to be intrinsically safe. The CO-200 fire sensor detects carbon monoxide. Its output signal switches from a low (~0.5V) level to a high (~5V) level when the CO concentration exceeds 150 ppm. The CO-200 detector active element can become fouled, so a purge capability is provided. On receipt of a PURGE command the active element is heated slightly to drive off contaminants. During the 4½-minute purge cycle, a status output is provided to warn users that the instrument readings are invalid. Detailed descriptions of these instruments are contained in the VDCS/TEMS Technical Manual (2).

PHASE II DETAILED ENGINEERING DESIGN

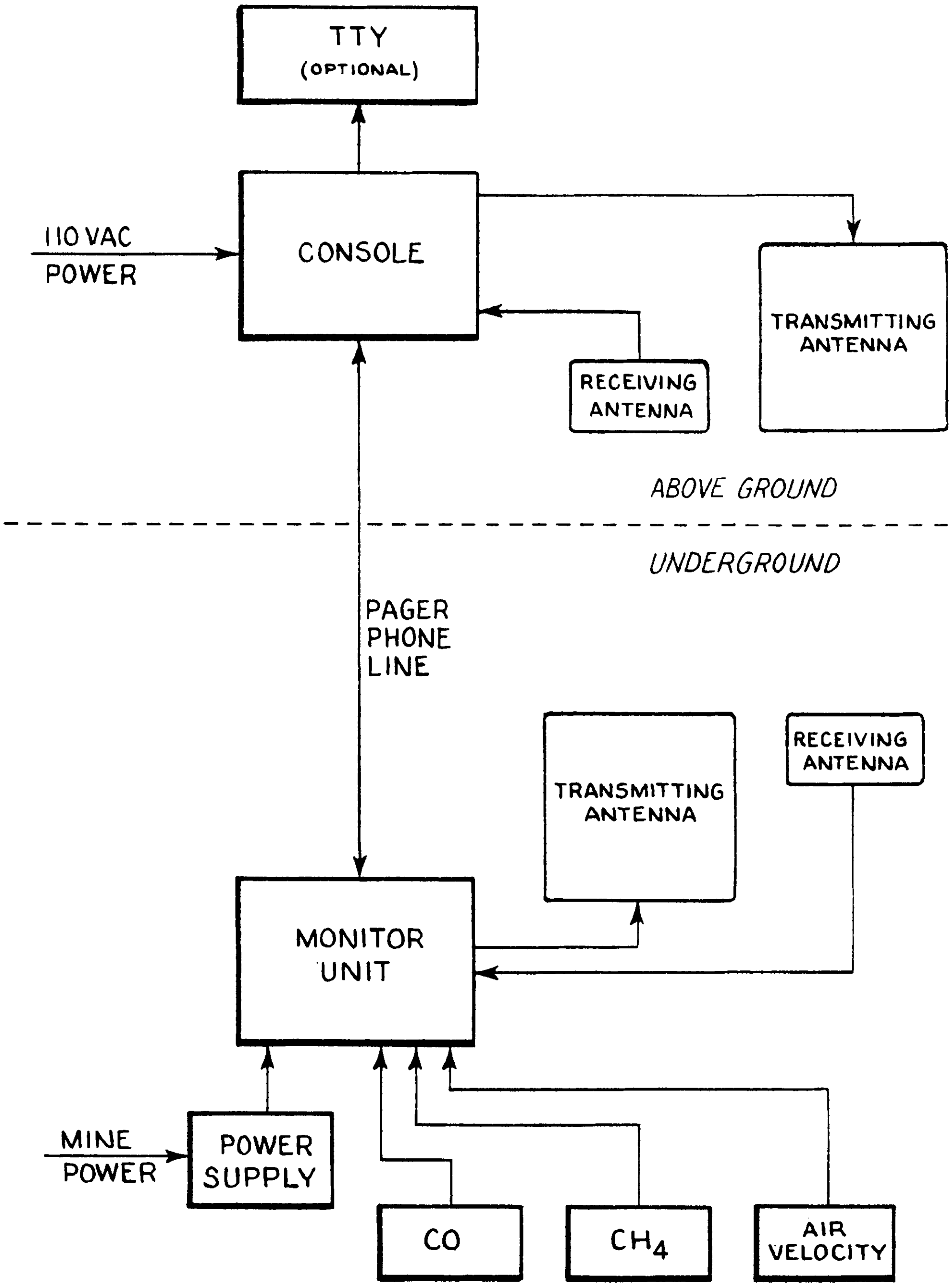
Figure 1 shows the interconnection of the components of this TEM system.

Figure 2 is a block diagram of the TEM system which evolved in response to the functional requirements developed in Phase I. The primary design activities in Phase II related to the ELF communication link, the ELF link interface to the wireline link, and the remote monitor unit. The wireline transceiver design is the same as the corresponding design in the Visual Display and Control System (VDCS) (1).

ELF Communication Link

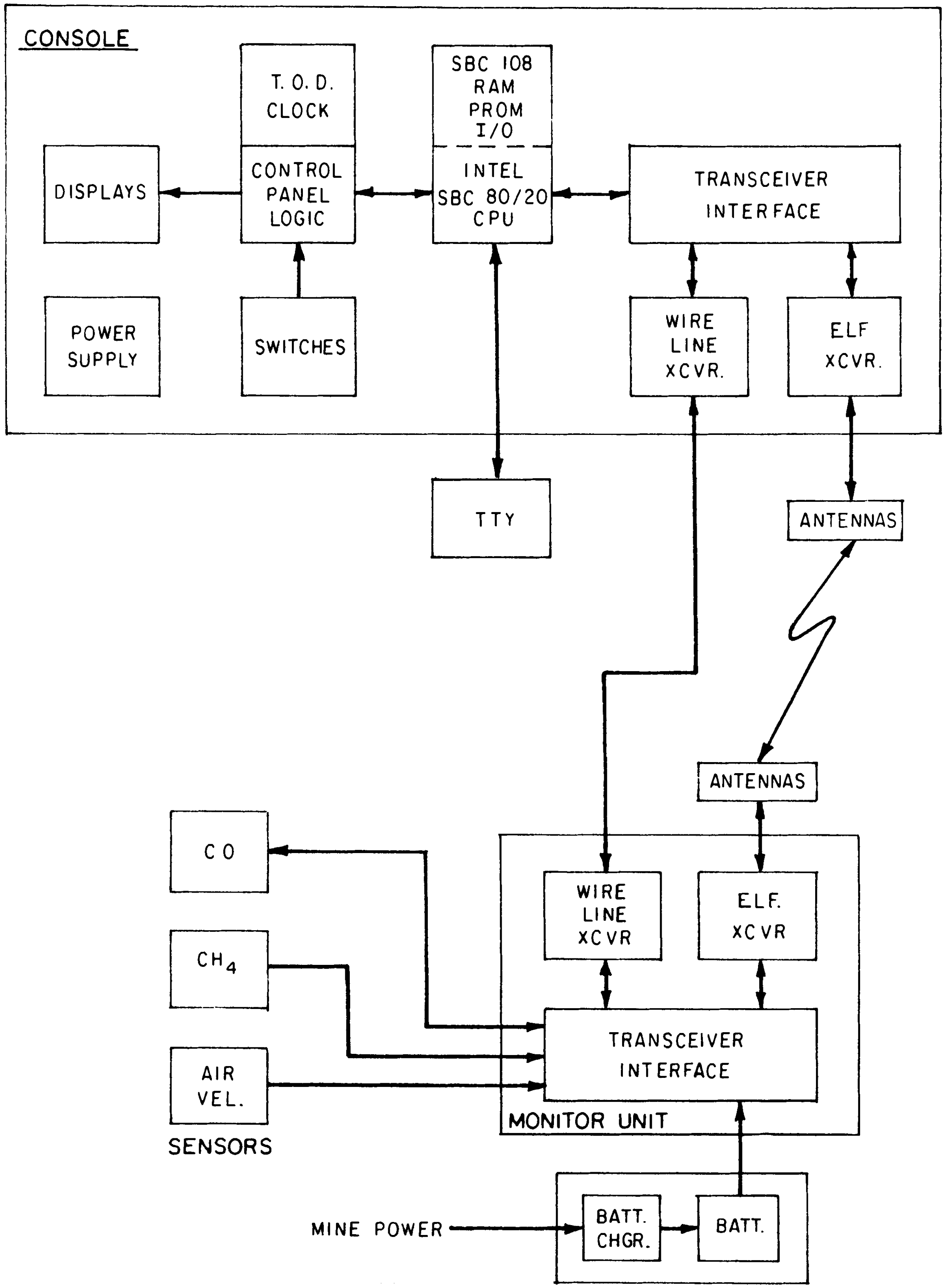
The design process, including parameter tradeoffs, is described in detail in the TEMS Phase II progress report (3) and is summarized here. The Sinha and Bhattacharya propagation model (4) was used, assuming a homogeneous conducting earth. This model permits computation of the magnetic field at the earth's surface due to a vertical dipole at various frequencies and dipole depths. The underground transmitting antenna design was constrained by intrinsic safety requirements which limit the antenna energy to 10^{-3} joules. This constraint restricts the number of ampere-turns so the antenna area must be made large to achieve reasonable transmitted signal levels.
The final antenna design is a multiconductor cable with connectors at either end. This cable can be carried around a 60 foot coal pillar and, when the connectors are joined at the transceiver, becomes a large area multi-turn coil.

The receiving antenna is a 300 turn, 12 inch diameter coil which gives an induced voltage greater than that contributed by the receiver electronics. System performance will therefore be limited by ambient noise rather than receiver design.



TEM SYSTEM

FIGURE 1



TEMS Block Diagram
Figure 2

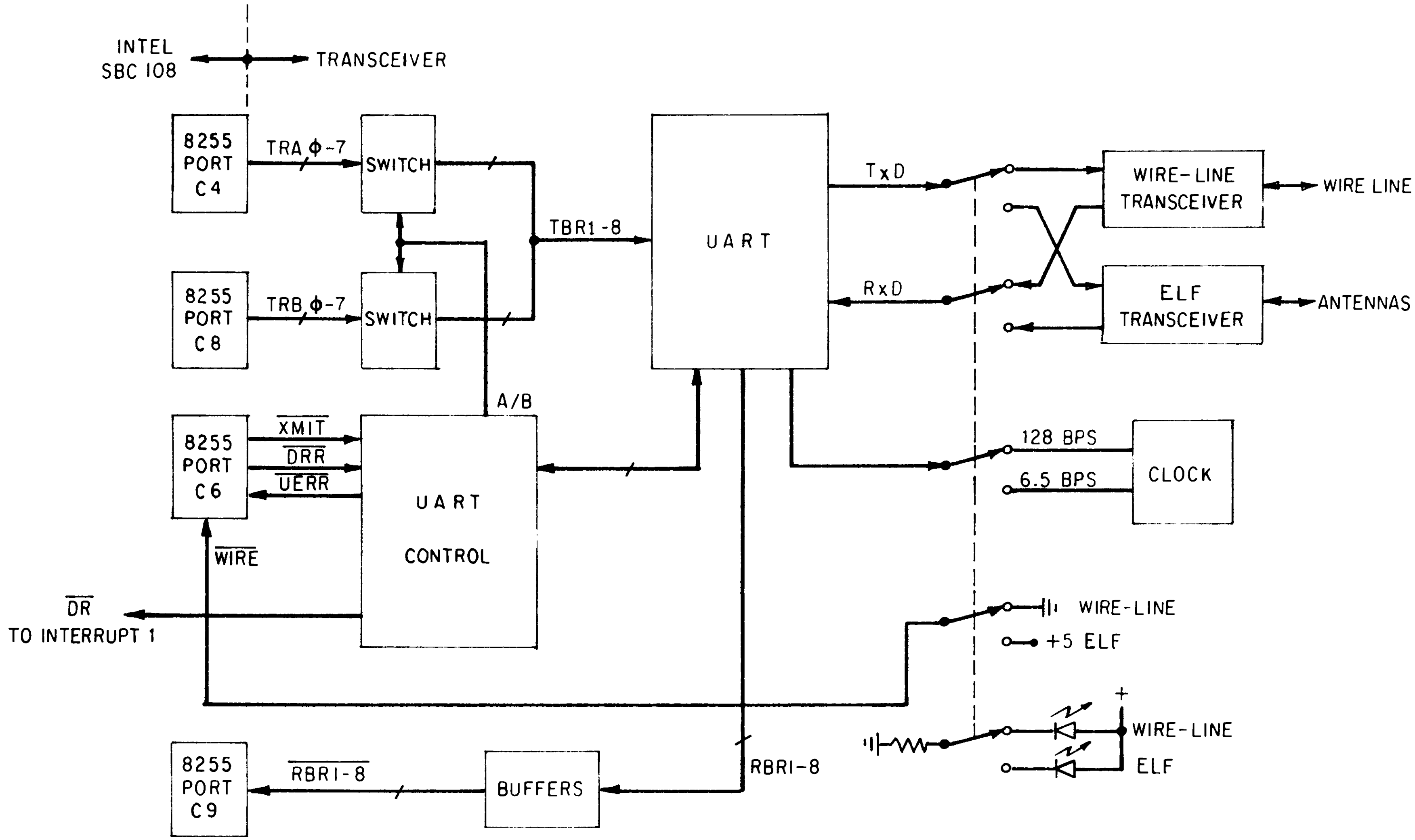
The ELF carrier frequency of 208 Hz was chosen following an analysis of measured ambient noise data from several mines which showed a broad minimum at 180 and 240 Hz. The receiver bandwidth was chosen as 12 Hz to accommodate the desired signalling rate and the receiver filter was designed to give at least 50 dB rejection at 180 and 240 Hz. Phase inversion modulation is used as in the wireline communication link. The detector is a phase-locked loop, the loss-of-lock signal indicating a binary zero.

Transceiver Interface

Figure 3 shows the transceiver interface design for the surface control unit. The wireline or ELF channel is selected by a switch on the control console. The UART and its various buffers and control circuits are shared by the two channels, only the clock rate and the data paths being changed by the switch. The switch also sends a signal, WIRE, to the controller which sets the time out period for the selected channel. Figure 4 illustrates the signal timing on the communication link for the wireline channel. Signals and timing on the ULF channel are identical except for a twenty-fold reduction in bit rate.

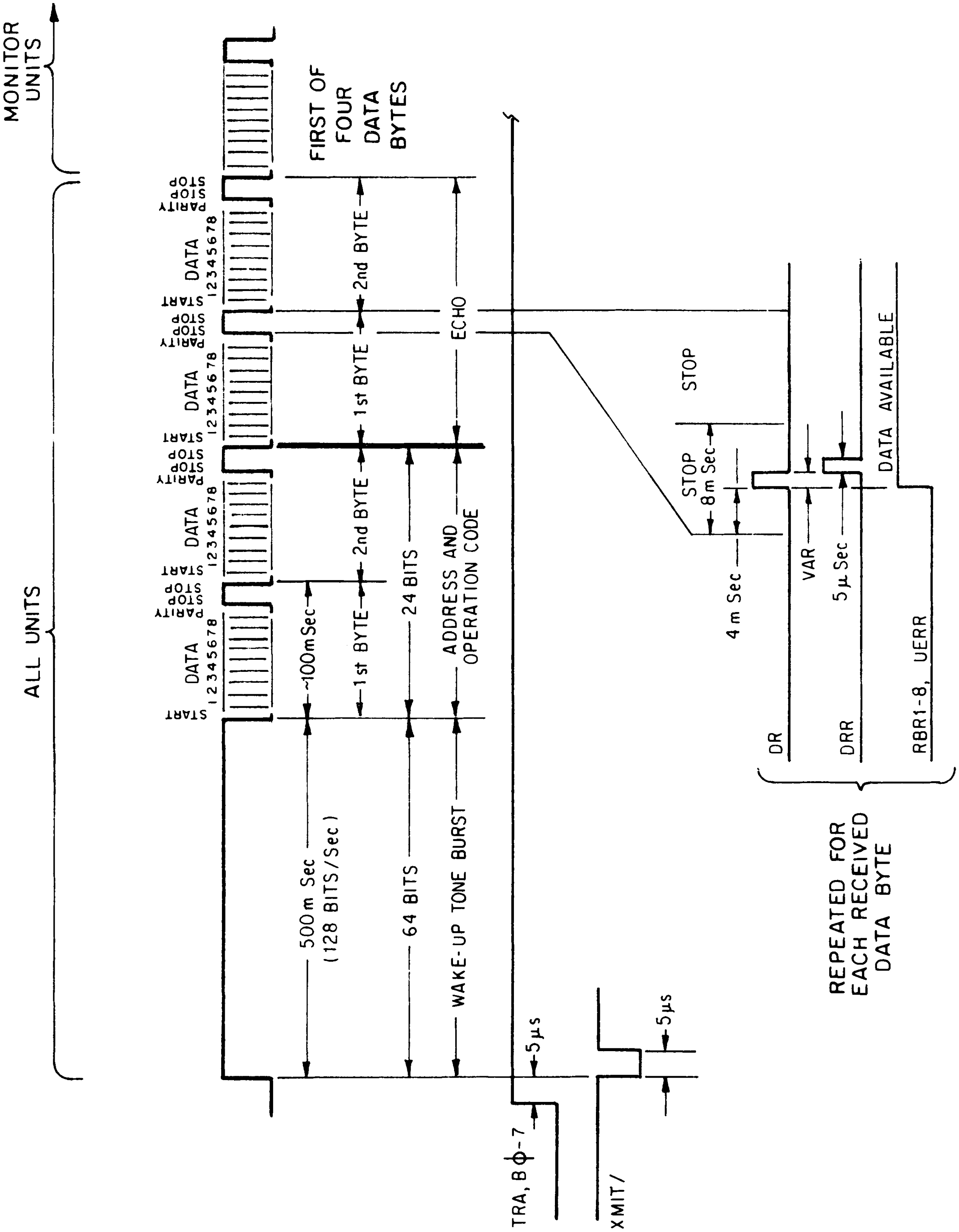
The communication cycle begins when the system controller sets up two data bytes, TRA and TRB, in its output ports C4 and C8. These bytes contain the 10 bit remote unit address and a two bit command code. Transmission is initiated by the signal XMIT which causes the transmitter to send a string of 64 bits as a training sequence for the underground receiver phase-locked loop. The two data bytes are then transmitted and the transceiver switches to the receive mode to await a reply from the underground unit.

When the UART has assembled the first received data byte it sends a DR (Data Ready) signal to the controller. The controller interrupts whatever it is doing, collects the data byte, and issues a DRR (Data



Surface Unit Transceiver Interface

Figure 3



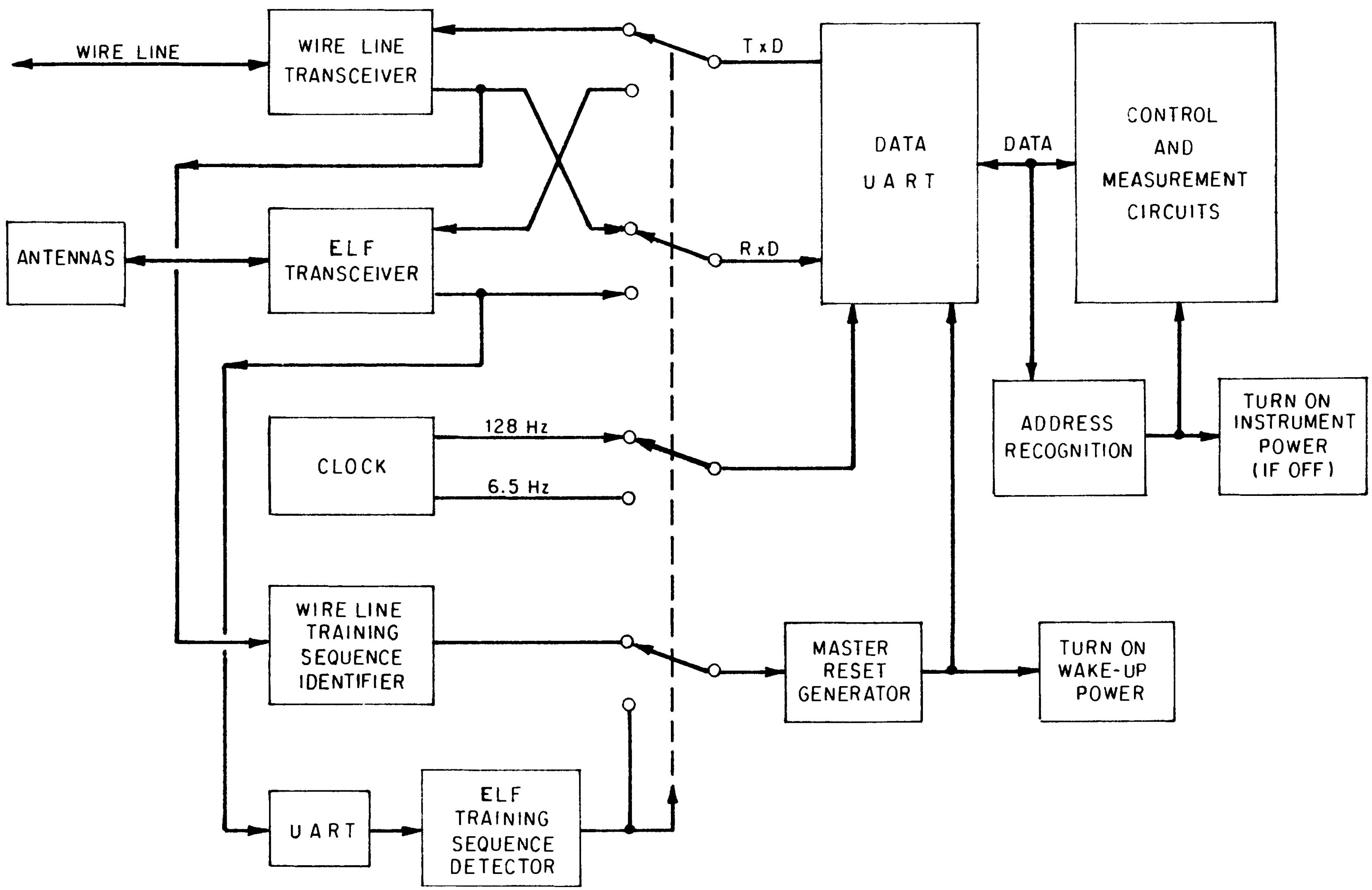
Signal Timing and Communications Link
Figure 4

Ready Reset) to the transceiver to acknowledge receipt of the data. After all six data bytes, the address, command code, and four bytes of monitor data have been received, the controller checks the received address and command for equality with those transmitted, then processes the monitor data for display. The second received byte also contains bits indicating the loss of mine power and the state of the CO unit purging circuit. The four monitor data bytes contain measured levels of carbon monoxide, methane, air flow, and battery voltage.

The underground unit transceiver interface is similar in principle but is complicated by the necessity for the unit to recognize when it is being addressed, either via the ELF or wireline channel, and when that occurs to turn on the wake-up power to the remaining communication circuits and control electronics and, in the event that mine power is off at that unit, to turn on instrument power. Figure 5 shows the interface logic. A separate UART monitors the ELF receiver output continuously. When it recognizes the ELF training sequence a switch is operated to connect the data UART to the ELF transceiver.

Monitor Unit

Referring to Figure 2, the monitor unit is seen to consist of the transceivers and interface described above, sensors for carbon monoxide, methane, and air flow, and a battery/charger unit. In normal wireline operation with mine power on, the monitor unit replies with a set of four sensor and battery voltage readings each time it receives a POST command. The CO sensor, however, has a special purge state into which it can be placed by a PURGE command from the surface. While in this state, which lasts for about four minutes, the semiconductor CO sensor element is heated to drive off impurities which may effect its readings. During the purge state, CO readings will be incorrect so a PURGING flag in the second echo byte is set to warn the controller to discard readings from units interrogated while in their purge cycle.



Interface Logic
Figure 5

When mine power is on, the gel cell battery is kept charged by the charger circuit. When mine power goes off, the remote unit is powered down so that only the transceiver circuits essential to signal reception are operating. A MINE POWER OFF flag in the second echo byte signals this condition to the controller on the surface. When the powered-down monitor unit receives a POST command, full power is restored to the unit. However, it can not report data immediately because the CO sensor goes into a four minute purge cycle when it is powered-up. Under these circumstances the control console indicates that the unit has gone into a WARM-UP state. After five minutes has elapsed the system controller automatically re-posts the unit at which time the correct sensor and battery voltage readings are sent to the surface. Following the data transmission the remote unit reverts to its low power state.

The monitor unit was designed to operate for one week with interrogations every four hours.

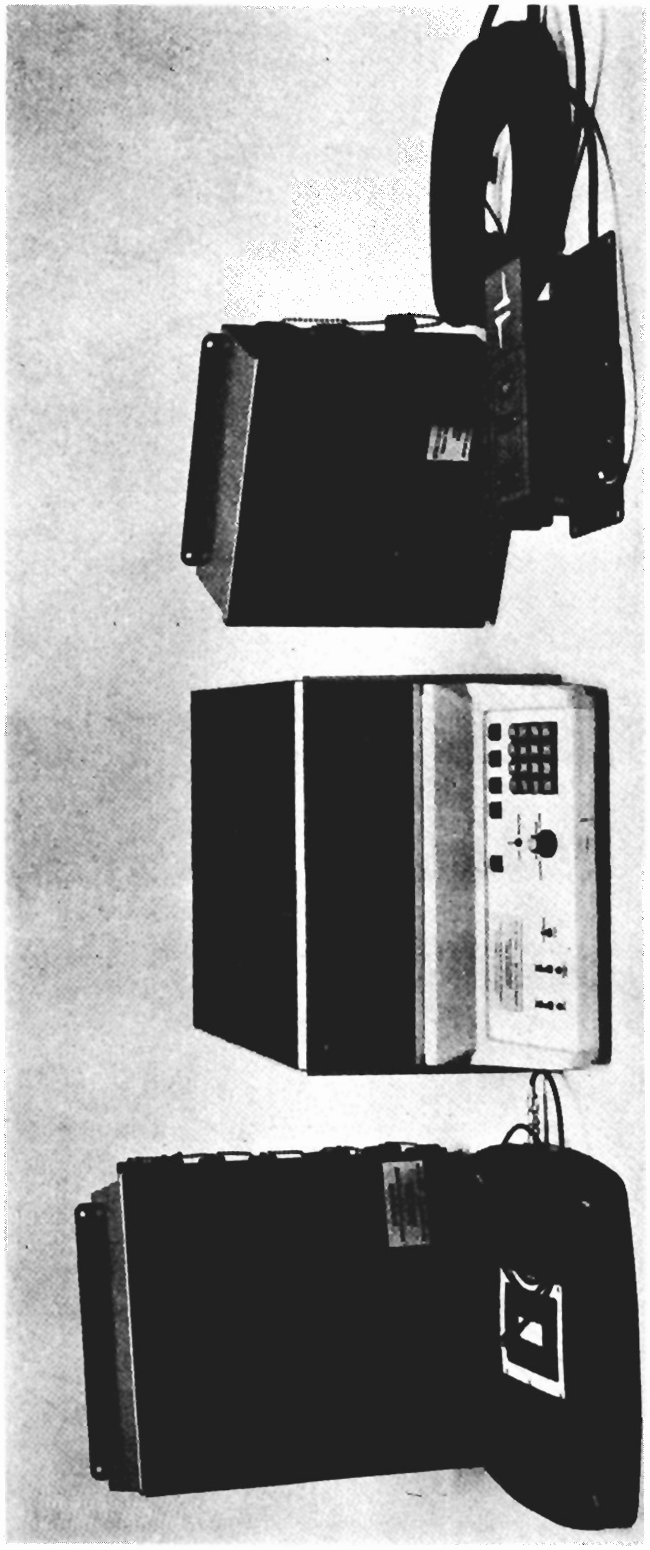
PHASE III - SYSTEM FABRICATION AND PERFORMANCE EVALUATION FABRICATION

Fabrication

Figure 6 shows most of the TEM system components. At the left is the monitor unit and its receiving antenna. The control console containing all surface electronics is in the center and on the right are the battery and charger unit and one of the three sensors. Not shown are the receiving antenna for the control unit, the two transmitting antennas and the other two sensors. Figure 7 is a closeup of the control console. Operating controls and displays duplicate to a large extent those found on the VDCS console and described in the VDCS final report (1). TEMS controls and displays are also described in detail in the TEMS Operator's Manual (5). Displays not found in the VDCS are:

- Mine power - On/Off,
- Battery voltage - Adequate/Low,
- Carbon monoxide level - Safe/Alarm,
- Methane level - Safe/Alarm,
- Air flow - Safe/Alarm,
- Purge,
- Warm-up,
- Monitor/List, and
- Time of day.

The first seven displays listed report on the state of the remote unit as described above. The LIST LED indicates that, in the Automatic mode, the STATION STATUS display is cycling through items on the CURRENT, OLD, ERROR, or ALARM list as specified by the setting of the LIST SELECT switch. The MONITOR LED indicates that, in the Automatic mode, the STATION STATUS display is cycling through the list of all monitor units which have been posted since the last System Reset and which are not on the ALARM list by virtue of a measured value of battery voltage, CO level, CH_4 level, or air flow being outside a specified range. LIST/MONITOR display mode is selected by



TEMS Components
Figure 6

TEMS Console
Figure 7

the switch of the same name. The Time of Day Clock indicates 24 hour time and is set by fast and slow buttons at the rear of the console.

When an alarm condition is detected an audible alarm sounds. This alarm can only be turned off by the ALARM RESET or SYSTEM RESET buttons.

Performance Evaluation

The wireline receivers will respond to signals as small as 18 millivolts which permits operation with transmission losses as high as 54 dB. The completed system was tested in the wireline mode for performance in the presence of noise by injecting white noise, band-limited to 20 KHz, onto the wireline and recording the noise level at which errors began to occur in data reception. These values, normalized to the receiver bandwidth of 500 Hz, were about 5 millivolts for the surface and underground receivers. Since the noise level in the noisiest mine is expected to be as high as 35 millivolts in a 500 Hz band, the wireline receivers would have to be operated at reduced gain in such a mine. This is not a real problem because the receiver sensitivity is larger than necessary to meet system design goals based on 40 dB wireline loss.

Measured performance of the ELF receivers is summarized in Table 1, from which it can be seen that a signal strength of at least 28 microvolts at the antenna terminals is required for reliable operation. From the Phase II report on this contract, that signal strength is predicted to be:

$$V = 2\pi f \mu_o N_r A_r Q H_z \text{ Volts}$$

where f = Frequency = 208 Hz

N_r = No. of turns in receiving antenna = 300

A_r = Area of receiving antenna = .07 sq. meters

Q = 3.6

H_z = Vertical component at surface due to buried dipole

Surface Unit	Measured at Test BNC	Referred to Input
Receiver self-noise (input shorted)	0.65 mV	3.7 μV
Minimum signal for operation	5 mV	28 μV
Maximum signal for operation	500 mV	2.8 mV

Receiver gain to BNC = 45 dB

Dynamic range = 40 dB

Mine Monitor Unit		
Receiver self-noise (input shorted)	0.40 mV	3.6 μV
Minimum signal for operation	2.8 mV	25 μV
Maximum signal for operation	800 mV	7.0 mV

Receiver gain to BNC = 41 dB

Dynamic range = 49 dB

Table 1

Measured ELF Receiver Performance

and $$H_z = \frac{N_T I A_T G}{2\pi D^3}$$ Amperes/meter

where N_T = No. of turns in transmitting antenna = 12

I = Maximum value of transmitting antenna current permitted by intrinsic safety = 0.25 amperes

A_T = Area of transmitting antenna = 334 sq. meters

D = Depth of mine monitor unit in meters

G = Attenuation factor from propagation model, a function of frequency and overburden conductivity

When the known system parameters are used in the above equations, the received signal strength is predicted to be:

$$V = \frac{19.8G}{D^3} \quad \text{Volts}$$

Table 2 shows the variation in predicted received signal strength as a function of mine unit depth and overburden conductivity. The table shows that to achieve 28 microvolts of signal the maximum operational depths will be 87 and 78 meters with conductivities of 0.05 and 0.5 Mhos/meter, respectively.

Current drain for the completed monitor unit was measured to be 0.011 amperes in the quiescent state, or about 1.8 ampere-hours for a week. Posting the unit every four hours, including the warm-up/purge cycle, consumes another 1.2 A-H for a total of 3.0 A-H for a weeks' operation. Since the battery is rated at 6 A-H the performance exceeds the specification.

	Depth (meters)	G	Signal (microvolts)
σ = 0.05 Mhos/m			
	60	.947	87
	80	.929	36
	87	.923	28
	100	.912	18
	120	.894	9
σ = 0.5 Mhos/m			
	60	.788	72
	78	.671	28
	80	.659	25
	100	.530	10
	120	.426	5

Table 2

Predicted Maximum Operating Depths

CONCLUSIONS

The Through-the-Earth Monitor System has the capability of making remote measurements at many locations in a mine and transmitting data to the surface either over pager phone lines or directly through the earth. In their present form the wireline transceiver circuits have more than enough sensitivity to operate with the specified maximum line transmission loss of 40 dB. In noisier mine environments they can be operated at reduced gain with little, if any, sacrifice in communication range.

The present ELF transceiver design is predicted to permit communication to depths of 87 meters through overburden of conductivity 0.05 Mhos/m and to depths of 78 meters through overburden of conductivity 0.5 Mhos/m. The performance is presently limited by a high value of receiver noise, a consequence of the choice of a low power active filter as the receiver tuning element. This performance could be improved at the cost of size or battery life by using a passive filter, lower-noise amplifiers, or both.

INVENTIONS

There were no inventions made in conjunction with this contract.

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