SLAC-PUB-753
June 1970
(EXPI)

THE SLAC LH_2 TARGET CONTROL SYSTEM*

by

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Liquid Hydrogen (LH_2) is utilized as a target for the high energy electron beams, up to 20 GeV, available from the two-mile Stanford Linear Accelerator because hydrogen is the purest form of protons attainable and liquefaction increases the density of the protons available for bombardment. This paper will deal with the necessary control systems required for the LH_2 target, and special systems desired by experimenters.

Figure 1 is a sketch of the system. Components are situated at three or four locations. The target assembly itself is located directly in the beam line and is usually in an inaccessible high radiation area. The LH_2 supply is located outside the high radiation area as close to the target as possible and the controls are in an accessible location, near the experimenter's equipment.

The only component of the system of any interest to the experimenter is the LH_2 cell - target of the electron beam. Ideally the experimenter would like a mass of LH_2 suspended in a vacuum with a zero mass container. Since this is not yet available, they have accepted such materials as mylar (between 5 to 15 mils thick depending upon the size and shape of target), aluminum No. 6061 T-6 (3 to 6 mils), and stainless steel No. 314 (1 to 3 mils). The experimenter might be interested in any of the following parameters of this cell:

(Presented at the Third International Crogenic Engineering Conference, May 25-27, 1970, Kongresshalle, West Berlin, Germany

* Work supported by the United States Atomic Energy Commission

1. LH_2 level (full and empty)
2. Cell pressure
3. Cell temperature

Density determinants

An LH_2 reservoir is situated within the vacuum chamber above the LH_2 cell. In the case of "direct-fill" targets a valve allows the target to be gravity filled from the reservoir. In "condensation" type targets the LH_2 in the reservoir cools a heat exchanger which in turn cools pressurized hydrogen gas in the cell which condenses. In this case the LH_2 cell is isolated from the reservoir.

The reservoir capacity is generally between 50 and 100 liters and contains two independent techniques for measuring the LH_2 level. One technique uses carbon resistors to define a reservoir empty condition or an overfill condition (> 90% full). This is basically the same circuitry as that developed at Brookhaven[1] and utilizes a 300 Ω, 1/2 watt Allen-Bradley carbon resistor in a bridge circuit. At LH_2 temperatures with no current through the resistor, its resistance will increase to $\simeq$ 1100 Ω. In our circuit 150 milliwatts of power is dissipated in the resistor and a comparator trip level is set to $\simeq$ 620 Ω. Greater resistance than 620 Ω shows that the resistor is in liquid and less than 620 Ω shows gas. In actual operation there is a discrete jump in resistance when the resistor goes from a gaseous to a liquid ambient. This jump may be from 550 Ω to 700 Ω at the 150 mw dissipation level.

Figure 2 is a picture of the SLAC LH_2 continuous level indicator. This technique uses 32 silicon diodes connected in series and a 300 volt power supply, with a series resistor to power the diode string. The current in the string is monitored to indicate LH_2 level. All preliminary developmental work for this probe was done using LN_2. Three types of probes were considered for indicating LH_2 level: series connected diodes, series connected resistors, and a capacitance probe. Electronics associated with the diodes or resistors is much simpler than the capacitance probe which appeared to be most desirable from the mechanical designer's viewpoint because there is no power dissipation and output is insensitive to temperature changes. All three types were evaluated with the following results:

1. The resistor probe: Repeatability was poor and the $\frac{\Delta R}{\Delta T}$ was small in comparison with the diode probe. The results of two test runs are shown in Fig. 3. Due to the lack of repeatability of the probe we abandoned it in favor of the diode probe.

2. The capacitance probe: Considerably more electronics are required: an oscillator, a capacitance bridge, and detector circuitry. The factors we considered in deciding against the use of a capacitor probe were:

   The stray capacitance of feedthroughs, cables and connectors was greater than the capacitance change due to the difference in dielectric constant between the gaseous and liquid states. Since the dielectric constant increases by 20% when the gas liquifies, the maximum capacitance change is only 20% of the base capacitance of the probe. Extreme care must be taken to limit the capacitance to ground. These problems were never completely solved. After considering the simplicity of the diode probe we abandoned the capacitor probe.

3. The diode probe:[2] Although we knew of no previous work done with silicon diodes at $\sim LH_2$ temperatures, it appeared that they should exhibit a large $\frac{\Delta R}{\Delta T}$ and therefore present a reasonably large amplitude signal for processing. Initial tests were run with LN_2. Thirty-two diodes were

serially connected and spaced along a perforated epoxy board approximately 25 cm long. The board was suspended vertically in a dewar with an indicating float. LN_2 was added and both float levels and diode current recorded. Figure 4 is a sketch of the test set up. The test results for 5 fill cycles using this circuit are shown in Fig. 5. The voltage supply shown in Fig. 4 is adjusted to cause a current of 1 mA to flow through a 1 K Ω sensing resistor when the probe is totally immersed in LN_2. This voltage averaged approximately 32 volts for 32 diodes. Allowing for a higher voltage requirement when immersed in LH_2, an automatic fill system was designed for the target utilizing this diode probe, and the voltage was set at 90 volts. When we first attempted to fill the reservoir with LH_2, the probe failed miserably. It oscillated between full on and full off with lights flashing and relays chattering and the system looked like a pinball machine. Diagnosing the problem, it became apparent that there was insufficient voltage available from the power supply to sustain conduction at the LH_2 temperature. All of our previous tests had been performed at LN_2 temperatures ($\simeq 77^\circ$ K), but since LH_2 ($\simeq 20^\circ$ K) is so dangerous to work with, we decided to perform some additional tests at Liquid Helium ($\simeq 4^\circ$ K) temperatures. A test set up consisting of a constant current generator, series resistor, and a diode immersed in LHe was assembled.

The diode selected for use in our probe is type 1N3064 manufactured by Computer Diode Corporation (No. CDC 6611). A voltage vs. current curve was obtained at LHe temperatures (Fig. 6) and an examination of this curve lead us to conclude that there appeared to be a negative resistance region on the curve since the current increases as the voltage decreases. This characteristic is similar to the V-I characteristic of gas tubes, which require a certain voltage to ignite then regulate at a lower voltage. This diode in LHe requires more than 12 volts before it will conduct but requires less than 3 volts to sustain conduction currents of ≥ 50 mA.

Next we decided to try the same test using LH_2. The results are shown in Fig. 7. The shapes of the curves are quite similar, the voltage necessary to initiate conduction in LH_2 is lower (approximately 9.5 volts). Data points were taken at a fixed current of 1 mA for three cryogenic liquid environments: LHe, LH_2 and LN_2. This curve is shown in Fig. 8. From this curve a linear approximation over the range LHe to LN_2 can be made. The empirical relationship is:

$$V_{(1mA)} = \left\{ 12.2 - 0.15\ T \right\} .$$

The basic diode equations [3] of $I = I_o \left(\epsilon^{\frac{nV}{V_T}} - 1 \right)$ do not hold in the temperature range of LHe and LH_2. Actually this is what appears to be occurring at the diode junction:

(i) With no voltage impressed and no power dissipated within the diode, the junction reaches thermal equilibrium at the temperature of the liquid cryogen. After sufficient voltage is impressed on the diode to cause current flow, power is dissipated and heat is generated at the junction. However, as long as current flow is low enough the thermal conductivity of the diode removes the generated heat and the junction temperature remains low and fairly constant and the voltage required for conduction does not decrease. As the current through the junction is increased though, power dissipation increases until a point is reached where the thermal conductivity is not enough to transfer heat from the junction fast enough, the junction temperature increases, and a lower voltage is required to sustain the same current through the diode. Therefore, if the voltage is held constant, the current will continue to increase - a negative resistance characteristic (see Fig. 7). More effort is being planned to expand the available information on this subject. One possible use for this phenomena is as a very simple but extremely low power level sensor. If a voltage below the conductive threshold is applied to the device when it is in a liquid cryogen, virtually no conduction occurs, and no power is dissipated. As the device comes out of the liquid the heat transfer away from the junction is lessened and the junction temperature rises, causing the device to conduct.

The Semiautomatic Vacuum System

A fully automated vacuum system for our LH_2 target systems would not be too difficult to design but the vacuum systems themselves have not reached the state of the art where a fully automatic system would save time. It has been demonstrated at SLAC that a vacuum system operates more efficiently if an operator is included in the decision-making process and the electronics is used to do three things:

1. Display the necessary information of vacuum levels and valve status.
2. Prevent the operator from making an error by opening a valve when it should not be opened.
3. Limiting cell pressures.

Figure 9 is a typical vacuum system used for the E-41 target. The logic restrictions placed on the valves are shown in the table on Fig. 9. Figure 10 is the electronic circuitry utilized to perform this protective monitoring. The circuit utilizes standard Motorola 5 volt integrated logic circuits mounted on a plug-in printed circuit board. On initial installation there were excessive unwanted multiple valve closings. To get the system to operate satisfactorily all DC voltages used to verify valve positions (clear signals on Fig. 10) were bypassed with small 1.0 μfd capacitors located right on the printed circuit board. The normal operating logic level for these I.C's is 5 volts. A +25 volts supply on the chassis was used for tripping the I.C.'s and was attenuated to a +5 volt signal on the printed circuit board itself. Once these changes were made, the system functioned beautifully.

The Air Flow Monitor

Each LH_2 target at SLAC has an air blower associated with it capable of exhausting the air surrounding the target within a minute. The early targets had a two-speed blower which normally operated at low speed until one of the hazardous atmosphere detectors sensed H_2. The blowers were then switched to the high speed to remove the H_2 as quickly as possible. In the latest target design the blowers operate at high speed continuously and an independent airflow monitor circuit monitors this function. Should the airflow rate drop below a preset level, alarms are actuated which call the operator to the target. Figure 11A is a picture of the airflow monitor; Figures 11B, C and D are schematics. The sensor itself consists of two thermistors self-heated to a temperature of approximately 200°C. One thermistor (the reference) is isolated from the airstream and the other is directly in the flow path. The two thermistors are wired in a bridge circuit. Airflow past the sensor thermistor cools it and offsets the bridge indicating a safe condition. During initial testing of this circuit, a cold mass of air would cause the sensor thermistor to latch off with an extremely long recovery. A special circuit to sense this condition and boost the voltage available to the thermistor is incorporated in the control units. Depending on the shroud covering the sensors, the device will sense a very gentle airflow of a foot per second or, depending on the shroud, a high velocity limited only by the ability of the device to sustain the mechanical stresses.

H_2 Detectors

The manufacturer selected to supply the hazardous atmosphere detectors (HAD's) for the hydrogen target system was General Monitors, Inc. of El Segundo,.California. These units operate satisfactorily as long as they do not remain in a hydrogen contaminated atmosphere very long. Continued operation in this environment results in deterioration of the detecting element - a dangerous condition since hydrogen gas could be present but undetectable. The detectors used on the hydrogen target are in a H_2 environment only during a fault condition which should not last any longer than a few minutes. Regular maintenance checks are made on the elements to insure their proper operation and each target system has redundant detectors. Detection of a hazardous atmosphere causes the automatic fill system to latch off, audible alarms to sound and lights to flash locally and at a remote control point.

Pressure Transducers

The standard pressure transducer we use is the Computer Instruments Corporation (CIC) Model 4000. Its range is 0 to 60 psia with a 500 Ω resistance element and is used with our vapor pressure bulbs for temperature measurement of LH_2 and remoting this information. The experimenters use these devices to monitor the hydrogen cell temperature and, in addition, when the temperature begins to increase, an alarm system alerts them to a possible problem. Figure 12A is a picture of our temperature monitoring circuits; Figures 12B, C and D are schematics.

System

Figure 13 is a picture of our first LH_2 target control system. It is the control system used for our less complicated direct fill targets: the top chassis contains logic and switching for the vacuum system, status summary for all the protection systems, and reservoir filling status and control. The chassis immediately below the top one displays the LH_2 level status in both the reservoir and the cell. The diode probe is controlled and read out from this chassis; so this chassis controls the LH_2 reservoir level automatically. Below this chassis is a recorder for monitoring signals such as reservoir level. The two chassis immediately below the recorder are the HAD controls. Below these two are the vacuum gauge controls. The lowest chassis is an electrical circuit breaker for the rack and above this is the air solenoid chassis with air solenoids to supply air pressure to open and close valves mounted on the target. These controls could normally control a simple type "B" direct fill target. An experimenter wanting background information would occasionally like to direct the beam into the cell without any LH_2 present. To do this, he closes valve V_2 which closes off the vent line from the cell and pressure increase due to heat leaks forces the LH_2 back into the reservoir. When he wishes LH_2 to be present in the cell he opens the valve and the cell will gravity fill from the reservoir. Depending upon the size of the cell the emptying operation may take from

1 minute to an hour. The experimenters operating in our End Station A have chosen to use a condensing type target with a separate dummy cell, and, by moving the target vertically, they can select a dummy or LH_2 target with a minimum of delay (less than a minute). Once this system was perfected they chose to have an LD_2 target with a dummy cell along with the LH_2 system. In addition, we provided a total of 9 separate solid targets for them. Our latest target installation (E-49a) has a total of 13 possible target selections with target selection control done in two ways: (1) An encoder is attached to a drive motor and reading corresponding to certain target positions are determined. When a certain target is desired, the corresponding number is dialed into the control chassis and the target will be positioned automatically. (2) Selector switches, corresponding to different possible targets, are depressed and the target is moved until a second positioning switch is actuated.

After working with the control systems for a few years, we decided to improve the system to make it easier and clarify the operation of various valves. Figure 14 is the result of this attempt. The control system displays and controls have been integrated into a flow diagram. Figure 15 is included to show the complexity to which the control system has grown.

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3. Transistor Engineering, A. B. Phillips, McGraw-Hill (1962).

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   Domingo Cheng
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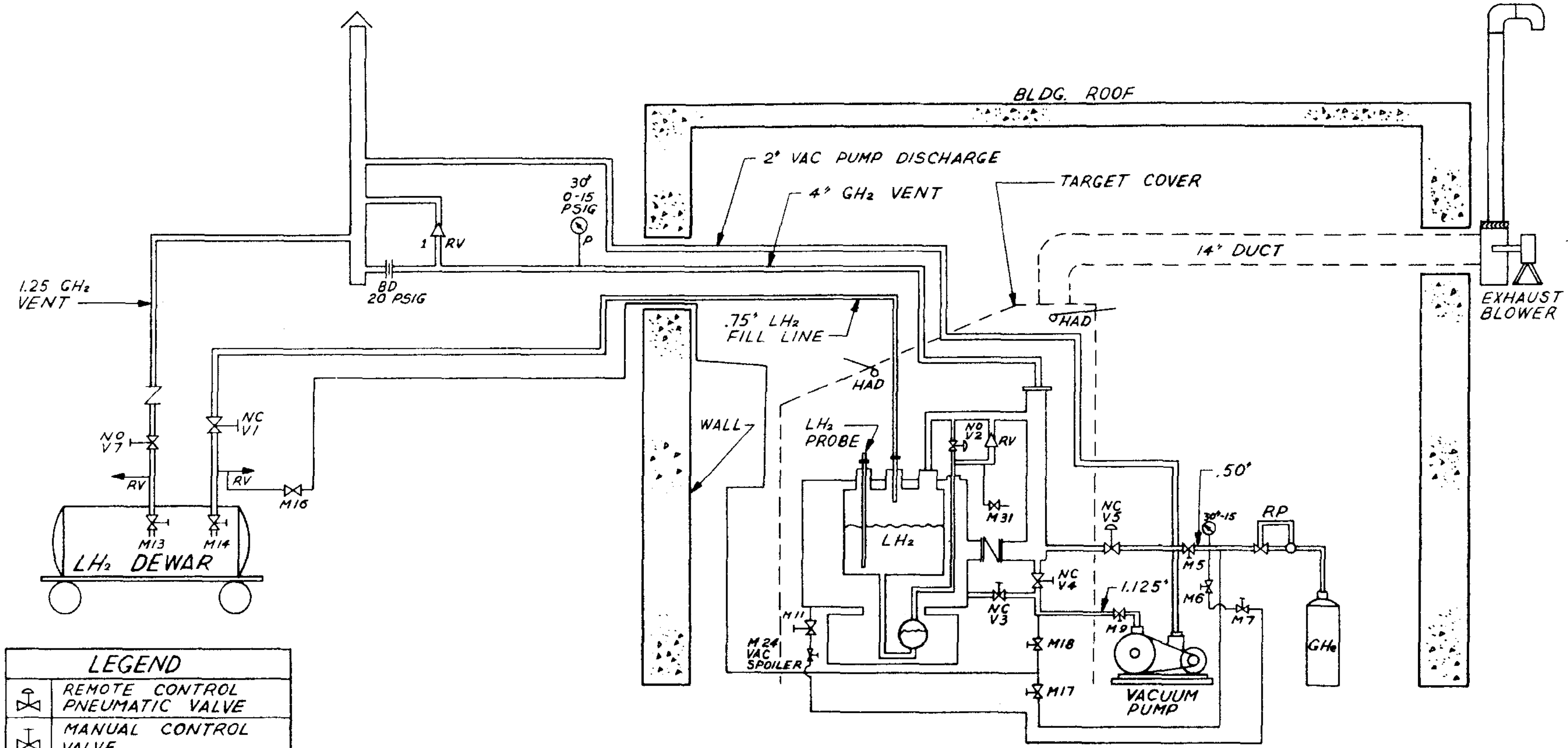
   Randolph Champion
   Wesley Adams



LEGEND	
	REMOTE CONTROL PNEUMATIC VALVE
	MANUAL CONTROL VALVE
NO	NORMALLY OPENED
NC	NORMALLY CLOSED
P	PRESSURE GAUGE
PR	PRESSURE REGULATOR
RV	RELIEF VALVE
BD	BURSTING DISC
PT	PRESSURE TRANSDUCER
HAD	HAZARDOUS ATMOSPHERE DETECTORS

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FIG. 1--LH_2 target system.

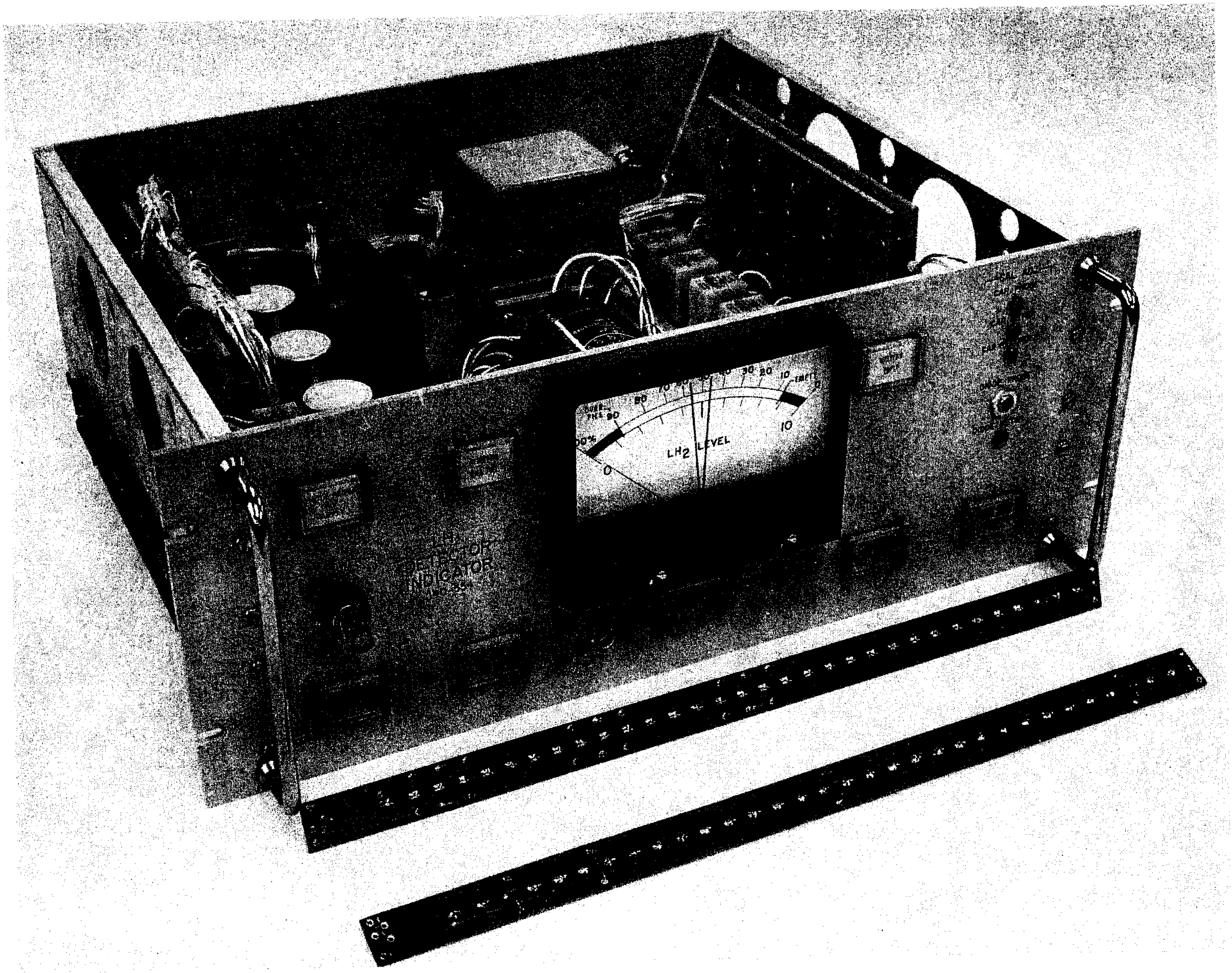

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FIG. 2--Diode probe with control unit.

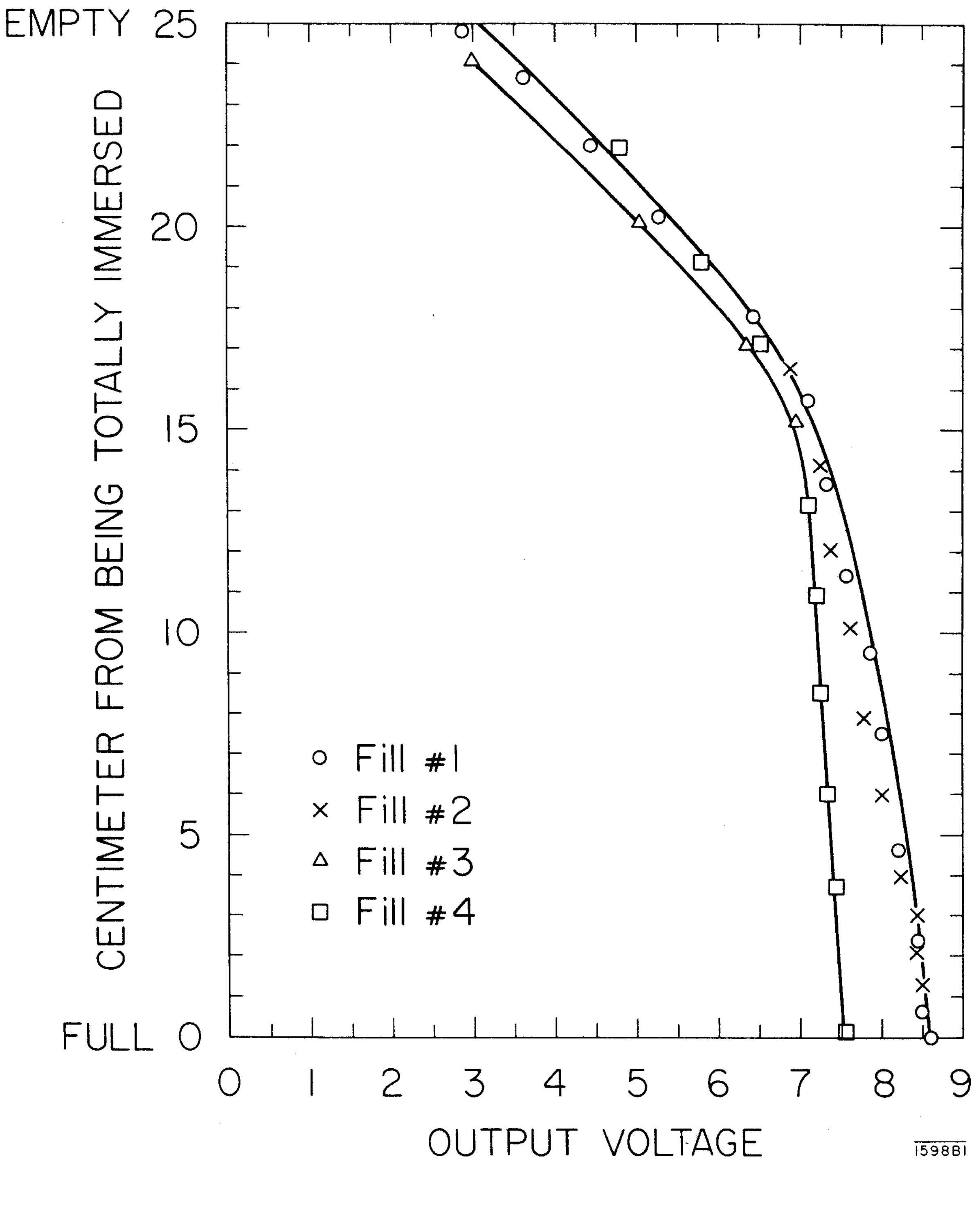


FIG. 3--Resistor probe voltage vs. LN_2 level. (47 each, 10Ω, $\frac{1}{2}$W resistors in LN_2.)

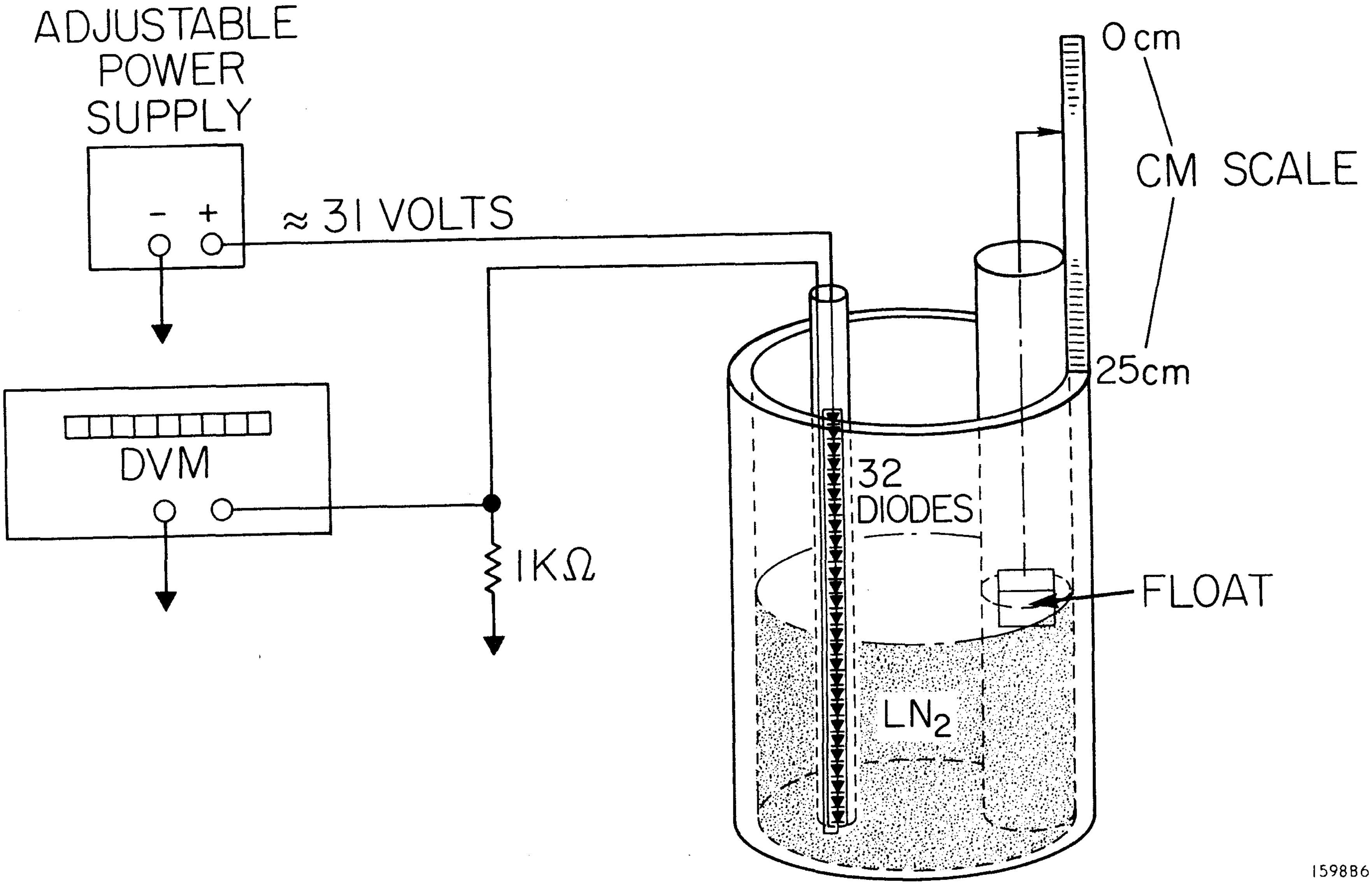


FIG. 4--Diode test setup.

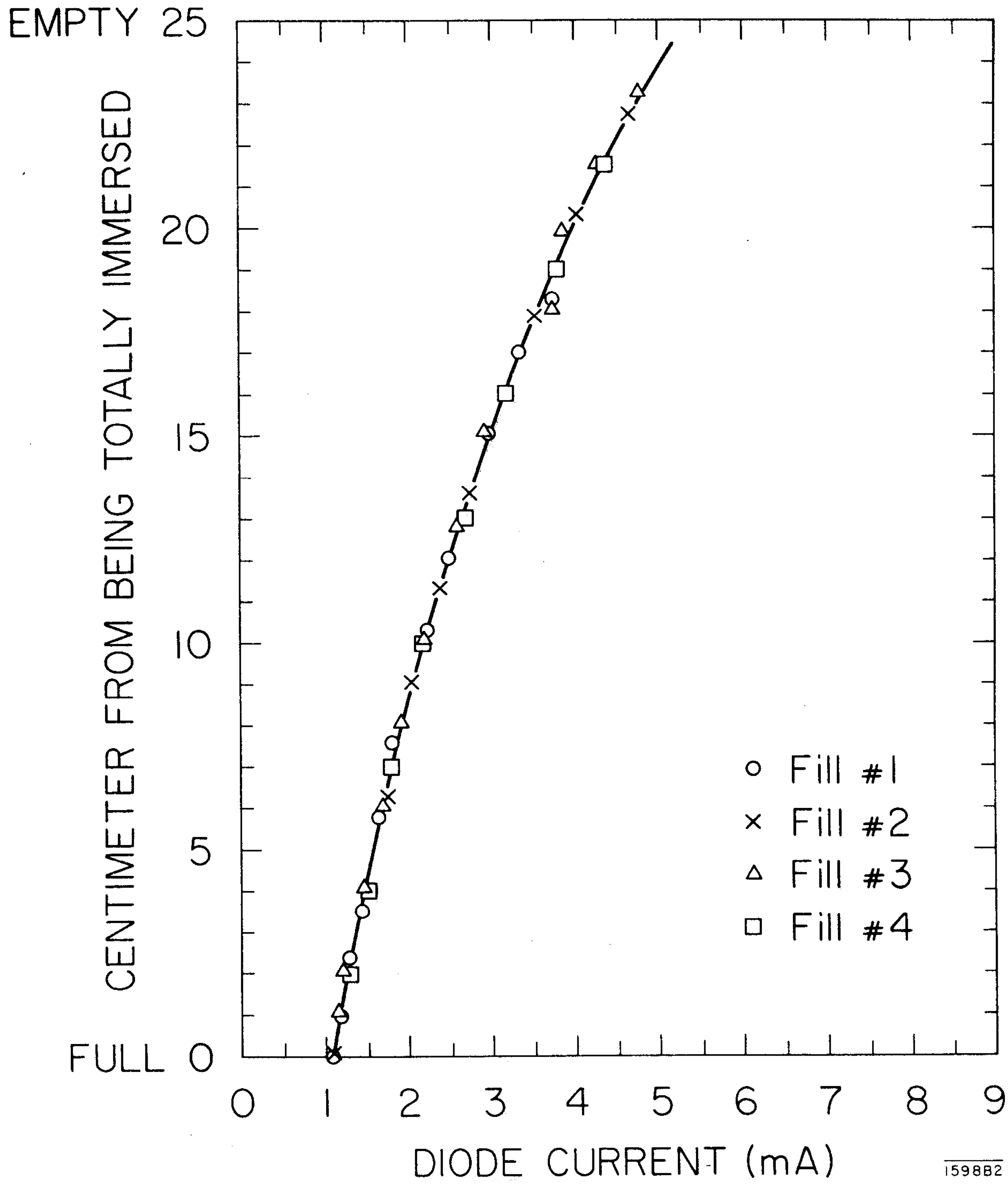
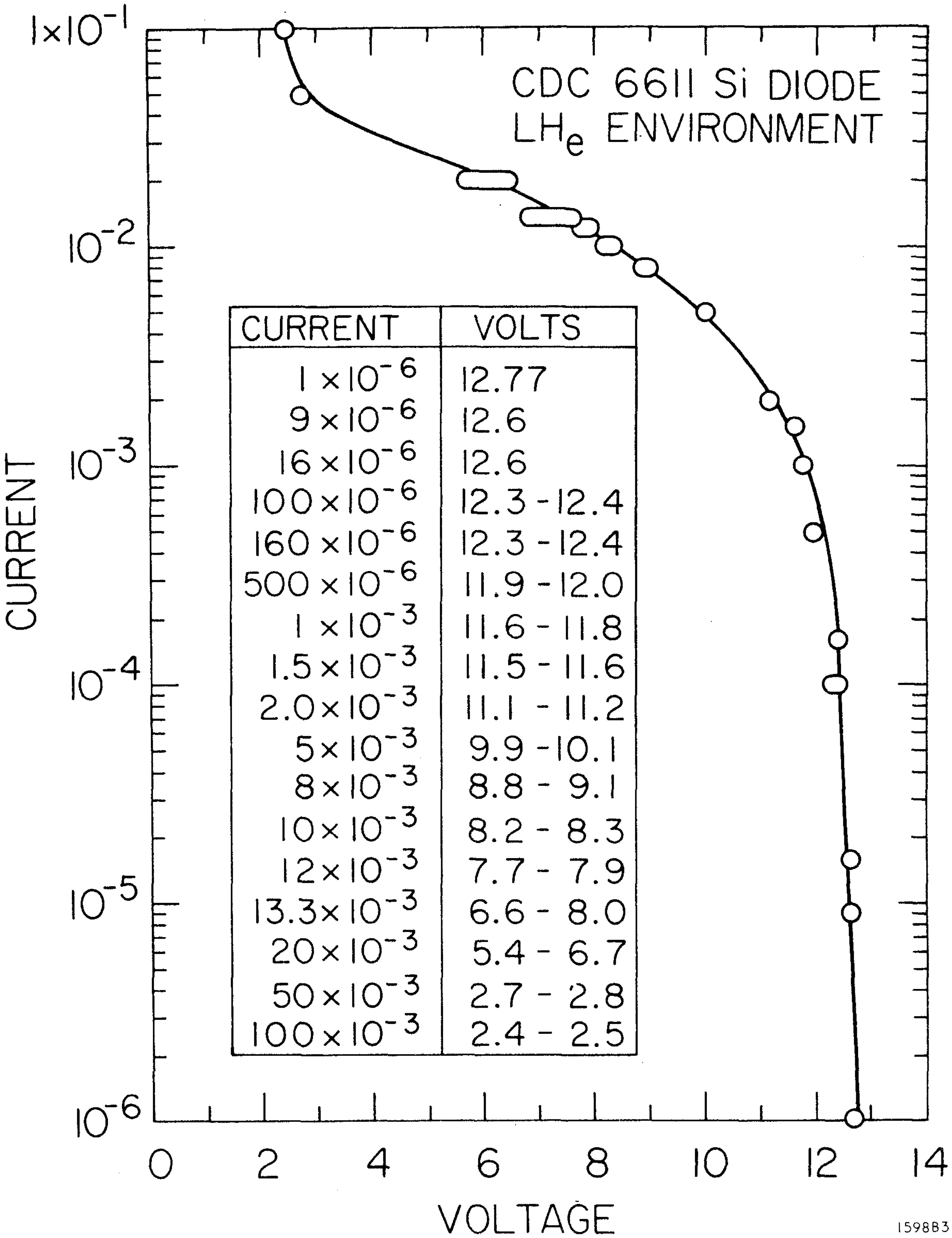
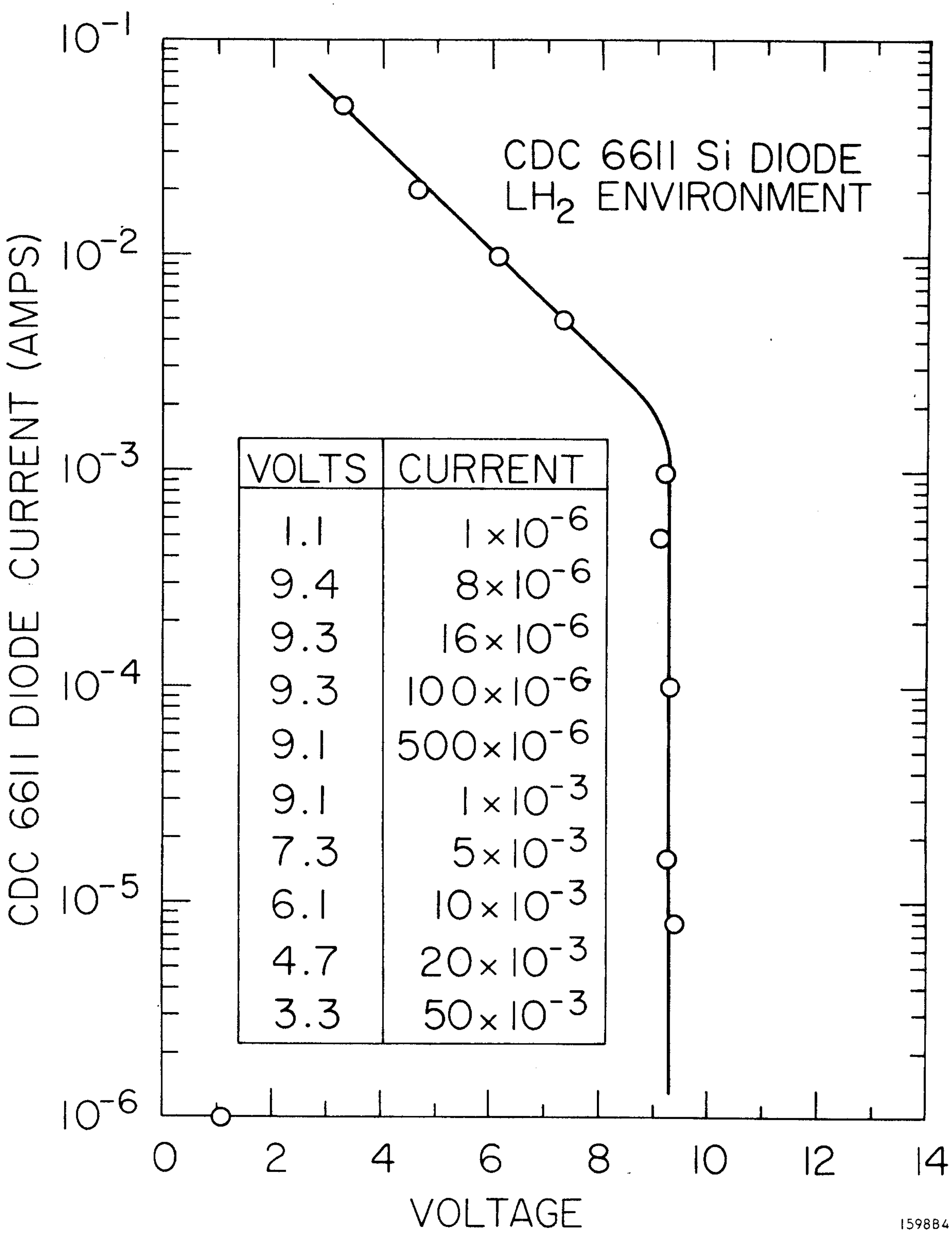


FIG. 5--Diode probe current vs. LN_2 level.
(32 each, CDC 6611, four separate fills.)



CURRENT	VOLTS
1×10^{-6}	12.77
9×10^{-6}	12.6
16×10^{-6}	12.6
100×10^{-6}	12.3 - 12.4
160×10^{-6}	12.3 - 12.4
500×10^{-6}	11.9 - 12.0
1×10^{-3}	11.6 - 11.8
1.5×10^{-3}	11.5 - 11.6
2.0×10^{-3}	11.1 - 11.2
5×10^{-3}	9.9 - 10.1
8×10^{-3}	8.8 - 9.1
10×10^{-3}	8.2 - 8.3
12×10^{-3}	7.7 - 7.9
13.3×10^{-3}	6.6 - 8.0
20×10^{-3}	5.4 - 6.7
50×10^{-3}	2.7 - 2.8
100×10^{-3}	2.4 - 2.5

FIG. 6--Voltage vs. current. (CDC 6611, Si diode, LHe environment.)



VOLTS	CURRENT
1.1	1×10^{-6}
9.4	8×10^{-6}
9.3	16×10^{-6}
9.3	100×10^{-6}
9.1	500×10^{-6}
9.1	1×10^{-3}
7.3	5×10^{-3}
6.1	10×10^{-3}
4.7	20×10^{-3}
3.3	50×10^{-3}

FIG. 7--Voltage vs. current. (CDC 6611, Si diode, LH_2 environment.)

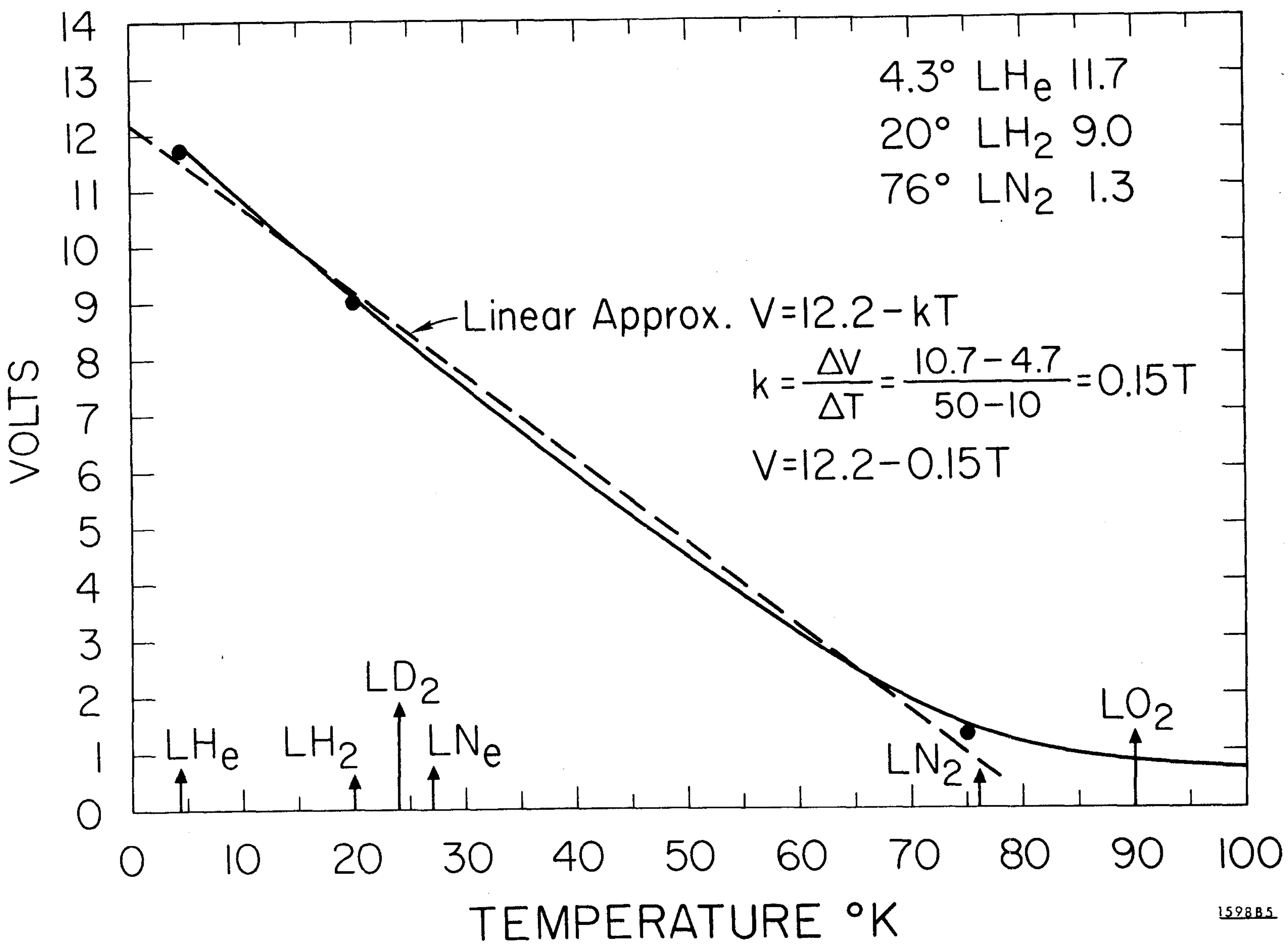
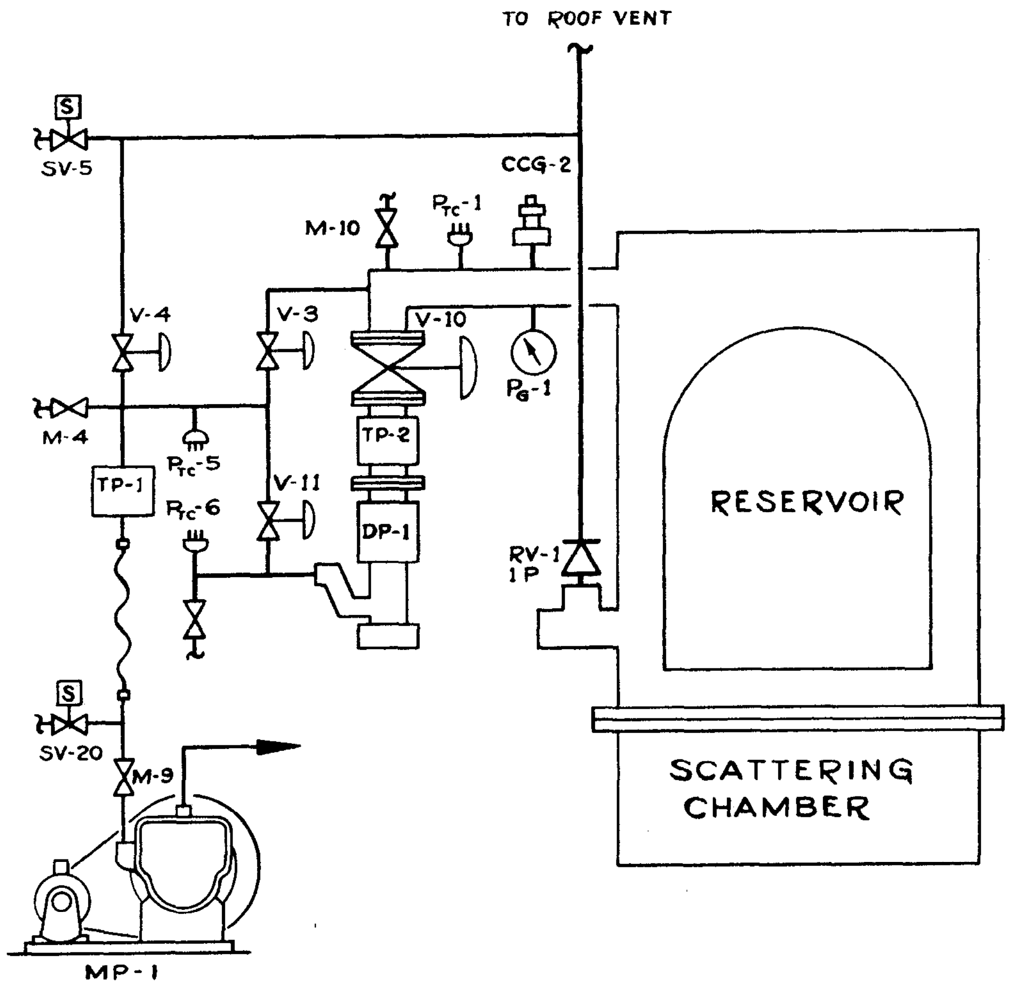


FIG. 8--Volts required to initiate 1 mA conduction in a CDC 6611 silicon diode vs. cryogenic temperatures of liquid cryogen.



FUNCTION OR OPERATION REQUESTED	LOGIC RESTRICTION
1. Mechanical Pump On	A. Motor not overheated.
2. Diffusion Pump On	A. Vacuum at PTC-6 above set point. B. Thermo-switch o.k. C. MP-1 on.
3. Open V-4 (Vacuum Purge)	A. MP-1 running. B. V-3 closed. C. V-11 closed.
4. Open V-3 (Mechanical Pump Vacuum)	A. MP-1 running. B. V-4 closed. C. V-11 closed. D. V-10 closed.
5. Open V-11 (D.P. Foreline Vacuum)	A. MP-1 running. B. V-4 closed. C. V-3 closed.
6. Open V-10 (D.P. Isolation)	A. Vacuum at PTC-6 below set point. B. V-3 closed. C. DP-1 running.
7. SV-20 Automatic Opening	A. MP-1 off. B. V-3 closed. C. V-4 closed. D. V-11 closed.

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FIG. 9--Typical vacuum system.

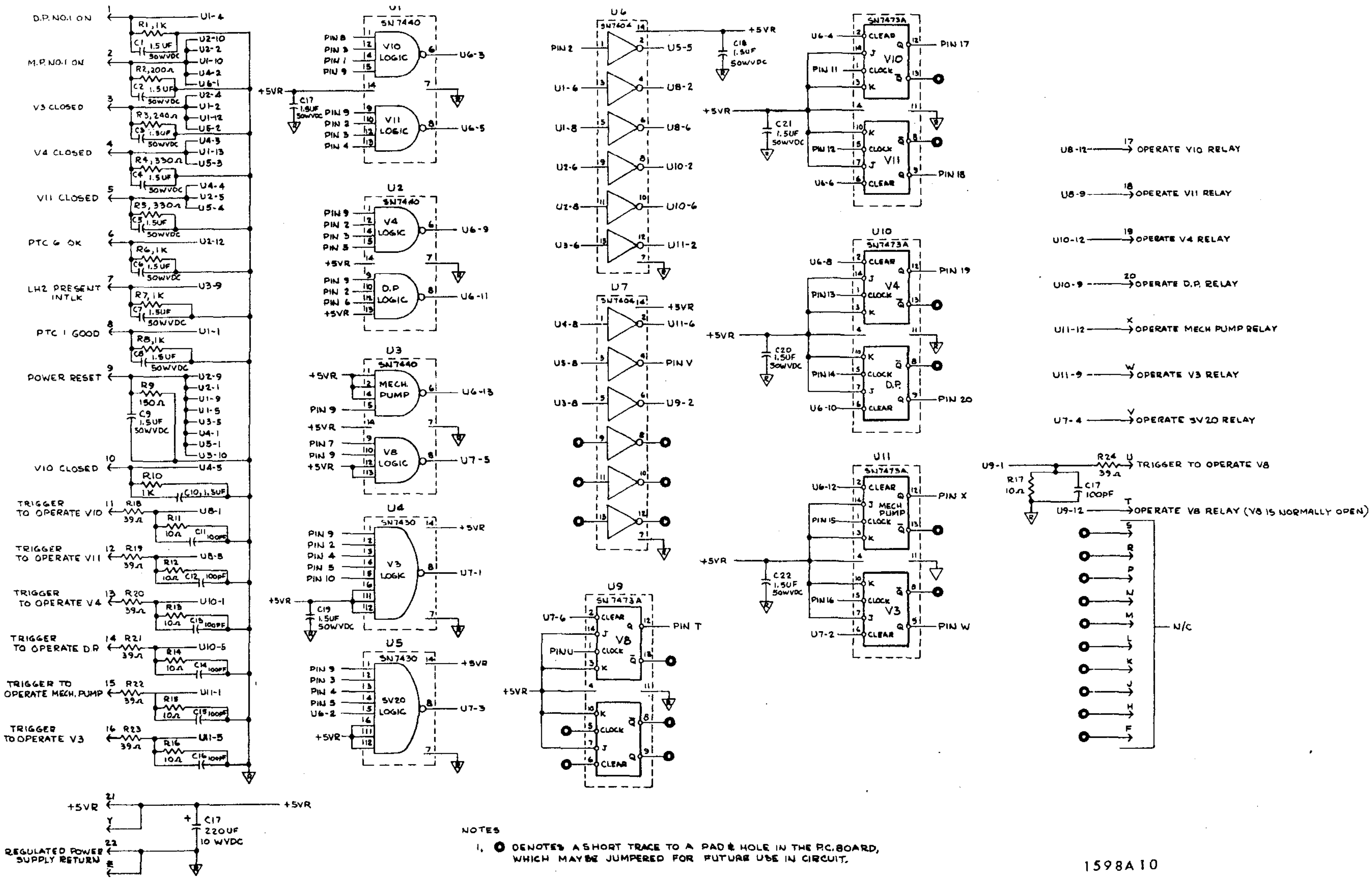

FIG. 10--Integrated circuit vacuum logic P.C. board.

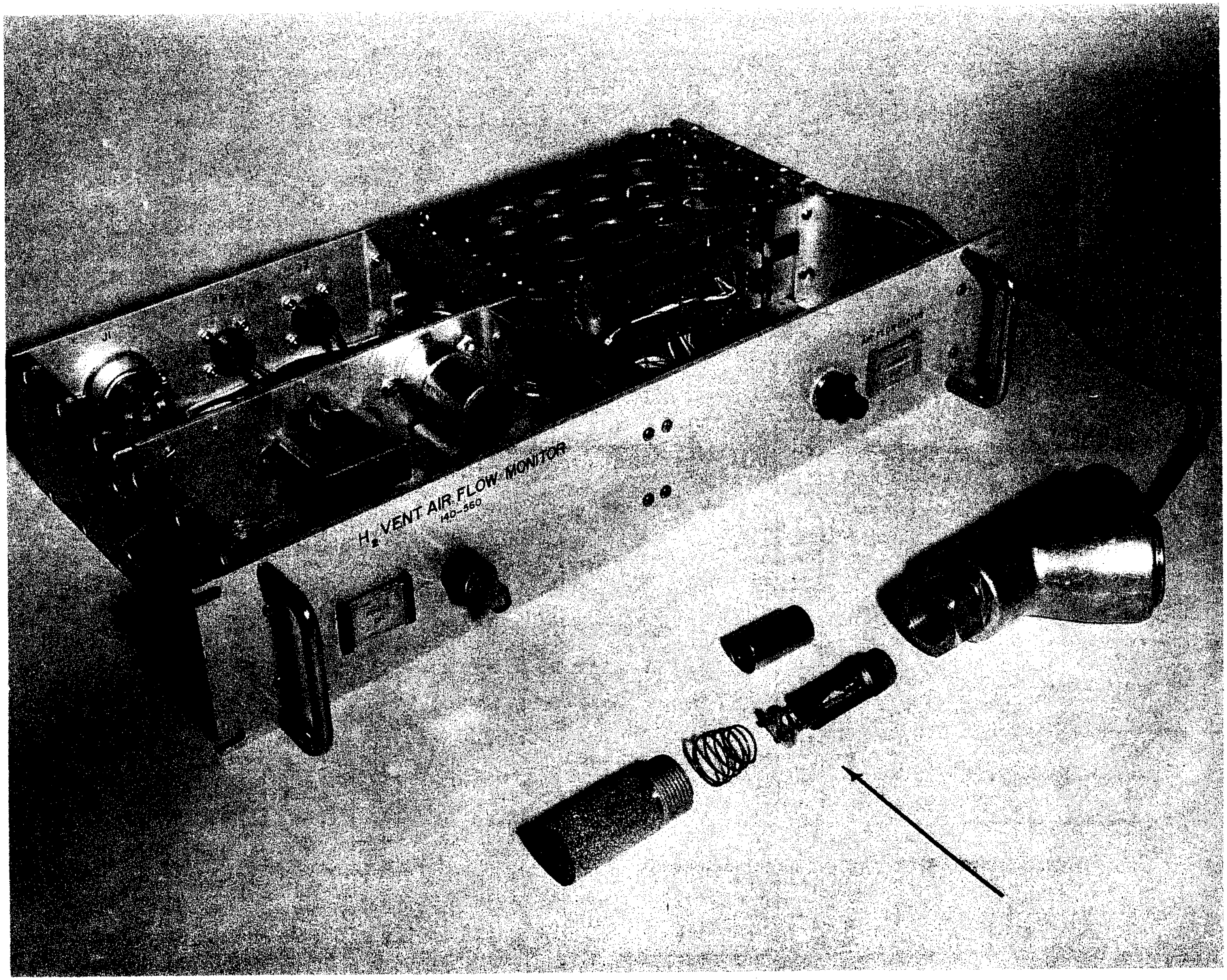

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FIG. 11a

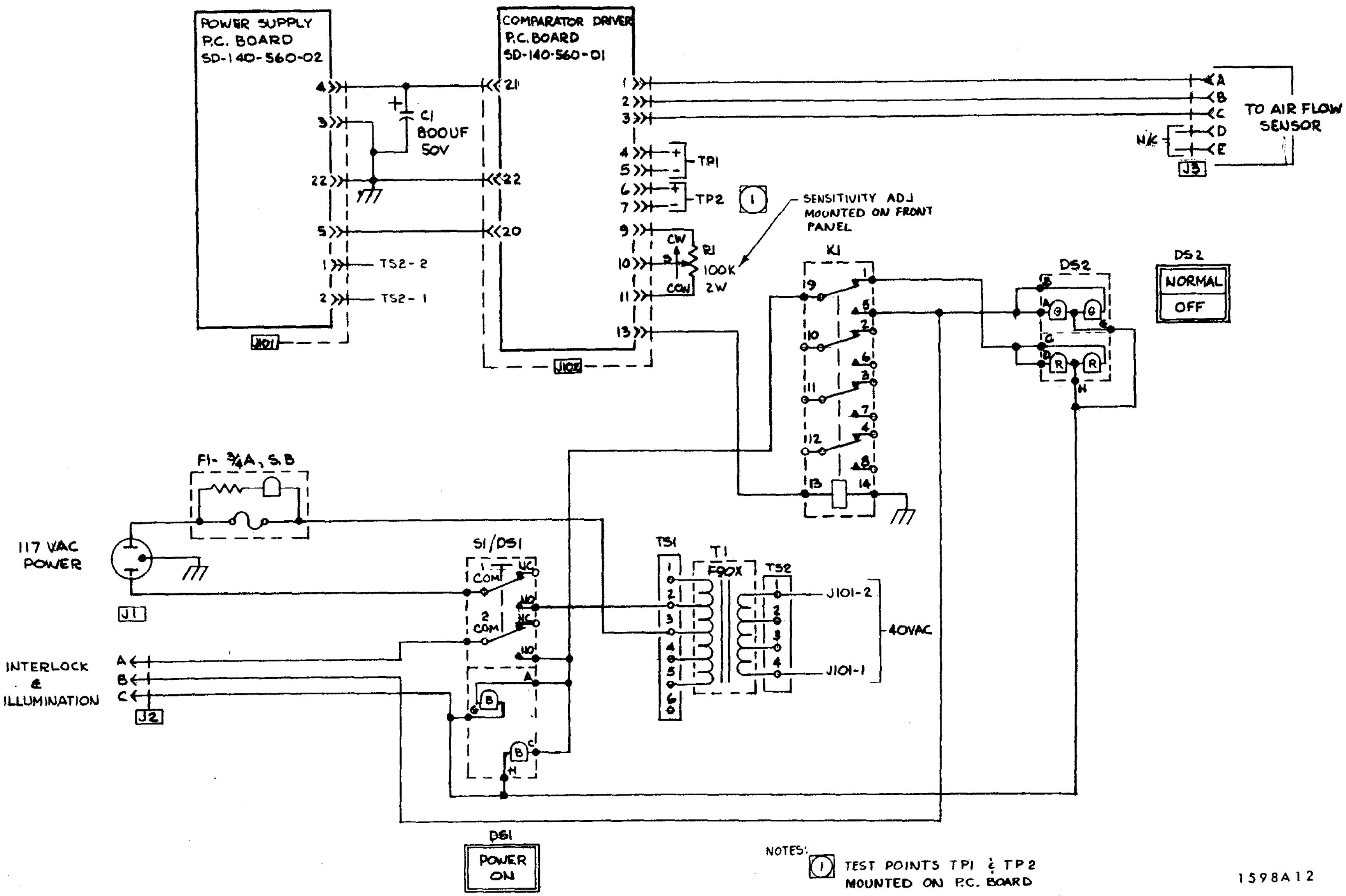
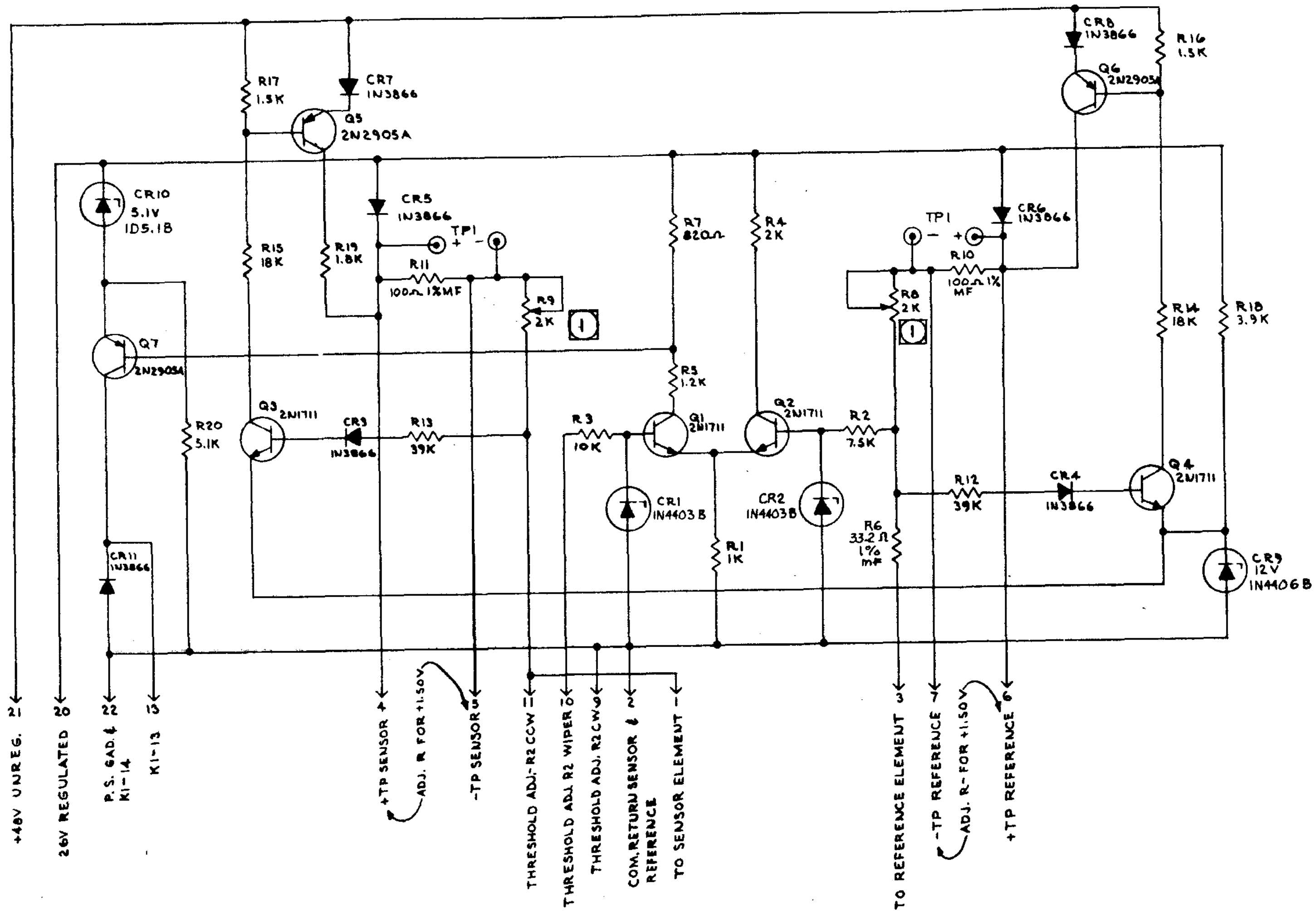


FIG. 11b--H_2 vent air flow monitor.



NOTES:

1. R8 & R9 ARE ADJUSTED TO READ 1.50V AT SENSOR & REFERENCE TEST POINTS WITH DETECTOR HEAD INSTALLED IN VENT AND BLOWER MOTOR OFF.
2. TP'S ARE TO BE BROUGHT OUT TO PIN JACKS AT TOP OF CARD.

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FIG. 11c--Comparator driver P.C. board – H_2 vent air flow monitor.

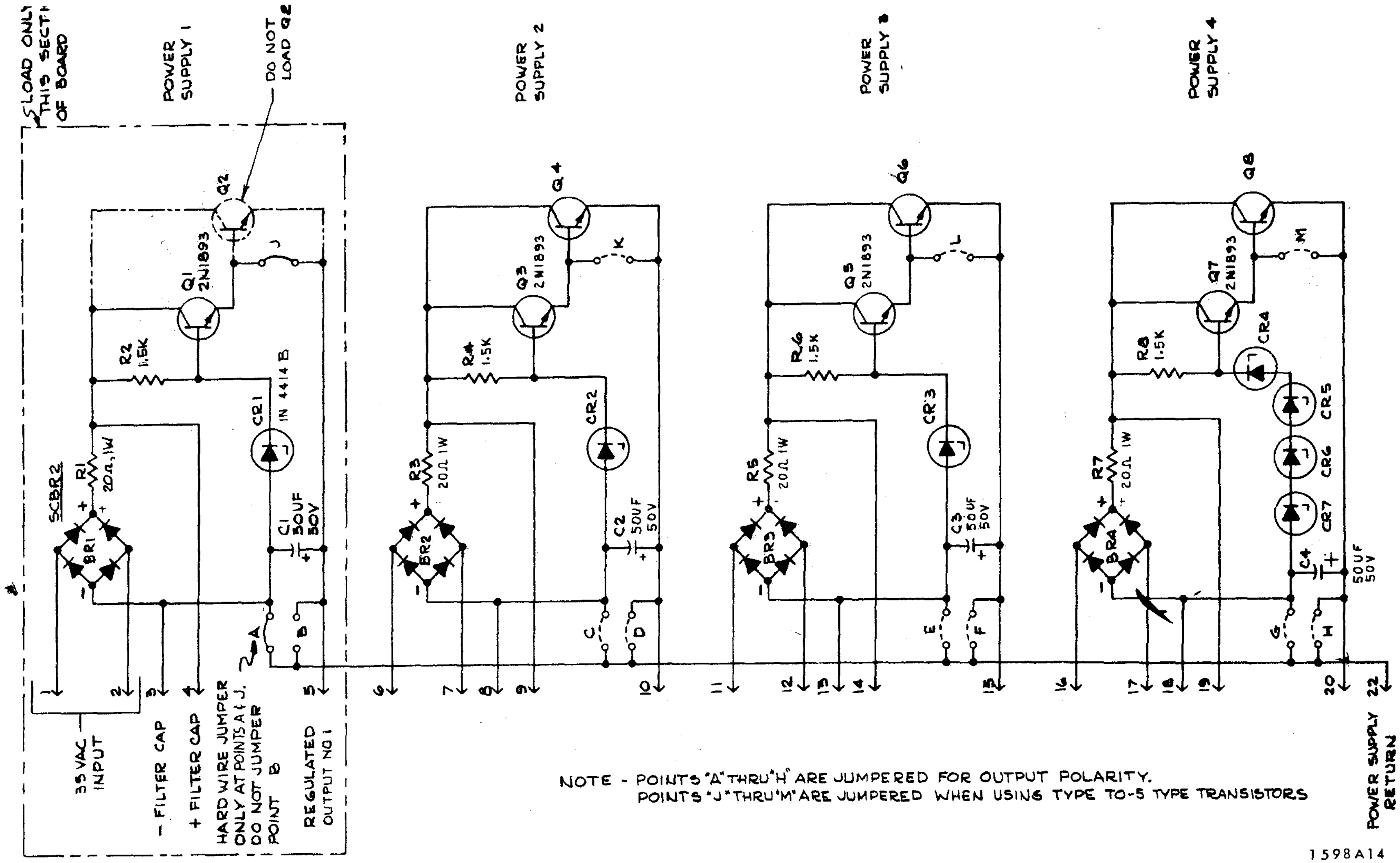

FIG. 11d--Power supply P.C. board — H_2 vent air flow monitor.

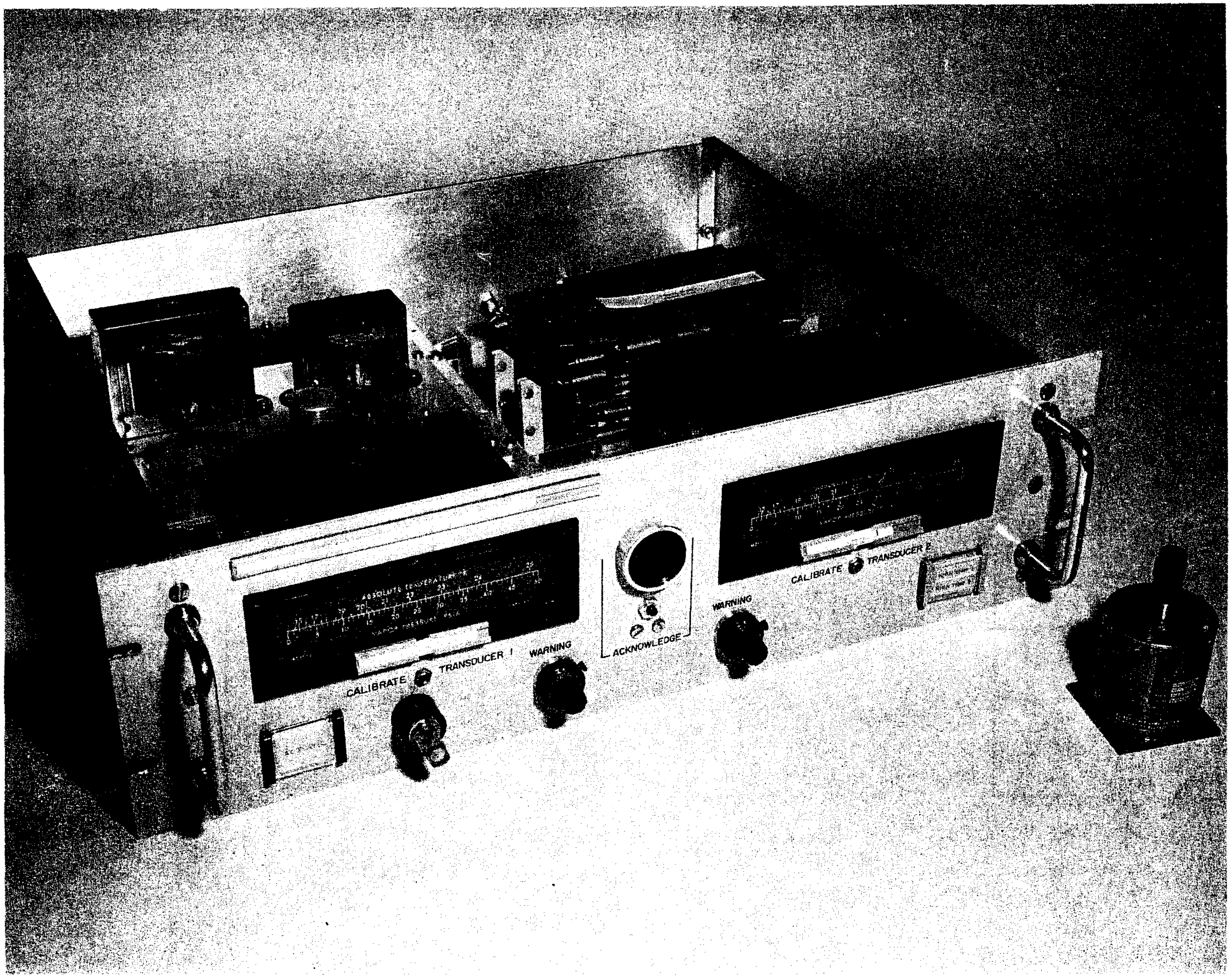

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FIG. 12a--Cryometer control.

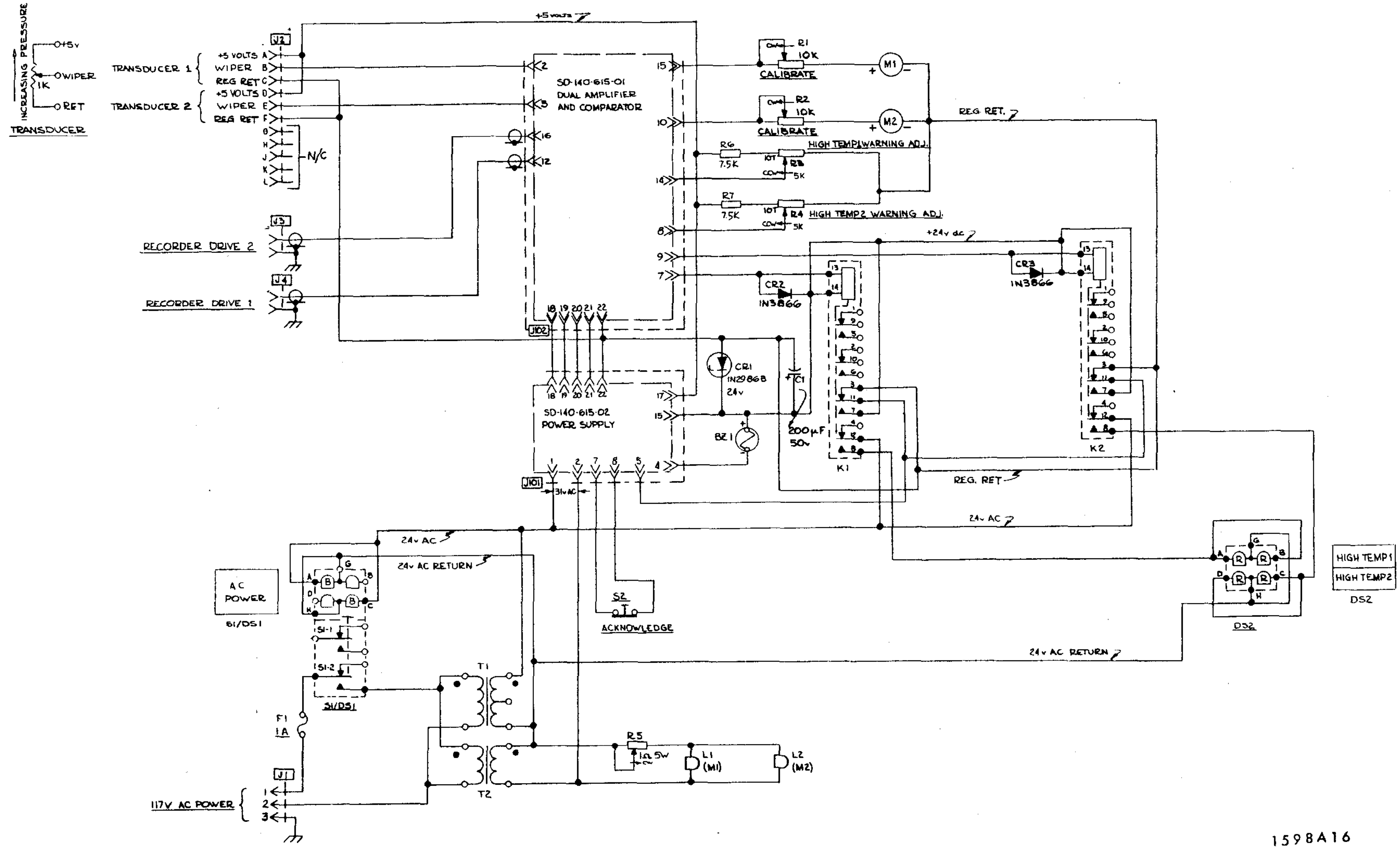

FIG. 12b--Cell temperature indicator.

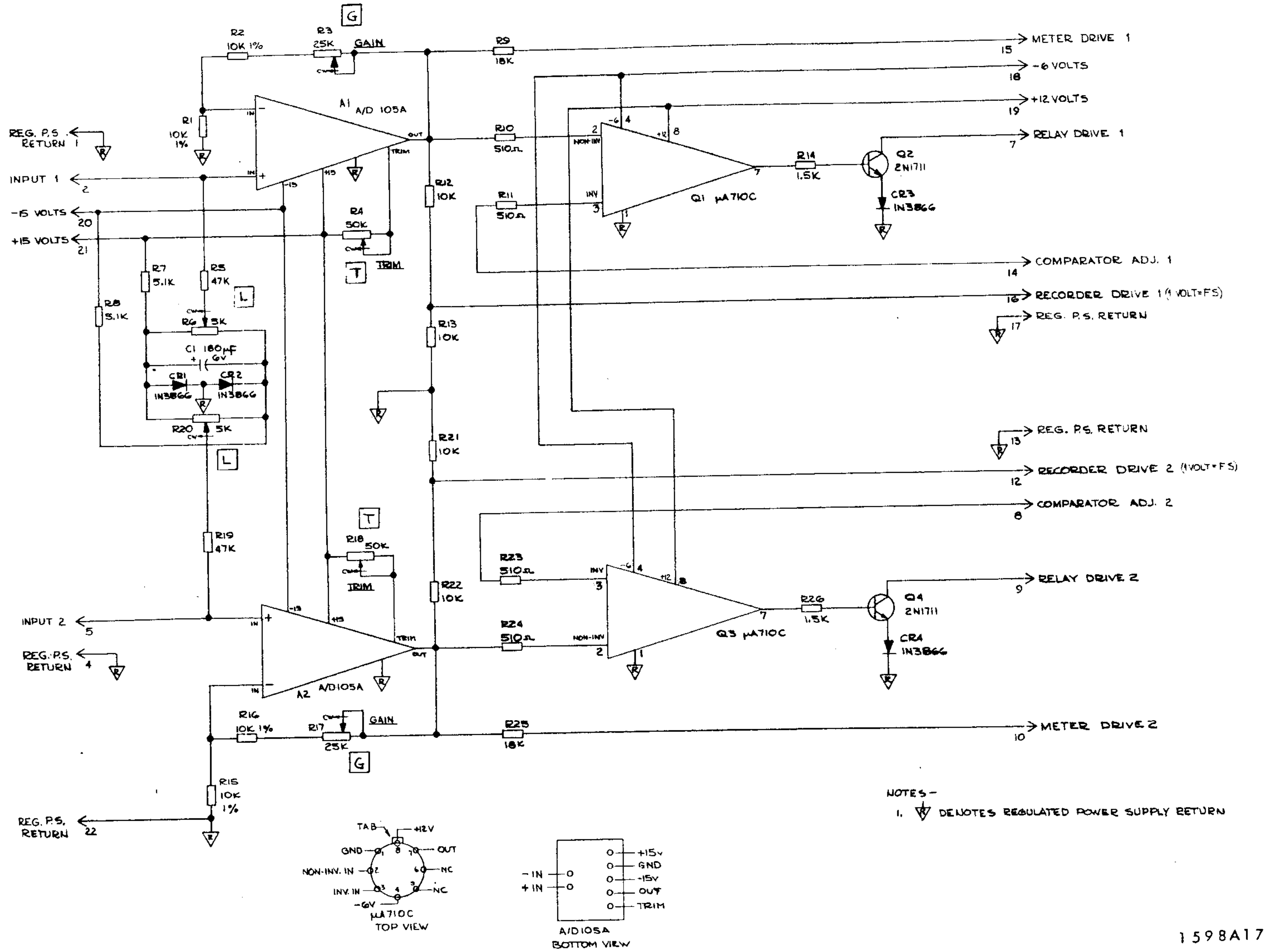

FIG. 12c--Dual amplifier and comparator P.C. board.

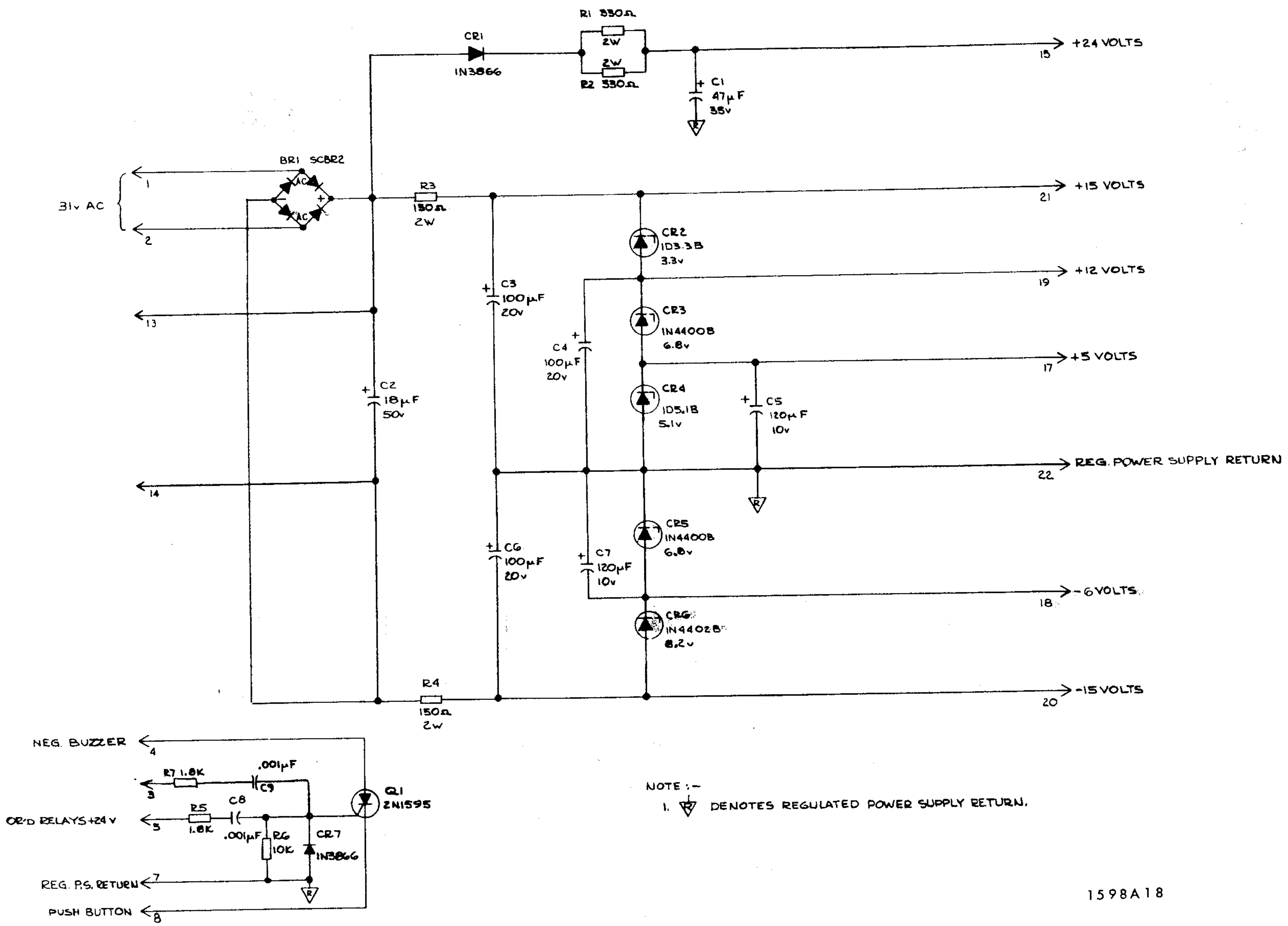

FIG. 12d--Power supply P.C. board — cell temperature indicator.

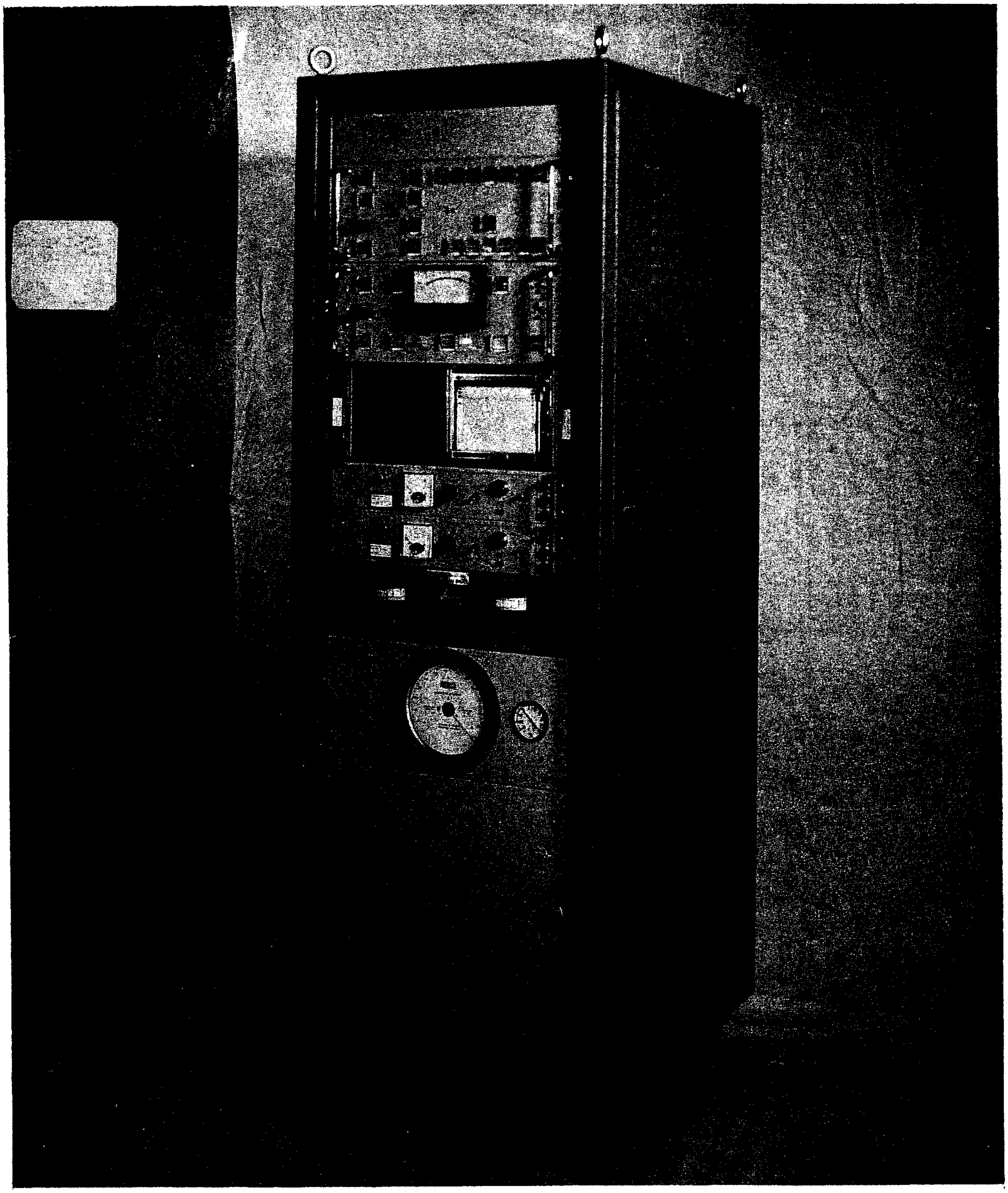

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FIG. 13--Typical "B" target control.

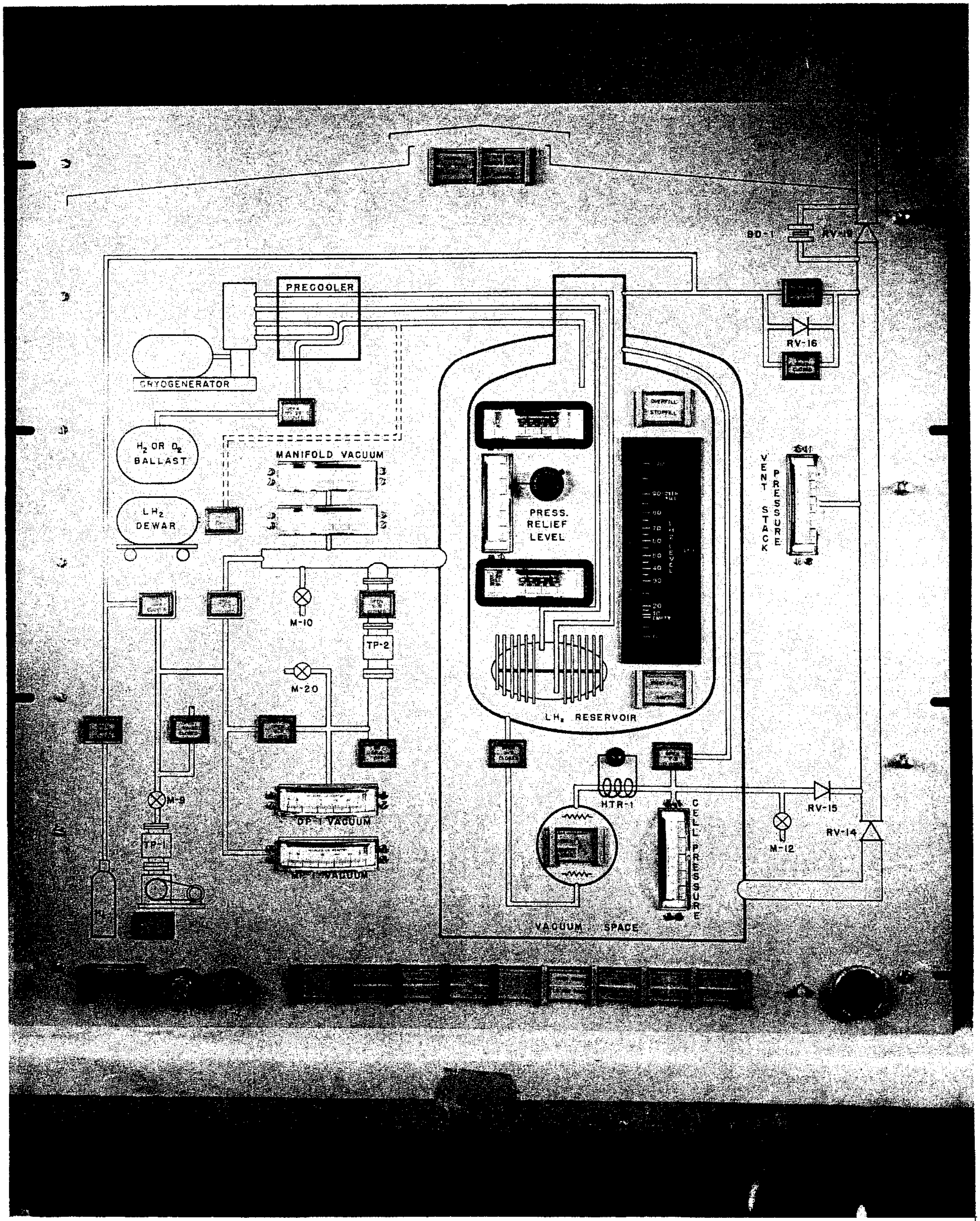

FIG. 14--Latest model target control.

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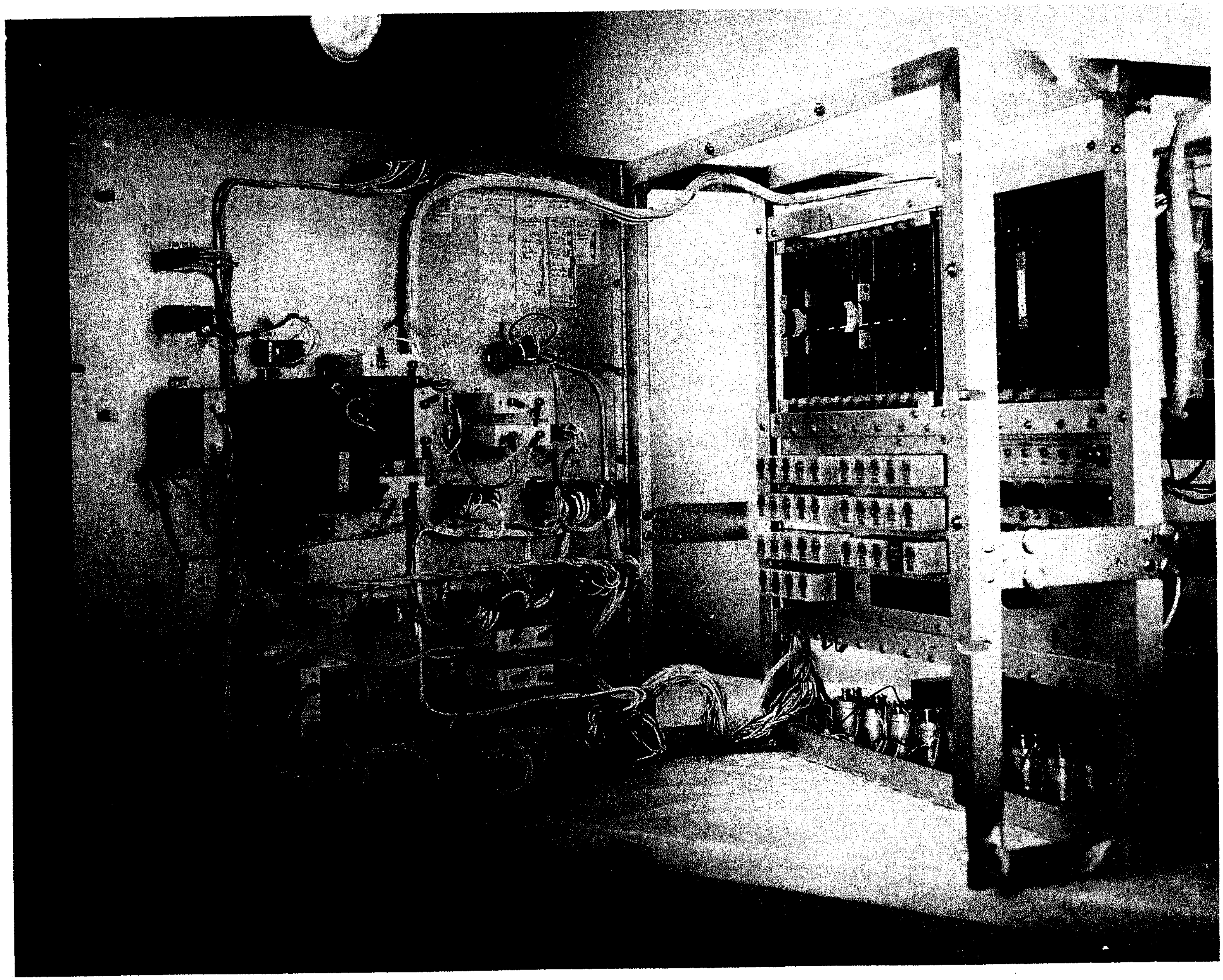

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FIG. 15--Internal view of Figure 14.