Low-Level Counting Methods for Isotopic Tracers

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Although the peaceful uses of atomic energy have captured the interest and stimulated the imagination of scientists throughout the world, the principal uses actually realized are the applications of radioisotopes and nuclear radiations. This is the field of radiochemistry. With the ready availability of radioisotopes made possible by the nuclear reactor, modern radiochemistry has found many applications in research, development, control, and manufacturing. In recent years, advances in radiochemical instruments and techniques have simplified measurements, extended the usefulness of radiochemical applications, and opened up new fields for the large-scale use of radioisotopes.

Perhaps the most versatile application is the use of radioisotopes as tracers. These applications range from simple bulk tagging to highly sophisticated tracings of atoms and molecules in complex chemical reactions. A few examples of bulk tracing are the tagging of sewage for tracing effluent patterns near beaches, the labeling of heating oils in underground storage for tracing leakage from pipelines, and nature's tracer experiment whereby air masses are naturally tagged with cosmic-ray-produced tritium, by means of which enterprising meteorologists can trace the movements and sources of air masses. The "bird band" tagging of the interphase between grades of oil in a pipeline, the use of gross specific activity as a measure of the degree of physical mixing or, conversely, as a volume measurement, and the timing of injected radioisotopes for monitoring flow rates are good examples of further applications that have been pioneered principally by the petroleum industry, which has been a leader in the industrial use of radiochemistry.

In the field of atom tracing, the use of radioisotopes has made possible classically "impossible" experiments—for example, the study of the kinetics of reactions at equilibrium and the tracing of a reaction mechanism by pinpointing the chemical route of a specific source atom or molecule. This has become one of the most powerful tools in the repertoire of the research chemist.

In general, these uses of tracers depend on the chemical and physical near-identity of the radioisotope to the natural element and on the unexcelled sensitivity by which radioisotopes can be detected and measured. It is in the latter category that recent advances in radiochemical instrumentation have made possible new large-scale uses for radioisotopes. This is the field of low-level counting.

The purpose of low-level counting is the detection and measurement of minimal quantities of radioisotopes in order to increase greatly the allowable dilution factors of tracer experiments. The increased dilution factors make possible the natural tracer experiments of radiocarbon dating and natural tritium studies. In a similar way, large-scale industrial tracing for product labeling and geologic tracing are made feasible. Only by low-level counting can the attendant radiation exposure be fully minimized.

In the development of low-level counting, the goals of instrumentation have been (i) to maximize the primary sensitivity of detection and (ii) to minimize the noise level of response to the background radiation from cosmic rays and from naturally occurring radioisotopes. The latter goal has involved massive shielding, electronic cancellation of many of the cosmic-ray pulses, and sometimes energy discrimination. The detectors themselves may be considered to belong in two classes, the gas-tube counters and the scintillation detectors.

Low-Level Gas-Tube Counting

The first major application of low-level counting was the work of W. F. Libby and coworkers (*1*). Their discovery of carbon-14 in nature and their establishment of the important method of radiocarbon dating required the development of the first low-level counting instruments, which were capable of measuring down to a few disintegrations per minute of this weak beta emitter per gram of carbon.

The necessary detection sensitivity was obtained by the use of the Libby screen-wall counter (*1–3*), which is discussed in a subsequent paragraph. The problem of the signal-to-noise ratio that resulted from the high background activity of this relatively large counter was solved by the use of massive shielding for gamma radiation plus electronic shielding for the mesons of the cosmic rays. These techniques of background reduction have been adopted in subsequent developments in gas-tube low-level counting.

The massive shielding usually consists of 8 inches of iron or steel. Almost as good results can be obtained with 4 inches of iron plus 4 inches of lead. A shield entirely of lead, however, is unsatisfactory, because of contamination by natural radioactivities. Of the many possible designs, one that we have found satisfactory is shown in Figs. 1 and 2 (*4*). Additional shielding is provided by an annular tank of mercury, as is shown in Fig. 2. Kulp and others have shown that placing mercury between the iron and the counter will further improve the background count by removing some of the contaminating radiation (*5*).

The problem of radioactive contamination in low-level shielding materials needs further study. Although it appears that commercial aluminum contains more radium than some types of stainless steel and that copper piping is less contaminated than most brass tubing, a general program for evaluating materials is important to an optimum design of a low-level counting assembly. An excellent start in this direction has been made by Grummitt and coworkers (*6*). An important evaluation with large samples is contemplated by E. C. Anderson at Los Alamos. With the ever-increasing use of safe, low levels of radiotracers in manufacturing and the presence of world-wide long-lived strontium-90 (*7*), it may become desirable to create a national stockpile of appropriate shielding materials.

In addition to massive shielding, it is necessary to use electronic shielding against certain components of the cosmic radiation. The mesons and some showers are detected in what has been called an "umbrella"—or, perhaps more appropriately, a "raincoat"—of Geiger counters surrounding the sample counter. A group of these counters in "mass production" in our laboratory is shown in Fig. 3. A typical installation of some of these counters surrounding a large sample counter inside the massive shield, but without the mercury shield, is illustrated in Fig. 4. During operation, the counts detected by these Geiger counters are electronically subtracted by placing them in anticoincidence with the counts

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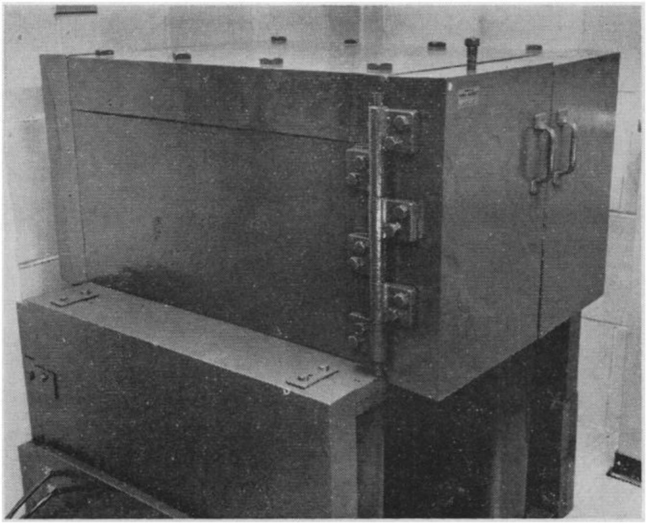


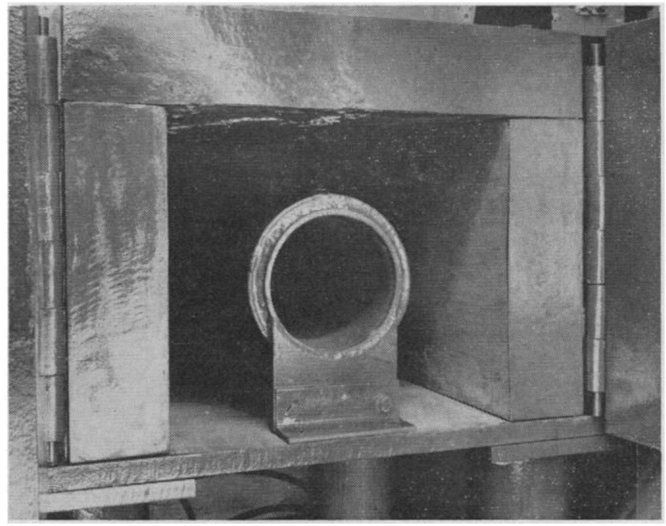


Fig. 1 (Left). Massive iron shield for low-level gas-tube counting. Fig. 2 (Right). Inside of massive shield showing the annular tank of the mercury shield.

of the central sample counter. In this arrangement, the counters of the envelope can be operated in parallel from a single high-voltage supply. A number of satisfactory circuits are available for accomplishing the anticoincidence operation (*8, 9*). It is, of course, possible to operate more than one sample counter under a common "raincoat." Some effects of massive shields and anticoincidence shielding are summarized in Table 1.

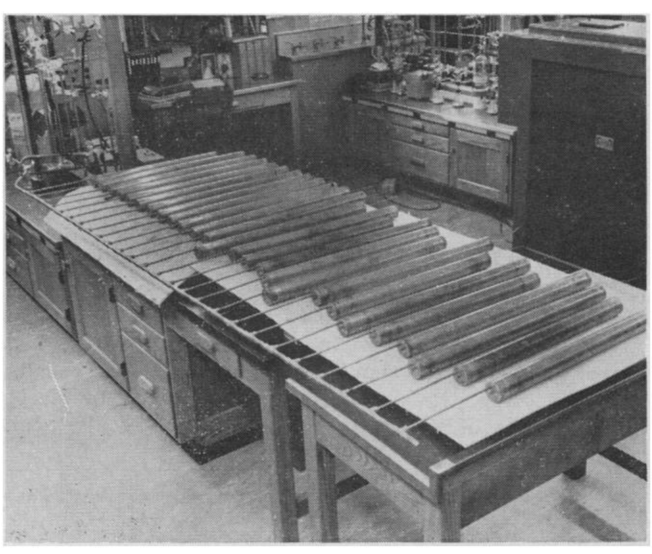
It is interesting that the separate anticoincidence Geiger counters may be conveniently replaced by a multiple-anode annular counter with a common counting gas (*6, 10*). It is preferable to minimize the dead volume and to allow independent operation by separating each anode compartment by a fine grid of cathode wires rather than by using the vanes of Raeth (*11*).

Screen-wall counter. The first type of gas-tube counter to be discussed is the screen-wall counter (*1, 3, 9*).

The sample, in solid form, is mounted on the inside surface of a cylinder that surrounds a Geiger tube. The "wall" or cathode of the Geiger tube is an open grid of wires; thus the usual absorption by a "window" is eliminated. The sensitive volume is extended to the surface of the sample by placing a suitable electric field between the sample and the screen wall or grid-cathode of the Geiger tube. The effective geometry is essentially 50 percent, and the detection of beta rays leaving the sample is essentially 100 percent.

With elemental carbon, 8 grams of sample, in which the thickness is equal to the maximum range of the beta radiation, is usually used. The self-absorption losses are therefore high. On the other hand, the large size of the sample cylinder provides an unusually large sample area of 400 square centimeters. With the optimum sample of elemental carbon, the absolute efficiency is 5.4 percent for carbon-14 (*1*).

Internal-gas counter. The second type of gas-tube counter that is important for low-level counting is the internal gas counter. In its simplest form, this counter consists of a Geiger tube with provision for placing the sample in gaseous form inside the counter as part of the counting gas. The discovery and measurement of the distribution of tritium in nature were made with this instrument (*12*). The simplicity of this counter and the associated electronics, its ease of operation, and its high efficiency, which approaches 100 percent, make this an attractive method, provided that the sample can be readily incorporated as part of the counting gas. Anderson and Levi (*13*) have shown that for carbon-14 the greater sample ac-



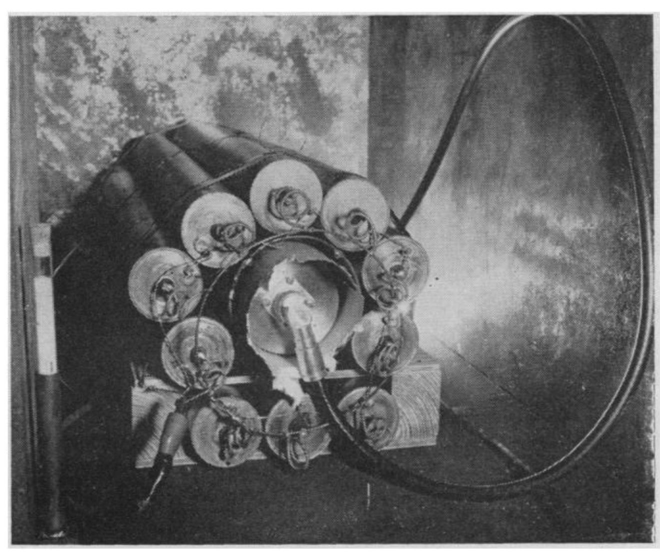


Fig. 3 (Left). "Mass production" of Geiger counters for anticoincidence shielding. Fig. 4 (Right). Anticoincidence Geiger counters surrounding sample counter in massive shield.

commodation of the screen-wall counter approximately compensates for the greater efficiency of the internal-gas Geiger counter. For less energetic beta-emitting isotopes, such as tritium, the gas counter is more efficient; for more energetic beta-emitting isotopes, the screen-wall counter is preferred. This conclusion does not apply to high-pressure proportional gas counting. On the other hand, for small samples and for many routine measurements, the internal-gas Geiger counter is preferred.

In an effort to increase the sensitivity of measurement of natural radiocarbon, DeVries and Barendsen (*14*), Suess (*15*), Crathorn (*16*), Fergusson (*17*), and Williams and coworkers (*18*) have developed the low-level, internal-gas proportional counter that uses acetylene or carbon dioxide at pressures above 1 atmosphere. The increased pressure gives increased sensitivity. The proportional region allows further reduction of the background rate by pulse-height discrimination. The theory, design, and operation of proportional counters have been covered extensively in the literature (*19*).

Early efforts to use carbon dioxide as a counting gas were unsuccessful because of electron attachment by electronegative impurities. It is necessary, therefore, to remove these impurities by a procedure such as that of Rafter (*20*) or DeVries and Barendsen (*14*). The carbon dioxide is absorbed on calcium oxide at a temperature of 700° to 750°C and is reevolved at 800° to 900°C. It has been shown by Fergusson (*17*) and others that the electronegative impurities remain on the lime. The purity requirements are very stringent. In order to keep the electron loss by attachment less than 1 percent, the concentration of oxygen must be less than 1 part in 10^6, and the concentration of chlorine must be less than 1 part in 10^7. These purity specifications and the relative complexity of the associated electronics make this beautiful method useful chiefly for such problems as radiocarbon dating of old samples. The absolute efficiency for carbon-14 is about 68 percent (*17*). Although much higher efficiencies could be obtained, the increase in background rate would increase the statistical error of the net sample count.

Foil counters. The third type of low-level gas-tube counter is the foil counter of Libby and coworkers (*21, 22*). In its simplest form, this counter is a cylindrical, thin-walled Geiger flow counter. The wall is made of an aluminum-coated plastic film of Mylar, which is less than 1 milligram per square centimeter in area density (*23*). Such a film will pass almost 75 percent of the beta radiation of carbon-14. Furthermore, the cylindrical shape provides a large surface area, in contrast to the usual commercial

Table 1. Effects of shielding and anticoincidence in the reduction of the background rate of gas-tube counters (after Anderson, *9*; and Kulp, *5*).

Shielding	Background rate (count/min)	Difference	Remarks on difference
None	450		
5 centimeters of lead	142	308	Cosmic radiation and laboratory contamination
20 centimeters (8 inches) of iron	110	32	Contamination of the lead
20 centimeters of iron plus anticoincidence	5	105	Mesons
20 centimeters of iron plus anticoincidence plus 1 inch of mercury	2	3	Contamination in iron

counter. In design, cylindrical end-pieces of plastic are fixed with respect to each other by thin brass rods. The rods and end-pieces support the plastic foil wall, which is mounted with the aluminized surface inward as the cathode. The counter gas, which is maintained very slightly above atmospheric pressure, is usually a mixture of helium and 2 percent isobutane. This gas is commercially available as "Q" gas (*24*). A foil counter and sample holder made by A. G. Schrodt are shown in Fig. 5.

When solids are to be counted with the foil counter, the sample is usually mounted on the inside of a split cylinder of plastic. The sample holder is in turn supported concentrically around the foil counter. It is not difficult to obtain about 40-percent geometry. In mounting, the sample is slurried with a volatile liquid such as methanol or ether plus a small amount of agar in alcohol. Although the operation of spreading this slurry evenly onto the sample cylinder appears to be difficult, it actually can be done easily and routinely. The spreading is done with a glass rod and spatula, and the slurry is usually dried briefly with a hair dryer or heat lamp. In the absolute assay or the precision counting of very small samples, it is more convenient to convert them to finite size by homogeneous mixing with an inert material. Schrodt and Libby (*22*) have shown that talc, acid magnesium metasilicate, is an excellent material for routine use in this manner. Of course, care must be taken to avoid radioactive contaminants such as radium. In this regard, it is interesting to note that the plastic sample cylinders should be made from ancient carbon compounds—for example, from petroleum. A cylinder containing only contemporary carbon would add about 6 counts per minute to the background rate of a counter 1.5 inches in diameter and 10 inches in length (*22*).

In counting volatile liquids with the foil counter, either refrigeration or a cover of rubber hydrochloride has to be used. If care is taken to check on fractionation effects, a liquid of low volatility can be counted after it has been absorbed in blotter paper, as a slurry in talc, or as the liquid in a shallow tray.

In counting gases with the foil counter, several modifications may be used. If a small sample is required, a modification of the 4π counter may be used in which the sample is placed in one hemisphere, which is separated by

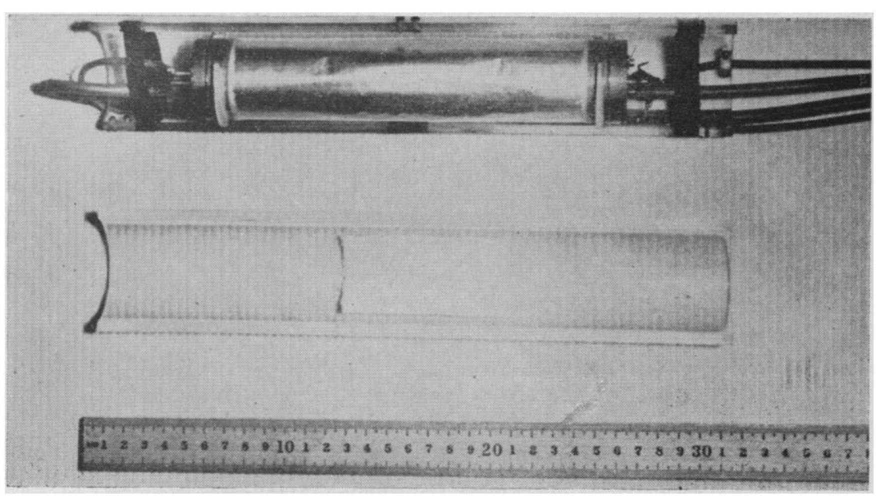


Fig. 5. Foil counter and sample holders.

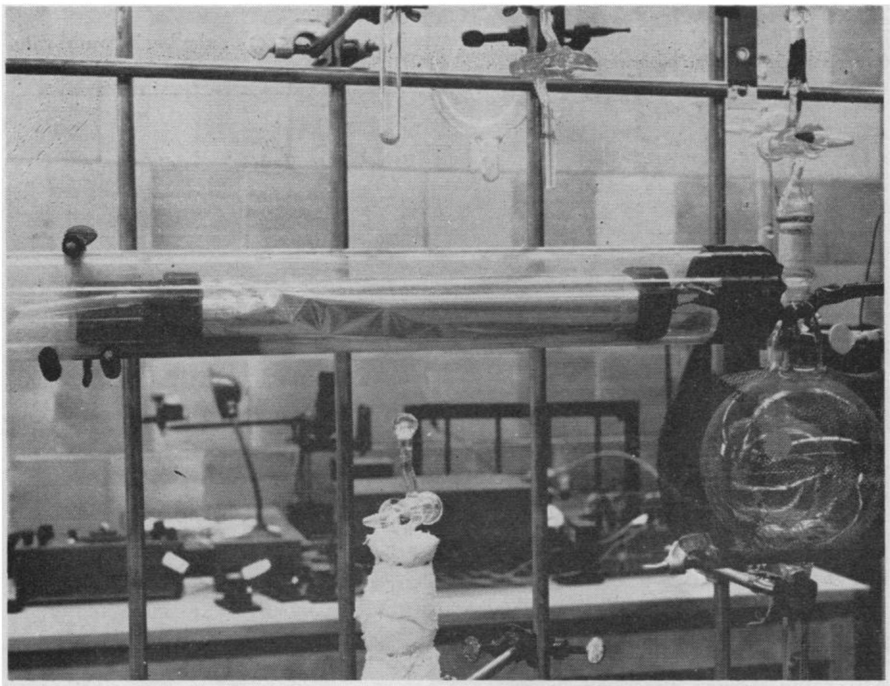


Fig. 6. The annular foil counter for gas samples.

Mylar foil from the other hemisphere, which operates as a Geiger counter with "Q" gas. For larger samples and for greater sensitivity, a cylindrical foil counter may be mounted inside a metal or glass jacket, as is shown in Fig. 6. The sample to be counted is introduced by flushing it into the annular space; alternatively, the annular space may be evacuated simultaneously with the counter before filling. During these operations, a simple mercury U-tube may be used to warn against a dangerous pressure differential. The relative simplicity of instrumentation and the lack of rigid purity specifications on the gas sample make this method desirable for many applications.

An interesting proportional counter using the thin foil between sample and detector is the Sugarman counter (*25, 26*). This device is a methane-flow proportional counter with a foil window. The precision design and the segregation of the counter gas give remarkably stable and reproducible operation. Plateaus are long, flat, and reproducible over years of operation; counts of a sample taken on two counters agree within statistics to 0.1 percent (*27*). For moderate-level counting and ordinary low-level counting of strong beta emitters, this counter is very useful.

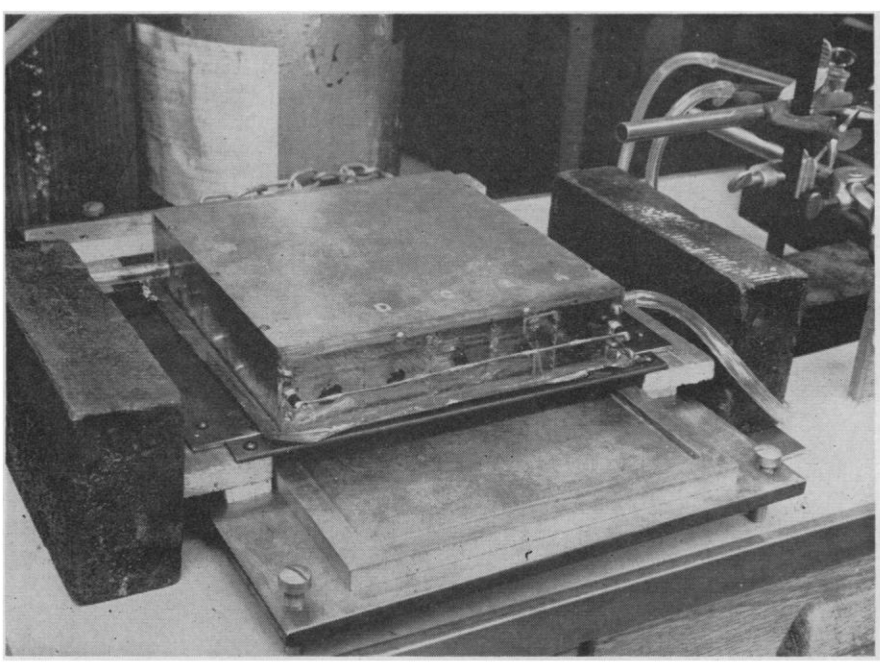


Fig. 7. A large area multiple-anode foil counter ("sandwich" counter).

Recently the foil window was combined with a multiple anode-wire cathode flow counter to provide a flat counter of active area of 400 square centimeters (*28*). For many types of samples, this counter, which we call a "sandwich" foil counter, simplifies sample preparation and mounting and provides the increased sensitivity of detection that is needed for routine low-level counting. By accurate leveling of the large sample holder, liquid samples can be conveniently measured. In the case of a weak beta emitter such as carbon-14, it is easy to operate with an "infinite" thickness of liquid and, in many experiments, to avoid the chemical conversions frequently needed with an ordinary area detector. A "sandwich" foil counter and sample tray is shown in Fig. 7.

The various gas-tube counters described here are compared and summarized following a discussion of the low-level scintillation detectors.

Low-Level Scintillation Counting

In recent years, improvements in photomultiplier tubes (*29*) have made possible low-level counting with scintillation devices. In general, the advantages of scintillation detectors over gas-tube counters depend on the greater stopping power of a crystal for gamma rays and on the larger inherent sample-handling potential of liquid scintillators for beta radiation. The principles of the scintillation counter have been reviewed extensively (*29, 30*). The applications to low-level counting are discussed here in terms of the low-level sodium iodide scintillation spectrometer for gamma radiation and the multiple-channel liquid scintillation spectrometer for beta radiation. The single-channel liquid scintillator is mentioned briefly.

In low-level gas-tube counting, the reduction of the background rate was accomplished by massive shielding and by anticoincidence meson shielding. In low-level scintillation counting, some massive shielding is also used. In addition, pulse-height analysis by at least two discriminators electronically discards the meson counts and, in many applications, the background events of energy different from the counted pulses. In view of the energy discrimination, less massive shielding is required in many applications. The most satisfactory shielding material is mercury (*31, 32*).

Low-level scintillation spectrometer. For low-level gamma counting, an ordinary sodium iodide scintillation spectrometer is modified in two ways. First,

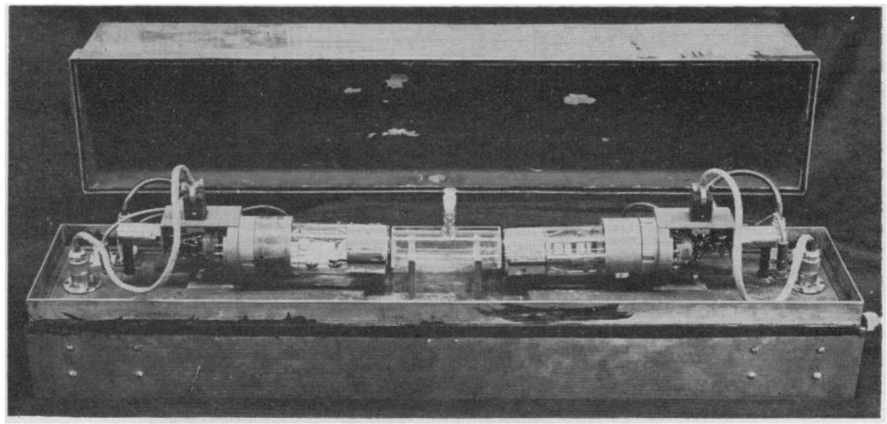


Fig. 10. A simple dual-channel liquid scintillator.

the crystal is surrounded with the mercury shield. Second, the electronic circuits are designed for maximum stability. It should be possible to focus on a photopeak and remain there during at least 48 hours of counting. Particular attention must be given to the long-term stability of the high-voltage supply that operates the photomultiplier tube. For many measurements, this tube should have a low thermionic noise rate at room temperature.

Several studies have been made using instruments of this type. Arnold's discovery of beryllium-7 in nature (*33*) and his measurements of lutetium-176 (*34*) and our tracer study with chromium-51 (*35*) are examples. In the latter study, with only moderate attention to low-level detection, the counting rates were 20 times higher with the scintillation spectrometer than with a Geiger counter. Another study was made using iodine-131 for the measurement of a very slow reaction (*36*). This apparatus is shown in Figs. 8 and 9. The mercury shield is clearly visible; in Fig. 9, it contains a liquid sample. When a reasonable amount of this tracer was used, the limit of detection with the low-level scintillation spectrometer gave a theoretical limit of greater than 10^6 years for measurable half-reaction. In this study, the counting rate of a liquid sample containing the iodine-131 was 100 times greater in the scintillation spectrometer than it was in a Geiger counter of the same size and geometry as the sodium iodide crystal. Of course, the efficiency of detection will vary with the energy of the gamma radiation. At energies up to 200,000 electron volts, the efficiency of a 1-inch crystal is 100 percent; at 300,000 electron volts, it is about 75 percent; and at 1 million electron volts, it is approximately 10 percent (*37*). Of course, an efficiency approaching 100 percent can be obtained with any reasonable energy by the use of a large enough crystal.

Liquid scintillators. The development of low-level liquid scintillators was carried out chiefly by Hayes and his collaborators at Los Alamos (*38, 39*) and by Arnold at the University of Chicago (*39, 40*). In liquid scintillation counting, the sample is simply incorporated in solution with a liquid scintillator. This arrangement gives essentially 100 percent geometry and no self-absorption. Unfortunately, the decreased efficiency of liquid scintillators over solid scintillators and the desirability of detecting the lower energy pulses of beta spectra require the measurement of "equivalent electron" pulses or those pulses that result from single-electron emission from the photocathode of the photomultiplier tube. These pulses, however, are indistinguishable in size from the thermionic pulses of the tube. This problem is solved by the use of two photomultipliers looking at the solution. By placing the pulses from the two channels in coincidence, it is possible to accomplish a large discrimination against the separate random thermionic pulses of each tube. In addition, some cooling is required, usually to a temperature of –20°C. Such an arrangement essentially eliminates tube noise provided that fast electronic circuits are used (*41*). Our apparatus is shown in Fig. 10.

Although the choice of the liquid-phosphor solution depends somewhat on the choice of the photomultiplier, an excellent solution consists of 2,5 diphenyloxazole as the primary solute and 1,4 di(5-phenyl-2-oxazolyl)benzene as the secondary solute or wave-length shifter in toluene. The sample to be counted is incorporated in this mixture and must not quench the scintillation. Although solutions can be prepared to count almost any beta emitter, the cost of this instrument is not usually justified except for the measurement of weak beta emitters. Thus the counting of tritium and carbon-14 has received much attention (*26, 38–42*). Tritium can be counted in the form of water added with alcohol to the afore-mentioned solution or, alternatively, by the procedure of Nir (*43*). Here the THO is mixed with fuming sulfuric acid (or SO_3) and toluene. The tritium enters the toluene by exchange, and the latter is separated and used for the solvent of the scintillation solution. With carbon-14, the choice of this method may depend on the chemical form of the sample. One of the advantages of the multiple-channel, liquid scintillator is the unlimited size of the sample that can be accommodated in principle. Thus Reines and his collaborators at Los Alamos have constructed an instrument containing 300 liters of scintillation solution (*44*). In this counter, which was used in a search for direct evidence of a neutrino reaction, 90 photomultipliers were used to detect the scintillation pulses. An even larger liquid scintillator assembly was used by this group in the recent observations of a neutrino-induced reaction.

In regard to the sensitivity of the dual-

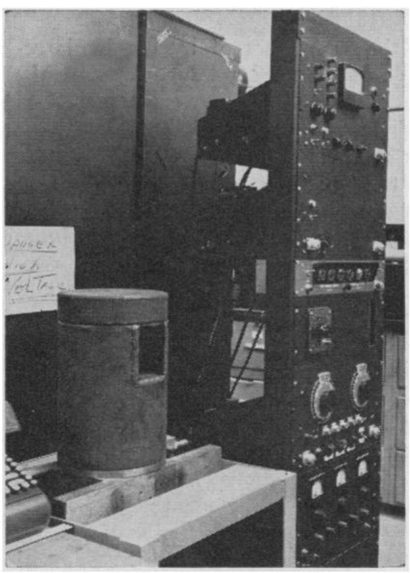


Fig. 8. A low-level scintillation spectrometer.

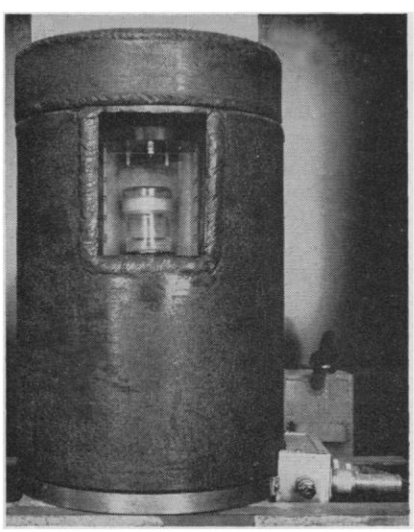


Fig. 9. Mercury shield and sample holder of the low-level scintillation spectrometer.

channel liquid scintillator, Arnold obtains an absolute efficiency for carbon-14 of about 60 percent for a 30-milliliter solution containing approximately 50 mole percent of carbon (*45*). The counting rate was 70 counts per minute against a background of 12 counts per minute. In the same instrument, the efficiency for tritium was much less, approaching 25 percent.

An interesting technique developed by Hayes and others at Los Alamos for measuring solid samples is to suspend a fine precipitate in a liquid scintillator. Although surprisingly high efficiencies are obtained, the problem of decreasing counting rate with settling indicates a preference for the technique of Helf and White in which the suspension is stabilized by the formation of a gel (*46*).

The possibility of using a single-channel liquid scintillator for low-level counting has been examined by Pringle and coworkers with considerable success in radiocarbon dating (*42*). It is clear, however, that the photomultiplier tubes used were better in terms of lower thermionic noise than any ordinarily available today. The widespread use of this method for carbon-14 must await the development of a better commercial photomultiplier tube.

One interesting potential of both liquid and solid scintillation counting is the possibility of multiple tracers. For example, with a sodium iodide scintillation spectrometer, the photopeaks of such tracers as chromium-51 and iron-59 can be separated (*47*). With the liquid scintillator, tritium and carbon-14 can be counted simultaneously (*26*).

Applications and Conclusions

In choosing a low-level counting method for a specific job, a number of factors must be considered. Some of these are the type and energy of the radiation, the size of the samples that are available, and the degree of sensitivity required. In Table 2, the low-level instruments for beta counting are summarized according to these factors. Weak beta emitters are nuclides such as carbon-14 and sulfur-35; strong beta emitters are phosphorus-32 and silver-111. Tritium is not included in Table 2. In tracer studies with tritium, the suggested method is the internal-gas counter. In moderately low level counting of tritiated water, a convenient procedure is to count as acetylene gas (*48*). In extremely low level counting, hydrogen is counted in a Geiger counter (*12*). In special cases a dual-channel liquid scintillator can be used, or else the method of Bernstein and Ballantine can be modified to include anticoincidence background reduction (*49*).

For counting a gamma emitter, the low-level scintillation spectrometer is used. In cases where the tracer emits both beta and gamma radiation, it is sometimes more convenient to measure the gamma radiation with this instrument, because of self-absorption of the beta radiation.

The present-day commercial availability of low-level counters is unsatisfactory, but it is steadily improving. Several companies are offering several of these instruments or their components. A complete gas-tube low-level counting assembly with provision for Geiger and proportional counting in our laboratory is shown in Fig. 11. A similar assembly will be offered soon by at least one manufacturer (*32*).

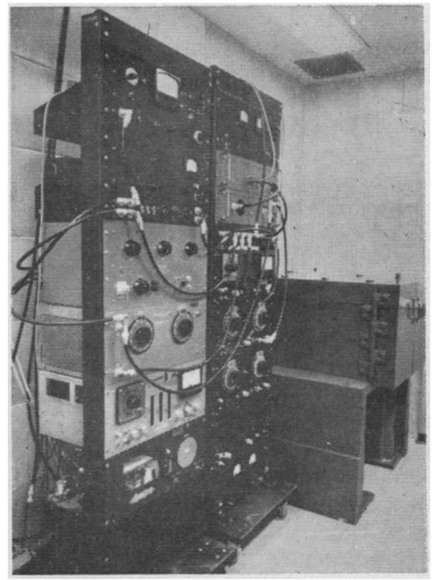


Fig. 11. A complete low-level counting assembly.

Tracer Applications and Low-Level Counting

Several reviews indicate the great diversity of tracer applications (*50*). In research, the chief studies involve self-diffusion, reaction mechanisms, surface phenomena, isotope effects, kinetics, and isotopic-exchange reactions. In all of these applications, low-level counting is potentially valuable. In some cases, the increased sensitivity is important scientifically. In other cases, the total amount of radioactive material needed can be decreased.

The use of industrial tracers for development and control is in an early stage of development. There are many direct applications of low-level counting in the many uses of tracers for large-scale labeling of products and in the tracing of oil fields. A great variety of radioisotopes provides valuable methods for measuring flow rates, volumes, flow patterns, mixing rates, and chemical arrangements and for making identifications. Recently some of these techniques were described for use in refinery control (*51*). Although some of these uses cannot tolerate the long counting times of extremely low level counting, the principles of low-level counting are important to all these applications.

One of the obstacles to the large-scale industrial use of tracers is the problem of residual radioactivity in the final product. One solution to this problem is the use of tracers of short half-life. By extraction techniques, short-lived daughter products can be conveniently obtained from long-lived parents. Thus, iodine-132 (half-life, 2.4 hours) can be "milked" from tellurium-132 (half-life, 78 hours). Such procedures can be made automatic by the use of continuous extraction methods. Thus, in the control of flow patterns and mixing rates, one could use a steady-state injection of the short-lived tracer.

Another solution to the problem of the residual radioactivity is the use of low levels of tracers. It is here that low-level counting is essential. A number of tracer studies using carbon-14 have counted the final samples as barium carbonate by using an ordinary thin-window Geiger counter. Under these conditions, a sample of contemporary carbon would be expected to show the immeasurable counting rate of 0.006 count per minute against a background of 20 to 50 counts per minute. With low-level counting, the same natural carbon would measure 7 to 150 counts per minute against background rates of 2 to 30 counts per min-

Table 2. Low-level beta counting.

Availability of sample	Low-level counting	Suggested counter	
		Weak beta radiation*	Strong beta radiation
Small	Moderate	Foil Geiger counter	Sugarman proportional counter
Small	Extreme	Internal gas Geiger counter	Libby screen-wall counter
Large	Moderate	Foil Geiger counter	Foil Geiger counter or Sugarman proportional counter
Large	Extreme	Dual-channel liquid scintillator or internal gas proportional counter	Libby screen-wall counter or multiple-channel liquid scintillator

* For example, carbon-14 or sulfur-35 (not including tritium).

ute. In this example, low-level counting would make possible a factor of 10^{-4} or better in the necessary residual radioactivity.

One of the questions concerning the realization of the potential future of large-scale industrial tracers is the danger of the residual radioactivity to the consumer. The natural tracer experiments with tritium and carbon-14 indicate the answer. Consider the use of tritium as a tracer in the petroleum industry—for example, in the tagging of oil for identification of leaks from underground storage. Even if a world output of 7×10^9 barrels of oil per year were tagged at a measurable level of 10^{-6} curie per barrel, the steady-state increase in the world inventory of tritium would be less than 1 percent. Even the maximum transients in water would be less than 0.5 percent of the maximum permissible amount (*52*) of tritium in water. In the case of carbon-14, the entire world output of sugar could be regularly tagged at the easily measurable level of 10^{-11} curie per gram of carbon with a corresponding maximum increase of only 0.1 percent in the world inventory of radiocarbon. It is clear that with reasonable care and modern instrumentation, safe large-scale tracer operations can be realized.

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Electronics for Measuring Human Motions

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Measuring the performance of people at various work activities has been an essential task in many fields, both academic and industrial. Physiology, psychology, and physical education are some of the academic endeavors requiring a measure of output or performance of persons for purposes of studying relationships to various factors. For example, the physiologist wants to measure the direct result of some muscular activity that he may be studying, in order to correlate the two results. The psychologist in biomechanics wants to measure the output of a subject when he is trying to design man-machine relationships. The physical educationist should be able to make a complete measurement of every part of a tennis or golf swing.

Although industrial engineering is both an industrial function and an academic pursuit, most of the research problems stem in some way from problems in the industrial situation. A review of some of these problems will point out the essential necessity for measuring operator performance in industry and how the lack of suitable measurements has led to the development of a device which should help all activities concerned with human performance.

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