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APPLIED BETA DOSIMETRY*

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INTRODUCTION

The objective of this paper as a part of the Summer School on External Dosimetry is to discuss Beta Dosimetry from an applied perspective. Most of the fundamental concepts relating to external dosimetry should have been discussed, hence only those fundamental aspects directly related to an understanding of the applied concept being discussed will be reemphasized.

As with any area of science, some aspects of external dosimetry are more simple than others. Beta dosimetry is an area which presents major problems--for reasons which will be discussed in more detail in this report.

Past Practice

Because of the difficulties associated with beta and/or nonpenetrating radiation dosimetry as well as a lack of understanding of these difficulties, many of the past practices have been less than desirable. For example, though film and TLD chips (the most common TLD dosimeters for many years) demonstrate dramatic energy dependent responses, personnel dosimetry results under various filters were accepted as the dose to tissue at the equivalent depth. In other situations field surveys were used to verify that the beta or nonpenetrating component of the radiation fields in the work place were not "limiting" and then were simply "ignored" or not measured/recorded. An evidence of the lack of consistent nonpenetrating data is demonstrated in several reports which summarize penetrating exposure only. [EP(84)]

Dose Limits

Nonpenetrating dose limits have changed through the years more than those related to penetrating or whole-body dose. In addition, there are different "skin" dose limits in DOE (15 rem/yr) as compared with the NRC (30 rem/yr) limit. Further, there is a difference in defining the depth at which the germinal or sensitive skin cells exist (NCRP establishes 7 mg/cm^2 as the critical depth while ICRP uses a depth between 5 and 10 mg/cm^2). Experimental results tend to indicate a lack of dose response at depths more shallow than 40 mg/cm^2. All of this has resulted in rationalizing less concern for accurately detecting and monitoring the beta dose--particularly when the lack of technology available made measurement imprecise and difficult.

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Accuracy of Recorded Dose

As previously stated, past dosimetry systems were designed with an apparent lack of complete understanding and complicated by criteria intended to provide conservative results. This has resulted in some degree of uncertainty in recorded personnel dosimetry results (generally conservative) in a few situations. As an example, a "standard" badge design for use in the nuclear power field was a two-chip TLD badge with a 30-40 mg/cm nonpenetrating filter and a penetrating filter in the 300 mg/cm^2 range. The first filter was a practical minimum thickness and was used and calibrated to provide a calculated 7 mg/cm^2 dose. The second filter was intended to provide a measure of the penetrating dose to the lens of the eye and further conservatively assume that dose to organs at deeper locations would receive the same exposure. However, the more energetic beta particles penetrate the 300 mg/cm^2 filter and record a dose at efficiencies dependent upon the energy of the particles which reach the detector. Table 1 indicates the results of a laboratory calibration of a typical two-chip badge with varying ratios of beta to gamma radiation fields. Note that the badge would record penetrating doses up to 20 times the actual dose depending on beta to gamma ratios and the calibration source used to establish the badge conversion factors. The two times high values for Sr/Y-90 beta exposure results from using a uranium calibration.

Another example to illustrate personnel dosimetry uncertainty in extreme cases is demonstrated in Table 2. This example is taken from an actual job at a chemical processing plant using a "standard" two-chip TLD badge with a 9 mg/cm^2 "open" window and approximately 600 mg/cm^2 shielded (penetrating) chip. This is a better design in the fact that the nonpenetrating chip has a much thinner filter and a thicker penetrating filter for the other chip. However, the inconsistencies in the data obviate the problem. Each reading represents the exposure results for an individual worker each of whom worked in the same field on the same job. Direct Reading Dosimeters (DRD) have stainless steel walls of approximately 280 mg/cm^2. It is of interest to note the lack of consistency in nonpenetrating (NP) to penetrating (P) ratios and the DRD to P ratios. These variations occurred as a result of differences in worker orientation to the source, angular response, spectral shift, etc. In any event, the frustration of an Applied Radiation Safety Technologist in estimating/predicting personnel exposures and the questionable accuracy of the recorded exposures should be obvious.

Recent Efforts to Upgrade Capabilities

These inconsistencies and the difficulties in providing adequate control programs in high nonpenetrating, mixed fields have been a concern of radiation protection professionals for many years. Applied radiation protection personnel have developed a variety of "rules-of-thumb" techniques to provide a conservative program and assure personnel protection within the limits. Instrumentation and dosimetry development has also progressed with improvements and upgrade demonstrated. However, high uncontained mixed fission product fields at TMI following the accident resulted in several incidents which focused attention on the lack of technology and resulted in an accelerated development program. The following is a partial listing of the most recent concerted development efforts within the international radiation protection community:

1.	Beta Dosimetry Workshop at EML	12/81
2.	Beta Dosimetry Technical Session and Continuing Education Session at Las Vegas - Annual Health Physics Society Meeting	06/82
3.	International Beta Dosimetry Symposium, Washington, D.C.	02/83
4.	Portable Instrument Workshop, Knoxville, TN	05/84
5.	International Beta Dosimetry Symposium, Paris	10/85
6.	DOE Beta Dosimetry Workshop, Albuquerque	03/86.

Major improvements and technology advances have resulted as a consequence of the cooperative development programs within DOE, NRC and international programs. Some of these recent advances and current capabilities are discussed later in this paper.

FUNDAMENTALS REVIEW

Several fundamental concepts should be reviewed briefly in order to lay the foundation for further discussion.

Beta Spectra

Each radionuclide decays in a unique manner, and may emit a variety of betas with different end point energies. However, even the betas from isotopes with a single energy decay scheme (see Figure 1) are emitted as a continuum of energies. The energy listed for each beta represents the maximum or endpoint energy of the continuum. Thus the betas from the most simple (single decay scheme) nuclide are emitted in a complex spectrum. Some isotopes (see Figure 2) decay in a variety of ways and the total spectra is a combination of the different continuum. In field conditions a variety of isotopes (mixed fission products, for example) may be encountered thus resulting in an even more complex spectra.

Beta Absorption

Beta particles are relatively easily shielded. As little of 2-3 gm/cm^2 shielding will stop the most energetic beta particles normally encountered (see Figure 3), and even a few inches of air can provide significant attenuation for lower energy beta particles (see Figure 4). Figures 5 and 6 also demonstrate the spectral shift resulting from relatively small amounts of shielding. Figures 7 and 8 demonstrate the shift of both endpoint energies and average energies of simple spectra from single isotopes.

Beta vs. X-Rays

Low energy photons in the few tens of keV range can also be considered "nonpenetrating." It is well known that most instruments and dosimeters exhibit nonlinear response to photons below 200 keV (see Figures 9 and 10). Typical fields in the work place have significant low energy photon components which make mixed field dosimetry increasingly complicated.

Tissue Equivalency

Of primary concern in any personnel dosimetry system is to obtain measurements which can be converted to dose received by the human tissue of concern. Figure 11 shows another area of concern--that of the variability in air vs. tissue dose for photon radiation as an example. For this reason dosimetry results and instrument readings generally require conversion factors to convert the air dose to tissue dose or provide "tissue equivalent" response. The ideal detector would be tissue equivalent, and many attempts have been made to design this equivalency into the detectors. However, even plastic scintillation detectors (some of which are very nearly equivalent) do not respond precisely as tissue.

Dose Limit Considerations

Nonpenetrating or skin dose limits are currently being changed from 15 rem/yr (DOE) and 30 rem/yr (NRC) to 50 rem/yr (recommended by the ICRP). Obviously this increase in permissible dose to the skin will decrease the number of work places in which skin dose will be limiting.

Currently an NCRP subcommittee is reconsidering biological effects data to determine if it is justified to define the sensitive skin tissue to be at a depth below 7 mg/cm^2 (40 mg/cm^2 is a depth being considered). A change of this type would also reduce concern for skin limits being "controlling."

However, as indicated briefly in the introduction, it is necessary to measure the nonpenetrating component in order to accurately measure the penetrating component, which is recognized to be the more biologically significant concern. There have already been skin melanoma causation cases raised; hence it is anticipated that there will be future occupational injury skin cancers claimed to result from skin exposures to nonpenetrating radiation. Thus it is considered essential from these two considerations to develop technology and techniques for measuring the skin dose.

Typical Work Place Radiation

Figures 16 to 21 are beta spectra taken from a variety of work places, showing the type of radiation fields which can be expected. Though the makeup of the radiation fields in a specific facility may be fairly consistent from time to time, it is important to recognize that spectral shifts will occur as a function of 1) distance from the source, 2) the matrix of the sources (water, dirt, etc.), 3) orientation of the worker to the source, etc.

PERSONNEL DOSIMETRY

The purpose of personnel dosimetry is to record the energy deposited in the dosimeter which can then be related to the energy which would have been deposited in tissue at a depth of interest. The primary interest in beta dosimetry is the dose to the layer of tissue between 5 and 10 mg/cm^2 (the "skin" dose), and the dose to the lens of the eye at approximately 300 mg/cm^2. Since the eyes can be protected from beta radiation by relatively thick materials in respirator masks or safety glasses, the skin dose may be the principal concern in the average applied situation.

As personnel dosimetry principles have been discussed in previous lectures, this discussion will be limited to application considerations only. Since the personnel dosimetry results become the "legal" dose records and the values by which personnel exposures are controlled, it is important to understand the characteristics and limitations of the dosimeter in use. Hence it is important to recognize the major sources of error in any personnel dosimetry system:

- Energy response
- Angular response
- Mixed field response
- Badge placement considerations.

Energy Response

The magnitude of energy response variations is detector-dependent and can range from unity to over a factor of 20. Thin dosimeters generally demonstrate less variation. Tissue equivalency is a concern, since dose deposition in tissue is also energy dependent. The conversion of a dosimeter response to an equivalent dose in tissue at a specified depth requires detailed knowledge of the energy response curves of both the dosimeter and tissue and the spectrum of the radiation in the field.

Angular Response

Angular response is a source of error for both personnel dosimeters and survey instrumentation. Again a thin layer of tissue will have a definite and characteristic angular response which should be matched by the ideal dosimeter and/or detector. The magnitude of the angular response variation is in the 20-40% range maximum. However, the beta angular response can be greater for badges which are not well designed.

Mixed Field Response

When a mixture of betas and photons of various energy spectra are present, a complex dosimetry problem exists. Figure 2 illustrates the possible magnitude of this source of error resulting from poor design and a lack of source characterization.

Badge Placement Considerations

Standard practice in the field requires placement of the personnel dosimeter on or near the part of the body (excluding the extremities) which is expected to receive the highest exposure. Typically the indicated dose is recorded as the whole-body dose. This practice is designed to be "conservative" and produces personnel dose values generally greater than the dose received by many of the organs of concern. Badge placement can result in inaccurate (low) results if the worker orientation to the source is such that the badge is effectively shielded by the body. This is particularly important in the case of exposures to nonpenetrating radiation.

Current Approaches

Several relatively recent badge design changes have increased the ability to better define the correct tissue dose at various depths. Multifilter chip badges establish an "effective" nonpenetrating energy which allows selection of a calibration factor more appropriate for the actual exposure received. Other thin detector (15 mg/cm^2 TLD powder, for example) badges are available which reduces the variability in the calibration factors resulting from energy dependency. Continued investigation into badge and detector design to produce a more "tissue equivalent" response is continuing. [Si(86) and others]

PORTABLE SURVEY INSTRUMENTS

The use of survey instruments can be categorized as follows:

1.	Detection/search	For this purpose the instruments are designed with maximum sensitivity in order to make detection at low levels fast and sure
2.	Relative response	This purpose requires evaluation of existing radiation fields to determine change from the previous survey(s). For this purpose consistency is of greater value than accuracy, if there is assurance that the radiation source is being detected.
3.	Exposure control	For this purpose survey instrumentation must provide accurate results and be consistent with personnel dosimetry results.

Number 3 is the primary use of interest for purposes of this report.

It is relatively easy to design a radiation survey instrument capable of measuring the deep penetrating tissue dose due to high energy photons and electrons. There are a number of commercially available survey meters and personnel dosimeters which accomplish this task with acceptable accuracy. On the other hand, designing an instrument to measure the dose equivalent to the skin at a tissue depth of 5-10 mg/cm^2 is a much more difficult problem, particularly in complex fields composed of a combination of penetrating and nonpenetrating radiation. Window thickness, detector size, as well as the effective thickness and materials of the detector, are critical parameters for this measurement.

Standard Survey Meters

Thin window air ion chambers are widely used. These dose rate survey meters typically are equipped with a beta filter to differentiate between the "penetrating" and "nonpenetrating" components of a mixed beta/gamma radiation field. A beta/gamma survey meter normally is calibrated with a standard Cs-137 photon source so the meter will read the correct 1 cm (D10) tissue dose rate with the beta shield in the closed position.

When used in the field the ion current generated in an air chamber survey meter with the beta shield in the open position is due both to photon interactions within the sensitive volume and to the residual beta energy deposited after the betas have traversed the thin entrance window. Beta particles with incident energies less than about 70 keV cannot penetrate the typical 7 mg/cm^2 thick aluminized Mylar windows used in most portable survey instruments. Beta energy loss per unit path length (dE/dx) is strong function of the beta energy, with the energy deposition greatest near the end of the path. Since the residual range of the lowest energy beta particles that successfully penetrate the window can be less than the chamber depth, the energy deposition and resulting radiation dose can be quite nonuniform over the chamber depth even when the total air thickness is only a few centimeters. Ion chamber meters average the energy deposited over the entire air mass of the sensitive volume which results in a lower average dose rate for the lowest energy betas than is actually deposited in the first few mg/cm^2. Consequently the meter reading of the "standard" air ion chamber survey meter, when it is exposed to a mixed beta/gamma radiation field with the beta shield open, is neither the deep penetrating D(10) dose rate nor the true skin tissue D(0.07) dose rate.

Some nuclear installations simply report the ratio of two meter readings taken with the beta shield open and closed as the ratio of the nonpenetrating to penetrating dose. If a beta correction factor has been determined empirically by standard beta sources or from personnel dosimeter readings, a corrected reading representing an estimate of the D(0.07) dose rate may be reported. Such values range between 2 and 4 and will be reasonably accurate if the energy spectra of the beta radiation fields actually encountered are consistent and/or similar to the energy spectrum of the calibration standard. This is seldom true in practice.

At the present time the Eberline Model RO-2 thin window ion chamber is one of the most widely used instruments for surveying potentially hazardous beta radiation fields in U.S. nuclear facilities. The detector for this instrument is an ion chamber which has a window diameter of 7.6 cm, a window thickness of 7 mg/cm^2, and an effective air thickness of about 5 mg/cm^2. Since this instrument is commonly used and utilizes a chamber of typical size and design, it was used in the comparisons which will be discussed.

Dual Ion Chamber

A dual ion chamber instrument (HP-1075), designed at the INEL and manufactured by Health Physics Instruments, overcomes some of the problems encountered in monitoring complex fields. In this survey instrument the side walls and front window of the first ion chamber are constructed from 7 mg/cm^2 foam plastic providing an excellent angular response of greater than 2 π steradians. The second ion chamber, located directly behind the front ion chamber, is completely enclosed with approximately 1 g/cm^2 bakelite walls to shield the nonpenetrating component. Both chambers have identical volumes of 300 cm^3. The first chamber responds to the ion current generated by both nonpenetrating and penetrating radiation, while the second indicates the penetrating radiation response only. The second chamber is calibrated by standard photon sources to read the D(10) tissue dose rate, while the first chamber is calibrated to a D(0.07) dose rate using an intermediate energy beta source such a Tl-204. As a beta survey meter, the HP-1075 has the advantages of a larger diameter window and relatively shallow air volume with high angular response. It provides shallow and deep dose readings simultaneously with reasonable accuracy, provided the nonpenetrating/penetrating ratio is high and the beta energy spectrum corresponds roughly with the Tl-204 spectrum. This instrument is also used as a reference point in field calibrations which are presented in the intercomparisons in Figures 12 through 21.

Plastic Detectors

The beta dose to skin tissue is defined as the dose to a thin layer of basal epithelial tissue lying at an average depth of 7 mg/cm^2 or as the dose to the skin tissue lying between 5 and 10 mg/cm^2.

As previously indicated, low energy betas are important in skin dose considerations and are less accurately measured by standard ion chambers. The ideal detector would duplicate a thin (5 mg/cm^2) tissue thickness. It was these considerations, and the beta scattering considerations, that led J. L. Alvarez to initiate the effort at the Idaho National Engineering Laboratory toward the development of a tissue equivalent (TE) survey meter.

The INEL tissue equivalent survey meter was designed to duplicate as closely as possible the absorption and scattering properties of the important skin tissue layers. The detector is a 5 mg/cm^2 layer of tissue equivalent plastic scintillator covered by approximately 5 mg/cm^2 aluminized Mylar window and backed by 1 cm thickness of tissue equivalent plastic which has not been doped with scintillation phosphors. The backing material serves as a light pipe to transmit the UV scintillation photons to the photocathode, and also simulates the beta and x-ray backscattering properties of the deeper lying tissues. The energy deposition in the plastic scintillator is the average dose delivered by both betas and photons to the layer lying between 5 and 10 mg/cm^2.

Unfortunately the actual output pulses of the photomultiplier tube are complicated by a direct response to x-ray photons in the photocathode and dynodes, and to certain particle interactions that occur within the light pipe and PM tube window. Higher energy betas easily pass completely through the thin plastic scintillator with little energy deposition and some produce Cerenkov light in the light pipe. Very energetic Compton electrons from higher energy photon interactions in the detector or light pipe also can produce Cerenkov light. These are problems associated with very thin plastic scintillator detectors that otherwise would not be of as much concern for thicker detectors.

The Cerenkov and direct response photomultiplier output pulses rise and fall with the inherent response time of the PM tube circuitry, while the scintillation pulses exhibit a decay of a few nanoseconds. Very fast pulse shape discrimination circuitry, with consequent high power consumption, is required to reject the unwanted Cerenkov pulses and direct response pulses while retaining the majority of the scintillation pulses. To accomplish this discrimination each output pulse is fed simultaneously into separate circuits, one of which involves a delay line of approximately 30 ns to provide time for rejection of that pulse if the shape discrimination circuit indicates the pulse length is too short to be a scintillation event. A complete description of the pulse shape discrimination circuitry has been published earlier. [Jo(78)]

Thin Ion Chambers

Work with very thin ion chambers has produced encouraging results and may provide a simple approach to providing acceptable accuracy in field situations. C. L. Graham of LLNL modified the Eberline Model RO-2 and the Victoreen 471 survey instruments as indicated in Figure 22, resulting in a 1 cm thick ion chamber (with 1 mrem/hr sensitivity). The Figures 23-28 illustrate the dramatic improvement in response through utilization of thin chamber designs. However, a thin ionization chamber alone will not guarantee an accurate instrument. The Eberline RO-7 beta/gamma detector is an instrument with a thin collecting volume, but the instrument is energy and directionally dependent. The entrance window is recessed in the instrument, and consequently the sensitive volume is shielded from betas coming from large angles. The diameter of the RO-7 sensitive volume is somewhat too small, which also causes excessive shielding from the chamber's wall. (The area of the wall is proportional to the chamber's radius, whereas the chamber's volume is proportional to the radius squared.) The modified RO-2 and 471 have much better directional and energy response than the RO-7. Hence a thin detector with attention to chamber design to assure an acceptable angular response, etc., can offer excellent response. [Ha2(82)]

Field Tests

The response of the INEL portable TE survey meter has been tested and compared in radiation fields at a variety of facilities, including a fuel reprocessing plant, a uranium metal fabrication plant, and several power reactors. Except in a few locations in these plants, the penetrating tissue dose due to photons is "limiting," rather than the nonpenetrating beta plus gamma dose to the skin. Examples of locations where the beta skin dose is limiting include the handling of U metal parts, spills in which radiation fields from exposed fission products are present, and exposed internal surfaces of areas such as steam generators in power reactors. Although it was not practical to make extrapolation chamber measurements in each high level work site, "calibration" and intercomparison was made using contamination removed from the work site locations. Thus the relative response of the instruments and dosimeters being evaluated was obtained in fields representative of those encountered in the work place at each facility.

Reference to Figures 12-2' [illegible] cates that when compared to single isotope laboratory sources ranging from Pm-147 to Sr-90/Y-90 beta spectra, the TE survey instrument is in good agreement with extrapolation chamber values. The RO-2 ion chamber meter readings typically were a factor of 2 to 3 lower than the extrapolation chamber D(0.07) values. The HP-1075 dual ion chamber also indicated values in fair agreement with the extrapolation chamber.

SPECIALTY INSTRUMENTS

Extrapolation Chambers

The ion current generated in the air volume of an ion chamber obviously depends on the path length of the beta particle within the sensitive volume, and on the dE/dx of the incident beta particle. Most ion chamber survey meters have thick side walls which effectively shield much of the sensitive volume from betas which approach at high off-axis angles. Such instruments will have an angular response that is determined largely by the effective cross-sectional area presented to the parallel beta flux incident at each angle off-axis. This leads to a cos θ angular response, where θ is the angle of incidence with respect to the chamber axis.

On the other hand an extrapolation chamber is a very thin air ion chamber with air walls. The diameter of the entrance window is much larger than the diameter of the sensitive volume due to the guard ring construction. Extrapolation chambers have been selected as the primary standard for beta dose measurements because the very thin air cavity is surrounded by tissue equivalent materials in a geometry that satisfies the Bragg-Gray principle. The extremely small depth of the air cavity of extrapolation chambers makes the angular response of this instrument quite different from the angular response that characterizes most commercial survey meters. A beta particle incident on the thin air cavity at large off-axis angles will travel diagonally across the cavity until its range is exceeded or it is scattered out of the sensitive volume. A particle incident normally on the window will have a relatively short path length through the thin cavity. The path length of a beta particle within the thin cavity then becomes a secant function of the angle of incidence provided scattering is ignored. This will be true for any thin detector.

Angular Response

The angular response of an extrapolation chamber of the same design as those used by the PTB and the U.S. National Bureau of Standards has been measured experimentally in a parallel beam of beta particles from the Amersham-Buchler Sr-90/Y-90, Tl-204, and Pm-147 beta sources. Air scattering is expected to be small for the higher energy betas but not necessarily small for the lower energy betas in each source.

The relative angular responses of the extrapolation chamber to the three sources are shown as polar plots in Figure 29. The angular response of the chamber to Tl-204 beta particles follows the 2π response expected for a thin detector to beyond 50° off-axis. At larger angles the dominance of the cosine window dependence is apparent. The angular response to the higher average energy Sr-90/Y-90 beta particles has very pronounced side lobes extending beyond the expected 2π response resulting from a simple product of the secant and cosine functions. This added response probably is due to backscattering from the thick tissue equivalent piston material. Very energetic betas striking the chamber at normal incidence pass completely through the thin sensitive volume with very little energy deposition and penetrate deeply into the piston material. Some are backscattered for a second pass through the sensitive volume. Energetic betas which are incident on the chamber at 60° off-axis pass diagonally through the air cavity and penetrate less vertical distance into the piston. These betas have a higher probability of scattering back into the sensitive volume than those that penetrate deeper. The much weaker betas from the Pm-147 source are scattered by the 20 cm intervening air and by the window material resulting in fewer betas reaching the sensitive volume in the original direction. The angular response of the chamber to the Pm-147 betas is essentially that of the cosine window dependence.

Figures 30 and 31 show the experimentally determined angular responses of the Eberline Corporation Model RO-2A ion chamber survey meter and the Health Physics Instruments Model HPI-1075 dual ion chamber meter to the three beta sources. The RO-2A meter shows, as expected for a deep air ion chamber, an angular response that is confined well within the cosine dependence of the window. The HPI-1075 angular response exhibits a better response to beyond 90° because the front window and the side walls are constructed from thin styrofoam plastic. Both survey meters are deep air ion chambers and do not exhibit the enhanced off-axis response of thin detectors or the side lobes due to backscattering.

Since the INEL TE meter closely approximates the geometry of actual skin tissue, we have measured its angular response to off-axis betas with the assumption that the angular response will be very similar to that of skin tissue itself. Figure 32 indicates a very similar but not identical angular response to each of the three beta sources as those recorded for the extrapolation chamber.

The enhanced response of both the extrapolation chamber and the thin TE meter beyond the theoretical uniform 2π response indicated in Figures 29 through 32 suggests that backscattering by the materials located behind the thin sensitive volumes is a significant factor in the dose actually deposited in these detectors. The backscattered fraction of the dose would be expected to be a function of both energy and direction of the incident beta particles. These data indicate that the angular response to extreme off-axis betas should be a primary consideration in the design of commercial beta survey instruments, if these meters are expected to provide output readings that are equivalent to an extrapolation chamber.

Assuming the INEL TE meter approximates the true tissue response to off-axis betas, it follows that an extrapolation chamber also simulates the response of a thin tissue layer with sufficient accuracy to be the primary standard for determining the beta skin dose. Either instrument could be used for accurate measurements of the beta dose to the skin for a wide variety of field or laboratory sources. Field measurements can be made rapidly with the INEL TE meter while considerable time and effort are required for field measurements with a standard extrapolation chamber.

Since most commercial beta/gamma survey meters are very unresponsive to betas approaching at high angles off-axis, most commercial survey meters will underrespond significantly to the distributed beta sources typically encountered in the field. A possible exception is the HPI-1075 dual ion chamber meter which has good response to off-axis betas even though the angular response curve differs substantially from those of the extrapolation chamber and the TE meter. Commercial meters also tend to underrespond to the Amersham-Buchler Pm-147 secondary standard when the specified beam flattening filter is used, primarily because the betas reaching the calibrated detector location are approaching at high angles off-axis and because these meters have poor off-axis responses. Many investigators have interpreted this underresponse incorrectly as an energy dependence rather than lack of sensitivity to off-axis betas. As previously indicated it is possible to design a very thin air ion chamber with a large window that would have the angular response characteristics of the extrapolation chamber and the INEL TE meter.

Spectrometer

Only recently has it been practical to obtain beta spectra in the field. Several laboratories have assembled spectrometers using silicon surface barrier, plastic scintillation and other detectors. These portable beta spectrometers are useful for characterizing the beta energy spectra encountered in the field.

At the Idaho National Engineering Laboratory (INEL) an attempt has been made to extend the usefulness of portable beta spectrometers by incorporating features that also allow calculation of the D(0.07) tissue dose rate and the D(10) dose rate from spectra collected in a mixed beta/gamma radiation field at the work site. The spectra in Figures 12-21 were taken with a plastic scintillation detector spectrometer.

The key element of the INEL portable beta spectrometer is the 2.5 cm diameter by 0.9 cm thick tissue equivalent plastic scintillator (Bicron Corporation BC-470) used as the detector. This tissue equivalent detector responds to both betas and photons producing photomultiplier output pulses that are almost exactly proportional to the energy that would have been deposited in an equal volume of tissue by each particle interaction. These output pulses, after initial amplification by a preamplifier stage incorporated inside the detector module, are fed directly to a Nuclear Data Corporation ND-6 portable multichannel analyzer. The ADC of the ND-6 has been modified slightly to handle higher pulse rates.

In field applications two separate spectra are collected at each location, the first with an open window (1.8 mg/cm^2 of aluminized Mylar), and a second spectrum with a 1 cm thick lucite cap covering the window to shield the betas and allow the higher energy photon component to pass through with minimal attenuation. Spectra are recorded on the ND-6 tape cassette and returned to the laboratory for performing the dose calculations on an IBM personal computer.

Because the plastic scintillator detector is nearly tissue equivalent, the unfiltered spectrum represents the energy deposited by betas plus energy deposited by the Compton electrons resulting from photon interactions. The low effective atomic number of tissue essentially precludes photoelectric interactions above about 50 keV.

CALIBRATION SOURCES

Since all instruments are energy dependent to some degree and are designed to respond specifically to the various types of radiation, it is of considerable importance to choose the correct source to define or "envelop" the expected field conditions. The need to characterize the working field is also obvious in order that the proper source(s) can be chosen to provide a response calibration for the instrument applicable in the situation in which it will be used. The evaluation of the relative response of the field instruments and dosimeters is only possible if the proper choice of calibration sources is made. Energy response curves, etc., require a variety of sources.

Radiation Type

Typical fields in the work place can be "simple," such as those associated with a single radionuclide in a contained configuration or "complex," such as mixed radiations from a combination of radionuclides in a variety of configurations. In any event there are many types of fields possible depending upon the circumstances and a variety of sources are typically needed to provide a complete calibration.

Radiation Energy

Photon sources of the required energy spectra are provided by x-ray machines with specified filters or K fluorescent irradiators (below 300 keV) and isotopic sources, e.g., Cs-137 and Co-60 for MeV range energies. Beta fields are complex, and the calibration sources are generally radionuclides mounted with thin coverings. Recently electron accelerators have been used in an attempt to provide monoenergetic electron calibration fields for better defining the instrument response characteristics.

Calibration Intensity

Calibration intensities necessary to evaluate any given instrument could range from a few millirem/hr to greater than 100 rem/hr, depending upon the intended use of the instrument. Choice of the source and/or the calibration facility arrangement must take the intensities into account.

In addition high enough intensities must be provided to evaluate instrument linearity and saturation characteristics.

Source to Detector Geometry

A number of considerations should be taken into account in choosing a source to either reduce geometry dependencies or to evaluate such dependencies. Examples of these are summarized as follows:

- Point vs. distributed source
- Angular response characteristics of the instrument
- Partial instrument detector irradiation.

Traceability of Source Calibration

It is common practice to establish a "nondebatable" reference for establishing the calibration fields in a reputable facility. This is accomplished in several ways--examples of which ar listed:

- Sources are sent to the NBS for calibration
- Instruments are sent to the NBS for calibration. These instruments are then used to calibrate the facility sources/fields
- Sources or instruments are sent to a secondary calibration laboratory for calibration
- Instruments or sources are interchanged in an intercalibration program.

Contaminating Radiations

In choosing sources for calibrations it is important to understand that in the manufacture of sources it is possible to have contaminants. For example Cs-134 is a common contaminant in Cs-137 sources, and Pm-146 is a common contaminant of Pm-147 sources (see Figure 33). These are examples in which it is very difficult to remove isotopes of the same element. However the different energy radiation from the contaminants can completely change or distort the calibration even though the contaminant is present in small percentage amounts.

APPLIED TECHNIQUES

There are nontechnical but important aspects which determine utilization and/or acceptability of specific instruments for field use. One example is the use of digital vs. analog readout for portable survey instruments, which is discussed here for recognition of the principle only. The average health physics technologist prefers an analog readout for the primary reason that observing the meter movement provides immediate qualitative information regarding the field strength, variability of the field, etc. In many applications simply observing the meter movement characteristics allows evaluation sufficient without waiting for the reading to stabilize. This qualitative information is much less easy to obtain with a digital readout.

Physical weight, ruggedness, balance and the other human factor design features also make instruments of more or less utility and could lead to a difference in probability of error. These factors are important--in some cases (such as the analog readout consideration above) they could result in less time in the field and a resultant reduction in the total exposure received in doing the survey.

Surveys vs. Dosimeter Results

The characteristics or makeup of the radiation fields in the work place vary from facility to facility based on the materials being processed or handled and the facility design. Components of the radiation field can consist of any or a combination of particles and photons. The energies produced run the entire spectrum characteristic of the producing radionuclides or machines and become further changed through shielding interactions or scattering.

Each instrument and dosimeter responds to the radiation based on the instrument and detector design. However, the energy response may be different for each type of radiation (and variable), thus producing an inconsistency of response between instruments and dosimeters. This produces a number of concerns which may be summarized as follows:

- The ability to predict the response of the personnel dosimeter is limited, since the sensitivity of the survey instrument and the dosimeter to the radiation in the field are probably different.

- Even the ability to accurately repeat surveys from a comparative basis is limited due to changing response with changing spectra, which in turn changes with location or other field conditions.

Thus the design and/or selection and use of radiation detectors and instruments requires detailed knowledge of response characteristics and judgement in application. Applied personnel develop "rules-of-thumb," "favorite instruments," and unique techniques for each situation based on detector response experience. However, with response varying up to an order of magnitude it is not unusual in complex, mixed-field situations for the field radiation control personnel to be "surprised" by significant amounts, i.e., the predicted dosimeter result considerably different than expected. As a general rule this has resulted in significant conservatism in control techniques. The conservatism has taken the form of more frequent change of work crews in order to verify the reading on the dosimeter before allowing further exposure of the individual worker. This approach or procedure results in an increase in "nonproductive" exposure.

In addition the dosimeter response design has generally produced conservative results on a routine basis, i.e., the results are higher than that actually received due to "nonpenetrating" radiation exposing the elements of the dosimeter which record the deep dose, etc.

Dose Estimation and Control

Recognizing the problems above makes development of instruments, dosimeters, and techniques to provide an increased compatibility in results an important objective. At present personnel dosimetry systems and portable survey instruments have inherent sources of error. Major improvements in both systems are being developed as discussed above. As they become available in the field, improved field survey and dose prediction capabilities will be possible, thus providing for increased recorded dose accuracy as well as reduced total dose used.

Characterization of Fields in the Work Place

The discussion of sources of error indicates the value of thorough characterization of the work place radiation environs. For example a knowledge of the beta and gamma spectra would allow a more judicious choice of calibration factors for both the personnel dosimeters as well as the survey meters. This would in turn allow more accurate prediction of anticipated personnel exposure results.

Field Survey Precision and Accuracy

There is a tendency to treat field survey data and/or dosimetry results as "absolute." It is instructive to consider a few of the independent sources of error which lead to an evaluation of the overall accuracy of the results which form the basis of the "legal" records.

• NBS calibrations	3-5%
• Transfer standards and/or experimental error in setting up facility calibrated sources	5-10%
• Precision of field surveys	4-10%
- Technologist to technologist 3-7%	
- Locating sources 3-7%	
• Personnel dosimeter precision including badge placement	30-50%
Total	31-52%

CLOTHING SHIELDING

The INEL portable beta spectrometer was used to measure the beta skin dose protection afforded by typical items of protective apparel and equipment worn by radiation workers at the INEL. The purpose of these measurements was 1) demonstrate utility of the spectrometer in measuring shielding effects directly, 2) investigate the range of protection afforded in mixed beta/gamma radiation fields where high beta sources were known to be present [Sr-90/Y-90 and natural uranium metal], and 3) to observe the changes produced in the beta energy spectra by the insertion of protective apparel between the source and detector. The effectiveness of the protective apparel in reducing the skin dose rate is implied by the ratio of the D(0.07) dose rate to the D(0.07) dose rate without the protective apparel.

The measurements were made at a distance of 10 cm from point and plaque Sr-90/Y-90 sources, and at distances of 1 cm from the Tc-99 and Tl-204 beta plaques and natural uranium metal. The 1 cm distance from the beta plaques and uranium metal allowed sufficient room for the insertion of samples of the protective apparel, and also simulated the off-axis beta particles expected from the extended beta sources encountered at work sites.

The results of these measurements are presented as plots of the net beta energy spectra before and after the beta particles have passed through the protective apparel, with the measured D(0.07) dose rates behind each type of protection covering the body, hands and face listed on each spectral plot in Figures 34-38.

As would be expected from the mass stopping power curve, low energy beta particles are easily stopped by a few mg/cm^2 of absorbing materials. High energy beta particles penetrate the protective apparel readily, with energy losses shifting the beta spectra toward lower energies. The ratios of the D(0.07) dose rate without protection to the D(0.07) dose rate with protection are listed for each set of materials.

The protection afforded by two sets of coveralls and the paper anticontamination suit is almost complete for a low energy beta source such as Tc-99, while only limited protection is afforded by the same materials from high energy beta sources such as Sr-90/Y-90 (E_{max} = 2270 keV) or uranium metal (Pa-234, E_{max} = 2280 keV). The three layers of clothing reduce the skin exposure by only 28% and 20% for these sources.

OTHER CONSIDERATIONS

Organ Dose--Causation

Radiation injury litigation cases have focused attention on the need to establish the dose to the organ or whole body in order to derive a probability that the occupational exposure caused the injury. However, the prime purpose of personnel dosimetry systems is to protect the workers through assuring that governmental limits are not exceeded and that the recorded doses are conservative (higher than actually received). Several practices ensure conservatism.

1. Badges are generally placed on the part of the body in the highest expected dose area--and recorded as average whole-body dose.

2. Penetrating doses are generally measured at 1 cm depth while many organs are deeper.

3. Nonpenetrating (some betas of high energy) penetrate to the penetrating dosimeter area and deposit energy with a higher calibration factor than photons, thus resulting in higher recorded dose than actual.

For these reasons it becomes increasingly important to learn to measure occupational radiation with enough definition to allow more accurate reconstruction of organ dose.

Record Keeping

Though it has been the practice for many years in the radiation protection community to carefully document and record the calibration procedures, factors, etc., used for specific exposure results, the anticipated need to reconstruct organ doses indicates the need to keep more detailed records to ensure adequate information. More detail in characterizing the radiation fields in the work place may be invaluable in the future as an example.

Negative Numbers

Examination of personnel dosimetry records in litigation cases emphasizes two aspects of "negative numbers." First, the lack of data which indicates that measurements were not made--as in the case where only "penetrating" radiation was measured may lead to a conclusion of negligence. However, the existence of negative results (zero readings) indicates a program was in place and no measureable exposure received. This argues for "conservative" badging programs beyond that required by Federal agencies.

Limits--A Warning

The most recent skin dose limits will result in an increase from 15 rem/yr (DOE) and 30 rem/yr (NRC) to 50 rem/yr. On the surface this would tend to indicate less needed concern for nonpenetrating dosimetry and could lead to complacency in this area.

SUMMARY

Measurements of beta and/or nonpenetrating exposure results is complicated and past techniques and capabilities have resulted in significant inaccuracies in recorded results. Current developments have resulted in increased capabilities which make the results more accurate and should result in less total exposure to the work force. Continued development of works in progress should provide equivalent future improvements.

BIBLIOGRAPHY

Al (84) Alvarez, J. L., Daniel, S. H., Johnson, L. O., Martz, D. E., and Rich, B. L., Radiation Field Characterization and Radiological Equipment Evaluation at the Feed Material Production Center, NLO Inc., HS-84-033, 5/84.

Al (83) Alvarez, J. L., Beta Measurements for Dose Estimation, Radiation Protective Management, 10/83.

Ba (82) Baker, K. R. and Dyer, N. C., Personnel Protection from Beta Particles, INPO Good Practices, 1/82.

Bi (80) Bingo, K., Suga, S., Kajinoto, Y., Numakuma, T., "B-Ray Survey Meter for Measuring Absorbed Dose Rate Independently of B-Ray Energy, Health Physics, 39:21.

EP (84) EPA 52011-84-005, Occupational Exposure to Ionizing Radiation in the United States. A Comprehensive Review for the Year 1980 and a Summary of Trends for the Years 1960-1985, 9/1984.

Gr (86) Graham, C. L., Improving the Accuracy of Beta Survey Instruments, UCRL-94034, 1/86.

Ha (76) Hajnal, F., McLaughlin, F., O'Brien, K., Beta-Ray Dosimetry in Mixed Radiation Fields, Operational Health Physics, Proceedings of the Ninth Midyear Topical Symposium of the Health Physics Society, Denver, Colorado, February 9-12, 1976.

Ha (82) Hankins, D. E., Beta- and Gamma-Dose Measurements of the Godiva IV Critical Assembly, UCRL-88284, 10/82.

Ha2 (82) Hankins, D. E., Beta-Energy Response of the Eberline RO-7 Survey Instrument, UCID-19484, 10/82.

Ha3 (82) Hankins, D. E., Evaluation of Beta Energy (E_{max}) and Spectral Type Using Survey Instruments, UCRL-88275, 10/82.

Jo (78) Johnson, L. O., A High Rate Detector System, 1978 Nuclear Science Symposium, Washington, D.C., October 18-20, 1978, Transactions of the IEEE, 1978.

Ka (75) Kathren, R. L., Standard Sources for Health Physics Instrument Calibration, Health Physics, 29: 143-153 July 1975.

Ke (86) Kenoyer, J. L., Swinth K. L., Shoetzel, G. A. and Selby, J. M., Performance Specifications for Health Physics Instrumentation for Use in Normal Environmental Conditions, Part II: Test Results, PNL document, '86.

Ma (86) Martz, D. E., Rich, B. L. and Johnson L. O., "Measuring the Skin Dose Protection Afforded by Anti-Contamination Clothing with a Beta Spectrometer," submitted to Radiation Protection Management, 5/86.

Ma2 (86) Martz, D. E., Johnson, L. O., Rich, B. L. and Daniel, S. H., "Field Tests of a Tissue Equivalent Beta Survey Meter," to be published in Radiation Protection Dosimetry. Proceedings of Workshop on Dosimetry of Beta Particles and Low Energy X-Rays in Saclay, 10/85.

Ma3 (86) Martz, D. E., Rich, B. L. and Johnson L. O., "A Portable Beta Spectrometer for Tissue Dose Measurement," to be published in Radiation Protection Dosimetry. Proceedings of Workshop on Dosimetry of Beta Particles and Low Energy X-Rays in Saclay, 10/85.

Ma4 (86) Martz, D. E., Rich, B. L., Johnson L. O. and Daniel, S. H., Field Test of a Portable Tissue Equivalent Survey Meter for Monitoring Mixed Beta Gamma Radiation Fields, NUREG/CR-4553, EGG-2448, 6/86.

NBS Requirements for An Effective National Ionizing Radiation Measurements Program, NBS 603.

Nu (83) Proceedings of the International Beta Dosimetry Symposium, NUREG/CP-0050, 2/83.

Ra (84) Rathbun, L. A., Endres, G. W. R., Fox, R. A., Roberson, P. L. and Scherpetz, R. I., Beta Particle Measurement and Dosimetry Requirements at NRC-Licensed Facilities, NUREG/CR-3544, PNL-4886, 8/84.

RA (86) Rathbun L. A., Swinth K. L., and Haggard D. L., Beta Measurements at Department of Energy Facilities, Draft PNL report in preparation, 3/86.

Ri (81) Rich, B. L., Alvarez, J. L. and Adams, S. R., Interim Status Report of the TMI Personnel Dosimetry Project, GEND-0004, 1/81.

Si (86) Simons, G. G. and Higginbotham, J. F., "Beta-Particle Spectroscopy with Active Gamma-Ray Discrimination," presented at DOE Beta Dosimetry Workshop, Albuquerque, 1/86.

Si2 (86) Simon G. G., Beta-Particle Dosimetry with Thin Graphite-Backed TLDs, presented at DOE Beta Dosimetry Workshop, Albuquerque, 1/86.

So (85) Soares, C. G., Prediction of Instrument Response to Monoenergetic Electrons, NBS/NRC draft, 9/25/85.

So (86) Soares, C. G., Dick, C. E., Pruitt, J. S. and Sparrow, J. H., Development of Monoenergetic Electron Beam Sources for Radiation-Instrument Calibration, NBS draft report, '86.

Sw (85) Swinth, K. L. Rathbun, L. A., Hooker, C. D., Roberson, P. L. and Keneyer, J. L., "The Beta Response of Selected Instruments," presented at the Health Physics Society Meeting, Chicago, 5/85.

US (70) U.S. Department of Health, Education, and Welfare, Radiological Health Handbook, revised ed., 1970.

TABLE 1. RESPONSE OF TYPICAL COMMERCIAL 2-CHIP TLD PERSONNEL DOSIMETER TO CALIBRATED SOURCES

β/γ ratio	Gamma (^{137}Cs)			Beta ($Sr/^{90}Y$)		
	rem Given	rem Reported	Diff.	rem Given	rem Reported	Diff.
	0 0 0 0	0.1 0.6 4.7 47.4	20% β Pen.	0.27 2.7 27.0 270.0	0.5 5.1 55.0 578.0	2x
0.1/1	2.7	2.7	OK	0.27	0.0	No. β
1/1	0.27 2.7	0.3 3.1	20%	0.27 2.7	0.3 3.0	11%
10/1	0.27 2.7	0.8 7.5	3x	2.7 27.0	5.1 48.6	2x
100/1	0.27 2.7	5.4 52.0	20x	27.0 270.0	47.5 579.0	2x

6 10 208

TABLE 2. "TYPICAL" MIXED FIELD JOB EXPOSURE EXPERIENCE

DRD	NP/P	Ratio DRD/P	Ratio NP/P
70	0/105	0.7	0.0
90	55/70	1.3	0.8
90	70/95	1.0	0.7
120	90/85	1.4	1.1
130	110/80	1.6	1.4
160	60/170	0.9	0.4
160	45/150	1.1	0.3
180	225/180	1.0	1.3
220	160/200	1.1	0.8
220	320/110	2.0	2.9
220	50/180	1.2	0.3
320	810/185	1.7	4.4
320	970/220	1.5	4.4

6 10 207

TABLE 3.

Accuracy Requirements at Various Levels in the Measurement Support System

Kind of Measurement	Field Measurement Accuracy Required (%)	Intermediate Level Calibration Accuracy Required (%)	NBS Calibration Accuracy Required (%)
Medical			
Radiation therapy	3	2	1.5
X-ray diagnosis	10	5	3
Nuclear medicine	10	5	2-3
Ocupational			
Restricted area survey	15	10	3
Personnel monitoring	30-50	5-7	3
Unrestricted area survey	20	10	5
Environmental			
External radiation	20	10	3
Air, food, and water (activity)	10	5	2
Liquid effluents (activity)	15	8	3
Surface contamination (activity)	10	5	2

5 4001

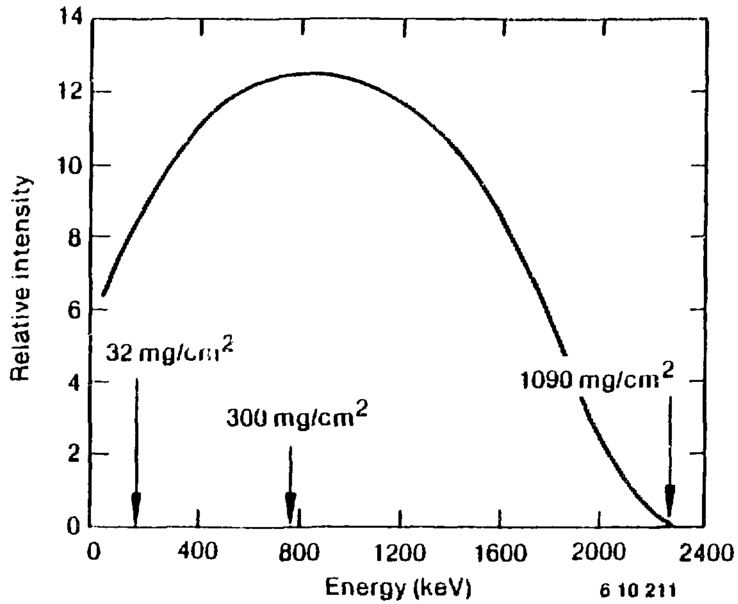

Figure 1. ^{90}Y theoretical beta energy spectrum

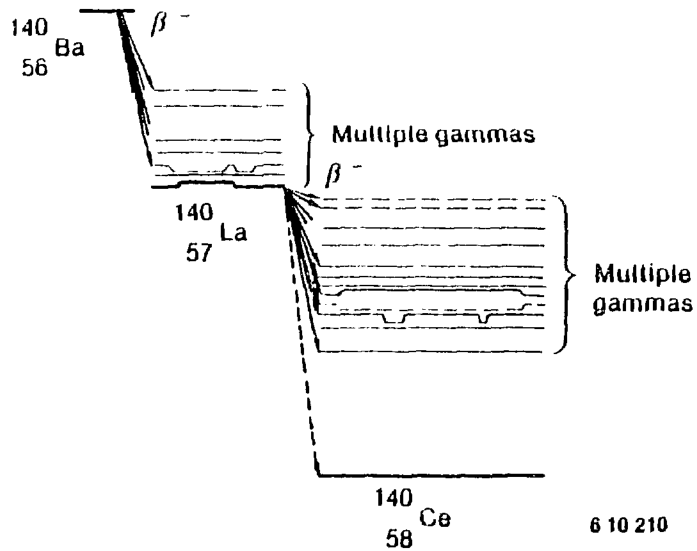

Figure 2. Example of multiple decay scheme of single isotope.

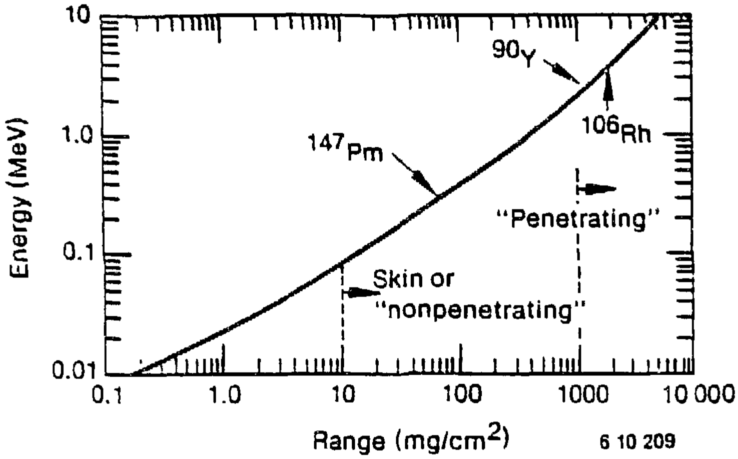

Figure 3. Beta particle range energy curve

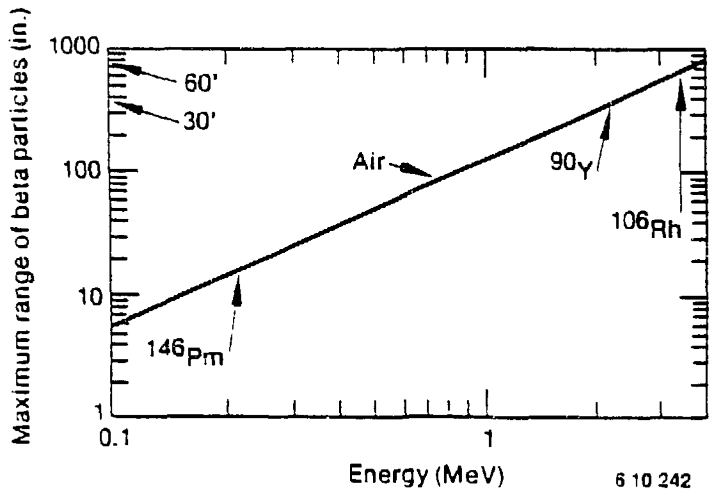

Figure 4. Penetration ability of beta radiation

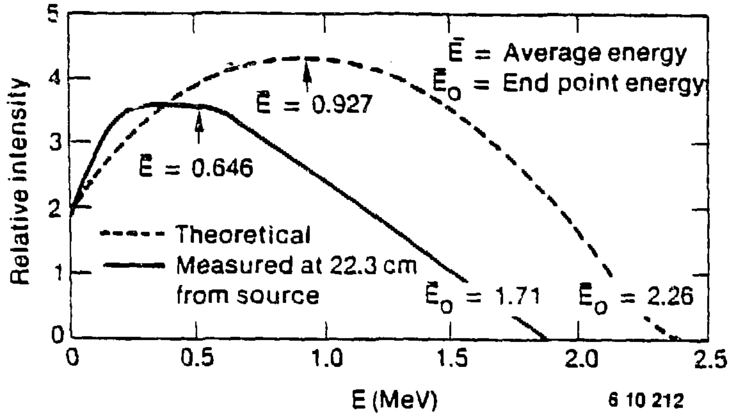

Figure 5. Comparison of measured-to-theoretical beta spectra for Sr/^{90}Y

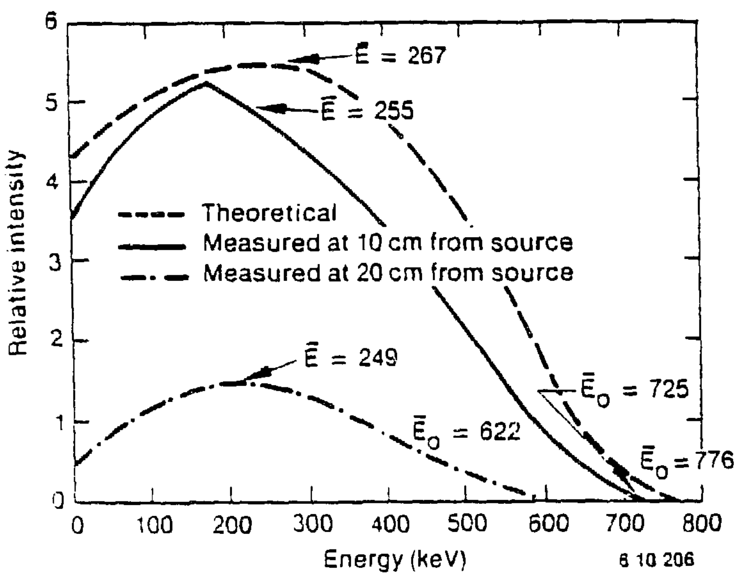

Figure 6. Comparison of measured-to-theoretical beta spectra for ^{204}TL

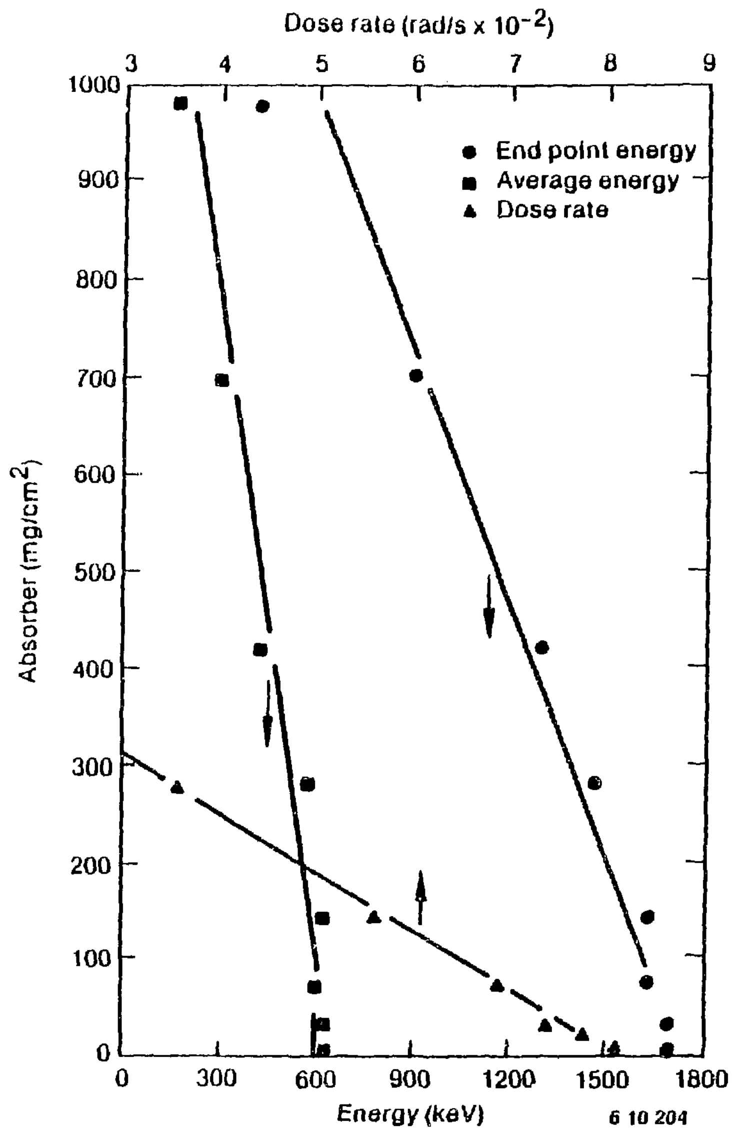

Figure 7. Dose rate and energy response vs. absorber Sr ^{90}Y

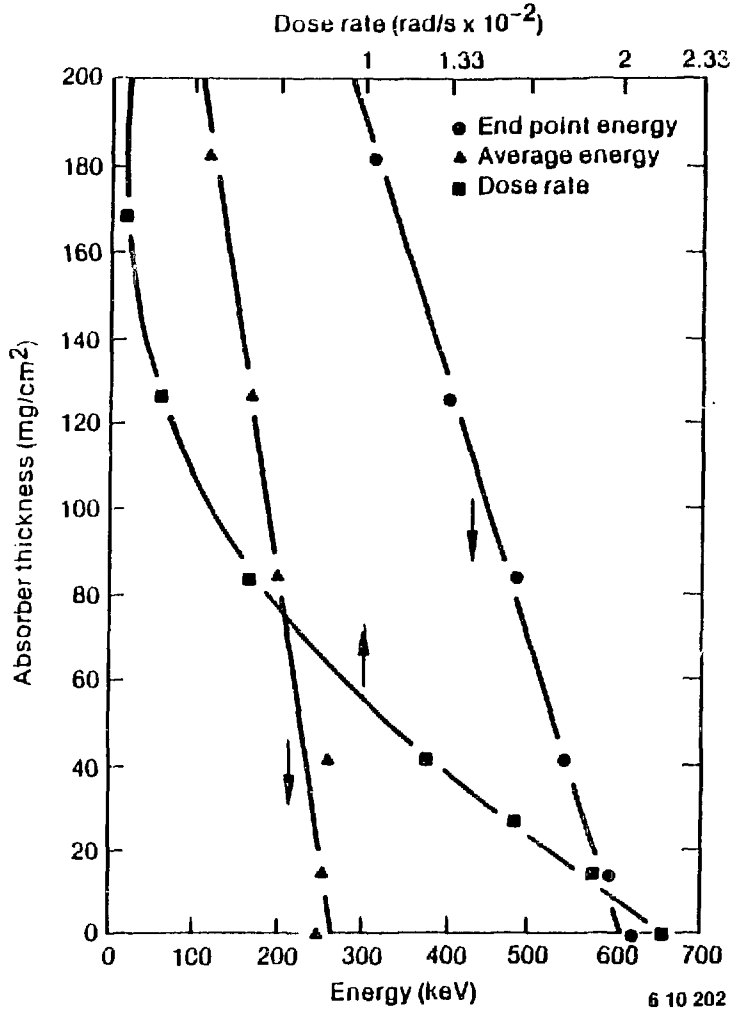

Figure 8. Dose rate and energy response vs. absorber ^{204}TL (20 cm)

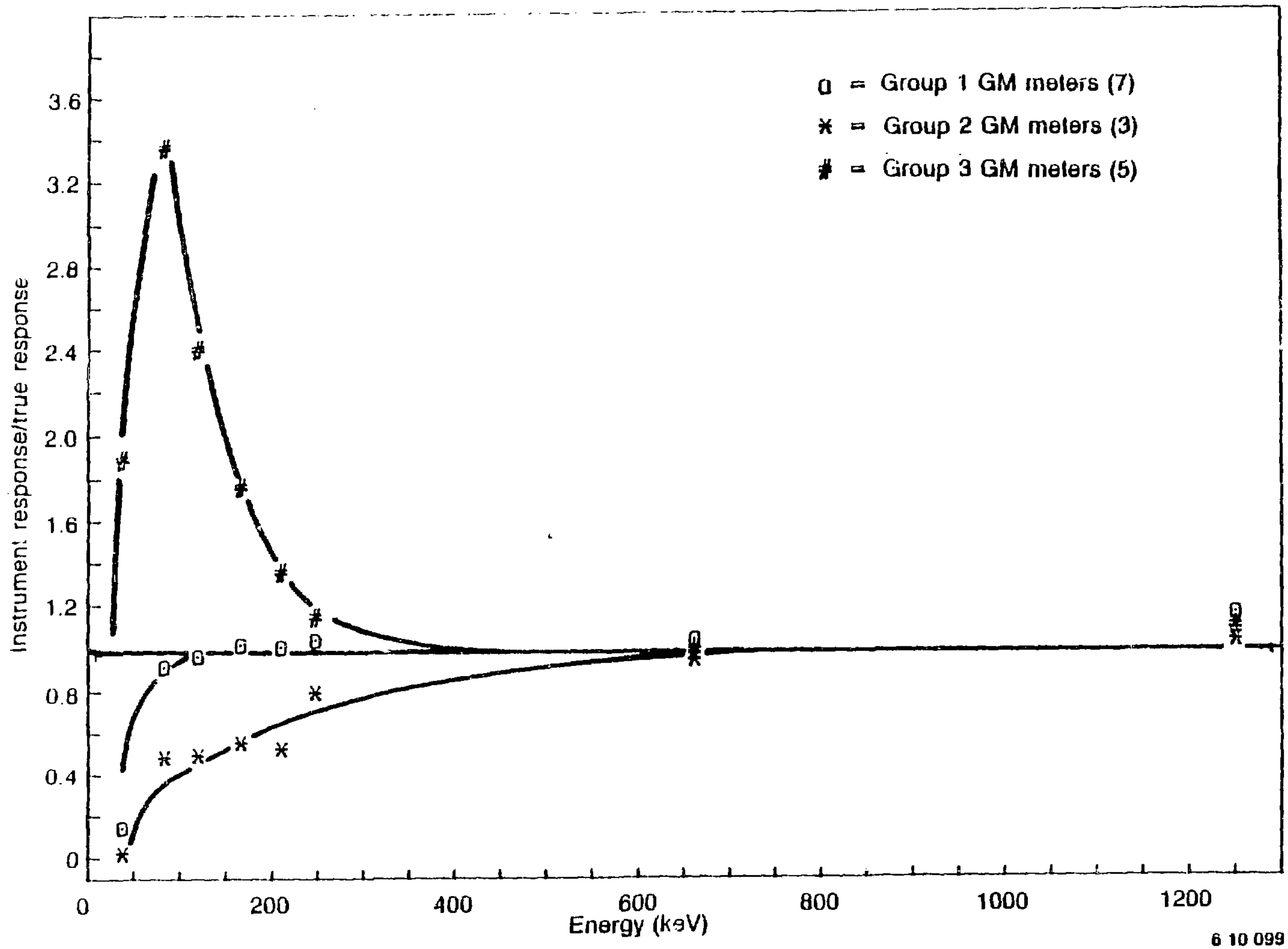

Figure 9. Average GM survey meter energy response by group

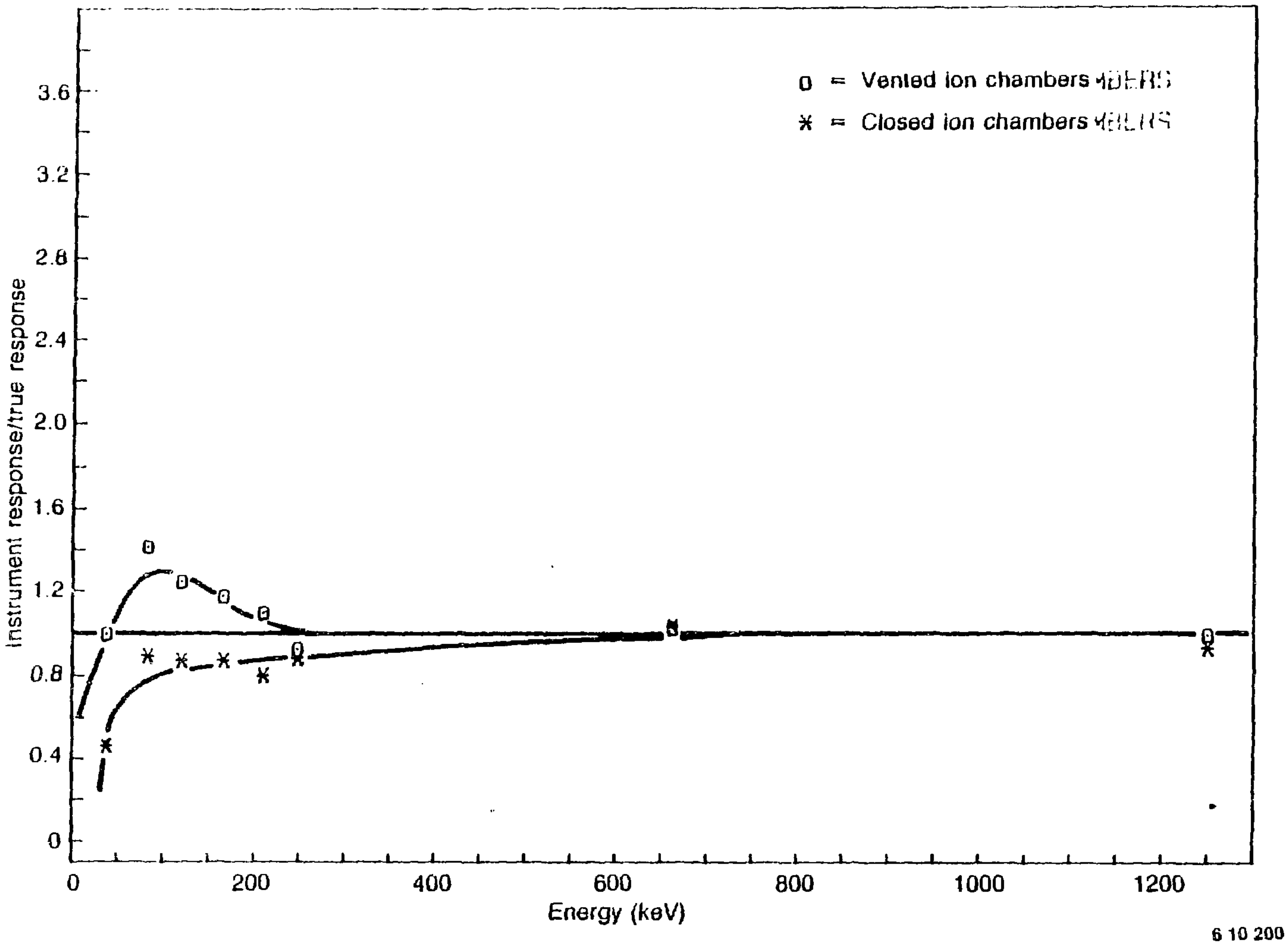

Figure 10. Average ion chamber survey meter response by group

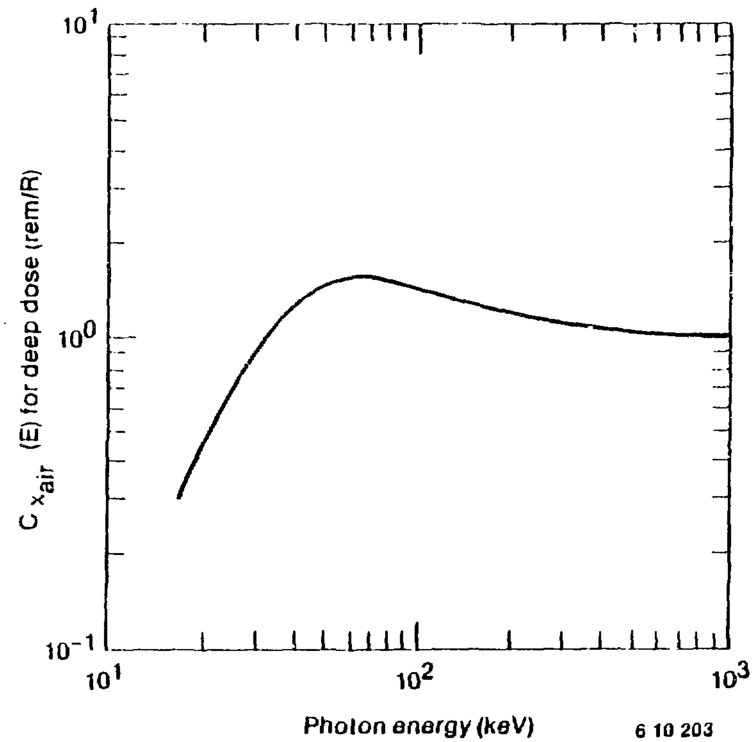

Figure 11. Air-to-tissue doses conversion factors as given in ANSI N13.11

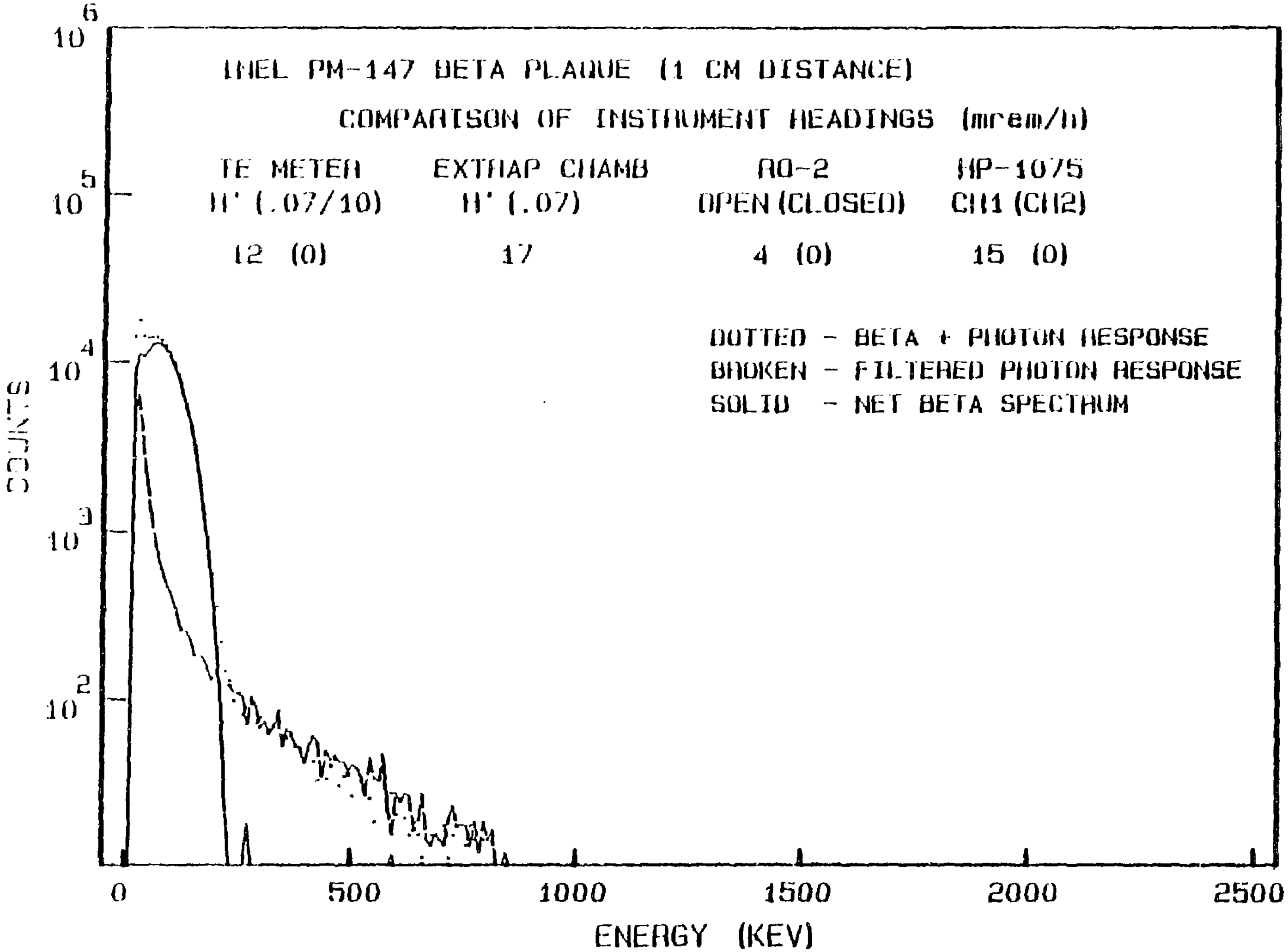

Figure 12. Comparison of meter readings to a Pm-147 beta plaque source.

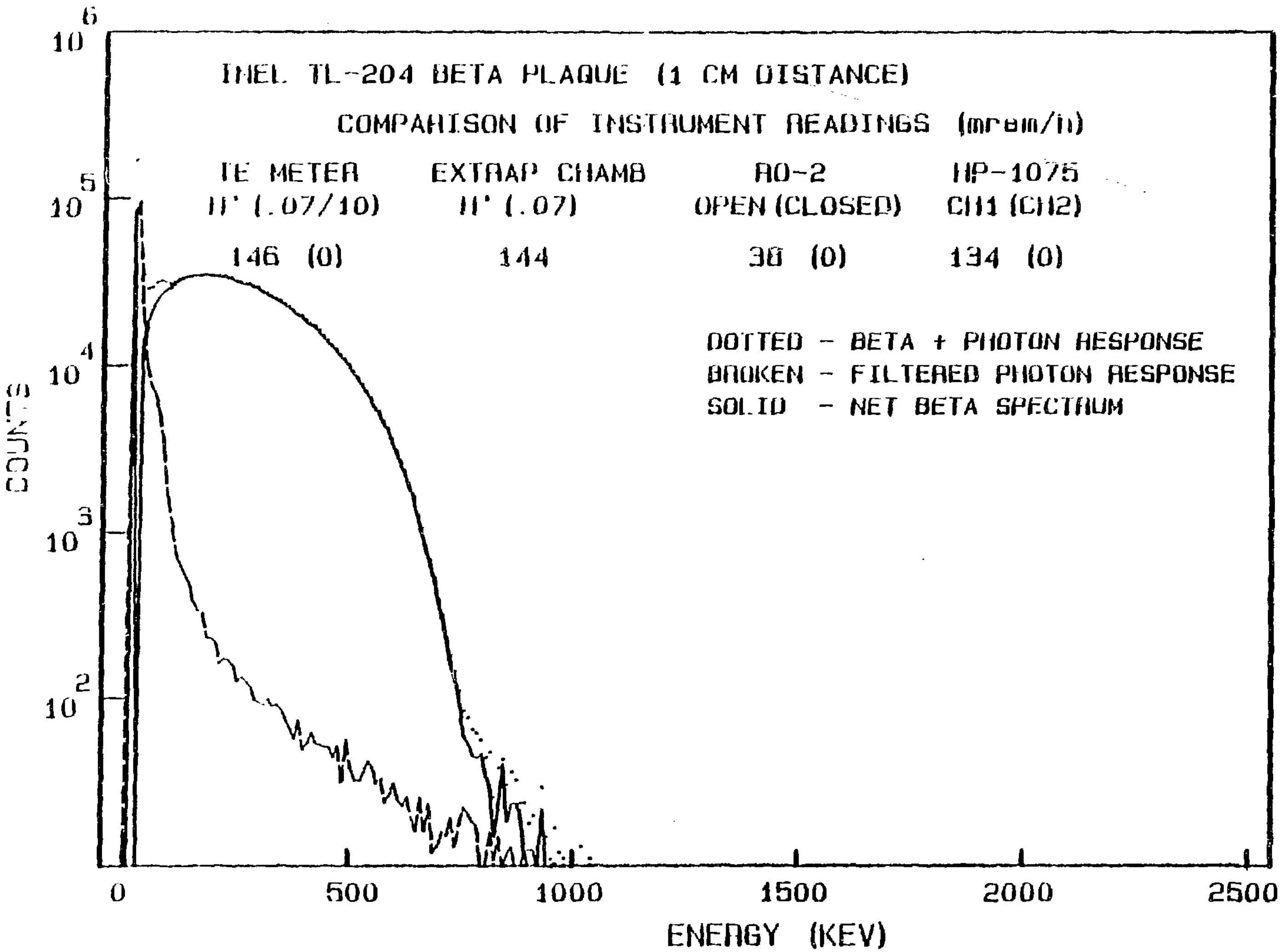

Figure 13. Comparison of meter readings to a Tl-204 beta plaque source.

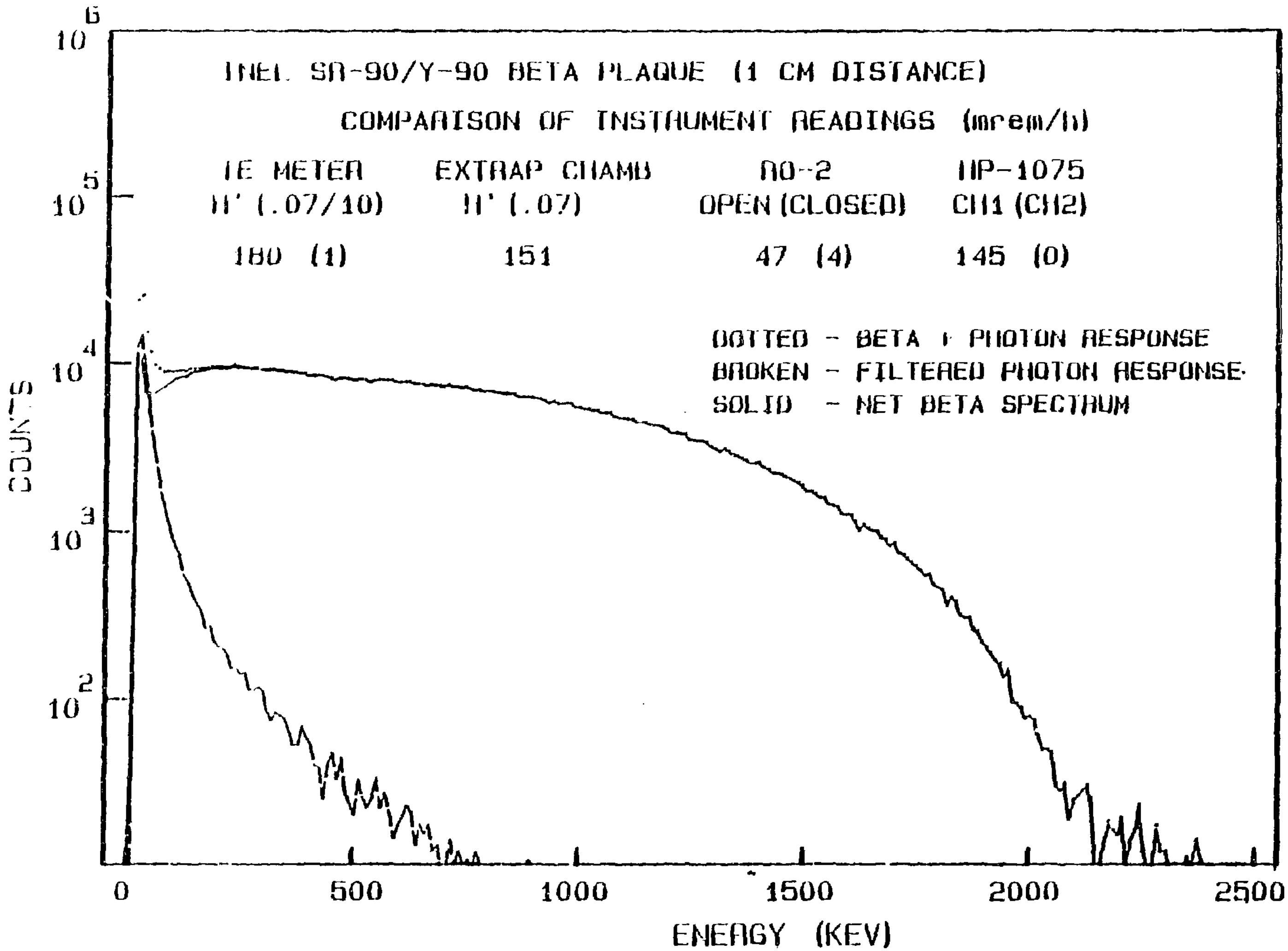

Figure 14. Comparison of meter readings to a Sr-90/Y-90 beta plaque source.

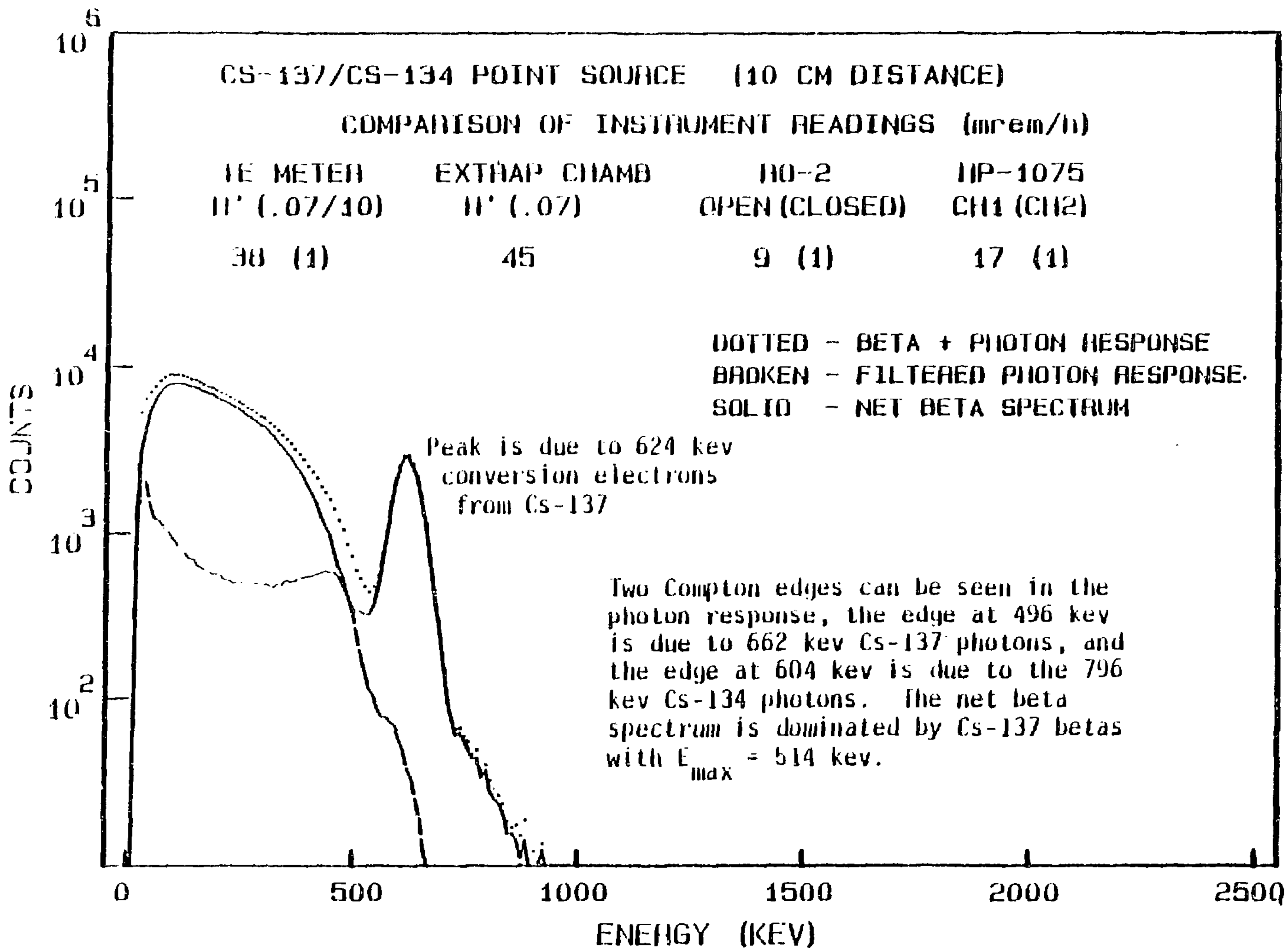

Figure 15. Comparison of meter readings from a mixed Cs-137/Cs-134 point source.

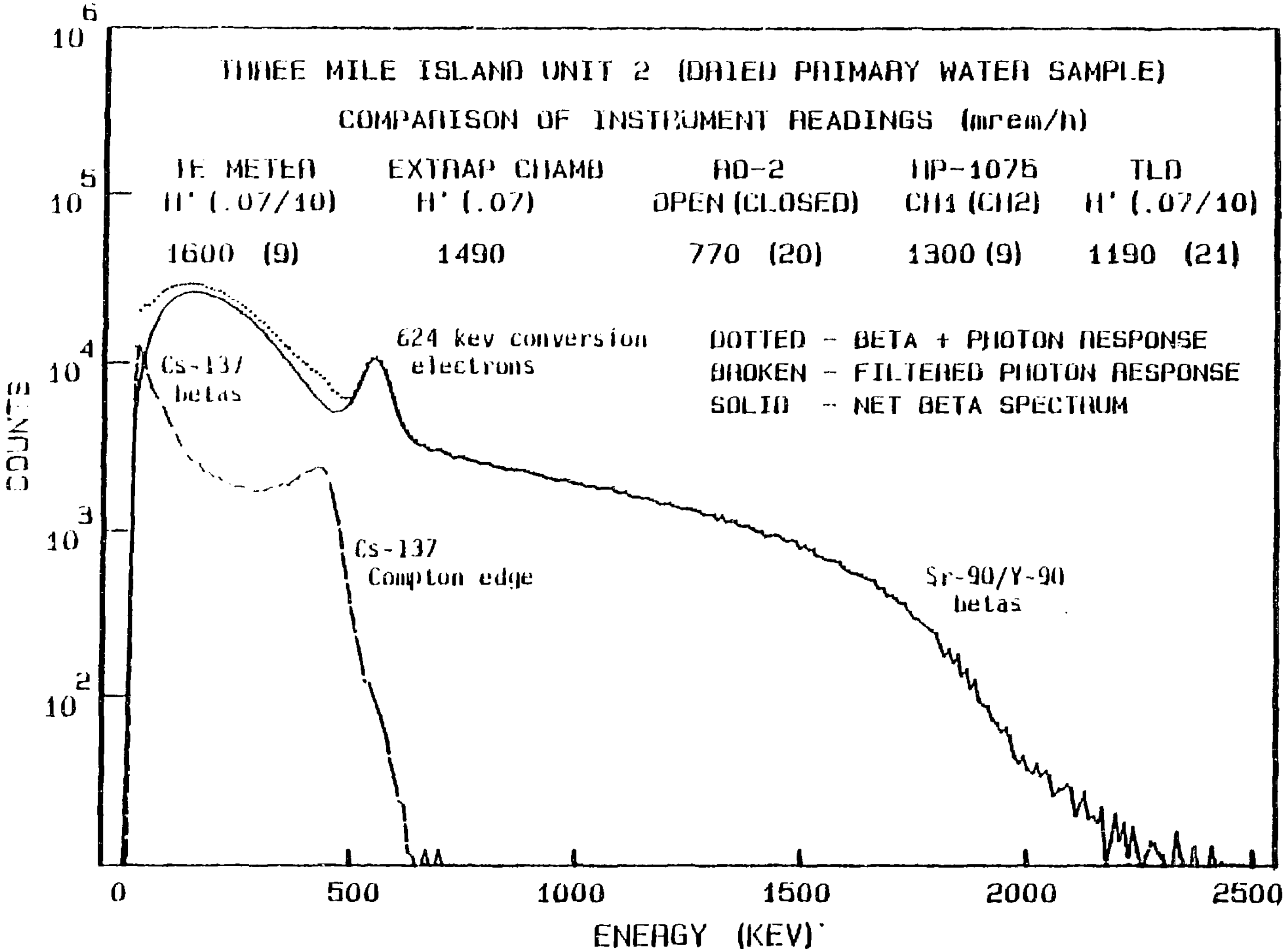

Figure 16. Comparison of meter readings from a dried primary water sample from the damaged Three Mile Island Unit 2 reactor containment building.

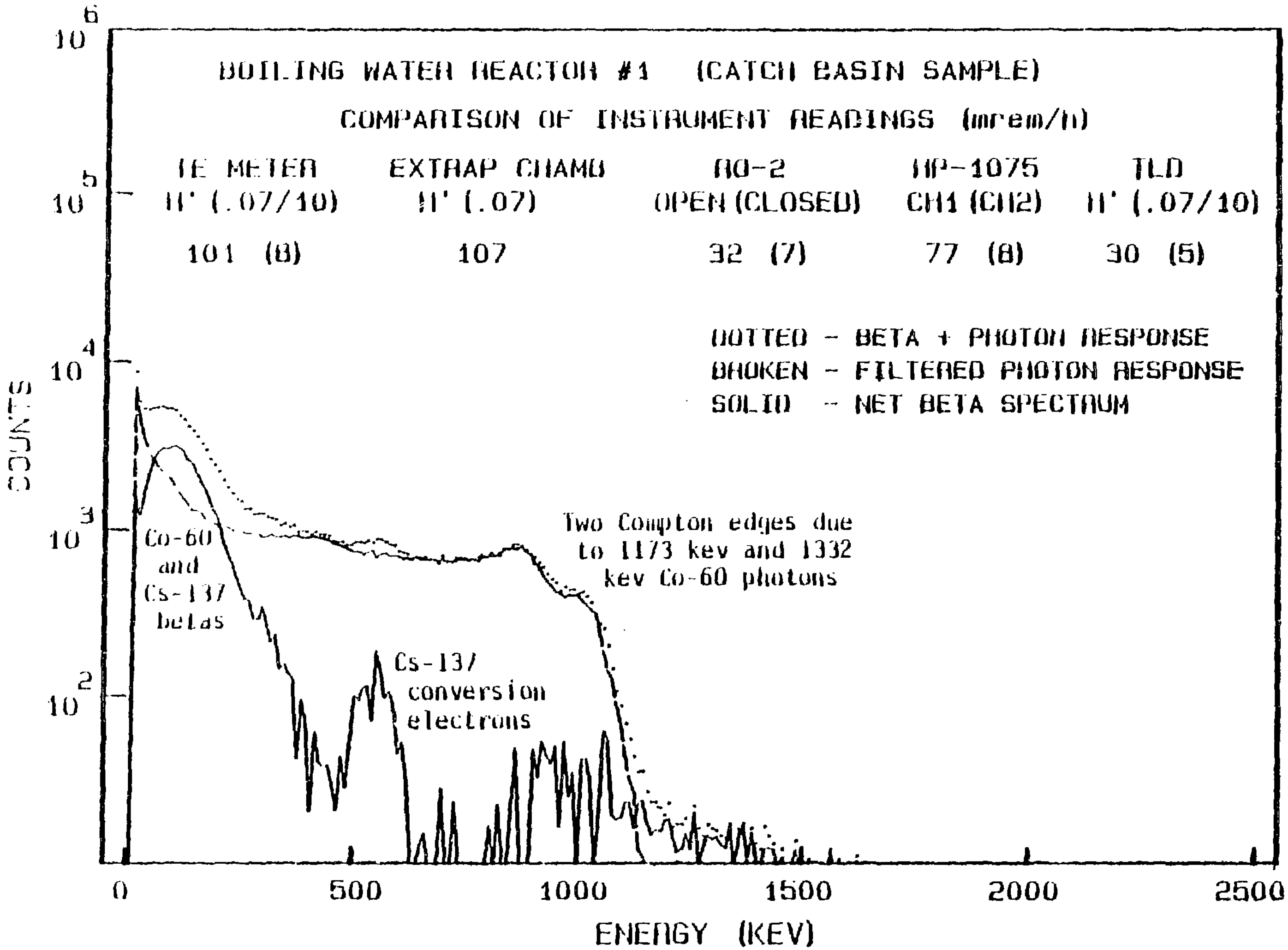

Figure 17. Comparison of meter readings for a BWR sludge sample. The activity is due to Co-60 with some Cs-137.

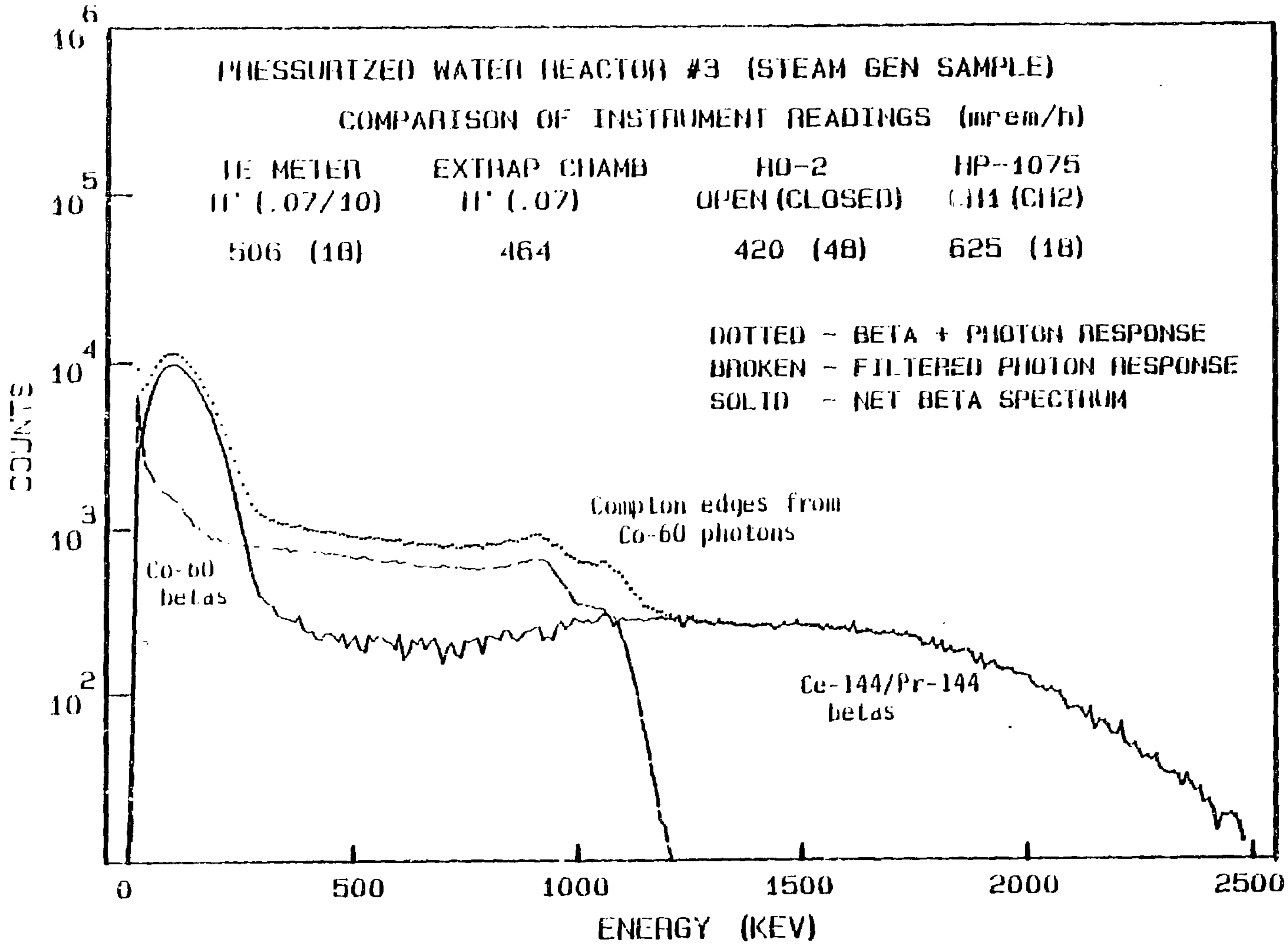

Figure 18. Comparison of meter readings for a PWR steam generator sample.

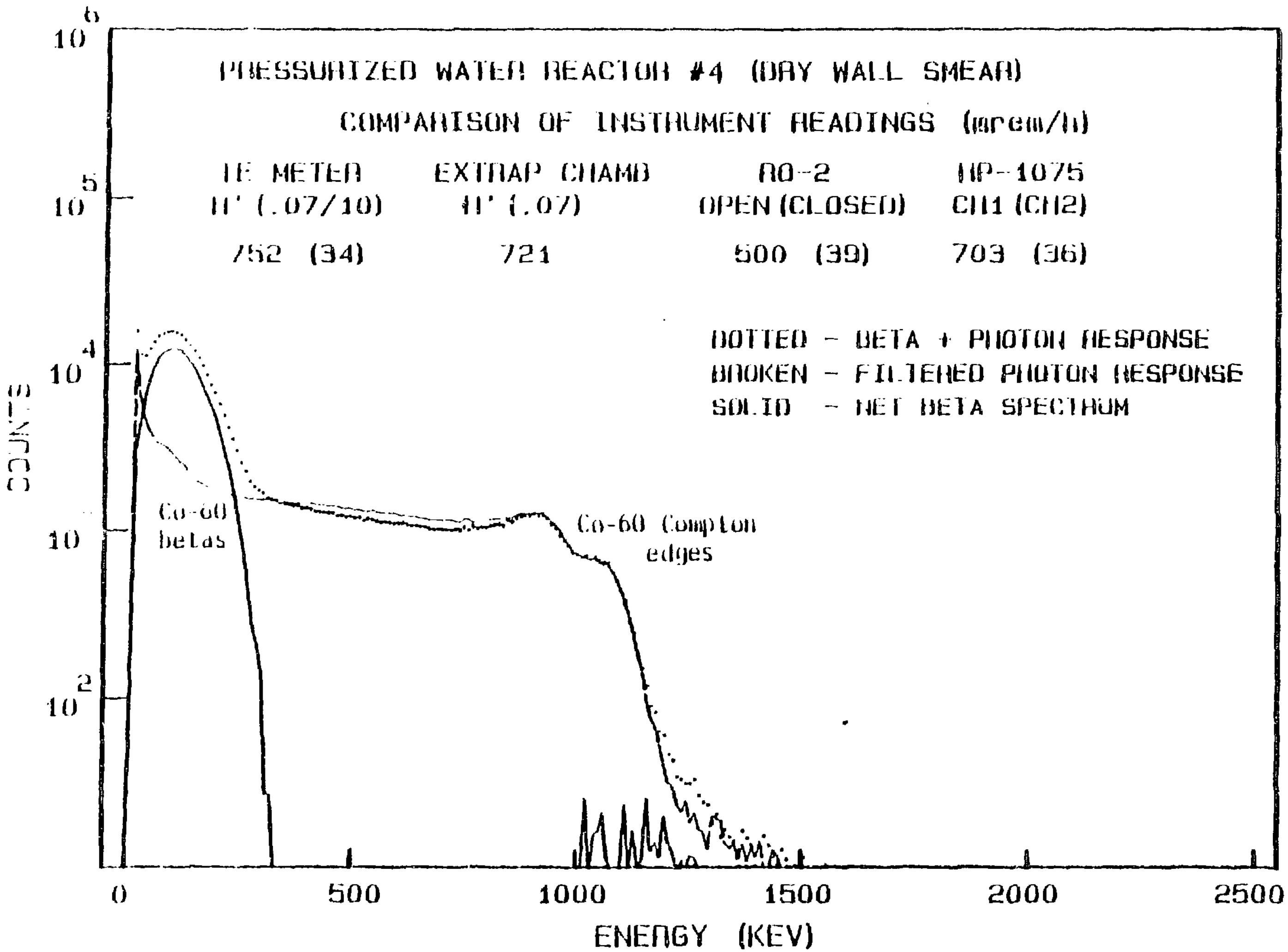

Figure 19. Comparison of meter readings for a PWR smear sample.

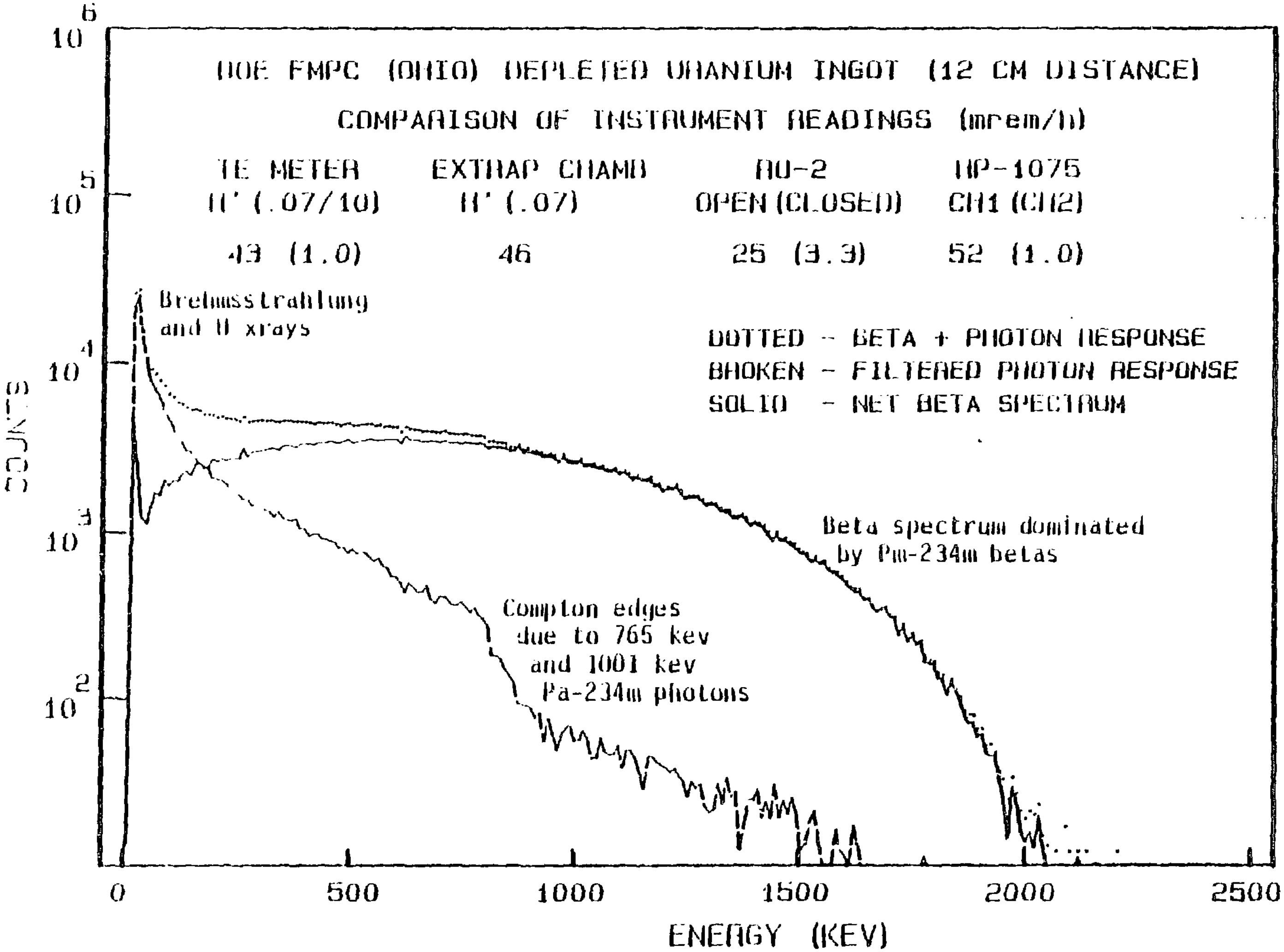

Figure 20. Comparison of meter readings for a depleted uranium ingot.

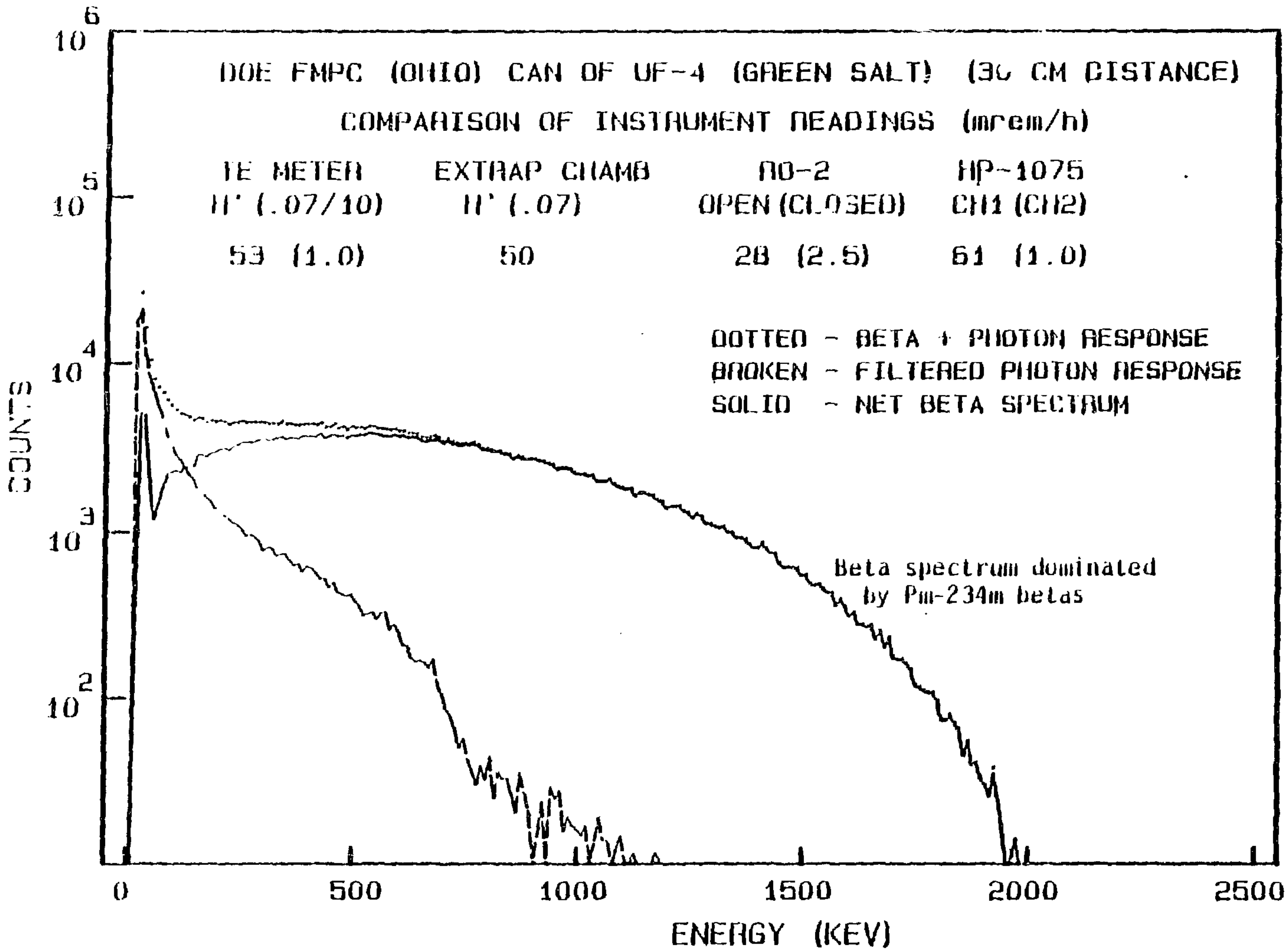

Figure 21. Comparison of meter readings for a open drum of UF_4 (green salt).

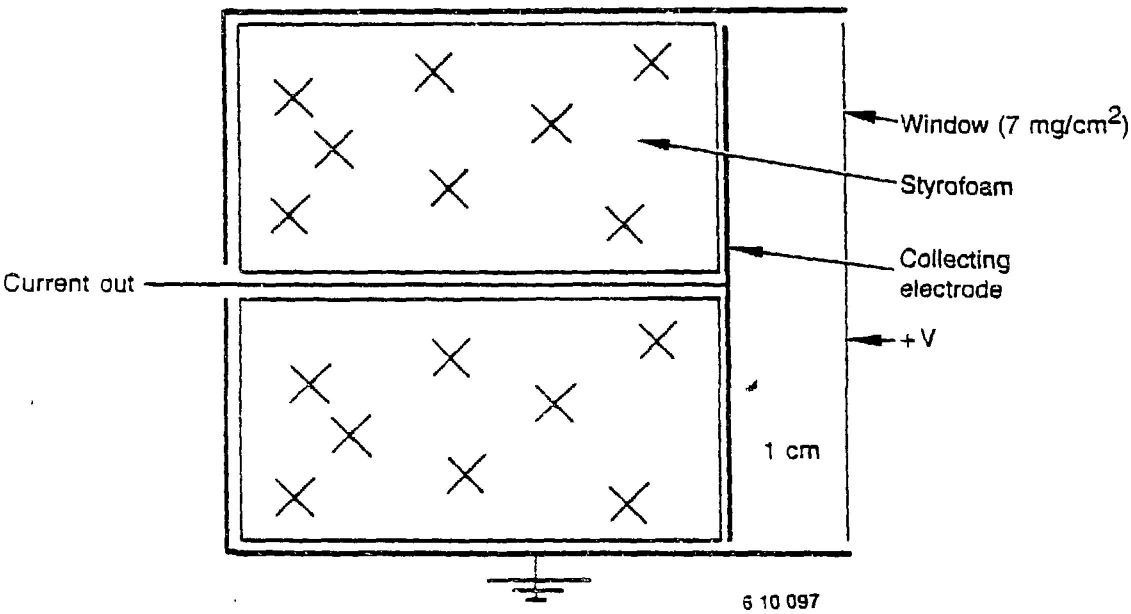

Figure 22. Modification to the ionization chamber of Eberline RO-2 and Victoreen 471.

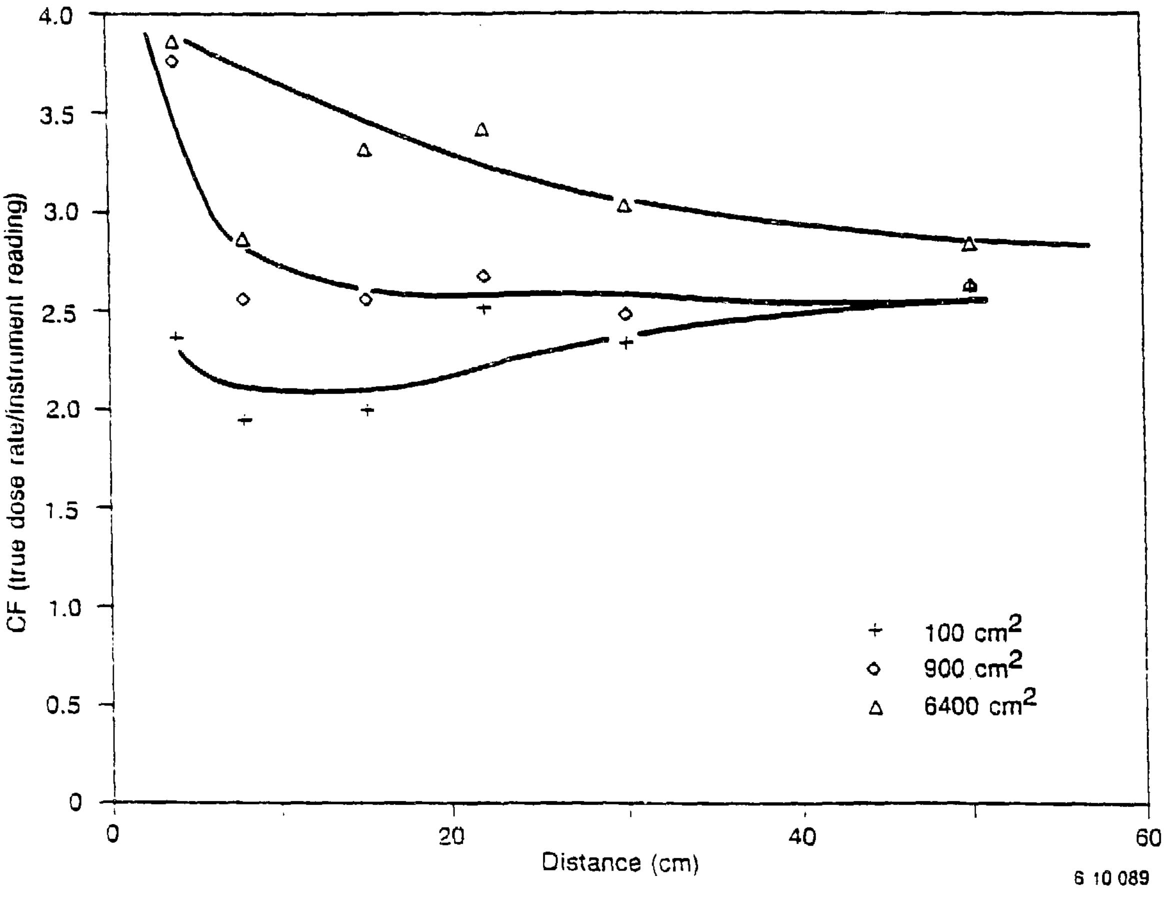

Figure 23. Calibration factors for an Eberline RO-2 vs. distance for three sources of ^{36}Cl (E_{max} = 0.71 MeV)

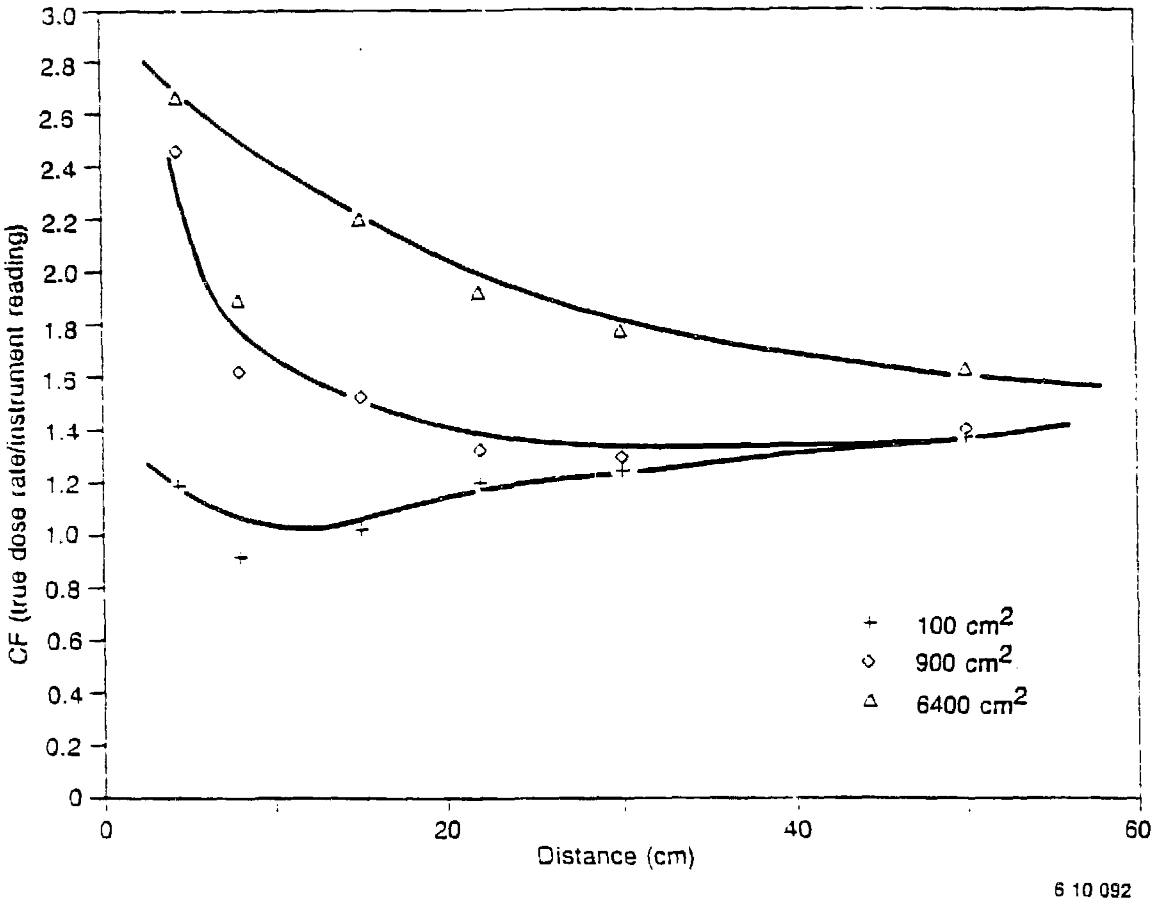

Figure 24. Calibration factors for a Victoreen 471 vs. distance for three sources of ^{36}Cl (E_{max} = 0.71 MeV)

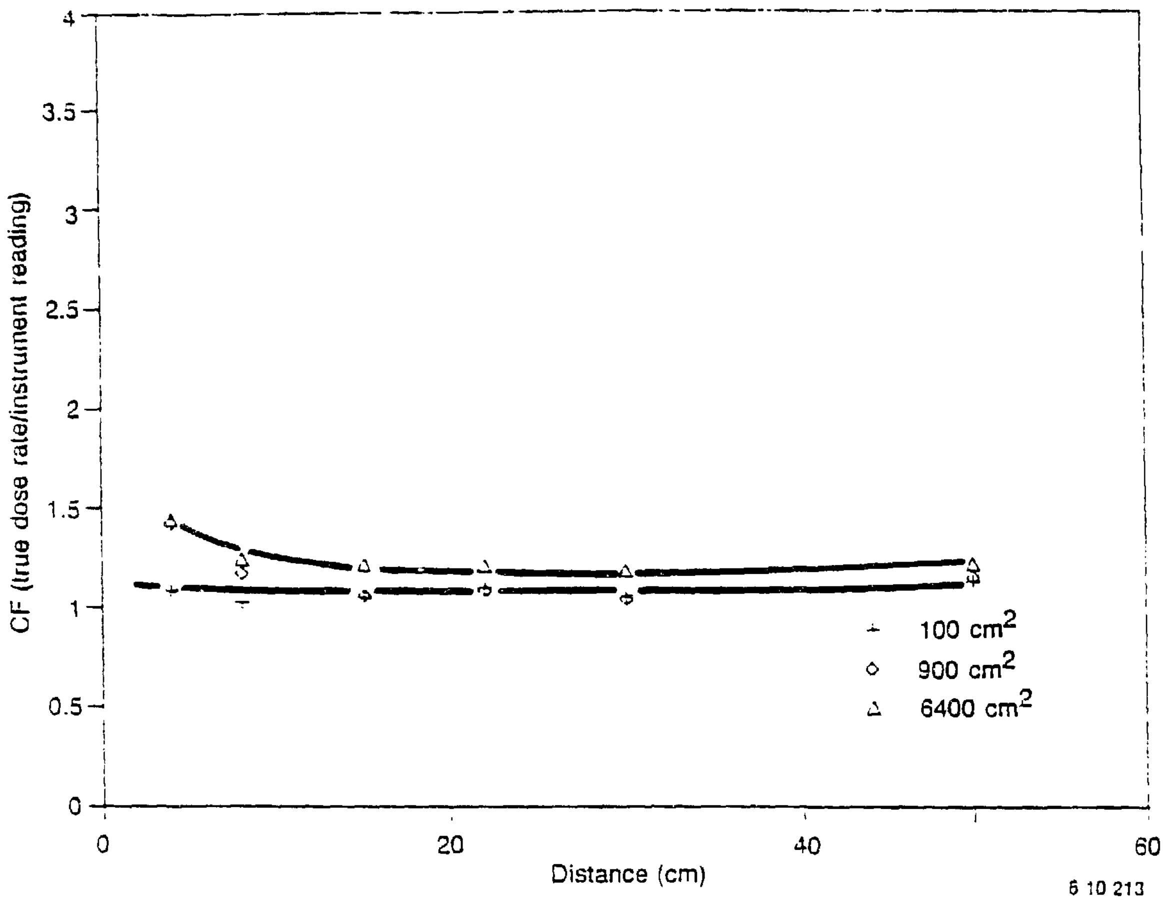

Figure 25. Calibration factors for the modified Eberline RO-2 vs. distance for three sources of ^{36}Cl (E_{max} = 0.71 MeV)

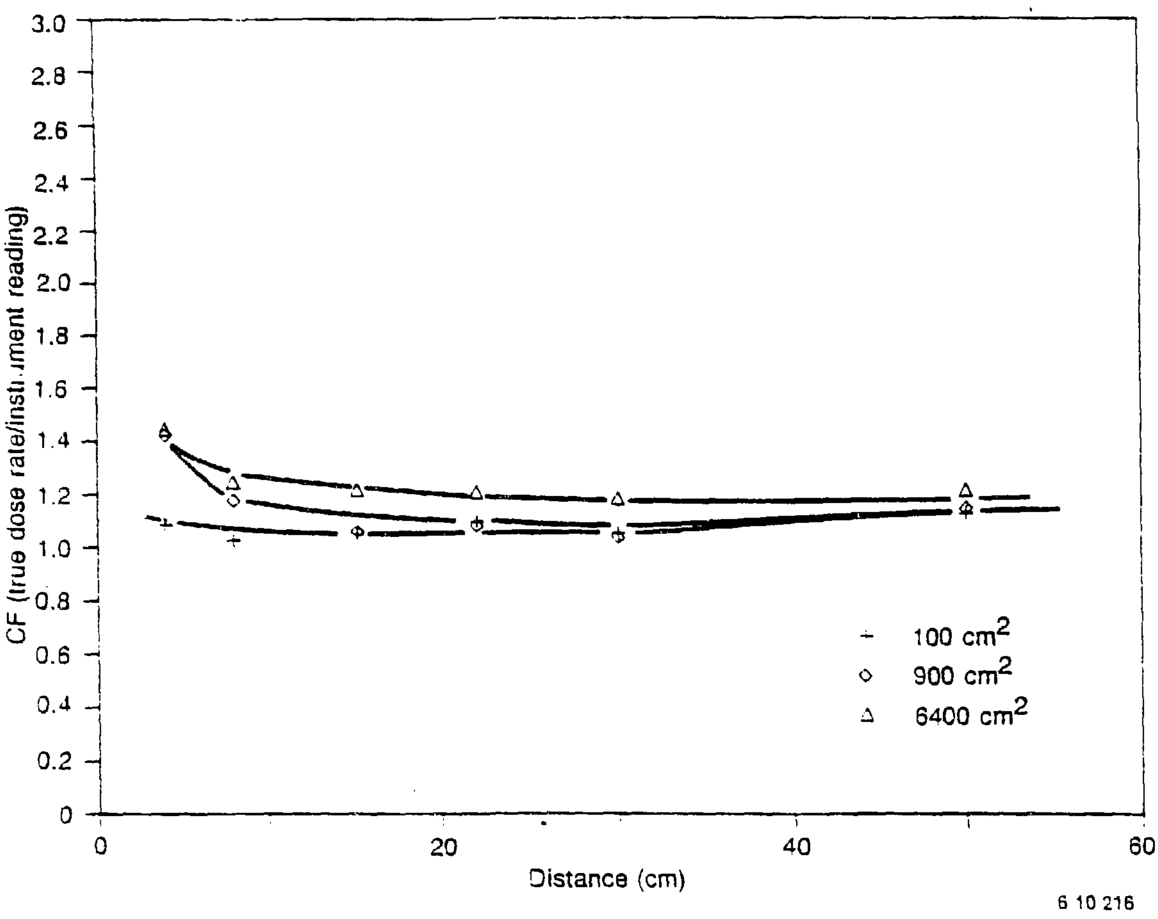

Figure 26. Calibration factors for the modified Victoreen 471 vs. distance for three sources of ^{36}Cl (E_{max} = 0.71 MeV)

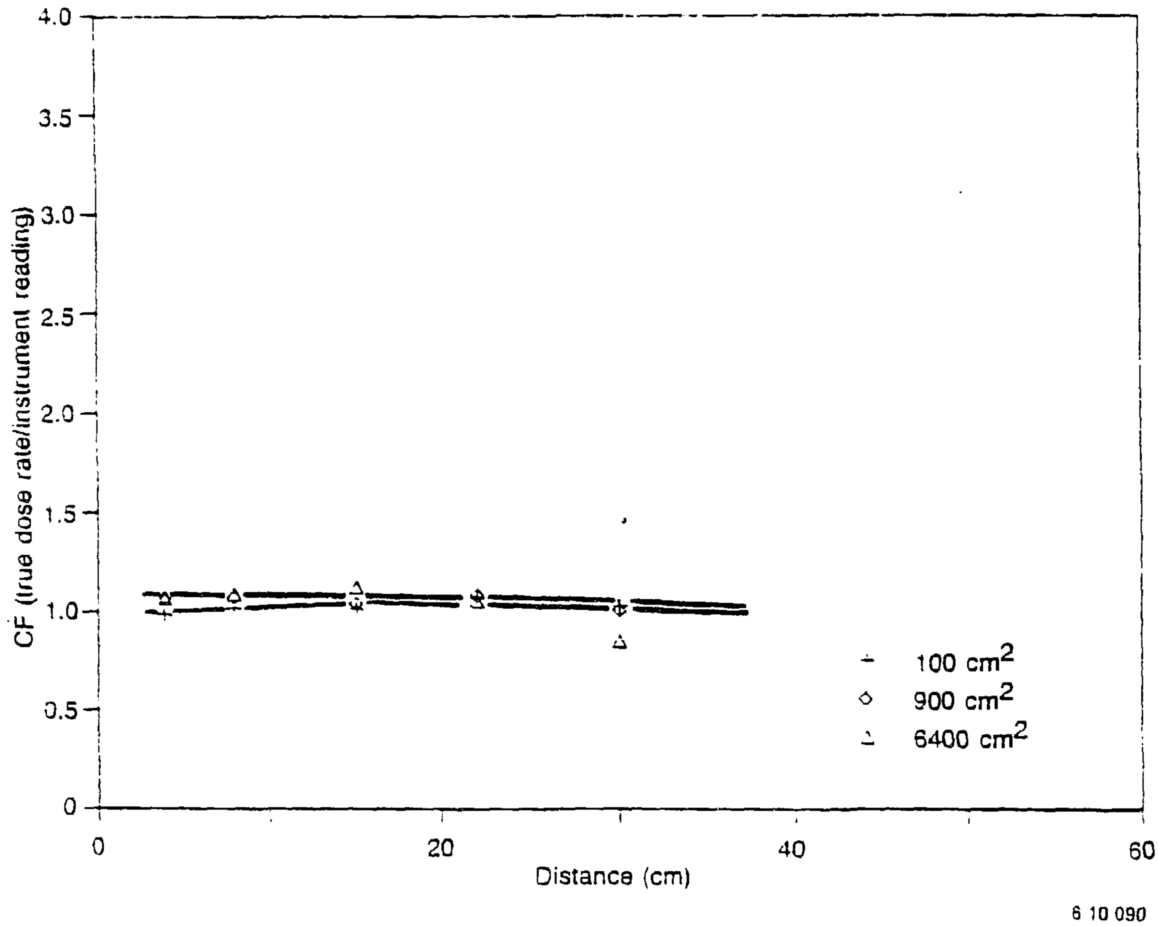

Figure 27. Calibration factors for the modified Eberline RO-2 vs. distance for three sources of ^{90}Sr (E_{max} = 2.3 MeV)

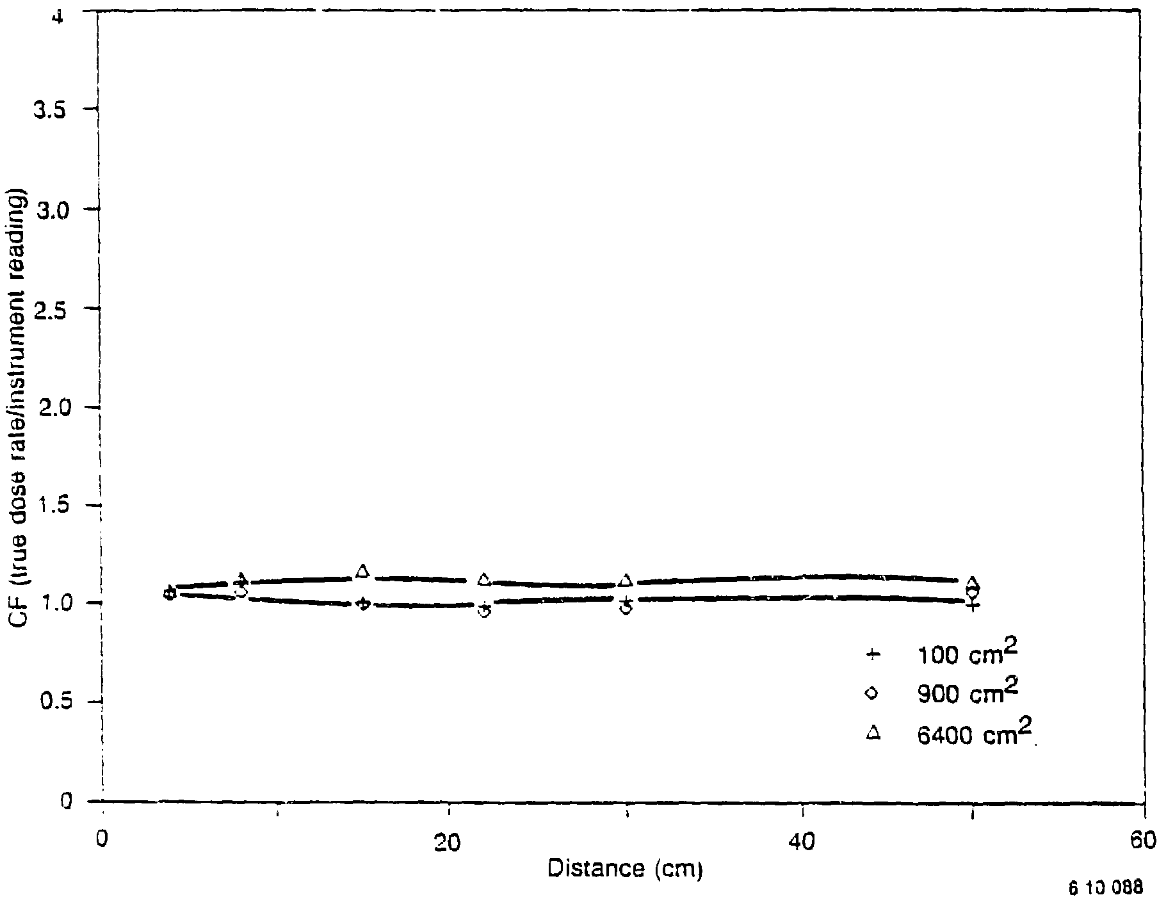

Figure 28. Calibration factors for the modified Eberline RO-2 vs. distance for three sources of ^{99}Tc (E_{max} = 0.29 MeV)

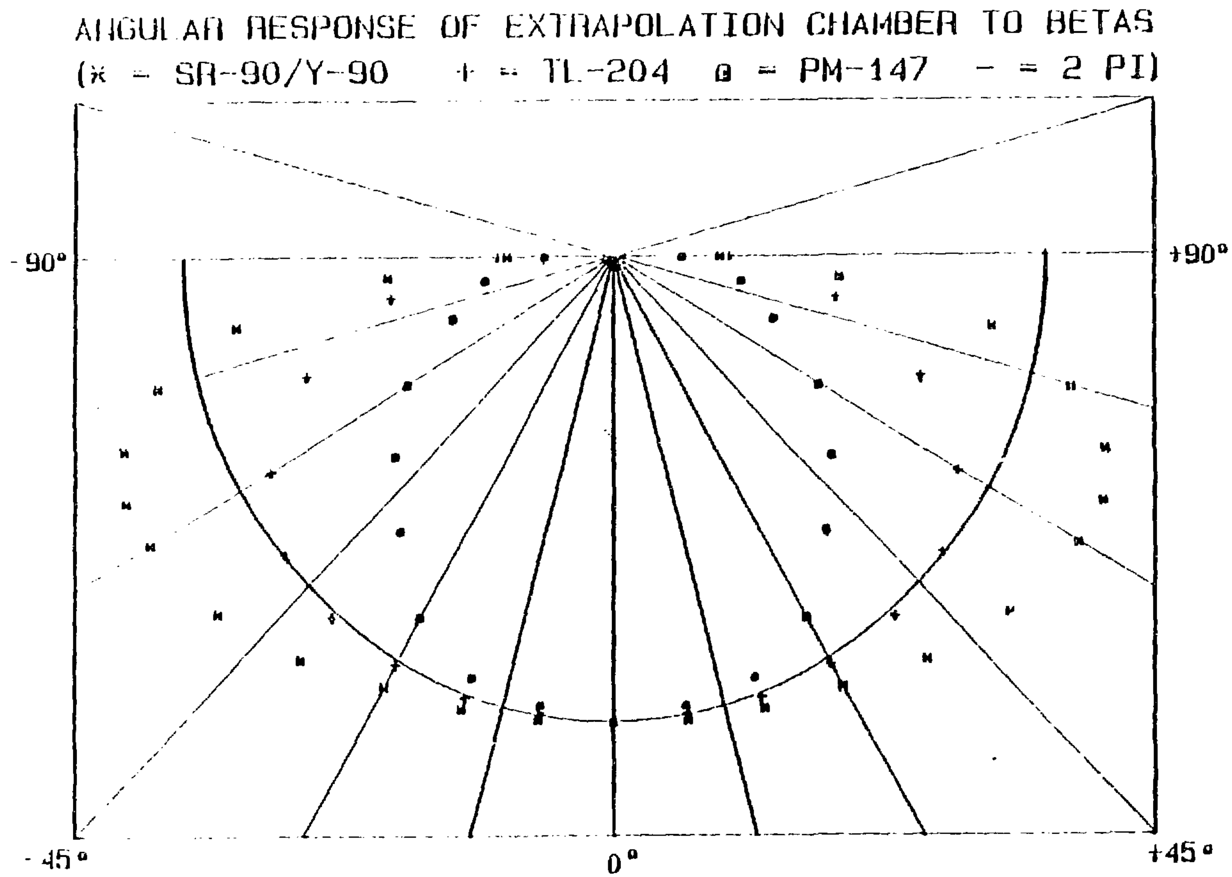

Figure 29. Measured angular response of an extrapolation chamber to parallel beams of beta particles from the three Amersham-Buchler point sources.

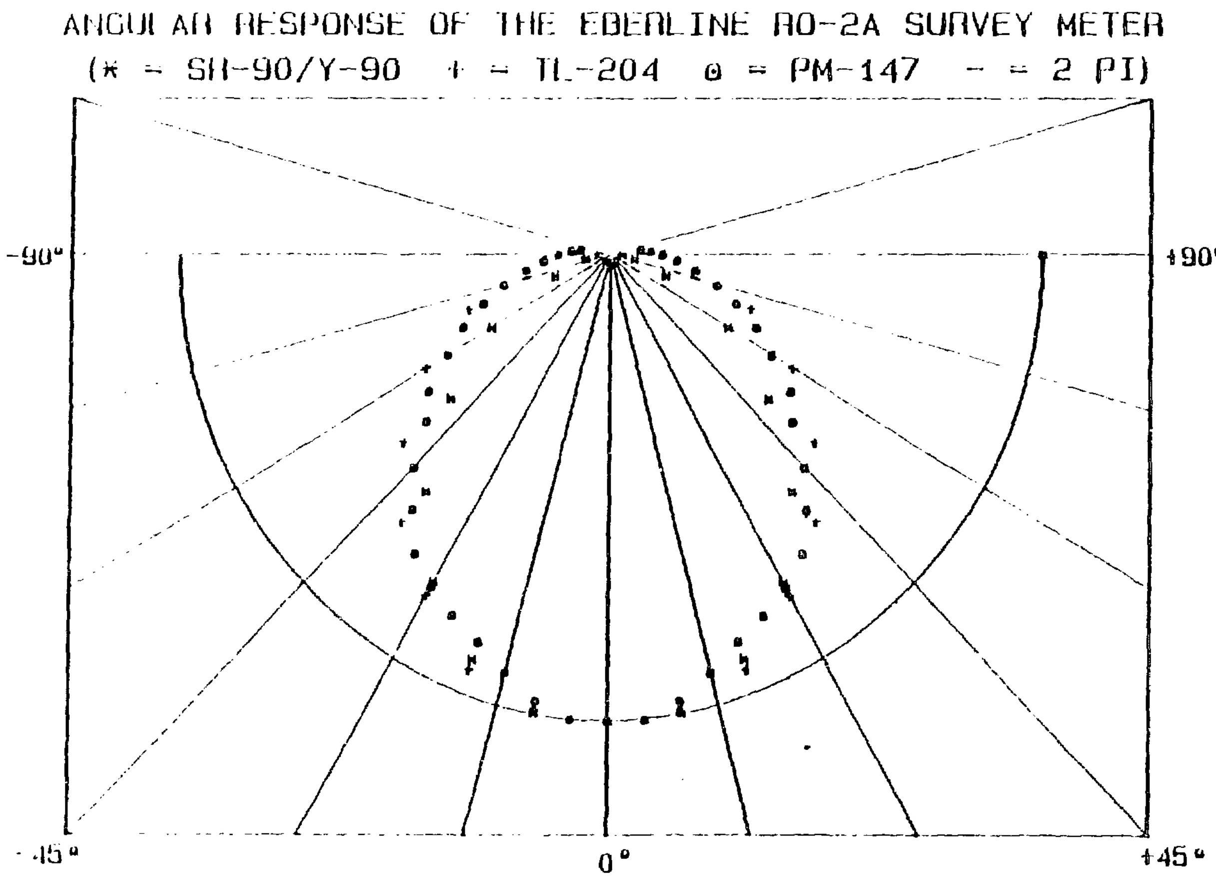

Figure 30. Measured angular response of the Eberline RO-2A Survey Meter to parallel beams of beta particles from Amersham-Buchler point sources.

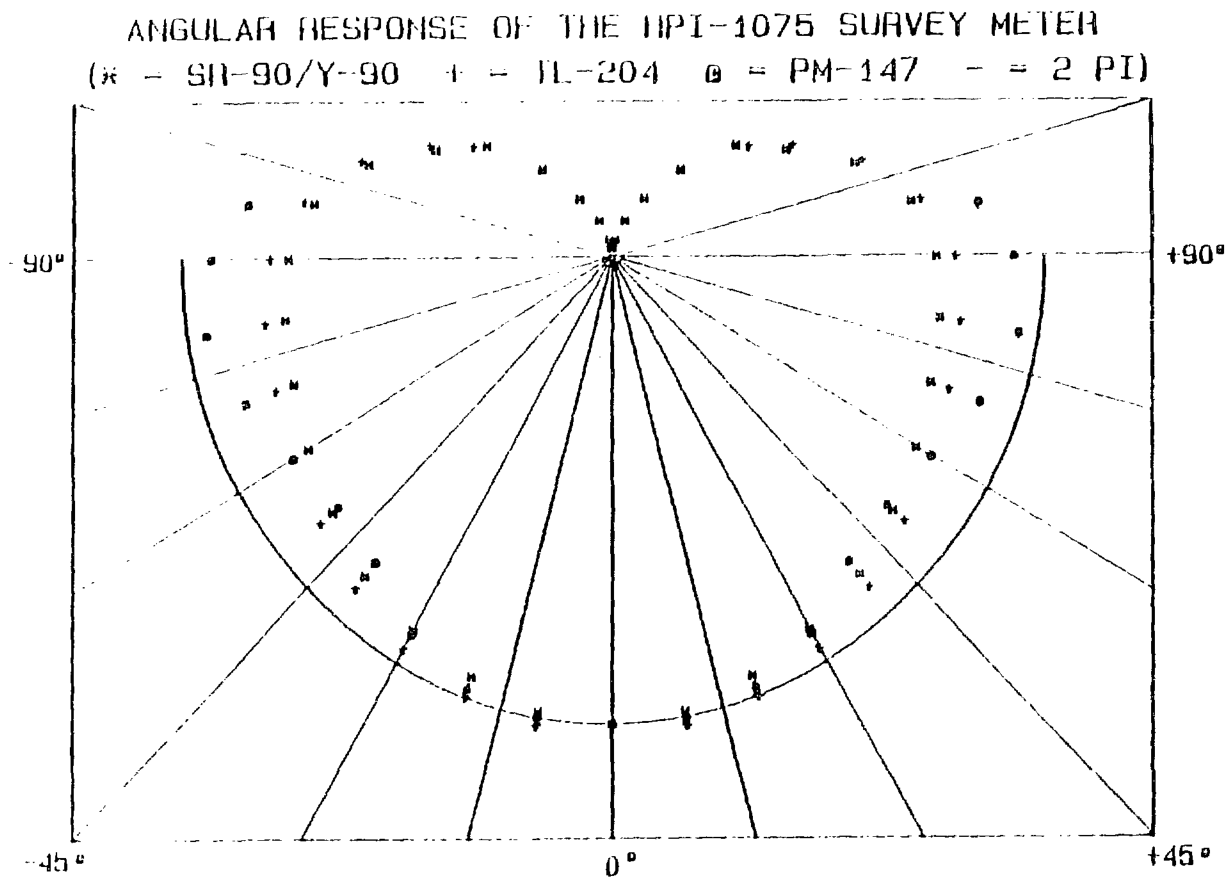

Figure 31. Measured angular response of the Health Physics Instruments Laboratory Model 1075 Survey Meter to parallel beams of beta particles from the Amersham-Buchler point sources.

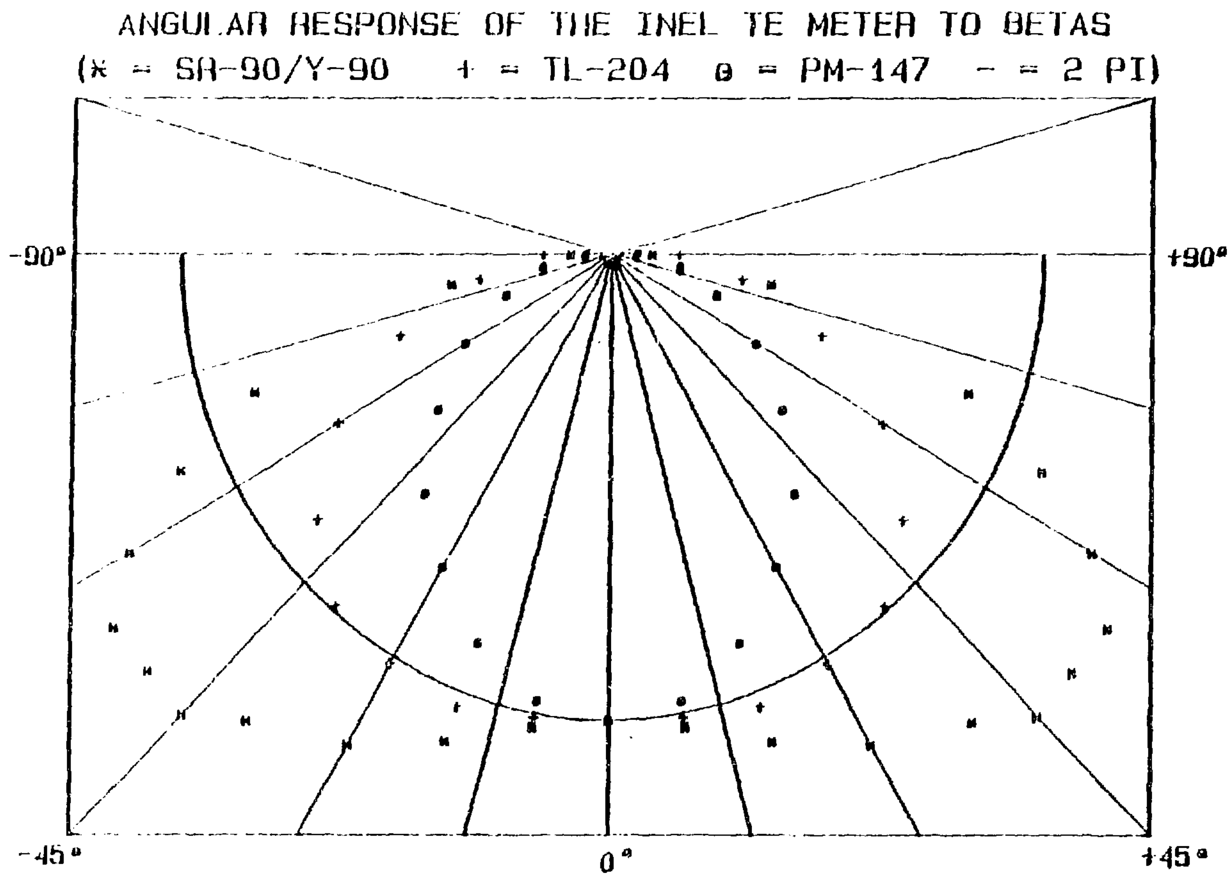

Figure 32. Measured angular response of the INEL TE Meter to parallel beams of beta particles from the Amersham-Buchler point sources.

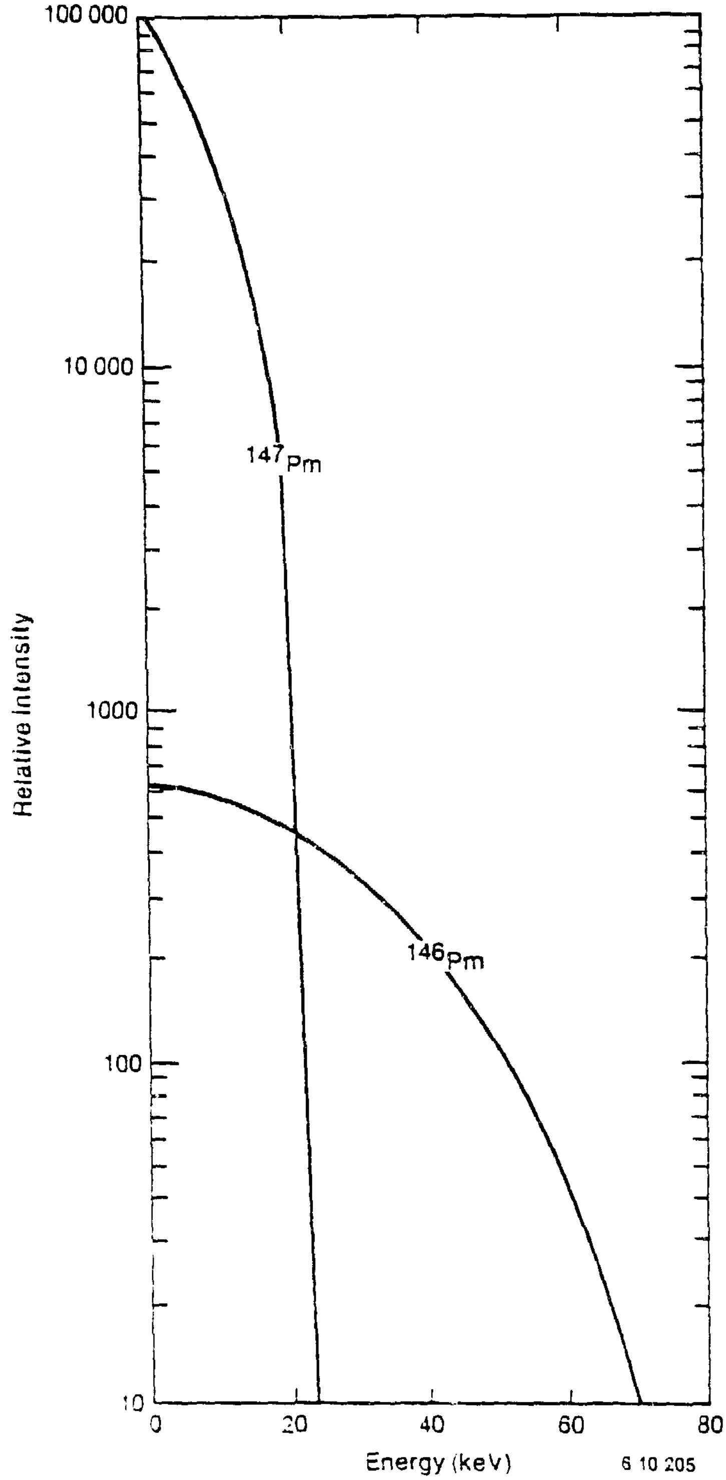

Figure 33. Measured beta spectra for the promethium source

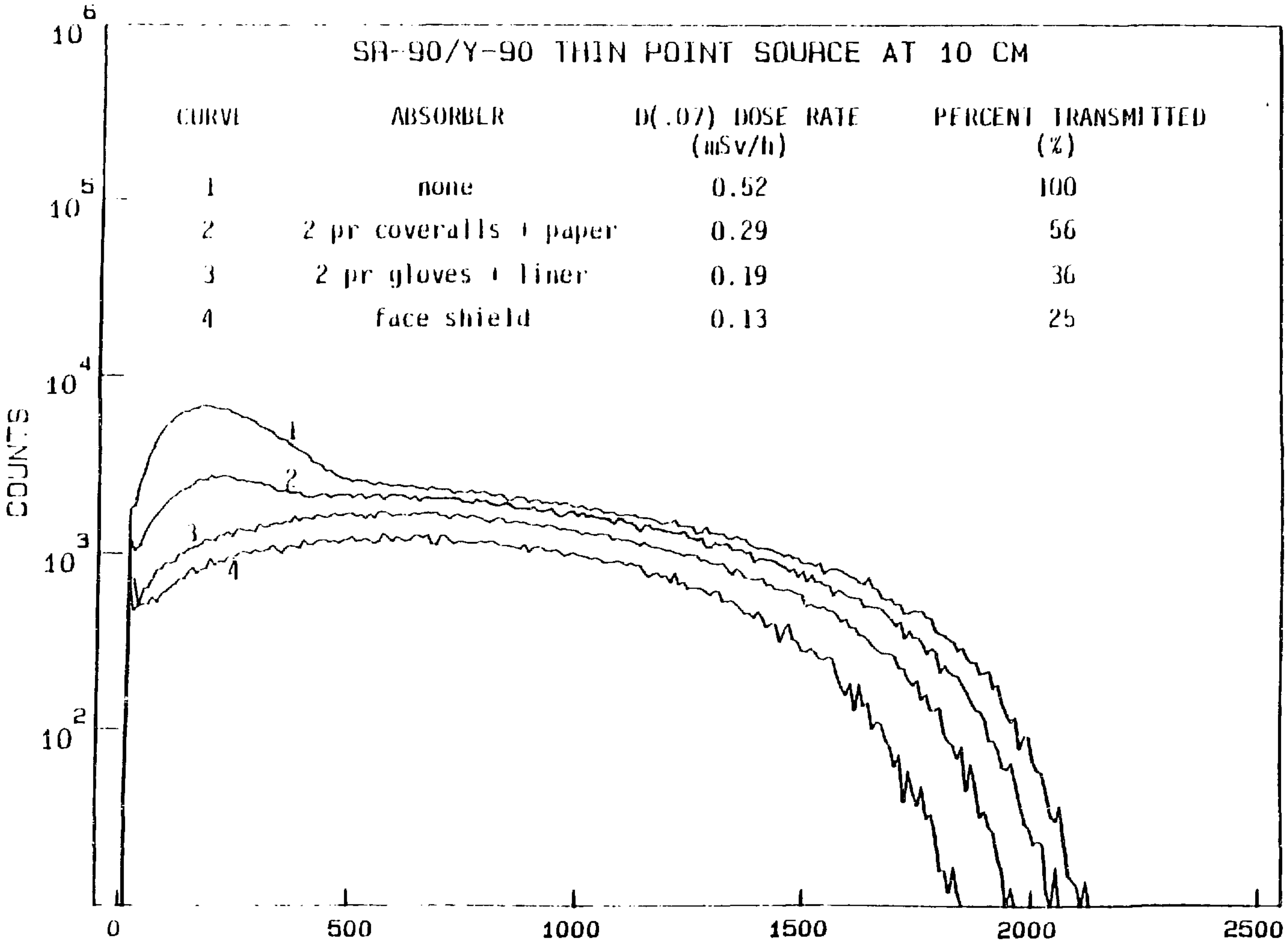

Figure 34. Changes in the beta particle energy spectra and D(.07) dose rate caused by the insertion of standard thickness of protective apparel in the beam.

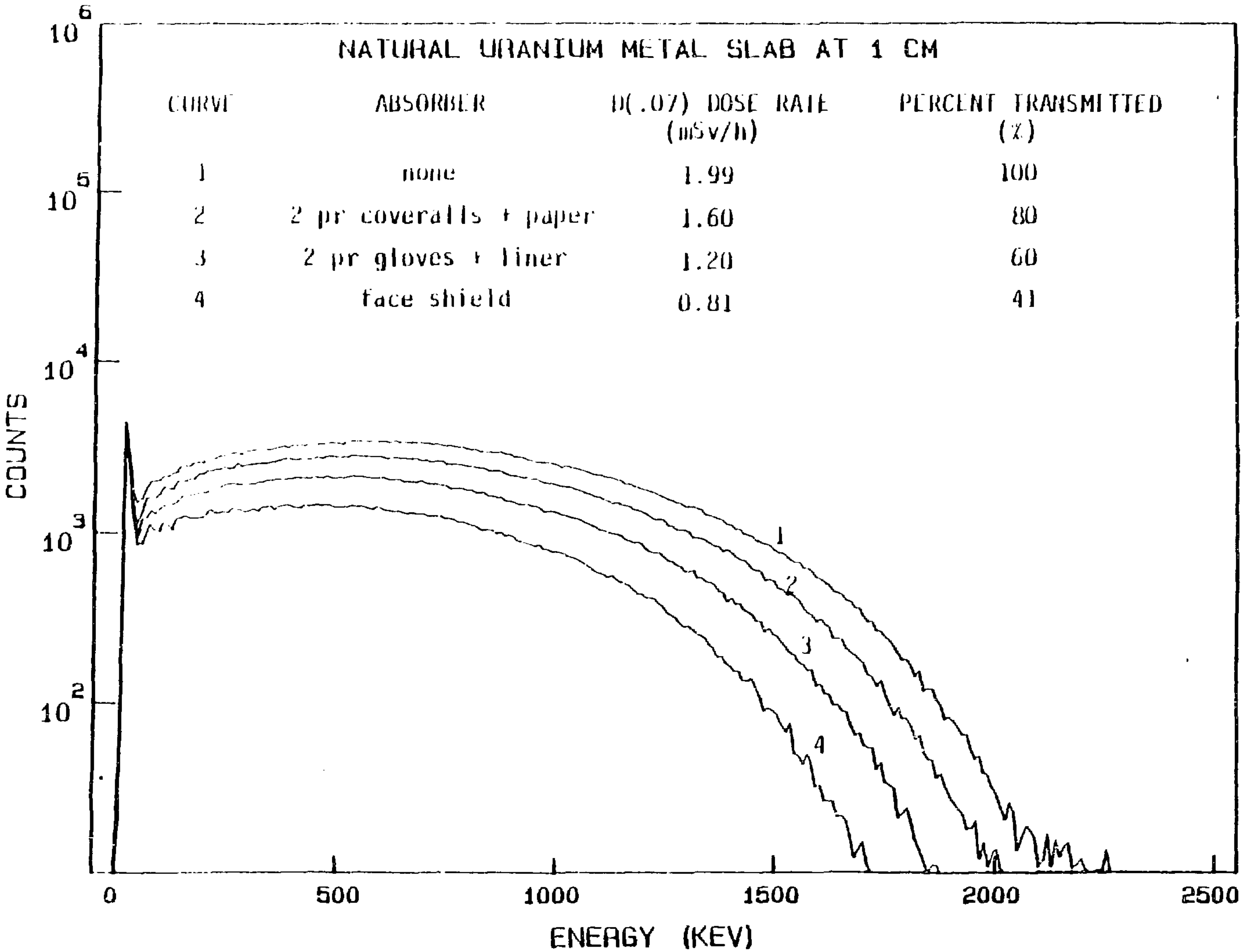

Figure 35. Changes in the beta energy spectra and D(.07) dose rates from a natural uranium metal slab source caused by the insertion of standard thicknesses of protective apparel in the beam. Note the brehmsstrahlung peak at low energies.

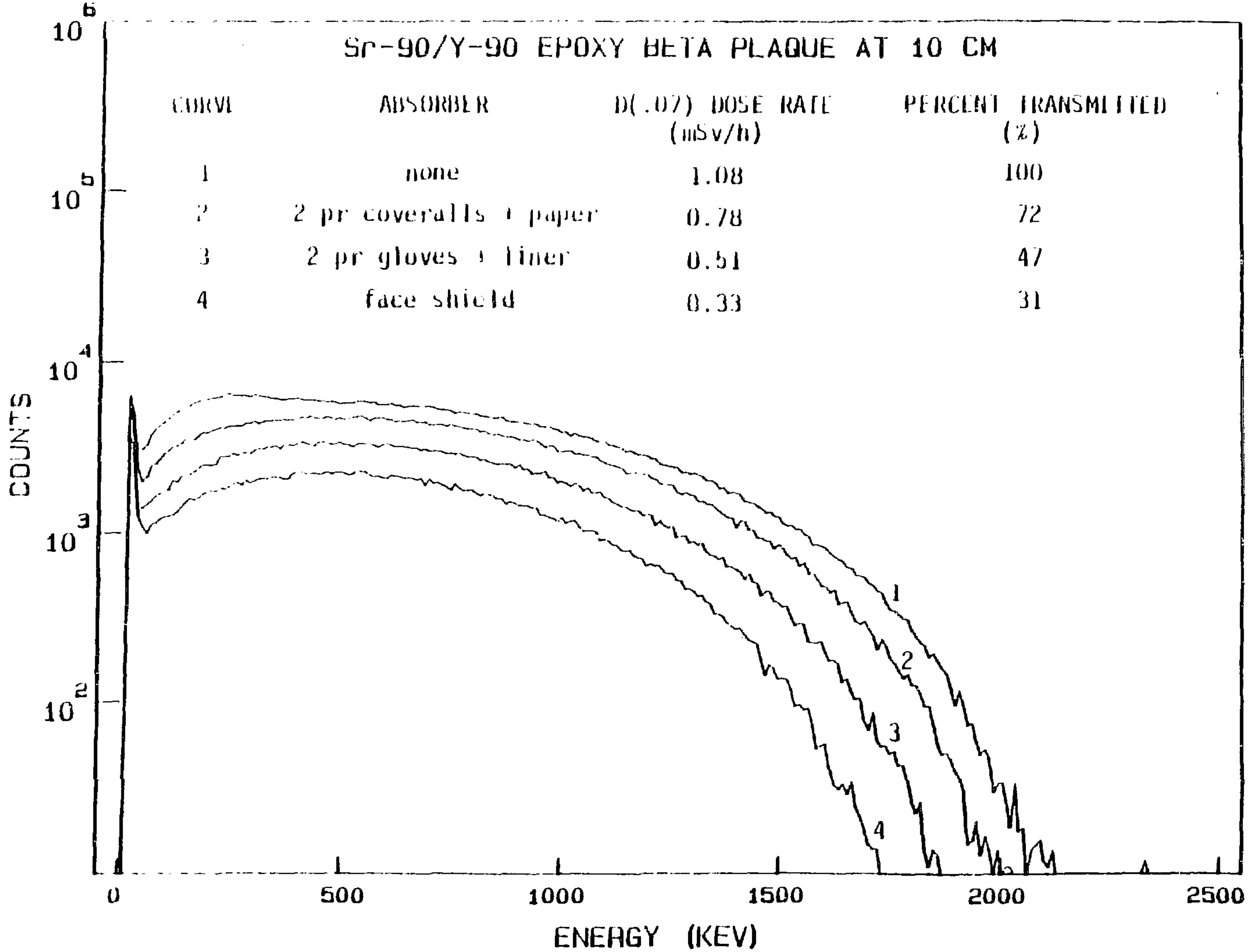

Figure 36. Changes in the beta energy spectra and D(.07) dose rates from a Sr-90/Y-90 epoxy plaque source caused by the insertion of standard thicknesses of protective apparel. Note the virtual absence of the lower energy Sr-90 beta particles in this thick slab source compared with Figure 4.

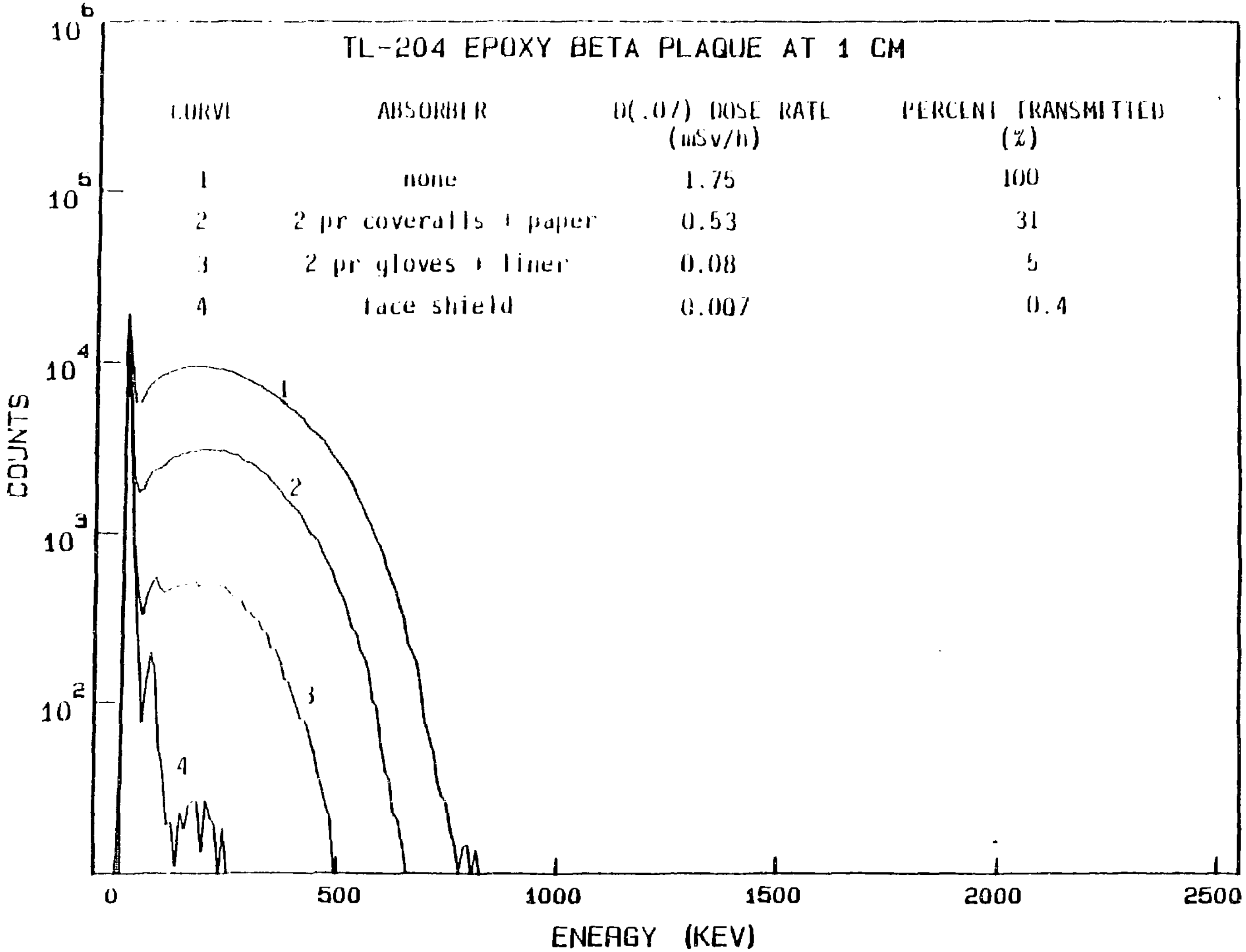

Figure 37. Changes in the beta spectra and D(.07) dose rates from a Tl-204 epoxy plaque beta source caused by the insertion of standard thicknesses of protective apparel.

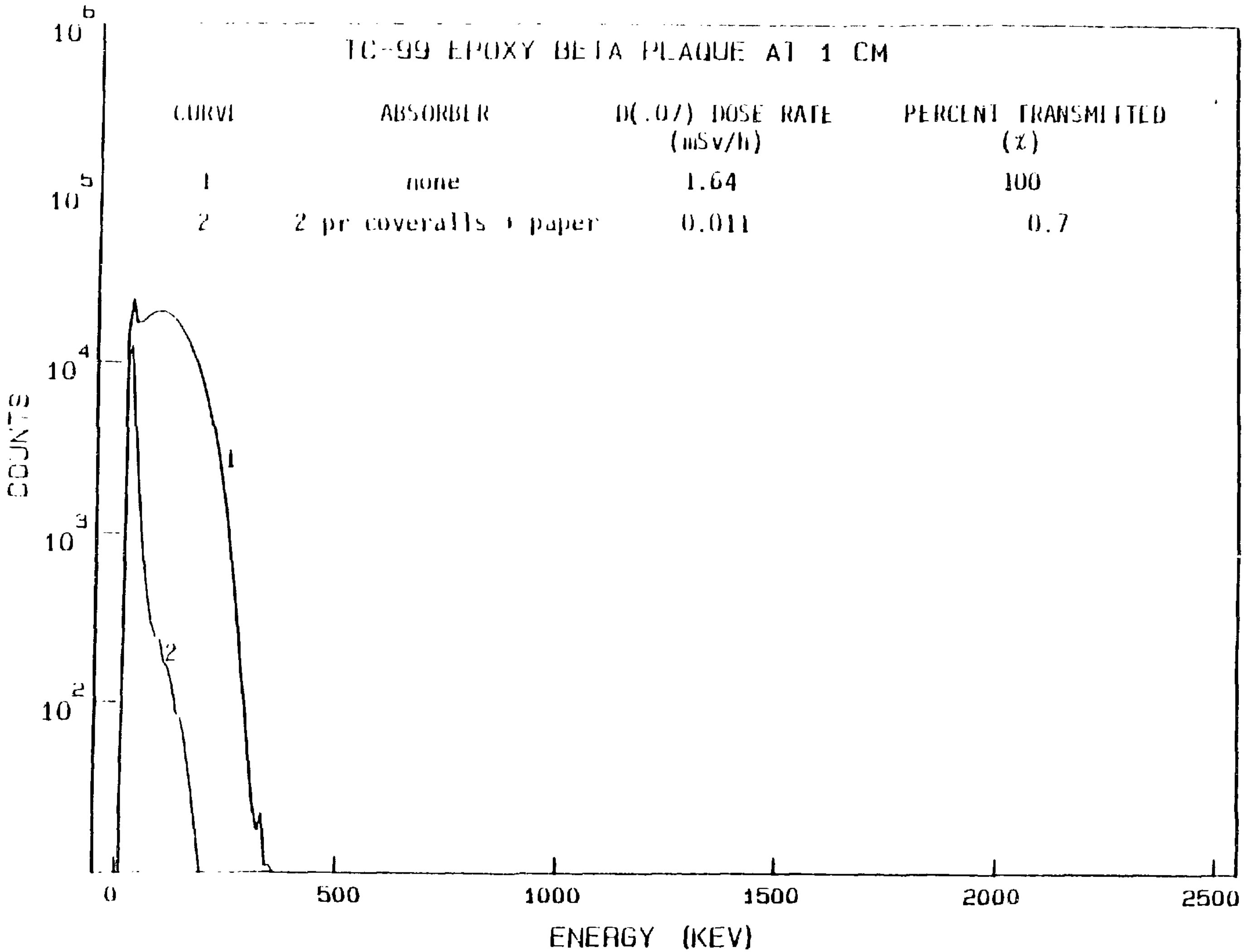

Figure 38. Change in the beta spectrum and D(.07) dose rate from a Tc-99 epoxy plaque beta source caused by the insertion of two pair of coveralls and paper suit.