# A SOLID STATE DETECTOR HEAD FOR ASTRONOMICAL APPLICATIONS

by

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# ABSTRACT

A detector head for housing self scanned silicon photodetector arrays has been constructed for use in astronomy. It employs a unique frozen methanol cooling system and, although built specifically for the linear Reticon devices, it is capable of housing other linear or two dimensional monolithic arrays. This detector head is used with a control and data acquisition system that was developed at the University of British Columbia by the Institute of Astronomy and Space Science.

A previous detector head used with the above control system had incorporated a dry ice cooled 256A/17 Reticon array in a housing constructed specifically for use on an F/1 concentric mirror spectrograph camera. This older device had many problems associated with it which made it difficult to operate and unreliable. With the 256A/17 Reticon mounted in the new camera head these problems have been eliminated. In particular, frosting no longer occurs, dark current has been reduced to a negligable level, and the readout noise has been reduced by a factor of two.

As a result of this success, a 1024C/17 Reticon has been substituted for the 256 element array and there are plans for mounting a 100 x 100 two dimensional array in this detector head.

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ACKNOWLEDGEMENTS

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Many thanks go to my wife, Cathie, for the typing of this thesis and for her patience and support.

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# I. INTRODUCTION

Self scanned silicon photodetector arrays have been in routine operation as astronomical detectors for some time now, and many more groups are proposing or building detectors employing solid state sensors (Livingston 1976).

The operation of these detector arrays is similar to that of the silicon diode vidicon except that the electron reading beam has been replaced by on chip scanning and addressing circuitry. As a result, these monolithic detectors are very compact and there is absolute geometric stability between array elements. This, together with silicon's high quantum efficiency and linearity of response, makes self scanned sensor arrays very attractive for astronomical applications.

The photodetector arrays in common use today are of two basic types, photodiode arrays and charge transfer devices.

1) Photodiode arrays -- These sensors utilize the depletion region capacitance in p-n junction diodes for the integration of photogenerated charge. The individual photodiodes are coupled sequentially to one or a few video lines via MOS switches and an on chip shift register. The usual arrangement is shown schematically in Figure 1. In operation, the diodes are first reverse biased to a fixed potential and then isolated. Photogenerated minority carriers will subsequently

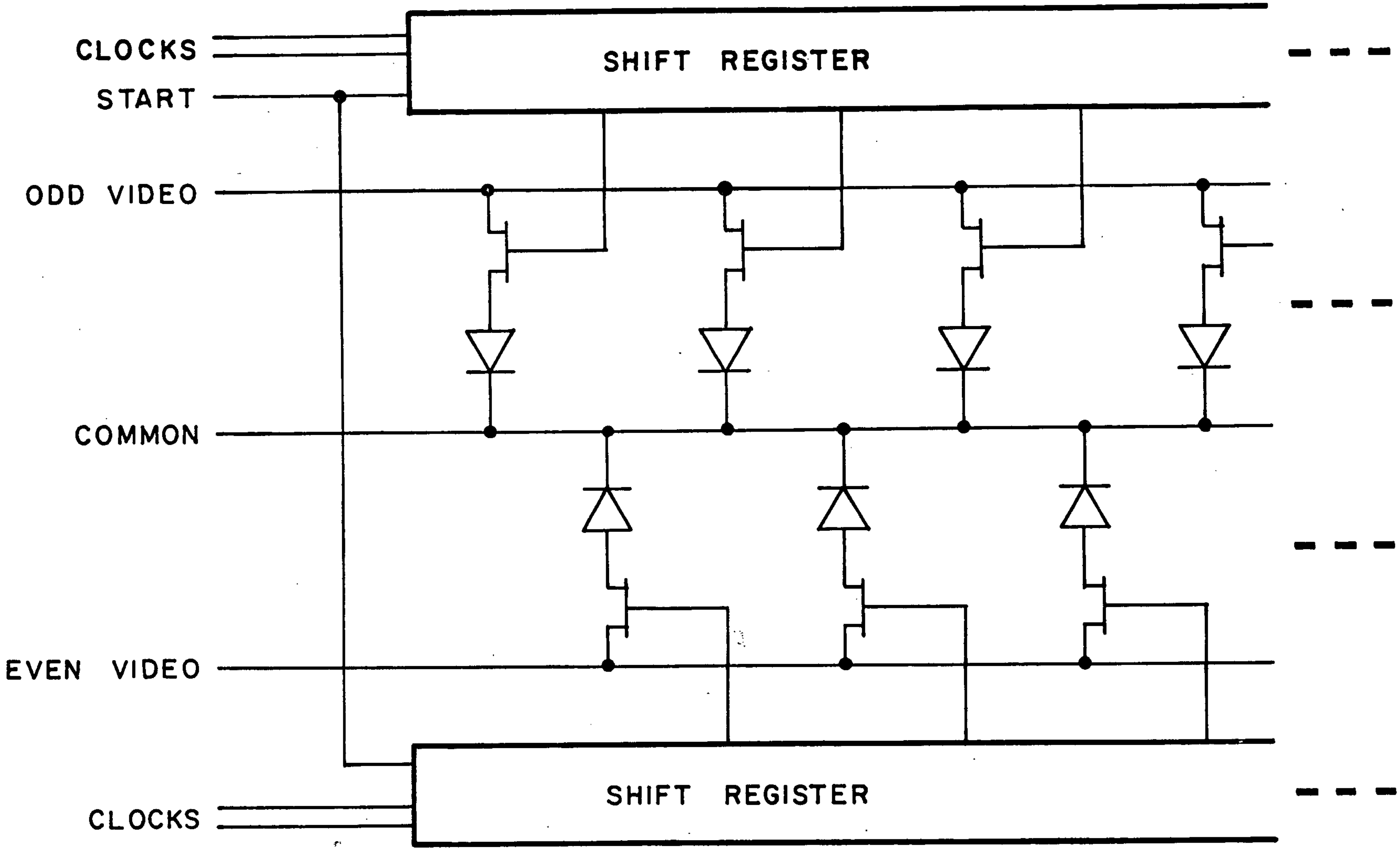



FIGURE 1. Simplified schematic of a linear diode array.

discharge the individual diode capacitances. Readout occurs when the diodes are rebiased through the video line, resulting in a train of recharging current pulses, each proportional to the amount of light that had fallen on the corresponding diode. A more detailed account of photodiode arrays is given by White (1975).

2) Charge transfer devices -- These use arrays of MOS capacitors for the integration of photogenerated charge. The gates of each capacitor are biased so as to drive the bulk silicon underneath into depletion. The potential wells thus formed collect and store the photogenerated minority carriers. Charge transfer devices (CTD's) include both charge coupled arrays (CCD's) and charge injection arrays (CID's). The operation of each of these arrays is quite different.

In CCD's, the charge packets collected under the array of capacitor gates are transported along the surface of the device to the input of an on chip amplifier. Figure 2 demonstrates, with the use of a potential well diagram, how the proper pulsing of the gate potentials can accomplish this charge transfer process. For more detail see Sequin (1975).

In CID's, the individual sensing elements consist of a pair of gate electrodes. In a two dimensional CID array the gates are connected in rows and columns. One gate from each element forms the rows, the other forms the columns. The row and column gate voltages can be used to read out a particular element, as shown in Figure 3. This readout is non-destructive since the charge packet is still intact, therefore, many

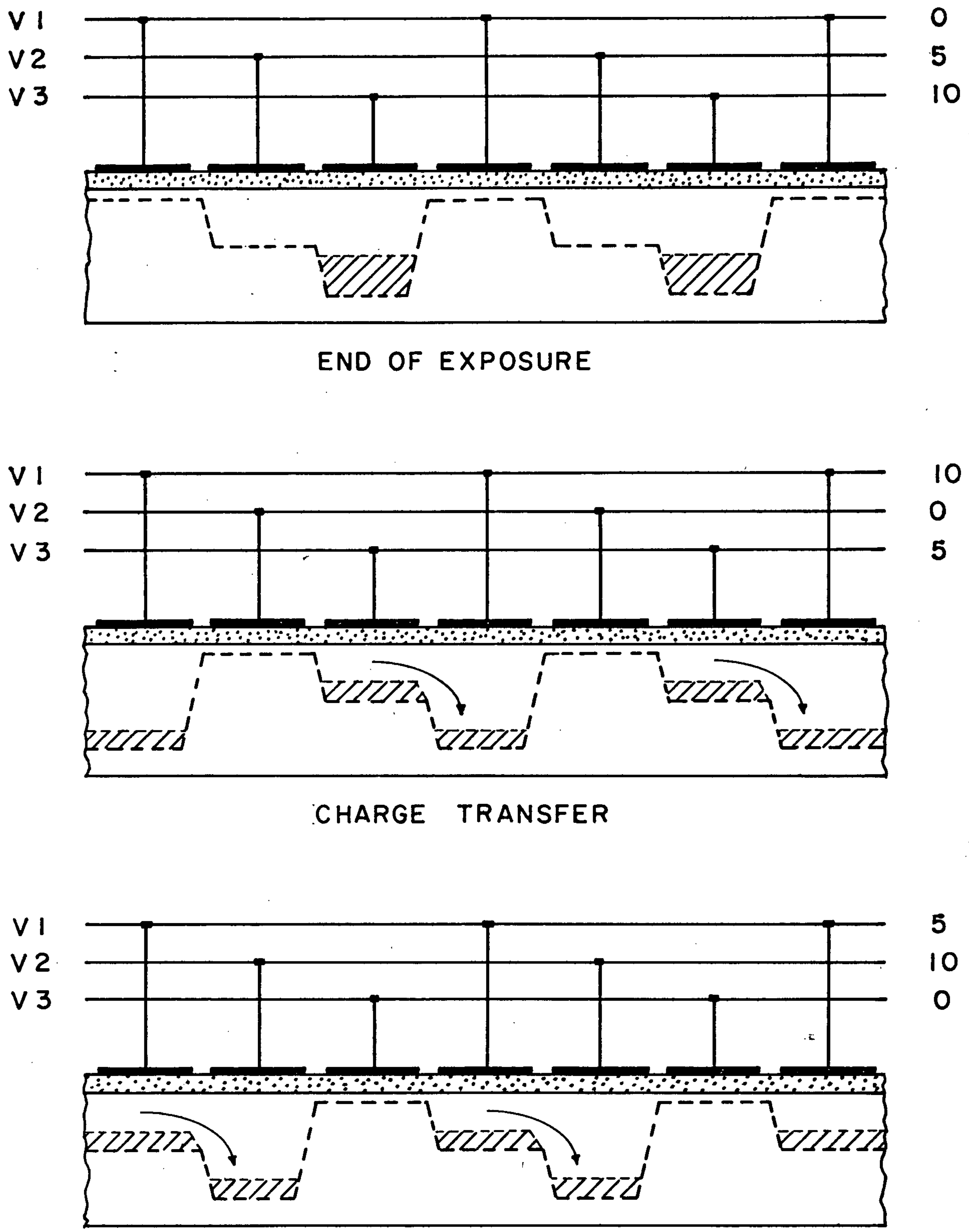



FIGURE 2. Charge transport in the CCD.

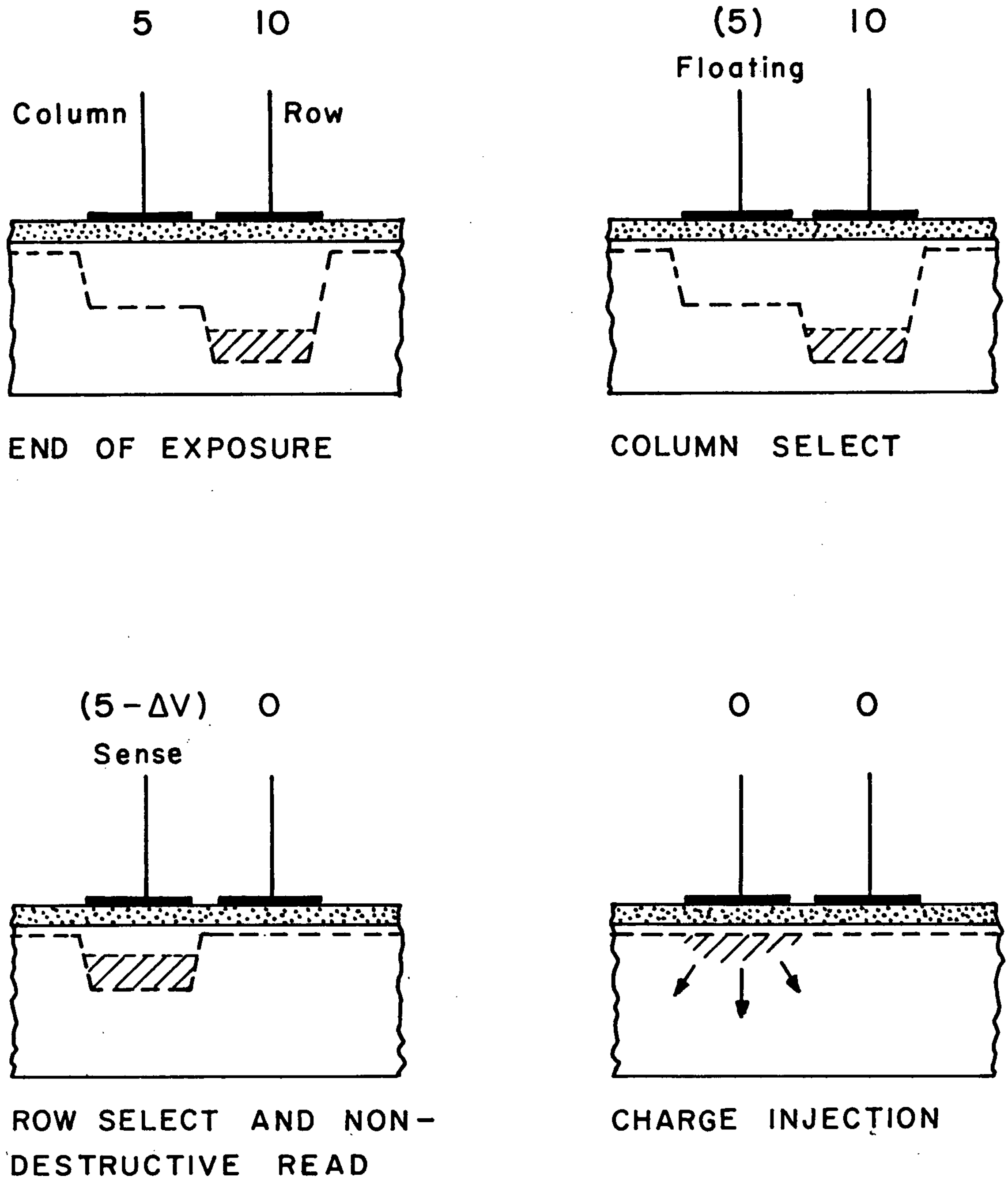



FIGURE 3. Readout of the CID. $\Delta V$ is equal to the signal charge divided by the column capacitance.

readouts of the same charge packet can be made. The sensing element is cleared for the next integration by removing the potential on both gates simultaneously. This injects the minority carrier charge into the bulk silicon where it recombines. For more detail see Michon et al (1975).

Thermally generated minority carriers will saturate CTD's and photodiode arrays in several seconds at room temperature. Fortunately, this leakage current, commonly referred to as dark current, decreases exponentially with temperature and it is possible to make exposures of several hours with a cooled array. A more detailed account of this dark current is given in Appendix A.

In astronomy, the linear diode arrays, in particular those of Reticon Corporation, have been used more than any other self scanned array. These particular arrays have proven to be very rugged, capable of withstanding repeated rapid cooling to temperatures below 173 K. The Reticon devices are easy to operate, requiring only very simple driving circuitry. They are available with as many as 1872 elements and 430-750 micron wide aperatures, making them suitable for astronomical spectroscopy. The diode to diode separation is from 15 to 25 microns and there is no dead space between sensor elements as there is in CTD's. Reticon also makes a dual array with two 370 micron wide arrays separated by 8 microns, which would be useful in cases where a sky subtraction is needed.

The principle disadvantage of Reticon's diode arrays is the large video line to substrate capacitance, which makes low noise signal extraction difficult, and the existence of a large value of reset noise. The origin of this reset noise is described in Appendix B. For Reticon arrays the reset noise is typically 250 carriers per diode, at 173 K. It is here where CTD's have a distinct advantage, since reset noise can be eliminated by using a correlated double sampling read-out technique (Hall 1975).

The remainder of this paper describes a solid state detector head which was designed and constructed by the author for astronomical applications. It employs a unique solid methanol cooling system, and although built specifically for the linear Reticon detectors, is capable of housing other linear or two dimensional self scanned arrays.

## II. DESIGN FEATURES OF THE DETECTOR HEAD

This detector head was designed and built for use with an existing control and data acquisition system which was developed by the Institute of Astronomy and Space Science at the University of British Columbia (Walker _et al_ 1974). Two 1024 element Reticons and one 256 element Reticon have been in routine use with this control system for the detection of astronomical spectra (Walker _et al_ 1976). The linear 256 Reticon was cooled with dry ice in a housing built specifically for use on the F/1 Wynne spectrograph camera of the Dominion Astrophysical Observatory's 1.8 meter telescope. Although much useful astronomy had been done with this Reticon camera head, there were many problems associated with it, and its operation was not dependable. The main problems were:

— Excessive dark current due to inadequate cooling by the dry ice.
— Excessive readout noise.
— Lack of adjustments required to properly align the Reticon.
— Frosting.

It was hoped that the new detector head would eliminate these problems and provide a dependable diode array system that could easily be operated by observers not familiar with the equipment. Although the new detector head was built for use on the Wynne camera with the 256A/17 Reticon, it was designed so that it could easily be adapted for use on other instruments and house other solid state arrays.

1. The Housing

A cut-away exploded view of the new detector housing is shown in Figure 4, and the detailed drawings are shown in Figures 5, 6, 7, and 8. The main features of the layout are as follows:

— The Reticon, its clock drivers, and the preamplifier are all on one easily removable plug-in circuit boards. This simplifies the change over to a different self scanned array.

— All the electrical connections are made through an aluminum front plate (part no. 3) on which the circuit board mounts. The circuit board, plate, and connection cable can be removed as a unit, as shown in Figure 10. This simplifies the testing and debugging of the electronics, and allows modifications to the rest of the device to be made without having to disturb the Reticon or any of its electrical connections.

— A teflon socket holds the Reticon diode array which is housed in a ceramic dual in-line integrated circuit package. This socket has a central slot to allow a copper cold probe to come in contact with the back of the Reticon. When the detector housing is assembled, the copper probe bears firmly against the Reticon, flexing the printed circuit board slightly. This ensures good thermal contact and a rigidly defined focal plane.

— The end of the copper probe is removable so that different tips can be used with each array. This is a modification that was made during the construction and is not shown in the drawings.

— The quartz window of the Reticon's I.C. package lies 0.1 inches above the surface of the front plate. This allows field flattener lens elements to be placed as close as possible to the active surface of the diode array.

— The front plate has an O-ring groove and eight threaded mounting holes so that a variety of windows, or field flattener assemblies, may be fitted to the housing.

— O-ring seals ensure that the inside of the housing is completely sealed off from the outside.

— Two valves (not shown in the drawings but which can be seen in Figure 9) are provided to allow the inside of the housing to be flushed with very dry nitrogen. This is necessary to prevent frosting of the diode array, or the inside surface of the window or field flattener.

— The field flattener necessary for the F/1 concentric mirror spectrograph consists of two air spaced lenses (see Figure 8). In order to prevent the outer lens from getting cold and fogging, these two lenses are mounted in an evacuated stainless steel cell. This also provides some thermal isolation for the Reticon which lies very close to the inner field flattener lens. The field flattener assembly can be seen in Figures 9, 10, and 11.

- The field flattener cell is fitted with a high vacuum valve so that it may be re-evacuated periodically.
- The assembled housing slides into a flanged aluminum sleeve (part no. 9). This sleeve is made to mount on the F/1 camera after the existing field flattener lens assembly has been removed.
- The six mounting holes in the flange are slotted, and a positioning screw is provided so that the detector may be aligned vertically on the spectrum. This is not shown in the drawings but can be seen in Figure 11.
- The diode array may be rotated so as to lie parallel to the dispersion direction, by adjusting a slot in the aluminum sleeve. A pin on the housing engages this slot. This arrangement can be seen in Figures 9 and 13.
- An adjustable stop (parts 15 and 16) determines how far the housing slides into the aluminum sleeve and provides a means of focussing the detector.
- A quick-release latch on the aluminum sleeve locks the detector housing in place once the alignment adjustments have been made.
- The copper probe that supports the Reticon passes through the rear of the housing to the outside where the cooling system couples to it. The rear plate on the housing supports the copper probe.

— The rear of the housing, seen in Figure 12, was designed specifically to accept the cooling system described below. However, there is ample space around the copper probe to allow other cooling systems to be fitted and tried.

2. Cooling System

The cooling system was designed so as to maintain the Reticon array at a temperature of -90 C or lower. From Figure 15 it can be seen that this ensures negligible dark current for exposure times of many hours. Such a low temperature ruled out the use of dry ice as a coolant. However, an equally simple and inexpensive cooling method was devised which uses a sealed copper canister full of frozen methanol instead of dry ice. The methanol is frozen by cooling the copper canister in an open mouthed dewar of liquid nitrogen. The canister is then screwed into the detector housing, placing it in thermal contact with the Reticon array.

Methanol freezes at -98 C and the latent heat of fusion is 99 Joules/gram. With the estimated heat input of 5 watts, this gives 20 seconds of cooling per gram of methanol, or 4.4 hours per liter.

Figures 4 and 12 show the details of the methanol canister and how it is attached to the housing. The canister shown holds one liter of methanol and uses urethane foam for insulation. The parts numbered 18 are fill and vent plugs. The end of the canister that attaches to the copper probe is not insulated so that the methanol may be frozen by immersion into liquid nitrogen. The urethane foam lining in the rear section of the detector housing provides insulation for this part of the canister when it is screwed in place.

3. Detector Electronics

The detector electronics consist of the Reticon's clock drivers and the video preamplifier. Since the Reticon 256A/17 array used in the older system was to be made operational in the new detector head as quickly as possible, no attempt was made to improve upon the existing electronic design. However, an attempt was made to improve the layout of the detector electronics in order to reduce the amount of fixed pattern signal and to hopefully achieve a lower readout noise. In the older system the readout noise was 3600 carriers/diode (rms). The origin and nature of the fixed pattern signal is described in Appendix C.

Figure 16 is a schematic of the detector electronics, and Figure 17 shows a block diagram of the complete control and data acquisition system. The 5 volts for the Reticon is delivered from rechargeable ni-cad batteries. Noise on this supply appears directly as noise in the readout, and it is of utmost importance that this supply be low noise and stable. Batteries provide such a low noise supply. The other supply voltages are delivered down a fifty foot cable from remote power supplies in the control box.

The right and left clock pulses are generated in the video processing box from a basic clock supplied down the long cable. The start pulse is generated in the control box and supplied to the video processing box and to the camera electronics board. The video signal from the preamplifier is sent to the video processing box where it is integrated, sampled, and held. It is then digitized and sent down the fifty foot cable to the computer.

The main improvements made to the layout of the detector electronics are as follow:

— The Reticon is located in a specially made teflon socket.

— Short teflon insulated leads are used for the two video lines that go to the nearby amplifier. These leads leave the Reticon socket directly and never come in contact with the printed circuit board. This detail can be seen in Figure 10.

— The preamplifier electronics are copper shielded and placed away from the driver electronics.

— The two sets of driving circuitry are laid out symmetrically on each side of the Reticon. This was done in order to reduce the amount of fixed pattern. It required the leads on two of the IC's to be bent backwards so that they could be mounted upside down.

— Decoupling filters were used on the supplies to all the IC's.

— Special attention was paid to the grounding in order to reduce pick-up. For example, the system ground was isolated from the housing so that a ground loop could not occur when the instrument was attached to the telescope.

## III. FINAL PERFORMANCE

Figures 13 and 14 show the detector head in use on the telescope.

The first observing run with the new detector head clearly demonstrated it to be superior to the older device. Mounting and aligning the Reticon was now a simple operation and a significantly better focus could be achieved. Frosting of the diode array was no longer a problem and the outer surface of the field flattener did not fog up. The new frozen methanol cooling system was able to maintain the Reticon at a temperature below -80 C for a period of about three hours, which is warmer and shorter than originally planned. This is probably due to inadequate insulation by the urethane foam. Ethanol freezes at -114 C and when substituted for the methanol it was able to keep the Reticon below -90 C, but for even shorter durations.

It takes approximately 45 minutes to cool the canister from room temperature to the point where all the methanol will freeze. However, it takes only 15 minutes to refreeze the canister if the temperature has not been allowed to rise above -70 C. At present, this causes some loss of observing time since only one canister was contructed.

The new electronics resulted in a tremendous reduction of the fixed pattern signal, to a level approximately 3% of saturation, and lowered the readout noise by a factor of two.

The resulting performance of the diode array system, when used on the F/1 spectrograph of the 1.8 meter telescope, is as follows:

A) Grating - 300 l.p.mm., blazed at 7500 Å, centered at 7500 Å.

Coverage - 5,000 Å to 10,000 Å

Resolution - 16 Å/diode

Speed - signal/noise = 200/1

wavelength = 7,000 Å

V = 14.0 for G or K star

<u>integration time ≈ 3,600 seconds</u>

B) Grating - 1,200 l.p.mm., blazed at 7500 Å, centered at 6500 Å

Coverage - 6,000 Å to 7,000 Å

Resolution - 3.7 Å/diode

Speed - signal/noise ≑ 200/1

wavelength ≑ 6,500 Å

V = 11.0 for G or K star

<u>integration time ~ 3,600 seconds</u>

## IV. APPLICATIONS

Plans have been made for use of the detector head on other instruments besides the F/1 Wynne camera. At the time of writing, the detector head, with a 1024C/17 Reticon array installed, has been used on the 32" coude spectrograph camera of the Dominion Astrophysical Observatory's 1.2 meter telescope. The 1024 Reticon is on its own circuit board, with its own drivers and preamplifier.

Plans are also in progress for mounting the detector head on the 21" off-axis spectrograph camera on the 1.8 meter telescope. In addition it is thought that the two dimensional 50 x 50 element diode array system at the University of British Columbia might also use this detector head. When they become available, a 100 x 100 Reticon array could be substituted for the 50 x 50.

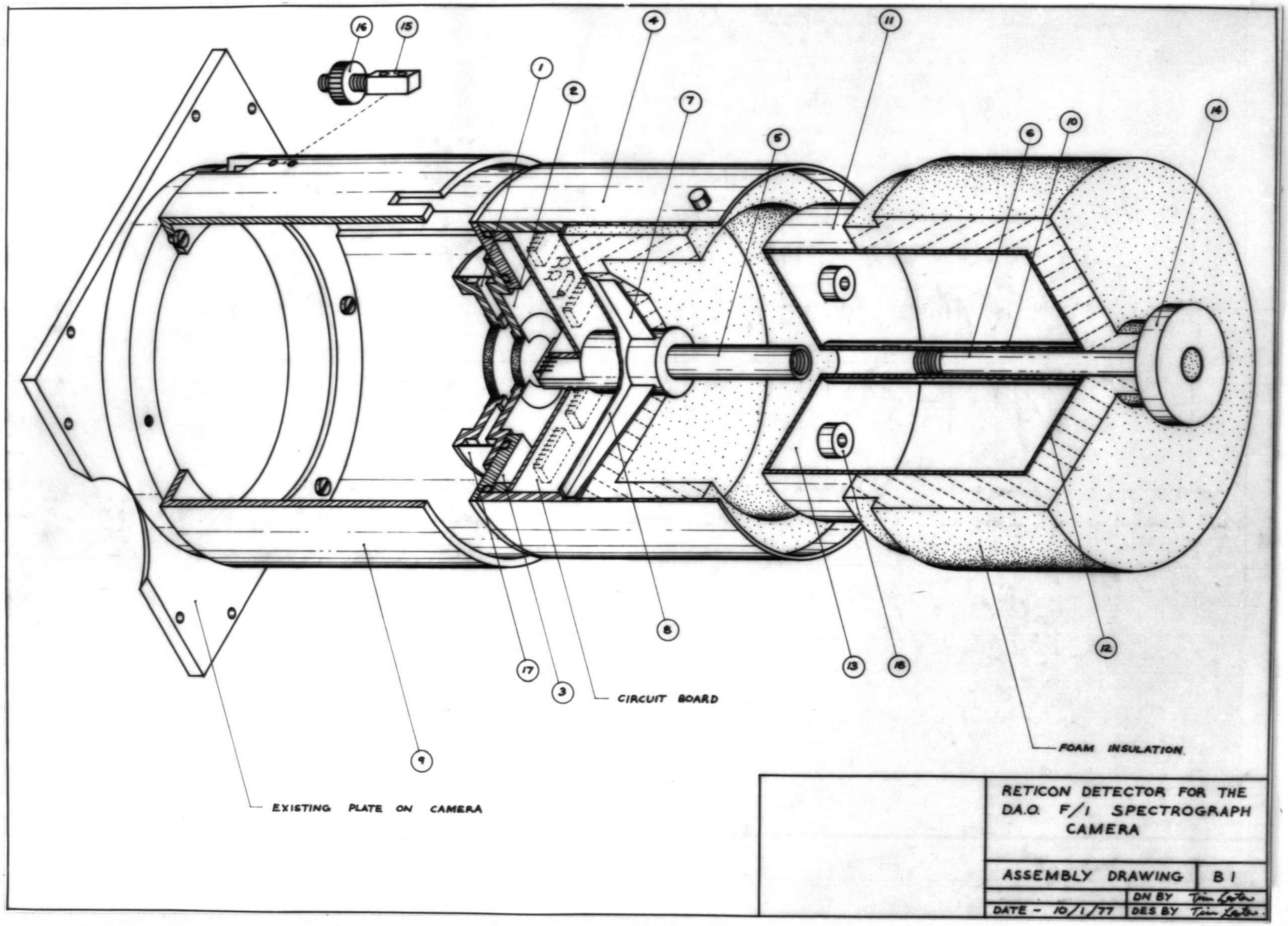



FIGURE 4. Exploded cut-away assembly drawing of the detector head.

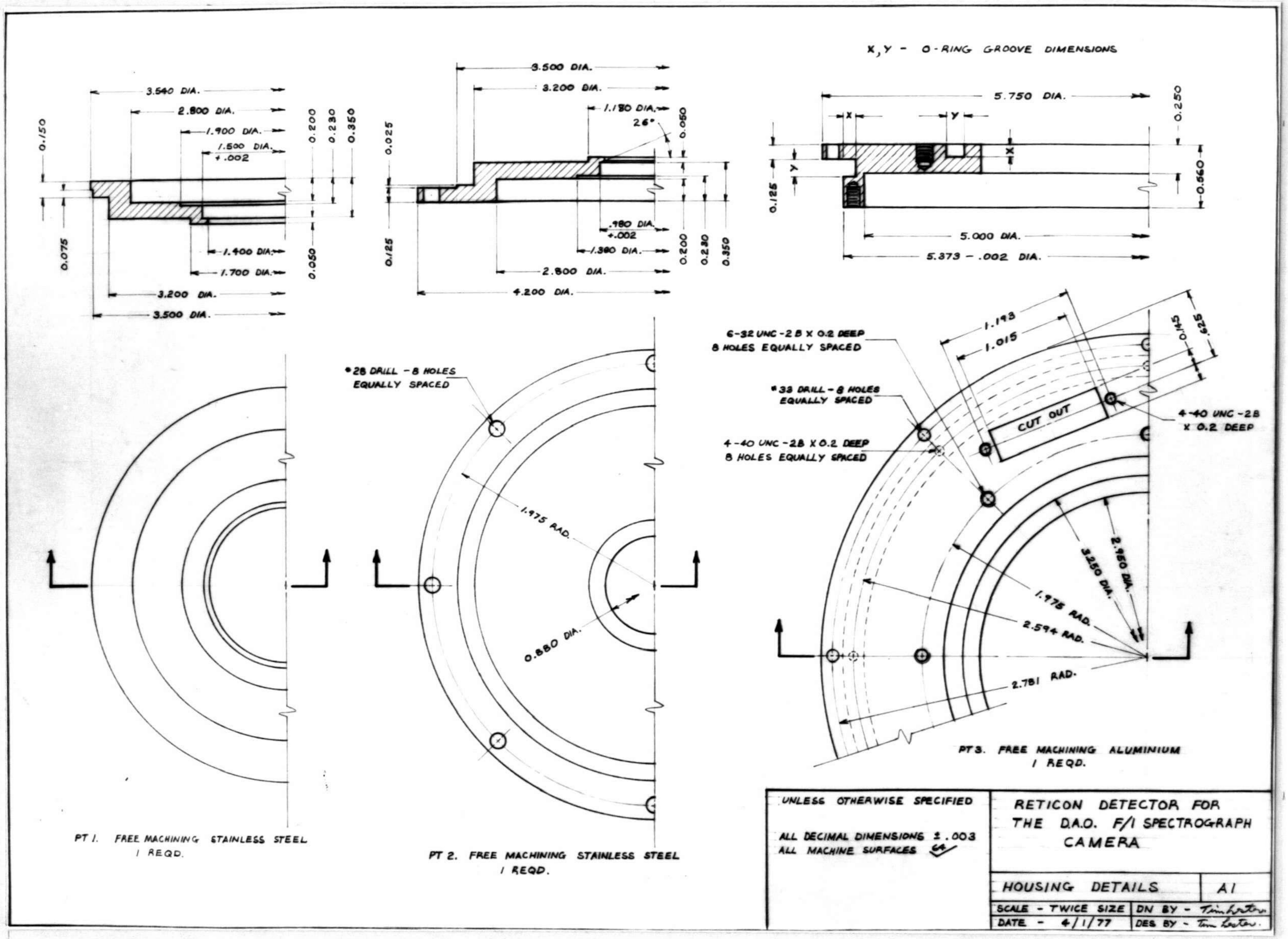
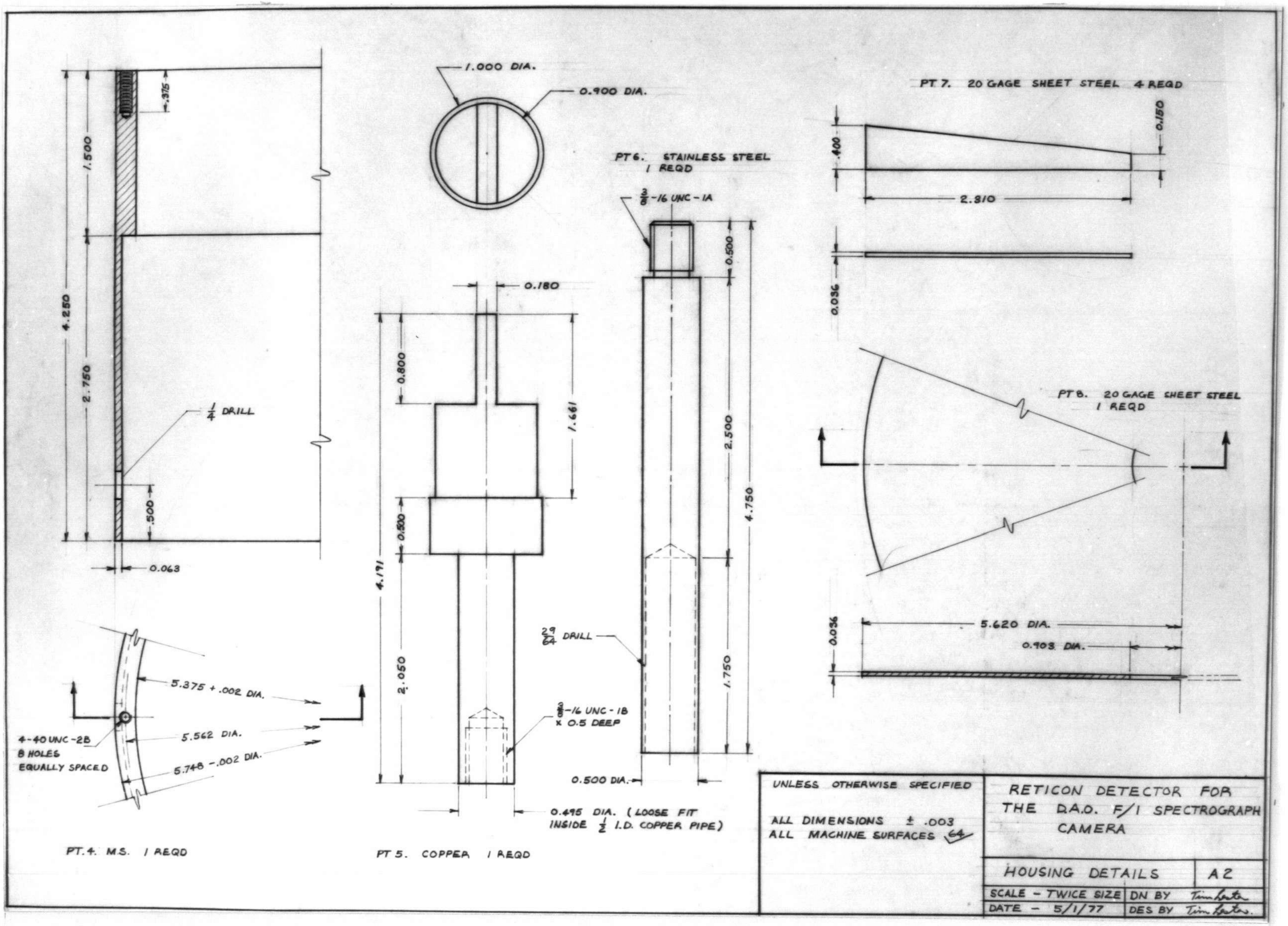



FIGURE 5. Detailed drawings.



PT.4. M.S. 1 REQD
PT 5. COPPER 1 REQD
PT 6. STAINLESS STEEL 1 REQD
PT 7. 20 GAGE SHEET STEEL 4 REQD
PT 8. 20 GAGE SHEET STEEL 1 REQD
1.000 DIA.
0.900 DIA.
.375
1.500
4.250
2.750
1/4 DRILL
.500
0.063
0.180
0.800
1.661
0.500
4.191
2.050
3/8-16 UNC-1B × 0.5 DEEP
0.495 DIA. (LOOSE FIT INSIDE 1/2 I.D. COPPER PIPE)
3/8-16 UNC-1A
0.500
2.500
4.750
29/64 DRILL
1.750
0.500 DIA.
.400
0.150
2.810
0.036
5.620 DIA.
0.903 DIA.
5.375 +.002 DIA.
5.562 DIA.
5.748 -.002 DIA.
4-40 UNC-2B
8 HOLES
EQUALLY SPACED
UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS ± .003
ALL MACHINE SURFACES 64
RETICON DETECTOR FOR THE D.A.O. F/1 SPECTROGRAPH CAMERA
HOUSING DETAILS
A2
SCALE - TWICE SIZE
DN BY Tim Lester
DATE - 5/1/77
DES BY Tim Lester


FIGURE 6.

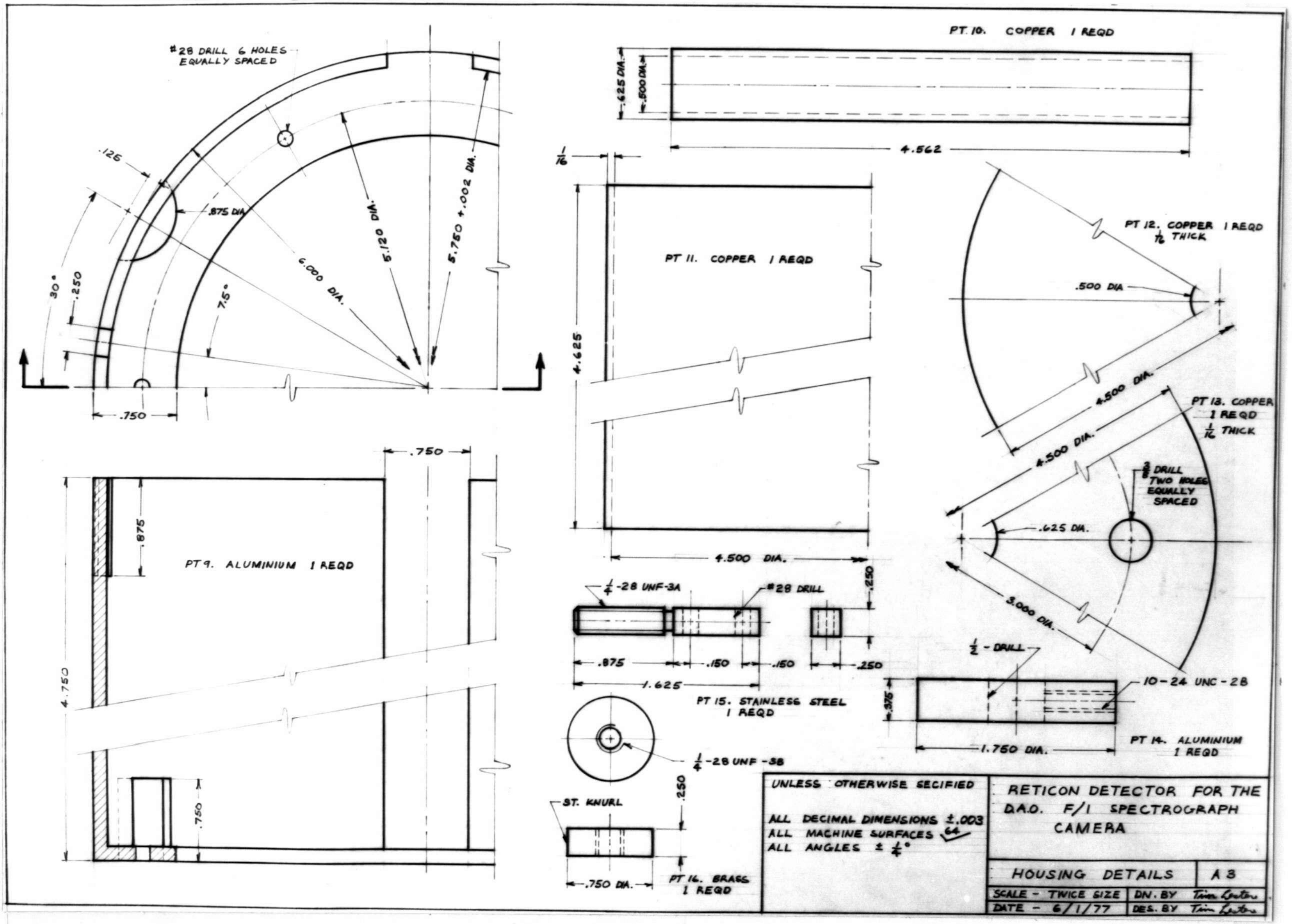

#28 DRILL 6 HOLES EQUALLY SPACED
.125
.875 DIA
6.000 DIA.
5.120 DIA.
5.750 +.002 DIA.
30°
.250
7.5°
.750
PT. 10. COPPER 1 REQD
.625 DIA.
.500 DIA.
4.562
1/16
PT 11. COPPER 1 REQD
4.625
4.500 DIA.
PT 12. COPPER 1 REQD 1/16 THICK
.500 DIA
4.500 DIA.
PT 13. COPPER 1 REQD 1/16 THICK
3/8 DRILL TWO HOLES EQUALLY SPACED
.625 DIA.
3.000 DIA.
PT 9. ALUMINIUM 1 REQD
.750
.875
4.750
1/4-28 UNF-3A
#28 DRILL
.250
.875
.150
.150
.250
1.625
PT 15. STAINLESS STEEL 1 REQD
1/4-28 UNF-3B
ST. KNURL
.750 DIA.
PT 16. BRASS 1 REQD
1/2-DRILL
10-24 UNC-2B
.375
1.750 DIA.
PT 14. ALUMINIUM 1 REQD
UNLESS OTHERWISE SECIFIED
ALL DECIMAL DIMENSIONS ±.003
ALL MACHINE SURFACES 64
ALL ANGLES ± 1/4°
RETICON DETECTOR FOR THE D.A.O. F/1 SPECTROGRAPH CAMERA
HOUSING DETAILS
A 3
SCALE - TWICE SIZE
DATE - 6/1/77
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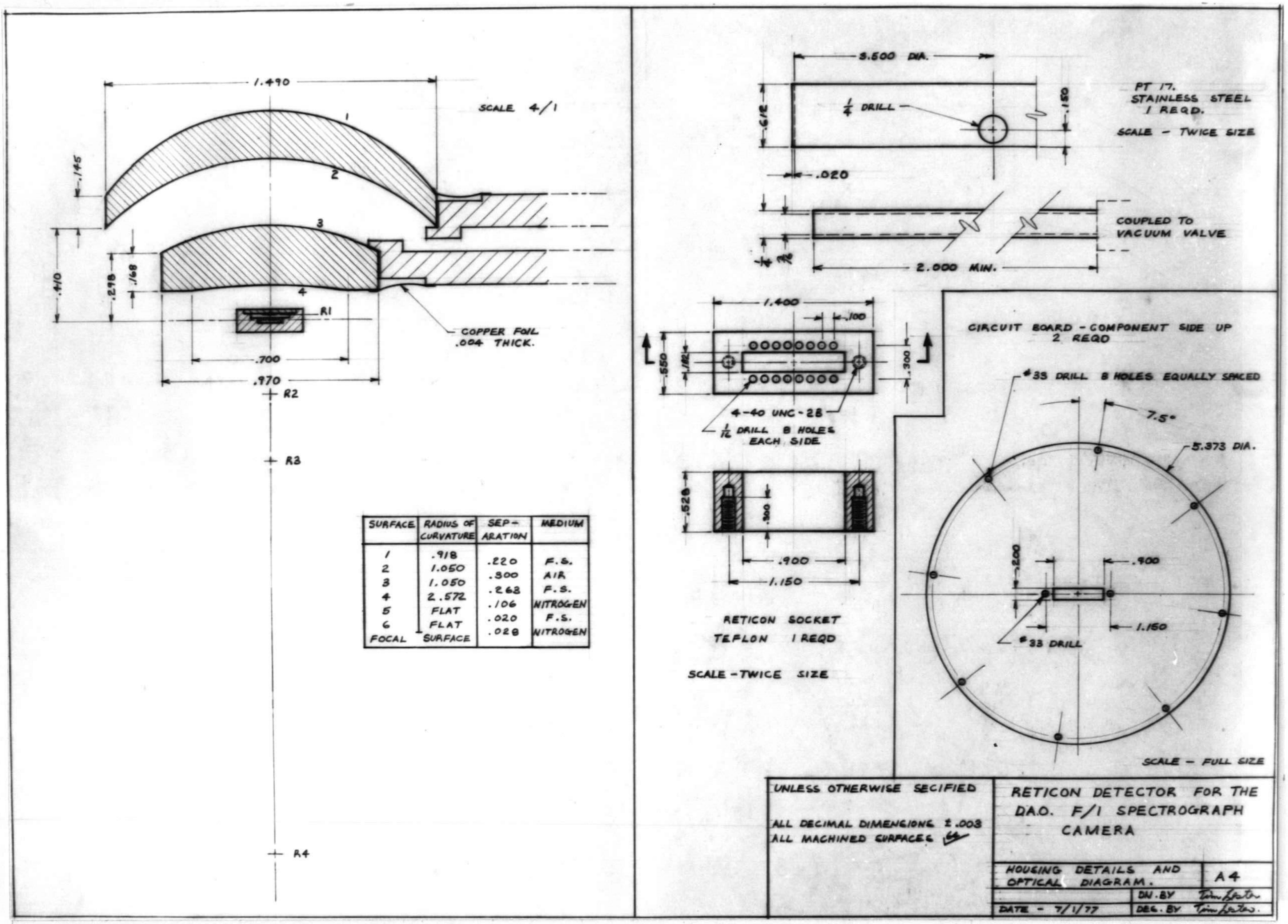
FIGURE 7.




| SURFACE | RADIUS OF CURVATURE | SEP-ARATION | MEDIUM |
|---|---|---|---|
| 1 | .918 | .220 | F.S. |
| 2 | 1.050 | .300 | AIR |
| 3 | 1.050 | .263 | F.S. |
| 4 | 2.572 | .106 | NITROGEN |
| 5 | FLAT | .020 | F.S. |
| 6 | FLAT | .028 | NITROGEN |
| FOCAL | SURFACE | | |

FIGURE 8.

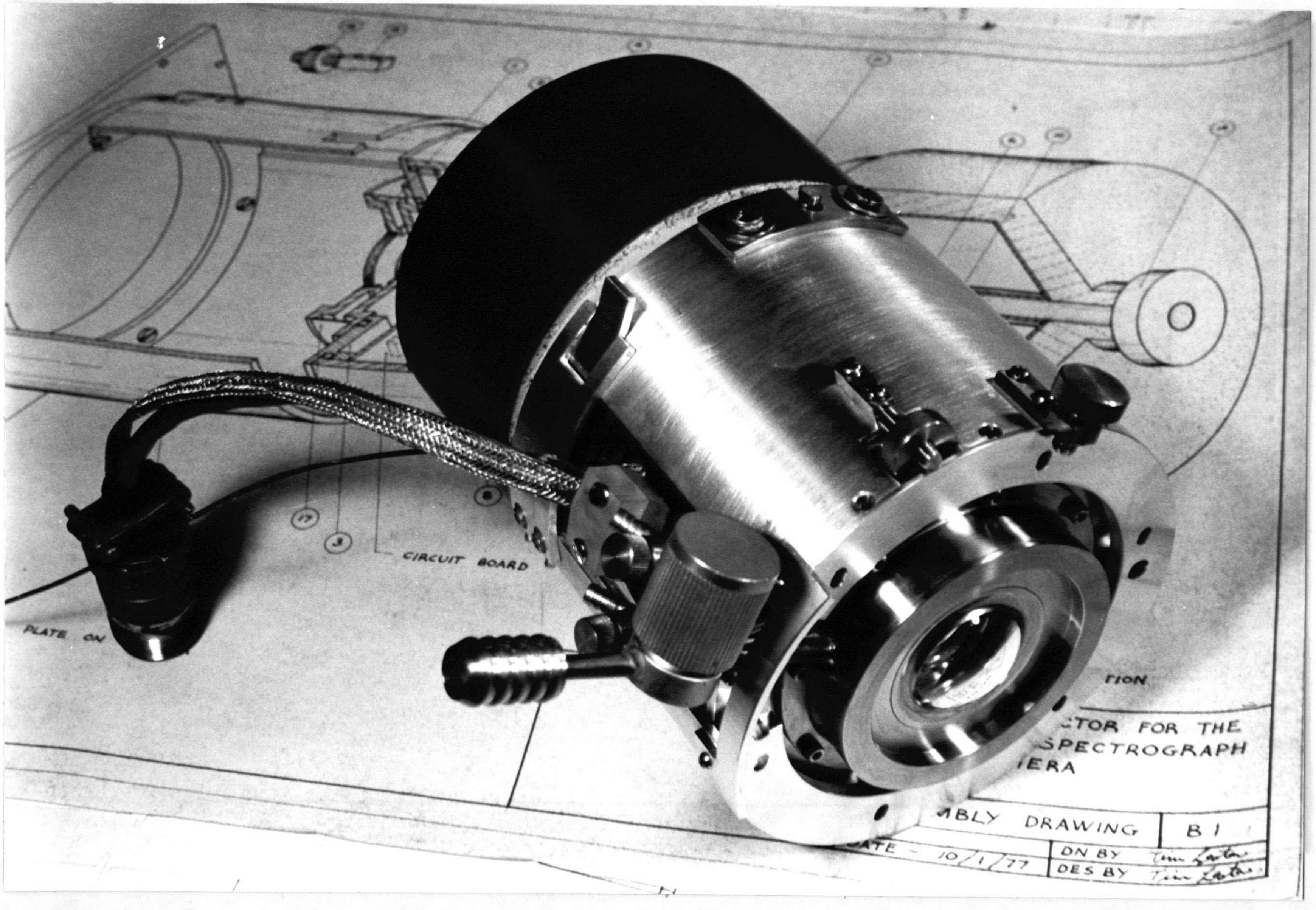



FIGURE 9. The completed detector head.

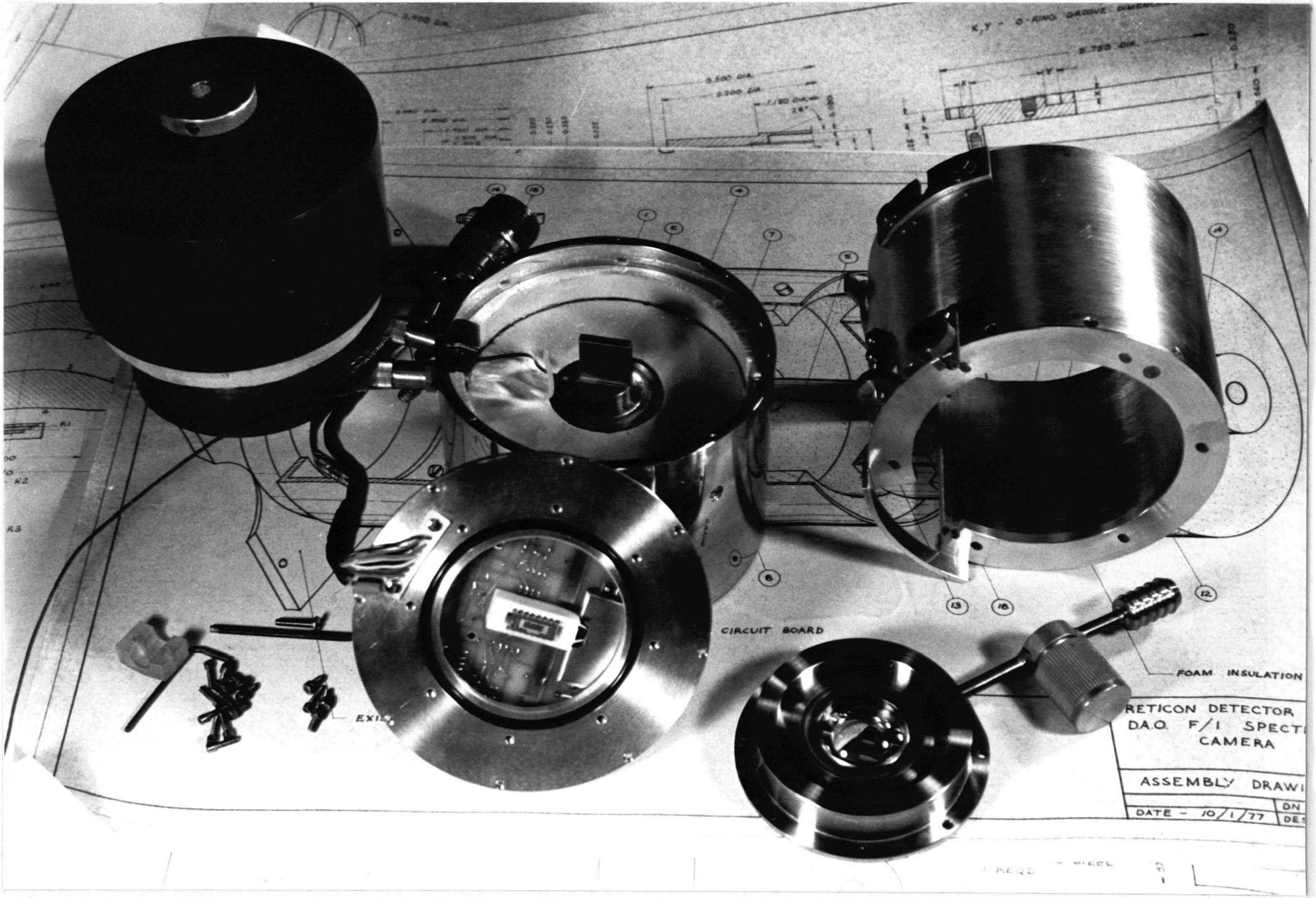



FIGURE 10. Partially dismantled detector head.

FIGURE 11. Front view. The Reticon can be seen behind the field flatteners.

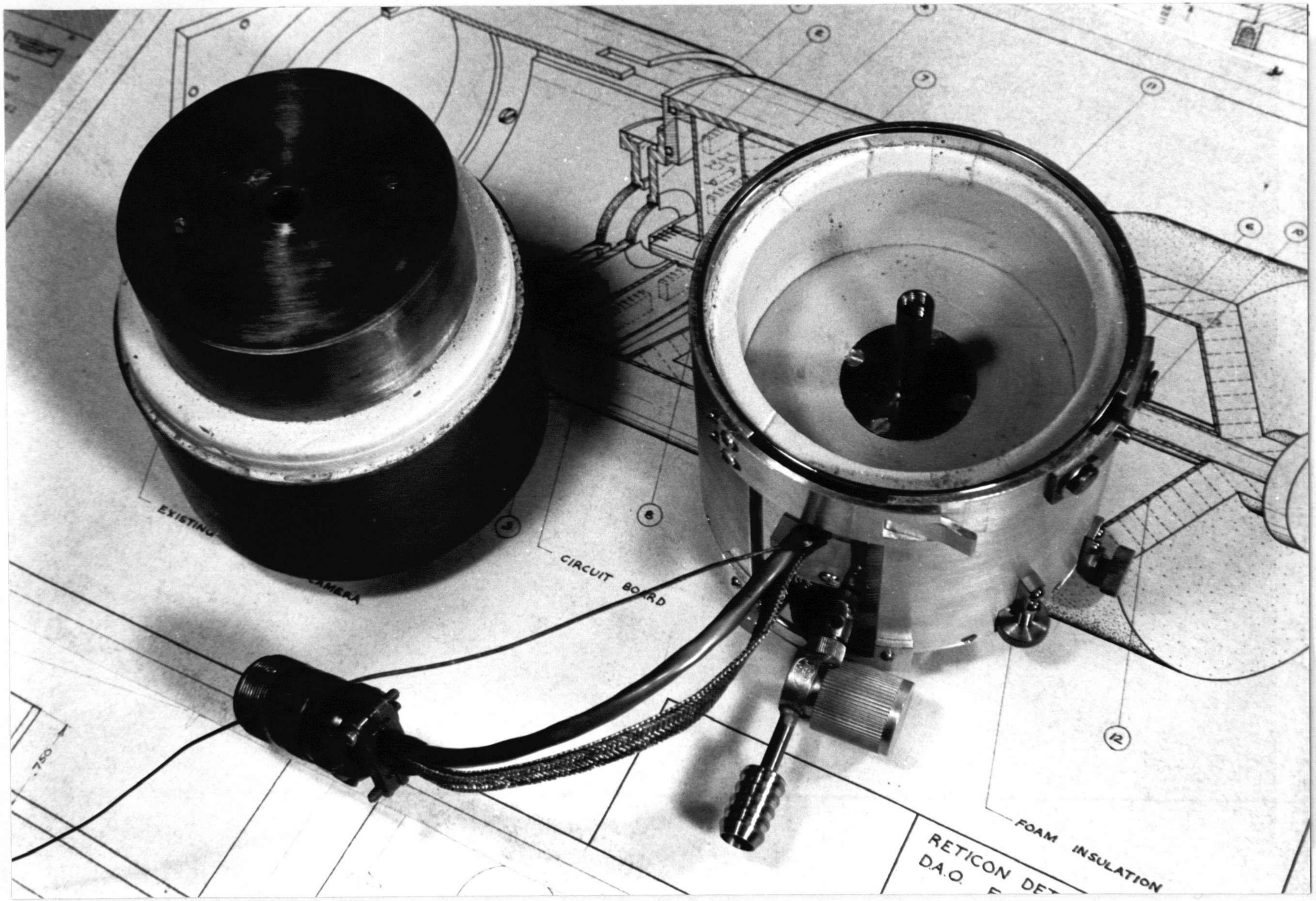



FIGURE 12. The methanol canister and the rear of the detector housing.

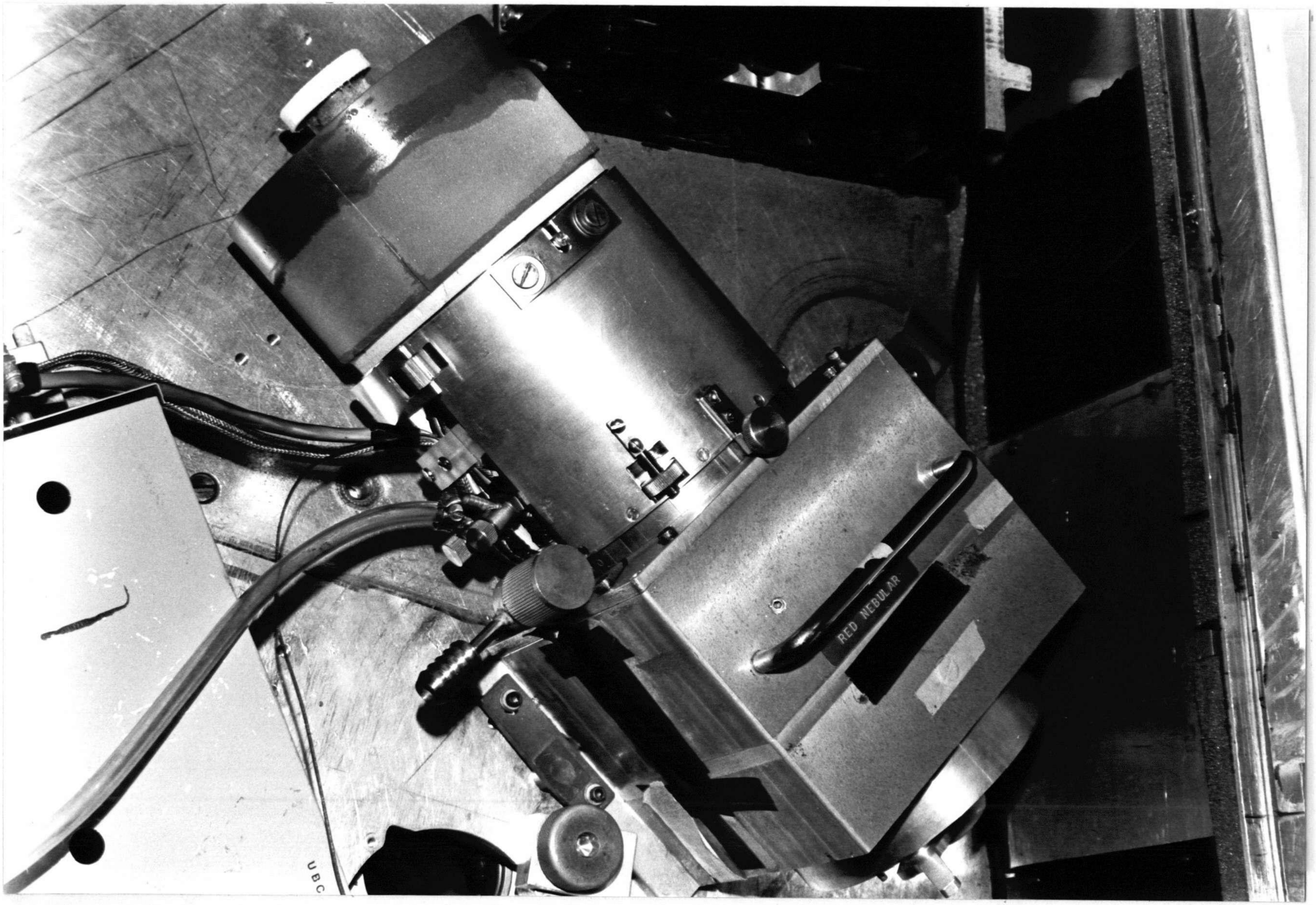



FIGURE 13. The detector head mounted on the F/1 spectrograph.

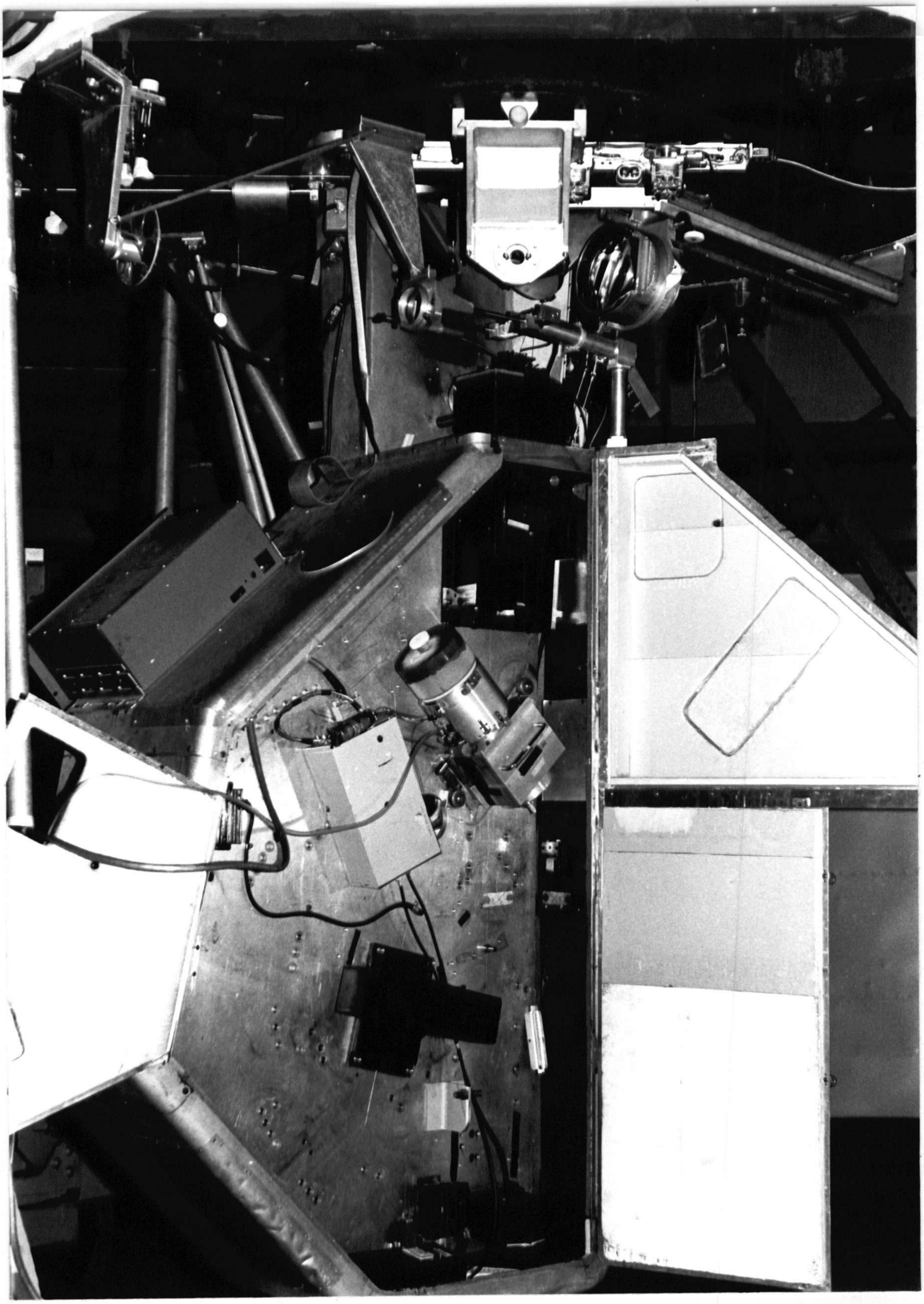


FIGURE 14.

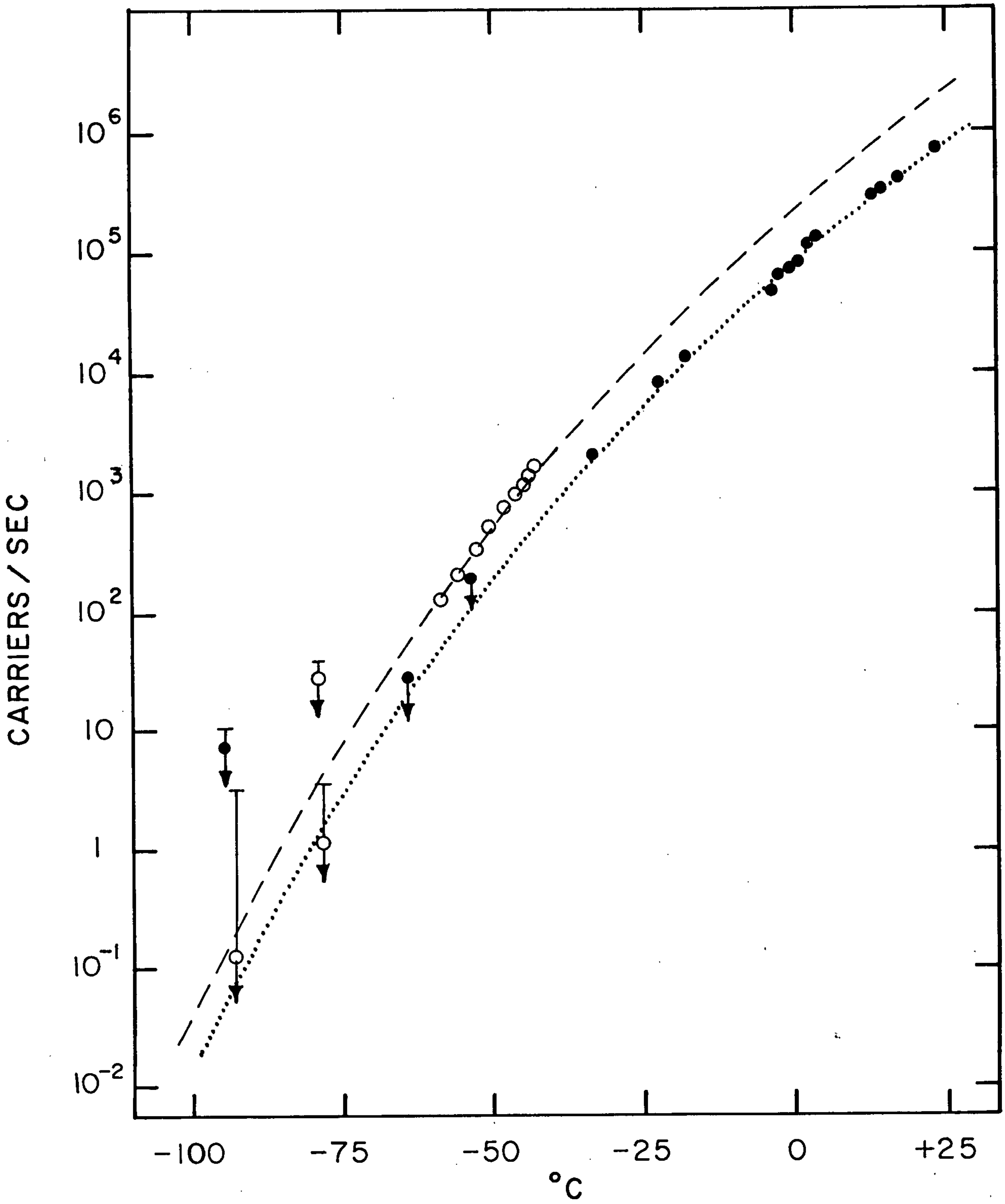



FIGURE 15. Dark current as a function of temperature. Open circles apply to a Reticon 256A while solid circles apply to a 256C. The dashed and dotted lines are theoretical curves derived from equation 2 in Appendix A.

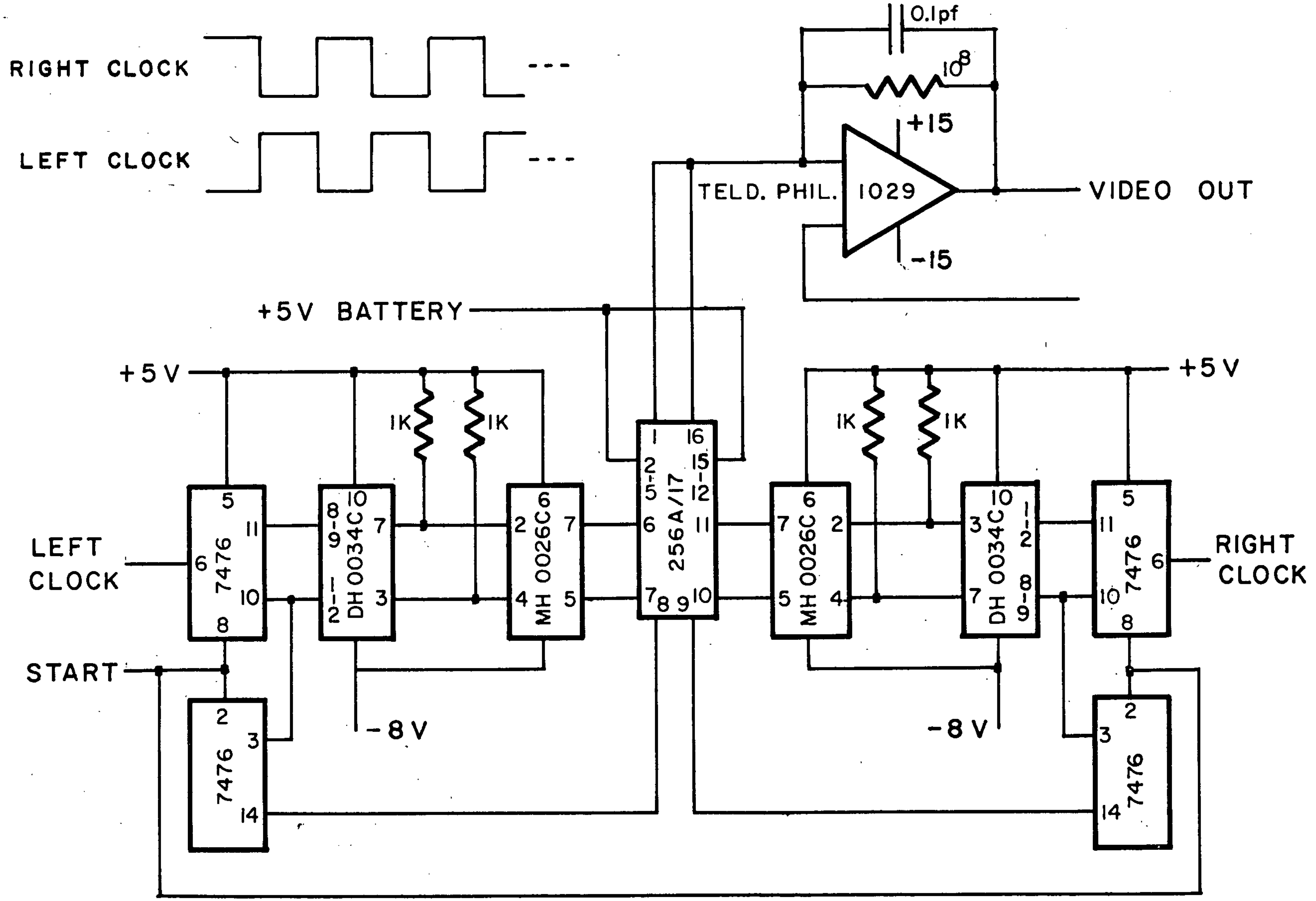



FIGURE 16. Camera electronics.

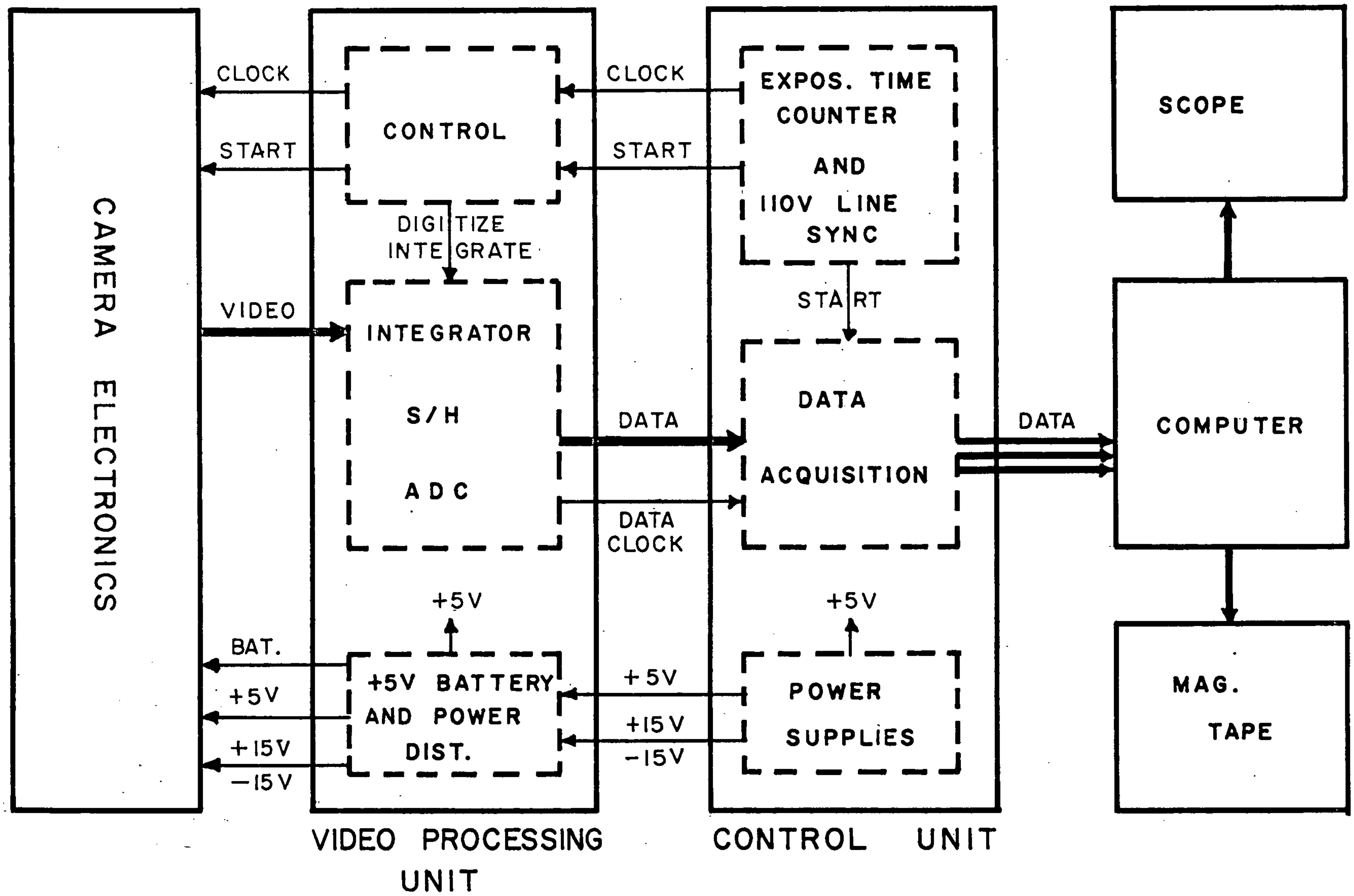



FIGURE 17. Block diagram of Reticon control and data acquisition system

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APPENDIX A

For semiconductors with wide energy gaps, such as silicon, the dark leakage current is due almost entirely to the hole electron pairs being created thermally in the space charge region. From Sah et al (1957), the magnitude of this dark leakage current is given by:

$$J_d = \frac{qn_i}{2}\left(\frac{W_d}{t_o} + S_o\right) \qquad \text{----1}$$

where, $J_d$ = leakage current density

$W_d$ = width of the depletion region

$n_i$ = intrinsic concentration of free carriers

$t_o$ = minority carrier lifetime in the depletion region

$S_o$ = surface leakage parameter

The dark current parameters $t_o$ and $S_o$ can be temperature dependant, however, empirically it has been found that they are effectively constant. Advances in silicon device technology have made possible very low values of surface leakage current and the bulk leakage term predominates down to temperatures below -50°C for presently available detector arrays. Neglecting surface leakage the temperature dependance of leakage current is approximately given by:

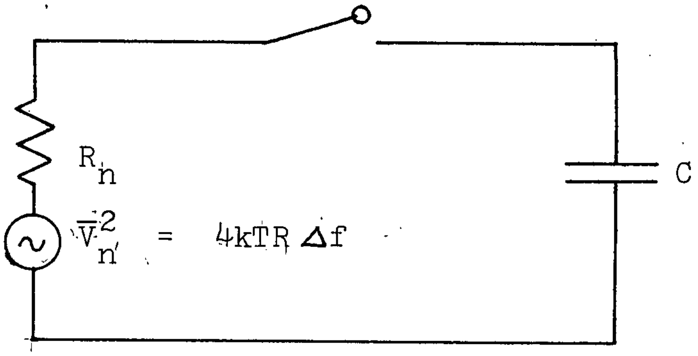
$$J_d(T) = Cn_i(T) = CT^{3/2}\exp(-7015/T) \qquad \text{----2}$$

In Figure 15 this temperature dependance is plotted along with some actual measurements on two Reticon linear arrays (from Campbell 1976). It is evident that for these devices, surface leakage is still negligible at temperatures as low as -80 C.

The thermal dark current is not linear but is a function of the residual charge on the photosensitive elements. This nonlinear behavior is due to the parameter $W_d$ in equation 1 above. The width of the depletion layer that forms the storage capacitance in the photosensitive element is a function of the stored charge, and it is this same capacitance that is discharged by the photogenerated hole electron pairs and by the thermal dark current. Such nonlinear behavior makes accurate dark subtractions virtually impossible and it is therefore desirable to cool self scanned arrays to such a low temperature that dark current is totally negligible.

## APPENDIX B

When a switch is used to set the voltage across a capacitor, Johnson noise in the switch resistance results in an uncertainty in the capacitor voltage. A simple equivalent circuit for this situation is shown below.




R is the switch resistance and $V_n$ is its associated noise voltage generator. Provided that the switch is closed for a time $t \gg R_nC$, then the bandwidth $\Delta f$ of this simple series RC circuit is given by:

$$f \sim \frac{1}{2}\int_0^\infty \frac{dw}{1 + w^2R_n^2C^2} = \frac{1}{4R_nC}$$

Therefore, $\overline{V}_{nc}^{\,2} = \frac{kT}{C}$ , $Q_{nc}^{\,2} = kTC$

When the switch is opened again the instantaneous value of this noise charge is held on the capacitor. An expression for the reset noise is therefore:

$$(NEC)_r = \frac{1}{q}\sqrt{kTC} \text{ electrons.}$$

A typical value for C in self scanned arrays is 0.5 pf and R is generally less than 200 ohms, therefore, $RC \sim 10^{-9}$ seconds and the assumption that the reset time $t \gg RC$ is a good one.

# APPENDIX C

In Reticon diode arrays unavoidable parasitic capacitances are present between the shift registers and the video lines. These capacitances couple the transients of the clock driver signals onto the video line. Two complementary clock waveforms are used for each shift register in order to reduce the net charge induced. However, the capacitive coupling generally differs slightly for each of these clock signals and a net fixed pattern on the video output is observed. Provided the clock waveforms are very stable and the temperature is steady, this net induced charge is a fixed constant for each diode and may be calibrated out or removed with a second dark readout. Any changes in clock timing or array temperature will result in a residual fixed pattern and for this reason it is important to make the original fixed pattern as small as possible. In addition, a large amount of fixed pattern will reduce the dynamic range of the device.