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STERILIZABLE OPTICAL DETECTOR SCINTILLATION CRYSTAL ASSEMBLY

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FOREWORD

This is the final report of contract number 950982 entitled "Sterilizable Optical Detector-Scintillation Crystal Assembly". Work on this program was performed at the Isomet Corporation, 433 Commercial Avenue, Palisades Park, New Jersey.

This report was submitted on September 23, 1968. It contains no classified information extracted from any source.

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ABSTRACT

The purpose of this program was to develop the technology necessary to make a solid state, sterilizable scintillation assembly. Various optical detectors were studied as individual components and together with scintillation crystals in prototype assemblies.

1. INTRODUCTION

Instrumented near and deep space vehicles will require scintillation detectors for a variety of missions. At the present time, NASA requires that all planetary vehicles be heat sterilizable. Previous programs have established that such scintillation crystals can be fabricated. However, the sterilization of the photomultiplier tube appears to be a very difficult task and a solution to the problem does not appear to be near at hand. The combination of solid state detectors with scintillation crystals appears to offer a solution to the problem of providing a sterilizable scintillation package. Advances in solid state technology have raised the sensitivity of optical detectors to the point where they can be used to replace the photomultiplier in a scintillation assembly. These detectors also offer the advantage of easier packaging, low voltage operation, reliability, ruggedness, low cost and sterilizability.

A detector suitable for converting the light emission from a scintillation crystal to an electrical pulse should have the following characteristics:

1. A time response of the order of a microsecond or less.
2. A sensitivity high enough to provide a high signal to noise ratio even for low energy nuclear particles or rays.
3. A linear response to incident photon intensity.
4. High stability.
5. Low voltage and power requirements.
6. Ability to withstand temperatures of 145°C during heat sterilization.
7. Mechanical ruggedness.

The solid state detector can meet these requirements.

2. THEORETICAL AND EXPERIMENTAL PROGRAM

2.1 Comparison of Photon Detectors

2.1.1 Photomultiplier Tubes

Photomultipliers are widely used with scintillation crystals for the detection of nuclear radiation. They have the following advantages:

1. Fast response time; transit times being of the order of 10^{-8} seconds.
2. High gain in the order of one million.
3. Good sensitivity over a wide spectral region.
4. Low power consumption.

The disadvantages of photomultipliers are:

1. Low quantum efficiency of the photocathode, of the order of 5%.
2. High sensitivity to small supply voltage fluctuations.
3. Need for high voltage supply.
4. Relatively fragile glass envelope.
5. Instability of the photocathode at temperatures of 145°C, thus rendering them non-sterilizable at present.

2.1.2 Solid State Detectors

Solid state detectors coupled to scintillation crystals offer promise as nuclear detectors. The devices have much higher quantum efficiencies than photomultipliers with efficiencies approaching 100%. They operate with low voltage supplies such as are commonly available in spacecraft. The net component gain is, at worst, directly proportional to the applied voltage. If photodiodes are used, the bias and electrical feedback can be applied in such a manner as to make the variation in gain with voltage minimal (negligible compared to photomultipliers). Solid state detectors can be operated at suitably high frequencies when used with the proper electronics. The maximum operating frequency is determined in the detector itself by the size (in photodiodes) or the intensity (in photoconductors). Since the maximum gain of a solid state photodetector is unity, these devices require the use of a sensitive preamplifier. These amplifiers can also be solid state, operating at the same bias voltage as the detectors. The photodetector preamplifier essentially replaces the electron multiplier in a photomultiplier.

Photodetectors are mechanically rugged and are simple since they consist of only one basic part. They are quite rugged and can be operated at 125° and sterilized at 145°C. Cooling of photodetectors to reduce noise is easily achieved by using solid state coolers. The fatigue experienced in a photodetector is negligible compared to that of a photomultiplier.

2.1.2.1 Photoconductors

When a photoconductor is illuminated by photons, electrons are raised to the conductive levels and are free to move through the crystal lattice under an applied field. The positive charges may also be mobile and if so they contribute to the primary photocurrent.

Photoconductors can be readily fabricated as large area detectors of almost any desired configuration. Detectors of this class suitable for operation at room temperature are PbS, CdS, CsDe, PbSe, and InSb.

For the detection of scintillation photons, some of these materials can be immediately eliminated. In CdS and CdSe, due to the presence of electron traps within the forbidden energy gap, the effective junction capacity does not respond instantaneously to the incident illumination. As a result, there is a variation in the effective time constant as a result of the present and past illumination. Therefore, it exhibits a time dependent optical hysteresis. In a scintillation detector, this effect would manifest itself as a variation in pulse height as a function of total count rate.

Lead selenide can also be eliminated since its sensitivity for visible photons is poorer than lead sulfide.

2.1.2.2 Photodiodes

Since a diode junction can serve as a collector of an excess minority carriers which may be present, it is sensitive to such carriers from various sources: emitter junctions, thermal generation, light falling on the semiconductor. The action of light is similar to that from an emitter. An incident photon of energy greater than the activation energy of the forbidden gap can excite an electron from the valence band to the conduction band. The hole-electron pair thus produced corresponds to one minority carrier per quantum absorbed, with its comparison serving to preserve charge neutrality.

The quantum efficiency, or number of electrons collected per quantum of light absorbed varies with wavelength of the incident light. The long wavelength limit is determined by the energy gap in the semi-conductor. For shorter wavelengths the quantum yield remains close to unity but can fall off because of surface recombination of the minority carriers.

The spectral response, particularly at the long wavelength limit, is determined by the type of semiconductor employed. It is not much affected by the lifetime, and is essentially independent of the resistivity. Excessive surface recombination may lower the response at short wavelengths, as well as degrade the electrical properties. The spacial response, or size of the sensitive area, is very dependent on the lifetime, since it is proportional to life path. The number of quanta absorbed near the junction can be improved by focussing the available light close to the barrier and by reducing the surface reflection with suitable coatings.

Photodiodes suitable for operation at room temperature, are silicon and germanium. Silicon detectors can be made in disc form to sizes suitable for this application. Germanium on the other hand, is not commercially available in sizes greater than a few millimeters across. Both crystals are extremely fast detectors with excellent detectivities. However, there is some limitation in the frequency response of these detectors in that the device capacitance is directly proportional to the area of the detector.

2.2 Resolution Considerations

The resolution of a crystal-detector combination used for gamma ray pulse height analysis depends on a multitude of factors. Some of these are:

1. Luminescent conversion efficiency of the incident energy of the radiation to visible photons.

2. Linearity of the photon emission by the crystal with incident radiation energy.

3. Transmission characteristics of the crystal for the emitted radiation.

4. Photon absorption at the crystal walls.

5. Coupling efficiency of the crystal to the detector.

6. Quantum efficiency gain and linearity of the detector.

2.3 Crystal Characteristics

Let us consider the properties of the three most important scintillation crystals: NaI(Tl), CsI(Tl) and CaI(Eu). Thallium activated sodium iodide has a quantum conversion efficiency of approximately 8%, where the quantum efficiency, q, is defined by the equation:

$$q = \frac{E_p n_p}{E_i f},$$

Where E_p = energy of the emitted photon

n_p = number of photons emitted

E_i = energy of the incident particle or ray

f = fraction of E_i which is dissipated in the crystal.

Let us take the case of a 1000 ev gamma ray incident upon a NaI(Tl) crystal which totally absorbs the rays and emits photons. The emitted radiation peaks at 4100A and has a full width at half maximum of approximately 850A. Taking the average photon wavelength as 4100, the energy per photon is 5×10^{-12} ergs.

Substituting in equation (3) and solving for n_p we get:

$$n_p = \frac{qE_i f}{E_p} = \frac{(0.08)\ (1000\ \text{ev})\ (1.6 \times 10^{-2}\ \text{erg/ev})}{5 \times 10^{-12}\ \text{erg.}}$$

n_p = 26 photons

If only 20% of these photons reach the detector, we are just at the limit of the ability of a photomultiplier tube to distinguish a signal from the noise at room temperature. This result will be used in a later section which treats the problem of signal to noise ratios and expected solid state detector performance.

The conversion efficiency of CsI(Tl) is of the order of 3%, while that of CaI(Eu) is estimated to be in the range of 12 to 15% on the basis of pulse height measurements which are compared with NaI(Tl). The performance of these crystals with a solid state detector can, therefore, be expected to be better for CaI(Eu) and poorer for CsI(Tl) than for NaI(Tl).

The absorption spectrum of NaI(Tl) is in the ultraviolet with peaks at 2930A and 2340A. The crystals are, therfore, highly transparent to their own radiation. In the absence of absorbing impurities, there will not be significant attenuation of the emitted photons in the crystals from the time of emission to the time they leave the crystal through the exit window. During this period there may be many reflections from the crystal walls and surrounding reflector.

Flaws, poor distribution of activator and quenching impurities all contribute to photon absorption or non-uniform photon emission, both of which degrade the resolution.

The output of NaI(Tl) crystals has been shown to be quite linear as a function of incident radiation energy for any particular particle or ray. However, a heavily ionizing particle of a given energy will produce less light in a crystal than an electron of the same energy.

2.3.1 Wall Losses

When a photon strikes the output window in an optically perfect crystal at greater than the critical angle it will be reflected. Materials such as powdered MgO, which have coefficients for diffuse reflection of the order of 0.99, surround the walls of the scintillation crystal, so as to scatter the photon in such a manner as to increase the probability that the next impingement on the exit window will be at less than critical angle. This allows the photons to pass out of the crystal to the photodetector.

Since the walls are not perfect reflectors, and in most instances the detector area is small relative to the surface area of the crystal, there will be some photon absorption at the walls and not in the detector.

Consider the cylindrical scintillation crystal surrounded by diffuse reflecting material on all sides, except for an exit window to which is coupled a detector. Fan(1) has shown that the photon collection efficiency, is given by

$$E = \frac{KA}{Ao} \quad \frac{1}{1-\eta \ [1 \ - KA/Ao]} \qquad (4)$$

where Ao = total surface area of the Scintillator

A = surface area of the scintillator to which the detector is coupled

η = diffuse reflectivity of the reflector

K = probability that a photon impinging on A is absorbed by the detector

In addition to making E as high as possible, increasing the ratio A/Ao by making detector area as large as possible will improve the light collection.

(1) Fan, C.Y., Rev. Sci. Instr. 35, '58 (1964)

2.4 Detector Coupling

The greater the percentage of scintillation photons which reach the detector, the larger the signal level and the higher the resolution. In order to have intimate optical contact, a coupling fluid or cement is generally placed between the crystal and the detector.

The optical transmission at an interface is given by:

$$T = [4n/(n+1)^2] \qquad (1-\cos\theta)$$

where n is the index of refraction of the material the light is entering with respect to the material it is leaving and where

$$\theta = \sin^{-1} \quad (1/n)$$

If the two materials have the same index of refraction, then $T = 1$ and there is no loss due to reflection.

Current work under way at Isomet has shown that a dry coupling between a NaI(Tl) crystal and a glass window does not materially degrade the resolution. At the same time it avoids the problems of optical coupling agent degradation during dry heat sterilization. For a thin, light, solid detector the problem of optically coupling to the crystal may be materially reduced.

2.4.1 Limiting Factors

Consider a scintillation assembly in which a silicon photovoltaic detector is used to replace the photomultiplier. The number of photons released per Kev of incident particle or ray energy has been derived above. Based on this number, the limit of resolution of the optical detector can be derived. The derivation presented below uses two separate techniques to arrive at the same answer. An all solid state scintillator assembly should have a limit of resolution of 50 to 65 Kev.

The first consideration is the efficiency with which the scintillator photons generate photoelectrons in the material. The probability, E, that a photon is absorbed in a photodetector was given in equation (4).

Let us take a 2" diameter x 2" long NaI(Tl) scintillation crystal with a reflectivity of 0.98 on the walls; a reasonable detector with 90% photon to electron conversion efficiency (K); and a photodiode diameter of two centimeters. Substituting these values into equation (4) yields:

$$E = 0.58$$

The noise equivalent power (NEP) of such a device would be 2.8 x 10^{-12} watts at the peak spectral sensitivity (0.85 u). However, since NaI(Tl) peaks at 0.41 u the NEP will be increased to 9 x 10^{-12} watts. These figures are for a 15 cycle per second bandwidth. Increasing the frequency response to the limits required to track a NaI(Tl) photon pulse requires a bandwidth of roughly one megacycle. The NEP of a practical detector noise limited detector-preamp assembly will, therefore, be 1.0 x 10^{-9} watts. The limit of sensitivity of the detector can now be calculated by two methods.

First, the incident photon flux can be converted to a power function, since the incident energy and time constant are known, by the relationship:

$$P\ (t) = \frac{E n h \nu e^{-t/T}}{T} \qquad \text{(watts/Kev)} \qquad (5)$$

which is valid as long as n is a large number.

Here n = # photons/Kev
h = plancks constant (Joule-sec) = 6.6 x 10^{-34} J-S
t = time (sec)
T = decay time of scintillator (sec) = 0.25 x 10^{-6} sec
$\nu = c/\lambda$ = frequency of photon (sec^{-1}) = 7.3 x 10^{14} cps

Substituting the above values into equation (5) and using n = 30 photons/Kev and t = 0 the peak power is found to be

$$P\ (o) = 3.5 \times 10^{-11} \quad \text{(watts/Kev)}$$

The number of Kev required for P (o) to be equal to the NEP is:

$$\#\text{Kev} = \frac{\text{NEP}}{\text{P (o)}} = 54 \text{ Kev}$$

The minimum width of a peak on the N vs V curve will be 54 KEV according to this first derivation. Consider now a second technique for deriving the resolution limit.

The probability for absorption of a photon by the detector for the case cited is 0.58. The number of electrons freed in the photodetector is, therefore, 174.4 per Kev. The current time function is related to the total charge flow on the time constant by,

$$I\ (t) = \frac{q\ ne^{-t/T}}{T} \qquad \text{(amperes/Kev)} \qquad (6)$$

where q = the charge per electron
n = the number of electrons per Kev

The peak current will, therefore, be

$$I(o) = 1.1 \times 10^{-11} \text{ amperes/Kev} \qquad (7)$$

If the photocell drives a 50K resistor, the signal voltage will be,

$$V\ (O) = I(o)R = 5.5 \times 10^{-7} \text{ volts/Kev} \qquad (8)$$

Assuming a noise level of 33 watts gives a limit of resolution of

$$\#\text{Kev} - V\ \text{noise}/V(o) = 60 \text{ Kev}$$

The detector should, therefore, have a resolution limit on the order of 50 to 75 Kev. This would mean that a detector limited scintillator system would have a 10% resolution at 500 to 700 Kev energy levels.

2.5 Electronics

The electronic circuitry required to process the detector output signal is essentially a low noise transistor amplifier. The necessity for a large area detector imposes certain unique requirements on the amplifier. The high detector junction capacity, (in the order of 0.1 uf), will limit or seriously degrade detection capability if the usual high input impedance amplifier is utilized. This is due to the shunting effect of the detector junction capacity on the fast rise time and narrow pulse width of the detector output signal. The junction capacitance is represented by the shunt capacitor C_p in the detector high frequency equivalent circuit shown in Figure 1. If a high input impedance amplifier is connected to the detector terminals, C_p would integrate the detector output pulses thus preventing the amplifier from obtaining sufficient drive current to operate as an amplifier. In addition, pulse height resolution would be affected since C_p would charge exponentially to various levels as a function of count rate.

A solution to this problem may be obtained by use of a current amplifier with an input impedance small relative to the generator impedance of the detector. Current amplifiers are characterized as feedback amplifiers in which a portion of the output current is fed back in parallel with the input signal in such a manner as to cause voltage variation at the input to approach zero. The net result is detection of charge variation on the detector. This form of current amplifier is referred to as a charge sensitive amplifier. The block diagram of such a circuit is shown in Figure 2.

The extremely low input impedance essentially prevents current from being "wasted" in the detector capacitance (C_p), thereby maximizing the signal current flowing into the amplifier. The low input impedance also eliminates appreciable charge buildup across C_p. This makes the pulse height independent of the count rate.

"REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR"

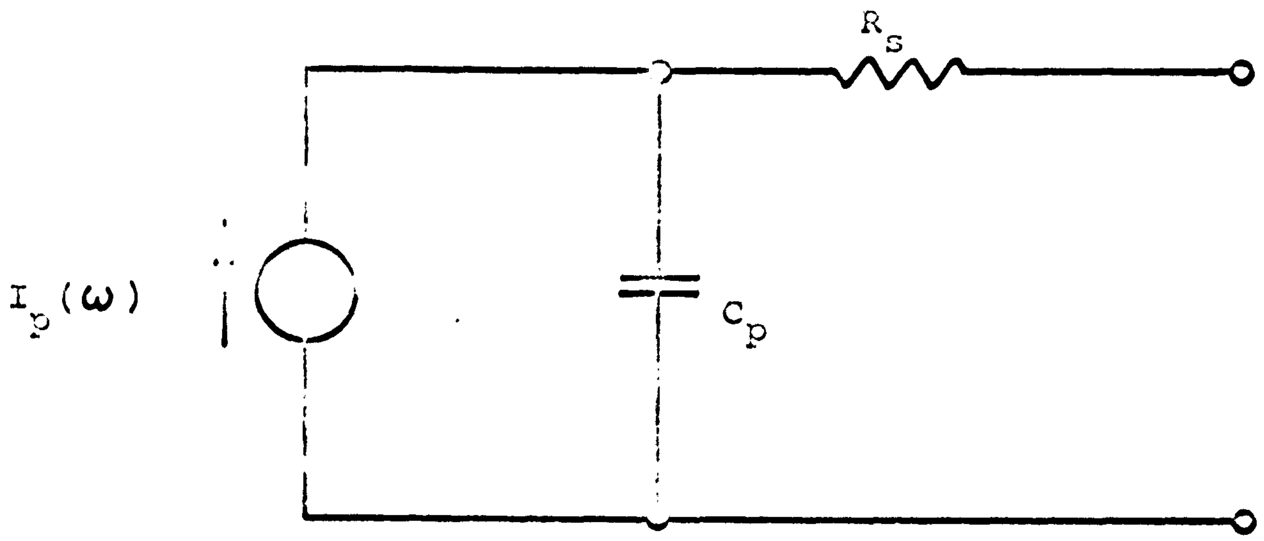

Figure 1. Photodiode High Frequency Equivalent Circuit

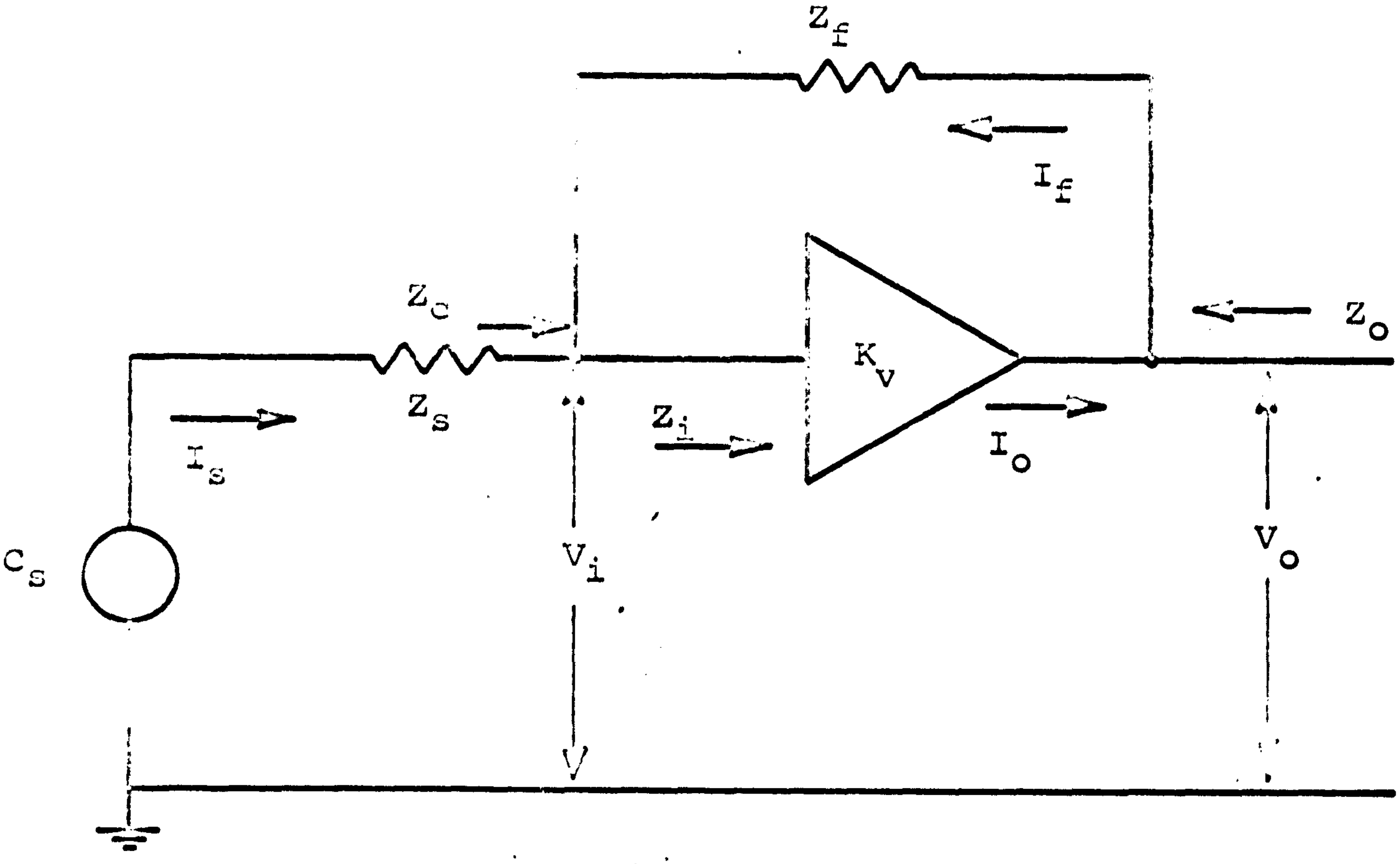

Figure 2. Charge Sensitive Amplifier Block Diagram

2.5.1 Circuit Design

An analysis of the system indicates that low input impedance levels may be obtained by proper choice of open loop voltage gain, feed-back and feed-back resistor. In Figure 2 the parameters are as follows:

e_s = signal voltage
Z_s = source impedance of signal
I_s = signal current
Z_c = closed loop input impedance = V_i/I_s
V_i = voltage across input terminals = $(I_s + I_f)Z_i$
Z_i = amplifier open loop input impedance
K_v = amplifier open loop voltage gain
V_o = voltage across output terminals
Z_o = amplifier closed loop output impedance
I_o = amplifier output current
Z_f = feedback impedance
I_f = feedback current
$I_f = V_o - V_i/Z_f$
$K_v = V_o/V_i$ and $V_o = K_v V_i$
$I_f = (V_i o K_{v-1})\ Z_f$
$V_i = (I_s + I_f)Z_i = [I_s + V_i\ (K_{v-1})/Z_f]Z_i$
and $Z_i I_s = V_i [1-(K_{v-1})]Z_i/Z_f$
but $Z_c = V_i/I_s$

$$Z_c = Z_{i/1}{}^{-(K}{}_{v-1}{})Z_i/Z_f$$

if $Z_i = Z_f$, then $Z_c = Z_i/K_v$

The final equations for Z_c indicate that the closed loop input impedance can be closely controlled by selecting appropriate values for K_v Z_f, and Z_i. For example, if $Z_f - Z_i - 10K$ ohms and the open loop voltage gain = 10,000, then by use of either the exact or approximate formulas for Z_c, the closed loop input impedance is 1 ohm. Under these conditions, the photodetector response will extend into the 100 MC region.

2.5.2 Electronic Components

The electronic components utilized in the amplifier circuit can be high reliability types as currently specified for use in the Apollo, Mariner and Gemini programs. Typical of these components is a high reliability type transistor 2N930A which is commercially available.

3.0 PROGRAM ORGANIZATION

The work effort was divided into three basic categories as described in the Isomet proposal, No. 42-65, dated February 11, 1965. The categories are redefined below:

3.1 Detector Analysis

The detector analysis consisted, essentially of the study, procurement and evaluation of suitable solid state optical detectors for scintillation application.

3.2 Electronic Analysis

The electronics effort paralleled the detector work. The goal was to design a preamplifier to match the optical detector and to provide an optimized scintillator output.

3.3 Optical Coupling and Crystal - Detector Configuration

The best means for coupling the optical detector was evaluated. A wide variety of detector crystal geometries, couplings and applications was considered.

The configuration of the breadboard and prototype assemblies was designed on the basis of the information gathered in other phases of the program. Testing was a major part of this task.

4.0 EXPERIMENTAL PROGRAM

4.1 Detector Analysis

At the beginning of the program a number of manufacturers who produce photodetectors were contacted for bids on a detector capable of detecting scintillation photons. The initial specifications for the detectors were:

Spectral Response Peak	4100A
D* @ peak response	1×10^{13} @ 25°C
Rise Time	100×10^{-9} second
Decay Time	200×10^{-9} second
Operating Temperature	-10°C to +70°C approx.
Active Area Dimensions	1.0 inch diameter

NOTES:

1. Active Area: Would eventually like diameters greater than 2 inches.
2. Device must be capable of being heat sterilized at 125°C for 24 hours with no degredation of performance.
3. Multiple detectors will be considered, however matching the units will be necessary.
4. Unit will eventually be required to withstand a missile environment.

Replies from various manufacturers indicated that the detectors used for scintillation detection fall into two classes. The first is a silicon surface-barrier diode bid by Electro Nuclear Laboratories. Prior work in the field of solid state optical detector-scintillation crystal assemblies (1,2) was done with this type of detector.

The second type of detector is a diffused junction, oxide passivated silicon detector with a guard ring design to reduce leakage currents. This detector, bid by EG & G, is claimed to offer higher reliability and stability. One of each type of detector in a standard production size was ordered and tested.

1. C.Y. Fan, Rev. Sci. Instr., 35, 158, Feb. (1964)
2. A.J. Tuzzolino, E.L. Hubbard, M.A. Perkins and C.Y. Fan, J. Appl. Phys. 33, 1, 148, Jan. (1962)

EGG could only supply a 0.44" diameter active area, which was considered to be too small. Electro-Nuclear Labs. Inc. bid two detectors with the following specifications:

Option II - Minimum order of two units, detector with active diameter: 1.0 inch, D* (4100A, 270, 1): 1 x 10" cm cps 1/2 /watt at 25°C ambient. Unit Price $1,000.

Option I - Type 602-10D detector per ENL spec sheet detector active diameter: 1cm, D* (4100A, 270, 1): 1 x 10^{12} cm cps 1/2 /watt at 25°C ambient. Unit Price: $270. No minimum order. A single type 602-10D detector was purchased.

United Detector Technology offered a PIN diode (Type PIN-10) which would be suitable for direct contact with a large area scintillation crystal. A single such unit was purchased.

4.2 Detection Evaluation

The first measurement made was a comparison of the two detectors under identical test conditions to determine the variation of reverse leakage current with reverse bias. The results are shown in Figure 3. The UDT detector was more than an order of magnitude superior to the ENL detector in this consideration. Data were taken on the ENL detector only up to 10.5 volts reverse bias as the rate of increase of leakage current above the vicinity of 8 volts indicated the approach of a detector breakdown region. In this respect also, the UDT detector proved superior since it may be operated safely up to 50 volts.

The next problem was the detection of modulated radiation. Figure 4 shows the experimental test set up. The approach, that of a high speed, mechanically chopped source, was first employed. A new, multi-aperture blade was fabricated for use with a high speed a.c. motor. In this manner, chopping frequencies up to 6000 hz were obtainable. Using a black body source, there was a loss of discernable signal when optical filtering was employed.

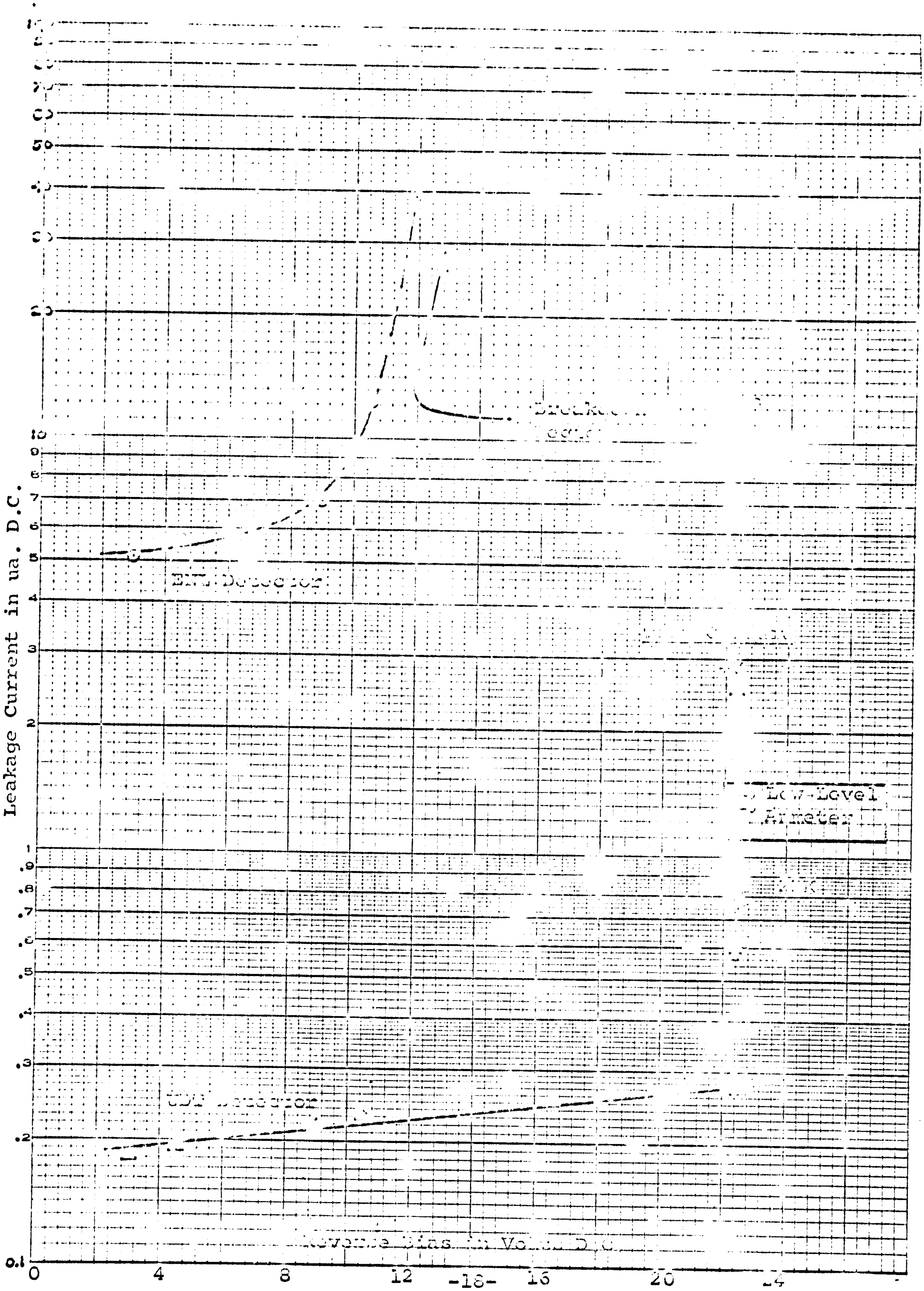

FIGURE 3. Leakage Current as a Function of Reverse Bias

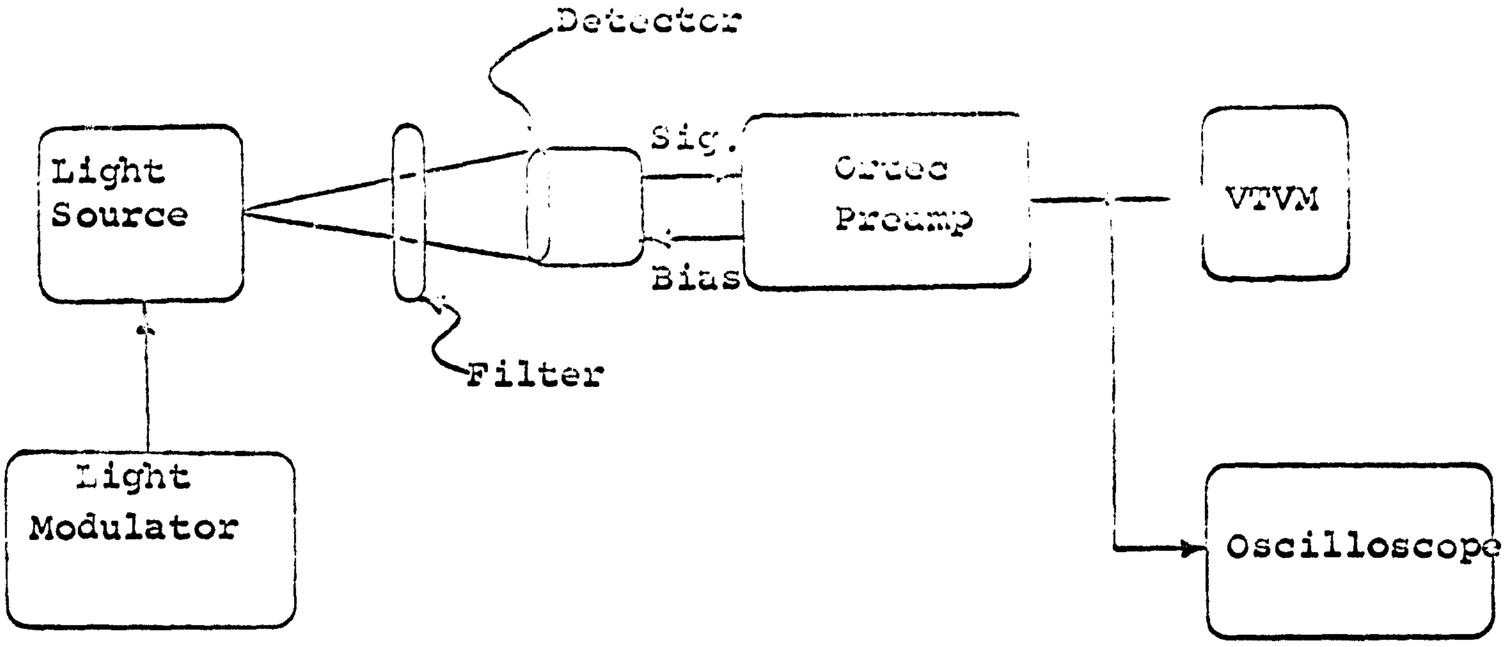

FIGURE 4. Test Set Up for Detector Measurements

The second approach to this problem, however, proved to be successful. A Sylvania glow modulator tube, R1168, was driven by an audio oscillator to provide the modulated signal desired. The advantages of this device are several. Nearly 80 percent of its output is below 4300 angstroms which is the spectral region of interest. In addition, this tube is modulated electrically rather than mechanically which removes problems of motor variations and chopper alignment. The only difficulty, albeit minor, is that the measurement is an implicit one since the glow modulator tube is an uncalibrated device. To remedy this, a standard photometer, one that was measured against a standard black body source of radiation, was utilized to measure the energy output of the glow modulator in the spectral region around 4300 angstroms. In this manner, the light source, detector and associated electronics under test were calibrated and the detector parameters of interest were obtained. Table 1 is the set of data pertinent for detector comparison and sample calculations are included for the detectivity of the devices. From the values obtained, it was evident that the UDT detector was the superior device by a factor of four. It should be noted that this value of detectivity, or D*, is not the conventional one which is normalized with respect to amplifier bandwidth. Since the objective was to compare the performance of the two detectors under identical test conditions, the amplifier bandwidth was the same for both and the ratio of one detectivity to the second is the same. Therefore, since this unit proved to have significantly lower leakage, greater biasing range and higher sensitivity, all further testing was with the UDT detector.

TABLE 1

CALCULATION OF DETECTOR DETECTIVITY

Total power emitted by the glow modulator tube in the spectral region of interest (4060-4540 angstroms at the 50 percent points) is 1.61×10^{-4} watts. Detector No. 1 is the ENL 602-10D. Detector No. 2 is the UDT PIN-10.

H_1 incident power on detector no. 1 per unit area (irradiance)

$$= \frac{P_e}{\pi r_1^2}$$

where P_e = power emitted by lamp

r_1 = distance from source in centimeters of detector no. 1

$$H_1 = \frac{1.61 \times 10^{-4} \text{ watts}}{\pi \times (7.95)^2}$$

$$= 8.1 \times 10^{-7} \text{ w/cm}^2$$

D_1^* Detectivity in $(\text{watts/cm}^2)^{-1}$ of detector no. 1

$$= \frac{e_{s1}}{H_1 \, e_{n_1}}$$

where e_{s_1} = signal voltage in volts (p-p).

e_{n_1} = noise voltage in volts (rms).

$$D_1^* = \frac{1.25}{8.1 \times 10^{-7} \times .320}$$

$$D_1^* = 4.82 \times 10^6 \ (\text{watts/cm})^{-1}$$

For Detector No. 2:

$$H_2 = \frac{1.61 \times 10^{-4} \qquad \times \qquad 1}{}$$

$$= 5.7 \times 10^{-7} \text{ w/cm}^2$$

$$D_2^* = \frac{1.20}{5.7 \times 10^{-7} \times .110}$$

$$D_2^* = 1.92 \times 10^7 \ (\text{watts/cm})^{-1}$$

Sample calculations were made to determine the approximate strength of a radioactive source necessary to produce an observable output from the detector. Let

$$\text{number of Kev} = \frac{\text{N.E.P.}}{P(o)}$$

where N.E.P. is the noise equivalent power of the detector in watts and P (o) is the power distribution due to the incident photon flux. In turn,

$$P\ (o) = \frac{\epsilon \eta h \nu}{T}$$

where ϵ is the photon collection of efficiency, η is the number of photons per Kev, h is Planck's constant, ν is the photon frequency and T is the decay time of the scintillator material. Assuming a photon collection efficiency of 0.6, a not unreasonable value, considering the present detector and a two inch crystal, and values of $\eta = 30$, $T = 0.25$ microseconds and $\nu = 7.3 \times 10^{14}$ hz., all characteristic of the material,

$$P(o) = \frac{0.6 \times 30 \times 6.6 \times 10^{-34} \times 7.3 \times 10^{14}}{0.25 \times 10^{-6}}$$

$$= 3.47 \times 10^{-11} \text{ watts/Kev}$$

$$\text{and no. of Kev} = \frac{\text{N.E.P.}}{P(o)}$$

$$\text{where N.E.P.} = \text{NEPD} \times A_o$$

$$= \frac{1}{1.92 \times 10^{7}} \times \frac{\pi \times 1.6^2}{4}$$

$$= 1.045 \times 10^{-7} \text{ watts}$$

Therefore,

$$\text{no. of Kev} = \frac{1.045 \times 10^{-7}}{3.47 \times 10^{-11}}$$

$$= 3.01 \times 10^{3}$$

or 3.01 Mev.

A survey of commercially available radioactive sources was undertaken in order to determine which, if any would be suitable for test purposes.

4.2.1 Large Area Detector

The possibility of obtaining a detector with improved physical characteristics was discussed with United Detector Technology.* A one inch diameter detector was not compatible with their production facilities at that time but they proposed a 0.800 inch diameter active area. This is the dimension "X" in Figure 5.

UDT reduced the detector wall, making it closer to the detector surface and left the inside surface a natural aluminum finish for higher reflectance.** The lead bonded to the detector surface was replaced with an evaporated lead. The cost of a 0.800 inch diameter detector with the above modifications and the same electrical characteristics as the previously purchased detector was $200 for a single unit with quantity discounts available for five or more units.

In anticipation of the tests with the nuclear source and crystal assembly, a 0.800 inch detector with the improved mechanical characteristics was ordered. The new detector will greatly improve the optical coupling with the crystal.

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*The drawing of the advanced photodetector and housing is shown in Figure 5.

**Dimension "Y" of Figure 5 will therefore be made as close as possible to dimension "Z".

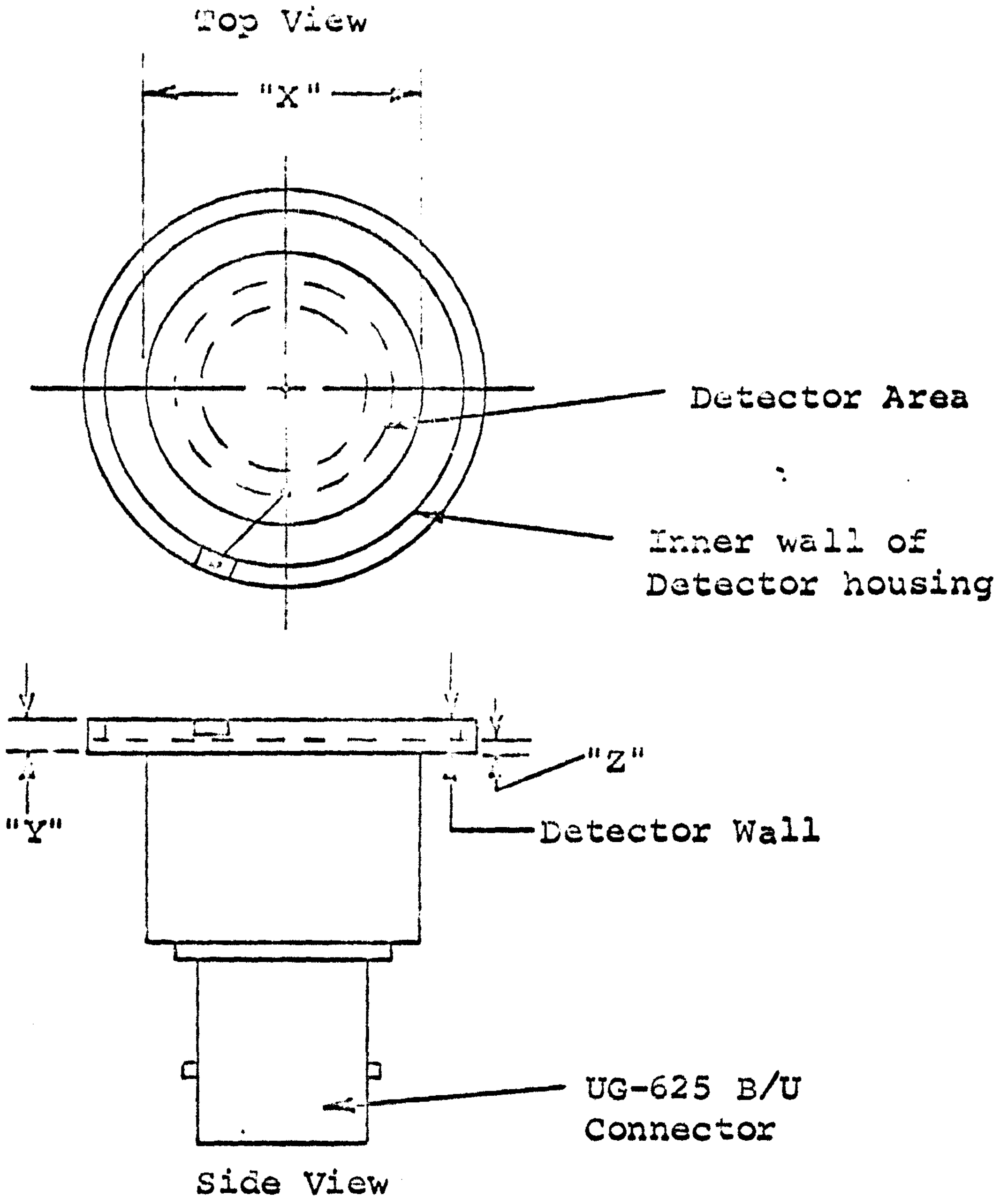


Figure 5. Photodetector and Housing

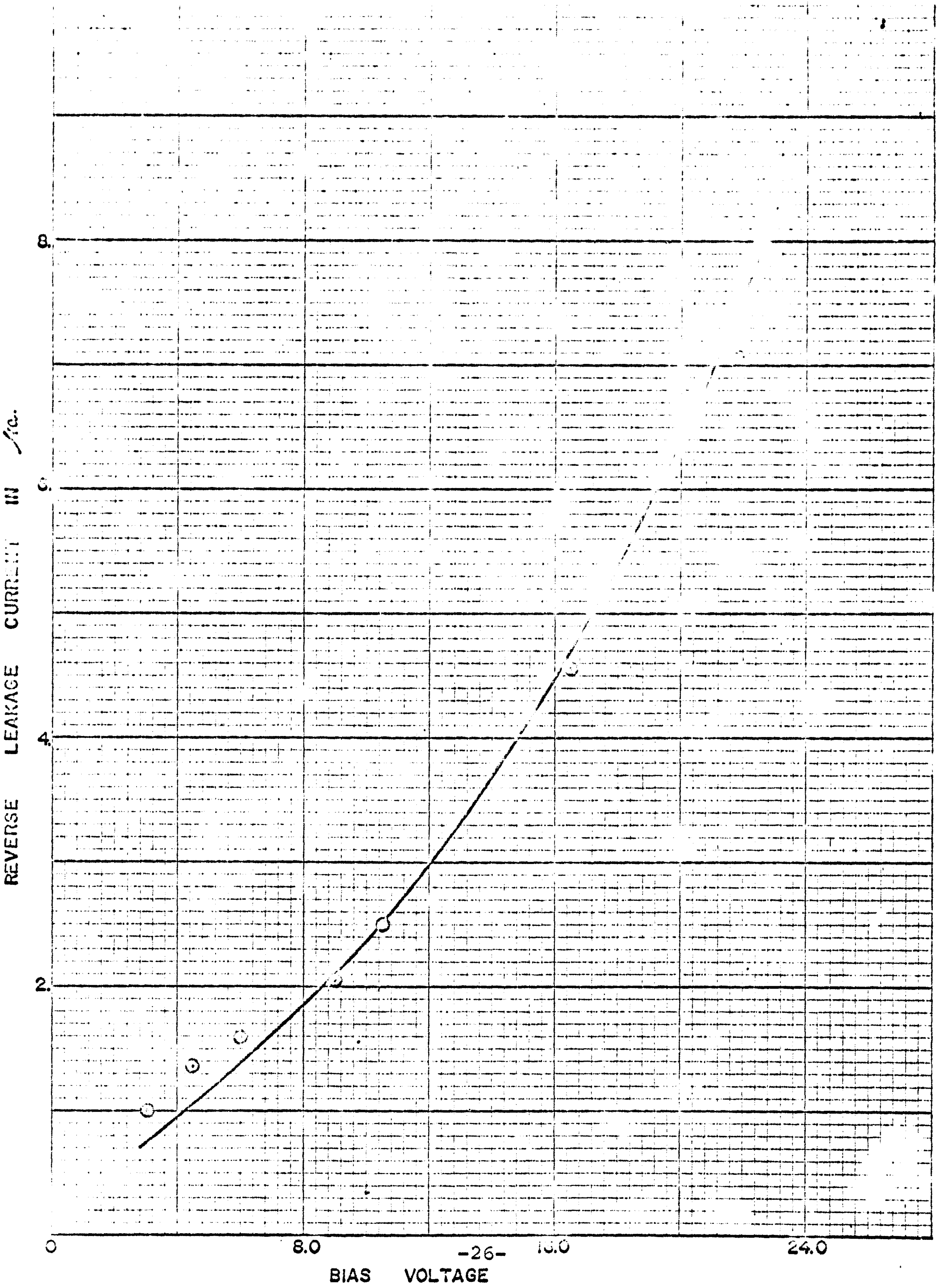
The new United Detector Technology detector was put through initial tests. Figure 6 shows the measurement of reverse leakage current versus d.c. bias voltage. The measured values are within specification for this unit.

From a physical standpoint, however, this unit was clearly superior to its predecessor. The housing wall was eliminated and the active area was slightly greater than 3cm^2. The lead attached to the active surface was replaced with a deposited lead. This resulted in a flat surface which allowed closer optical coupling to the crystal surface.

A series of measurements was then performed on both detectors from United Detector Technology. The testing configuration is shown in Figure 7. The comparative readings for UDT-1 and UDT-2 (the 0.625 inch and 0.80 inch diameter detectors, respectively) were used to determine detector performance. A sample calculation for detectivity has been included as Table 2.

The results were in agreement with theory. A large area detector is noisier, and hence less sensitive, than a smaller area detector. This was shown by the measurement of leakage currents and detectivity. The advantage of the large area detector, however, lies in the fact that it provides a better match to the standard scintillator crystals being used and hence, a more efficient coupling.

FIG. 2 - BIAS VOLTAGE VS REVERSE LEAKAGE CURRENT FOR IMPROVED U.D.T. DETECTOR



[redacted]

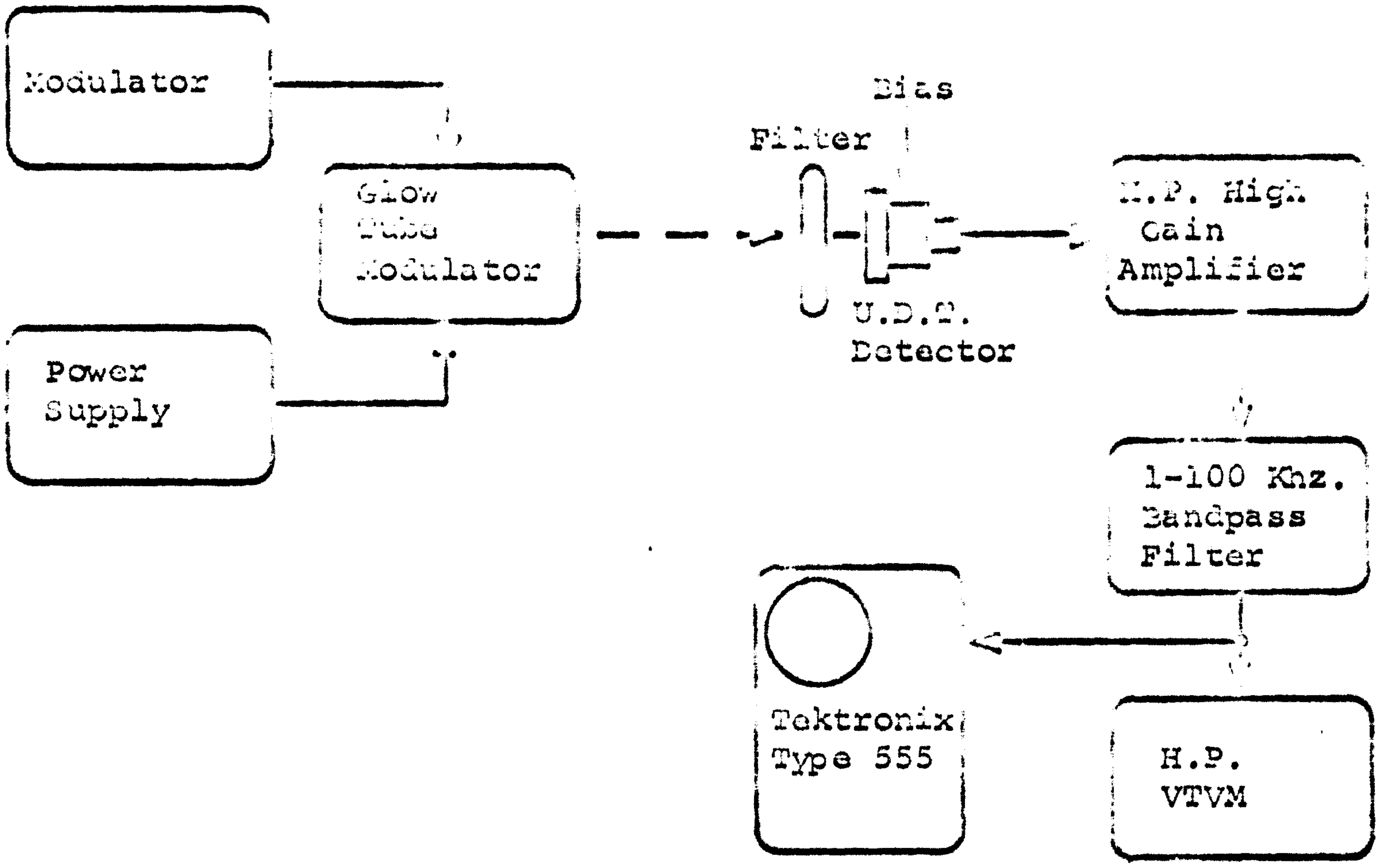


Figure 7. Test Set Up for Detector Measurements

TABLE 2

CALCULATION OF DETECTIVITY

Total power emitted by the glow modulator tube in the spectral region between 4060 and 4540 angstroms (at the 50 percent points) is $.92 \times 10^{-4}$ watts at a drive level of 8 volts p-p.

For UDT-1:

H_1 incident power on detector per unit area (irradiance)

$$H_1 = \frac{P_o}{\pi r_1^2}$$

Where P_o = power emitted by lamp

r_1 = distance from source in cm

$$H_1 = \frac{.92 \times 10^{-4}}{\pi \times (11.0)^2}$$

H_1 = Detectivity in $(\text{watts/cm}^2)^{-1}$

$$H_1 = \frac{e_{signal1}}{e_{noise1}} \times \frac{1}{H}$$

$$H_1 = \frac{320}{68} \times \frac{1}{2.42 \times 10^{-7}}$$

$$H_1 = 1.94 \times 10^7 \ (\text{watts/cm}^2)^{-1}$$

Similarly, for UDT-2:

$$D^* = 0.54 \times 10^7 \ (\text{watts/cm}^2)^{-1}$$

4.3 Electronics

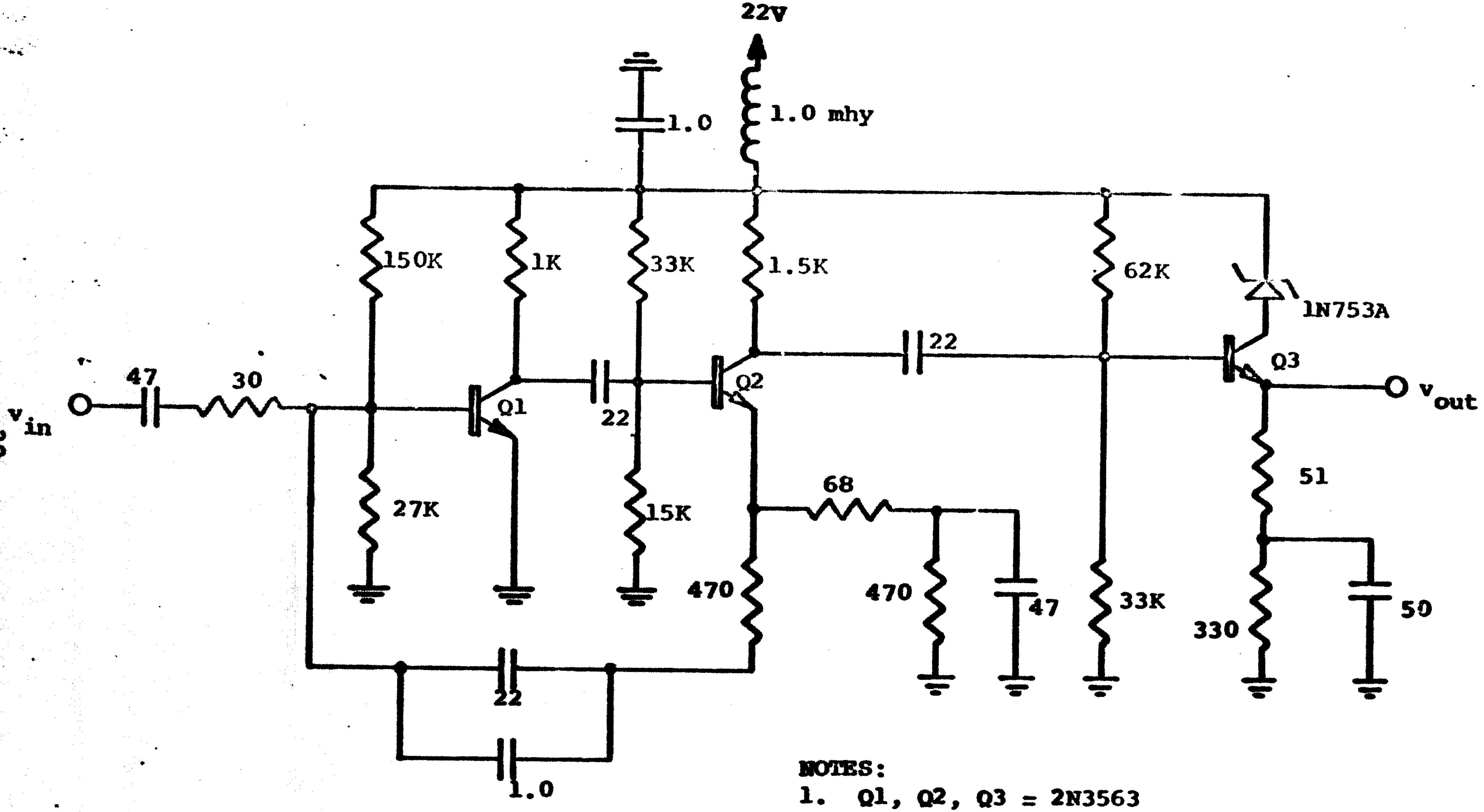
The work effort was concentrated on obtaining an amplifier for use in testing detectors. The design, shown in Figure 8, is a modification of a wide band amplifier previously developed at Isomet. This amplifier has the following characteristics:

Voltage gain, center frequency	40db
Rise time	35 ns
Fall time	35 ns
Delay time	15.5 ns
Power Requirement	0.57 watts @ 22 volts
Input Impedance	8.5 ohms

The frequency response for the amplifier circuit is shown in Figure 9.

Additional circuit work performed on the preamplifier showed that for the common emitter input configuration selected, no further improvements in equivalent noise input could be anicipated. The best level obtained was 12×10^{-9} amperes which is eight times the detector noise level. The reason for this limitation is the bias level used for the first transistor stage of the preamplifier. Some preamplifier performance characteristics are listed in Table 3.

For best detection sensitivity, the preamplifier must have an equivalent input noise level that is lower than the detector noise level. To reach the lowest possible noise levels, the first transistor must be biased at a specified low collector current. In the bipolar transistors used for this application (as well as all known bipolar transistors) the collector bias current for best low noise performance is not the same as that required for adequate high frequency response. By varying the collector current, the frequency response and equivalent input noise could also be varied simultaneously.



NOTES:

1. Q1, Q2, Q3 = 2N3563
2. All Resistors 1/2 Watt, 5%
3. All Capacitors are Mfd

Figure 8. Wideband Amplifier

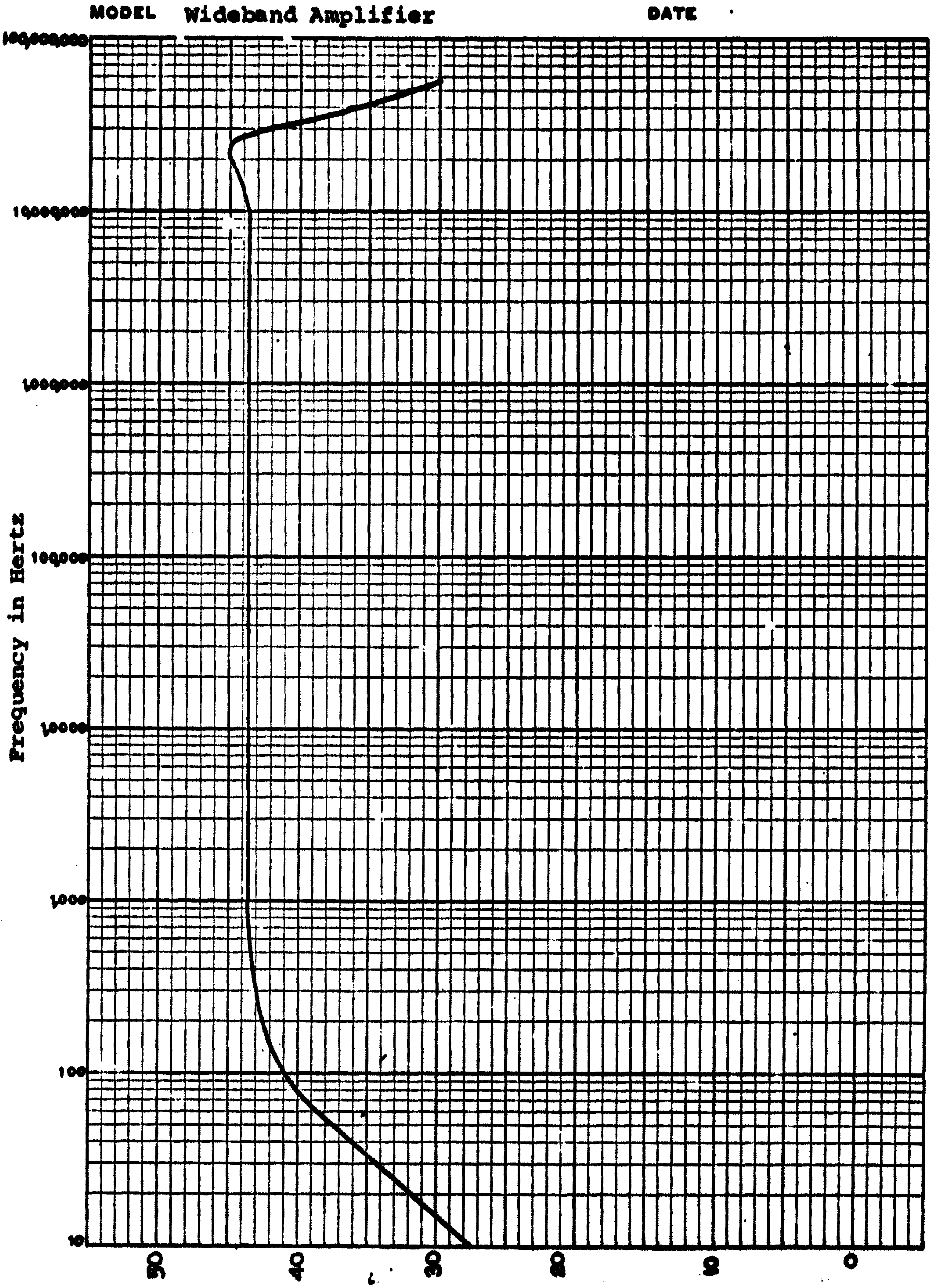


Figure 9. Voltage Gain in db

TABLE 3

Preamplifier Characteristics

Pulse gain, closed loop	3250
Output Pulse Rise Time	80×10^{-9} seconds (10% - 90%)
Time Delay	64×10^{-9} seconds (10% - 10%)
Output Pulse Fall Time	80×10^{-9} seconds (0% - 10%)
Z in	252 ohms (approximate)
Equivalent Noise Current Input	16×10^{-9} amps.

Lowest noise performance was obtained at low collector currents, typically between 10 microamps and 150 microamps. In this current region, the preamplifier gain of 3250 (at a collector current of approximately 1 ma) was reduced by a factor of 2 and the rise time increased to approximately 425 nanoseconds; the change being caused almost entirely by the first transistor. The ENI was calculated to be 12 nanoamps. Since the detector noise is 2 nanoamps, this particular type of amplifier even when optimized, is inadequate for use with the scintillation detector.

In order to allow immediate tests of the detector with various crystal configurations, an ORTEC Model 105 Preamplifier was used. This equipment was capable of being modified for matching detectors with different shunt capacitance.

4.4 Optical Coupling

The operating characteristics of the scintillation assemblies are greatly affected by the shape, surface finish and reflecting surfaces of the NaI(Tl) and CsI(Tl) crystals. Since the silicon optical detectors require maximum efficiency in light collection, the reflecting material surrounding the crystal must be chosen with great care.

Measurements of the effect of optical detector diameter on the scintillation detection process were made using a 2" x 2" NaI(Tl) crystal package. Highly reflective aperture stops, ranging in size from one-quarter inch to two inches, were inserted between the two inch by two inch crystal and the two inch photomultiplier window. The photomultiplier output was coupled to a TMC 400 channel analyzer. The pulse height distribution for each one of several apertures was measured. The data are presented in Table 4. For future reference, the exact pulse height distribution was recorded on punched paper tape.

The 400 channel analyzer was calibrated so that for each measurement, a recording of the peak channel number and the input gain setting for each measurement could be converted to give a relative pulse amplitude. In this manner, the efficiency of the scintillator could be evaluated as a function of aperture. Table 4 shows the data after correction for system nonlinearities. The area of the aperture, A, was divided by the total crystal surface area, A_o, to get a relative collection efficiency reference. The corrected peak channel is the relative channel location of the scintillation peak, giving the relative strength of the signal pulses. The resolution is the ratio of the full width at half maximum to the peak position. The total count is an approximate number found by summing the total counts in channels centered about the peak. This number is an approximate indicator of the

TABLE 4

Effect of Detector Diameter on a 2" x 2" NaI(Tl) Scintillator

Tape No.	Aperture Size	A/A_0 (#)	Corrected Peak Channel (#)	Resolution %	Total Count (#)
7	2	0.17	1,210	8.25	1661
1	1 1/2	0.094	1,160	10.5	1723
2	1	0.042	701	11.3	1642
3	3/4	0.023	391	13.6	1545
8	1/2	0.010	180	18.4	
4	1/2	0.010	180	17.4	
6	1/4	0.0026	36	40.5	732

number of counts per unit time as a function of detector size.

The data indicated that a detector size of one inch or more is desirable for the 2" x 2" crystal assembly. The larger the better, but at one inch, operation is satisfactory. It is worth noting here that the photocathode diameter of the photomultiplier was approximately 1.75 inches.

The 602-10D detector was mounted on a two inch NaI crystal in a laboratory fixture and exposed first to a Co^{60} source and then to a Cs^{137} source. According to approximate calculations, the expected signal level into the Ortec amplifier from this configuration was too low to produce an observable output on the oscilloscope. Part of this was attributed to the relatively loose optical coupling between the scintillation crystal and the silicon detector. This was necessary because of the high walled can surrounding the detector surface.

Two one inch scintillator crystals were fabricated. One of these (serial number 0412) was a CsI crystal and the other (serial number 0413) was a NaI crystal. The data taken on the pulse height analyzer and the resolution calculated from this data for each crystal are shown as Table 5.

An initial mechanical configuration is shown in Figure 10. It should be noted that this package delineates a philosophy of design rather than a detailed, dimensioned blueprint. For example, the configuration of the detector portion of the fixture was dependent on which detector was selected.

One problem is the wall surrounding the detector surface. This wall increases the distance between the crystal and the detector surfaces which, in turn, introduces considerable attenuation of signal. For the purposes of feasibility testing, a small crystal could have been fabricated which would fit inside the detector housing and rest on the active area surface. An alternate approach was to remove the black anodized finish from the inner wall of the present detector and to fill the space between the

TABLE 5

RESOLUTION DATA FOR ONE INCH

CsI AND NaI CRYSTALS

NAI(Tl)   #0413   1" 1"

START   CH200

```
000135  000170  000142  000166  000148  000140  000137   000134  000097  000115
000138  000118  000121  000141  000133  000135  000127   000142  000158  000169
000166  000164  000190  000195  000205  000193  000223   000247  000269  000303
000324  000383  000390  000430  000523  000502  000521   000589  000677  000687
000766  000834  000908  000990  001037  001126  001176   001242  001332  001447
001485  001574  001532  001541  001641  001613  001547   001570  001596  001447
001483  001420  001311  001225  001200  001115  000970   000929  000794  000698
000557  000482  000425  000346  000325  000261  000184   000192  000130  000103
000069  000061  000047  000046  000034  000028  000013   000018  000019  000009
000004  000010  000014  000016  000007  000004  000008   000006  000009  000008
```

Gain 0.640
Live Min 4
Supply   1Kv
Tube Isomet 2" standard
Width 26
Height 255
Res. 10.4%

CsI (tl)   #0412   1" 1"

START   CH200

```
00193   000184  000190  000181  000155  000129  000148   000157  00014
000139
000138  000116  000115  000147  000159  000144  000143   000132  000152  000170
000158  000168  000164  000191  000216  000217  000236   000237  000287  000290
000329  000308  000365  000422  000427  000481  000504   000572  000622  000712
000733  000770  000831  000881  001021  001046  001128   001147  001256  001301
001357  001413  001390  001488  001427  001503  001562   001576  001564  001595
001535  001509  001438  001439  001423  001373  001284   001250  001144  001049
000972  000927  000873  000881  000763  000671  000602   000567  000491  000470
000383  000335  000286  000244  000225  000200  000185   000142  000118  000120
000084  000076  000068  000063  000042  000042  000038   000028  000035  000026
```

Gain 2.240
Live Min   4
Supply   1Kv
Tube Isomet 2" standard
Width 34
Height 260
Res.   13.1%

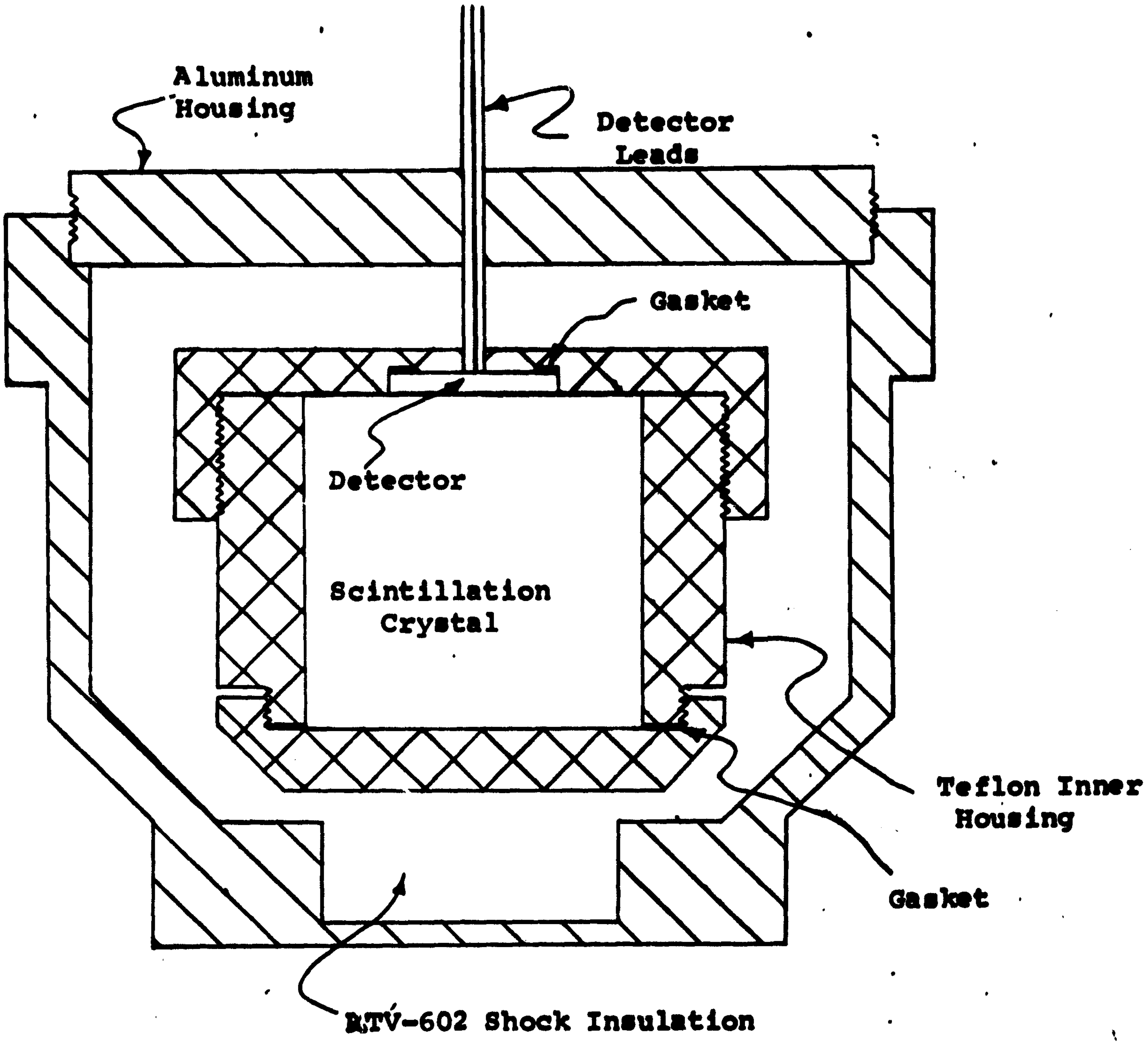


FIGURE 10. Initial Mechanical Configuration

crystal and detector surfaces with a high purity silicone grease. The former acts to reflect light incident on the wall back into the assembly; the latter to provide more efficient optical transmission.

Teflon was employed as the material for the inner housing because of its durability, resistance to heat, shock and fungus and its ease of machining. The RTV-602 potting compound was chosen because it offers excellent protection against thermal shock, vibration, mositure, dust and chemicals. It is transparent and repairable and meets thermal shock requirements as outlined in MIL-STD-202A, test condition B (five temperature cycles from -65°C to 125°C.) It will provide continuous protection at 150°C in a standard atmosphere; this limit is even higher in inert or oxygen-free environment. RTV-602 employs a catalyst cure rather than an air cure and is solventless and non-toxic. From all apparent considerations, RTV-602 was an excellent answer to the question of selecting the proper material between the inner and outer housings. The shape of the inner and outer housings was changed to cylindrical for ease of fabrication and handling. Further refinement of the inner teflon housing of the scintillation assembly was made in the form of a teflon adaptor section. The purpose of this adaptor is to permit the use of a one inch scintillation crystal with a housing designed for a two inch crystal.

The outer portion of the teflon adaptor has the same dimensions as the standard two inch crystal housing.

The design of the breadboard scintillator assembly was carried out with the thought of incorporating a nuclear source in the crystal package as a calibration device to be used in the assembly as an alternate to or instead of the standard scintillation crystal, as required.

A breadboard scintillator package was fabricated and consisted of an Americium $_{241}$ source and a 1 inch diameter, 0.25 inch thick, NaI scintillation crystal slice. This assembly was enclosed in an aluminum housing with a glass window and sealed to prevent hydroscopic deterioration of the crystal. The United Detector Technology units were placed on top of this package and coupled to the appropriate electronic instrumentation.

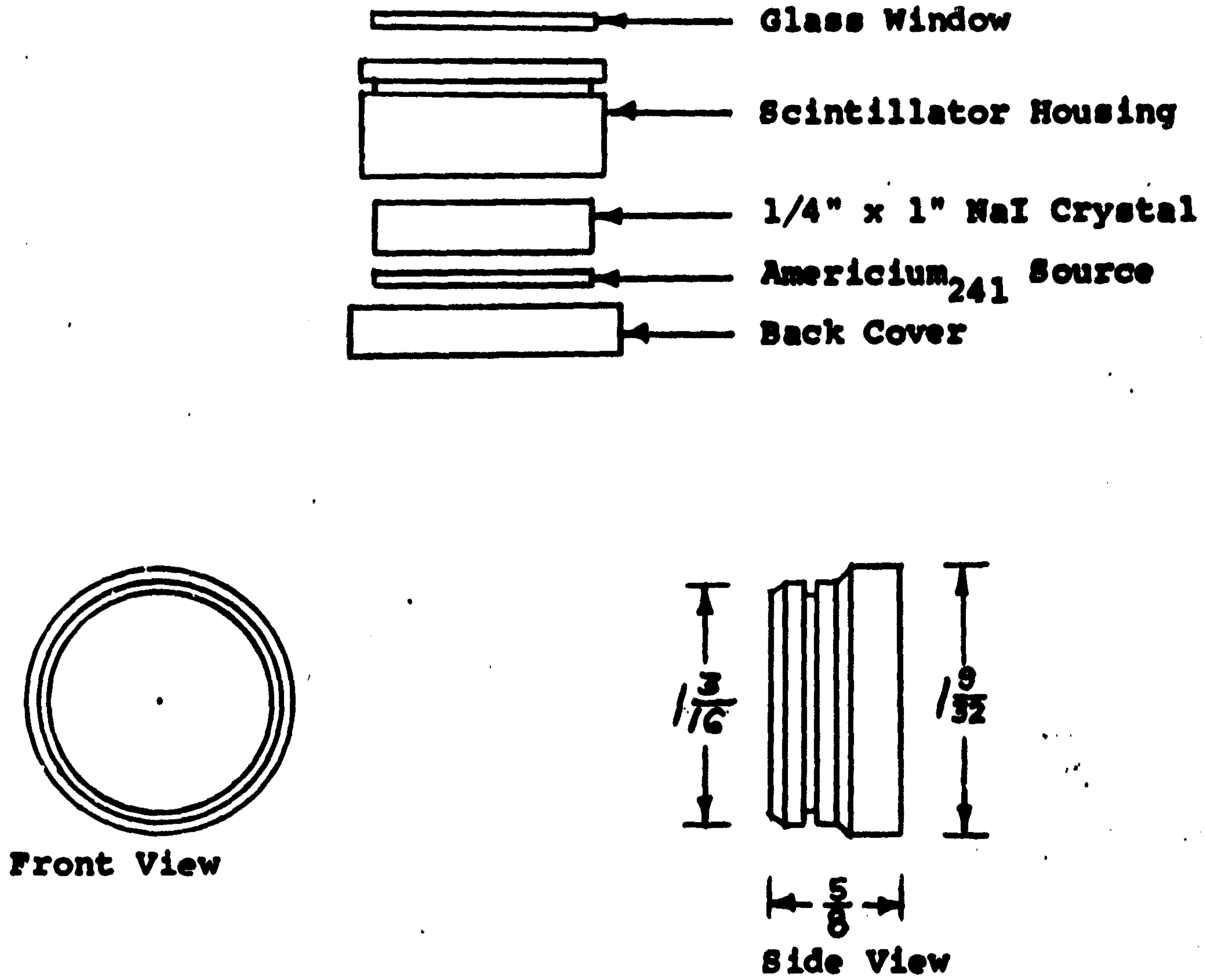
The source was a Monsanto AM241 disk which emits 5 Mev alpha particles. No silicone grease or aluminum oxide was used for optical coupling since the source-crystal package was mounted directly on the detector source.

Three individual experiments were conducted in preliminary tests of the breadboard scintillator. In the first, a standard photomultiplier tube, RCA Type 6199, was used to observe the scintillations from the combination Americium source-NaI crystal package with a Cs_{137} source added as a calibration marker. A drawing of the source-crystal configuration is shown as Figure 11. In the second test, a CsI crystal slice, 1" x 1/4" was used with an AM_{241} source and a Cs_{137} marker. The third experiment employed the solid state detector with the Cs_{137} marker and the CsI crystal-Am_{241} source since this is the more intense crystal source combination. The equipment used in these tests is shown as Figure 12.

In the first and second experiments, it was possible to observe the scintillations with a photomultiplier but these count rates were low. Typical values at the AM_{241} peak were three or four percent of the Cs_{137} peak. In addition, the count rate from the CsI was approximately 8-10 times higher than the NaI.

With the solid state detector, no scintillations were visible from either the NaI or CsI crystals. The output from this configuration was observed on an oscilloscope and the TMC four hundred channel analyzer both with and without the Ortec preamplifier. In Figure 2, if the switches are in the "A"

Exploded View



Front View

Side View

FIGURE 11- Source-Crystal Configuration

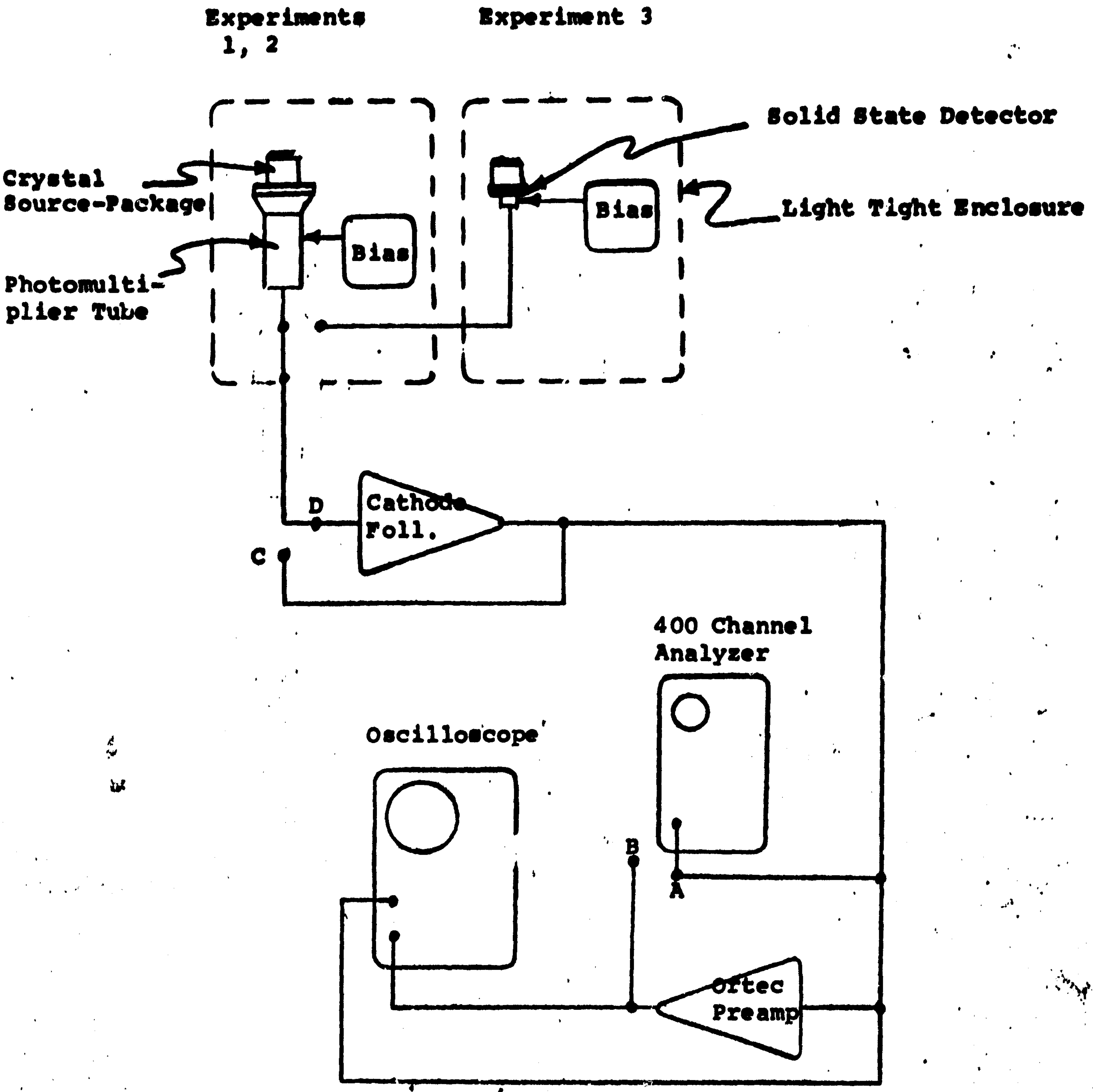


FIGURE 12 - Testing Configuration for ~~Scintillator~~

position, the Ortec Preamplifier is out of the signal path. If the cathode follower switch is in the "C" position, this circuit is removed from the signal path. For the solid state detector, tests were conducted with each configuration, that is, with and without the Ortec preamplifier and with and without the cathode follower.

On April 3, 1967 the sodium iodide-silicon photodetector assembly was tested using the Columbia University Van der Graaf generator. The experimental setup was as shown in Figure 13. A continuous beta spectrum from 12 Mev down was used as the radiation source.

No detectable scintillation events were observed.

The experiment was analyzed afterwards to determine why negataive results were observed when the theoretical calculations had shown that the threshold should be 3.0 Mev. A number of possibilities exist: (a) the detector had a lower detectivity than the manufacturer stated and lower than we measured (b) the electronics were not sufficiently sensitive to measure the output pulses or (c) the assumptions made for the light cell efficiency in the assembly were inaccurate.

Until we are able to establish an effective threshold it is difficult to determine which of these factors are valid. Negotiations were begun with Yale University to use their accellerator, which can produce particules with an energy as high as 20 Mev. Once a threshold is measured it will be possible to modify some of the characteristics of the package to optimize the performance. There were inadequate funds and time to carry out the higher energy accelerator tests.

No sterilization tests were made since a workable prototype was not achieved.

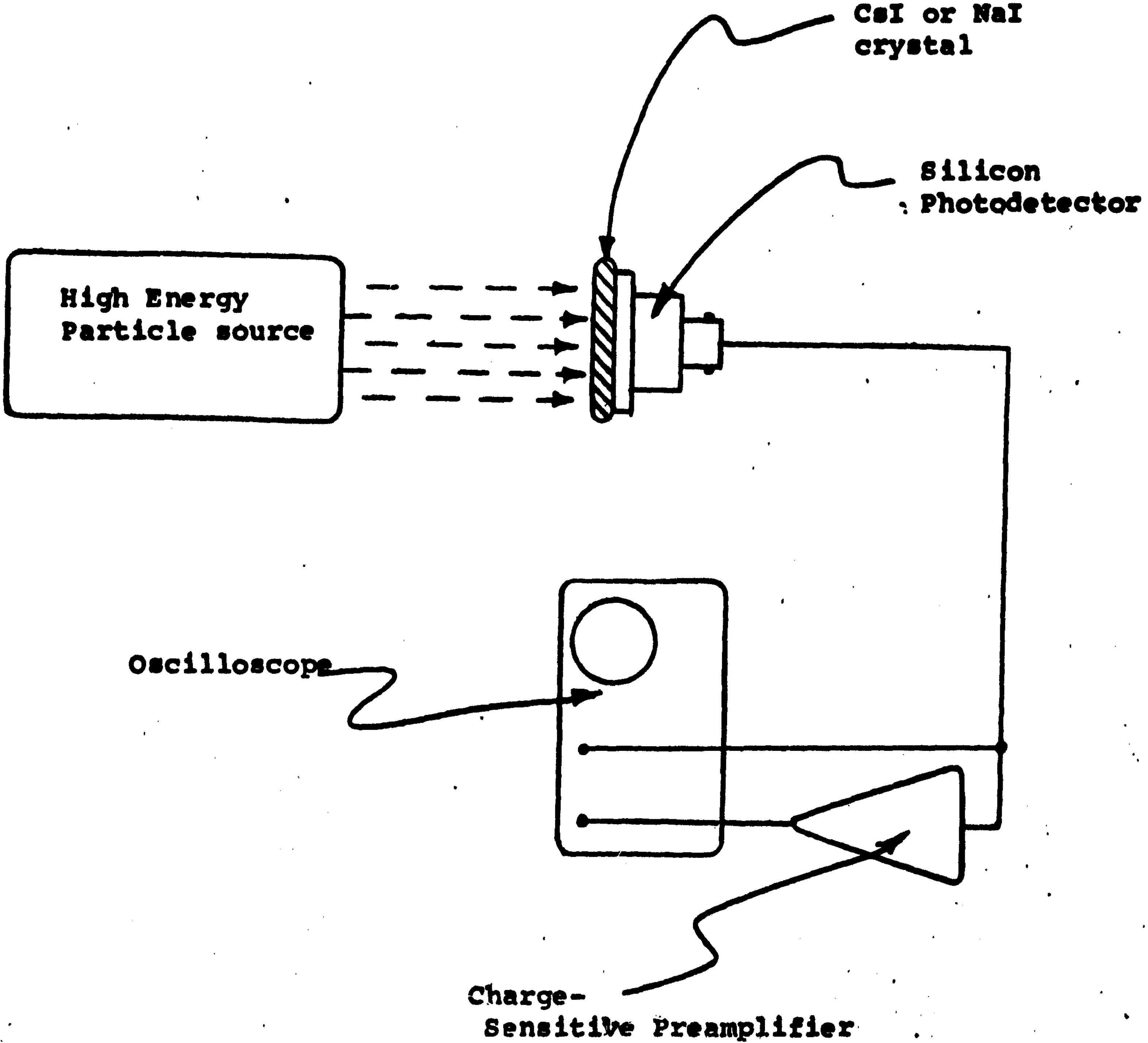


Figure 13 - Test Set-up For Breadboard Scintillator

5.0 Conclusion

1. A study was made of available solid state diodes useful for detecting low light level signals from scintillation crystals. Tests were performed on the most suitable diodes.
2. The Ortec, Model 105 Charge Sensitive Amplifier was used to detect the output from the photodiode. The state of the art of both diode and amplifier was such that the assembly was not detector-noise limited, as is desirable.
3. A prototype scintillation crystal solid state device assembly was designed, fabricated and tested. No observable signal was detected over 12 Mev electrons from a Van der Graaf generator.
4. An analysis of the results was made but it was not possible to determine which of the following contributed to the high threshold:
    a. Inadequate detectivity of the diode,
    b. Insufficient sensitivity of the amplifier.
    c. Incorrect assumptions in calculating the anticipated overall efficiency of the system.
5. It is recommended that any continuation of this work start with a review of the current state of the art in photodiodes and amplifiers to determine if a more sensitive combination can be achieved. Tests should start at a higher radiation energy such as 20 Mev.