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A CRYOGENIC MONITOR SYSTEM FOR THE LIQUID ARGON CALORIMETER IN THE SLD DETECTOR*

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ABSTRACT

This paper describes the monitoring electronics system design for the Liquid Argon Calorimeter (LAC) portion of the SLD detector. This system measures temperatures and liquid levels inside the LAC cryostat and transfers the results over a fiber-optic serial link to an external monitoring computer. System requirements, unique design constraints, and detailed analog, digital and software designs are presented. Fault tolerance and the requirement for a single design to work in several different operating environments are discussed.

I. INTRODUCTION

The SLD is the latest particle detector designed to work with the new Stanford Linear Collider experiment at the Stanford Linear Accelerator Center. The Liquid Argon Calorimeter in the SLD presents several distinct monitoring problems. Cryogenic temperature and level monitoring, as well as the monitoring of electronic parameters associated with the data acquisition and readout electronics in the LAC, are required from 64 different locations. The cryogenic temperature measurements are made with thermocouples (TC) and platinum resistance temperature devices (RTD), while the level sensors are LEDs which exhibit a marked increase in forward bias voltage when immersed in cryogenic liquids.

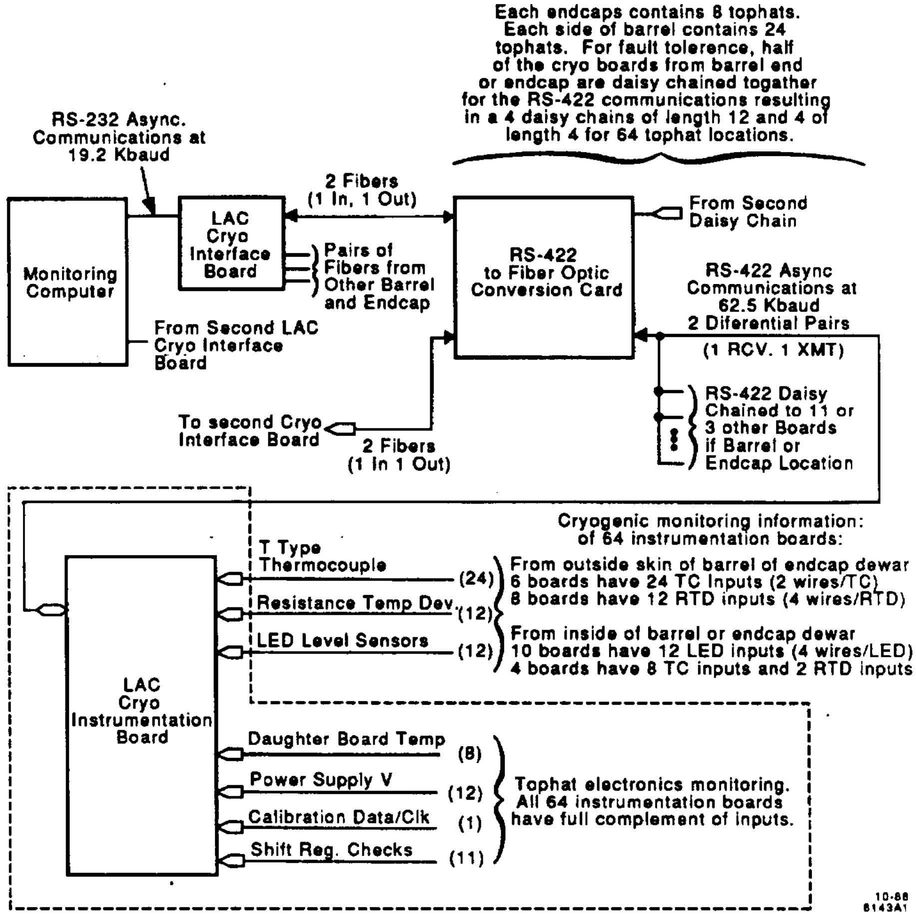

Fig. 1 System block diagram.

A restrictive design constraint is imposed on this system in that the monitoring electronics is located in close proximity to the low level signal processing electronics and EMI considerations dictate that—during beam crossing, data acquisition and readout—the monitor circuit must be electrically quiet, with no free-running clocks or other sources of noise. A design has been implemented which uses 68HC11 microcontrollers—together with analog circuits—to measure the cryogenic data and then transfer the measurements over a serial link to an external monitoring computer. The 68HC11 microcontrollers are configured to turn off during the beam crossing interval, and to wake up, make measurements and communicate with the outside world during the detector off-time. The 64 LAC cryo instrumentation boards communicate with the monitor computer, which processes monitor information from all SLD components through a redundant fiber-optic serial network, providing electrical isolation and fault tolerance.

Part of the communications system includes buffering interface 68HC11 microcontrollers, which coordinate serial messages between cryo instrumentation processor off-periods (see Fig. 1). Due to the fact that there are five distinctly different kinds of locations in terms of cryo transducer connections, a very flexible hardware and software design was required. The result was that—with four different combinations of parts—all the various transducer options could be handled without circuitry for one type of transducer interfering with the measurements made with another.

SYSTEM OVERVIEW

The Liquid Argon Calorimeter consists of three major components. The LAC barrel is cylindrical in shape with an inside radius of 1.92 m, an outside radius of 2.64 m and a length of 6 m.[1] On both ends of the barrel, there are 24 circular hermetic signal feedthroughs—called the cold feedthroughs—which conduct signals from inside the LAC. Surrounding the entire barrel is a vacuum space which insulates the LAC electronics and the rest of the SLD detector from the cryo temperatures of the LAC. On both ends of this vacuum vessel are 24 circular warm feedthroughs directly corresponding to the cold feedthroughs which conduct signals emanating from both the cold feedthroughs and inside the vacuum space. On top of these warm feedthroughs reside the LAC tophats, so named for the black circular shield/heat sink which covers the electronics.

The electronics inside a tophat consists of a circular mother board with connectors for interboard data transfer between the cryo instrumentation board, 15 LAC daughter boards, a controller board, an A/D board and power supply boards.[2] The center of the mother board is cut out to allow another set of connectors which route signals from the warm feedthrough

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to either the 15 daughter boards, which constitutes the hadronic and electromagnetic calorimetry data, or to the cryo instrumentation board.

The LAC endcaps fit over the ends of the barrel to give full 360° calorimetry coverage. They are disk-shaped, 1.7 m in radius and .72 m thick. Each endcap has eight tophat locations. Although a different shape for the feedthroughs and mother boards makes the name top hat a less obvious choice, they are equivalent electrically from the standpoint of the cryo instrumentation board.

Temperature information is received from TCs and RTDs located inside both the barrel and endcap dewars, and from transducers screwed down in brackets to the outside skin of the dewars. The LED level sensing strings are located inside both barrel and endcap dewars. The signals from transducers inside the dewars must proceed through both a cold and a warm feedthrough, while the transducers on the skin of the dewars pass through a warm feedthrough only.

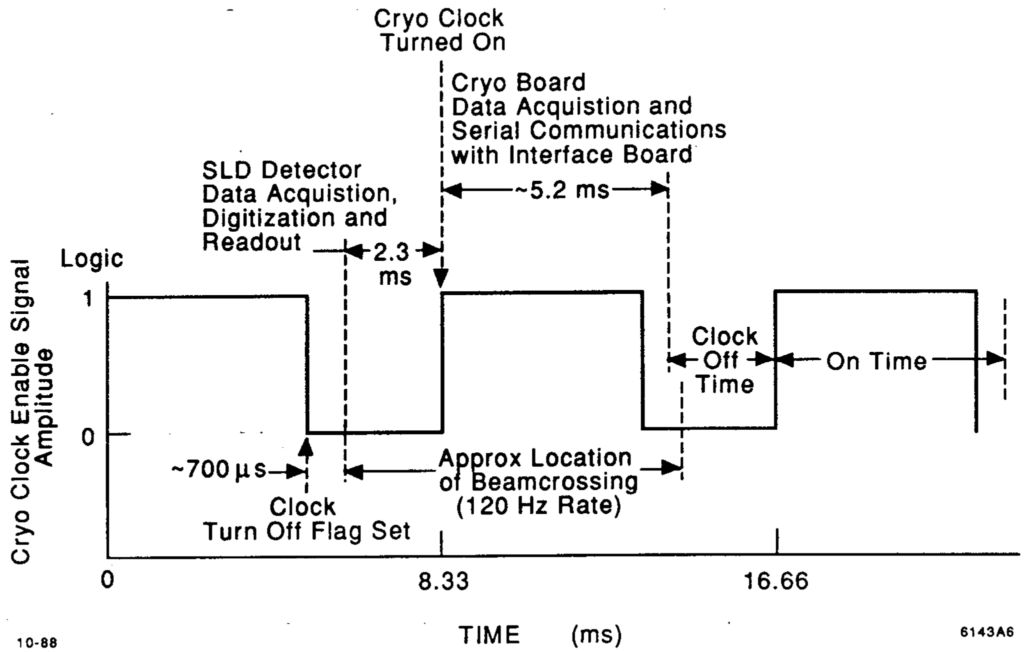

Fig. 2. Cryo instrumentation board clock on/off timing.

The 64 cryo instrumentation boards are organized into eight groups, two groups of four boards in each of the two LAC endcaps, and two groups of 12 boards in each end of the LAC barrel. Each group has its members daisy-chained together with an RS–422 serial link that is connected to a fiber-optic transceiver unit, which allows bidirectional communications at 62.5 Kbaud with the LAC cryo interface board (see Fig. 1).

There are two LAC cryo interface boards, each of which is connected through the fiber-optic network to 32 cryo instrumentation boards. These are interconnected so that half of the data coming from each endcap or each barrel end is processed by one interface board. Therefore, if an interface board—or the communications link to one board—fails, at least half the data from each part of the LAC will remain valid. In addition, the data from 32 cryo instrumentation boards is carried in four separate fiber-optic links, which isolate the endcaps and barrel ends from each other. If an individual cryo instrumentation board fails (tying up the RS–422 daisy chain and, therefore, the fiber-optic link to the interface board), at most, one out of eight serial links would be destroyed and the data from 12 out of 64 cryo instrumentation boards would be lost. Since the cryo transducers are arranged so that the same temperature and level data is obtainable from either of the two groups in each endcap or barrel end, any single communications link or board failure will not result in a condition necessitating shutdown of the entire SLD detector for maintenance.

SYSTEM OPERATION

The basic operating premise is that, upon powerup, each 68HC11 on the cryo instrumentation board—which is operating in the single chip mode, using only on chip EEPROM and RAM memory—will read a data byte from an onboard buffer, which contains information regarding the address and type of location that it is plugged into. This data is preset by cutting, or not cutting, traces located on the outside layer of the board. Provisions have been made to reinstate traces via jumpers if a board address or type needs to be changed. (Unfortunately, not enough extra pins were available on either of the two connectors to facilitate the transmission of this address and board type information.)

The board will then proceed to configure its complement of switches and multiplexers to do the correct analog conditioning and data acquisition. Thereafter, it loops through a program which continuously refreshes either a 48 or 96 byte data table—depending on location type—which will contain all cryo information, as well as the temperatures and power supply voltages of the tophat electronics. During this normal operation, a signal—cryo clock enable (see Fig. 2), which is basically a 120 Hz clock with approximately a 75% duty cycle—is coordinated so that it is low (approximately 700 µS) before the crossing of the beam of electrons and positrons (when a collision may occur) until about 2.3 MS after—to allow for LAC data acquisition, analog to digital conversion and readout.

The falling edge of this signal causes an interrupt, whose service routine sets a flag. The code is configured so it never runs for more than 200 µS before checking the status of this "shutdown" flag. Upon noticing the shutdown flag is set, the code branches to a routine which delays 300 µS to make sure the cryo interface board hasn't recently sent a serial data byte which is in the process of causing a receive character available interrupt. After the delay, the routine stops the microcontroller clock and enters a dormant state. The rising edge of the cryo clock enable signal wakes up the sleeping microcontroller to allow continued program execution.

This mode of operation continues indefinitely, unless a serial instruction is received from the interface board, which tells the microcontroller to send back its 48 or 96 byte data table and to continue normal processing thereafter. Another message instructs the microcontroller to reverse this on/off mode and to measure tophat digital parameters during its normal off-period. A third mode exists where the microcontroller captures additional digital data during normal "on" time. Lastly, it is possible to do the regular data acquisition in a reversed mode to measure power supply voltages when the tophat electronics are drawing the most current, during the data acquisition, digitization and readout processes.

Upon powerup, the LAC cryo interface boards establish communications with each of the 32 instrumentation boards under their charge. The interface board can either transmit to the instrumentation board in a global broadcast mode or can individually address a communication to a particular board. A command for the instrumentation boards to perform a different operational sequence—such as noted above—would most likely be global. However, any time a response is required the message must be specifically directed to a particular instrumentation board since the transmitters of up to 12 instrumentation boards are tied together; the interface board must know where that board physically resides in order to multiplex the correct fiber-optic link to its RXD input.

The interface boards receive the same cryo clock enable signal that the instrumentation boards receive. This signal is used to inhibit the transmission of data from the interface board to the instrumentation board(s), when the instrumentation boards are "sleeping" during a beam interval. The status of this signal is checked before each byte of either a global or individual message is transmitted.

There is always the possibility of the cryo clock enable signal going logic low immediately after a byte has been transferred to the transmit buffer. However, at 62.5 Kbaud, the time required to transmit a single byte—including start, stop and parity bits—is less than 200 μS, which is 100 μS less than the time the instrumentation boards must wait before stopping. Therefore, the receive interrupt service routine of the instrumentation boards will always have time to get the data byte before stopping the clock and disabling the receive and transmit functions.

Communications going the other way are unaffected by the stopping and starting of the instrumentation boards, as the receive routines of the interface boards wait a period of time greater than several beam crossing intervals before abandoning an instrumentation board as dead. Although the interface boards provide a useful data buffering and reorganization function, the inability of the monitoring computer to know when to communicate with the instrumentation boards is the real reason for their existence.

After communications have successfully been established, the interface board enters a polling sequence whereby it asks each board in turn to send back its normal data table. Since each type of location results in a different data table, a lookup table in EEPROM inside the microcontroller—which is running in the expanded multiplexed mode of operation with external EPROM and RAM memory—contains the board type versus board address information. Depending on the board type, different routines are required to process the data coming back and place it in the correct location in the 256 byte data table allocated to each cryo instrumentation board. A 256 byte by 32 or 8K by 8 bit data RAM is required to hold all the information from 32 cryo instrumentation boards.

This operation continues until the computer in charge of monitoring such data from all SLD subsystems needs information from the LAC tophats. The monitor computer then requests the data be sent to it, organized by instrumentation board type. This results in five different return messages, ranging in length from 112 bytes to 453 bytes, due to differences in the relative numbers of instrumentation board types. The monitor computer may also tell the interface board to have the cryo instrumentation boards perform any of the various special modes of operation described above. The interface board will obtain the results from each instrumentation board and then transmit the collated data back to the monitor computer. The serial messages that result may range in length from 69 to 3045 bytes.

The above details the basic operation of the monitoring system from a functional viewpoint. Following is a detailed description of the cryo transducers and their organization, and a detailed description of the analog circuitry on the instrumentation boards.

CRYOGENIC TRANSDUCERS

The thermocouples used for temperature measurement are T-type, manufactured by OMEGA, part number 5TC–GG–T–24–36–STD. The RTD devices are also manufactured by OMEGA, part number 1PT100KN2528.[3] One of each of these is mounted in a pretested module with an outer casing of aluminium that has a centrally located hole to facilitate being screwed down to the outer skin of the dewar. These modules are placed at 48 locations on the inner and outer cylindrical skin of the barrel dewar. Each TC requires two signal wires—one of copper and one of constantin—for a T-type thermocouple. Each RTD requires four signal wires—two to supply the current source and return, and two to read the differential voltage across the device. This results in 96 TC signal wires and 192 RTD signal wires. Since the cryo connector has 50 pins—48 of which will be used—two warm flanges are required for the TC signals and four are required for the RTD signals. These are evenly split between the barrel ends.

In addition, four cold/warm flange pairs are used to bring out signals from eight RTDs and 32 TCs that are located inside the dewar. This results in two warm flanges on each end of the barrel containing signals from two RTDs and eight TCs.

An important consideration is that the thermocouple leads maintain their elemental continuity—i.e., the copper and constantin leads of a T-type TC remain uninterrupted—through all intervening connectors—or that those connectors have no thermal gradients, otherwise the resulting measured temperature will be in error.

The LEDs used for level sensing are Seimens LDG5171. From an electrical viewpoint, the LEDs are treated exactly like the RTDs; that is, a current source is connected to the LED, forward biasing the device, while the differential voltage is read across the device into a high impedance amplifier. There are six strings of 12 LEDs each located inside the barrel, which results in three warm flanges on each end of the barrel containing the 48 signals from 12 LEDs. The six LEDs at the top of the string have a spacing of 1/2 inch; this increases to nine inches for the six LEDs at the bottom. Adjacent strings are offset to work together to give 1/4 inch level resolution at the top of the string and 4 1/2 inches resolution at the bottom.

The LAC endcaps each contain two strings of 12 LEDs similar to those in the barrel, which will require two warm flanges for the 96 signal wires.[4] Each endcap will contain four TCs inside the dewar similar to the TCs used inside the barrel dewar, and require one warm flange for the eight signal wires. Each endcap will use 12 of the TC/RTD modules described above, four on the inner radius of the outside skin of the vessel and eight on the outer radius. This will require one warm flange for the TCs and one warm flange for the RTDs. See Table 1 for a summary of this information.

ANALOG SIGNAL PROCESSING

As noted above, the cryo instrumentation board must measure cryo temperatures and liquid levels via a number of different combinations of TCs, RTDs and LEDs. The analog circuits selected for these functions have been designed to minimize the total parts count (through multiplexing techniques) and to achieve high accuracy (through the use of precision passive components and stable voltage references). This design philosophy eliminates any adjustable components, allows replacement of cryo instrumentation boards without recalibration or loss of accuracy, and incorporates built-in testability via control of the 68HC11 on board.

TABLE 1. CRYOGENIC TRANSDUCERS

Type	T–type Thermocouples (TCs) (For Temperature Measurement)	Platinum Resistance Temperature Devices (RTDs) (For Temperature Measurement)	Light Emitting Diodes (LEDs) (For Cryogenic Fluid Level Measurement)
Electrical Requirements	Two-terminal device, produces electrical potential relative to temperature. Requires second junction in series, held at known temperature to give meaningful result, or electrical equivalent.	The resistance changes as a function of temperature. Four-terminal device, requires injection of precise reference current into resistor, measure differential voltage across resistor into high impedance amplifier.	Treated exactly like RTD. Forward bias voltage changes in discrete manner as the device is immersed in cryogenic liquid.
Barrel Locations	Forty-eight located on outside skin of barrel dewars in fabricated aluminum brackets also containing one RTD. Two warm flanges required for the 96 signal wires, one on each end of barrel. Thirty-two located inside the dewar at various positions in hadronic and electromagnetic stacks. Four cold and warm flange pairs, each bring signals from eight TCs (16 wires), two on each end of barrel. These four locations also have signals from two RTDs each.	Forty-eight located on outside skin of barrel dewars in fabricated aluminum brackets, also containing one TC. Four warm flanges required for the 192 signal wires, two on each end of barrel. Eight located inside the dewar at various positions in hadronic and electromagnetic stacks. Four cold and warm flange pairs each bring signals from two RTDs (eight wires), two on each end of barrel. These four locations also have signals from eight TCs each.	Six strings containing twelve LED devices located inside barrel dewar. Six devices near bottom spaced nine inches apart, six devices near top one-half inch apart, two adjacent strings are offset to give four and one-half inch resolution near bottom and one-quarter inch resolution near top. Six warm flanges required for the 288 signal wires, three on each end of barrel.
Endcap Locations (Per Each Endcap)	Twelve located on outside skin of endcap dewars, four units on inner radius, eight units on outer radius, in fabricated aluminum brackets also containing one RTD. One warm flange is required for the 24 signal wires. Four located inside endcap dewar. One warm flange required for the eight signal wires.	Twelve located on outside skin of endcap dewars, four units on inner radius, eight units on outer radius, in fabricated aluminum brackets also containing one TC. One warm flange is required for the 48 signal wires.	Two strings containing twelve LED devices located inside endcap dewar. Six devices near bottom spaced 20 inches apart, six devices near top one-half inch apart, two adjacent strings are offset to give ten inch resolution near bottom and one-quarter inch resolution near top. Two warm flanges required for the 96 signal wires.

Figure 3 presents a block diagram of the analog processing functions on an instrumentation board. All of the analog measurements are ultimately digitized by the analog-to-digital converter within the 68HC11 microcontroller. The analog signal-processing paths consist of multiplexers which select a particular transducer, and offset and gain circuits which scale the result to the 5 V range of the 68HC11 A/D inputs.

The thermocouple measurements are made via an FET multiplexer which selects one of 24 (or less) T–type thermocouples within the vacuum space, or dewar, and a commercial monolithic TC amplifier with electronic ice point compensation. The TC amplifier output is offset in a precision difference amplifier, which subtracts a fixed offset corresponding to a 75°K temperature. This signal is amplified in two separate amplifier channels which provide dual range measurements of 75–100°K and 75–325°K. This dual range approach uses the 8 bit digitizer to allow approximately 0.1° resolution for operating temperatures, and 1° resolution during the detector cooldown, from ambient temperatures.

The absolute accuracy of this circuit is primarily determined by the stability of the ice-point compensation and the A/D conversion. The components have been selected so that the absolute accuracy achieved in the system is ±1.5°K. Of more importance is the relative accuracy between two TC channels. This accuracy should be > 0.2°K. Note that, due to the input multiplexing, all 24 (or less) thermocouples on a board are subject to the same offset and gain errors so that for differential temperature measurements only the TC amplifier gain stability determines the relative accuracy.

The RTD temperature measurements are made using a four-wire arrangement with current source excitation. As noted before, up to 12 RTD devices are multiplexed together on one board. An FET multiplexer selects a channel, allowing a precision 5 mA current source to excite the RTD, while a high input impedance instrumentation amplifier measures the voltage across the RTD. An injected offset zeros the output for a 75°K temperature and, just as in the TC circuit, a dual range amplifier arrangement provides 0.1°K and 1°K ranges.

The components used for the multiplexer, current source and instrumentation amplifier have been selected so that the overall accuracy is dominated by the RTDs themselves, allowing a ±1°K measurement accuracy. Again, due to the multiplexing, differential measurements using two RTDs provide relative temperature measurements of better accuracy than in the absolute temperature mode.

The LEDs used to measure the liquid levels in the dewars show a marked increase in forward-biased voltage when immersed in cryo liquids. At room temperature, the forward-biased voltage averages 2.5 V. This changes little, even when the diode is supported just a few millimeters above liquid argon. However, once immersed completely in liquid argon,

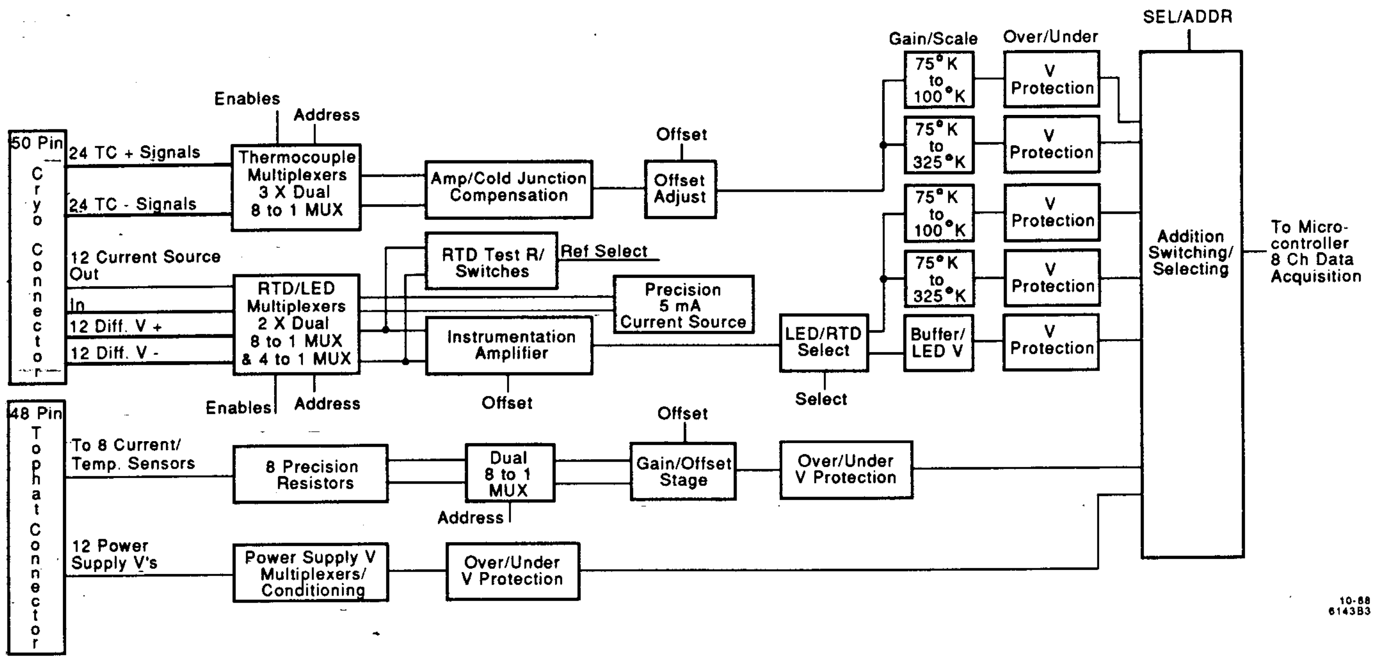

Fig. 3 Cryogenic instrumentation board analog circuit block diagram.

the forward-biased voltage increases immediately to approximately 3.0 V. The circuitry of the RTD excitation and multiplexing is utilized to drive the LED level sensors and measure the forward-biased voltage. A single voltage follower directly drives an A/D input of the 68HC11, bypassing the gain scaling of the RTD circuits.

Both the TC and RTD amplifier sections, as well as the accuracy of the A/D converter, can be tested by the resident 68HC11 microcontroller. A test mode can be software enabled, which connects known stable inputs to the TC amplifier and RTD instrumentation amplifier, and disables the outputs of the FET multiplexers. This test mode verifies proper operation of the gain and offset stages, and allows for possible software gain correction.

The monitor board measures conditions within the tophat, as well as in the cryo volume. Each of the 15 daughter boards (which contain 720 channels of calorimeter processing) has on it a temperature-to-current sensor whose current source resides on the cryo instrumentation board. A multiplexer and current-to-voltage converter allow the microcontroller to measure the daughter board temperatures. Additionally, the tophat contains 12 individual power supplies which the cryo instrumentation board conditions and digitizes, as well.

CURRENT STATUS

As of mid–October 1988, the cryo instrumentation prototype PCB has been fully tested in a working tophat in a laboratory environment. The hardware and software perform as expected and very few changes need to be made before final production begins. The cryo interface prototype PCB is in fabrication and, due to its relative simplicity, no problems are anticipated there. The software for the interface board has been fully debugged and interfaced with the instrumentation board software. The development of the monitoring computer software has not been started—however, the interface has been fully specified and is straightforward. The production quantities for all parts used in both the instrumentation board and interface board have been placed on order. Most have already arrived and the rest are expected to arrive well in time to install and integrate into the LAC, before the expected early–1989 initial cooldown.

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