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# A Nuclear Radiation Snow Gage

**by George A. McKean**

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# FOREWORD

The information presented in this bulletin was derived from an investigation conducted by the University of Idaho Engineering Experiment Station for the Walla Walla Corps of Engineers under Contract Number DA-45-164-CIVENG-62-172. Subsequent to the conduction of this contract, the University continued to study program aspects which contractual obligations precluded. This continued effort was aided financially by the Office of Water Resources Research, U. S. Bureau of Reclamation, and the U. S. Army Corps of Engineers in addition to funding from the State of Idaho.

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George A. McKean

Moscow, Idaho
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George A. McKean[1]

## ABSTRACT

The measurement of water stored in snow packs is important to determine the efficient utilization of this water. Various methods have been used for this measurement but have not provided accuracies sufficient for precision analyses.

Nuclear radiation is shown to be a useful tool for nondestructive water equivalent measurement. The scintillation detector was selected as a desired instrument, and the selection criteria, design features, and performance are presented. Although a unit of relatively high cost, this detector is shown to be capable of arbitrarily high resolution.

## INTRODUCTION

For many years attempts have been made to forecast the rate and absolute magnitude of water yield from remote, mountainous environments. The difficulty of acquiring and assembling the necessary data has resulted in forecasts created more from artistic judgment than from scientific analysis. The complexity of present-day society demands increased forecasting accuracy for application to the technologies of hydroelectric power generation, irrigation, soil conservation, and perhaps most critical, flood control.

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Certain of these applications place stringent requirements on the methodology used in forecasting water yield. Even an inexhaustive list of these requisites would include the determination of which parameters are needed, the measurement of these parameters, the acquisition of these data, and the final data processing.

To the most thorough of analysts, the appropriateness and usefulness of the numerous available parameters remain conjectural. Accumulated total precipitation, quantity of water stored in a snow pack, depth of a snow pack, wind velocity, net solar radiation, soil moisture, ground temperature, and air temperature form but a partial list of parameters which may be of transcendent importance in hydrologic prediction. Any or all of these factors might be useful but, in any event, their usefulness cannot be evident until made available by measurement.

There remains the problem, which has continued for more than two decades, of both measuring hydrologic parameters and acquiring the measured results with sufficient expedience before final forecasting can result from data processing. The entirety of this bulletin will dwell on parameter measurement, further constrained to the determination of water storage in snow packs.

## THE NUCLEAR RADIATION METHOD OF MEASURING SNOW

Nuclear radiation can be shown to be a practical method for measuring the amount of water stored in a snow pack. A knowledge of nuclear radiation theory gives an awareness that mass attenuates, or deters the passage of nuclear radiation. Snow is actually water in a solid, crystalline state; hence its mass must be due to the water content. If the attenuation of nuclear radiation through a snow pack can be measured, it seems that this attentuation can be interpreted in terms of the mass of water stored in the snow pack.

Determining the amount of water in a snow pack by using radioactivity is heuristically justified by examination of the narrow beam radiation attenuation equation.

$$I = I_0 e^{-\mu x} \qquad (1)$$

where the above equation,

$I$ = radiation intensity after attenuation
$I_0$ = initial intensity of impingent radiation
$\mu$ = total linear absorption coefficient
$\chi$ = thickness, or depth, of the radiation absorber.

The total linear absorption coefficient, $\mu$, includes both the true absorption of gamma photons and the scattering from the collimated beam. It is sometimes referred to as the "narrow beam" coefficient since its validity depends in part on two conditions: (1) The collimation of the radiation beam must be sufficient to minimize the eventual detection of scattered photons that have departed from the main beam; (2) The absorber should be but slightly larger in area than the area of the collimated beam in order to create maximal probability of the permanent elimination of any photons scattered from the beam. These conditions are stated since the narrow beam absorption coefficient is greater than that which would be measured by an arrangement in which scattered gamma photons reach the detector.

The total absorption coefficient, $\mu$ is composed of three parts as expressed by the equation

$$\mu = \tau, \quad \xi, \quad \kappa$$

where $\tau$, $\xi$, and $\kappa$ are partial coefficients described:

$\tau$ = coefficient due to photoelectric effect
$\xi$ = coefficient due to Compton effect
$\kappa$ = coefficient due to positron-electron production.

Insofar as the attenuation of 1 Mev gamma radiation is concerned, pair production effects are almost nonexistent and attenuation due to photoelectric effect is so small as to be considered negligible. For the application under discussion, it may then be assumed that gamma attenuation is entirely due to Compton effect.

In order to justify the use of radiation attenuation as a practical method for measuring the water equivalent of a snow pack, it is necessary to write Equation (1) on a mass basis. Conventionally this is written as

$$I = I_o e^{-\mu_m x_m} \qquad (3)$$

where the new parameters are defined by

$\mu_m$ = total mass absorption coefficient = $\mu/\rho$

$\rho$ = mass density (mass/unit volume) of absorber

$x_m$ = mass thickness of absorber = $\rho x$

It is known that the mass absorption coefficient, $\mu_m$, is a function of both photon energy, E, and the atomic number of the absorber Z. This function will be defined as

$$\mu_m = f(E,Z) \qquad (4)$$

where the nature of the general function, $f(E,Z)$, will be discussed in more detail later.

From Equation (4) and the relation between $\mu$ and $\mu_m$, the narrow beam absorption coefficient may be expressed as

$$\mu = \rho f(E,Z) \qquad (5)$$

If the mass density, $\rho$ is expressed as mass per unit volume, and the volume of the absorber, V, is expressed as the product of absorber thickness, x, and absorber cross-section, A, then Equation (5) may be written as

$$\mu = (M/V)\ f(E,Z) = (M/Ax)\ f(E,Z) \qquad (6)$$

Replacing $\mu$ in Equation (1) by the expression in Equation (6) gives

$$I = I_o e^{-\mu x} = I_o e^{-(M/A)\ f(E,Z)} \qquad (7)$$

Examination of Equation (7) shows what conditions must be met in order to measure accurately the water equivalent of a snow pack with nuclear radiation techniques. For a given amount of snow and a correspondingly given amount of water equivalent, the exponent of e in Equation (7) must be a constant. This requires that the mass, M, of water in the beam of radiation must remain fixed, that the area, A, of the absorber in the beam must not vary, and the function, f(E,Z), must be an appropriately selected constant. The first two of these conditions are met if the radiation is cylindrically collimated to prevent a conical beam from encompassing varying mass and area with changing snow depth. The last condition, that f(E,Z) be an appropriately selected constant, is one used in selecting the source of radiation.

## Selection of Radiation Source

In selecting the nuclear radiation source, it seems most practical to mention alpha, beta, X, and gamma radiation. The relative inability of alpha and beta radiation to penetrate appreciable quantities of water mass precludes the use of such radiation. Since X-rays are lower in energy than most gamma radiation, it seems that the selection of gamma radiation is the most practical of all the possibilities mentioned.

It is to be noted that neutrons could be used for this purpose since neutron energies are certainly sufficient for penetration of snow pack water levels. However the relative difficulty in procuring neutron sources makes the initial selection of gamma radiation still the most practical of all the possibilities mentioned.

The particular radiation source chosen for use is selected partly on the basis of the total linear absorption coefficient, $\mu$, mentioned in the preceding section. This coefficient was shown to be dependent upon the energy of the radiation source and the atomic number of the absorber. Since the absorber is the snow pack, it only is necessary to consider the relationship between this coefficient and the energy level of radiation.

Generally speaking this coefficient, $\mu$, increases with photon energy. Inspection of Equation (1) reveals that larger values of $\mu$ give more positive curve slopes of radiation attenuation as a function of absorber depth. Since the operating range of the intended measurement device increases with increased slope, a radiation source with relatively large photon energies should be selected.

A further condition in source selection is that the source should be as monoenergetic as possible. This limits the selection of easily obtainable radioisotopes to Cesium-137 and Cobalt-60. Cesium-137 is actually monoenergetic, having a single photopeak at 0.66 Mev. Cobalt-60 is not monoenergetic since it has two photopeaks, one at 1.17 Mev and another at 1.3 Mev.

Cobalt-60 was selected for use in the nuclear radiation method. Although it is not a truly monoenergetic source, the two photopeaks are sufficiently close in energy ratings such that it can be considered monoenergetic for purposes of measuring snow pack water content. Furthermore, the increased photon energies of Cobalt-60, compared to those of Cesium-137, allows the cobalt source to provide better measurement resolution over either a 60 or 100 inch range of water equivalent.

## Radiation Geometry

The section concerning attenuation theory, presented earlier, indicates that this nuclear radiation method is premised on the narrow-beam attenuation equation. The narrow-beam nature makes mandatory the consideration of system geometry.

The narrow-beam conditions of the attenuation equation will be most closely satisfied if the radiation beam is of cylindrical configuration. Unfortunately, if a radiation beam is to pass through a snow pack which is twelve to fifteen feet in depth, the radiation from a point source makes a strictly cylindrical beam unattainable. Good collimation of the source will aid the approximation; it could be further improved by collimation of the radiation source. In any event, the radiation beam will be either conical or of the configuration formed by upright and inverted intersecting cones.

It is to be expected that the result will be at least a slight departure from the conditions predicted by the narrow-beam attenuation equation. This, of course, can be taken into account by the method used for calibrating the system.

## Scattering

The nuclear radiation method of measuring snow pack water content depends on the attentuation presented to a radiation beam by the snow pack. The mechanics of this attenuation are of a scattering nature. If, for example, a gamma photon is emitted with a certain energy, E, and passes through the snow pack without collision with mass, it will be measured at the detector unattenuated, having an energy of E. If another photon, emitted with an energy E, passes through the snow pack and collides with mass, it may either be scattered out of the beam and hence will not be detected or it loses some of its energy and is detected at some energy level less than E; this latter case is that of Compton scattering.

Later in this bulletin, when the selection of the radiation detector is discussed, these two types of scattering will play an important role. Examining the nature of scattering offers the conjecture of whether or not scattering will occur to equal extents as the measured snow changes in density from one extreme of fluffy snow to the ultimate state of liquid water.

## RADIATION SNOW GAGE SPECIFICATIONS

The conception of a radiation-type snow gage is dependent upon some rather general specifications which are of a systems nature. A survey of these criteria reveals the most important to be those discussed in the following three sub-sections.

### Range, Resolution, and Accuracy

Measurement experience indicates that, in the Pacific Northwest, the equivalent amount of water stored in snow packs rarely exceeds 60 inches except on a few high mountain peaks. This figure has been taken as the maximum range of snow gage operation. It should be emphasized that 60 inches of water is not necessarily a measure of snow depth since the snow quality, or percentage ratio of equivalent water depth to snow depth, usually lies in the range from 10 per cent to 40 per cent, the precise value depending on previous weather history and the progression of a snow season.

From the attenuation discussion presented earlier in this bulletin, it is evident that, due to the exponential relationship between radiation attenuation and absorber depth, the accuracy of measurement will depend on the absorber depth. Measurement accuracy can therefore be specified at a low value of absorber depth with a resulting decreased accuracy at high depths, or an accuracy can be specified at the maximum depth with a correspondingly greater accuracy at low depths. Neither one of these cases is an optimum solution for reasons of sound engineering judgment in the first case and economics in the second. Based on the needs of flood control prediction, it was felt that the most desirable accuracy specifications could be achieved by dividing the total gage range into three sub-ranges and defining an accuracy figure for each of these sub-ranges. In terms of inches of water equivalent, these accuracies were specified as 0.10 inch in the sub-range from 0 to 20 inches, 0.25 inch in the sub-range from 20 to 40 inches, and 0.50 inch in the sub-range from 40 to 60 inches.

The accuracy figures can also be interpreted as resolution figures depending on the length of time considered with respect to gage operation. For purposes of flood control it is desirable to have resolutions of this order of magnitude for day-to-day operation. However, if the gage were accurate to within these figures over an entire snow season period, these figures would represent absolute accuracy. In this analysis, absolute accuracy was taken as being secondary since flood occurrence depends on the rate of runoff which can be measured in terms of gage resolution.

## Environment Conditions

The determination of water storage in snow packs must be made at the source which is in remotely located, mountainous locations. Representative gaging sites are determined and these are inherently in regions mostly inaccessable during the winter months. This inaccessability to general travel is usually accompanied by lack of commercial electrical power at a site and thus the need for battery operated gaging equipment is established.

To merely specify that batteries must be used for operation would be an oversimplification of the problem. Since travel to these sites is nearly impossible during the winter months, even by helicopter in some cases, a given battery pack must be expected to last during the entire snow season which may be as long as ten months. The use of arbitrarily high capacity batteries does not represent a practical solution since, during the short periods of time that a site is free of snow, all equipment must be delivered to some of the more remote sites by animal pack train. It can be concluded that the snow gaging device must be battery operated, but must be of sufficiently low power requirement to permit its power to be supplied from batteries of a practical size.

From the discussion of the site access difficulties encountered in these mountainous terrains, it follows that the snow gage will be operated by remote control since it cannot be attended by personnel. The usually high elevations at these sites causes inclement weather conditions, the most important of which is low temperature. Low temperatures cause operating difficulties in electronic circuitry required for both radiation detection and radio communication, particularly if this circuitry is transistorized to minimize electrical power consumption. Typically these temperatures reach -30 °C several times during a winter snow season.

## Data Acquisition

The nature of the gage site locations creates the requirement for remotely controlled snow measurements. Land transmission lines, being nearly impossible to install and maintain, are precluded from possible use. Radio transmission is therefore required and must be designed such that the entire system may be summoned on an "on call" basis from a conveniently located data collection station, sometimes called a base station.

It is well recognized that the most practical method of transmitting quantitative data is through the use of pulse coded information. Unfortunately pulse coded information is considerably more subject to radio-frequency interference, or noise, than is the more commonly encountered voice communication. The conjecture of whether a frequency modulation or amplitude modulation system is better for this purpose has been demonstrated. It has been shown that, for a given transmission bandwidth, amplitude modulation is superior to frequency modulation for a specified rejection of impulse noise. However, it has long been felt that the converse was true and hence most commercial radio systems suitable for pulse transmission are of the frequency modulated type. For this reason alone, frequency modulation radio systems will be discussed in this bulletin although a suitable amplitude modulated system has been developed at the University of Idaho.

Regardless of whether amplitude or frequency modulation techniques are employed, the Federal Communications Commission has imposed some rigid restrictions on the transmission of hydrologic data. These data must be transmitted in the 170 MHz band allocated for hydrologic telemetry. The bandwidth, which limits both data handling capacity and permissible pulse durations, is set at 8KHz. Finally, the carrier frequency tolerance is limited to the federally assigned value ± 0.0005 per cent. This last requirement is particularly important in view of the lack of frequency stability of an electronic oscillator under conditions of widely varying temperatures.

## RADIATION SNOW GAGE AND DEVELOPMENT

Although the presentation in this section is not necessarily chronological, various segments of developing a radiation snow gage are presented in the order of necessary consideration for creating such a device. The results of several years of University of Idaho investigations are presented as an analysis rather than in the order that they were actually disclosed.

### Scattering and Snow-Water Equivalence

It is important to determine whether or not a radiation measurement made of a snow pack to determine its water equivalent will yield the same result when that amount of liquid water is measured. Thus the subject of so-called snow-water equivalence is essential to consider.

Extensive testing in University of Idaho laboratories has shown that some attenuation differences do occur as the absorber changes in physical state. It should be mentioned that the extent of this variation determines, in addition to radioisotope disintegration statistics, the theoretical limit of accuracy that can be obtained from such a measurement system.

System measurement error caused by scattering becomes evident when using the entire spectrum of Cobalt-60. Figure 1 shows a typical spectrum of this radioisotope. The photopeak region, which is that region representing the principal energies of photons emerging from the radioactive source, is the most desirable portion of the Cobalt-60 spectrum to use in the snow water measurement system. This desirability is explained by considering the effect of the absorber on the impingent photons.

If a single photon collides with a molecule of the absorber, then it either is scattered completely out of the beam and is not detected, or else it loses a portion of its energy and arrives at the detector with less energy than its initial amount at the time of emission. Those photons which were emitted with photopeak energies will be detected in the so-called Compton region, if they are scattered, and still arrive at the detector. Thus the degree of scatter, which is dependent upon the physical state of the absorber, will determine the number of counts obtainable in the scatter regions of the spectrum. To eliminate this dependence upon scatter, it is necessary to provide the detector with a means of counting only those photons in the photopeak region, thereby minimizing the error due to scattering differences. With the detector

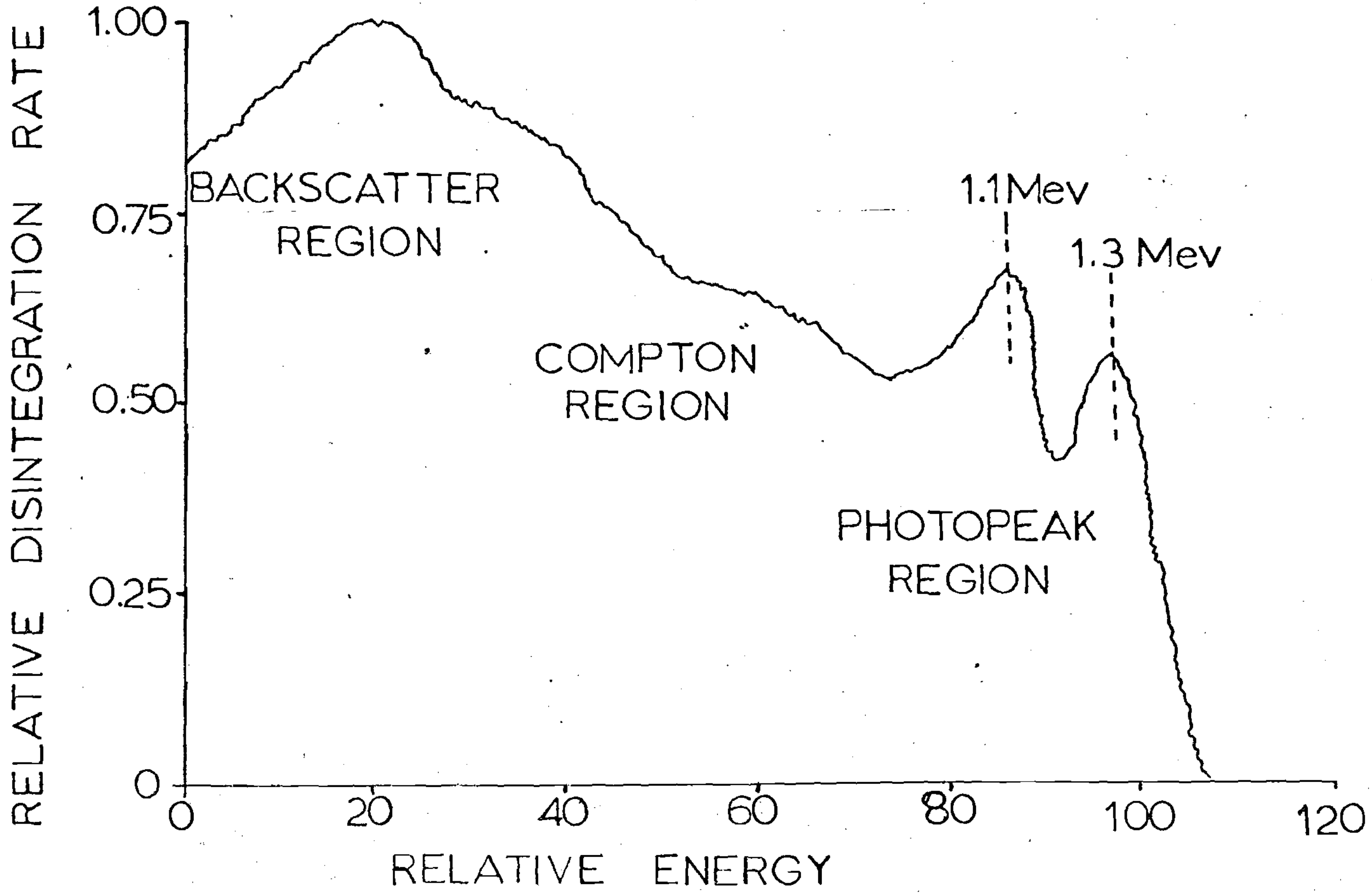


Figure 1. Typical Cobalt-60 spectrum.

set to accept only those photons with photopeak energies, these photons are those which have passed from the source through the absorber without attenuation due to the collision and resultant scattering. Hence this "energy discrimination" technique allows the unattenuated photons to be compared with the original number of photons emitted from the source.

Figure 2 shows the Cobalt-60 spectra for both snow and an equivalent amount of water. If an entire spectrum were used for counting, the count rate would be proportional to the area under the spectral curve and hence the error would be within the area difference of these two spectral plots.

## Selection of Radiation Detector

As just mentioned, errors due to count rate difference between snow and an equivalent amount of water may be minimized by counting pulses due only to high energy photons. This may be accomplished by a scintillation type radiation detector. In a scintillation detector, pulse height descrimination is possible due to the linear dependence between energy of impingent photons on the detector and the height of the corresponding output pulse. A pulse height discriminator is capable of selecting either all the pulses in a certain energy interval (differential operation) or all the pulses above a preset level (integral operation). To maximize the number of counts per unit time, which is equivalent to creating maximal detection efficiency for a given source strength and detector crystal size, the integral mode of operation can be used.

Figure 3 shows some discriminator settings above which all counts will be detected. From the standpoint of snow and its water equivalent, if the discriminator is

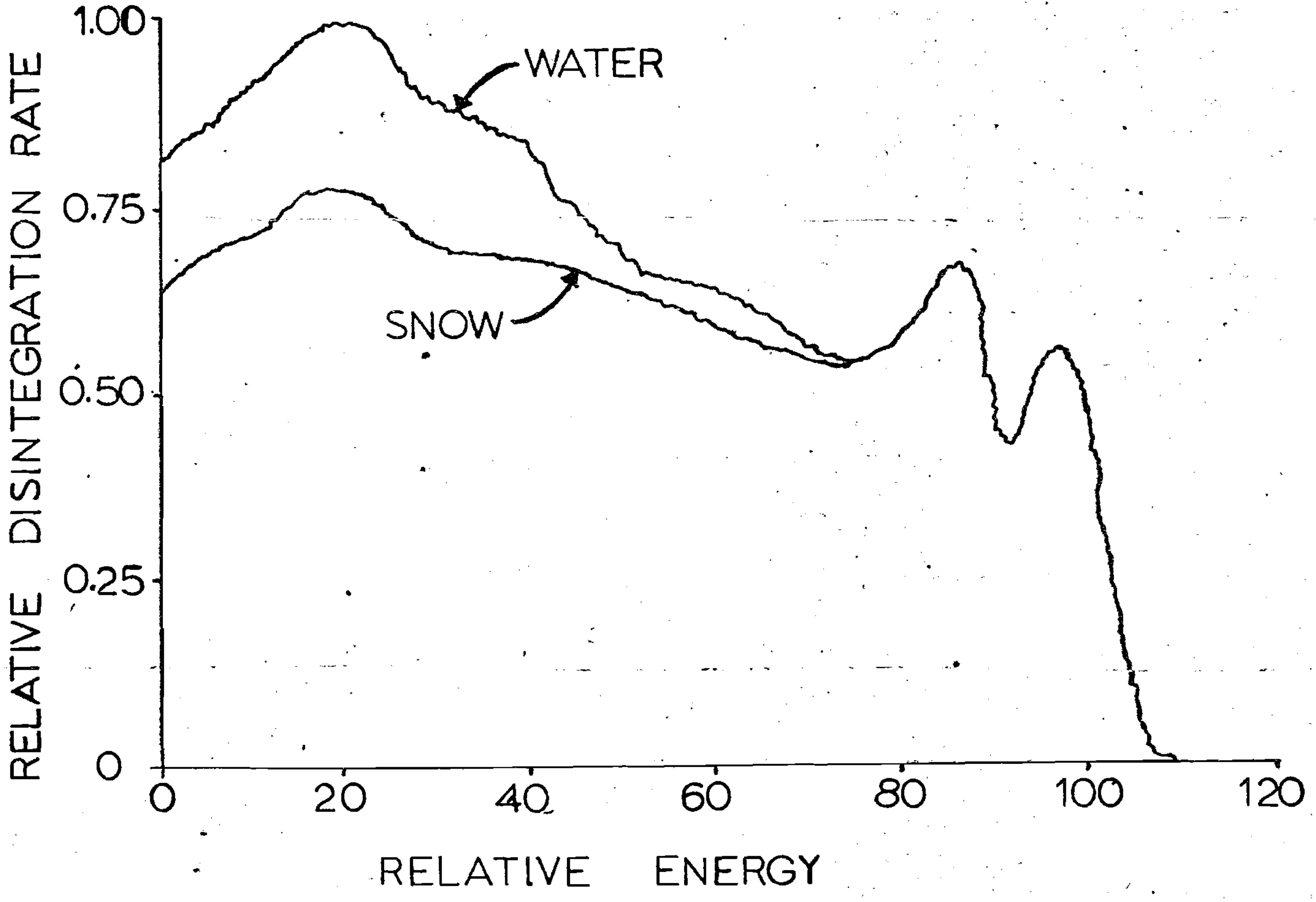


Figure 2. Cobalt-60 spectra using water and snow absorbers.

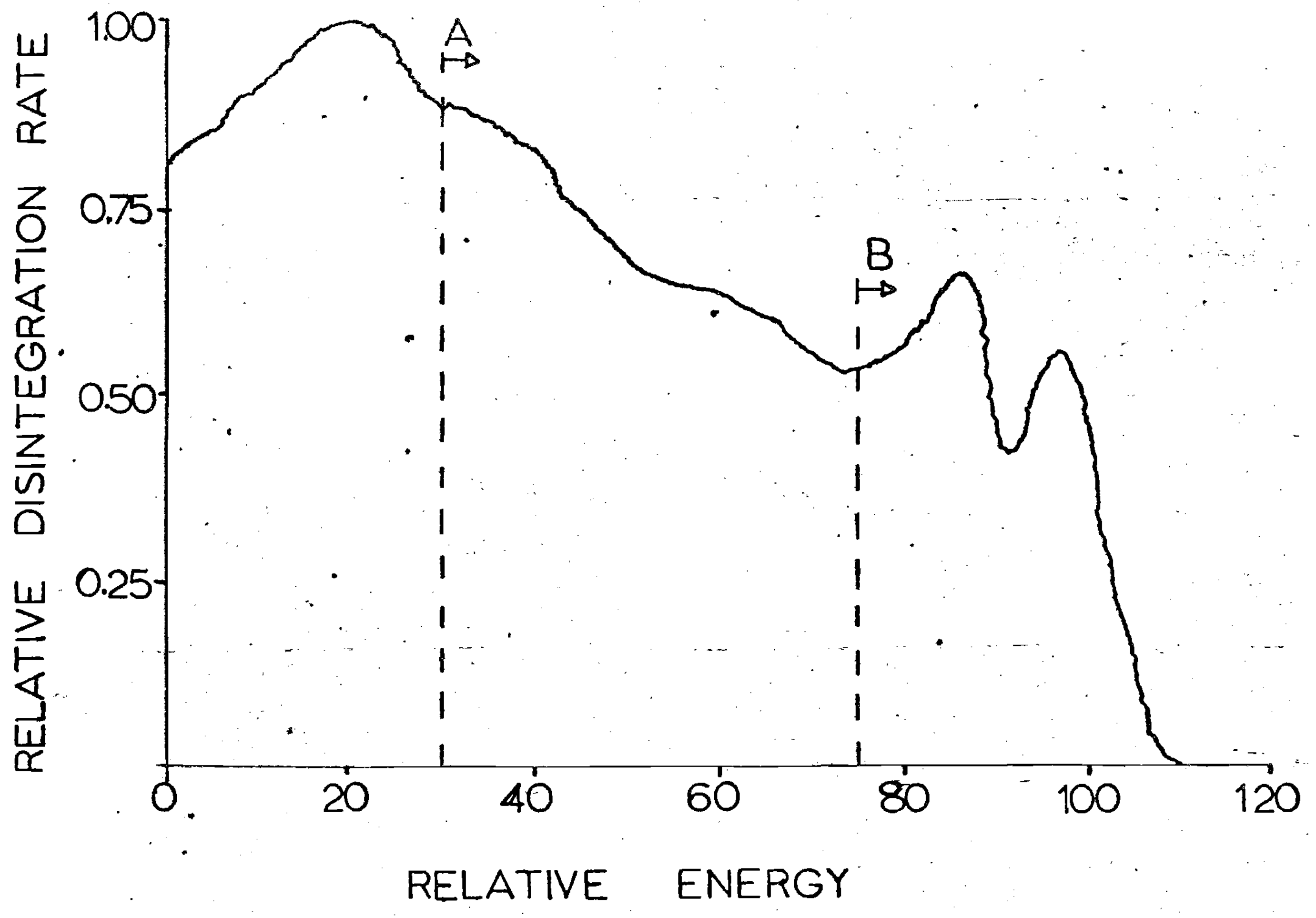


Figure 3. Threshold settings concerning error between snow and water.

set at A on this figure, then the scattering differences between snow and water will create as high as 30 per cent error. On the other hand, if the discriminator level is set at B, only the photons of essentially photopeak energies will be detected, thus minimizing this scattering error.

As a parenthetic note it is mentioned that Geiger-Muller type detectors have no energy discrimination capability. Unless some sort of mechanical energy discrimination were used with this type of detector, errors in snow water equivalent measured, compared to the actual amount of water present, could easily approach 50 per cent.

## Detector and Radiation Source Location

The decision to use a scintillation type radiation detector provides useful information to determine the relative positioning of the radiation source and detector. Relative positioning is taken to mean whether the detector is to be placed above the snow pack and the source underneath, or to position the source overhead and the detector underneath. Both cases will be discussed.

First consider the case in which the detector is placed above the snow pack and the source is buried beneath the snow pack. This has the advantage of having little measurement error from the detection of inherent background radiation since lead shielding can be used in the direction of the sky. Unfortunately, this particular gage configuration has a major disadvantage. Since the scintillation type radiation detector contains considerable electronic circuitry which must be transistorized for electrical power conservation, its exposure to the extremely inclement weather conditions would cause excessive system variance. This variance is caused by the inherent temperature stability problems common to many transistorized circuits.

For reasons of temperature stability, the second suggested configuration was chosen for use. In this case the source is placed above the snow pack and the scintillation detector is placed beneath. University of Idaho measurements show that ground temperature variation, during the period of an entire winter, varies about 3°C around the freezing point of water. Thus the burial of the detector affords a stable temperature environment.

With the detector buried, it necessarily looks toward the sky in which direction the radiation source is located. This precludes the possibility of shielding against inherent background radiation. However, errors due to this background radiation are high only when the water levels are high and the detected radiation is low. Under these conditions, the water stored in the snow pack serves as a shield against some background radiation. A typical snow gage configuration, as conceived herein, is depicted in Figure 4.

## Radiation Geometry

An earlier discussion concerning attenuation of nuclear radiation mentioned the basic attenuation equation as the "narrow beam" attenuation equation. To reiterate, this name was given since the equation holds under the condition that the cross-sectional area of the beam is small compared to the transverse dimensions of the absorber. Furthermore, the ideal geometric configuration of this beam is that of a right circular cylinder.

While the actual radioisotope source would be located approximately 15 feet over the ground surface, as depicted in Figure 4, this distance will cause the beam to be definitely conical in configuration. In the earlier discussion of the narrow-beam attenuation equation, the transverse dimension of the beam, called A, was taken to be a constant. Of course with a conical beam, it is

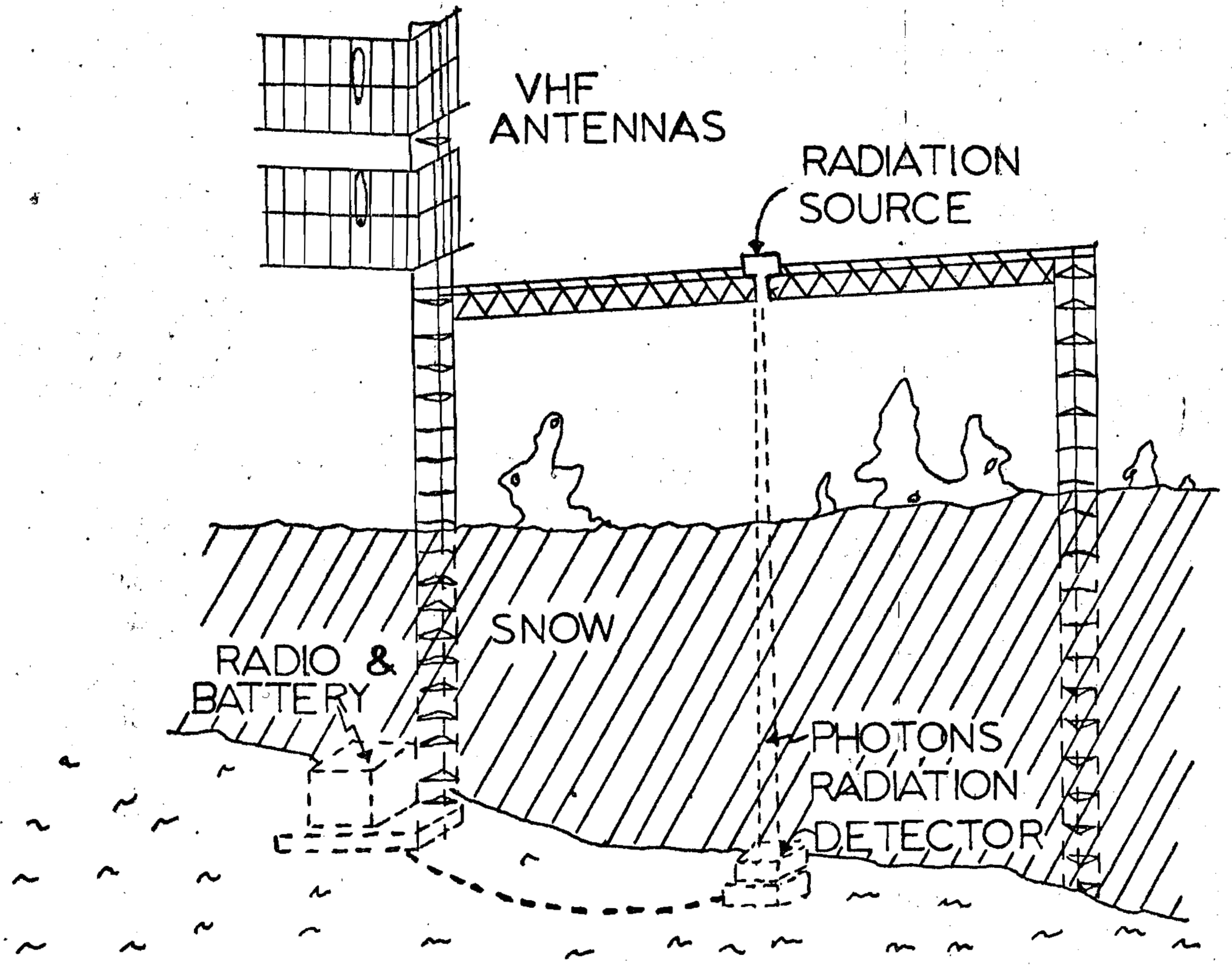


Figure 4. Selected snow gage configuration

quite apparent that this cross-sectional area varies with distance from the radiation source. Conceivably, this could cause error as the snow melts due to a change in "effective cross-sectional area".

As a further consideration of radiation geometry, it is important that the radiation beam width should be kept as small as possible in order to minimize variance of the beam area with variation in distance from the source. The beam width is minimized by collimation which then requires very careful physical alignment of source and detector.

## The Scintillation-Type Detector

A block diagram of a scintillation-type radiation detector is shown in Figure 5. The essential components of such a detector are the crystal, photomultiplier tube, linear amplifier and pulse height discriminator. In addition to these components, divider circuits and a pulse generator are added solely for compatibility with radio transmission requirements.

A scintillation system derives its name from the flashes of light, called scintillations, emanated from certain crystals as a result of radiation incident on the crystal. The number of scintillations is dependent upon radiation intensity at the crystal and the intensity depends on energy levels of the impingent radiation. These scintillations may be electronically detected by a photomultiplier tube yielding an overall input-output correspondence of radiation intensity to electrical pulse magnitude. It is, of course, the ability to detect energy levels that makes the scintillation system attractive for measuring water equivalent of snow by nuclear radiation techniques.

The complexity of the scintillation type detector caused considerable difficulties in its development for

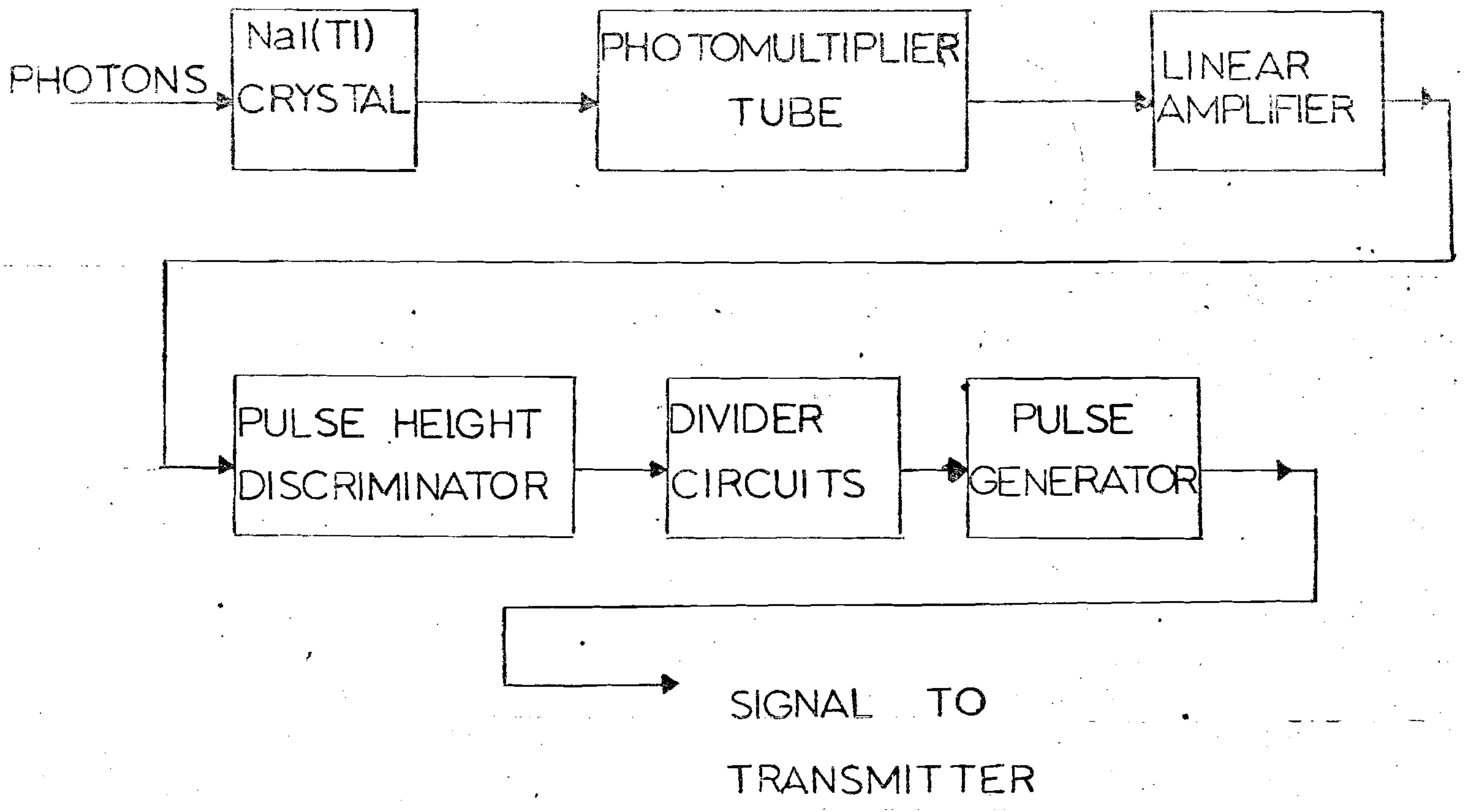


Figure 5. Scintillation-type radiation detector.

location in inclement weather conditions. Taking each detector component separately, these difficulties will be discussed.

Scintillation crystals. The general class of crystals most suitable for use in scintillation-type detectors are those in the alkali halide family. The most efficient of these is the thallium-activated, sodium iodide crystal, usually referred to as a NaI(Tl) crystal.

Sodium iodide is a highly hygroscopic material and hence must be encapsulated for protection from moisture. The encapsulant configuration is that of a metal cylinder with a transparent glass faceplate through which scintillations may be detected by the photomultiplier tube. The main difficulty encountered in using these crystals in non-laboratory applications is that there exists a tendency, as temperatures vary widely, for the crystal to separate from its transparent faceplate. This creates an opaque optical void, diminishing the efficiency and calibration of the scintillation detector. It should be noted that this problem is more prevalent in larger crystals than in smaller ones; that is, 1-1/2 inch diameter crystals are less susceptible to this effect than are 3 inch diameter crystals. A possible solution is to insert a transparent epoxy bonding material between the crystal and the faceplate. This problem is currently under investigation by crystal manufacturers, such as the Harshaw Chemical Company, but no solution has yet been announced.

Another preventive measure is to encapsulate the crystal in a ruggedized mounting assembly containing a spring to force the crystal against the faceplate. This method has been shown to be quite satisfactory and minimizes the crystal warpage with varying temperature. Not only does the effect of this warpage cause opaque optical voids but it can cause crystal fracturing as well. A 1-1/2 inch diameter NaI(Tl) crystal, encapsulated in a ruggedized mounting assembly, has proved to be extremely reliable in tests over long periods of time and with repeated temperature cycling from -30°C to +25°C.

Photomultiplier Tubes. A photomultiplier tube contains a photoemissive cathode, a collecting anode, and a number of interstage anodes called dynodes. Light impinging on the cathode results in emission of electrons. Once emitted, these electrons are attracted to a dynode which has a more positive electrical potential than that of the cathode. From this first dynode both the primary and secondary emission electrons move to a second dynode having a potential exceeding that of the first dynode. This process continues from dynode to dynode until the greatly increased number of electrons finally arrives at the collecting anode which is the most electrically positive element in the tube. It can be seen that current amplification is achieved in such a multi-stage tube, the number of stages taken to be equal to the number of dynodes in the tube.

It is known that photomultiplier tubes are susceptible to drifts of various types. Since the accuracy of measuring snow pack water content is dependent upon stability of the scintillation type detector, two types of drifts must be examined. At the outset of this investigation, a variety of photomultiplier tubes were tested in University of Idaho laboratories. Based on these investigations, which are fully discussed in reports (2, 10), an EMI brand, type 9536B tube was selected for this application. As each type of drift is discussed, testing results will be given for this particular type of tube.

The first of these types of photomultiplier drifts, called time drift, is the effect of changing gain, or current amplification, with increasing time after application of electrical power to the tube. The cause of this drift is the variation of the photocathode work function with changing cathode temperature, resulting from electron emission and the change in near-cathode space potential distribution.

Time drift is of importance to the application under discussion since, to conserve power at a remote measuring location, continuous power application is not practical. A tube which has severe drift during the short measurement period would not provide repeatable data if it became necessary to recall a radiation snow gage for, say, a check count. Furthermore, severe drift would greatly affect gage calibration which will later be discussed.

Of all the photomultiplier tubes tested, the EMI 9536B proved to be the least affected by time drift. A typical time drift plot for such a tube is shown in Figure 6.

Since it may be necessary to recall a gage for a check count, it is desirable to know how long a tube remains "on" and then how long it must remain "off" before the next power application. One suitable figure for the EMI 9536B tube is that, for power application of five minutes, the gain will return to its original gain value fifteen minutes after power has been removed from the tube.

The second type of photomultiplier drift to be considered is that of changing gain with changing temperature. Although the scintillation detector will be buried in the ground which maintains near-freezing temperatures, calibration usually takes place in the fall when temperatures are considerably higher. Figure 7 shows the effect of temperature on the EMI tube. It can be seen that temperature compensation factors should be taken into account when actually measuring snow pack water content.

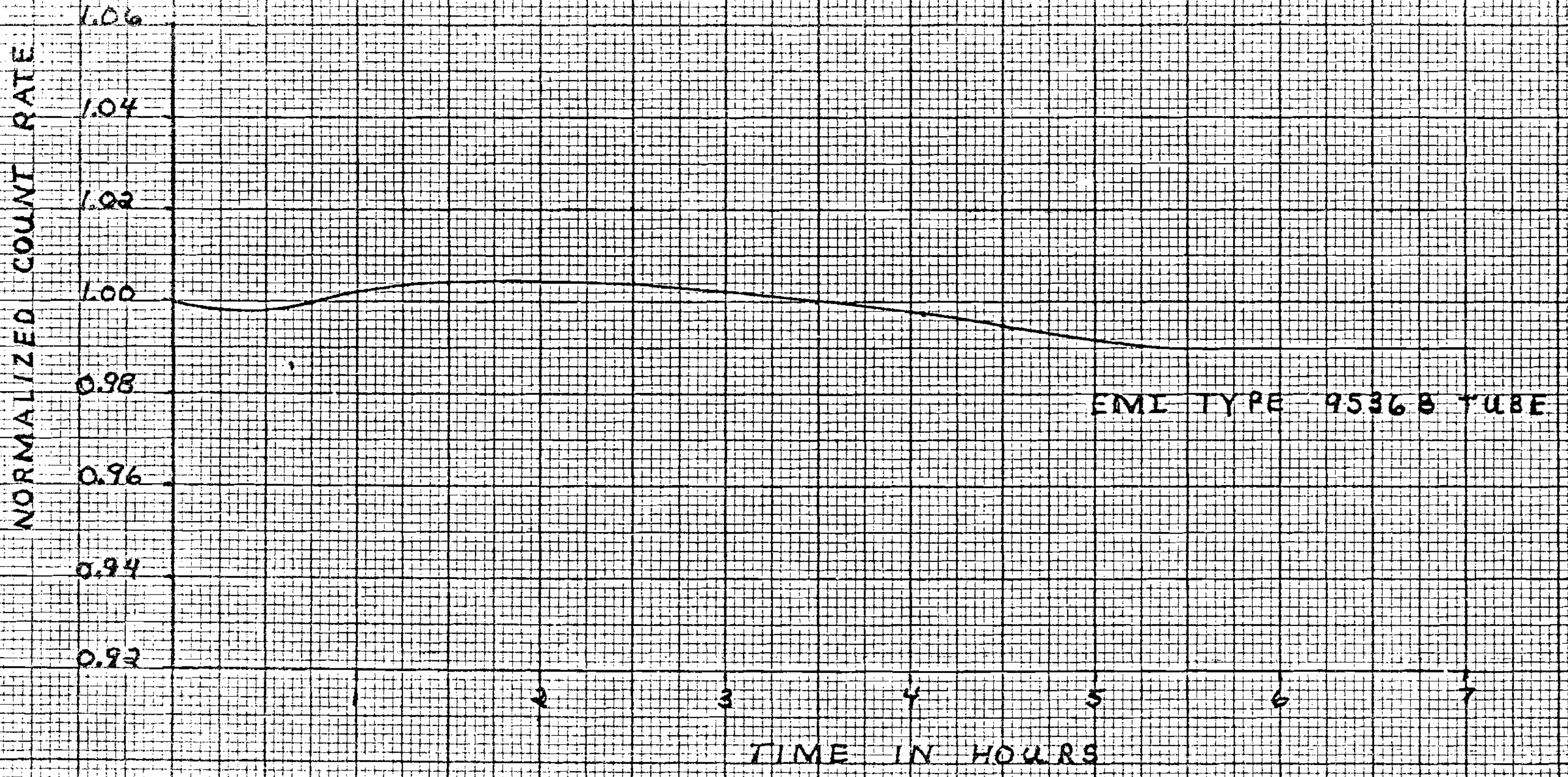


Figure 6. Time drift of EMI 9536B photomultiplier tube.

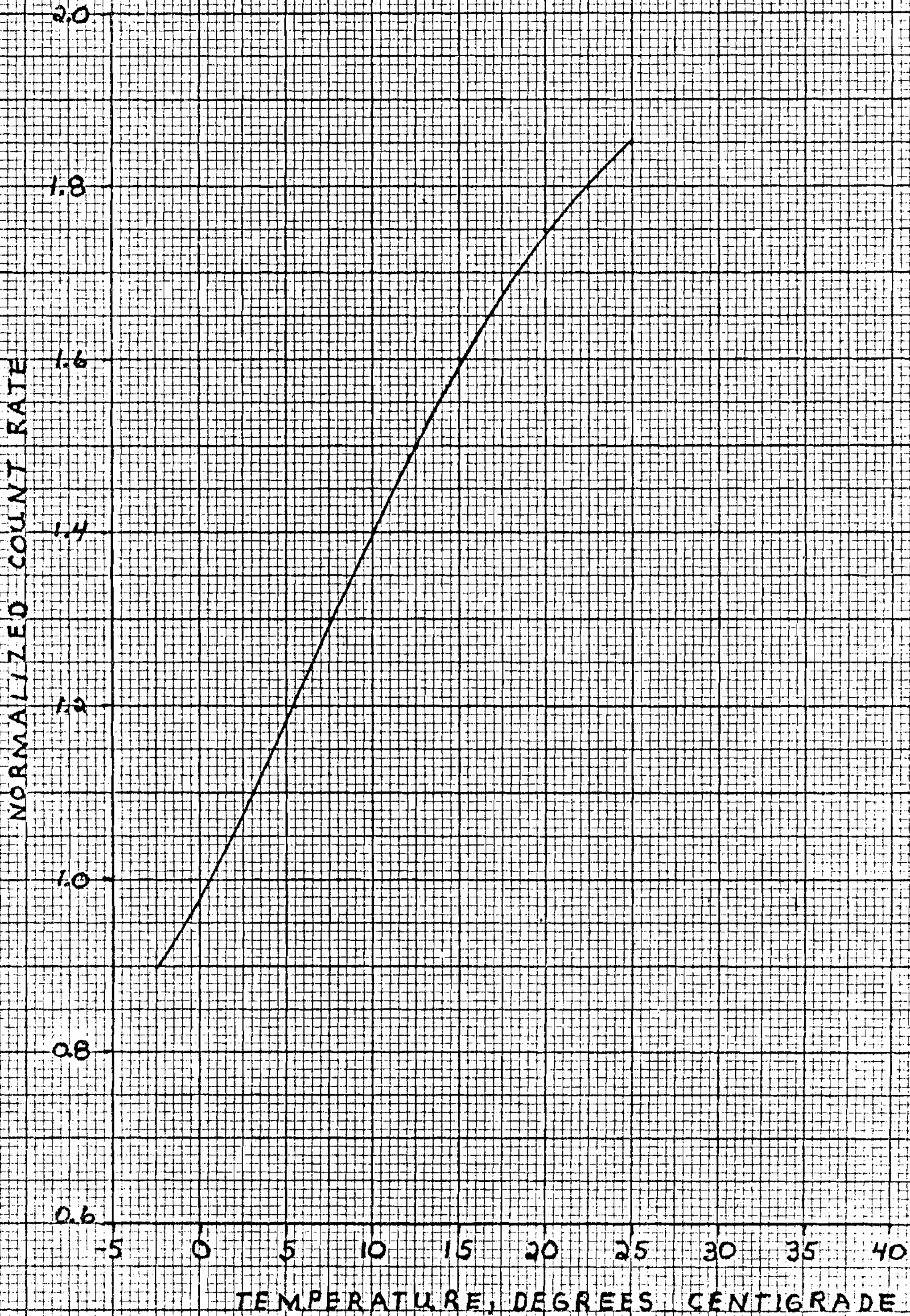


Figure 7. Photomultiplier tube gain vs. temperature

Linear amplifier and pulse height discriminator. The pulses obtained from the photomultiplier tube contain the information necessary, namely, the repetition rate of pulses in a certain height interval. Before these pulses can be counted to determine repetition rate, the unwanted pulses must be eliminated. This elimination technique, called discrimination, is accomplished with a pulse height discriminator circuit.

Before pulse height discrimination is possible, amplification is necessary to eliminate extreme criticality of discrimination, or threshold adjustment. Pulses emanating from photomultiplier tubes have a range of pulse heights centered in the vicinity of 50 millivolts. In order to preserve the linear dependence of radiation photon energy to pulse height, these photomultiplier pulses are amplified linearly. Hence a linear amplifier is interposed between the photomultiplier tube and the pulse height discriminator.

Results of a University of Idaho investigation (2) indicated that, for good stability and low power consumption, the best commercially available combination of linear amplifier and pulse height discriminator was manufactured by Picker X-Ray Corporation. To provide a readily available supply of these circuits, these Picker circuits were incorporated in the snow gage. Test data revealed these circuits to be nearly totally insensitive to changes in environmental temperature in the range from -5°C to +20°C. Furthermore, a 10 per cent deviation from rated supply voltage causes no significant change in operating characteristics.

## Statistical Accuracy

Radiation statistics. Due to the random nature of the gamma events which are detected by the radiation snow gage, the timed counts obtained by this system will show fluctuations for a constant amount of snow pack water content. The distribution of the time intervals between pulses will closely obey the Poisson law except for a slight deviation caused by the "dead-time" of the detector circuitry (7). At high levels of water equivalent, the uncertainty introduced by these statistical variations presents one limit of snow gage accuracy.

Statistical theory shows that to minimize measurement deviations due to this randomness, the largest possible number of pulses should be counted, from which count rate will then be determined. For simplicity, nomographs have been developed which show, for any total count obtained, what accuracy should be attributed to the data with a particular confidence level. Such a nomograph (7) is presented in Figure 8. A confidence level of 0.9 means that, 9 times out of 10, the data will be within the per cent error intersected by a line drawn from the confidence level figure to the total count number. In this example, once in 10 readings, the data may be somewhat more in error than indicated. It is thus seen that if a greater confidence level is desired, an increased number of total counts must be measured. In this discussion, total counts are those from the photomultiplier tube prior to any division for purposes of radio transmission.

A final comment concerning the nomograph of Figure 8 applies to uncertainty. An error indicated on the nomograph is a deviation from the statistical average of radioisotope disintegrations. Although the calibration data are presented later in the text, if these data are used to convert counts, or disintegrations, into measured water equivalent, it can be seen that the nomograph indicated error is pessimistic. For example, a counting error of ±3.5 per cent corresponds to a water equivalent determin-

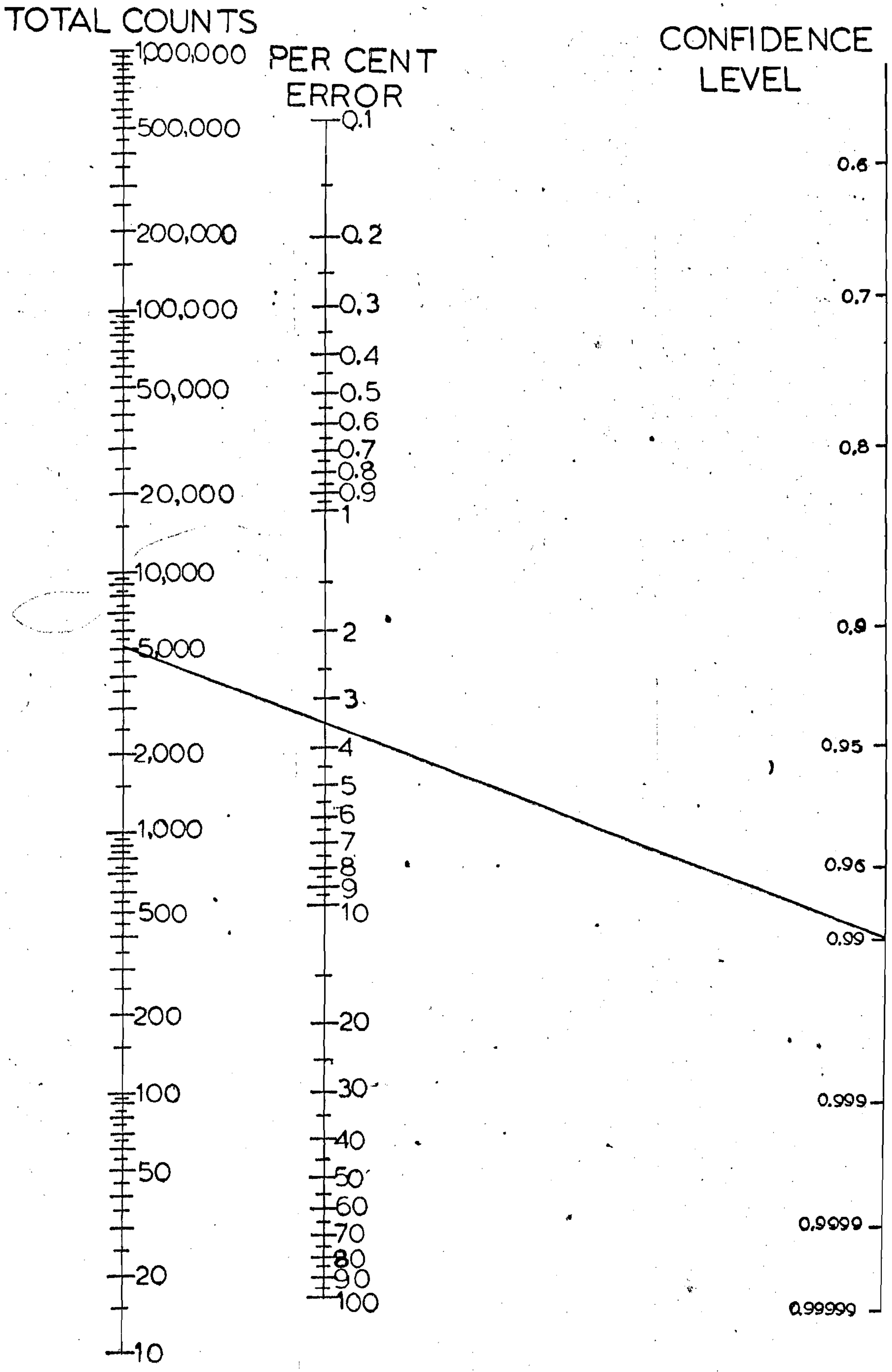


Figure 8. Nomograph for statistical counting error.

ation uncertainty of ±0.25 inch. A graph relating the actual uncertainty in water equivalent due to a certain expected count rate error is given in Figure 9.

*Size of radiation source.* Since the total number of pulses counted determines the statistical accuracy of measuring water equivalent (8), it is necessary to consider the size of radiation source required to give a specified, unattenuated count rate. The calculation of required source strength can only be approximated due to the many variables involved, including alignment of source and detector, positioning of the source in the collimator, scintillation crystal efficiency, the extent of collimation, the geometry of the terrain in which the measurement is made and the maximum count rate which will avoid system saturation. University of Idaho investigation revealed that, for the snow gage configuration indicated in Figure 4, an unattenuated count rate of the desired 5000 counts/sec is attained when the radiation intensity is 0.013 roentgens/hr at the detector surface. Since Cobalt-60 has a characteristic intensity of 1.3 roetgens/curie/hr at 1 meter and this intensity varies inversely as the square of the distance from the source, the required source strength can be calculated. A separation distance of 15 feet, or about 4.5 meters, requires a source strength of

$$4.5^2\left(0.013\ \frac{\text{roentgens}}{\text{hr}}\right)\ \frac{1}{(1.3\ \text{roentgens/curie/hr})}$$

## Radio and Data Acquisition System

*The radio system.* The selection of radio link equipment for the radiation snow gage system (8) was dictated by a multiplicity of parameters which were imposed by the agency using the system, the Corps of Engineers. Basically these requirements were for off-the-shelf availability of frequency modulated (FM) radio equipment. Of course the

Figure 9. Water equivalent error vs. per cent count rate error.

Federal Communications Commission regulations of ±8KHz bandwidth and ±0.0005 per cent frequency stability were simultaneously required.

Two methods of frequency modulating a transmitter carrier with the snow gage pulses are available. One method is to use direct frequency-shift keying modulation and the other is to use phase shift modulation. The method of direct frequency shift keying permits a direct carrier shift during the presence of a pulse. It has been shown that modulating pulse lengths should be less than 1.2 milliseconds if the bandwidth is to remain in the ±8KHz tolerance limit (6). The phase shift modulating method uses an oscillator, whose frequency is usually about 2 KHz, which is turned "on" and "off" by the respective application and removal of a pulse. For preservation of ±8 KHz bandwidth, it has been shown that these pulses should be at least 2.5 milliseconds in duration.

Based on a University of Idaho survey of radio equipment suitable for this telemetry application, it was found that only phase shift modulation methods were commercially available. The requirement of off-the-shelf availability indicated that the most suitable equipment was made by Motorola Communications and Electronics, Incorporated (8).

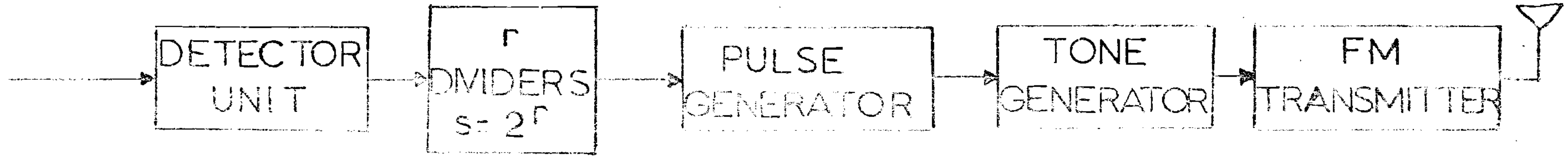
The Motorola equipment was evaluated and found to meet all environmental specifications. For the Motorola "Radiophone", the transmitter consumes no power at standby and 12.6 watts during transmission. The receiver of this same unit requires 100 milliwatts during standby and 200 milliwatts during the receiving operation.

A noise elimination feature of a phase shift FM system is inherent in the tone signal discrimination technique. The tone actuated decoders used are highly frequency selective, thereby responding only to the basic oscillator frequency.

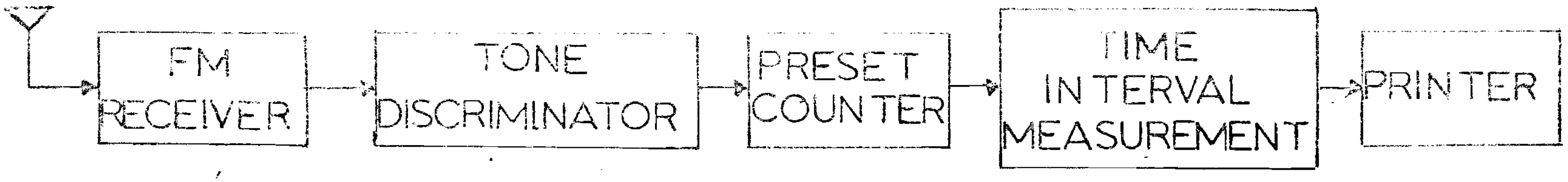
The data conversion system. The emission of 1 microsecond duration pulses from the photomultiplier tube and the transmission bandwidth requirement of pulse information at least 1.5 milliseconds long are incompatible. This problem is solved by interposing divider circuits between the pulse height discriminator and the transmitter modulator as shown in Figure 5. This figure shows the dividers, each one of which divides the incoming counts by 2, and a pulse generator used to form a pulse sufficiently long for transmitter modulation. The basic divider circuit is that of a bistable mutivibrator; the pulse generator is a monostable multivibrator.

The interposing of the dividers in the detector causes a difficulty in measuring output count rate. The number of dividers, r, will provide a divisor of $s = 2^r$. A system weakness is possible since, at the base station, pulse counting will take place during a time interval specified by the desired measurement accuracy. Hence an observed count may be in error by as much as s-1 counts stored in the detector dividers at the instant the base station counting interval is ended. A similar error can occur at the beginning of the timing interval which will cause the count to be high by s-1 counts. This uncertainty is eliminated by starting and ending the timing interval at the precise instant that a pulse is received. Thus the total detector count would be sN, where N is equal to the number of pulses counted at the base station.

Figure 10 shows the data conversion equipment as incorporated into both remote and base stations. In this system the initially random count rate is divided by a large factor, s, to produce a regularizing effect on



a. REMOTE STATION



b. BASE STATION

Figure 10. Data conversion system.

the randomness. This regularizing effect increases with the increased values of s (5). The resultant benefits are: (1) regularization of the time intervals between binary output pulses allows the transmitted pulse length to be maximized with little danger of losing any pulses due to time intervals shorter than the transmitted pulse lenth; (2) the average time interval between pulses is multiplied by the factor, s, allowing the transmission of long pulses with attendant advantages in bandwidth reduction and noise elimination.

A number of factors determines the optimum value of the division ratio, s:

1. Minimum count rate (Length of counting time)

2. The length of the transmitted pulse should be two orders of magnitude greater than the length of the pulses emanated from the photomultiplier tubs.

3. The bandwidth required by the radio transmission system depends on the length of the transmitted pulses. For optimal use of bandwidth, two successive pulses should be separated by an interval equal to one pulse length.

The operation of the system in Figure 10 is described. For each s pulses from the photomultiplier tube a single output pulse will modulate the transmitter. One of these modulating pulses will be used to initiate the timing interval at the base station. At this instant a time interval is begun and the preset counter continues to count the transmitter output pulses. This counter is set for N pulses according to the desired accuracy determined by sN. When the Nth pulse arrives at the preset counter, the counter stops the time interval measuring unit. Thus a number of pulses, N, have been counted over a known time interval.

## Snow Gage Calibration

The information given in previous sections of this report is applied to a practical method of calibrating a detector when installed at a snow site. It is possible to calibrate such a detector by using actual amounts of water in a barrel or by using lead disks (10).

A barrel may be placed directly above the detector and detector count rates measured as water is added to the barrel. This method is quite satisfactory when a 22-inch diameter barrel is used for levels of water approaching 40 inches. As can be seen in Figure 11, this method causes a departure from predicted linearity on a semilogarithmic plot. Since this water-filled barrel does not represent an "infinite" absorber area, as implied by the narrow-beam attenuation equation, a similar calibration procedure was tested in a swimming pool.

For the swimming pool test, the radiation detector was submerged in the pool and a radiation source was suspended above the water surface and detector. Detector count rates were taken as the water was drained from the swimming pool. These data are also shown in Figure 11. This figure shows that the use of a small barrel will not give a linear semilogarithmic plot at high water levels as is the case with the "infinite" area of the swimming pool. Thus, for the purposes of field calibration, a small barrel may be used for increasing water levels until the calibration curve becomes nonlinear. At this point the calibration curve is completed by linear extrapolation of the data taken for lower water levels.

Since a water barrel is difficult to transport to a typical field site, the possibility of calibration with lead disks was investigated. The lead disk test was conducted similarly to the water barrel test: Data were taken for increased levels of lead until the calibration curve became nonlinear; the remaining portion of the curve was obtained by linear extrapolation of the data.

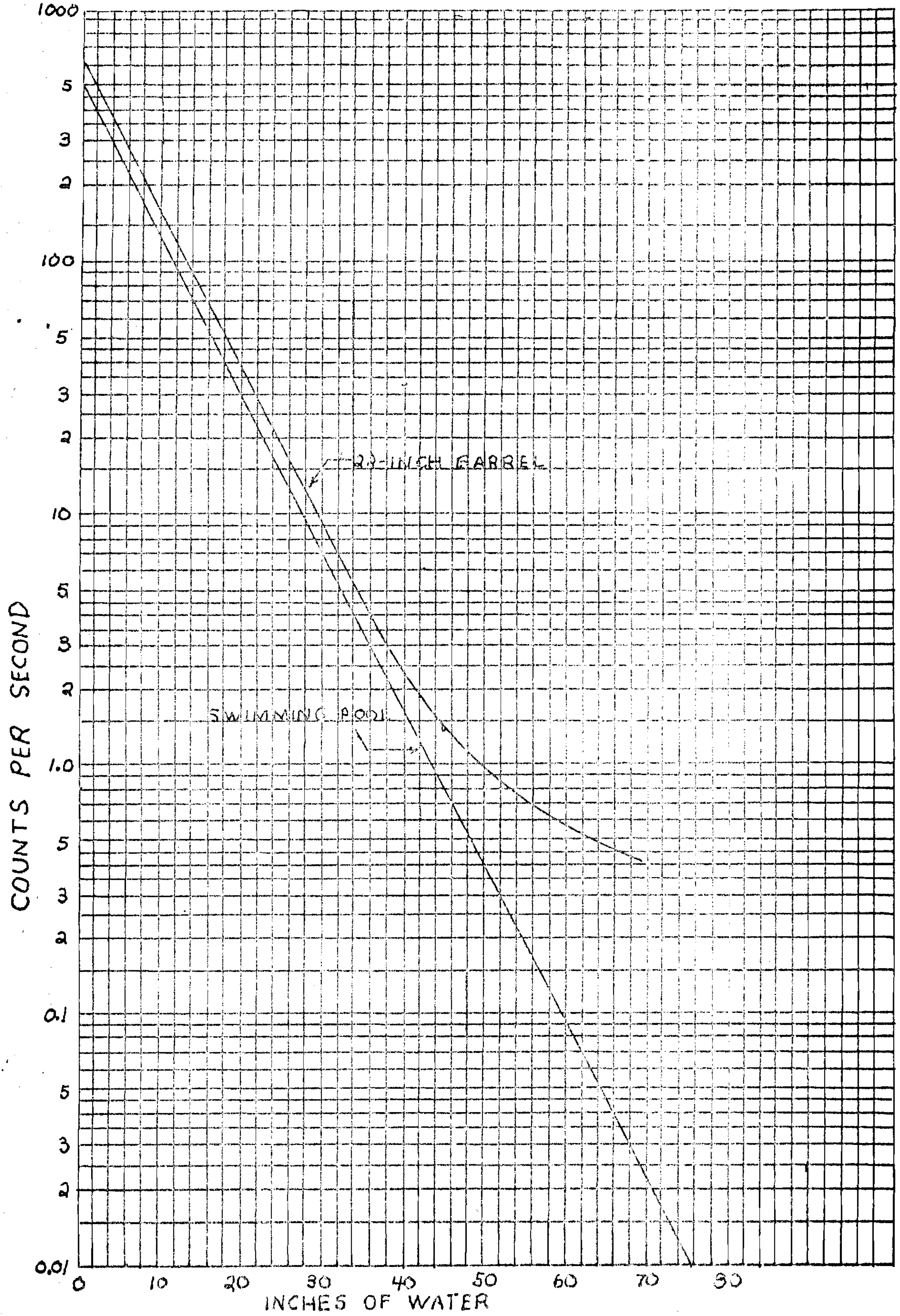


Figure 11. Barrel and swimming pool calibration data.

These data, depicted for both the swimming pool and lead disks in Figure 12, show that a 1-inch thick lead disk is equivalent to about 10.1 inches of water. Of course this linear relationship ceases to exist above the point at which the lead disk curve becomes nonlinear.

*Some notes on field calibration.* Since the data obtained from the snow gage are certainly no better than the validity of the calibration curves used for data interpretation, a few notes on the calibration of this device are in order. The majority of these comments are based on the experience of the author and would be difficult to evaluate quantitatively (4).

At least 48 hours before the calibration procedure is started, the source should be mounted on the tower and the detector buried in its underground container. This allows all of the detector components to reach a uniform and stable temperature. A survey should be made to ensure that the radiation beam is centered with respect to the detector photomultiplier tube. This survey should be made at the time the source and detector are installed in order that any changes in configuration will be made before the system is allowed to temperature stabilize.

When setting up the apparatus for actual calibration, careful attention must be given to the geometry of the gaging system. If lead disks are used, it is recommended that these disks be at least 12 inches in diameter and, when placed in the radiation beam, they should be accurately centered over the photomultiplier tube. When a barrel is used for calibration, a barrel should be selected whose configuration is that of a right circular cylinder: The peripheral side of this barrel should be straight and oriented normal to the bottom. This barrel should be centered accurately over the photomultiplier tube; the

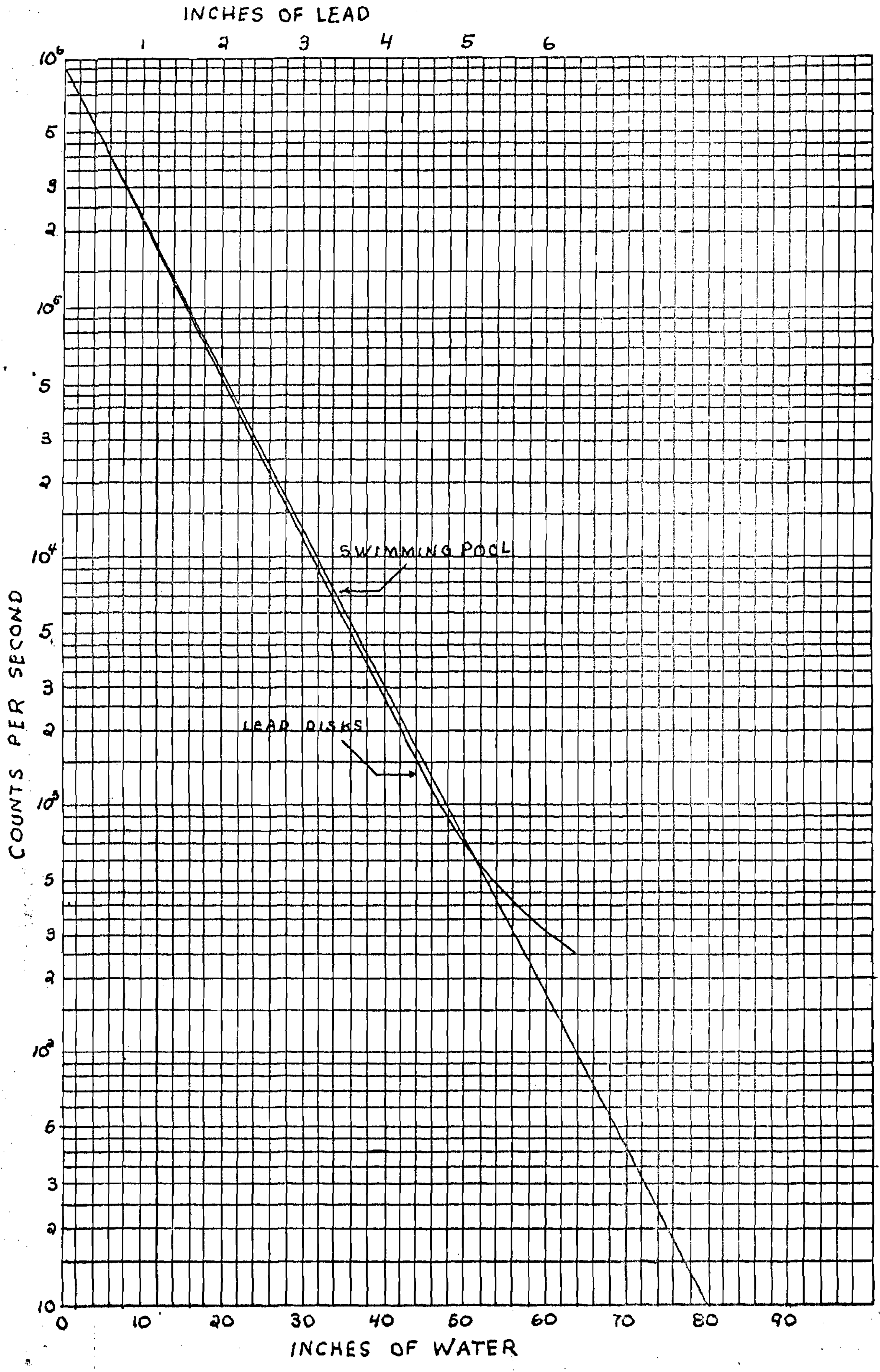


Figure 12. Lead disk and swimming pool data

barrel should be "leveled" so that the longitudinal axis of the barrel is normal to the cross section of the radiation beam. Failure to perform this alignment may result in a nonlinear semilogarithmic curve.

The calibration data are taken as the depth of water, or lead as the case may be, is increased and then a graph is prepared showing count rate on a logarithmic scale and inches of water on a linear scale. Data taken with lead disks and barrels, both in the laboratory and in the field, have indicated that any nonlinearities that may arise in the resultant calibration curve will appear at either very high count rates or very low rates. At extremely high count rates the "bending" is caused by saturation of the detector [illegible] [9]. This results from the inability of the [illegible] to recover from the effect of a pulse before the next pulse arrives. This long recovery time causes the detector to register fewer counts than actually occur. If extremely strong source strengths are not used, this effect is minimized. For extremely low count rates, the calibration data will indicate, if used for snow survey purposes, that a given count rate corresponds to [illegible] water in a snow pack than it did when the barrel was used. This phenomenon at low count rate corresponds to less water in a snow pack than it did when the barrel was used. This phenomenon at low count rates is caused by the geometry of the calibration barrel and absorber. Statements made in this paragraph indicate that, if extremely strong sources (giving zero water count rates of [illegible] counts per second) are not used, then the calibration [illegible] are valid from zero up to about 40 inches of water, or from zero to about 4 inches of lead. Beyond this point, the calibration curve is obtained by linear extrapolation of existing data.

Finally it should be mentioned that it is necessary that all power be supplied to the detection assembly for at least 15 minutes preceding a period of power application not [illegible] requirement is absol[illegible] to hysteresis effects [illegible].

## THE [illegible] TECTOR

Using [illegible] the discussion of the radiation [illegible] problems and the encountered [illegible] in previous sections of this thesis [illegible] system, as presently in operation [illegible] Basin, will be summa[illegible]

[illegible] of the scintillation [illegible] converter, nickel cadmium [illegible]. The DC-DC conv[illegible] battery voltage [illegible] to supply operating power to [illegible] amplifier, and pulse height [illegible]. The high voltage suppl[illegible] required by the phot[illegible]

The [illegible] converter which is mounted [illegible] housed in a large water-tight [illegible] cobalt-60 source. The battery and [illegible] from the water-tight box to a [illegible] radioisotope support [illegible] the batteries as well as the [illegible] control circuitry.

The gamma [illegible] amplified by a conven[illegible] multiplier tube combi[illegible] corona tube regulated [illegible] photomultiplier tube and [illegible] regulated by another [illegible] to the photomu[illegible] the pulses from

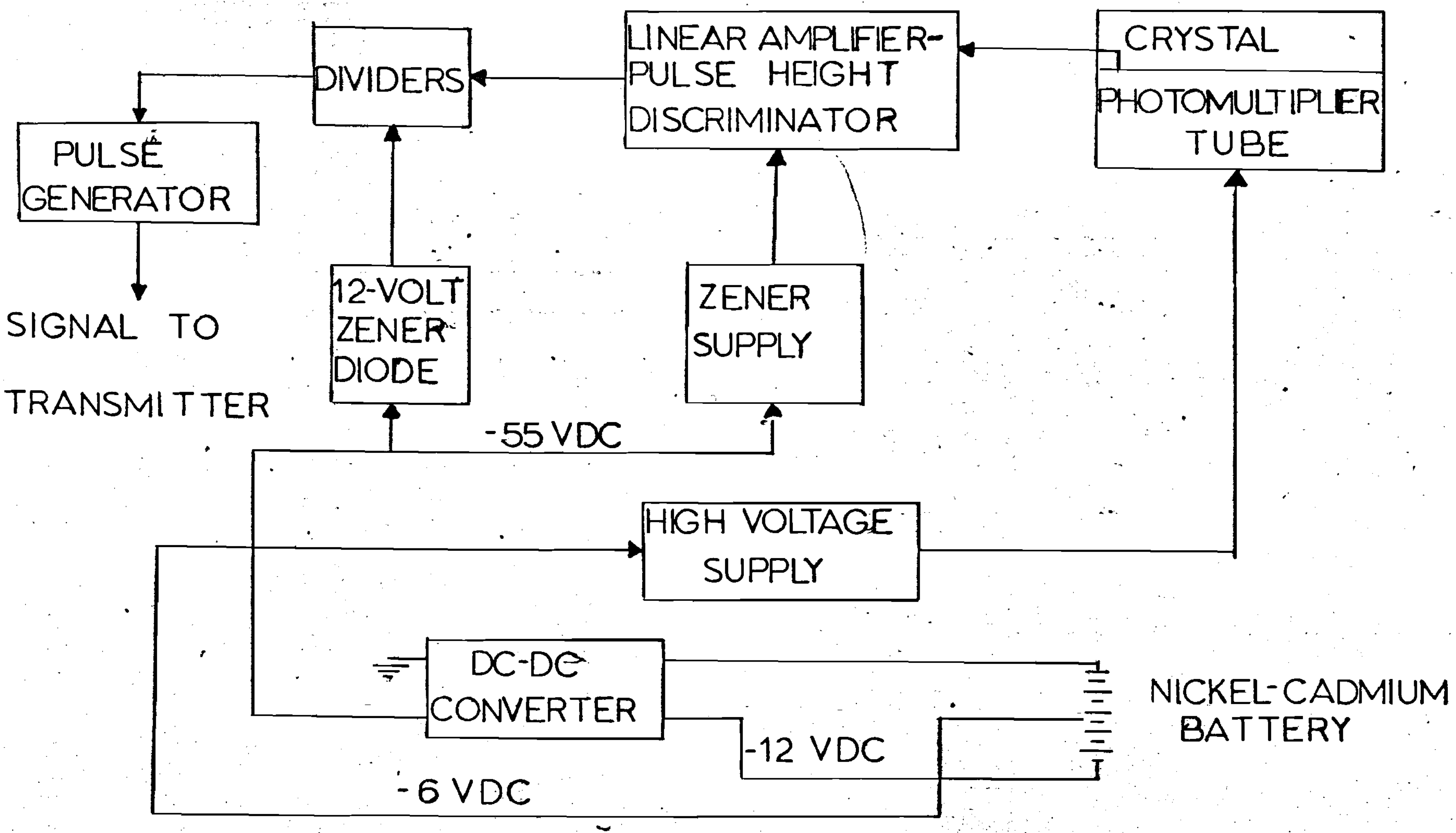


Figure 13. Block diagram of detector and power supply.

the photomultiplier tube representing the Cobalt-60 photopeaks are in the range just below that required to saturate the linear amplifier.

The linear amplifier output pulses, which correspond to photopeak energies, are applied to the pulse height discriminator which is capable of operating in any of three modes: (1) The upper and lower levels of descrimination may be selected independently; (2) A window width may be selected which is from 0 to 10 per cent of the lower level discrimination setting; (3) An integral mode of operation can be selected in which all pulses above a certain amplitude, as determined by the lower level discrimination setting, are passed by the discriminator. This latter mode of operation is used in the radiation snow gage with the lower level of discrimination, or threshold, set slightly below the Cobalt-60 photopeaks as shown in Figure 3.

The output pulse rate from the pulse height discriminator is reduced by binary dividers to a rate compatible with the radio transmission system. A monostable multivibrator pulse generator shapes the output waveform which is used to modulate the radio transmitter.

## SNOW GAGE SYSTEM RESULTS

Since the development of the radiation snow gage, three of these gages have each had four successful years of operation in the Clearwater River Basin(8, 10). The snow gages have had no operational failures. Before mentioning the data obtained from this system, it should be noted that no reliable standard of measuring snow pack water content is available. The inherent inaccuracies in the more conventional means of measurement, such as the snow tube method, are sufficiently large that, at best, normal deviations in readings exceed the expected error

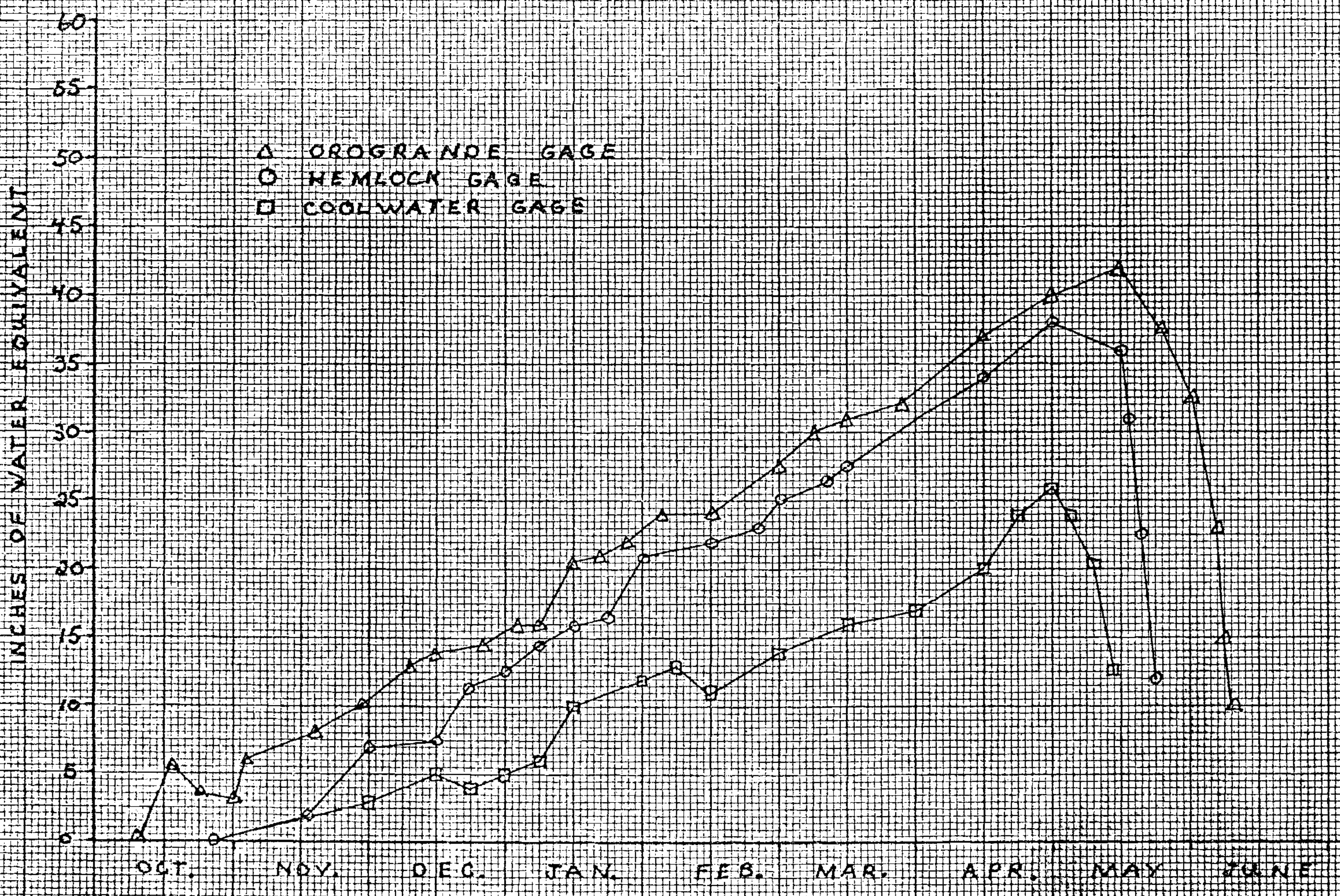


Figure 14. Snow gage results for 1962-63 winter.

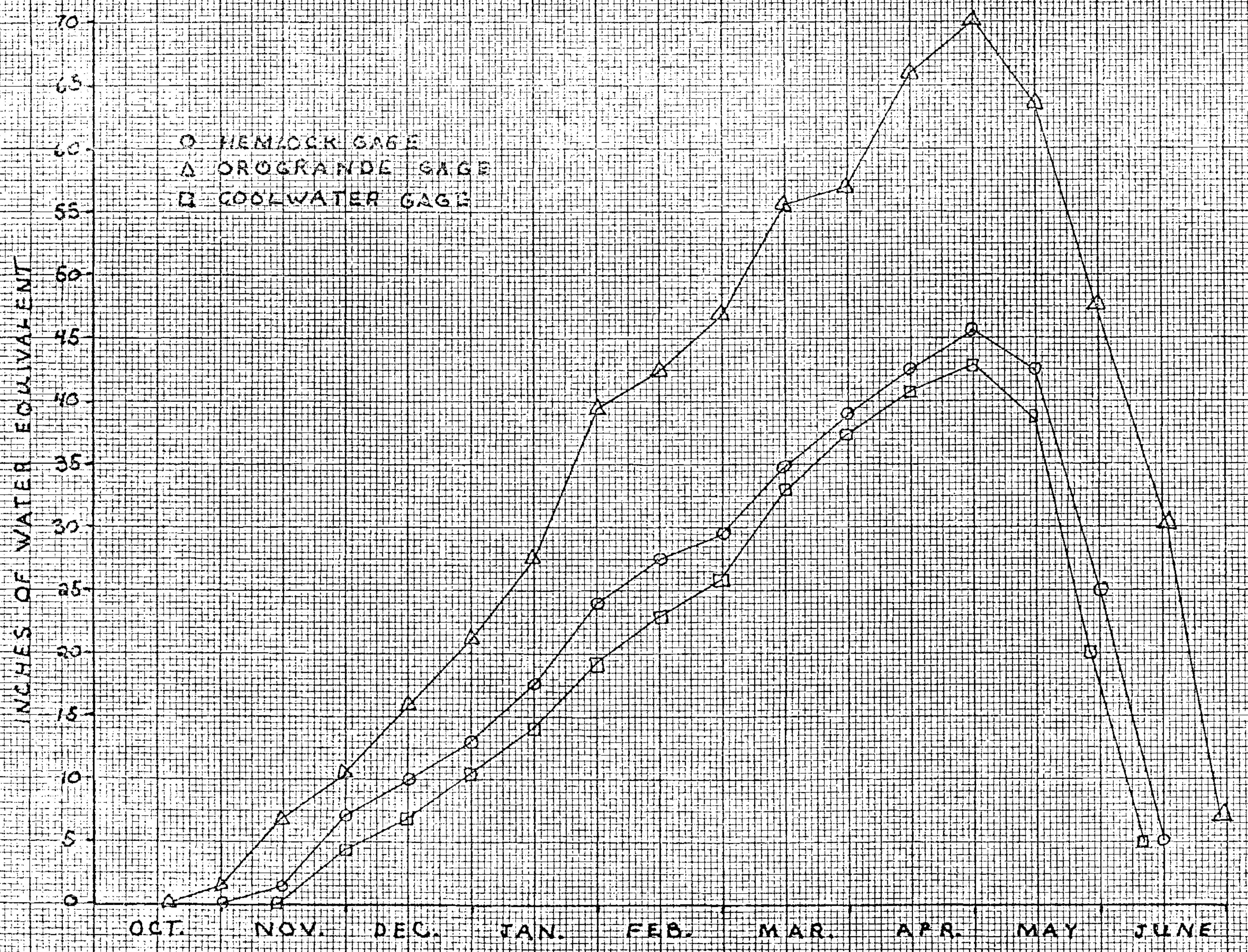


Figure 15. Snow gage results for 1963-64 winter.

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