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ANNUAL REPORT FOR 1967
TO THE
USAEC DIVISION
OF
BIOLOGY AND MEDICINE
VOLUME II: PHYSICAL SCIENCES
PART I. INSTRUMENTATION**

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DEVELOPMENT REPORT**

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Part 1. Instrumentation

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These reports are drawn principally from personnel of the Instrumentation Section of the Applied Physics and Electronics Department. Contributions and coauthors from other organizations may also be included and occasional related activities not sponsored by the Division of Biology and Medicine may be included. Such facts are acknowledged by footnotes.

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Part 1. Instrumentation

INTERPRETING COUNTING DATA FOR INTERNALLY
DEPOSITED PLUTONIUM*

K. L. Swinth

Developmental, sensitive counters presage enhanced measurement of internally deposited plutonium by counting the low-energy photons (17 keV X rays, 60 keV ^{241}Am gamma) emitted by the plutonium. General factors influencing the interpretation of counting data include:

- *The change in photon emission rate with variable isotopic composition*
- *The low penetrating power of the radiations*
- *The variable background due to high-energy radiations of other isotopes.*

The 17 keV plutonium X rays show a half-value thickness for tissue of only 0.6 cm; hence, factors changing the absorption such as internal distribution, surface contamination, and variable overlying tissue masses, affect the interpretation of counting measurements. Data from phantoms and animals indicate the relative importance of these factors. This paper discusses methods of correcting for such effects.

Background variations become critical for low-level counting and data show that differences in low-energy (~17 keV) backgrounds of greater than a factor of two can be expected and are caused primarily by the contribution from other internal radionuclides. As described, such information can be correlated with count rates in other energy regions.

Finally, the paper discusses the role of pulmonary clearance effects as related to counting.

INTRODUCTION

Gamma-ray emissions of ^{239}Pu lack intensity for the detection of plutonium at levels near the maximum permissible body burden (MPBB), but the gamma rays at 100 keV and the 384 keV complex have been used for

measuring body burdens of experimentally exposed dogs.⁽¹⁾ For the low levels of plutonium, likely to

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be encountered in health physics work, the significant radiations are the L X rays from the uranium daughters. These X rays at 13.6, 17.0 and 20.2 keV (average energy of 17 keV) result from the internal conversion of gamma rays from excited states in the uranium daughters. For pure ^{239}Pu , the emission of four X rays occurs for every 100 alpha particles emitted. In general, the presence of small amounts of isotopes other than ^{239}Pu increase the ratio of X rays emitted per alpha particle.

The small but significant amounts of ^{241}Am present results from the beta decay of ^{241}Pu , which has a 10 year half-life. The ^{241}Am emits a 60 keV gamma useful as a tracer for measuring plutonium, but this approach requires accurate knowledge of the isotopic composition, and the assumption that differential metabolism does not occur. Such an assumption is open to criticism⁽²⁾ and will require further investigation. The 60 keV photon occurs 35.9 times for every 100 alpha particles⁽³⁾ emitted, a low intensity compared to the X-ray activity of a plutonium sample. Other minor, low-energy radiations present include 39 keV (^{241}Am) and 52 keV (^{239}Pu). The L X-rays and the 60 keV gamma are of low intensity and easily absorbed. Although major difficulties exist in such measurements, the feasibility of in vivo counting has been demonstrated.⁽⁴⁾

Various laboratories investigating the in vivo measurement of body burdens of plutonium focus on the

use of proportional counters.⁽⁵⁻⁸⁾ Proportional counters provide large, sensitive areas at low cost and can be applied with anticoincidence techniques for background control. Proportional counters also evidence resolution superior to scintillation counters at low energies. One disadvantage exists in the application of a suitable counting gas with high absorption coefficient. Commonly used argon-methane provides an efficiency of only 12% in a layer 5 cm thick. Although other gases have higher absorption coefficients, they are either contaminated (krypton with ^{85}Kr)⁽⁶⁾ or expensive (Xe). They require a closed purification system since the gas can become poisoned by out-gassing of counter materials.

Scintillation counters can provide essentially 100% efficiency for 17 keV X rays since a 0.025 cm thick layer of NaI exhibits a 95% efficiency for that X ray. The scintillation counter also evidences superior efficiency for the detection of the 60 keV ^{241}Am gamma ray. The problems with scintillation counters concern phototube noise and the difficulty of obtaining large, sensitive areas; but commercial availability of low cost, low noise phototubes makes feasible the development of a large area scintillation system. At present, Dow Chemical at Rocky Flats uses a 4 mm thick by 4 in. diameter NaI(Tl) crystal for the monitoring of plutonium in vivo by utilizing ^{241}Am as a tracer.⁽⁹⁾

Much of the data presented in this paper result from information obtained with a scintillation counter designed for detection of plutonium in vivo.⁽¹⁰⁾ This counter consists of an array of 52 phototubes and NaI(Tl) crystals divided into four groups and housed in stainless steel boxes 6 in. by 12 in. by 7-in. deep. Each crystal of 1 mm thickness provides a 1.75 in. active diameter and has a 1 mil aluminum window.

Useful interpretation of data acquired by sensitive counters under development requires thorough understanding of the various parameters affecting the count rate for internally-deposited material. Interpretation of counting data will be influenced by a number of factors:

- The change in emission rate with variable isotopic composition
- The low penetrating power of the radiations
- The variable background caused by high energy radiations of other isotopes
- The time since reactor exposure of the material.

Each factor requires discussion in light of its role in data interpretation. The paper does not treat wound monitoring and its relatively simple interpretative difficulties, but concentrates on insoluble material deposited through inhalation processes.

BACKGROUND

Plutonium must be detected with high efficiency because of the weak radiations emitted and the low

levels involved. A Maximum Permissible Body Burden (MPBB) based on bone is 40 nCi (NBS Handbook 69); whereas, a maximum permissible lung burden of only 16 nCi appears to be correct when based on dose to the lungs. These low limits, coupled with the high absorption and low abundance of the measurable radiations, necessitate a low and predictable background. The major problem, variation in background, arises from the fact that individuals have distinct and different amounts of radionuclides (^{40}K , ^{137}Cs , ^{65}Zn , ^{51}Cr , etc.) in their bodies. This problem leads to different background rates for individuals and for the same person at different times.

Many of the background counts in a plutonium counter result from the high energy photons emitted from radionuclides in the subject. These photons scatter only slightly in the NaI(Tl) scintillators, producing pulses mistaken for plutonium X rays or 60 keV gamma rays. This problem suggests two methods of controlling the background rate: correlation of the plutonium counter background with the subject's radionuclide content (other than plutonium) or the counting of scattered photons via an anticoincidence system.

Anticoincidence techniques have been investigated by use of a scintillation counter.⁽¹⁰⁾ By placing a 6 in. thick, plastic scintillator around one of the counter units and covering all but the sensitive face, scattered photons could be detected. With the plastic scintillator in anticoincidence with the plutonium

counter unit, a background rate reduction to about 14% of the normal background rate in the empty counter resulted. People present in the counter permitted an average background reduction of only about 33% using the anticoincidence system. The variation in background between people remained about the same as before.

The best solution to the stated problem would be the establishment of an independent measure of the background contribution of an individual with subsequent correlation with his background in the plutonium counter. The most desirable correlation would provide a sensitivity equal to or greater than changes in the background rate. Whole body counts, chest scans, and simultaneous chest counts were investigated by using such techniques. These did not prove to be any better or as simple as using a higher energy region in the plutonium counter spectrum. Figure 1 shows the plutonium counter counts from bands of channels containing the X-ray peak versus the count from all channels of the Shadow Shield Counter.⁽¹¹⁾ Use of only those counts from the Shadow Shield Counter in a low energy region (40 to 400 keV) did not improve the correlation nor did using the sum of the body burdens of specific isotopes, such as ^{137}Cs and ^{40}K . A similar correlation existed for the ^{241}Am gamma-ray channels.

Figure 2 illustrates data obtained for a high energy region of the scintillation plutonium counters

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FIGURE 1. Correlation Between Background Rate of Plutonium Counter and Count Rate in a Whole Body Counter for Several Individuals

(136 to 176 keV) versus the background rate in the 17 keV X-ray channels. A similar correlation exists for the X ray plus the 60 keV ^{241}Am gamma-ray channels. Figure 2 also shows a least squares fit to the points (bordered by two dotted lines at twice the standard error of estimate). The least squares analysis does not include the data noted by solid circles. The standard error of estimate equates to 3.8 counts/min in the case of the X-ray channels and 29.6 counts/min in the case of the X-ray plus gamma-ray channels.

The background count must be kept as low and as predictable as possible since the lower limit of detection is proportional to the square root of the background. If

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FIGURE 2. Correlation of X-Ray Count Rate of Unexposed Subjects with Count Rate at Higher Energies

the presence of other isotopes affects the background rate, low level detection will require adjustment of the background situation. If an adjustment cannot be effected, a background distribution determined from the normal background rates of many individuals can be used. This approach will tend to increase the lower limit of detection considerably, due to the wide variation in these rates.

A final question on background effects concerns the results of counting an individual with unusually high internal or external

amounts of another isotope. An Alaskan native containing large amounts of ^{137}Cs received examination both in the Shadow Shield Whole Body Counter and the scintillation plutonium counter. This individual evidenced over 20 times the integrated count rate of other individuals counted with the Shadow Shield, but only slightly more than half the count rate expected from linear extrapolation of data from lower level individuals. A suitable explanation will require additional investigation into this area of high contamination levels.

ISOTOPIC COMPOSITION

Because radiation intensity depends upon the isotopic composition of the material, counting and interpreting the low energy emission of plutonium becomes difficult and complicated. Typically, a plutonium sample contains small, but significant percentages of ^{238}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu , and ^{241}Am in addition to the ^{239}Pu , where the amounts depend upon the irradiation history of the material.

Both specific activity and the X-ray yield vary among plutonium isotopes but unfortunately, ^{239}Pu , the most abundant constituent in most plutonium samples, evidences low values for each. Because of this, the number of X rays per alpha particle becomes quite sensitive to changes in the presence of other isotopes. For instance, ^{241}Am , which results from the decay of ^{241}Pu , emits X rays and 27 and 60

keV gammas, and markedly affects the X/ α ratio. Although the presence of other isotopes increases detection sensitivity, sometimes by more than a factor of two, such radiations cause difficulties in interpretation of data. The alpha particle rate (dose) cannot be inferred from the X-ray and gamma-ray counts without knowledge of the isotopic composition or measurement of the ratio. For a typical source containing 94% ^{239}Pu , calculations indicated that less than 50% of the X rays came from this isotope.

Calculations of the number of X rays resulting per alpha particle emitted provided the information shown in Figure 3, which describes the calculated number of 17 keV X rays emitted per alpha particle for four different isotopic compositions and illustrates the ratio variation with time. The number of 60 keV gammas per alpha shows a similar variation with time and isotopic composition. Measurements with a plutonium sample containing 94% ^{239}Pu and 0.08% ^{241}Am by weight gave an X-ray/alpha ratio of 0.074 and a 60 keV gamma/alpha ratio of 0.019.

Although important for relating the measured activity to the alpha activity (and thus the dose), the X-ray/alpha ratio does not give the complete picture. Table I, which shows the X rays per Maximum Permissible Body Burden (MPBB) for sources containing various amounts of ^{239}Pu , indicates that the content of ^{241}Pu (not an alpha emitter) becomes important in determining the

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FIGURE 3. Change in X Ray to Alpha Ratio with Time for Various Initial Isotopic Compositions

MPBB and lowers the ratio of X rays to MPBB. The amount of ^{241}Pu present depends upon the total irradiation history of the material.

To accurately assess hazards of an exposure to plutonium, the isotopic composition should be available, but for normal sources accurate estimates can be achieved. The ^{239}Pu content will be relatively high, on the order of 95% by weight. By neglecting the ^{241}Pu activity and using the X-ray/alpha ratio for assessing the hazard, a ratio of 0.06 can be assumed. Expected X-ray/alpha ratio variations could typically range from

TABLE I. Effect of Isotopic Composition on Maximum Permissible Body Burden

^{239}Pu , wt%	MPBB per Unit Mass of Sample (relative)	X-rays/MPBB (relative)	X-rays/alpha	Percent of MPBB due to ^{241}Pu
0.9939	1.56	6.09	0.041	0.4
0.9665	1.80	6.34	0.046	7.8
0.6917	9.50	2.76	0.074	74.0
0.406	16.5	3.28	0.093	73.0
0.336	11.47	1.80	0.082	85.5

0.04 to 0.08, but most likely from 0.05 to 0.07. This limits the initial measurement of the in vivo activity to about $\pm 20\%$ which can later be corrected for isotopic composition by analysis of the exposure material.

ATTENUATION EFFECTS

The 17 keV plutonium X ray has half-value thicknesses for tissue and bone of 0.6 cm and 0.3 cm, respectively.⁽⁸⁾ For the 60 keV gammas, these respective values become 3.4 cm and 1.1 cm. Thus, for all practical purposes, the skeleton appears opaque to the X rays. An experiment with a dog skeleton⁽¹²⁾ indicated that the presence of the skeleton decreased the count rate for 17 keV X rays by 46%.

Because of the low penetrating power of these radiations, especially the X rays, factors changing the absorption such as internal distribution, surface contamination, variable overlying tissue masses, and particulate self-absorption, can

affect the interpretation of count data. Calculations and experiments with phantoms and animals aid in the definition of these variables.

Internal Distribution

The internal distribution of plutonium from inhalation exposure varies with the particle size and the chemical form of the material. The major portion of the material (80%) will be distributed among the lungs, bronchial lymph nodes, liver, and skeleton for the first few weeks after an inhalation exposure.⁽¹³⁾ In the case of PuO_2 for a few years after exposure, very little of the material will be found in the bone. Most of the plutonium will be in the lungs and bronchial lymph nodes with a small fraction in the liver.⁽¹⁴⁾ In an intravenous exposure, the liver and bones can be considered the major areas of deposition.⁽¹³⁾ Since X-ray counting of the bone is not feasible, the lungs, liver, and bronchial lymph nodes become the

organs of major importance for plutonium distribution. For short periods after an inhalation exposure, almost 100% of the material will be in the lungs, unless absorption from a wound occurs simultaneously.⁽⁹⁾

Figure 4 illustrates the change in counting sensitivity as a function of distribution: the sensitivity increases with increasing deposition in the liver and decreases with translocation to the bronchial lymph nodes. These data result from measurements made with an Alderson Research Co. "Remab" phantom. Uniform distributions of plutonium were used in the organs of interest and with lung-equivalent material in the lung cavities. Scintillation counters positioned over the chest areas and the sides of the chest provided these measurements.⁽¹⁰⁾

The experimental results indicate that with 12% of the material deposited in the liver--assuming that negligible translocation to the bronchial lymph nodes occurs--an

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FIGURE 4. Variation of Counter Sensitivity with Changes in the In Vivo Distribution of Plutonium

increase of about 4% in the sensitivity is obtained. Discounting a simultaneous wound exposure or delay in whole body counting, it can generally be assumed that the activity resides in the lungs.

Results of experiments using various distributions of plutonium sources in a dog phantom indicated an interesting relationship between the sensitivity and the ratio of the X-ray count rate to the "X ray plus 60 keV" count rate, Figure 5. Unfortunately, data collected on dogs did not demonstrate such a well-defined relationship, due, in part, to individual variations among the animals.

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FIGURE 5. Counting Sensitivity Versus Ratio of X-Ray Count Rate to X-Ray Plus Gamma-Ray Count Rate for Various Plutonium Distributions in a Dog Phantom

The use of phantoms for the calibration of plutonium lung counting raises certain questions. Although excellent agreement has been obtained between dogs and a good phantom,⁽¹²⁾ it may be desirable to calibrate with inhalation of a "mock mixture" of isotopes with X-rays similar to plutonium, as suggested by Taylor and Rundo.⁽⁶⁾

External Contamination

Because of the low penetrability of the plutonium radiations, a small amount of surface contamination can completely destroy the interpretation of counting data for internal material. Material deposited just below the skin can be counted very efficiently, producing similar results.

Figure 6 shows the calculated effect of external contamination representing a fraction of 1% of the internal deposition. The calculation assumes a uniform deposition in tissue-like material 10 cm thick with 1 cm of tissue-like material overlying it. Calculations were made with the formula:

$$I_s = \frac{c}{2\mu} [E_2(\mu t + \mu x)]$$

where,

- I_s = intensity at surface
- c = concentration of activity
- μ = absorption coefficient of material
- t = thickness of active slab
- x = thickness of overlying material.

Thus, significant errors in interpretation of data can occur for sur-

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FIGURE 6. Calculated Change in Ratio of Measured Count Rate to In Vivo Count Rate as the Percent of Surface Activity Decreases. Also shown is the change in the measured X-ray to γ -ray ratio with surface activity.

face contamination representing less than 0.01% of the internal activity. Of course, this represents the worst case: a small area detector directly over the surface contamination. In real counting situations, the large area detector necessary will reduce the effect of small amounts of surface contamination.

Interestingly, the gamma ray activity appears not to be so radically affected by surface contamination; thus, the ratio of the X-ray to gamma counts facilitates data interpretation. If an approximately normal ratio can be expected for a particular case, ratio tabulation will disclose any gross surface contamination.

Individual Variations

Subjects likely to be counted for internal deposition of plutonium vary in their physical size, thus affecting the count rate from a plutonium source. Figure 7 shows the change in count rate calculated for a varying amount of overlying tissue (chest wall thickness). A 2 cm change in chest wall thickness can cause more than an order of magnitude change in X-ray sensitivity and a 50% decrease in gamma sensitivity. The ratio of the count rates shows a marked change with overlying tissue mass, and if an expected value is known, a correction could be made. To make a correction, both a distribution and a ratio of X rays to gamma for the contamination and calibration sources must be known. The calculations represent the worst possible case using a small area detector with a large volume source.

Experiments with dogs and a dog phantom give further insight into the problem of individual variations.⁽¹²⁾ In one experiment, sources were placed in the lung section of a dog phantom, and tissue and fat equivalent pads representing the addition of 2 kg (20% weight increase) of tissue served to adjust the phantom's weight. Distribution of the pad material about the trunk simulates the condition in a larger dog and represents an addition of about 1 cm of tissue. X-ray count rate reductions of 36% and 50% occurred with the addition of fat and tissue equivalent pads, respectively.

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FIGURE 7. Calculated Change in Count Rate and Ratio (X-ray/ γ -ray) with Increase in Thickness of Overlying Tissue Contained no Activity

In another experiment, 13 dogs were counted with and without a 0.24 μ Ci source of plutonium inserted down the trachea to the bifurcation. The X-ray count rate plotted against the mean radial dimension of the chest at the seventh rib indicated a half-value thickness of 1.3 cm.

The count rate in the X-ray channels for the various dogs showed a standard deviation of 31% of the average and a range of 100% of the average.⁽¹²⁾

To a large degree, interpretation of data in this case will be effected by the appropriateness of the phantom used in calibration. Without corrections--assuming the dog phantom to be representative--the data expected will be limited to a range of about $\pm 40\%$. Data taken from the gamma ray count rate could be expected to be within $\pm 20\%$.

Self-Absorption

In the case of plutonium in wounds, self-absorption of X rays in the contaminating particle can be important.⁽¹⁵⁾ Fortunately, the pulmonary system acts as a filtering device, which makes this effect minor for inhaled materials. Taking deposition data from the Task Group on Lung Dynamics⁽¹⁶⁾ and adjusting it for the density of plutonium oxide,⁽¹⁷⁾ results in calculations indicating that 85% of the particles deposited in the pulmonary compartment will emit over 99% of their X rays. Only about 1% of the total number of X rays will be absorbed.

In the case of the tracheal-bronchial compartment, similar calculations indicate that 48% of the particles will emit over 99% of their X rays and that about 2.5% of the total number will be absorbed. For the nasopharynx compartment, the situation will not be so favorable,

but this compartment evidences little consequence for in vivo lung counting.

CLEARANCE EFFECTS

The material deposited after an inhalation exposure will be cleared from the pulmonary system at a rate dependent on the chemical form (solubility) and the location of deposition as determined by particle size. Although the clearance of inhaled material effectively enhances the sensitivity of in vivo counting, it adds uncertainty in the interpretation of initial counts.

Thirteen dogs given inhalation exposure of PuO_2 were studied by whole body counting of the X rays and gamma from ^{241}Am .⁽¹⁸⁾ In general, the clearance of the material on a short term retention basis could be characterized by two exponentials as shown in Figure 8. An average initial retention half-time of 1.1 days with a standard deviation of 0.8 day resulted from the ^{241}Am gamma counting. The half-time varied from 0.3 day to 3.24 days and, in one case, appeared infinite. The average retention of 16% ranged from about 6% to almost 100%.

An individual counted after inhalation exposure following a glove-box explosion clearly illustrates the role of pulmonary clearance. Figure 9 shows the count data taken after exposure to an aerosol of uranium enriched with plutonium. Twenty-four hours after the incident,

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FIGURE 8. Change in Count Rate for an Inhalation Exposure to Plutonium Oxide. This shows the early elimination of inhaled material.

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FIGURE 9. Change in Body Burden with Time for Inhaled Material Containing Plutonium

the individual had a count rate indicative of a body burden of 250 nCi. The activity levels should be considered relative as they do not include corrections for isotopic composition or other variables. This activity disappeared rapidly with a half-time of 38 hr, with background levels reached within 5 to 6 days after the incident. Bioassay results confirmed a retained body burden below the limits of detection of the counter.

CONCLUSIONS

Present instrumentation can provide rapid indications of inhaled amounts of plutonium at levels near

the Maximum Permissible Body Burden (40 nCi). This equipment, coupled with the enhancement of sensitivity by radiations from the rapidly eliminated portion of the inhaled material, will yield information on exposed individuals having a retained body burden constituting a fraction of an MPBB. As shown earlier, the sensitivity can be enhanced by a factor of five. Unfortunately, this enhancement varies to a degree depending on exposure conditions.

Estimation of the accuracy with which a body burden estimation can be made by *in vivo* X-ray counting provides useful information. When the primary concern is with material in the lungs and the amounts present at the time of counting, only the external contamination, background rates, isotopic composition, and individual variations must be considered. External contamination will probably be eliminated prior to any counting procedures and should be readily suspected and accounted for if present in gross amounts. Unless gross amounts of another radionuclide evidence their presence, it should be possible to adjust the background to a value that will not radically affect the interpretation of data. Thus, limitations of about $\pm 20\%$ by isotopic composition and perhaps $\pm 40\%$ by individual variations occur. Because of this, first estimations of the amount of material present will probably be accurate to $\pm 60\%$. Later counts should improve through better estimation of body variations and isotopic composition. As the count rate

approaches background levels, the accuracy of estimated amounts will be much worse.

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IRRADIATION EFFECTS ON SEMICONDUCTOR DETECTORS AND COMPONENTS

L. D. Philipp and N. C. Hoitink

The operating characteristics of semiconductor devices such as field effect transistors and diode detectors must be known to accurately predict circuit/detector operation in ionizing radiation environments. During irradiation of metal-oxide-semiconductor (MOS) transistors, a positive charge builds up in the surface oxide layer and surface states are introduced which change the operating characteristics of the device. Irradiation of 33 devices, representing 3 types of units, in the ^{60}Co gamma facility demonstrated that radiation resistance can be improved by proper selection of device type and operating point.

INTRODUCTION

Many situations arise where it is necessary to make radiation measurements in high intensity radiation environments. To perform satisfactory and dependable measurements, the effects of radiation on the characteristics of both detectors and amplifier must be known. The ^{60}Co gamma irradiation facility available at PNL provides ideal conditions for

obtaining data on irradiation effects. Studies were performed and experiments run on a number of metal-oxide-semiconductor (MOS) field effect transistors. Optimum bias conditions and device types were determined as a result of these studies. Charge-multiplying diode radiation detectors will be subjected in later studies to similar experiments to determine optimum or permissible bias settings for such diodes.

DISCUSSIONMetal-Oxide-Semiconductor Field
Effect Transistors

The degrading effect of ionizing radiation on semiconductor devices becomes a problem when electronic devices must operate in radiation environments.

The MOS field effect transistor (MOS-FET or MOS transistor), particularly sensitive to surface damage due to radiation, demonstrates versatility with unique and desirable characteristics. Its high input resistance (approximately $10^{15} \Omega$) allows it to be used in electrometer circuits where previously only vacuum tubes could be used.

The present work examined gamma-radiation effects on MOS-FETS to determine optimum electrical bias points and device limitations. Figure 1 shows the drain voltage-current characteristics of a typical device before and after exposure to 4×10^6 R of ^{60}Co . Irradiation occurred during operation with a drain voltage (V_D) of 10 V and a gate voltage (V_G) of 0.5 V. A shift in the drain curves for a constant gate voltage comprises the major change. In a practical circuit, such a change would produce a large shift in the operating bias point of the transistor. This shift may be characterized by a measurement of the transistor threshold voltage, V_T , defined as the gate-source voltage at the onset of conductance along the channel.

Changes in V_T result from an increase in the positive charge trapped

FIGURE 1. Drain Characteristics of MOS-FET Before and After Irradiation of 4×10^6 Rad

in the oxide of the MOS-FET.⁽¹⁾ Ionizing radiation impinging the oxide forms electron-hole pairs, which are swept apart by the applied electric field. Electrons leave the oxide, but the holes become trapped, resulting in a net positive charge. The charge tends to induce a change in the number of mobile charged carriers in the semiconductor close to the oxide surface layer: it will increase the number of electrons or decrease the number of holes in the channel; thus, the conductivity of an n-channel MOS-FET is increased and the conductivity of a p-channel unit is decreased. This accounts

for the basic cause of the drain-current shift observed in Figure 1; the physical model predicts that the charge will build up to a saturation value--a sensitive function of the gate bias applied during irradiation. Once saturation occurs, the charge in the oxide should remain constant with further irradiation as long as the gate bias does not change. This same phenomenon occurs for all types of MOS-FET units. The sensitivity of the oxide charge buildup to the irradiation gate voltage leads on to expect that optimum-device types and optimum-bias points exist that would minimize these effects of radiation damage.

Another important radiation-induced surface effect occurs: irradiation increases the number of "fast" interface surface states that act as surface recombination and generation centers for holes and electrons.⁽¹⁾ This effect, a function only of the irradiation dose, does not depend on the bias voltage. One result to be expected from the increase in surface-state density would be a reduction in the transconductance of the device. A very high density of fast surface states might even cause the semiconductor near the surface to become intrinsic, thus turning off the transistor entirely. Thirty-three irradiations were performed on three types of devices:

- (Type A) n-channel depletion unit
- (Type B) n-channel enhancement unit

- (Type C) p-channel enhancement unit.

The MOS-FET devices were irradiated while operating at fixed gate and drain voltages.

The transistors were enclosed in a length of evacuated pipe inserted through a water shield and exposed to elements containing approximately 1.5×10^5 Ci of ^{60}Co as shown in Figure 2.

The gamma dose rate for each experiment reached approximately 6.25×10^5 R/hr during irradiation times ranging from 6 to 30 hr. Specific test conditions included a constant 10 Vdc drain voltage and gate voltage constant at values ranging from +6 to -30 V, with drain current recorded throughout irradiation. Drain characteristics were recorded before and after irradiation.

The complete results and analysis of the experimental data appear in the literature.⁽²⁾ However, the experiments show that for both positive and negative gate voltages, a change in threshold voltage on MOS-FET devices occurs in the negative direction. The observed change increases with higher gate voltages (both positive and negative), but evidences a smaller effect at negative than at positive gate voltages. The lateral charge distributions along the channel length become important effects in transistors irradiated under normal bias conditions.

In general, the results indicate:

- A and B device types withstand irradiation damage best

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FIGURE 2. Gamma Facility and Experimental Set Up

- Optimum bias points exist for MOS-FET devices operating in an ionizing radiation environment
- To obtain minimum change in threshold voltage, the MOS-FET gate should be biased near 0 V
- To obtain minimum change due to the lateral distribution of charge along the channel length,

the gate-bias voltage should be less than or equal to zero. The latter point along can represent improvement up to a factor of 10 in resistance to radiation over other bias points. These experimental results and conclusions indicate possible improvements in device selection and design considerations

regarding MOS-FET devices for use in radiation environments.

Irradiation Effects on Charge-Multiplying Diode Detectors

Investigations continued with the charge-multiplying diode detectors. These devices operate very near breakdown, in which mode they exhibit charge multiplication analogous to that obtained with photomultiplier tubes but with much lower multiplication. In the near future, considerable use will be made of these detectors in high intensity radiation fields. Therefore, effects of various kinds and amounts of radiation on the operating characteristics of the devices must be known. Planned experiments in the ^{60}Co gamma facility will provide some of this information.

Operation of the charge-multiplying diode detector requires that it be biased within a few percent of breakdown to have charge multiplication occur. If the breakdown voltage changes during irradiation, the multiplication will be affected. This specific possibility will be investigated during the planned studies.

Acquisition of contoured diode detectors,⁽³⁾ developed especially for this type of work, continues to be difficult considering the present state of development. Other investigators⁽⁴⁾ have reported and we have verified that charge multiplication occurs in certain high voltage, high power avalanche (Zener) diodes. Though considerably less than that

for contoured diodes, multiplications of 15 to 20 have been achieved. These devices, commercially available at lower cost, will be used in forthcoming experiments.

Twenty Motorola 1N2846 200 V, 50 W diodes have been obtained and are being irradiated to various total doses of up to 2×10^7 R in the ^{60}Co gamma facility. Half of the experiments in progress operate the diodes biased very near breakdown (where multiplication occurs), and the other half use diodes biased into breakdown. For all experiments, V-I curves made at selected intervals throughout the irradiation and measurement of reverse current provide the desired information. A vacuum of 50 to 100 μ maintained in the vessel containing the diode and the cables minimizes the ionization currents. The diodes will be examined following irradiation to determine both their recovery characteristics and permanent effects.

The results of these experiments should be of considerable importance, not only in the proper use of charge-multiplying radiation detectors but also in possible use of avalanche diodes as voltage reference units in electronic circuitry exposed to high-intensity gamma radiation.

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Both the specific activity and the yield of X rays vary among plutonium isotopes as shown in Table I⁽¹⁻⁵⁾ which gives the specific activity, the Maximum Permissible Body Burden, and the X-ray intensities for the important plutonium isotopes and daughters. Both the ^{237}U and the ^{241}Am occur from the decay of ^{241}Pu which beta-decays to ^{241}Am 99.99+% of the time and emits alpha particles in $4.4 \times 10^{-3}\%$ ⁽⁶⁾ of the disintegrations, resulting in ^{237}U , important because of its high specific activity. The long half-lives of other radioactive daughters make them unimportant in these studies. Upon decay, ^{241}Am also emits a 59.6 keV (60 keV) gamma ray with an intensity of 0.359 per alpha decay.⁽²⁾

Unfortunately, ^{239}Pu , the major constituent in most plutonium samples, has a very low specific activity and X-ray yield; hence, the number of X rays per alpha particle changes radically in the presence of other

isotopes. Table II indicates typical data from sources with the same alpha activity where X ray and 60 keV gamma ray intensities differ significantly.

Obviously, the alpha particle emission rate (dose) from the X-ray and gamma ray counts cannot be inferred without either knowing the isotopic composition or measuring the ratio of the two count rates. Both the radiochemical and the radiological health interpretation of plutonium X-ray counting data depend

TABLE II. Photon Emission Rate for Typical Plutonium Sources

Source	X Rays, cpm/ μCi	γ Rays (^{241}Am ; 60 keV), cpm/ μCi
1	5,288	1,918
2	4,332	812
3	7,400	2,160
4	4,950	533
^{241}Am	34,000	32,000

TABLE I. Relevant Data for Plutonium Isotopes and Daughters

Isotope	Specific Activity, dpm/ μg	Maximum Permissible Body Burden		X Rays Per Alpha
		μCi	μg	
^{238}Pu	3.85×10^7	0.04	0.0023	0.1055
^{239}Pu	1.36×10^5	0.04	0.65	0.04
^{240}Pu	5.02×10^5	0.04	0.18	0.10
^{241}Pu	2.49×10^8	0.90	0.0082	--
^{242}Pu	8.67×10^3	0.05	0.13	0.10
^{241}Am	7.14×10^6	0.05	0.016	0.376
^{237}U	1.82×10^{11}	--	--	0.376

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FIGURE 2. X-Ray-Alpha Coincidence Counter

the counter go from a white cathode follower to a single channel analyzer and amplifier which provides a coincidence signal and drives a scaler used to count the alpha pulses.

The counter, operated at 1400 V from a stable power supply, demonstrates excellent stability. For the alpha counter, the background count rate is 1.8 ± 0.4 cpm, of

which about 0.06 cpm can be attributed to noise from the power lines. The counting efficiency for a 1 cm diam source on a stainless steel planchet is 42% compared to the 40% efficiency obtained for a point source of activity.

For a 1 cm source, the NaI detector has a background count rate (chance coincidence rate) of essentially zero cpm (0.04 cpm) and a

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FIGURE 4. Coincidence Spectra (The effect of the iodine escape peak)

TABLE V. Unknown Sources

Source	Alpha Activity dpm	X-Rays/Alpha	γ -Rays/Alpha
1	1260	0.0783	0.0197
2	608	0.0783	0.0259
3	1260	0.0770	0.0225
4	292	0.0606	0.0096
5	4.5×10^4	0.0730	0.0108

the calibration limits the cited values which would appear high compared to the ^{238}Pu measurements of Halley and Engelkemeir.⁽²⁾ The counter does give the desired accuracy for intercomparison of sources and relative accuracy for checking photon intensities.

Solid State System

Fabrication of a solid state alpha X-ray coincidence system, Figure 5, improves the ratios measured with the former system and permits measurement of the isotopic composition of materials. A 3 mm deep by 110 mm², lithium-drifted silicon detector, coupled to a preamplifier with a cooled input stage, detects the X rays; a surface barrier diode detects the alpha particles. For a source plated on platinum, a resolution of $\sim 0.6\%$ (FWHM) for the 5.48 MeV alpha of ^{241}Am was obtained. Maximum resolution for the alpha particles requires careful source preparation. The sources used were made from material spread evenly on a Mylar film supported in an aluminum ring. Even with this care, the resolution remains poor, but the alpha groups,

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FIGURE 5. Solid State Coincidence Counter

due to ^{241}Am - ^{238}Pu (5.48 MeV) and ^{239}Pu - ^{240}Pu (5.15 MeV), can be resolved.

Coincidence operation leads to a method that can be used to determine rapidly (though roughly) the isotopic composition of a sample. A method similar to that of Watanabe, et al.⁽⁸⁾ was used in these studies.

Figure 6 shows a coincidence spectrum for a ^{239}Pu source set to reject pulses from ^{239}Pu and ^{240}Pu compared to a not-in-coincidence spectrum. The extra resolving power of this system--caused by both the natural resolution of the silicon detector and the enhancement from coincidence operation--provides the main advantage over the previous system. Furthermore, escape corrections can be eliminated, which

thus simplifies the interpretation of data. However, this method lacks the sensitivity of the previous system which requires both sources of greater activity and longer counting times.

CONCLUSIONS

The X/α ratio becomes an easily measured parameter than can yield information useful to the evaluation of the relative health hazard of plutonium samples. By measuring the L X rays, this ratio can also be used to compare alpha activities of samples against a standard during assessment for plutonium content.

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FIGURE 6. Spectra Recorded with the Solid State System
(Coincidence spectra for a ^{239}Pu sample)

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DEPENDENCE OF PLUTONIUM X-RAY COUNTING ON ISOTOPIC COMPOSITION

K. L. Swinth

Plutonium materials may often be analyzed by counting the low energy photons emitted (17 keV X rays, 60 keV ^{241}Am gamma). Since the specific activity and the yield of X rays vary among the plutonium isotopes and ^{241}Am , and plutonium samples differ in isotopic composition, difficulties arise during analysis of the amount of plutonium present or of the alpha particle activity (dose rate).

Calculations explored the changes in X-ray and γ -ray activity of plutonium with isotopic composition and time. For a source containing 90% ^{239}Pu by weight, 55% of the total X-ray activity results from the ^{239}Pu , but this falls to 27% after a 5 yr decay. This change with time results mainly from the decay of ^{241}Pu to ^{241}Am .

A typical source containing 94% ^{239}Pu and 0.08% ^{241}Am by weight has a calculated X/a ratio of 0.063 and a 60 keV gamma/a ratio of 0.013. This paper discusses the problems and the experiments pertaining to a number of different isotopic compositions which relate to the maximum permissible body burden (MPBB) for the material.

INTRODUCTION

Analysis of plutonium material by counting the low energy photons emitted, 17 keV X rays from the plu-

tonium and 60 keV gamma rays from ^{241}Am , tends to be difficult. Furthermore, interpretation of counting results becomes complicated because

the intensity of the radiation depends upon the isotopic composition of the material. Typically, a plutonium sample contains small, but significant percentages of ^{238}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu and ^{241}Am in addition to the ^{239}Pu . The amount of each depends upon the irradiation history of the material.

Both the specific activity and the yield of X rays vary between plutonium isotopes. Unfortunately, ^{239}Pu , the major constituent in most plutonium samples, has a very low specific activity and a low yield of X rays. Because of this, the number of X rays per alpha particle evidences sensitivity to changes in the presence of other isotopes. Americium-241, resulting from the decay of ^{241}Pu , has X rays and both 27 keV and 60 keV gamma rays; thus, it strongly influences changes in the X/ α ratio. Although the presence of other isotopes increases the sensitivity, sometimes by more than a factor of two, such radiations obfuscate interpretation of data. The alpha particle rate (dose) from the X-ray and gamma-ray counts cannot be inferred without knowledge of the isotopic composition or without measurement of the ratio. Both the radiochemical and the radiological health interpretation of plutonium X-ray counting data depend on an understanding of the variation in X-ray intensity with isotopic composition.

Figure 1 shows spectra of two different plutonium samples as measured with a thin NaI detector. The sources have the same alpha

activity, but obviously the X-ray and 60 keV gamma-ray intensities differ significantly.

DISCUSSION

Table I outlines the specific activity, the Maximum Permissible Body Burden, and the X-ray intensities for the important plutonium isotopes and daughters. Both the ^{237}U and the ^{241}Am result from the decay of ^{241}Pu . Plutonium-241 decays by beta emission to ^{241}Am 99.9+% of the time, but in $4.4 \times 10^{-3}\%$ ⁽¹⁾ of the decays alpha emission occurs, resulting in ^{237}U , important because of its high specific activity. Although radioactive, the long half-lives of the other daughters reduce their importance. Upon decay, ^{241}Am also emits a 59.6 keV (60 keV) gamma ray that appears in plutonium spectra with an intensity of 0.359 per alpha decay. ⁽²⁾

Calculations served to elucidate the changes in X-ray activity, gamma-ray activity, and biological hazards of plutonium samples with variations in isotopic composition and time. A computer program facilitated the handling of large amounts of data from the calculations, wherein the X-ray to alpha ratios and MPBB values shown in Table I were used. Several experimental measurements of X-ray to alpha ratios substantiated the calculated values.

Figure 2 shows the calculated intensities for the isotopic composition of a typical source. The intensity of the ^{242}Pu X rays, too

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*FIGURE 1. Low Energy Photon Spectra
for Two Different Plutonium Sources
of Equal Alpha Activity*

small to appear on the figure, can be neglected. However, the amount of ^{242}Pu builds up with the irradiation of plutonium and can become important. The figure also indicates that any changes in the X-ray intensity with time result from the

buildup of ^{241}Am . Plutonium sources contain small amounts of ^{238}Pu and ^{241}Am , the amount depending on irradiation history and the age of the material, which produce significant activity. Total alpha- and gamma-ray activity, also shown in Figure 2,

TABLE I. Relevant Data for Plutonium Isotopes and Daughters

Isotope	Specific Activity, dis/min/ μ g	Maximum Permissible Body Burden		
		μ Ci	μ g	X-Rays/Alpha
^{238}Pu	3.85×10^7	0.04	0.0023	0.1055
^{239}Pu	1.36×10^5	0.04	0.65	0.04
^{240}Pu	5.02×10^5	0.04	0.18	0.10
^{241}Pu	2.49×10^8	0.90	0.0082	--
^{242}Pu	8.67×10^3	0.05	0.13	0.10
^{241}Am	7.14×10^6	0.05	0.016	0.376
^{237}U	1.82×10^{11}	--	--	0.376

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FIGURE 2. Activity Versus Time for
a Typical Plutonium Sample

indicates that gamma-ray activity parallels that of the ^{241}Am X rays as expected, while the total alpha activity reflects a small increase due to the ^{241}Am buildup. Although similar to Figure 2, Figure 3 shows the results of a calculation excluding the initial presence of ^{241}Am , yet clearly illustrates the buildup of the ^{237}U and ^{241}Am activity with time.

The production of plutonium occurs primarily from the irradiation of ^{238}U within a nuclear reactor. Its isotopic composition varies with the flux level, the integrated flux, and the neutron energy spectrum. Flux levels and energy spectra vary from reactor to reactor; thus, the isotopic composition of plutonium for the same integrated flux depends upon the facility characteristics. Figure 4 shows the calculated variation in isotopic composition with total exposure for a flux level of 5×10^{13} nv. (3)

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FIGURE 3. Activity Versus Time for a Plutonium Sample
Containing No Americium Initially

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FIGURE 4. Change in Isotopic Composition of Plutonium with Irradiation Time

Plutonium produced in a reactor for use as a fissile material, will generally be greater than 90% ^{239}Pu by weight, but plutonium from power reactors or recycle systems will be on the order of 60% ^{239}Pu by weight. Different flux levels and spectra yield plutonium of slightly different composition.

Figure 5 demonstrates the manner in which the X-ray to alpha ratio of four typical isotopic compositions changes with time. Increases in ratio result almost entirely from the growth of ^{241}Am in the material, as shown previously. The 60 keV ^{241}Am gamma ray shows a parallel increase

with time, from zero at time zero, since the material contains no ^{241}Am initially.

Figure 6 shows the change in the X/ α ratio with increasing exposure of the material to neutrons. This figure does not indicate the large changes in the X/ α ratio that will be caused by the growth of ^{241}Am ; most plutonium contains ^{241}Am and larger ratios will be expected. The figure also indicates that contribution from ^{239}Pu X rays never equates to 100% of the total; this contribution decreases with time as the ^{241}Am increases.

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FIGURE 5. Variation of X-Ray to Alpha Ratio with Time for Four Compositions

For the health physicist, the biological hazard of a plutonium sample poses the major concern. Figure 7 indicates the change in the Maximum Permissible Body Burden (MPBB) per microgram (based on bone) with time for five isotopic compositions. The MPBB/ μg remains fairly constant for any isotopic composition, but it does show a slight decrease due to the decay of ^{241}Pu . Ratios of X rays or gamma rays per MPBB, though not plotted, will show variations similar to the X/ α ratios of Figure 5. The increase with time will be more rapid due to the slight decreases in the MPBB values, as opposed to slight increases in the alpha activity.

The change in the MPBB/ μg versus reactor-exposure history of the material is demonstrated in Figure 8. A rapid increase in the MPBB/ μg occurs with exposure, and this increase largely results from the buildup of

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FIGURE 6. Change in X-Ray to Alpha Ratio with Irradiation Time

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FIGURE 7. Change in Maximum Permissible Body Burden with Time for Five Isotopic Compositions

^{241}Pu . Unfortunately, the ^{241}Pu does not emit any X rays and will not be measurable using X-ray counting techniques. The variation in the number of X rays per MPBB with the change in the X/ α ratio is depicted in Figure 9. The X/MPBB presents an initial increase due to the buildup of isotopes with a greater X/ α ratio. As the amount of ^{241}Pu builds up, the increase in the X/MPBB changes rapidly to a continuous decrease as the X/ α ratio increases steadily.

A decreasing sensitivity for the assessment of the biological hazard by X-ray counting presents the major concern for most materials. The growth of ^{241}Am will increase the ratios, and calculations show that the X/MPBB value for the smaller amounts of ^{239}Pu reaches and rapidly surpasses the ratio for materials

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FIGURE 8. Change in Maximum Permissible Body Burden per Microgram with Irradiation Time

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FIGURE 9. Change in X-Rays/MPBB
with Change in X-Rays/Alpha

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FIGURE 10. Change in X-Rays/MPBB
with Time for Four Isotopic
Compositions

high in ^{239}Pu (Figure 10). Americium-241 grows into a plutonium sample at the rate of about 540 ppm/yr for a sample containing 1% ^{241}Pu by weight.

Measurements to date of the X/α ratio have verified the initial calculations. The sources were counted in a system comprising a proportional counter to detect the alpha particles and a thin NaI(Tl) crystal and phototube assembly to count the coincident X- and gamma-rays. Measurements give an X/α value of 0.0485 and a γ/α value of 6.03×10^{-4} for a source with 99.8% ^{239}Pu by weight. The calculated ratio for a source of 99.4% ^{239}Pu by weight equates to 0.0413. This indicates a low value of the X/α ratio for ^{239}Pu (0.04), but one still within quoted errors. Another sample (94% ^{239}Pu and 0.08% ^{241}Am by weight) yielded an X/α

value of 0.074 and a γ/α ratio of 0.019. Correcting the X/α measurement for the ^{241}Am resulted in a value of 0.055, comparing well with the calculated value of 0.050. A value of about two MPBB/ μg and an X-ray intensity of 60 X rays/sec/MPBB (plus the ^{241}Am contribution) for the latter sample can be predicted (Figures 8 and 9).

SUMMARY AND CONCLUSIONS

It is obviously incorrect to treat plutonium samples as if they contained only ^{239}Pu . In all X-ray counting techniques, the isotopic composition must be taken into account. For some applications, the direct measurement of the X/α

value and γ/α value may be much simpler than a mass spectrographic analysis which requires considerable time and will miss small fractions of ^{238}Pu and ^{241}Am . As seen from the figures, the X/α ratio (corrected for ^{241}Am) can be used to predict the biological hazard of the material.

The inventory of high exposure (low ^{239}Pu) plutonium grows rapidly with the use of recycle systems and power reactors. Neglecting the isotopic composition does not cause grave errors at present, but this will not be the case in the future.

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DEVELOPMENT IN THE TIDAL VOLUME AIR MEASUREMENT

R. L. Wilbur

Studies of deposition of inhaled radionuclides in canines require an accounting of the amount of air respired. An earlier instrument merely counted the breaths and measured the inhalation volume. Modifications to the basic instrument enable the digital portion of the device to accept many different transducers and to examine either the inhalation or the exhalation portion of the respiration cycle. Two remote operating stations increase the mobility and versatility of the instrument. Several internal circuit changes provide greater breath monitoring latitude, smoother printer operation, and greater operator safety.

DISCUSSION

A Series 151 single-channel Sanborn recorder (Figure 1) replaces the Series 150 recorder of the earlier model as the analog recorder. In the original configuration,⁽¹⁾ the input signal (an 8 V swing biased to

350 Vdc) to the digital portion of the instrument was taken from the galvanometer output. To prevent shocking and to eliminate the need for a balanced attenuator, the signal now originates at an internal point in the carrier preamplifier. An additional signal-processing

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FIGURE 1. Tidal Volume Air Monitor

1-2-5-10 step attenuator, a 1 to 10 variable-gain amplifier, and a unity gain inverter for use in monitoring the exhalation portion of the respiration cycle have also been added. This allows many different transducers to be used without loss of sensitivity or signal strength.

The signal-conditioning circuitry and counter- and logic-circuits remain unchanged; however, the reset circuitry, previously energized by

the trailing edge of the print command, has been modified. Now, the trailing edge of the print command energizes a multivibrator, providing a 640 msec delay before energizing the reset circuits, which generates the pulse (Figure 2, D) to return the volume-per-breath counter to the initial mode. This delay permits the printer to print before clearing the counter storage.

FIGURE 2. Tidal Volume Air Monitor--Waveshapes

Since the device must reside outside the exposure rooms, two remote stations have been incorporated into the system for start-stop and reset control from inside the exposure rooms. The attendants can start the instrument at precisely the proper moment without having an operator at the instrument itself.

Respiration pattern studies will utilize a pneumotachograph which has the necessary full scale linearity for these experiments.

Hot-wire mass flowmeters, also being investigated, may offer an

alternate to the venturi flowmeter transducer. Greater linearity (less than 5% deviation) and less aerosol deposition on the transducer prompt these investigations.

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SURFACE CONTOURED DIODE APPLICATIONS

K. L. Swinth

The availability of surface contoured diodes for use as charge multiplication detectors of low energy X rays, permits new approaches to improved plutonium wound counting techniques. Although the diodes evidence low detection efficiencies, their small size and low background count rates offer some advantage over more conventional approaches. To date, several different configurations, including a hypodermic needle probe, have been investigated for possible use. Advancing technology will produce a variety of possible applications as better units become available.

DISCUSSION

A new type of detector with application to low energy X-ray counting (^{239}Pu) has recently become more readily available. These detectors have been widely explored physically and some detection concepts have been developed in cooperation with personnel at the General Electric

Company. The low efficiency of the units limits immediate applications; however, some of the concepts may be of general interest and further development may improve the detection sensitivity.

The surface contoured diodes evolved from development by Huth and Locker at the General Electric Company in Philadelphia.⁽¹⁾ Because

of the surface treatment, the detectors can be operated at elevated voltages in a manner to produce internal charge multiplication, thus enhancing the detection of low-energy photons and reducing the circuitry requirements as well. Circuits developed for use with the diodes utilize a tunnel diode to detect the internally deposited charge due to a nuclear event.⁽²⁾ Circuit operation also provides low background counting rates even with the high noise currents developed in the detector by ambient temperatures and light.

Typical background count rates of about 1/3 cpm have been attained. Unfortunately, the units have low detection efficiencies resulting from the very small depletion region. Typical intrinsic efficiencies approximate 25% at 5.9 keV, $4.8 \pm 0.5\%$ for the ^{239}Pu L X rays and about $0.54 \pm 0.04\%$ for the 60 keV gamma. Efficiencies of 100% can be achieved for these same photon energies using thin NaI(Tl) detectors. Hopefully, germanium will be used in future diodes instead of silicon, thus leading to much higher efficiencies.

Low efficiency notwithstanding, the small size of these units leads to some unique possibilities, and investigations for possibly detecting plutonium in wounds continue. Figure 1 illustrates one detection concept, where a detector--the small shiny surface seen in the window near the tip--mounts in the end of a hypodermic needle 2.5 mm in diameter.

The metal box contains all of the electronics, exclusive of the power supplies, scaler, or other readout device. This conceptual unit offers little usefulness because of the presence of exposed high voltage and the large needle size. However, if the concept proves acceptable, the units can be sealed and possibly developed for mounting in a unit about 1 mm in diameter. Advanced units could also be fabricated to provide an end-view from the hypodermic needle, thus having higher efficiencies.

Another concept under active investigation centers on a simple matrix of diodes for fast location of plutonium contamination in a general area on the body. Such a device will use sophisticated electronics to drive a lamp bank readout system capable of delineating the points of interest for the attending physician. The readout geometry would correspond precisely to that of the matrix probe.

Other uses for these detectors could include in vivo detection (implanted or hypodermic probe) of β -emitters and of low energy X-ray emitters (^{55}Fe). These diodes could also detect alpha emitters, but only through a very thin section of tissue or body fluids. Furthermore, the units have very fast signal pulse rise times, which thus afford possible applications in timing for physics work.

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FIGURE 1. Hypodermic Wound Probe

DEVELOPMENTAL EVALUATION OF MINIATURE BIOLOGICAL SENSING TRANSDUCERS

R. L. Wilbur

Physiological and pathological studies being conducted at PNL require many different forms of bioinstrumentation. Present commercial transducers often fail during experiments or may not be acceptable for one or more physical and environmental reasons. An evaluation record of the performance of transducers used in past, current or future experiments should alleviate these difficulties, save money and time and provide accurate physiological data quickly. The program also provides selective information regarding transducers and aids in planning application methods appropriate to the acquisition of data in a manner that insures an acceptable attrition rate for the transducers. This report describes the information acquired to date on the characteristics, preparation, calibration, and operation of four selected implantable transducers.

DISCUSSION

Engineers and scientists at PNL conduct physiological and pathological studies requiring extensive instrumentation for measurement of basic parameters. Mammalian test subjects, primarily Hanford Miniature Swine and Beagle dogs, are utilized for most experiments. Environments, diets, parameter measurements, and experimental work plans vary in such a manner that selection of proper transducers for any particular measurement becomes a significant problem. Literature on commercial transducers yields information regarding excitation, sensitivity, output, size and configuration, but proper selection decisions must be based on analysis of the following requirements:

- Parameter to be measured
- Planned transducer location
- Transducer size
- Animal environment and temperament

- Type, cost, and number of transducers
- Electronics necessary for data retrieval
- Experiment duration
- Instrumentation compatible with other portions of the experiment.

Although commercial manufacturers of biomedical transducers attempt to fabricate general purpose devices satisfying some of the above requirements, no transducer has proved satisfactory in the initial configuration. One possible explanation may be that most manufacturers follow the clinical approach to bioinstrumentation where the test subject would be either totally or partially incapacitated and the majority of environmental conditions and events may be predicted. Bioinstrumentation requirements at PNL generally require that test animals be not adversely affected in any manner by the implantation of sensors, connecting cables and supporting devices and materials.

This study encompassed the test and evaluation of a number of available transducers, as used in a variety of experiments. Some devices were specifically biomedical transducers, but others were designed primarily for other uses. The latter units, modified in the laboratory to meet experimental requirements, were subjected to various types of implantations, implant location, and experimental conditions.

The obtained information focused on ruggedization, calibration, durability, and operation of a selected number of transducers subjected to both acute and chronic implantation experiments. Hanford Miniature Swine were used for the implantations because of availability, similarity to man, and current rigorous experimental programs in progress.

Platinum Resistance Sensor

A platinum resistance thermometer, implanted subcutaneously in a treadmill-trained swine, featured a glass seal and used solid #32 AWG copper lead wires. Teflon sleeving (FEP), heat shrunk along the entire length, provided a fluid-tight protective sheath. No laboratory preparation took place prior to implantation because of the desire to test the glass-Teflon seal. Calibration of the sensor agreed with the manufacturer's data within $\pm 1\%$, with a resistance change sensitivity of $2.185 \Omega/^{\circ}\text{F}$.

The sensor remained in the swine for 63 days and permitted extensive

periodic measurements. For example, indicated changes in subcutaneous temperatures were measured during treadmill experiments of 10 minutes in duration twice a day for two weeks. Use of a potentiometric bridge permitted accurate manual measurements.

After 63 days of satisfactory operation, the swine became distressed in the treadmill and caused damage to the supporting equipment which terminated the experiment. Postexperiment inspection revealed broken solid copper leads at a pinch point; However, with the exception of the signal leads, the transducer proved to be satisfactory. Had extensive measurements been desired in an extremely long term experiment, the signal leads would have been stranded copper encased in either a Dacron or Nylon velour to provide better fixation at the skin exit. Experience indicates that the velours hold percutaneous leads firmly, allow the wound to heal, and prevent infection.

Thermistors

Microminiature glass bead thermistors, with a nominal resistance of $10 \text{ k}\Omega$, found extensive application for body and blood temperature measurements. The signal leads were #40 AWG stranded copper, Teflon insulated, with the bead-lead interface encased in the Teflon tubing utilizing a pressure seal. Many of these transducers failed after only a few days of use, primarily because

of shorting of the bead-lead wires by tissue fluid permeating the glass-Teflon seal. Lead breakage anywhere from the bead to the connector box on the harness assembly accounted for another, but secondary, cause of failure. Most signal lead destruction could be ultimately traced to the activity and temperature of the swine.

A second type of thermistor featured epoxy-PVC, shrink-tubing seals at the bead-lead interface and #26 AWG, stranded, PVC-insulated, copper lead wire. After implantation, no apparent improvement in operation occurred; failure resulted from leakage at the bead-lead interface. Tissue fluids, entering under the PVC shrink tubing where air bubbles had formed in the sealing process, shunted the thermistor. Signal lead wire breakage did not occur. To correct the deficiency, six different sealing techniques were tried, the thermistors implanted, and results observed to determine any new failures. Two techniques proved successful in keeping tissue fluids out of the bead-lead interface: removal of the PVC shrink tubing with application of an additional coat of epoxy over the bead-lead interface and the addition of a sheath of medical grade silastic tubing, shrunk along the entire lead tubing and ligated with silk thread to the glass bead (Figure 1). As the epoxy dries, a suitable seal resulted; finally, with Nylon or Dacron glued in a sheath over the silastic tubing, the leads stayed firmly in place after implantation.

FIGURE 1. Modified Thermistor Configuration

Solid State Blood Pressure Transducer

Miniature implantable blood pressure transducers enabled acquisition of blood pressure data during various experiments. Before, failure caused by leakage and signal lead breakage often inhibited the acquisition of valid data, but coating the head of the transducer with a 1 mm layer of silastic solved the leakage problem. Initial signal lead wires consisted of five Teflon-insulated, #40 AWG, stranded, copper wires in a PVC sheath. The leads tended to break at the connection end and to continue to break as strain continued during experiments. To overcome this problem, the leads were modified (Figure 2, A), and the entire group of five wires encased in PVC shrink tubing (Figure 2, B). This provided the necessary strain relief to overcome lead breakage at this point of stress.

To further seal, strengthen, and protect the transducer from physical damage, medical grade silastic tubing and Nylon or Dacron velour were

FIGURE 2. Blood Pressure Transducer Leads--Modification

placed over the leads and held in place with a ligature at the transducer head (Figure 3).

Ultrasonic Flow Transducer

Formed polystyrene cuffs with mounted lead zirconate-lead titanate crystals (PZT-5) permitted blood flow sensing in recent experiments (Figure 4). The signal leads were #30 AWG, stranded, copper wire with PVC insulation. The crystals have a nominal resonant frequency of

8 MHz and provide excellent signals when used with the proper electronic circuits. The cuff arrangement requires placement encircling an artery, tying the two half-cuffs together, and insuring acoustic coupling by infusing fresh blood between the crystals and the arterial surface. The leads pass to the outside percutaneously and are held in place by their velour sheath. These actions achieved satisfactory operation, and the attrition rate from corrosive action on the crystal-lead

FIGURE 3. Pressure Transducer Velour Covered

solder joint proved low. Signal lead breakage, though still somewhat of a problem, remains a function of animal activity.

Alternate aids to solution of the breakage problem include the use of coaxial and stainless steel leads in place of the stranded copper. These provide better strength, but the disadvantages in handling and connection exceed the advantages.

CONCLUSIONS

The two major problem areas encountered with implantable sensors center on sensor-to-lead sealing and lead breakage, and complete solutions to these two problem areas remain elusive. Experience indicates that the final configuration of any particular transducer depends upon the duration of implantation, transducer location, animal environment, animal temperament, and the

FIGURE 4. Ultrasonic Blood Flow Transducer, Cuff Type

interconnection of the percutaneous leads with umbilical cables, telemetry devices, etc.

To elaborate on animal activity, Hanford Miniature Swine tend to "roll and rub" to relieve itchy sensations from healing incisions and to remove attached instrument assemblies. Beagle dogs have sufficient agility to bite and snap over the shoulder and thereby restrict transducer lead exit areas to particular body locations. Therefore, prior to transducer implantation, careful animal behavioral studies must determine the most appropriate locations for support instrumentation.

Insulation materials used with acute experiments (duration not over 90 days) included Teflon, Tygon, medical grade silastic and polyvinyl chloride (PVC). None of these produced any serious tissue reactions during implantation.

SURFACE TENSION INSTRUMENT

R. L. Wilbur

Material of marked surface activity has been obtained from the pulmonary alveoli of mammals. Experimental results indicate a hysteresis at the air-liquid interface of lung tissue which varies with the surface tension. This report describes an instrument that measures these effects in vitro in a manner closely analogous to the in vivo situation. It also discusses the instrument used, the derivation of the surface tension equation, and the operation of the instrument, with emphasis on the acquisition of accurate surface tension measurements.

INTRODUCTION

Recent studies of surface forces in the pulmonary air spaces of mammals suggest the importance of abnormalities of surface tension in many aspects of lung pathology.

It has long been known that lungs inflate and deflate at widely different pressures, thus producing the hysteresis apparent in a pressure-volume curve.⁽¹⁾ Investigations indicated that the ability of the pulmonary air spaces to hold air depends largely on surface tension, and they have shown that the surface tension at the interface between moist tissue and air differs during inspiration and expiration.⁽²⁾

To further study the dynamic effects of surface active lung tissue, biologists requested development of an instrument capable of measuring the surface tension of surfactants. No feasible method exists for measuring surface tension in the intact lung and for equating this to pressure-volume curves; hence, minced lung tissue placed in an aqueous solution offered an in vitro sub-

stitute. This surfactant solution can then be measured with respect to varying cross-sectional areas similar to those found in normal inhalation-exhalation area changes. This report describes an instrument which measures the surface tension (γ , dynes/cm) with respect to the percent change of the area of canine lung tissue samples in a surface balance.

DESCRIPTION

The surface-tension instrument consists of a surface balance, a strain gage transducer, an amplifier-indicator, and an X-Y plotter (Figure 1).

Figure 2--a top view of the surface balance--illustrates the configuration and method of operation. A Teflon cell holds the aqueous surfactant solution. A motor-driven piston resides in the cell and produces the linear change in area. This piston linkage and gear combination produce one complete cycle every 30 min. As the piston moves, the rack and pinion mounted on the piston rod

FIGURE 1. Surface Tension Instrument--Block Diagram

FIGURE 2. Surface Tension Instrument--Diagram

drive a 1-turn, 10 k Ω potentiometer which supplies a voltage directly proportional to the percent area change to the Y coordinate on the X-Y plotter. A 1 k Ω V-A potentiometer limits the magnitude of voltage available to the position transmitting potentiometer.

A Statham universal transducing cell, Model UC3, measures the forces relating to the surface tension. The cantilever arm, connected to the cell, holds a thin platinum plate that is lowered half way into the solution. Changes in surface tension create changes in vertical forces subsequently sensed by the transducing cell. A Hewlett Packard Amplifier/Indicator, Model 311A (Figure 1), provides excitation and the balancing and calibration functions for the transducer. It also amplifies the signals to a level suitable for recording on an X-Y recorder, Hewlett Packard Model 7035B, which provides permanent hard copy tracings of the surface tension versus percent area change. Calibration of both coordinates permits direct reading of the hysteresis, in dynes/cm, for any fraction or multiple of the base area.

THEORY

A number of methods may be used to measure the surface tension of a liquid. The technique chosen, especially suited for the measurement of surface tension of aqueous surfactant solutions, is the vertical or hanging plate technique. While the operation of the device does not

require the solution of an algebraic equation, some investigation of the method was desirable. Derivation of the basic equation, including all possible variables, demonstrated that the system provided a solution analogous to the algebraic equation.

Figure 3 illustrates a two dimensional configuration of the forces pertinent to the measurement of surface tension. To acquire the general equation for the calculation of surface tension, consider the summation of the forces in the vertical direction:

$$\Sigma F_v = T(\Delta h) + kM_O g + B(\Delta h) - (M + m)g - p\gamma = 0 \quad (1)$$

where

$$k = a_2/a_1$$

T = torsion of wire

M_O = counter balance, grams

B = buoyancy

M = weight of plate in grams

m = calibration weights

h_i = height of arm in cm (i = 1, 2)

γ_s = surface tension (solvent)

γ = surface tension (solution)

g = acceleration due to gravity

p = perimeter of plate in cm

After filling the bath with the solvent being considered and lowering the plate p (Figure 3) carefully into it while preventing wetting, the value of m corresponding to a h₁ becomes m₁ and the buoyancy B(h₁) = 0. Summation of the vertical forces then becomes:

$$\Sigma F_v = T(h_1) + kM_O g - (M + m_1)g - p\gamma_s = 0 \quad (2)$$

FIGURE 3. Surface Tension Measurement--Principle

It is now necessary to determine the weight sufficient to bring the arm to the position h_1 . After removing the plate and solvent, the weight M_1 is added to the arm until it deflects to the position h_1 . Again, summing the forces in the vertical direction:

$$\Sigma F_v = T(h_1) + kM_0g - M_1g = 0 \quad (3)$$

To measure the surface tension of a solution using the above solvent, replace the plate and bring it in contact with the solution as described above. Lower the plate to a deeper position, h_2 , by the addition of a suitable weight, m_2 , placed on the

hook at the end of the arm. If the error in calculation of surface tension due to the difference in density between the solvent and solution is negligible compared with the difference in surface tension between them, the summation of forces yields:

$$\begin{aligned} \Sigma F_v &= T(h_2) + kM_0g + B(h_2) \\ &- (M + m_2)g - p\gamma = 0 \end{aligned} \quad (4)$$

where γ denotes surface tension of the solution.

Further, the value of m necessary to bring the plate to the equilibrium position, h_2 , in the solvent alone satisfies Equation 1:

$$\begin{aligned} \Sigma F_v &= T(h_2) + kM_0g + B(h_2) - \\ &- [M + m(h_2)]g - p\gamma_s = 0 \end{aligned} \quad (5)$$

Solving Equations (2 through 5) simultaneously for γ , the following equation for the surface tension of the solution results.

$$\begin{aligned} \gamma &= [m(h_2) - m_2 + M_1 - M \\ &- m_1] \frac{g}{p} \frac{\text{dynes}}{\text{cm}} \end{aligned} \quad (6)$$

In Equation (6), M is a constant and $m(h)$, M_1 , and m_1 do not change if p , M_0 , and k are kept constant. Thus, we can calculate the surface tension, γ , from the measurement of Δh ; indeed, the electrical system does exactly this. The Statham cell produces a linear output for a change in Δh , thereby satisfying the analogous problem.

DISCUSSION

This instrument uses the full bridge transducer including four active resistive elements connected in a Wheatstone bridge configuration. The amplifier measures the surface tension by measuring the imbalance voltage from the bridge. Controls on the amplifier compensate for resistive and capacitive imbalance of the bridge, transducer, and its lead wires and can be used to roughly set

the operational range for the measurements of diverse instrument calibration procedures parallel to those described in the derivation of the basic equation.

By meticulously observing the balance and calibration procedures, the instrument can be expected to operate satisfactorily within 1% of true values.

However, two phenomena occurring in the laboratory tend to destroy accurate measurements, and corrective action must be taken to assure valid results. The air balance equipment causes vibrations in the laboratory so extensive that balancing cannot be achieved. A vibration pad placed under the surface balance dampens the vibrations sufficiently to proceed. All measurements must be taken with the plastic cover in place to prevent circulating air in the laboratory from altering the readings.

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NEUTRON AREA MONITOR FOR THE POSITIVE IONVAN DE GRAAFF GENERATOR FACILITY

E. M. Sheen and C. A. Ratcliffe

This report describes electronic instrumentation to be used with a moderated neutron proportional counter tube as an area monitor for the PNL positive ion Van de Graaff generator. The monitor comprises an adjustable high voltage power supply, a count rate meter readout, and an alarm with adjustable threshold. The alarm consists of blinking lights and a pulsed acoustic annunciator.

DISCUSSION

Use of the positive ion Van de Graaff generator necessitates a neutron-sensitive area monitor. One of the requirements included use of an existing proportional BF_3 counter tube. Figure 1 shows the block diagram of the resulting instrument design. Pulses from the BF_3 tube are coupled to a charge sensitive amplifier, the noise rejected by a discriminator, and the

resulting pulse rate determined by a count rate circuit. The output signal of the count rate circuit operates both a high trip level circuit for alarm annunciation and a low level trip circuit to indicate system failure or unexpectedly low background conditions.

The pulse amplifier used with the proportional counter consists of a charge-sensitive input group followed by two feedback pair amplifiers for additional voltage gain. The

FIGURE 1. Block Diagram

charge sensitive portion, shown in Figure 2, uses a cascade input stage, Q1-Q2, for low noise performance, and has a sensitivity of $V/Q = 1/C_{FB}$. In this case, C_{FB} is the feedback capacitance C3 of 10 pF (10^{-11} F). Thus, the sensitivity equates to 10^{11} V output per coulomb input.

The second gain group comprises a feedback-pair (Q4-Q5) with a voltage gain of 50, approximately determined by the collector resistance of Q5 divided by the feedback point resistance. Capacitor C5 together with the bias resistors of the base of Q4, differentiates the long-tailed positive pulses from the emitter of Q3. After voltage gain, the output pulse width of the second gain group measures approximately 8 μ sec. A shielded enclosure provides the input and first gain groups with rf noise isolation.

The second gain group (Figure 3), similar to the first gain group, provides an additional gain of three.

A discriminator for amplifier noise rejection follows the amplifier. Illustrated in Figure 4, it consists of an adjustable off-biased differential pair followed by a saturating output stage. Proper bias adjustment insures that amplifier noise does not cause counting in the rate meter circuit. Potentiometer, P1, reverse biases the emitter base junction of Q1, and positive input pulse heights exceeding the reverse bias voltage turn on Q1 (and subsequently Q3), resulting in a positive output pulse at the collector of Q3.

The discriminator output drives a dual count rate circuit (Figures 5 and 6) operating from positive pulses from the discriminator which

FIGURE 2. Pulse Amplifier Input

FIGURE 3. Pulse Amplifier Output

FIGURE 4. Discriminator

activate the binary (Q1-Q2) of Figure 5. Binary output pulses drive a complementary transistor emitter follower, Q3-Q4. Charge transfer occurs through the two sets of switched coupling capacitors to a dual diode pump network (Figure 6). Diode, D1, places charge on the capacitor, C1, during binary positive transitions, and the switching coupling capacitor recharges through diode, D2, to the emitter follower (Q1) output voltage. This circuit operates similarly to a conventional diode pump except that connecting diode, D2, to the emitter follower output greatly improves the output linearity. A panel meter measures the output diode, D1, voltage of the linear count-rate circuit with the full scale range indicated by the position of the range switch, a front panel screwdriver adjustment.

The high level trip circuit also monitors the voltage.

A conventional, diode-pump count-rate circuit monitors the background count rate. With normal background, transistor, Q1, of the low background trip circuit (Figure 6) is off; Q2 and Q3 are on; and relay, K1, is energized to give a "NORMAL" front panel indication. For count rates below normal background, K1 does not energize while the amber lamp does. This condition may mean a failure in the counting system, if it can be shown by independent means that the count rate remains below the trip setting. The low level trip has three ranges adjustable from the front panel.

The output of the high-level linear count-rate circuit drives the panel meter and the high level trip.

FIGURE 5. Count Rate Circuit, Part A

FIGURE 6. Count Rate and Low Background Trip Circuits

This trip circuit (Figure 7) comprises an off-biased differential transistor pair (Q1-Q2) with the bias adjustment, P1, on the rear of the chassis. If the rate circuit output voltage exceeds the present threshold, the amplifier energizes

a Unijunction* relaxation oscillator (Q4) which, in turn, drives a monostable multivibrator, Q1-Q2, (Figure 8). The output of this circuit

* Registered General Electric Company trademark.

FIGURE 7. High Trip Pulse Generator

consists of an audible annunciator (a Mallory "Sonalert" unit) and a relay that flashes a red lamp alternately with the green one.

A conventional half-wave rectifier and corona voltage-regulator circuit supply the high voltage for the detector tube. The voltage can

be adjusted over a range of from about 1000 Vdc to about 1500 Vdc. A simple bridge rectifier, a Zener diode stabilized transistor voltage regulator, and noise decoupling circuits comprise the low supply for the solid state circuitry voltage requirements.

FIGURE 8. High Trip Monostable Multivibrator and Alarm Circuit

IMPROVEMENTS IN RAINDROP CHARGE MEASURING SYSTEM

C. A. Ratcliffe and N. C. Hoitink

Improvements incorporated into the raindrop charge measuring system used in atmospheric studies reduced transducer microphonics, improved charge induction geometry, reduced adverse environmental operating characteristics, and increased the charge sensitivity to approximately 10^{-15} C. The use of an electrostatic pen recording method allowed system operating under adverse climatic conditions. Extensive field tests, on a continuing basis with power obtained by using batteries for the electronics and a portable ac generator for the recording equipment, evidenced marked operational improvement.

DISCUSSION

During the year, selective field tests of the raindrop charge measuring system led to incorporation of specific improvements in design and resulted in considerably enhanced operation. Earlier efforts^(1,2) proved satisfactory in the laboratory and under favorable field conditions; however, general performance problems occurred during adverse weather.

The improved transducer previously reported⁽²⁾ demonstrated partial but inadequate success. Some of the problems concerned microphonics, resulting from the use of long insulators, and minute capacitance changes that introduced extraneous charge signals.

A new ruggedized transducer design (Figure 1) used 0.25 in. aluminum alloy components. This design includes an insulator arrangement that provides high resistance to moisture problems, superior microphonic characteristics, and improved geometry for charge induction.

The electronic portion of the system comprises an amplifier, power supply, and recorder. The present amplifier uses a Philbrick Research Model P2A operational device rather than the more easily damaged MOS field-effect transistor method used in the earlier designs. The approach shown in Figure 2 operates at virtual ground mode by means of the feedback arrangement, which thus reduces amplitude fluctuations caused by changes in capacitance between elements of the transducer. The 1 to 2 pF feedback capacitor determines the charge sensitivity. This amplifier increases the sensitivity by approximately an order of magnitude over that previously reported;⁽²⁾ thus, charge measurements can be made down to about 10^{-15} C.

The included postamplifier--with gains of 1, 10, and 100--provides signal conditioning to produce signals compatible with the recording system, presently a Brush Mark II, Model RD 2522-20 dual-channel unit with electric writing to

FIGURE 1. Cross Section of Transducer

FIGURE 2. Electronic System for Detector

obviate pen inking troubles in outdoor, cold weather operation.

In the field, the amplifier and transducer power supply operate from six lantern batteries of 6 Vdc each and provide regulated outputs of

plus and minus 15 Vdc. Battery life during field operation exceeds 50 hr. The recording portion operates from a portable ac generator.

Calibration has been achieved by charging a stream of water drops in the laboratory and noting the response of the measurement system on an oscilloscope. The drop charge, thus determined, completes calibration. Figure 3 shows a satisfactory charging and calibration system. A variable voltage of changeable polarity applied to the ring near the drop generator placed a charge, by induction, on the drop as it forms. The charge remains on the drop as it falls from the generator.

A pulse generator, developed for charged-drop experiments, may be

FIGURE 3. Charge Calibration Arrangement

used for calibration purposes. As shown in the schematic of Figure 4, a Unijunction* oscillator sets the pulse repetition rate for the generator and varies, with the setting of the 500 k Ω potentiometer, between about 2 to 20 pulses/sec. The output of the oscillator triggers a monostable multivibrator with a variable-width pulse output, where the 100 k Ω potentiometer controls the pulse width from about 1 msec to about 10 msec. The pulse output of the monostable circuit turns on and saturates the output transistor--chosen for this application because

of its relatively high voltage rating. The quiescent output voltage varies from 0 to about 175 V positive with respect to circuit common.

Raindrop charge determination is accomplished by collecting and counting the drops in a system of known capacitance and measurable voltage. From $Q = nq = C(\Delta V)/n$; where n equals the number of drops, C equates to the combined capacitance of the collecting system and electrostatic voltmeter used for measuring ΔV (and varies with the voltmeter reading), and ΔV signifies the voltage increment attained over the period of time needed to collect the n drops. Obviously, the time for

* Registered General Electric Company trademark.

FIGURE 4. Pulse Generator for Charged Drop Experiments

charge to decay (leakage) should be large compared with the measurement time.

Additional improvements to the system will depend on the results achieved through further field testing. Although it would require considerable developmental effort, the capability of measuring drop velocity could also be added in the future if such information would be desirable.

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