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NUCLEAR CRITICALITY EVACUATION WITH TELEMONITORING AND MICROPROCESSORS

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ABSTRACT

At Argonne National Laboratory, criticality alarms are required at widely separated locations to evacuate personnel in case of accident while emergency teams or maintenance personnel respond from a central location. The system functions have been divided in a similar manner. The alarm site hardware can independently detect a criticality and sound the evacuation signal while general monitoring and routine tests are handled by a communication link to a central monitoring station.

The radiation detectors and evacuation sounders at each site are interconnected by a common two conductor cable in a unique telemonitoring format. This format allows both control and data information to be received or transmitted at any point on the cable which can be up to 3000 meters total length. The site microprocessor maintains a current data table, detects several faults, drives a printer, and communicates with the central telemonitoring station.

The radiation detectors are made with plastic scintillators and photomultiplier tubes operated in a constant current mode with a 4 decade measurement range. The detectors also respond within microseconds to the criticality radiation burst. These characteristics can be tested with an internal light emitting diode either completely with a manual procedure or routinely with a system test initiated by the central monitoring station.

Although the system was developed for a criticality alarm which requires reliable and redundant features, the basic techniques are useable for other monitoring and instrumentation applications.

INTRODUCTION

A nuclear criticality can be very hazardous to personnel in the immediate vicinity of the event. Therefore, it is mandatory to have reliable equipment to sound the evacuation alarms. This equipment is required by the Department of Energy regulations(1) where more than specified quantities of fissionable material are stored. This regulation defines a minimum criticality as an event which delivers an absorbed dose of combined gamma and neutron radiation of greater than 20 rad at 2 meters from the incident within a one minute time interval. In addition, Occupational Health and Safety Administration regulations(2) require the evacuation signal to be a 450 to 500 Hertz audible tone pulsating at 4 to 5 Hertz with greater than 75 decible sound level within 0.5 seconds of the event. Redundant detectors, emergency power sources, fault detection and test features are also required. At Argonne National Laboratory, where independent criticality alarms are required at widely separated locations, past experience has dictated a need for minimum manpower requirements for routine tests and an adaptability to modification of covered locations. A criticality system will be described which incorporates these requirements.

RELIABILITY CONCEPT

If system operation is to be maintained, an accounting must be made for equipment failure. High reliability does not eliminate the failure, but only reduces the probability of the occurrence. In an alarm system where the probability of the alarm (criticality event) is low, occasional failure can be accepted if corrected. Therefore, high confidence in the ability of the system to function can be obtained if failures are always detected and corrected quickly. The concept is incorporated by an equipment design which accentuates failure detection. Several techniques are used to provide failure detection. In general, dynamic circuit operation is preferred over static, e.g., circuit components are required to continuously function at various levels rather than remain in a nearly constant state. Functional blocks are shared between critical and less critical operation so that failure may be detected through the less critical operation.

SYSTEM DESCRIPTION

Each criticality alarm, which may be located at various buildings or sites around the Laboratory, consists of multiple radiation detectors and evacuation annunciators interconnected by a telemonitoring system(3). The telemonitoring hardware is capable of detecting an alarm level from two or more detectors and initiating the evacuation with control signals to all of the annunciators. An integral site microcomputer is programmed to maintain a channel data table, generate intricate control signals for battery discharge and detector test functions, and communicate with the central station. A functional layout is shown in Figure 1. Normally, the central station controls the communication link (telephone line) with periodic requests for data or test functions. Changes in status or abnormal conditions at the site will originate a message to the central station which must be answered. The site printer records both the brief message originating from the site and the more detailed monitoring and test results as generated by the central station from data requested from the site.

TELEMONITORING SYSTEM

All units at a site are interconnected with a two conductor cable. The signal format on the cable (see Figure 2) allows both data and control signals to be read from or transmitted to the cable at any point. A series of sync and reset pulses allocate "time slots" for each channel. Each unit contains a channel counter which is set to zero count by the reset pulse and advanced for each sync pulse. For a unit to transmit data to the cable, the proper time slot is decoded by the counter and that sync pulse is widened by an amount proportional to the input data. Control pulses are added to the cable between the normal reset pulse and the first sync pulse (during channel 0). As a result, the control pulses, which appear as additional reset pulses, do not affect the channel counter but can be used to advance control counters. The position of the control counter, at the time of the first sync pulse (channel 1), determines the control function.

The cable drive arrangement which allows the combination of reset and sync pulses to be read or transmitted at any point on the cable (up to 3000 meters total length) consists of a constant current charge which maintains the cable at 10 volts between all pulses. A sync generator initiates each sync pulse by shorting the line for about 50 microseconds at a 500 Hertz rate. If data is to be transmitted to the cable, the unit concerned maintains the cable short for the appropriate time, otherwise the cable will be recharged immediately. The arrangement does not require cable drive power to generate the sync pulses, therefore, optically coupled drivers can be used throughout the system to eliminate ground loops. The reset (one per 256 sync pulses) and control pulses drive the line to about 20 volts for 50 microseconds. The relatively slow sync and reset pulse waveforms allow high impedance discriminators to be used to separate the reset and sync pulses and, thereby, not contribute to the ground loop currents.

The previous description infers a single cable has been used. The basic cable format does not restrict the cable layout, but to reduce possible system failure from a single cable fault, the cable layout has been installed in two loops, each interfaced to the control unit at each end. If redundant units are installed on each loop, one loop can fail without total system disruption. Clean cable cuts will only temporarily (during the cutting) disrupt the system.

A dual cable arrangement also provides a simple method to detect transients on the cable which might cause erroneous data. A line fault detection scheme compares the signals on both cables. Since data should only be transmitted to the cable to which the unit is connected, the two cable signals will differ only immediately after a sync pulse and when the data is present from the unit. The logic circuitry will indicate a fault if the difference signal appears at any other time than immediately after the sync pulse timing. A cable transient will be detected unless it appears identically on both cables or is superimposed on one of the data pulses. A second logic circuit indicates a cable fault if either cable has not been recharged immediately prior to each sync pulse. Either of these cable fault conditions will inhibit the alarm or criticality output circuitry for only the cycle in which the fault occurred. A fault control signal is also transmitted on the cable.

Specific channels (up to 31) have been assigned as criticality detector channels. Any mid-scale or greater data from these channels is considered as a warning or high detector level by the hardware logic circuitry. Each high level channel is compared by channel number with the next channel to indicate high level as the monitoring cycle continues. When a second channel indicates high level, if within 8 seconds of the first channel, the criticality evacuation control code is sent on the cable. This condition is also latched on and can only be reset with a manual push button switch at the site. Once the evacuation is sounded, the system disregards all fault indications. If only one channel high level is detected, a warning control code is sent on the cable for 8 seconds and the system reverts back to normal operation.

The sounder units that drive the annunciator speakers monitor for the evacuation control code. When this code is detected, the sync pulse rate and channel timing are gated to speaker drivers to provide a 500 Hertz audio tone pulsing at 4 Hertz. As a result, all annunciators in the building are synchronized to the tone and pulse rate. Each sounder drives several speakers which are located to provide distribution of the sound level. Up to 127 sounder units can be accommodated by the system.

Each telemonitor unit (detector, sounder or control unit) is powered by an internal battery and charger. The battery voltage of each unit is assigned a channel in the telemonitoring system. The central station through the site microcomputer can discharge-charge all batteries and assess their condition. The battery voltages are also routinely monitored along with the detector levels and other system parameters.

DETECTOR ASSEMBLY

A Pilot B plastic scintillator-photomultiplier tube combination is used for the radiation detector. This scintillator is sensitive to both gamma and neutron radiation. High voltage for the photomultiplier tube is supplied with a DC-to-DC converter with a controllable duty cycle. The tube anode current is maintained constant by appropriate feedback control of the duty cycle. In this mode, referred to as current mode, the high voltage change is an approximate logarithmic function of the light intensity or radiation level from the scintillator as shown in Figure 3. A measurement of the high voltage thus becomes a function of the incident radiation. A high voltage clamp is provided to limit the voltage if a minimum radiation level is not present. This operation mode can be used for several decades of range. The signal output from the detector circuitry is sent to the central station and converted to the appropriate radiation readout format with a conversion table stored in the central station memory.

For response to the criticality burst, a dynode saturation characteristic is used. The current mode response time is about 0.3 seconds while the initial criticality burst may be on the order of hundreds of microseconds. During low level operation of the photomultiplier tube, the dynode currents are low and the dynode potential is a function of a resistor divider string. If an intense light pulse occurs, sufficient current may not be available for all dynodes. Since the dynode multiplication factor is a function of the potential between the dynodes, insufficient available current will tend to lower the dynode potential and thus lower the gain. The highest dynode current will be required by the dynode nearest the anode and progressively lower current required by the dynodes near the cathode. As a result, if the current is measured through the dynode resistor string, a high instantaneous light pulse will produce an increase in apparent resistor string current which is somewhat logarithmic with respect to light pulse intensity. This feature is used for criticality burst detection.

Since the scintillator produces light from the nuclear radiation, a simple light emitting diode (LED) can simulate this radiation for test purposes. Once the detector assembly has been calibrated, light levels equivalent to incident radiation can be simulated by the LED. This light level can be applied continuously to simulate average radiation levels or pulsed to simulate a criticality event. The test light can also simulate test levels that might be hazardous to personnel if actual radiation fields were used outside of a calibration facility. The detector transient response, including the electronic circuitry, has been evaluated with the simulated burst supplied by the LED test source and found to respond within a few hundred microseconds and, therefore, acceptable with regard to the ANSI Standard[4] which states the minimum criticality transient or burst to be one millisecond duration.

DETECTOR CALIBRATION AND PLACEMENT

The detector response to neutron and gamma radiation was evaluated using ^{252}Cf and $^{239}PuBe$ neutron and ^{226}Ra and ^{60}Co gamma sources. The equivalent neutron response was found to be 15 percent of the response to both gamma sources. All detector calibration adjustments and readout are with reference to the detector response to the ^{60}Co radiation field.

The detector placement involves many factors including: response of the detector, the neutron to gamma dose ratio of the event, the distance from the event and the interventing air and other shielding material. To eliminate detector alarms from high ambient levels or radiological material movements, the detector alarm levels have been set for 1 R/hr for both dose rate and burst levels. In general, the possible dose ratio (neutron to gamma) of a criticality event will vary greatly and depend upon many factors. In a dry metal system, the ratio may range up to 10 to 1, whereas, for a water moderated system, it could be as low as 1 to 10. Because of the lower neutron detector response, the more conservative approach is to use the value of 10 to 1. This decreases the maximum placement distance by about a factor of two as shown in Figure 4.

Since the detector placement is essentially a function of distance from the event and the thickness of the intervening shielding, the following expression was developed that equates the detector alarm level with the radiation expected from the criticality event as a function of distance and shielding (concrete) thickness:

$$1 \text{ R/hr} = \frac{1}{d}2\left[\gamma(e^{dA\gamma})(AF\gamma)+.15\ n(e^{dAn})(AFn)\right]$$

and is plotted in Figure 4.

Where: γ = gamma dose rate at 1 meter
- n = neutron dose rate at 1 meter
- d = maximum distance from the event in meters
- $A\gamma$ and An = air attenuation constants[5]
- $AF\gamma$ and AFn = concrete attenuation as a factor of thickness[5]

The neutron and gamma dose rates were calculated assuming that the regulation specified 20 rad is accumulated at a constant rate for 1 minute (20 R/min = 1200 R/hr = .33 mR/ms). Concrete attenuation factors have been used since it is the most frequently encountered material. If other materials were involved, the concrete equivalents were used.

SITE MICROCOMPUTER

A RCD CDP1802 microprocessor, 1K memory, and HD 6402 UART (Universal Asynchonous Receiver Transmitter) are the basis for the site microcomputer which is located in the control unit. This microprocessor was chosen because of the low power requirements and the direct memory access feature for program loading. The microcomputer interfaces to the telemonitoring hardware through three input ports (channel number, channel data, and status) and one output port (control command). The UART is connected to a telephone line in a full duplex coupler and communicates with the central station at 300 baud. Logic circuitry has been included to allow the microprocessor to be cleared or set in the direct memory access or program load mode with "break" commands on the telephone line. This feature allows complete program loading from the central station.

During normal operation, the microcomputer maintains a table of all channel data and telemonitor status (line fault, warning, alarm). It also answers requests from the central station for data transmission and applies control commands to the monitor. Control commands (battery discharge, detector test) require a sequence of operations based on appropriate monitor conditions to thoroughly test the monitor operation. As an example, the battery discharge cannot be applied unless a line fault is periodically simulated during a specific time. The detector circuitry will not respond to the test signal unless the battery discharge condition is present at the detector unit. These interlocking functions both assure proper test and immediately stop the testing process if the system is not in an otherwise normal mode.

SITE MICROCOMPUTER PROGRAMMING

The monitor cable signal is used to synchronize the program with the telemonitor operation. Program loops detect the line changes which occur at a 2.5 millisecond interval (time period for each channel). When the line changes from low to high new channel data is available which is used to update the channel data memory. The channel number is compared to determine if a jump to another program routine is required. As an example, the detector test and battery discharge control signals must be applied to the monitor hardware after the sync pulse for either channel 127or 255, but before the sync pulse for channel 0 or 128. Channels 1 and 129 are used to update system status. Also, during this line high condition, the message data from the central station is handled. This data is stored in a buffer until the message is complete at which time it is analyzed and appropriate routines executed.

During the line low condition, message data to the central station is sent. This data is also handled as a block in other program routines, stored in a buffer and sent character by character during this time in the loop.

Any status change will initiate a new message to the central station and abort any message in progress. All messages, except alarm conditions, require an acknowledgement from the central station within a few seconds or the message will be repeated. Alarm messages are periodically sent until the telemonitor hardware is manually reset. The alarm message contains the most recent burst and rate levels from all detector channels. An abbreviated form of this data is printed simultaneously on the site printer.

CENTRAL STATION PROGRAMMING

Each site telemonitor and microcomputer is connected through a separate telephone line and input terminal to the central microcomputer. In normal operation, the central microcomputer program has control of the message traffic on these lines. If abnormal conditions occur at a site, a message is originated at that site regardless of other traffic. These interrupted conditions must be handled without fail, especially in the case of a criticality event. A multiple criticality is very unlikely but because of conservative detector alarm levels, adjacent sites may alarm simultaneously from a single criticality event. To be assured of proper program operation, the programming must account for simultaneous criticality events from all sites.

During normal operation, the central computer program will periodically request data and status from each site location and respond with an acknowledgement and/or descriptive message as the data requires. This message is composed of a conversion of channel numbers to the appropriate abbreviated description or location of the channel unit and conversion of raw data (battery voltage, rate and burst levels) to understandable numerical data with parameter labels. Out-of-limit values are flagged and a system status description is included. The detector rate level conversion table is common to all detectors as are the battery voltage limits.

All input and output routines (site communication lines and local printer) operate in a program interrupt mode on a character by character basis. Individual circulating buffers are used for these routines which maintain the most current data for the assigned routine. The main program continuously polls the input buffer "end of message" flags. If a completed input message is detected, the appropriate routine is called and in most cases, the appropriate output buffer will be loaded with a composed message as described previously. The input buffer loading and output buffer unloading proceeds regardless of the main program status. In this manner, assuming sufficient buffer length, no data will be lost. In the case of a criticality event, message transmissions to the site are stopped and only the central printer receives traffic.

A local keyboard is available to insert commands to the system for monitoring and test purposes. In case of a criticality event, disaster instructions can be called up in addition to information displayed as part of the accident program in the computer.

CONCLUSION

Criticality notification for the purpose of evacuation is a very serious operation. The equipment must function without fail and it must also provide an assurance of its capability. Not only are redundant units used to provide this assurance but also a failure detection reliability concept has been incorporated. The common interconnecting cable of the telemonitor, with the time sharing for each channel data, requires dynamic operation of most components to function. All channel units also share the readout and test functions through the telemonitor and microcomputer. The battery discharge-charge and detector test function exercises most of the channel unit circuitry. With the exception of the evacuation annunciators, very little of the system circuitry is not required to respond with a change in some operational parameter at some time during normal operation and testing.

Although this system was developed for criticality evacuation, the monitoring features are applicable to other instrumentation. This system is especially useful when many widespread monitoring points are required which do not require high data accuracy or fast response time.

ACKNOWLEDGEMENT

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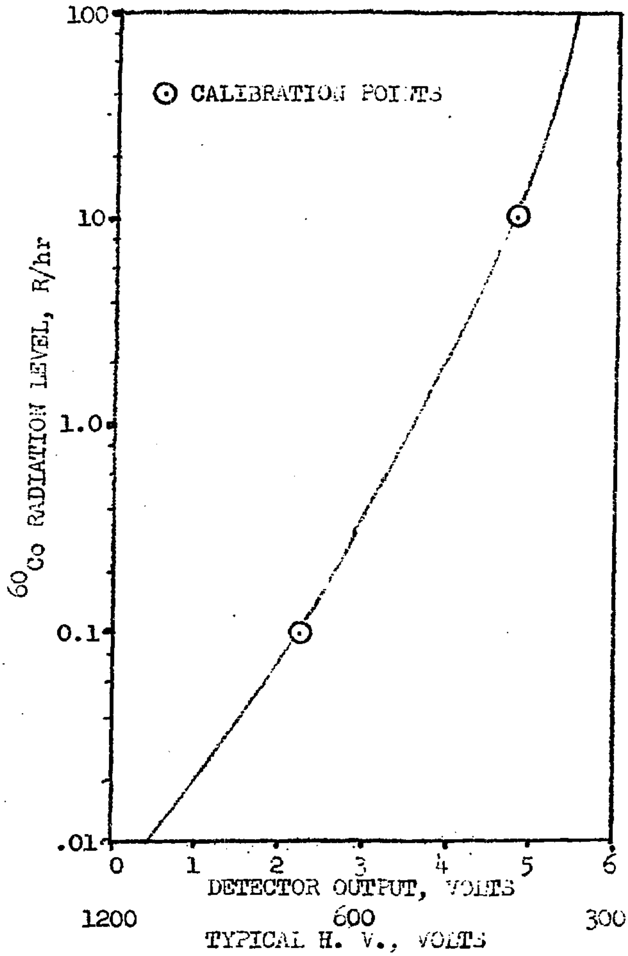

FIGURE 3
DETECTOR RESPONSE

Nuclear Criticality Evacuation
with Telemonitoring and Microprocessors
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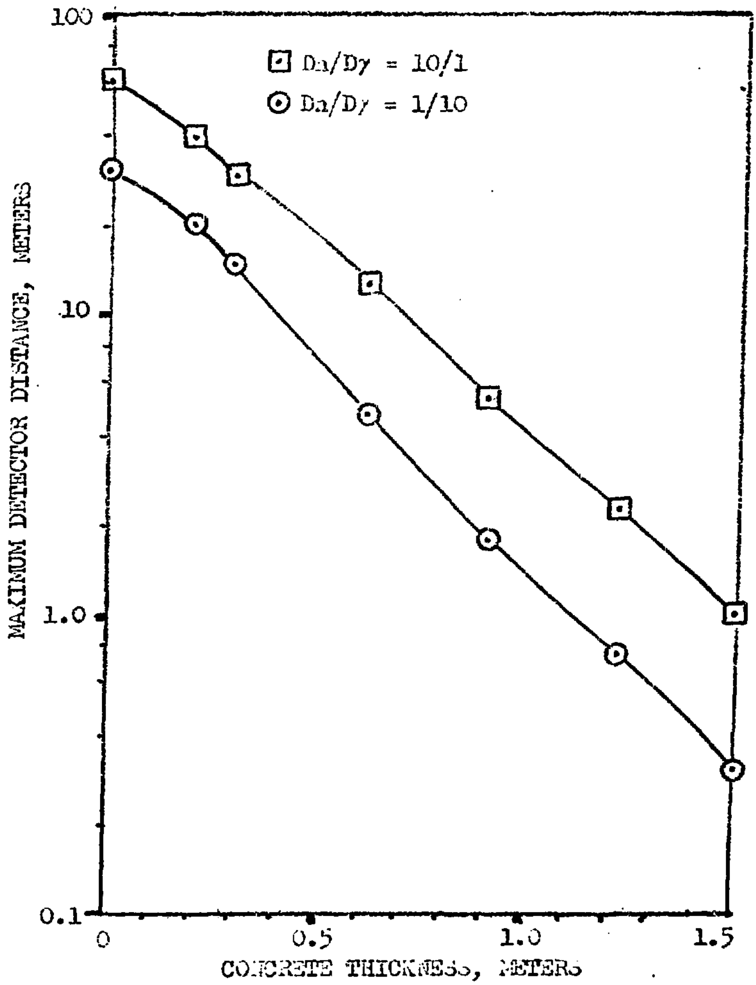

FIGURE 4
DETECTOR PLACEMENT

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with Telemonitoring and Microprocessors
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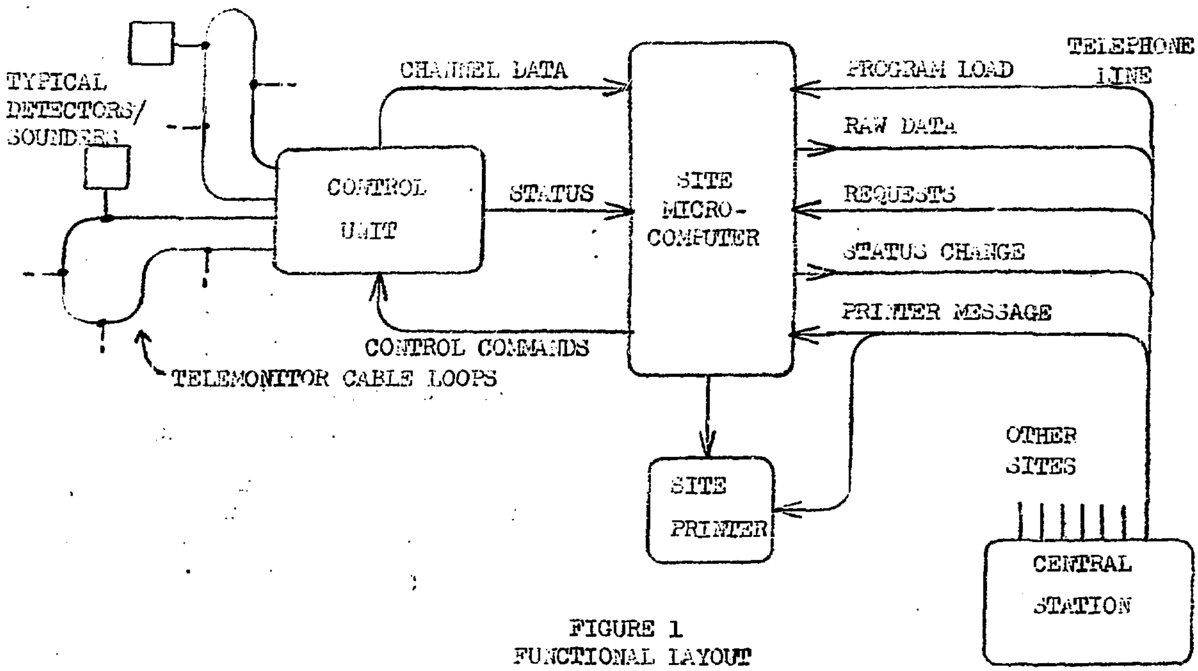

FIGURE 1
FUNCTIONAL LAYOUT

Nuclear Criticality Evacuation
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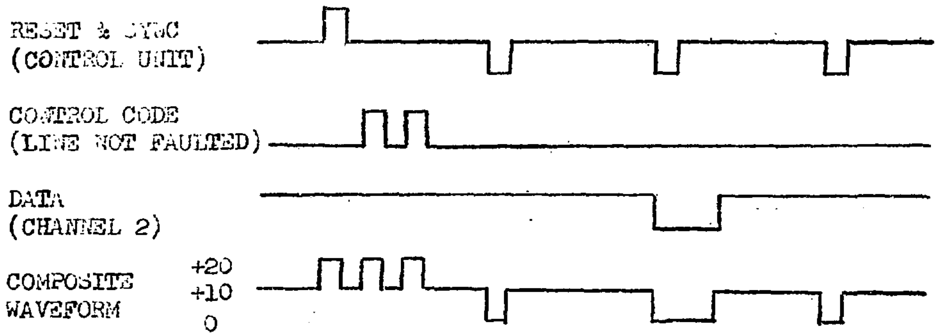

FIGURE 2

MONITOR CABLE WAVEFORM

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