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Surface Contamination: Decision Levels

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Surface Contamination: Decision Levels

by

J. W. Healy 3317

LOS ALAMOS NATL. LAB. LIBS.
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SURFACE CONTAMINATION: DECISION LEVELS

by

J. W. Healy

ABSTRACT

Levels of contamination are derived for over 180 isotopes for the skin and clothing of workers and individuals in the general public as based on the National Council on Radiation Protection and Measurements (NCRP) recommendations on dose limitation. These levels consider the dose to the skin, the possible inhalation or ingestion of the deposited material, and possible absorption through the skin. Estimates of the levels for transfer to the home are based on these mechanisms plus direct external radiation and resuspension using plausible transfer coefficients. The relation of these transfer levels to transfers to other areas is discussed. Readings on several of the more common types of instruments used to measure surface contamination are then derived. Appendices to provide background data on specific subjects include Appendix A, The Skin; Appendix B, Beta Dose to The Skin and; Appendix C, Resuspension. All derived values for the decision levels for individual isotopes are given in Appendix D.

I. INTRODUCTION

In controlling radioactive contamination on surfaces it is necessary to have guidelines for the level at which action is necessary. These guidelines define the required sensitivity of instruments and procedures and, when exceeded, signal that action is required. Such guidelines can be based on the necessity of keeping certain areas clean or on the possible radiation doses to people.

In the following derivations, we have considered only the radiation doses to people, either from direct contamination of the individual or from transfer to the environment of the individual.

Although a number of possible mechanisms of exposure have been considered, the derivations are by no means exhaustive. We consider, for example, a transfer to the home or to other areas but do not follow the ultimate fate in the environment of the material eliminated from the home.

In many of the situations considered, the physics of the behavior of the radiation is much better known and understood than the dose limits to be applied or the other physical and biological factors influencing the results. Exact solutions to the physics portion would require considerable time and effort without adding significantly to the accuracy of the final result and could result in complication of the presentation, perhaps to the point where attention may be directed away from the main points and the concepts would not be as readily grasped by the reader. A number of approximations and simplifications in this area are made without, we believe, detracting seriously from the overall final result.

In order to preserve continuity of presentation, more detailed discussions of three aspects have been moved to appendices with the conclusions abstracted in the body of the report. The three appendices are Appendix A, The Skin; Appendix B, Beta Dose to The Skin; and Appendix C, Resuspension. The values for the decision levels derived for each of the mechanisms have been accumulated in Appendix D to eliminate numerous tables scattered through the report.

II. SOME GENERAL CONSIDERATIONS

A. Terminology

The values for surface contamination are labeled as "decision levels" to emphasize their intended use. They are not "limits" in the sense that exceeding them is dangerous; in fact, we advocate permitting higher values under known and defined conditions where the principles applied here indicate such a practice to be appropriate. They could be considered as "guides" except that this term has been widely used for limits, particularly in regulations, without the real connotation of permitted discrimination in their use.

The real purpose of the numbers derived herein is to provide an index of a level which can be applied routinely with reasonable expectation that conditions will be satisfactory if they are not exceeded. Thus, they can be used to define the required sensitivity for routine monitoring procedures or instruments without resorting to "minimum detectable." However, the levels are generally derived for assumed conditions which are, in many cases, gross simplifications (or oversimplifications) of real life situations into which some conservatism has been deliberately introduced. Thus, exceeding of the levels is not a signal that harm is imminent, but is rather a signal that the situation should be further investigated by professional people trained in radiation protection work, perhaps by applying the principles given in this report to the specific situation. Hence, the term decision level to indicate the need for

further investigation and decision, taking into account the existing conditions.

B. Radiation Dose Limitations

The primary bases for derivation of surface contamination levels are the recommendations on dose limitation as given by national or international organizations or as required by regulations. In the United States the recommendations of the National Council on Radiation Protection and Measurements (NCRP) have served as a basis for the deliberations of the Federal Radiation Council and for the establishment of most regulations. The rationale for the NCRP recommendations has been well documented so that the background and reasoning can be understood and utilized. For internal emitters the derivations and the constants used by the NCRP[1] are the same as those which have been documented by the International Commission on Radiological Protection (ICRP)[2,3] although slight differences occur in the dose limitation recommendations between these two organizations. For these reasons, the most recent recommendations of the NCRP[4] have been chosen as the fundamental starting point for the further studies.

For the worker, the current recommendations limit the dose to the whole body, bone marrow, or gonads to 5 rems/yr with the stipulation that exposures modestly above this should not be considered as harmful if not frequently repeated. For internal emitters, the 5 rems/yr applies to the organs listed above with 15 rems to all others. Since values for internal emitters from dose to the thyroid and skin were derived on the basis of 30 rems/yr, the MPC's based on isotopes irradiating these organs must be reduced by a factor of two to be comparable to these limits. Past recommendations on bone seekers have been based on the 0.1 μCi body burden for radium with the particulate radiations from other elements considered to be five times as effective as those from radium. It is not currently clear whether these values will be revised to correspond to the 5 rems/yr to the marrow or whether the values based on 0.1 μCi of radium and biological comparison will continue. For our purposes, the bone-seeker values, as given in current recommendations, were used for the worker without change. For the skin, an important organ for surface contamination considerations, the dose limits are those of the current NCRP recommendations: 75 rems/yr to the hands, 30 rems/yr to the forearms and 15 rems/yr to the skin on the remainder of the body.

For the public, the NCRP recommends that the dose to any organ of an individual should not exceed 0.5 rems in one year and that the average dose to a group should not exceed one-third of this or 0.17 rems/yr. We will base our derivations for the public on 0.5 rems to any organ with the understanding that the decision levels should be revised if the contamination is widespread in large uncontrolled areas.

For internal emitters, the maximum permissible body burdens and MPC's published by the NCRP and ICRP have been based on worker

exposure limits. To meet the above public exposures, they must be reduced by a factor, R, which is dependent upon the critical organ. Values of R used are:

Whole Body, Gonads, Red Bone Marrow . . 1/10

Thyroid, Skin 1/60

Bone Seekers and all other organs . . . 1/30

The value for the bone seekers is arbitrary since the application of the rem to these values which were derived by biological comparison of a few isotopes rather than by dose considerations is uncertain.

It is important to note that the use of these dose limitations results in decision levels which are maximum for the conditions considered. There is no allowance for exposure from other sources. This has been done deliberately because it is believed that better decisions on any required reduction can be made by those responsible for the safety program while considering the actual conditions encountered.

C. General Applicability

In most places, contamination control is more absolute than would be indicated by the existence of the control levels. That is, individuals do not routinely operate with skin or clothing contaminated to a given limit, nor are surfaces routinely at the limit. Instead, it has been more satisfactory to clean any contamination until it is below the detection limit of the instrumentation, if this is at all practical. This means that the existence of significant contamination is an unusual situation. Further, any contamination which does occur is usually confined to a portion of the work area rather than being general over all surfaces. Thus, the exposure time for an individual is usually less than the full work time. Since there are no good bases for deriving a universal "frequency factor" for a given area, it can be assumed that the area and the individual are contaminated continuously to the limit. Although this is useful for deriving control limits to be used on a routine basis, it is certainly legitimate to include an estimate of these frequencies for the particular installation in making a final judgment.

D. Applicability to Monitored Areas

Possible radiation protection problems from surface contamination arise from the external radiation exposure of the individual directly from the contaminated area and from the intake to the body. The mechanisms by which these can occur will vary with the radioactive material, its chemical and physical form, and the nature of the area and work. In addition, the present knowledge of many of these mechanisms and their dependence upon the environment is such that variations of many orders of magnitude are noted in measurements.

Therefore, consideration of mechanisms for which more direct measurement of potential exposure are routinely made play only a peripheral role in this derivation. For example, external gamma radiation from a contaminated surface can be easily measured and controlled independently of knowledge of the quantity of material on the surface. Routine surveys for gamma-radiation exposure levels are made in working areas and will show significant exposure rates whether from contaminated surfaces or from other sources. Similarly, air samples are taken routinely in work areas and will detect air concentrations whether they result from resuspension of contamination or from a leak in a drybox. Thus, any resuspension is detected through such air sampling and corrective action can be taken in areas where this proves to be a problem without taking unnecessary action in areas where the surface levels may be high but resuspension is not a problem. Of course, it is necessary to consider these mechanisms of exposure if they occur in an area where routine monitoring is not available. Thus, they can be of importance for the release of contaminated clothing, people, or equipment to general public areas.

III. LEVELS BASED ON DIRECT RADIATION DOSE

Radiation doses can result to an individual because of contamination on his person either by external exposure of the skin or by intake of the radioactive material. Such exposures provide the basis for the estimates of what we call "direct levels." In the following section, the derivations of the values are described with all numerical levels consolidated in Appendix D.

A. Dose to Skin

1. Alpha Emitters. For alpha emitters, external radiation is normally considered to be unimportant because of the short range of the alpha particles and the existence of a protective layer of dead cells (Stratum Corneum) on the surface of the skin. The possibility of an alpha emitter penetrating the dead layer to a sufficient depth to permit the alpha particle to reach the living cells underneath has been raised by Chamberlain,[5] Dunster,[6] and Newberry.[5] Calculations based on various assumed distributions in the tissue have indicated that if such penetration does occur, it could result in a significant dose to these cells. For example, Dunster[6] has calculated the dose to the basal layer of the epithelium for a 7-MeV alpha particle (having a range of 60 μm) by assuming the radioactive material to be distributed with 1/30 in a 35-μm layer close to the basal layer, 1/15 in a 35-μm layer above this, and the remainder on the surface. For this configuration he obtains a dose-equivalent rate of about 80 rems/h for a surface contamination of 1 $\mu Ci/cm^2$. Chamberlain[5] is quoted as having assumed an exponential variation in concentration with depth in the skin and a concentration at a depth of 2 mm of 1% of that at the surface. The 1% value is reported to be based on experimental evidence. Under these conditions the dose-equivalent rate at the basal layer of the epithelium is 60E rems/h (where E is the energy of the alpha particle in MeV) for 1 $\mu Ci/cm^2$ on the surface.

Such calculations are extremely sensitive to the assumptions made as to the depth of penetration of the alpha emitter and the resulting concentrations in skin in the immediate vicinity of the basal cells. Such a distribution is undoubtedly strongly dependent upon the particular radionuclide involved, its chemical and physical form, and even any carrier solvent. Little evidence is available upon which to build a better model even for known specific situations. Tregear[7] presents evidence which indicates that the bulk of the resistance to penetration of the skin occurs in the stratum corneum, the layer of dead cells which comprises about one-half of the epidermis in most regions of the body. This would indicate that, at least for materials which do not pass through the skin to any great extent, the bulk of the radioactivity retained should be in this outer volume. Note that the Dunster model implies this if the upper 35-μm depth is taken as the stratum corneum and the lower 35-μm depth is taken to be the prickle cell layer. A more detailed description of the skin structure and a discussion of penetration of the skin by some materials are given in Appendix A.

It does not seem possible, without additional information, to base any numerical skin contamination level on a calculated radiation dose without the danger of being misleading. However, the possibility of an alpha dose to the skin must be considered in handling contamination cases. This position appears reasonable since the derived levels are only sporadically exceeded. In most of these cases, the contamination is removed readily by simple washing indicating that it is, indeed, on the surface and has not been absorbed or adsorbed on or in the stratum corneum. In cases of gross contamination, as much of the material as possible is removed without damaging the barrier to penetration. In this case, there could be a significant dose to the skin, particularly if the stratum corneum is removed or thinned by the decontamination efforts. However, the practical aspects of this case are that little further can be accomplished without fairly drastic means and such actions, if taken, must be directed toward the specific needs of the individual case.

In the intermediate case where the skin is continually (or frequently) contaminated, it is conceivable that a concentration gradient could be set up across the skin by a continual diffusion through the horny layer. In view of the present knowledge of the gradient, detailed estimates of the possible doses will not be made. This case, however, does indicate the importance of continual surveillance of skin contamination, of the possibility of keeping records of individuals to show the frequency of occurance of such cases, and of corrective action if needed.

The above conclusions must be regarded as generalizations based on experience with alpha emitters such as plutonium or uranium. The possibility exists that other alpha emitters, or even some compounds of the above materials, may penetrate more easily than the more common materials handled to date. In particular, high specific activity (shorter half-life) materials could result in increased penetration because of the small mass and increased activity solubility.

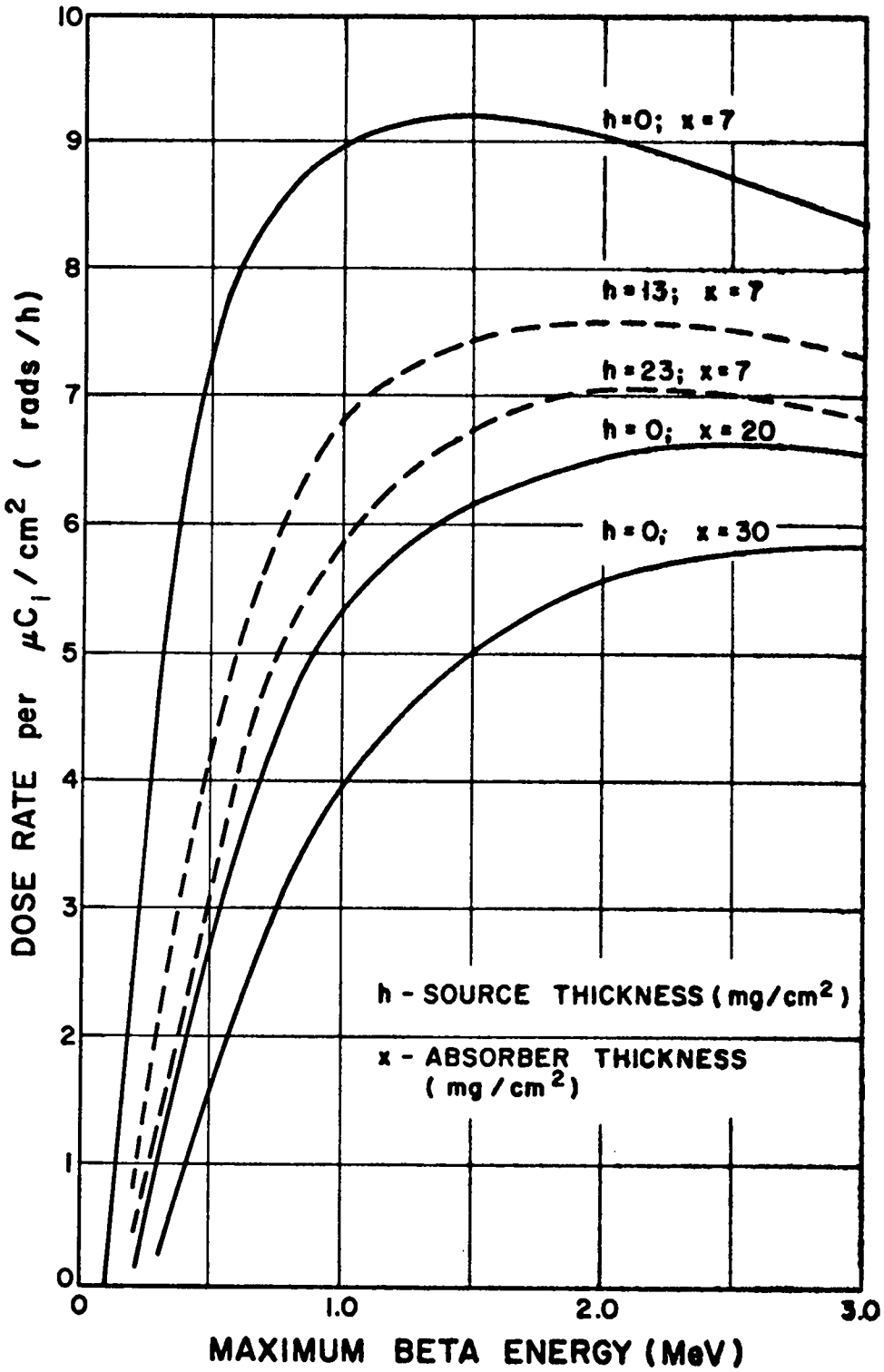

Fig. 1. Beta dose to skin.

Additional data will be needed to answer these questions, even in a general manner.

2. Beta Emitters. Because of the longer range of the beta particles, the dose to the presumed critical cells is not as sensitive to the precise location of the radioactive material as with alpha emitters. Exceptions to this are, of course, the very low-energy beta emitters, such as tritium, and these must be handled as special cases, both in consideration of possible radiation dose and in measuring contamination on the skin. Most contamination cases involve a thin layer of radioactive material on the skin or a thin source such as is obtained when liquids are absorbed in clothing. Under these conditions, the beta dose at contact is far greater than the gamma dose.

Calculations of the dose rate from beta emitters on the skin or clothing were made from Loevinger's equation.[8,9] A description of these calculations, with the necessary assumptions, is given in Appendix B. It should be noted that the dose rate is a function of the average energy of the beta particles. The ratio of this average energy to the maximum energy of the spectrum, as given in published tables, increases as the atomic number of the emitter increases. In addition, certain of the isotopes, including ^{90}Sr and ^{90}Y have anomalous spectral shapes. In the calculations such variations were ignored on the grounds that the accuracy of other factors (such as the thickness of the stratum corneum or the application to field measurements) did not warrant such refinement. To maximize the effect for most isotopes, the average energy was, therefore, computed for an emitter with an atomic number of ten.

Two distributions were evaluated: (1) the dose rate from a zero-thickness, infinite source deposited on top of layers corresponding to the presumed nonsensitive layer of the skin along with several thicknesses of clothing; and (2) the dose rate through the protective layer of the skin from thin, infinite plane sources uniformly contaminated through their thickness to simulate the wearing of contaminated clothing next to the skin. These data are given in Fig. 1 for a contamination level of 1 $\mu Ci/cm^2$.

For comparison with the assumed clothing thickness, Table I gives the weight per unit area of a number of typical fabrics.[10]

Because of the short range of the beta particle in tissue, a relatively small area uniformly contaminated can be considered to be an infinite plane. To check the influence of size of area, data given by Loevinger[8] for the dose rate at the center of a thin disk with no shielding was used for beta particles with maximum energies of 2.0 and 0.7 MeV. The ratio of the dose rate at the center of a disk with the given radius to the dose rate at the surface of an infinite plane for a 13 mg/cm^2 thick source is given in Table II.

Although interposed shielding or distance will require a larger source to approach an infinite plane condition, it is apparent that

TABLE I.

FABRIC THICKNESSES

Fabric	Material	Thickness (mg/cm^2)
Diaper cloth	cotton	13.5
Broadcloth	cotton	11.1
Chambray	cotton	9.6
Chintz	cotton	11.2
Corduroy	cotton	25.2
Covert	cotton	28.0
Denim	cotton	20.4
Flannel	cotton	11.7
Gabardine	viscose-acetate	21.9
	wool	29.0
Gingham	cottom	11.0
Hickory stripe	cotton	24.7
Butcher linen	linen	24.2
Organdy	cotton	4.1
Percale	cotton	11.0
Poplin	cotton	20.9
Seersucker	cotton	16.8
Serge	viscose-wool	17.3
	wool	65
Sheeting	cotton	13.6
Twill	cotton	25.6

TABLE II.

FINITE DISK SOURCE

2.0 MeV		0.2 MeV	
Disk Radius (cm)	Ratio of Dose Rate to Center to Dose Rate from Infinite Plane	Disk Radius (cm)	Ratio of Dose Rate at Center to Dose Rate from Infinite Plane
0.014	0.3	0.015	0.5
0.027	0.4	0.31	0.65
0.081	0.6	0.061	0.85
0.136	0.75	0.15	1
0.27	0.9		
0.68	1		

the infinite plane calculations are adequate for most conditions encountered in the field.

3. Electromagnetic Radiations. The electromagnetic radiations, including gamma radiation or the characteristic x rays from orbital electron displacements, can also contribute to the skin dose. The radiation dose from these components was calculated from the equation for the dose rate from an infinite plane source with an absorber between the source and the detector.[11]

$$D = 1.07 \frac{\mu_a}{\rho} \bar{E} \left[\bar{E}_i(\mu s) + ke^{-\mu s} \right] \quad \text{(rads/h)} \quad . \qquad (1)$$

D is the dose rate in rads/h, $\bar{E}$ is the average energy emitted/disintegration in MeV, μ_a/ρ is the energy absorption coefficient in cm^2/gm, μ is the total absorption coefficient in cm^2/gm, and s is the shield thickness in gm/cm^2. This equation has the constants for a surface source of 1 $\mu Ci/cm^2$. The term $\bar{E}_i(\mu s)$ is the exponential integral given in the tables of Jahnke and Emde.[12] The second term $Ke^{-\mu s}$ includes the buildup from scatter with $k = (\mu-\mu_a)/\mu_a$ and overcorrects for scatter under conditions such as the present ones where the source is close to the receptor.

Calculations were made using the absorption coefficients for water as given by Storm and Israel[13] with the results for the dose through thicknesses of 7 and 20 mg/cm^2 given in Fig. 2. A check was made of the difference in dose rate using the composition of skin as listed by the ICRP[2] at 10 and 100 keV to evaluate the effect of trace elements. Dose rates were slightly lower than for water because of the presence of relatively large quantities of nitrogen and carbon which serve to reduce the amount of oxygen and, thus, outweigh the small amounts of heavier elements. It should be noted, however, that conditions which could place heavier elements in the horny layer of skin, such as working in solutions or using them as medications could result in an increased dose to the sensitive layer of the skin from x rays.

4. Decision Levels-Skin Contamination. The curves discussed above provide an estimate of the radiation dose to the skin from beta particles and photons. If the radioactive material penetrates the horny layer of the skin so that the basal cells are within range of the radiations, a dose can also be postulated from Auger electrons and from the lower energy x rays. Until additional data become available on the degree of penetration, these sources of exposure will be ignored, but the possibility of their existence should be kept in mind, particularly if contamination is encountered which is not easily removed from the skin.

The isotopes to be considered have a half-life of about 1 day or longer and are listed in Appendix D, Table D-I along with their major radiations. The beta-particle energy given includes only the major particles emitted. That is, if an isotope decayed with a few

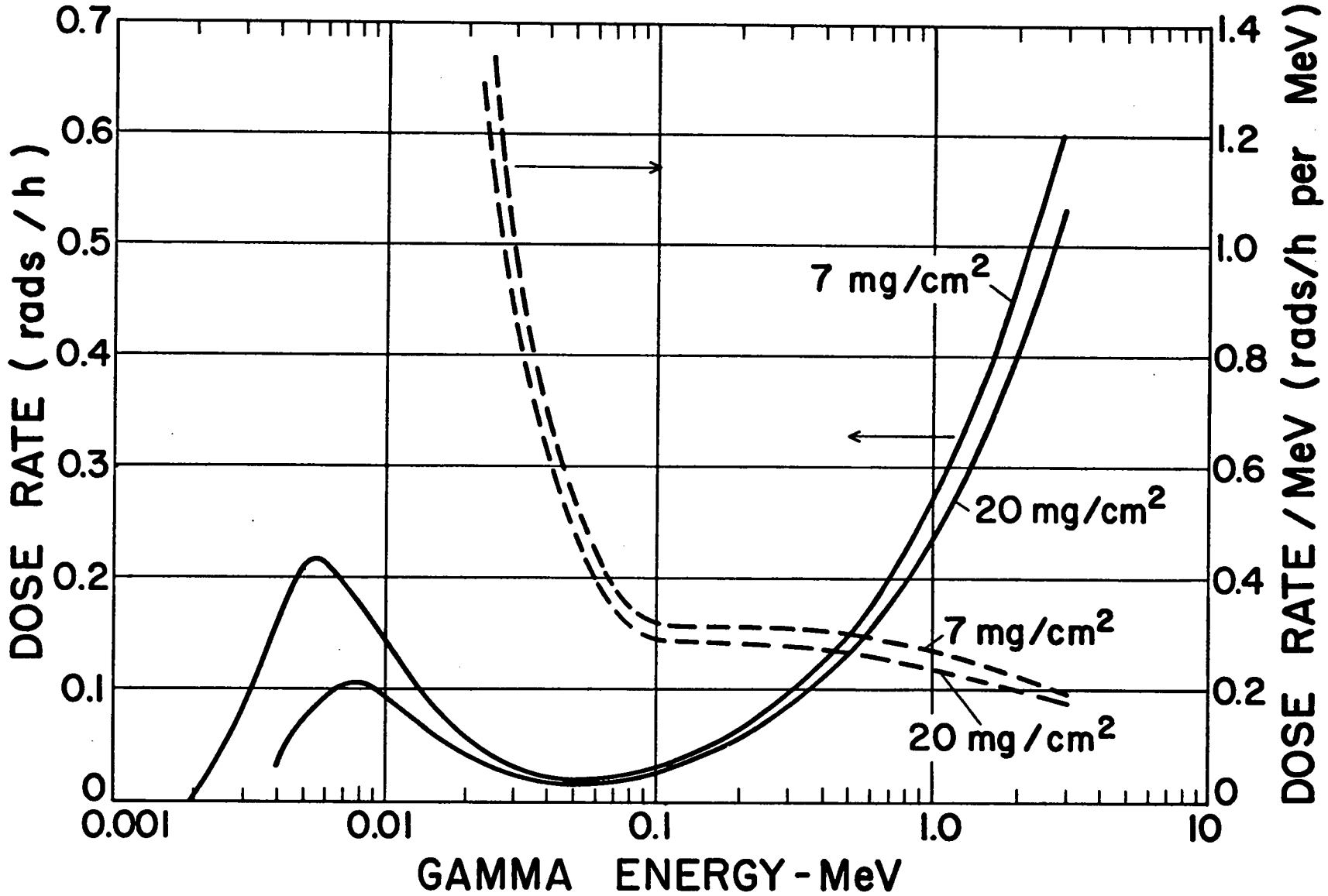

Fig. 2. Gamma and x-ray doses to skin, 1 μCi/cm².

percent of a different energy than is given, these contributions were ignored and only the predominant energies were listed. Beta particles from very short-lived daughters, where it seemed likely that the daughter would come to equilibrium rapidly and contribute to the dose or measurement of skin contamination, were included although no extensive search was made for such situations. For isotopes that decay by isomeric transition or orbital electron capture, the energy of the characteristic K x ray is given. An additional dose will be contributed by the conversion electrons but these are not included due to lack of information on their frequency for many isotopes. However, for most isotopes the conversion electrons occur in less than 1% of the transformations. The average gamma energy was obtained from tables of Lederer, et al.,[14] taking into account both the energy and abundance of the individual lines listed. The radioactive half-life as given in Ref. 14 is also included.

A review of the photon emissions from alpha emitters indicated that, in the majority of the cases, the gamma radiation was either very small or occurred primarily from the daughter products. For this reason, no attempt was made to estimate the gamma dose from these materials, but those isotopes which have significant gamma radiation, either from the material itself or from daughters, are indicated in Table D-I.

The decision levels based on skin contamination in Table D-I are based upon the continuous maintenance of the contamination on a given area of skin for the full period of interest. A dose limitation of 15 rems/yr was used for the worker and, in Table D-II, 0.5 rems/yr for individual members of the public. For the worker, the period of interest was taken as the time at work (40 h/wk and 50 wk/yr or 2000 h/yr). Note that this assumes that all contamination is removed from the skin before he leaves work. Any contamination left on the skin for the remainder of the day will contribute to the dose and a corresponding reduction in the "at work" levels should be made. For an individual in the public, the full 24 h/day and 365 days/yr or 8760 h/yr was used because of the lack of monitoring and control.

The beta dose rate for unit contamination was read from Fig. 1 for the beta energies emitted by the isotope. A value of the dose from gamma rays of 0.3 $\bar{E}$ rads/h per $\mu Ci/cm^2$, where $\bar{E}$ is the average energy emitted per disintegration, was used since this rate is fairly constant above 0.1 MeV. The error resulting for gamma rays with energy less than 0.1 MeV is negligible when the uncertainties in the dose calculations are considered. For isotopes decaying by orbital electron capture, the x-ray dose was estimated from Fig. 2 assuming all decays to occur by capture of the k electrons. The fluorescent yields from the k and l shells were obtained from Ref. 14 and the average binding energy for these shells was obtained from Ref. 13.

If D is the total dose rate from these sources in rads per hour (taken to equal rems per hour for these radiations) per microcurie

per square centimeter then the decision level for the worker becomes

$$DL_s = \frac{15}{2000\ D} = \frac{7.5 \times 10^{-3}}{D} \quad \mu Ci/cm^2 \quad . \tag{2}$$

Since the annual level for the hands is 75 rems, the decision level for hand contamination can be taken as 5 times the values listed and, for the forearms, where the decision level is 30 rems, the decision level can be taken as twice the listed value.

For the public, the decision level becomes

$$DL_s^p = \frac{0.5}{8760\ D} = \frac{5.7 \times 10^{-5}}{D} \quad \mu Ci/cm^2 \quad . \tag{3}$$

This value also applies to the hands and forearms.

The foregoing levels were based upon the continuous occupation of an individual in such a manner that contamination lost from the skin was followed by additional contamination to the same level so that exposure was continuous. In a more common case, a specific area will be contaminated in an incident and the radiation dose will persist only as long as this contamination is present. In such a case, the initial contamination level can be higher than the continuous value by a factor depending upon the persistence of the contamination. The factor to be applied depends upon the frequency with which such incidents occur within the year to produce contamination of similar areas of the body. Because the dose limits are essentially based on a 1-yr accumulation, the maximum averaging time is taken as 1 yr. The following considerations, then apply to the case of such incidents that occur with a frequency of 1 yr or less to the same individual.

For contamination of the skin, the lifetime of the contaminant is limited by the rate of renewal of the epidermis. If, for example, the contamination is uniform through the stratum corneum, about 1/15 would be removed per day, as based on the original quantity present, and at the end of 15 days it would be completely eliminated assuming further that there was no migration inward during this time. If, as appears likely, any fixed contamination occurs nonuniformly through the stratum corneum (and possibly into the prickle layer) with the highest levels at the surface, the effective rate of removal in the early period will be higher than 1/15 per day since the more contaminated outer layers will be sloughed first. Extensive efforts at decontamination could remove a portion of the stratum corneum which would tend to accelerate the division in the basal layer to replace the missing cells, but the rate of sloughing of the outer layers may also be delayed until the stratum corneum is essentially replenished. This could cause the residual contamination left in such areas to be somewhat slower in elimination. These factors plus the variability

among individuals in the replacement rate of the epidermis indicate that an effective half-life on the order of 15 days may be appropriate for consideration as the rate of removal of the contamination from the skin.

The total dose to the skin with this elimination rate will be delivered within the first year and is given by

$$\text{Dose} = 24\ D \int_0^\infty e^{-(\lambda+\lambda_s)t}\ dt \quad , \tag{4}$$

where D is the dose rate in rads per hour per $\mu Ci/cm^2$ as evaluated for the continuously maintained decision level, λ is the radioactive decay constant of the isotope in $days^{-1}$, and λ_s is the elimination constant for the skin (0.693/15). The factor of 24 arises from an assumption that the contamination is fixed in the skin and cannot be removed before leaving work. This leads to an expression for the decision level for the worker for a single event (*DL) of

$$*DL_s = \frac{15(\lambda+\lambda_s)}{24\ D} = \frac{0.693}{24\ D}\left(1 + \frac{15}{T_{\frac{1}{2}}}\right) \quad , \tag{5}$$

where $T_{\frac{1}{2}}$ is the radioactive half-life in days. The ratio of this to the continuously maintained level (Eq. 2) is

$$\frac{*DL_s}{DL_s} = 3.85\left(1 + \frac{15}{T_{\frac{1}{2}}}\right) \quad . \tag{6}$$

Thus, for a long-lived isotope, the single-event contamination level is about four times the continuous level. The ratio increases as the half-life decreases with a value of about 8 for a half-life of 15 days and about 60 for a half-life of 1 day.

For the public, the ratio based on a total dose of 0.5 rems becomes

$$\frac{*DL_s^p}{DL_s^p} = 17\left(1 + \frac{15}{T_{\frac{1}{2}}}\right) \quad . \tag{7}$$

5. Decision Levels-Clothing. The dose to the skin from contaminated clothing was estimated assuming the contamination to be uniformly distributed through a thickness of 23 mg/cm^2 with the dose delivered through the protective layer of the skin of 7 mg/cm^2. For the beta radiation, the dose rate was read from Fig. 1 and for the gamma radiation, a value of 0.3 $\bar{E}$ rads/h per $\mu Ci/cm^2$ per MeV was again used. The gamma value varies more with energy in this situation than for the contamination on the skin (Fig. 2), but the constant value for all energies is within the desired accuracy. The dose limit to the skin was taken as 15 rems/yr in this case without

a separate value for the hands and forearms because the clothing generally covers the portions of the body where the limit of 15 rems is applicable.

Calculations were made only for the beta emitters. The electron capture x rays are so weak that the dose will be dependent upon the exact assumptions. If a level is desired, it is suggested that it be obtained from the curve of Fig. 2 giving the transmission through 20 mg/cm^2. These levels are probably conservative in that the clothing thickness chosen is minimum and the contamination may be confined to the outer surfaces of the clothing rather than distributed through it. The difference or degree of conservatism does not seem to be great for most isotopes however, since the curves of Fig. 1 are generally within a factor of 2 or 3 of each other. Another element of conservatism is the fact that the levels are based on full-time wearing of the contaminated clothing, whereas, in practice, work clothing is only worn during a portion of the day and personal clothing is changed at intervals. Allowance for this can be made for the particular situation if the appropriate "occupancy factors" are known.

The decision levels for the worker and public are derived from the same equations as were used for skin with appropriate adjustment of the dose rate per $\mu Ci/cm^2$. Levels for the worker are given in Table D-I and for the individual members of the public in Table D-II.

There seems to be no good basis for deriving a single-event limit since the mechanisms and efficiency of removal of contamination from the clothing do not appear to be definable. Further, there seems to be no real need for such a limit since the countermeasures are relatively simple. The problem of "loose" contamination, which is removed from the clothing by wearing or even periodic washing, as opposed to "fixed" contamination, which essentially remains with the garment even after cleaning, also rises. Although no single-event levels are derived here, it is suggested that a conservative (perhaps) value could be obtained from the equations listed for skin with only the radioactive half-life considered (i.e., λ_s equal zero). This, in conjunction with a use factor for the garment, would overestimate the dose from any loose contamination but would give a reasonable estimate for the "fixed" contamination.

B. Absorption through Skin

A brief review of data on skin penetration is given in Appendix A. Data on only four materials were found for conditions where the quantity of materials present on the skin was less than that required to maintain a pool which could serve as a reservoir to maintain a fixed concentration on one side. For tributyl phosphate, Tregear[7] gives data which leads to a penetration rate in excised pig skin of 2×10^{-3} percent/min. Data from Hanford studies with rats[15-19] indicate a plutonium penetration rate on the order of 5×10^{-5} %/min. Here the plutonium was applied in a small quantity of 0.1 N nitric acid. Data from the use of 10 N nitric acid indicate

a much higher uptake but the skin was seriously damaged. Uptake from a slightly acid solution of tributyl phosphate and carbon tetrachloride was about five times greater with some indication that decontamination efforts could have increased the uptake by another factor of ten. These uptake rates appear reasonable when compared with the meager human data, particularly when it is remembered that rat skin is more permeable to most substances than human skin.

A Russian reference quoted in Nuclear Science Abstracts[20] indicated that 0.347% of a plutonium citrate solution placed on shaved, degreased skin of young pigs was absorbed in 6 days with 0.183% being absorbed the first day. The Russians indicate that the distribution of the plutonium in the animal was similar to an intravenous administration with 81% in the skeleton and 18.5% in the liver. These values amount to an average rate of 4×10^{-5}%/min over the 6-day period with a rate of 1.27×10^{-4}%/min for the first day.

A recent report by Watters and Johnson[21] indicates that $PuCl_3$ DMSO (dimethyl sulfoxide) solution applied to the extent that the circulating blood 5 min after application contained 0.26% of the applied plutonium. For a subcutaneous implant of this material, about 8% was absorbed in 10 days (6×10^{-4}%/min).

Another Russian reference in Nuclear Science Abstracts[22] indicated that ^{89}Sr absorbed quantitatively in different layers of rat skin. For example, an intense infiltration into the dermis was noted in the first few minutes following application of ^{89}Sr-hydrochloride. After a 15-min exposure, about 12% of the material penetrated the dermis (∿1%/min) and after 6 hours penetrated up to 40% (∿0.1%/min).

Harrison[23] has given data for the uptake of iodine through human skin. For iodide in aqueous solution, the rate of penetration is 1 to 2×10^{-3}%/min. For I_2 in aqueous solution the rate is 5×10^{-4} to 1×10^{-3}%/min, whereas for I_2 applied as a vapor, the rate is about 4×10^{-3}%/min although there may be some question as to skin damage with the vapor due to the amount of carrier used. Murray[24] has given data for the uptake through swine skin for iodide (with 15% I_2), which is 2 to 5 times higher than the values measured for humans by Harrison while for the uptake of I_2 the rate measured by Murray is about one-tenth that measured by Harrison.

Comparison of the permeability constant measured for bromide ion with other substances may also give a clue as to the relative probability of absorption through skin. Mercuric ion and chromate ion, say, penetrate 5 to 10 times as well as bromide while aluminum is about 1/10 to 1/100 as great.[7] If we assume bromide and iodide to be about equivalent in penetration rate, them some ions may penetrate at rates up to 10^{-2}%/min or greater. Unfortunately, evidence is meager on specific materials so that judgments cannot be based on firm evidence.

The possibility of absorption through the skin for various toxic materials is recognized in the Threshold Limit Values for

airborne contaminants as established by the American Conference of Governmental Industrial Hygienists.[25] Here certain of the materials are marked with the notation "skin" which implies: "Listed substances followed by the designations 'skin' refer to the potential contribution to the overall exposure by the cutaneous route including mucous membranes and eye, either by airborne, or more particularly, by direct contact with the substance. Vehicles can alter skin absorption. This attention-calling designation is intended to suggest appropriate measures for the prevention of cutaneous absorption so that the threshold limit is not invalidated." In the listing most of the substances so marked are organic compounds and these include a large number of halogenated materials. Others include carbon disulphide, cyanide, decaborane, dimethyl sulphate, mercury, organic compounds of mercury, tetraethyl lead, and soluble compounds of thallium.

Tregear[7] has pointed out that under conditions where the radioactive material is on the skin surface, and not as a solution in contact with the skin, the appropriate parameter is the fraction penetrating per unit time (Appendix A). This would indicate that within reasonable limits, the penetration and absorption is a function of the total amount of material on the skin and not the quantity per unit area. For this reason the decision levels are based on the total quantity on the body. This requires that the area contaminated be estimated or that routine levels be obtained by assumption of the area subject to contamination. For present purposes, we will express the levels as total quantity on the body and later will discuss possible routine monitoring decision levels. As a rough guide, the skin area of the average man is about 1.85 m^2. Thus, if one assumes the full body to be contaminated, a conservative decision level can be obtained by dividing the total amount on the body by about 20,000, or, within the accuracy of the data divide by 10,000. The latter factor provides the level in nCi/cm^2 if the number of μCi are divided by 10.

To estimate the quantity that could be continuously maintained on the skin, it was assumed that any isotope taken up by the blood after absorption through the skin is deposited in the body in the same distribution pattern as occurs after the absorption from the GI tract. The maximum permissible intake to the blood was then calculated from the MPC for soluble isotopes in water and the uptake from the GI tract as given by the ICRP.[2,3]

The ICRP assumes that 50% of the daily water intake of 2200 ml occurs during the 8-hr workday or, including weekends and vacations, the average intake at work is 750 ml/day. The MPC_w for a 40 h wk is based on this intake. For the worker, then, the quantity on the body to result in absorption equivalent to that from the GI tract at the maximum permissible level is

$$SAL = \frac{(MPC_w')\,(750)\ f_1}{330\ f_{ab}} = 2.27\ \frac{(MPC_w')\ f_1}{f_{ab}} \quad . \tag{8}$$

SAL is the decision level for skin absorption in microcuries, MPC_w' is the maximum permissible concentration in water for a 40-hr exposure as based on a critical organ other than the GI tract, f_1 is the fraction absorbed from the GI tract to the blood, and f_{ab} is the rate of absorption through the skin in min^{-1}. The 330 represents the average number of minutes worked per day by the individual to correspond to the 750 ml of water ingested per day. For isotopes having the thyroid or skin as the critical organ, the MPC_w' was reduced by 50% to conform to the latest recommendations of the NCRP concerning dose to these organs. It should be noted that no allowance was made for possible absorption from contamination left on the skin when leaving work.

For an individual in the public, it was assumed that the contamination was present 24 h/day and the corresponding level is

$$SAL = \frac{(MPC_w)(2200)\ f_1\ R}{24 \times 60\ f_{ab}} = 1.53\ \frac{(MPC_w)\ f_1\ R}{f_{ab}} \quad . \tag{9}$$

The symbols are as given earlier with the exception that the MPC_w is that for a 168 h week and R is the reduction factor appropriate to the critical organ.

The value of f_1 is important to estimate this absorption; however it is not used directly in estimating the MPC_w and, in many cases, is given as a "less than" value. In these cases, the value of f_1 was used as listed ignoring the "less than" connotation. This provides a decision level for these cases that is a maximum rather than a minimum and this uncertainty must be considered along with that in f_{ab}.

Data available for f_{ab} are inadequate to provide discrimination between isotopes, much less chemical compounds of a single isotope. It is apparent that the absorption of plutonium is lower than that of strontium or iodine since even the compounds normally regarded as soluble have relatively low penetration rates. There is a temptation to scale the available data according to the absorption from the GI tract, but the conditions under which the absorption takes place are so different that it was deemed to be inadvisable. In the GI tract, for example, the chemical and physical characteristics of the absorbing membrane and the medium carrying the radioactive material are relatively constant whereas the skin is subject to many external variables including those of temperature and the use of many agents such as soaps, lotions, medicines, and a varying amount of water. In addition, the radioactive material may be applied to the skin in a carrier that varies widely in acidity and content of possible complexing agents.

In view of the lack of data, f_{ab} was chosen as 10^{-3}%/min for all elements except plutonium and thorium. For these, a value of 10^{-5}%/min was chosen. Note that both the half-life of the isotope and the solubility of the chemical compound in the materials on the

skin may play a role in the absolute value. Short-lived isotopes will have a significant decay during the period of absorption and transfer to the critical organ. In these cases, the maximum permissible intakes to the blood may be conservative in the sense that the dose delivered to the critical organ will be less than the limit. For insoluble materials on the skin surface, it appears reasonable to assume that they must enter solution in some medium to penetrate the stratum corneum. (This assumption does discount the observation noted in Appendix A that powdered or colloidal sulfur has been reported to pass across rabbit skin on the grounds that such passage may be unique and that the rate is undoubtedly slow.) If this is the case, the rate of solution may be the limiting rate and one would expect the shorter-lived materials with the lower mass per curie to produce more activity in solution and, therefore, a more rapid penetration rate.

From a pragmatic point of view, one could claim that experience has indicated that the skin penetration of plutonium cannot be as important as the rate chosen indicates because people have been contaminated while working with this material for several decades without showing any significant body burden. Since the body burden is measured by urinalysis, however, it can be pointed out that the expected excretion rate for an administration of 3×10^{-6} μCi/day (6.6 dis/min per day), as measured 5 days after the exposure has stopped, is only about 0.36 dis/min after 10 yr of exposure and 0.45 dis/min after 20 yr.[26] Since the sensitivity of a good urinalysis procedure is about 0.05 to 0.1 dis/min, these data would only indicate that the plutonium was being accumulated at something less than 1/5 to 1/10 of the maximum permissible rate and do not <u>prove</u> that the transfer through the skin is not a problem.

The value of 10^{-3}%/min is undoubtedly high by several orders of magnitude for some materials but may be low by perhaps an order of magnitude for a few. Until data are obtained which permit a better assessment of the possibility of absorption, it is believed to be prudent to err on the side of conservatism particularly when the limit for other effects is usually equally or more binding.

A decision level for a single event during the year was derived assuming that the total intake is limited so that the total dose to the critical organ over a specified time does not exceed the dose that would be received by the same organ as a result of a continued maintenance of the skin decision level based on absorption for 1 yr. Since the total dose to the organ is proportional to the integral over time of the quantity of radioactive material in the organ, the ratio of the single-event decision level to the continuous decision level will be derived from these integrals.

For the continuous maintenance of a quantity of material on the body for 1 yr, the total μCi-days in the critical organ is equal to the integral during the period of accumulation (C) plus the integral during the following period of interest (B) during which the radioactive material is being eliminated by a constant fraction λ_{eff} per day.

$$\mu\text{Ci-day} = \frac{(\text{SAL})\ f_2'\ f_{ab}}{\lambda_{eff}^2}\left[\lambda_{eff}C - e^{-\lambda_{eff}B} + e^{-\lambda_{eff}(C+B)}\right] \quad . \quad (10)$$

The value f_2' is the fraction passing from the blood to the critical organ and the other symbols are as given earlier.

For a single contamination event, the quantity in the critical organ (qf_2) at any time after the event is

$$qf_2 = \frac{f_2'\ f_{ab}\ (*\text{SAL})}{\lambda_{ab} - \lambda_{eff}}\left[e^{-\lambda_{eff}t} - e^{-\lambda_{ab}t}\right] \quad , \quad (11)$$

where t is the time in days following contamination of the skin with a quantity *SAL (μCi) and λ_{ab} is the effective elimination constant for removal from the skin. The integral of Eq. (11) is

$$\mu\text{Ci-day} = \frac{f_2'\ f_{ab}\ (*\text{SAL})}{\lambda_{ab} - \lambda_{eff}}\left[\frac{1}{\lambda_{eff}}\left(1 - e^{-\lambda_{eff}t}\right) - \frac{1}{\lambda_{ab}}\right] \quad . \quad (12)$$

Note that t in Eq. (12) equals C+B in Eq. (10).

If we now consider the total μCi-days from Eq. (12) to be equal to that given by Eq. (10), the ratio between the single event and the values given in Tables D-I and D-II can be devised.

$$\frac{*\text{SAL}}{\text{SAL}} = \frac{\lambda_{ab}\ (\lambda_{ab} - \lambda_{eff})}{\lambda_{eff}}\left[\frac{\lambda_{eff}C - e^{-\lambda_{eff}B} + e^{-\lambda_{eff}(C+B)}}{\lambda_{ab}\left(1 - e^{-\lambda_{eff}\{C+B\}}\right) - \lambda_{eff}}\right] \quad . \quad (13)$$

For a material with a large λ_{eff} (short effective half-life), Eq. (13) reduces to

$$\frac{*\text{SAL}}{\text{SAL}} = \lambda_{ab}C \quad . \quad (14)$$

The effective half-life on the skin was again taken to be 15 days following the reasoning used for the skin dose. The total period of evaluation was taken as 50 yr in each case with the period of exposure (C) in the continuous case taken as 1 yr. Under these conditions, the ratio varied from 16.9 for a 1 day effective half-life to 16.7 for a 100,000 day effective half-life. It was, therefore, concluded that an appropriate single-event level would be about 20 times the levels listed for the continuously maintained contamination. However, for the worker leaving work with contamination

on the skin, absorption continues for the full 25 h rather than the 330 min/day at work and the ratio should be reduced by a factor of 0.23. In this case, the single event should be only about four times the continuously maintained level.

C. Direct Inhalation

Although most studies of contamination hazards consider the gross resuspension of radioactive material on all surfaces through the action of air currents or other mechanical disturbances, there are additional mechanisms for inhalation such as breathing in while rubbing the nose with a contaminated arm or hand and other mechanisms that can produce significant local concentrations in the vicinity of the nostrils, such as changing or wearing contaminated clothin (particularly when the clothing is pulled over the head). Such mechanisms, which provide a relatively direct path from the contaminated area to the air stream entering the nose or mouth, are considered in this category of direct inhalation. The available data on the probability of occurrence are primarily from studies of air contamination while wearing or changing contaminated clothing. Particularly with members of the public, including children, other possibilities exist including playing with the family pet or, in the case of a contaminated area, playing on the floor or in the yard.

Dunster[6] reports that studies of Bailey and Rohr indicate that a value of 0.1% of the contamination present on the hands would be a safe value to use for considering direct inhalation by smoking a cigarette. Actually he points out that their data indicate that the transfer was lower than this by about a factor of 50. If we consider both surfaces of the hand to be about 300 square centimeters area, this transfer by the single mechanism is equivalent to movement of the material from about 0.3 cm^2. Brunskill[27] studied the air concentration resulting from changing coveralls lightly contaminated with plutonium. His results with static samplers placed close and at bench height indicated that a contamination level of 1 unit per square meter on the clothing gave rise to air concentrations in excess of 10^{-3} units per cubic meter and with breathing zone samplers located near the shoulder, the air concentration was about 6×10^{-4} units per cubic meter. If one assumes that the act of changing coveralls requires about 10 min, and that the individual is breathing at the standard man rate of 10 cubic meters in 8 h, the amount of activity that would be inhaled at this time would be about equivalent to that originally on 1-1/4 square centimeters of the coveralls or, during the period of changing coveralls, a rate of inhalation of the contamination from about 8 cm^2 of the clothing per hour.

Butterworth and Donoghue[28] studied the air concentrations resulting from coveralls contaminated during normal wear in a uranium processing plant. The contaminated coveralls were worn for 1/2 h with about equal periods spent carrying boxes, walking, and filing a section of metal rod. Air samples were taken at head level, each side of the chest, and at several static areas in the laboratory.

Two different fabrics, cotton drill and 50% terylene-50% cotton were tested. For our purposes, it was assumed that the sampler worn on the helmet represented the air breathed by the subject with a note that the values measured at the chest frequently exceeded those at the head by a factor of 2 to 5. The air concentrations at the head under these conditions varied from 1×10^{-5} to 1×10^{-4} dis/min per m^3 per dis/min per m^2 on the coveralls. On the average the quantity inhaled (based on a breathing rate of 10 m^3/8 h) corresponded to the contamination on 0.5 cm^2 each hour for the cotton coveralls and about 0.3 cm^2/h for the others. There is a strong indication that the fraction released in this experiment decreased with increasing contamination level. As would be expected with the type of work done by the subjects, these releases and inhalations are lower than those measured by Brunskill for changing coveralls by a factor of about 0.1 to 0.05.

These results indicate the existence of one mechanism for direct inhalation and its order of magnitude importance for several contaminants and conditions. For the work situation where some control is provided by routine air samples, particularly if breathing zone sampling is used, a partial assessment can be made from these samples. There are many variables to influence the results including the nature of the contaminant, the type of clothing and fabric, the activity of the individual, the ventilation of the area, and the distribution of the contaminant on the clothing.

In deriving a decision level, we will consider an overall rate such that an individual will inhale the material from one square centimeter of clothing or skin per hour. This is considered to be an average rate for all types of activity of the individual. Although specific information is not available, it is likely that contamination on the upper portion of the clothing will be more important in contributing to this mechanism than that on the lower torso or legs. The result will be assessed as contamination per unit area although a small area contaminated to this level will be of less importance than a complete contamination of all clothing.

The basis for this level is, then, the MPC for inhalation as given by the NCRP with the inhalation rate for the standard man of 10 m^3 in the 8 h at work and 20 m^3 for the full day. For the worker, the decision level is

$$DL_{Inh} = 1.25 \times 10^6 \ (MPC'_{\alpha}) \quad \mu Ci/cm^2 \quad . \tag{15}$$

For an individual in the public, the decision level is

$$DL^{p}_{Inh} = 8.33 \times 10^5 \ (MPC_{\alpha}) \ R \quad \mu Ci/cm^2 \quad . \tag{16}$$

The decision levels based on this concept are given in Tables D-I and D-II. The values of (MPC_a) used were the lower of those based on "soluble" or "insoluble" forms of the isotope since, in the general case, the behavior of the material in the lung is not known. For most of the isotopes, the difference between these two categories is insignificant considering the many uncertainties in the derivations, but a correction can be made for this, if desired, in cases where the form of the contaminant is known and the behavior of this form in the lung is known.

No derivation is given for a single exposure because such contamination can be removed by changing clothing and it does not seem desirable to permit exposure when such countermeasures are available.

D. Direct Ingestion

There is little information available on the possibility of a transfer of contamination to the mouth and subsequent ingestion. Such transfer could occur by movement of the contamination to the lips or by contamination of items such as foodstuffs, utensils, cigarettes, etc., entering the mouth. One must also consider the transfer of contamination from the body, clothing, or environment to such objects and the likelihood of such ingestion would appear to be much greater for individual members of the public, particularly children, than for workers.

In view of the lack of data, it was assumed that the loose contamination on one square centimeter of the body or clothing could be taken into the mouth per hour. The assumption is entirely arbitrary and the 8 cm^2 per working day compares well with Dunster's assumption[6] of 10 cm^2. The 24 cm^2 per day for the public permits an allowance for the presumed higher intake by children.

The ingestion probability would seem to be a function of the area of the body contaminated and should apply only to relatively loose contamination. Thus, it would appear more likely that materials on the hands would be transferred to the mouth although a secondary transfer to the hands from other parts of the body or from clothing must be considered as possible so that the actual area that is contaminated would appear to be a second order effect. As a rule of thumb, it does not seem unreasonable to apply the resulting decision level to areas between 100 and 1000 cm^2 with primary interest in the hands and forearms. Due to possible transfer, it should also apply to major areas of loose contamination on the clothing.

The MPC_w from the NCRP was used as the basis for the values with the total intake of water per day assumed to be 1100 cc for the worker and 2200 cc for the member of the public, in accord with the derivation of the values. Again, the lower of the two values for soluble and insoluble materials was used on the grounds that differentiation between the two is not usually possible. Thus, for the workers, the decision level is

$$DL_{ing} = 138\ (MPC'_w) \quad \mu Ci/cm^2 \quad . \tag{17}$$

For an individual member of the public, the level is

$$DL^p_{ing} = 92\ (MPC_w)\ R \quad \mu Ci/cm^2 \quad . \tag{18}$$

IV. TRANSFER OF CONTAMINATION

In addition to the possible dose or intake by the worker, one must consider limitations on the quantity of radioactive material that can be transported to the environs by contamination of the person or clothing of the worker or by other objects removed from the work area. As with other radiation protection practices, such transfer should be minimized to the extent practicable.

The approach to be taken consists of evaluating several simple situations that are not intended to depict reality but which are, perhaps, at least partially responsive to the type of situation that could occur and which provide some feel for the radiation doses that could result at various contamination levels. The transfer required in these situations will then be estimated by considering certain plausible transfer coefficients. This approach does not provide a calculation of the dose to be actually expected, but rather, an estimate of what could occur under the stated conditions. The actual doses could be higher or lower although many of the assumptions will be deliberately on the conservative side. By considering the radiation doses from individual mechanisms and assumptions of transfer coefficients, it is possible to structure the problem and to focus attention on the individual parameters and the possible uncertainty or inaccuracy introduced by each. This, hopefully, will permit future investigation into each of the parameters that will lead eventually to a better understanding of the degree of variability in possible situations and to the definition of standard conditions that can be used in more accurate and more realistic calculations.

Since the hazard from transfer of contamination is a function of the total amount of material moved rather than the quantity per unit area, the levels will be derived in terms of the total quantity per unit time (μCi/day). This could result from a small, highly contaminated area or from a larger area contaminated to a lower average level. For routine monitoring, it is desirable to provide numbers based upon the contamination per unit area because this is essentially the way the instruments respond. In the general case, it is impossible to provide such numbers unless a reasonable assumption can be made about the total area involved. For the one case of contamination transfer by the worker to the home, one can assume that the full area of the body is uniformly contaminated to provide

an initial decision level. Thus, when leaving work, the warning level can be taken as the transfer level in μCi divided by 1.85×10^4 cm^2. If upon investigation, the total area contaminated is found to be smaller, decisions for this effect can be based on the area determined. This approach assumes that areas of the body are not contaminated twice (as with contaminated skin plus multiple layers of clothing) and may overweight, as a warning device, contamination on small areas most likely to be contaminated (such as shoes). As a reasonable first approximation of this level considering the many other variables, one can consider the area of the body to be 10,000 cm^2 so that the warning level in nCi/cm^2 is one-tenth of the transfer level in μCi/day.

Values for the decision levels based on such transfers are based on the factors given in the following discussion and are listed in Table D-III.

A. External Radiation

1. Gamma. External radiation in the home can be of concern for those isotopes which emit electromagnetic or beta radiations of significant energies. For electromagnetic radiation, the dose rates above thin disk sources with diameters from 20 to 800 cm and at distances from the center axis of the source from 10 to 200 cm were evaluated to investigate the effect of averaging over various areas and standing at different distances. A similar calculation was made for line sources to show the effect of this type of distribution. The results are given in Fig. 3 with the dose rates expressed in mrads per hour per μCi per MeV of gamma energy emitted per disintegration in the uniformly distributed source. Thus, a disk source 4 m in radius will have a uniformly distributed concentration of about 2×10^{-6} $\mu Ci/cm^2$, whereas a source 10 cm in radius will have a concentration of 3×10^{-3} $\mu Ci/cm^2$. The dose rates are given for a position above the center of the disk source.

These calculations were performed to approximate the dose rate to be expected in a room with contamination of one surface. It is to be noted that the dose actually delivered to an individual will be a function of the averaging of the position of the individual with respect to the source as well as the distribution of material in the source. Thus, if a point source of 1 μCi of a 1-MeV emitter is located at the center of a disk 4 m in radius and an individual spends equal times at all positions on this disk, the average dose rate will be the same as that calculated for a uniform source 4 m in radius. Similarly, a point source located on a wall with an individual spending equal times at all points along a line at the given distance will receive an average dose rate as given for that length of source. The above considerations, of course, ignore the perturbating effects of the body on the radiation field.

The interesting thing about the results is the surprisingly small spread in dose rates, even with distance from the source, if one considers both the averaging from the spread of the contamination

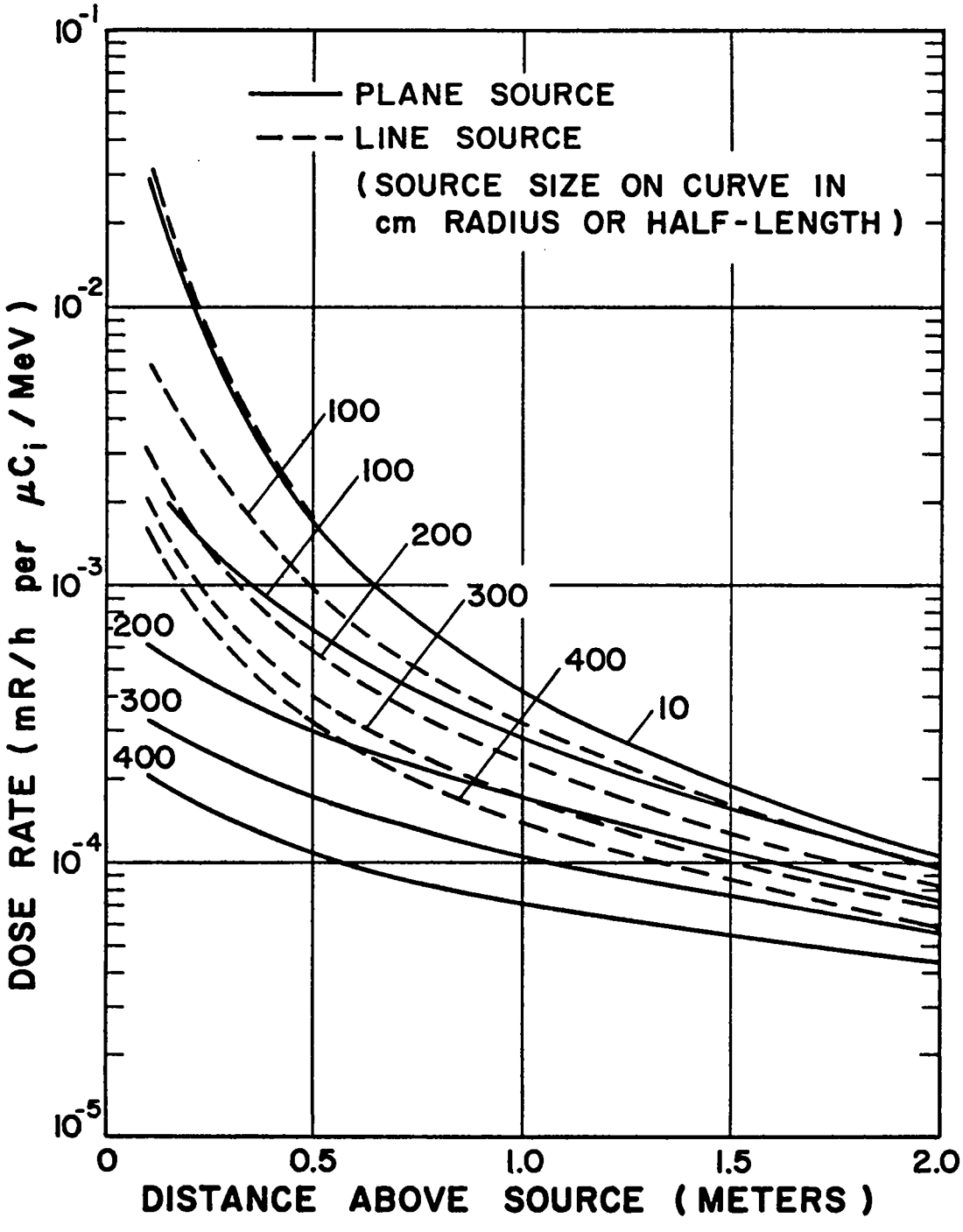

Fig. 3. Dose rate at various distances above gamma sources.

and from the movement of the body to be over a reasonable area. The line sources are generally higher for given distances than the plane sources, but only that portion of the body at the given distance receives this dose rate with other portions receiving lower dose rates. In other words, the radiation over the body is more nonuniform than with the plane sources. Although no specific allowance is made for this factor in expressing external radiation limits, there is little doubt that a uniform dose of a given magnitude over the whole body is more harmful than a nonuniform dose with the maximum point being the same as the uniform exposure.

A detailed application of such calculations to potential radiation exposures in the environs or home requires knowledge of the exact source distribution and patterns of movement of people. It is not possible to do even a "worse-case" calculation because this would undoubtedly consist of a point source close to the body for 24 h/day and the results would be meaningless. It is noted, however, that a 1-μCi source of a 1-MeV gamma emitter averaged over an area between a 2-m radius (136 sq. ft.) and a 4-m radius (550 sq. ft.) results in dose rates that vary only by a factor of 3 at close approaches and a factor of 2 at distances. The total variability at distance of 10 cm to 2 m is between 5×10^{-5} and 5×10^{-4} mrad/h. We propose that a value of 2×10^{-4} per μCi per MeV be used as the dose rate for material brought into an average-sized room. This value appears conservative (Fig. 3) because it occurs at close approached and small areas and represents the dose rate at the center of the area rather than at the edge where the radiation level would be lower. In addition, no allowance is made for shielding by furniture and other objects or possible self-absorption from penetration of the radioactive material into carptets and furniture. However, it is likely that the material would be preferentially spread in the areas of higher use (or occupancy) rather than being uniformly spread, so that the dose rates averaged over the time of occupancy may be higher than this. In addition, children will have their critical organs close to the floor which should be the most contaminated surface. (Note that contamination of walls or ceilings will give dose rates that can be read from Fig. 3 with proper choice as to area and distance and these dose rates will be additive if the same quantity of material is on all surfaces. The dose rate in the center of the room will be due to contamination on walls, furniture, floors, and ceilings and the value chosen is, at best, a "ball park" estimate.)

These considerations would indicate a whole body dose rate for continuous occupancy of about 1-3/4 mrem/hr for 1 μCi of a 1-MeV gamma emitter. To limit the dose to 500 mrem, the average quantity present over the year should not exceed about 500/1.75E μCi. For rooms seldom used, this value could be higher, but for many living areas, occupancy can range up to 50% and the uncertainties are such that a factor of 2 is of little importance.

For transfer, we will assume that 50% of the material taken into the home each day is effective in producing the gamma dose and

that the half-life in the home is 30 days. The 50% assumed transfer is higher than will be used in considering other sources of dose since the penetrating radiation can expose others while still on the worker's person or from the clothing before cleaning, with some residual contamination probably remaining even after cleaning. The 30-day half-life includes removal by washing, house cleaning, washing clothes, and by all the other removal mechanisms prevalent in the home. There is no real evidence to substantiate the assumption. In practice, it is probable that a large fraction will be eliminated with a shorter half-life but that a small fraction may be retained for a much longer period.

For continuous transfer, the amount of material that can be brought into the home is

$$TL_\gamma = \frac{500}{1.75\ \bar{E}_\gamma} (\lambda_1 + \lambda) \times \frac{1}{0.5 \times 0.7} \quad \mu Ci/day \quad . \tag{19}$$

λ_1 is the rate at which the material is removed from the house ($0.693/30 = 0.0321\ day^{-1}$), λ is the disintegration constant of the particular isotope in day^{-1}, and TL_γ is the resulting transfer level based upon external gamma dose to the occupants. The factor of 0.7 arises from an assumption of 250 working days/yr so that the amount actually brought in per working day can be increased by the ratio of the number of these day to the number of days in a year.

2. Beta. For the beta radiation, similar considerations exist as to averaging of the dose by movement of the people with respect to the source, but the variation in dose rate with distance from the source and with energy of the beta radiation is much greater than with gamma radiation. The possible effects of self-absorption from penetration of the radioactive material into surfaces is also of greater significance. Experience with mixed fission products, however, does indicate that the beta radiation can be more limiting than the gamma radiation when the contamination is spread thinly over the surfaces of the area.

Table III gives the calculated dose rate at various distances from a 4-m radius source having a uniform, thin layer of various energy beta emitters. Rather than using the Loevinger method for this calculation, an inverse square integration with the beta radiation falling exponentially due to absorption in the air was used.[9] The absorption coefficient was estimated from

$$(\mu/\rho) = 17\ E_{max}^{-1.14} \quad , \tag{20}$$

where E_{max} is the maximum energy of the beta spectrum. This calculation overrestimates the dose for close approached and overestimates for distances but was used for simplicity.

TABLE III

BETA DOSES AT GIVEN DISTANCE h
FROM PLANE SOURCE 4 m IN RADIUS

Maximum Energy (MeV)	μrads/h per μCi per MeV (max)			
	h=0.1 m	h=0.5 m	h=1 m	h-2 m
0.1	2.1			
0.2	8.4	0.01		
0.3	14	0.1		
0.5	17	0.8		
0.7	17	1.6	0.2	0.004
1	17	2.7	0.5	0.05
2	13	4	1.5	0.3
3	10	4	2	0.6

For comparison, the value of 2×10^{-4} mrads/h per μCi per MeV chosen for the gamma emitters is about 0.2 on the scale above. As can be seen, the height chosen for evaluation becomes critical in assessing the doses. If one averages over the distance to 3 m by using the above values as representative of the midpoints of the distances, the dose rates become 2.3 to 2.4 μrads/h for emitters of 1 MeV and above. This essentially assumes that the individual spends equal times at all distances up to 3 m. However, when self-absorption is considered, it would seem reasonable to use the values given for 1 m as a rough estimate of the beta doses. Thus, a 3-MeV beta emitter would deliver a dose rate of 6×10^{-6} rad/h and to limit the annual dose to 0.5 rads to the skin, the average quantity of a 3-MeV emitter present should be limited to about 10 μCi. The uncertainty in this value is much greater than for the gamma radiation because of the sensitivity to averaging and source location, but the same considerations on occupancy apply.

For limitation of the beta dose in the home, the approximate dose per year varies with the energy of the beta particle and we have adopted the following values as approximate guides

E_{max}	mrad/yr per μCi = M
>2.5	50
1.5 - 2.5	25
0.8 - 1.5	4
0.6 - 0.8	2
<0.6	0

This dose is from the general beta field and does not include the contact dose resulting from clothing or skin contamination. Neither would it include dose to the skin from contact with furniture having a spot of contamination. The same assumption of 50%

of the material brought in remaining in the home with a 30-day half-life, as was made for the gamma dose, is also made here. Based on an annual dose limit of 500 mrad to the skin, the quantity brought in per day would then be

$$TL_\beta = \frac{500\ (\lambda_1 + \lambda)}{M \times 0.5 \times 0.7} \qquad \mu Ci/day \quad . \tag{21}$$

3. Single Incident. For a single, infrequent contamination case, the dose is limited to 500 mrads for gamma or beta for 1 yr following the transfer of contamination. With the assumed 30-day half-life of residence in the home, nearly all of the infinity dose will be delivered within the first year even for long-lived isotopes. The calculation of this dose uses assumptions similar to those for the continuous transfer except that the factor of 0.7 is not applicable, and the 0.5 factor for transfer from the individual to the home is not used on the assumption that he changes his clothing after the incident and spends a reasonable fraction of the later time with his family so that the material remains in the home.

For a gamma dose rate of 1.75 $\bar{E}_\gamma$ mrems per year per μCi, the total dose from a single transfer of x μCi is

$$\text{Total Dose} = \frac{1.75\ \bar{E}_\gamma\ x}{365\ (\lambda_1 + \lambda)} \quad . \tag{22}$$

If the total dose is limited to 500 mrems, the quantity brought in is the decision level based on a single transfer ($^*TL_\gamma$) and is equal to

$$^*TL_\gamma = \frac{500 \times 365\ (\lambda_1 + \lambda)}{1.75\ \bar{E}_\gamma} = 1 \times 10^5\ \frac{(\lambda_1 + \lambda)}{\bar{E}_\gamma} \quad . \tag{23}$$

Similarly, the transfer level for a single incident based on the beta dose over the year ($^*TL_\beta$) is

$$^*TL_\beta = \frac{500 \times 365\ (\lambda_1 + \lambda)}{M} = 1.8 \times 10^6\ \frac{(\lambda_1 + \lambda)}{M} \quad . \tag{24}$$

Comparison of these equations with the corresponding ones for the continuously maintained levels indicates that the single incident could transfer about 130 times as much as the daily transfer decision level.

B. Resuspension

The possible resuspension of radioactive materials brought into the home depends upon many variables including the chemical and physical form of the material, the place of ultimate transfer in

the home, the degree and rate of possible fixation, the ventilation patterns of the home, and the amount of movement in the area of the deposition. A brief review of some concepts and information on resuspension is given in Appendix C. There it is concluded that the resuspension in an enclosed area is probably a function of the total quantity of contaminant present rather than the concentration on any given area. Because of the differing ventilation rates in the home, as compared to typical industrial areas where the measurements have been made, the appropriate parameter for such an extrapolation is the fraction resuspended per unit time rather than the more generally used ratio of the air concentration to the surface concentration. This parameter leads to an expression for the air concentration of

$$\chi = \frac{f\Omega A}{Vn} \quad , \tag{25}$$

where χ is the air concentration in $\mu Ci/cm^3$, f is the fraction resuspended per hour, Ω is the surface contamination level in $\mu Ci/cm^2$, A is the area contaminated in cm^2, V is the volume of the room in cm^3, and n is the number of air changes in the room per hour. Note that ΩA is equal to the total amount of contamination in the room. For an area where the contamination is confined to the floor area, the concentration from resuspension can be given as

$$\chi = \frac{f\Omega}{hn} \quad , \tag{26}$$

where h is the ceiling height and Ω is the average floor contamination. These equations are approximations since the only mechanism of removal of material from the air is considered to be by dilution from the air changes. In practice, other mechanisms of redeposition exist that could deplete the air concentration. These include gravitational settling, impaction, electrostatic attraction, adsorption or absorption, depending upon the chemical and physical form of the contaminant. These are considered to be unimportant for this work in view of the other major uncertainties although they can serve to spread contamination to surfaces, including body surfaces, other than those initially contaminated.

Data on the rate of resuspension have been obtained primarily for contaminated floors and smooth surfaces. One could speculate that other floor coverings, such as carpets, or furniture could trap the radioactive material and result in a decrease in the resuspension. On the other hand, movement of the fibers in cloth could provide a source of energy that could be transmitted to particles resulting in significant resuspension. Another possible effect could be the penetration of the radioactive material to a region where it is no longer available for resuspension or, if in a form to be readily absorbed or adsorbed, it may tend to hold on the fibers. From the data in Appendix C we have considered the following

resuspension rates to be reasonably, but not overly, conservative for our purposes.

Vigorous activity in the area. Includes cleaning or children at active play or running - - - - - - - - - - - $5 \times 10^{-3}\ h^{-1}$

Active. Normal traffic in the room. Children at normal play - - - - - - - - - $10^{-3}\ h^{-1}$

Moderate. Low traffic with reading, watching TV, and occasional movement - - - - - $10^{-4}\ h^{-1}$

Quiet. No movement. Room unoccupied or inhabitants sleeping - - - - - - - - - - - - $10^{-6}\ h^{-1}$

These factors were applied to two assumed situations. The first considered the average condition in a house with a floor area of 140 m^2 (1500 sq ft) and a 2.4-m (8 ft) ceiling. The second considered a single room with a floor area of 28 m^2 (∿300 sq ft) and the same ceiling height. The ventilation rate was taken as 2 changes per hour in each case which represents a reasonably tight room with windows and doors closed and moderately low wind speeds. The average resuspension rate was estimated using the following assumptions as to the degree of movement under these conditions.

	House	Room
Vigorous	1 h/day	1 h/day
Active	5 h/day	2 h/day
Moderate	6 h/day	4 h/day
Quiet	12 h/day	5 h/day
Not occupied	-	12 h/day
Average factor	$5 \times 10^{-4}\ h^{-1}$	$3 \times 10^{-4}\ h^{-1}$

The total quantity of radioactive material subject to resuspension can then be related to the maximum permissible concentrations in air for the general public (168 h) by

$$\Omega A = \frac{(MPC_a)\ Vn}{f} \quad . \tag{27}$$

For the average contamination in the house, this amounts to $1.4 \times 10^{12}(MPC_a)$ or expressed as average floor contamination $1 \times 10^{6}(MPC_a)$ μCi/cm^2. For the single room, the corresponding total contamination is $5 \times 10^{11}(MPC_a)$ μCi or about $1.6 \times 10^{6}(MPC_a)$ for the average floor contamination in μCi/cm^2. A value of 1×10^{12}(MPC (MPC_a) for the resuspendable amount in the home will be used.

The chief individual factor in the above calculation that adds to the conservatism is probably the value of n which, when averaged over the year, should probably be 2 to 10 times greater depending

upon the size and location of the home, room or apartment, and the method of heating and cooling as well as the type and quality of the construction. However, we have not considered the possibility of local high concentrations, as for example, the transfer to the breathing zone of a small child playing on the floor perhaps with the local pet, such as a dog or cat. Other factors not considered here may also be of importance. For example, it is known that movement of air into or out of cracks or other small openings will result in increased turbulence that, in turn results in high local deposition of material borne by the air stream. The operation of devices to recirculate the air, particularly if the air is filtered, can result in the accumulation of radioactive materials on the filter or on portions of the equipment where deposition from induced turbulence occurs. Such localized sources, if disturbed, can result in increased probability of intake to the body or *in situ* as possible direct sources of radiation exposure. For example, if the air in the room were maintained at the public limit of 3×10^{-10} $\mu Ci/cm^3$ of ^{60}Co by resuspension, and a filtered air conditioner recirculated one air change per hour, the filter could accumulate close to 0.5 μCi/day.

For estimating the quantity of material effective it was assumed that 30% of the material brought in per day was transferred to the area and that it remained in a resuspendable form with a half-life of one week ($\lambda_2 = 0.1$ day^{-1}). The transfer assumption raises the question of "fixed" vs "loose" contamination. Little information is available on which to base either the assumption of quantity transferred or the definition of these terms. We do note that, if the material were on the skin and was distributed uniformly through the stratum corneum, about 1/15 would be removed per day or about 7%/day. With "fixed" contamination on the skin, it is probable that there would be a strong concentration gradient with the higher contamination levels at the surface so that the initial transfer rate could be greater than 7%/day. In view of the difficulty of measuring "looseness" of the contamination in terms meaningful to the actual transfer, the 30% value does not seem overly conservative with respect to material on the skin. Clothing or shoe contamination or contamination on other object has no such built-in cleaning factor but, again, the assessment of the possible degree of transfer in a specific situation is difficult and the same transfer factor is used.

The shorter half-life for material in resuspendable form as compared with that used for the material in the dose calculations is intended to reflect the loose nature of material that can be resuspended and the probability that it will be removed from the premises, not only by ventilation but also by cleaning and other mechanisms. Again there are no data to indicate the order of magnitude for this effect and the 7-day figure for the half-life was arbitrarily chosen.

From these assumptions, the amount that can be brought in per day is

$$TL_R = \frac{(MPC_a)\ Vn\ (\lambda_2 + \lambda)}{f\ (0.7 \times 0.3)} = \frac{10^{12}(MPC_a)(\lambda_2 + \lambda)}{0.7 \times 0.3} \quad . \tag{28}$$

For a single event during the year, the average air concentration over the following year is taken to be limited to one MPC_a for an individual in the general public. Again the half-life assumed for the resuspendable material in the home is short enough so that essentially all of the inhalation will occur within 1 yr. Thus, the total amount brought in during the incident, again considering the 30% transfer to the home, is

$$^*TL_R = \frac{365\ (MPC_a)\ Vn\ (\lambda_2 + \lambda_1)}{0.3\ f\ A} \quad . \tag{29}$$

In comparison with the equation for the continuously maintained transfer, the ratio for a single event is about 250 times the average per day.

C. Personal Contamination

A portion of the material brought into the home will be transferred to the bodies and clothing of individuals living in the home. This will result in skin doses or intake by mechanisms postulated earlier (direct ingestion, direct inhalation, or skin absorption). One mechanism for such a transfer is briefly described in Appendix C where it is noted that an average transfer of 22%/h from the floor to adhesive tape patches on various portions of the body occurred when the floor was contaminated with copper oxide particles. Another mechanism would be the transfer from work clothing to other clothing if both are washed in the same batch, although it is to be expected that most of the loose activity will be eliminated in the wash water. Probably the most troublesome mechanism, from the standpoint of attempting to estimate dose, is the possibility of direct transfer by personal contact or secondary contact where the material is transferred to a surface by the worker and is then picked up by a member of the family contacting the same surface. In this discussion we have ignored the possibility of transfer of beta emitters to furniture with subsequent dose through the clothing to other individuals using the furniture on the basis of limited occupancy and reduction of dose by clothing. (Note that transfer to clothing is, at least partially, included in the following discussion although allowance for "hot spots" may not be adequate.) This, of course, assumes that the contamination is eliminated from the furniture at the rate postulated for other contamination in the home. Contamination of sizeable areas of frequently used furniture could lead to significant doses with respect to the limits. Again, contamination of small areas will result in effective averaging of the resulting dose over much larger skin areas due to movement of the body with respect to the contaminated area and displacements of the body relative to the contaminated area with repeated use of the furniture.

For purposes of deriving approximate indications of the decision levels, we will consider the material subject to resuspension to be transferable to the skin and clothing. This is assumed to be uniformly distributed over the floor area of the home (140 m^2) and the equilibrium contamination level on the skin and clothing will be the same as on the floor. This, then, assumes 30% transfer of the material brought in and a half-life of 1 wk in this form.

For the continuous case, the quantity that can be brought in per day under these assumptions is given by

$$TL = \frac{1.4 \times 10^6 \ (\lambda_2 + \lambda) \ L}{0.7 \times 0.3} \quad . \tag{30}$$

The factor 1.4×10^6 represents the floor area of the 1500 sq ft home in cm^2 and L is the contamination level on skin or clothing to limit skin dose or intake for the public, as given in Table D-11. Note that the area chosen is that of a moderate home which implies uniform distribution of radioactive material and uniform use of all areas. If living is confined to a single room, the quantity brought in per day should be proportionally smaller. On the other hand, no allowance is made for clothing changes, washing of skin, or part-time occupancy of possibly less contaminated areas.

For the single contamination case, the considerations on averaging over 1 yr, and on amounts brought into the home, are similar to those for resuspension. This would indicate that the monitoring limits for such a case should be about 250 times the continuous monitoring limit. However, the resulting doses in this case are much more dependent upon the actual distribution of the material in the home and direct transfer to the person of an individual could result in much higher doses.

D. Release of Equipment and Materials

The focus of the previous discussion has been on the movement of radioactive materials into the homes of workers because this seemed to present the major pathway of exposure to individual members of the general public. An alternate path for transfer of radioisotopes to the public domain is by disposal of equipment or unwanted materials either as scrap or by sale or gift to another organization or to individuals. The movement of such items from a contaminated area to a clean area in the same plant without imposing controls on the further use or disposal of the item is equivalent to direct transfer to the public domain since there is then no assured method for preventing later disposal without consideration of the contamination. An exception to this latter statement could be for the items with contamination with such a short half-life that it would decay before transfer could be accomplished.

Many of the basic considerations on potential radiation doses to the recipient of such equipment, as discussed under transfer to the home, are applicable to this situation. However, variable as

the home environment may be, there are additional factors in this case which must be considered.

1. The total quantity of radioactive material transferred for a given contamination level can vary widely depending upon the size of the items, the number of items, and the total surface area. In other words, there is no basis for even an arbitrary choice of the significant surface area.

2. The channel of disposal and subsequent further transfer of the item to another party is unknown and frequently uncontrollable. Scrap materials may go to a dealer and then to a processor or they may be sold locally to individuals or to local industry. Equipment may be sold to individuals for private use, to another industry or, even to schools. Further, such equipment may require extensive repair or modification which could bring it into still another locality.

3. The use of the equipment after disposal is unspecified. Scrap or small pieces of equipment can be disposed of to local industry or to a hobbyist where the material can be subject to actions such as sawing, grinding, polishing, and welding with probable movement of the contaminant into the air even where the contaminant is considered to be fixed. Probably the most disturbing would be the routine supply of such equipment to a local school for use in shop courses. Heavy or large equipment is probably not as subject to this type of use and is more infrequently transferred but there is potential for spread of contamination in repair of the equipment or in revision for another purpose.

4. The frequency of transfer to a given disposal channel is unknown and variable. It is visualized that continued transfer to a single dealer could result in contamination of his shop or yard by relatively large quantities of radioactive material that could eventually result in contamination levels approaching, or even exceeding, the levels on the transferred items.

These factors do not consider secondary problems such as the possible contamination of a university low-level measurement laboratory from contaminated equipment or the long-range problem of the eventual contamination of scrap and metal supplies as ore resouces dwindle and greater dependence is placed on recovery as a source of supply. At the present time the latter factor is of most importance for precious metals such as gold or platinum, and, perhaps, those in short supply such as copper or nickel, because of the favorable economics of recovery.

It would be possible to derive specific decision levels in cases where the types and quantities of equipment or materials and the disposal channels are reasonably well defined. For the general case, however, it is possible only to provide broad and sweeping generalizations as to the relative importance of the postulated contamination transfer channels. For example, the recipient of such material on a routine basis is likely an industrial organization with

handling or storage of the material in more spacious quarters than the homes considered or even outdoors. This means that an individual may have less exposure to the external beta and gamma radiation simply because he spends less time in the vicinity of the contamination. (Note that this assumes that the flow of contaminated material is only a small part of the business.) The increased area and volume, along with the shorter time of exposure (40 h/wk) and probable greater ventilation rate, would mean that greater quantities could be transferred before the resuspension became a possible problem. For example, in a room with 10 times the area of the home and 15 times the volume and 10 air changes per hour, one could permit 160 times the quantity brought in per day even considering resuspension rates corresponding to active work (10^{-3} h^{-1}). The transfer to clothing or skin are unpredictable as is the rate of elimination of loose contamination from the premises, but the shorter time of exposure and the larger area should result in quantitatively higher transfer levels.

However, when monitoring for contamination on an area basis, we must also consider the total area of the items transferred. A rough calculation indicates that 1 ton of iron scrap has a surface area of about 10^5 cm^2 if in the form of 1-in.-thick plates or about 10^6 cm^2 if in the form of 0.1-in.-thick plates. A desk has a surface area on the order of several hundred square feet or between 10^5 and 10^6 cm^2. These values are 5 to 50 times the body area of an average man and 10 to 100 times the area considered for converting total contamination transfer per day to warning levels for personnel contamination. It is, therefore, considered appropriate to use the same warning level in the monitoring of scrap or equipment as is used for personnel on the transfer of activity unless a specific review of the situation indicates that higher values are possible. Ideally, one would base such controls on the total quantity of radioactive materials on the items disposed of per day or per week through each channel, but this requires better controls and management than is now available,or perhaps, than can be economically provided.

In view of the possibility of abrasive or similar actions on items during repair or modification, it is believed that these limits should apply to the total contamination and not just to the "loose" component unless other information rules out such actions on the item.

E. Administrative In-Plant Levels

The foregoing limits have been based upon the possible radiation dose to the worker or to the public and can, therefore, be regarded as true protection limits although many questions must be answered in the specific case about averaging over space and time. As such, they apply with equal force to "clean" or "dirty" areas of the plant. There are other limits which, in themselves, are not designed to limit dose, rather, to limit the possibility of movement of the the contamination to areas where the radiation dose can occur. These limits include surface contamination in the laboratory and limits on movement from the laboratory to clean areas of the plant by personnel contamination or contamination of equipment or materials.

1. Work Place. In the work area many techniques are available for the control of contamination and the radiation dose that could result. These generally start with facility design where ventilation, surface characteristics, and containment provisions applicable to the type of materials handled are provided. In operation of the facility, additional controls include monitoring, use of protective clothing, cleaning as indicated by the need and control of entrance and exit. Thus, control of surface contamination becomes only one of the techniques available for control of exposure, and limitations on the surface contamination, as a method of control, must be tailored to the extent and effectiveness of the total program.

Possible bases for limiting the surface contamination levels would include direct radiation that could cause significant radiation fields, reentrainment in the air to produce high air concentrations, or transfer of the material to the bodies or clothing of workers. Although one could approximate the radiation levels or air concentrations from surfaces, the variability in distribution of contaminant in the room and in the neighborhood of the worker, the differences in chemical and physical form of the contaminant and the variability between different work areas adds considerable uncertainty to the results of any such calculation. Because the measurements of these quantities can be made directly in the particular situation with reasonably accurate assessment of the resulting exposure or intake, it does not seem reasonable to base surface contamination levels in the work area on these techniques. Of course, it may be desirable to study relationships between air concentrations or radiation levels and surface contamination in particular circumstances to aid in controlling these quantities under the particular conditions existing. However, transferring these numbers to other work places or even other radioactive materials involves many uncertainties.

This implies that transfer from surfaces to the worker is the chief concern, and that contamination which is truly fixed to the surface will be of interest only for external radiation dosage. For beta or gamma emitters, a limit on surface contamination may be necessary for surfaces with which the body comes frequently into contact, such as chairs, stools, or the edge or a work bench, because the dose rate actually delivered is difficult to measure with field instruments. Here, limiting to the level for clothing required to deliver the maximum permissible dose in 40 h would be conservative considering the occupancy factor and probable reduction in dose rate due to penetration and possible self-absorption.

A word of warning about fixation may be in order. There are instances in which contamination has been "fixed" by painting, replacing tiles on the floor, or even drastic cleaning only to have material either work its way to the surface or become exposed by wearing away of the protective film and once again appearing as loose contamination. It is not proper, therefore, to arrive at a final conclusion that contamination has been "fixed" by a given action and then to ignore it. Periodic surveys to detect any possible migration are proper.

Data on the transfer of contamination from surfaces to the body or clothing of workers are meager. One can postulate that the degree of transfer will depend upon how tightly the contamination is bound to the surface, the nature of the surface, the frequency and nature of the contact between the body and the surface, and the fraction of the laboratory surface that is contaminated. The cardinal principle would seem to be to keep the surfaces clean enough so that the skin and clothing limits are not exceeded and significant quantities are not transferred from the work area to other areas. This can vary widely with the conditions of work. For example, in an area where complete clothing changes and showers are required, high levels of contamination would seem to be acceptable. However, where only a laboratory coat is worn, limits must be based on the possibility of transfer to the body and to uncontrolled areas.

For the question of transfer of loose contamination to the worker, we will postulate what seems to be a general rule for contamination: The material will spread until all surfaces are uniformly contaminated. That is, if cleaning efforts are not made, movement of the material by tracking, air currents, etc., will tend to reduce the concentration of high spots and to contaminate previously clean areas. To reach unformity, it is obvious that time will be required and fresh, localized contamination cannot be introduced. As a corollary one can, then, presume that an individual working in a contaminated area will eventually become uniformly contaminated himself. (Note that this implies uniform susceptibility of the surfaces for retention of the contamination. It can be expected that the skin, clothing, or hair may be more efficient at retaining materials than many other surfaces. In this case, the worker may accumulate a higher localized contamination level than the average surface.)

This leads to the conclusion that the average loose contamination in the working area should not exceed the values established for skin or clothing. There is a conservative factor here in that the worker normally washes several times per day and changes clothing at intervals. However, the uncertainty in relative retention by body surfaces as compared to other surfaces would tend to work in the other direction.

Contamination, in practice, does not occur uniformly but rather in more limited areas or as "spots". One cannot average the total amount of radioactive material in these limited areas over the full area of the laboratory because the probability of body contact and transfer will vary with the nature of the area contaminated. A desk top or work bench top, for example, will permit far more transfer than a ceiling or a wall. It is proposed that the skin or clothing levels should apply to the major portion (say 10% or more) of any large surface and that spots of 100 to 1000 cm^2 should not exceed about 10 times these values.

2. Equipment or Materials. Equipment or materials used in the work area would not appear to differ from other surfaces in the same area, and as long as they are retained in the same area, are subject to the same controls.

The controlled release of equipment or materials to another location of the installation implies that some control of the future use and monitoring of the environment can be carried out. However. it is probable that these controls will be different in nature and less stringent than the controls exercised in the work place. For example, air sampling in the vicinity will probably be less frequent, if at all, and monitoring may consist of direct measurements of external radiation and, perhaps, occasional smear tests. One of the powerful reasons for the control of contamination movement is the minimizing of controls required for radiation protection in areas where the function is not the handling of radioactive materials. For this reason, administrative limits well below those regarded as necessary to keep radiation doses below the maximum permissible are considered good practice both from a health and economic point of view.

Health reasons for limiting transfer of contamination from the work area to other areas at the same installation are somewhat different from the reasons for limiting transfer to the environs. Review of Appendix D indicates that, for most isotopes, quantities of radioactive materials that correspond reasonally well with the limits based on radiation dose to the skin of the worker can be transferred to the home. For transfer to clean areas of the laboratory or industrial plant, the individuals potentially exposed are adults and, even if not formally designated as radiation workers, usually have the same medical programs and can be considered to be similar in resistance to radiation effects as those formally designated as radiation workers.

There are other reasons for limiting the transfer which cannot be well quantified. There may be many trips per day by workers between contaminated and clean areas or the amount of equipment or materials moved per day could be large so that a large surface area is available. Usually such an installation has measuring equipment for which it is important to provide constant and low backgrounds. Further, continued transfer to clean areas will eventually result in these areas becoming contaminated with the result that additional material will be transferred to the environs thereby increasing the number of people at risk. If several materials of different radiological properties are handled in the same installation, continued transfer of the more hazardous to the area where the material of lower hazard is handled can result in attributing an air sample, for example, to the less hazardous material when, in fact, it may contain significant quantities of the hazardous material.

For these reasons, it is good practice to minimize the movements of material from one area to another or to clean areas. Normally the criterion of no detectable contamination should be applied at least to the loose fraction with the levels given earlier for transfer to the environs considered as upper bounds for continued application.

V. MEASUREMENT STANDARDS

There remains the question of field measurements, using available survey instruments, of these levels of radioactive materials. For alpha emitters the instruments measure the disintegration rate of the material under the probe area so that the chief question is the influence of self-absorption. For beta-gamma emitters, the instruments are calibrated with gamma radiation so that the flux of electrons in the tube from this source can be considered to be standardized between instruments. For beta radiation or gamma sources spread over an area, however, only instrument-type calibrations are available with only one or two typical instruments of a given type.

The following rough estimates of the measurement capabilities of the instruments are based upon the few calibrations found in the literature and are intended to indicate the order of magnitude response to be expected for the contamination levels derived earlier.

A. Beta Emitters-Portable GM Counter

The primary instrument in use at the Los Alamos Scientific Laboratory for measurements of beta-gamma contamination is a portable Geiger counter containing a tube with a nominal 30 mg/cm^2 wall. The counter tube is a halogen-quenched, stainless steel tube about 2-1/2 in. long and 3/4 in. in diameter. The tube is mounted in a probe made of brass with eight slots on one side each extending about half way around the circumference of the probe. The slots can be covered with a shield that slides around the circumference of the probe. The halogen-quenched tube has been in use for the past 3 to 4 years. The calibration of the instrument for surface contamination used an 1B 85 aluminum wall GM tube with the same wall thickness and close to the same external dimensions. The 1B 85 tube, however, is vapor quenched rather than halogen quenched.

The instrument scale reads in "mR/h" and the instrument is calibrated in a known radiation field with gamma rays from ^{60}Co. The meter response is adjusted to indicate the proper reading in this field. Calibration for measurement of beta emission from surfaces has been done with the 1B 85 tube in the probe. Dummer[29] reports that the probe used gave about 3800 counts per minute per indicated "mR/h". The halogen-quenched tube has a lower response, reportedly between 1000 and 1400 counts/min per "mR/h". In one comparison using a ^{60}Co source to deflect the meter to a reading of 10 "mR/h", Lawrence[30] measured 2300 counts/min per "mR/h" in a 1B 85 tube and 1050 counts/min per "mR/h" on the halogen tube. Crude tests with a collimated gamma source indicated that the effective length of the halogen tube may be somewhat shorter than the 1B 85 which could affect its geometrical position with respect to a source.

In applying the calibrations from the 1B 85 tube to the halogen tube, it will be assumed that the relative response to beta radiation is similar to the relative response to the calibration radiation since the calibration provides a given number of electrons from the counter wall. The difference in sensitivity of the two tubes

to the same gamma-ray flux, however, may indicate a difference in response to changes in the energy spectrum of the electrons that could add uncertainty to the final result. In addition, changes in the effective length or diameter could change the geometry of the probe with respect to the beta particles emitted from extended sources.

Dummer[29] calibrated the probe by using the 1B 85 tube and ^{90}Sr sources in equilibrium with ^{90}Y. His results were expressed in terms of the quantity of ^{90}Sr only and are given in Table IV along with the response to the equilibrium mixture.

TABLE IV.

RESPONSE OF PROBE WITH 1B 85 TUBE TO ^{90}Sr EXTENDED SOURCES - PROBE IN CONTACT WITH SOURCE

Source Diameter (cm)	Response per μCi/cm² — Counting Rate (counts/min): ^{90}Sr	Counting Rate (counts/min): $^{90}Sr + ^{90}Y$	Indicated "mR/h"* (counts/min): ^{90}Sr	Indicated "mR/h"* (counts/min): $^{90}Sr + ^{90}Y$
0.75	1.4×10^5	7×10^4	37	19
4	3.8×10^6	1.9×10^6	1000	500
8	1.1×10^7	5.5×10^6	2900	1500

*Using Dummer's conversion factor of 3800 counts/min per "mR/h".

These data provide a calibration for the particular energies of beta particles used. To extrapolate to other energies it is necessary to consider the effect of the absorption of the beta particles in the tube wall. Although the nominal thickness of the tube is 30 mg/cm², this cannot be used as the effective thickness for a close approach to an extended source since the particles enter at angles other than normal to the tube axis. Calibration of eleven probes of different configuration but all having 30 mg/cm² tubes of cylindrical shape with ^{90}Sr, ^{32}P, ^{204}Tl, and ^{131}I were done at Columbia University[31] several years ago. In these calibrations, two sources, one 6 by 6 in. and the other 1 in. in diameter, were used with the probe at several distances above the source with the tube axis parallel to the source. The closest approach was 3/16-in. and these data were examined. The results were given as indicated "mR/h" per mrad/h to the sensitive layer of the skin as measured through 7 mg/cm² on an extrapolation chamber. These were converted to reading per μCi/cm² by using the Loevinger[8] calculations for the dose rate per μCi/cm². Since ^{90}Sr, ^{90}Y, and ^{204}Tl have forbidden spectra with consequent different spectrum shape, and the change in average energy with atomic number becomes of importance in the calculation, these values were reevaluated using constants recommended by Loevinger[8] rather than using the values from Fig. 1. For estimation of the effect of wall thickness, it was assumed that the counting rate could be expressed by

$$c/m = \Sigma\ (f')(\Omega)\ (G)\ e^{-\nu x} \quad , \tag{31}$$

where f' is the fraction of the disintegrations that lead to the given energy of beta particle, Ω is the source strength in $\mu Ci/cm^2$, G is the geometry factor indicating the fraction of the particles that start in the direction of the tube which strike it, ν is the effective absorption coefficient in cm^2/gm and x is the effective wall thickness in g/cm^2. Since the results from each source were converted to unit activity per unit area, the source strength has already been normalized. The geometry factor was taken to be the same for all sources although this can change with energy due to the difference in range of the betas. This means that for low-energy beta emitters, the fraction of the betas striking the tube which originate in the vicinity of the tube and that therefore penetrate at a lower angle, could be greater than for high-energy betas. This, however, was deemed to be a second-order effect in view of the inaccuracies already present and the uncertainties presented by the different construction of the probes. For purposes of the comparison, it was assumed that the absorption coefficient could be given by[9]

$$\nu = 17\ E_{max}^{-1.14} \quad . \tag{32}$$

From these considerations, it was possible to calculate the effective thickness of the tube wall in the Columbia data from the ratios of the readings obtained with the different sources. It was found that four of the tubes (or probes) had significantly different effective wall thicknesses when calculated in this fashion and these were evaluated separately. Results are given in Table V.

TABLE V

EFFECTIVE WALL THICKNESSES

Isotope Response Ratio	Thicknesses Group 1 (mg/cm^2)	Thicknesses Group 2 (mg/cm^2)
I/Tl	59	79
Tl/Sr	67	75
I/Sr	61	95
I/P	72	110
Tl/P	90	135

From these data, it will be assumed that 70 mg/cm^2 represented a reasonable estimate of the effective thickness.

From this, the response relative to the ^{90}Sr calibration was calculated for various energies considering that the ^{90}Sr source

gave 50% - 0.546-MeV betas and 50% - 2.27-MeV betas and using the calibration factor of 1500 "mR/h" per μCi per cm^2 for the $^{90}Sr + ^{90}Y$ source. This calculated response for various energies is given by the solid line in Fig. 4. Similar calculations were made for an effective wall thickness of 90 and 50 mg/cm^2 to illustrate the range of uncertainty provided by the uncertainty in effective thickness. These values are given as dashed lines in Fig. 4.

As a matter of interest, the reading on the GM counter which would correspond to a skin dose of 30 rad/yr from an extended source if the skin contamination were maintained for 40 h/wk and for 168 h/wk was estimated from Figs. 1 and 4. These values are given in Fig. 5 assuming an effective thickness of the probe of 70 mg/cm^2. As can be seen, this instrument loses sensitivity in comparison with this limit at energies much below 0.5 to 1 MeV.

B. Beta Emitters-End Window Counters

The portable Geiger counters used in the field are unsuitable for measurement of low-energy emitters. We will consider the response of a thin, end-window Geiger counter that could be used when low-energy betas are known to be present.

The response of a Geiger counter depends upon a number of factors. The first is the geometry that, for a point source at a distance from the window and in the center of the window, can be expressed as the ratio of the area on a sphere subtended by the counter window to the full area of the sphere. This can be calculated from the distance and the diameter of the counter window from[32]

$$\text{Geometry} = 1/2 \left(1 - \frac{a}{\sqrt{a^2 + b^2}}\right) , \qquad (33)$$

where a is the distance from the source to the window and b is the diameter of the window. For a spread source the geometry changes with displacement from the center of the window and the overall geometry is an average of the individual point sources that make up the full source. The work at Hanford[32] indicates that this effect can be calculated with good accuracy and, for a 1-1/8-in.-diam window with the source located 0.191 in. away, a 2.5-in. source will have an overall geometry about 25% of that of a point source. With these counter and source dimensions, addition of more material around the periphery of the source will make little change in the counting rate. The response of the counter to a source is increased by the backscatter of beta particles from the material underlying the source. This effect is increased as the atomic number and thickness of the backing material increases until a saturation thickness is reached. Measurements of the backscatter from isotopes emitting various energies of beta particles have been made at Hanford with a saturation thickness of aluminum. These measurements are shown in Fig. 6 with a curve drawn through the points by eye.

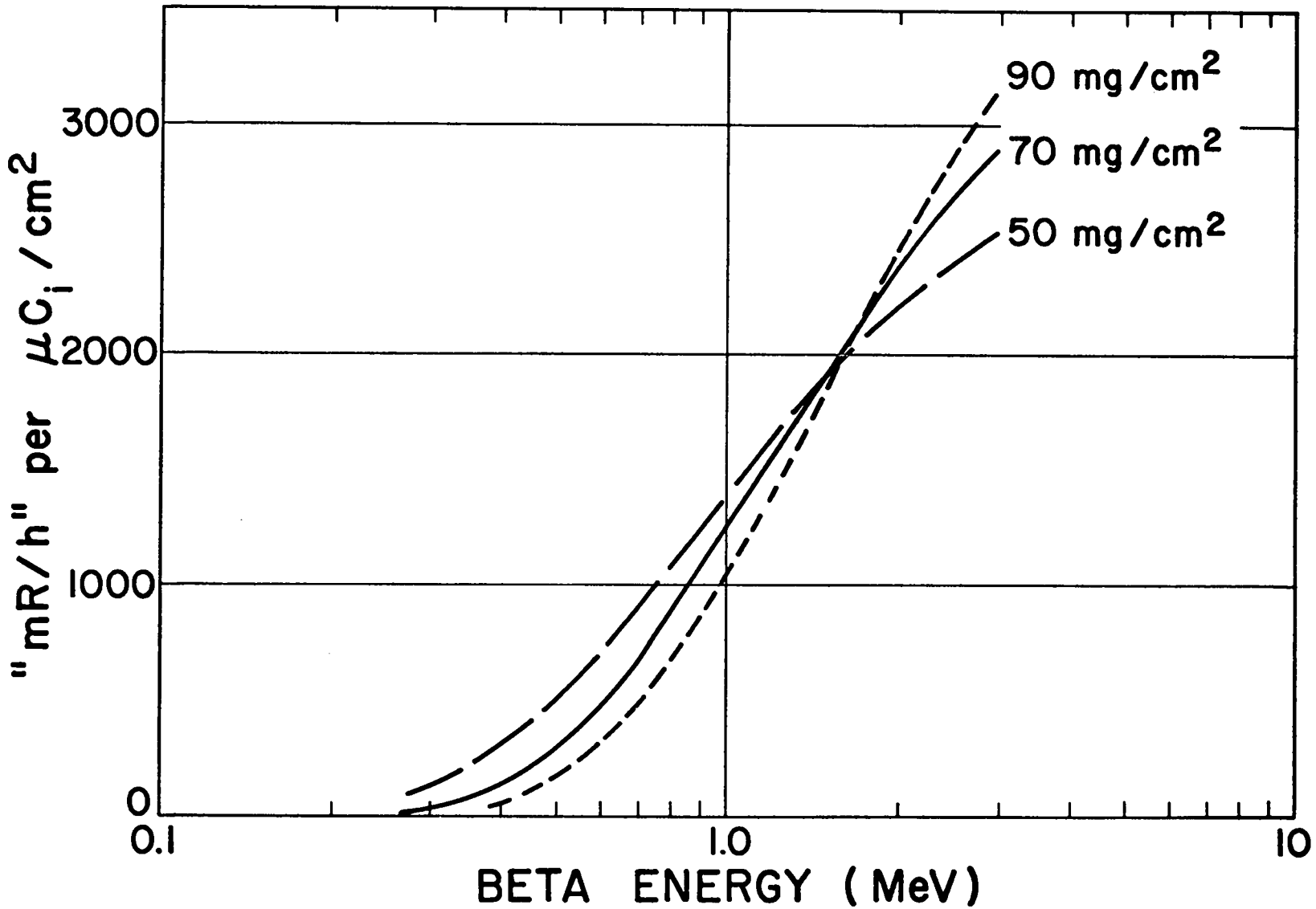

Fig. 4. Approximate calibration curve - portable GM - large area source.

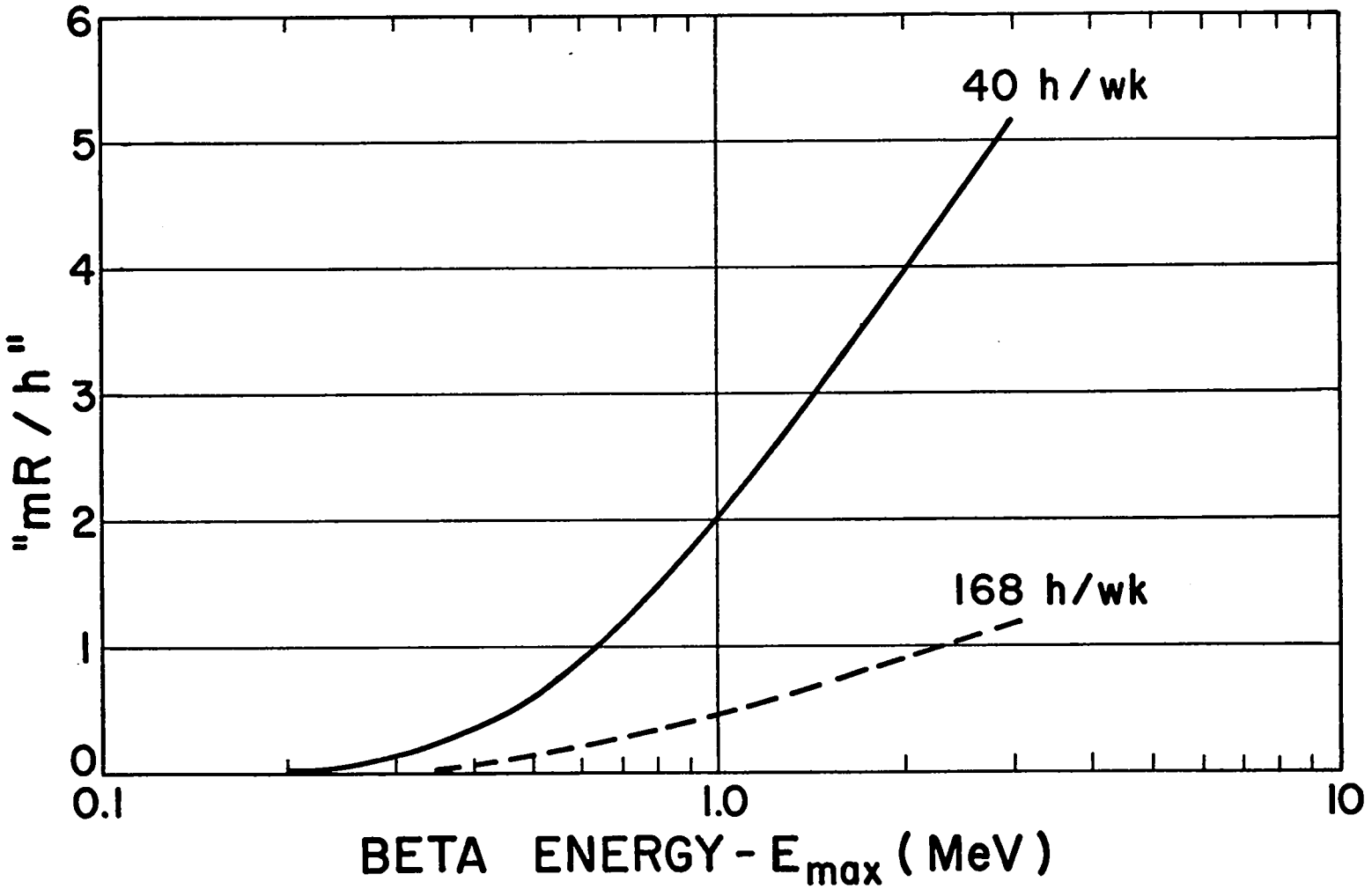

Fig. 5. Portable GM reading to deliver 30 rads per year to skin with skin contaminated hours/week shown. Extended source.

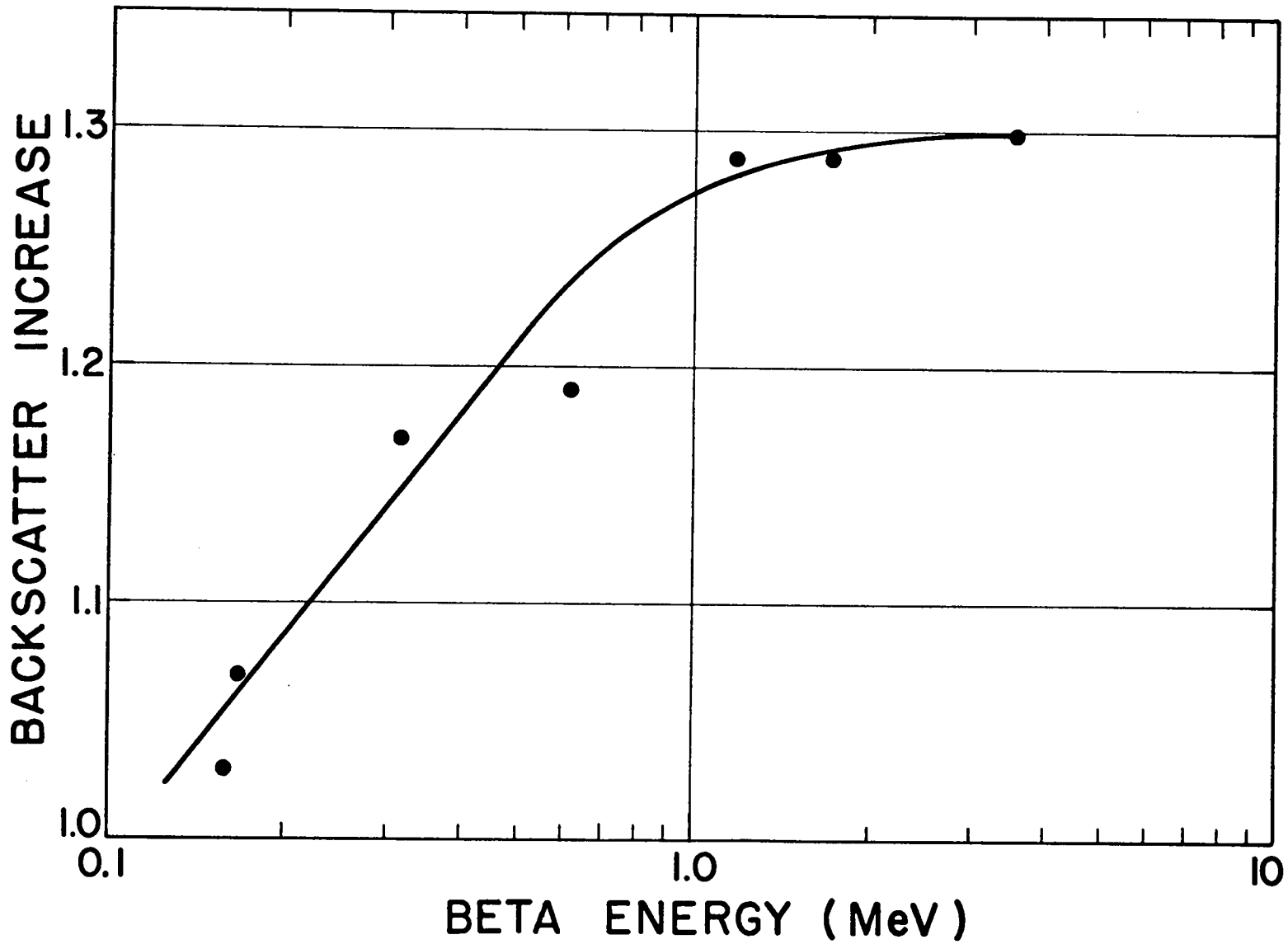

Fig. 6. Backscatter from aluminum.

For low-energy betas, the absorption in even a thin window can significantly affect the result. (Strictly, this is the absorption in both the air and the window when the source is not immediately against the window, but in this discussion we will consider the total thickness of the air and window to be the window thickness.) Because the first part of an absorption curve for beta emitters is approximately exponential, a correction factor can be applied if the absorption coefficient for the beta particles can be obtained. Measurements of the absorption coefficient for several energies over a small fraction of the range were made at Hanford by using aluminum absorbers. These are compared with the two empirical expressions used earlier in Fig. 7. It is noted that the values from the expression used for the portable Geiger counters do not fit the data for the lower energies although the values using Loevinger's relation fit well. This does not invalidate the previous calculations since both expressions are reasonably accurate at the higher energies where the portable counter is used. Because of the better fit at the lower energies, the Loevinger relation was used to derive coefficients to correct for the absorption in the window.

To minimize the calculations required, it was decided to evaluate the response of the counter at the same distance as was used for the top shelf of the Hanford counters, or 0.191 in. In estimating the geometry, it was noted that if one uses the distance from the counter flange to the source in the equation, this produces a geometry higher than that which is measured. This has been attributed to a dead space within the window of the counter where the particles will not produce a count. On the tubes used at Hanford the distance required to make the calculated and measured geometries on the top shelf agree is about 0.157 in. The tubes used were at about 10-cm pressure which resulted in an inward bulge of the mica window which may have accounted for at least some of the effect. For these calculations, it was assumed that the dead space was 0.08 in. Note that this may also be a function of the diameter of the tube which could affect the electrical field in the vicinity of the window.

Again to simplify the calculations, it was assumed that a 2.5-in. source on the Hanford counter was essentially an infinite source. The quantity of radioactive material on this source with a contamination level of 1 $\mu Ci/cm^2$ was calculated and the number of particles striking the counter window was evaluated from the point source geometry, the backscatter, and the measured 25% effectiveness of the spread source in contributing particles. For the smaller counter diameters, it was assumed that the size of the source which contributed to the response decreased in the same ratio as the counter diameter and that this size source still contributed 25% of the point source geometry. For example, if the counter diameter were one-half of the Hanford counter, the infinite source diameter was one-half of the 2.5 in. or 1.25 in. With the same activity per square centimeter, the source strength was one-quarter of that of the larger counter.

The calibrations calculated in this manner are given in Figs. 8 and 9 for energies between 0.1 and 1 MeV and for window diameters of 1-1/8, 1, 3/4, and 1/2 in.

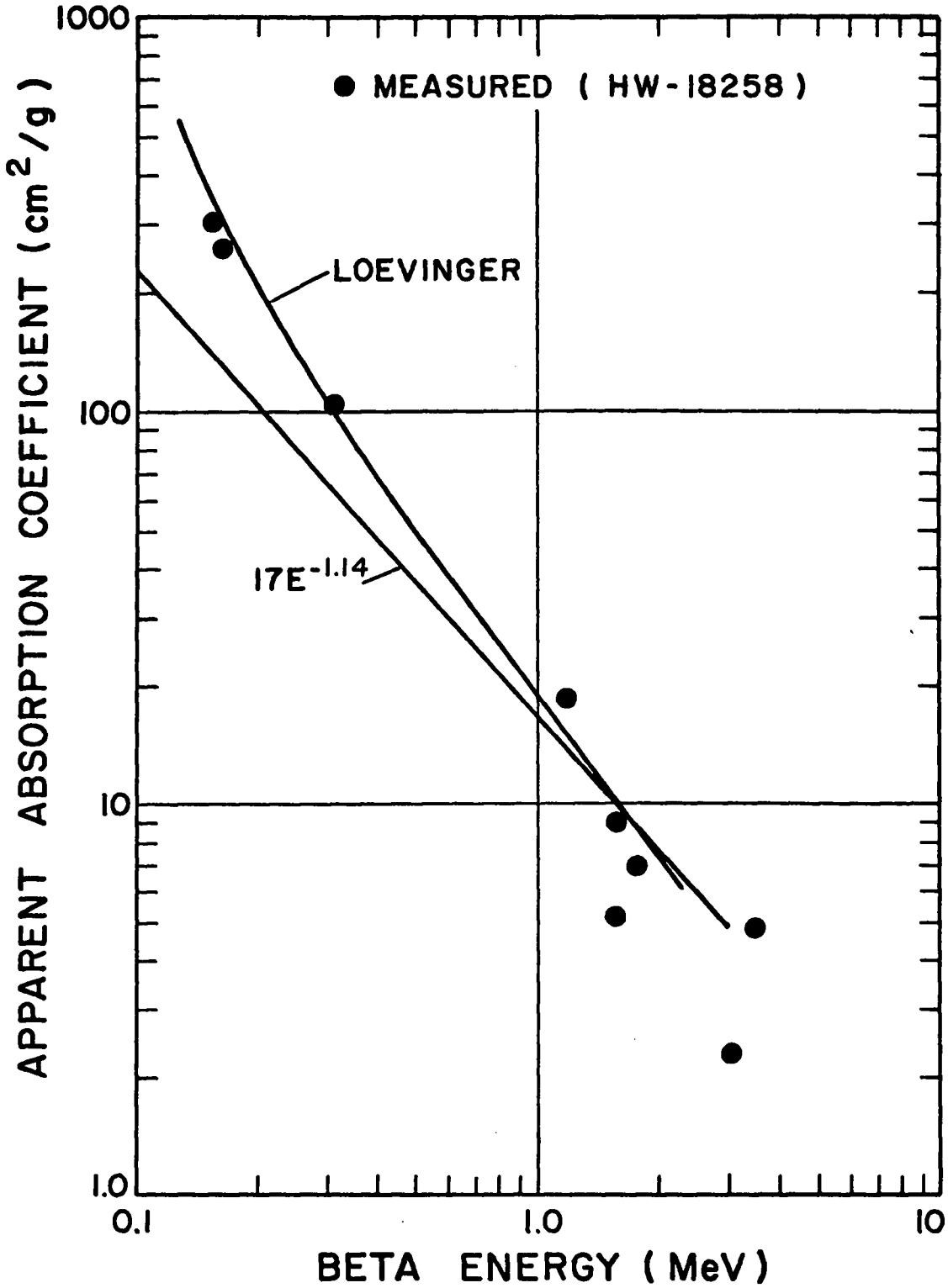

Fig. 7. Apparent absorption coefficients - betas.

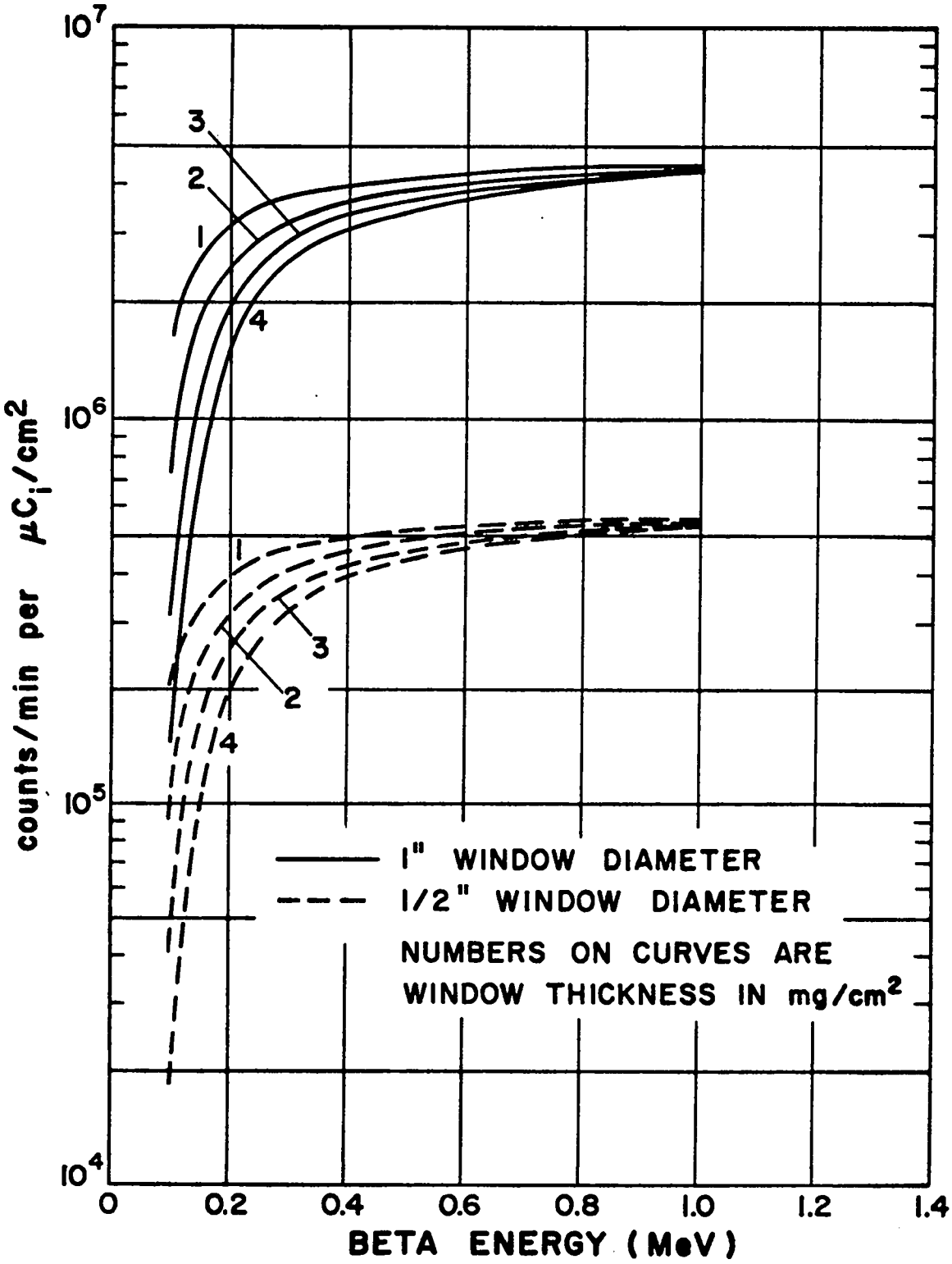

Fig. 8. End window counter calibration.

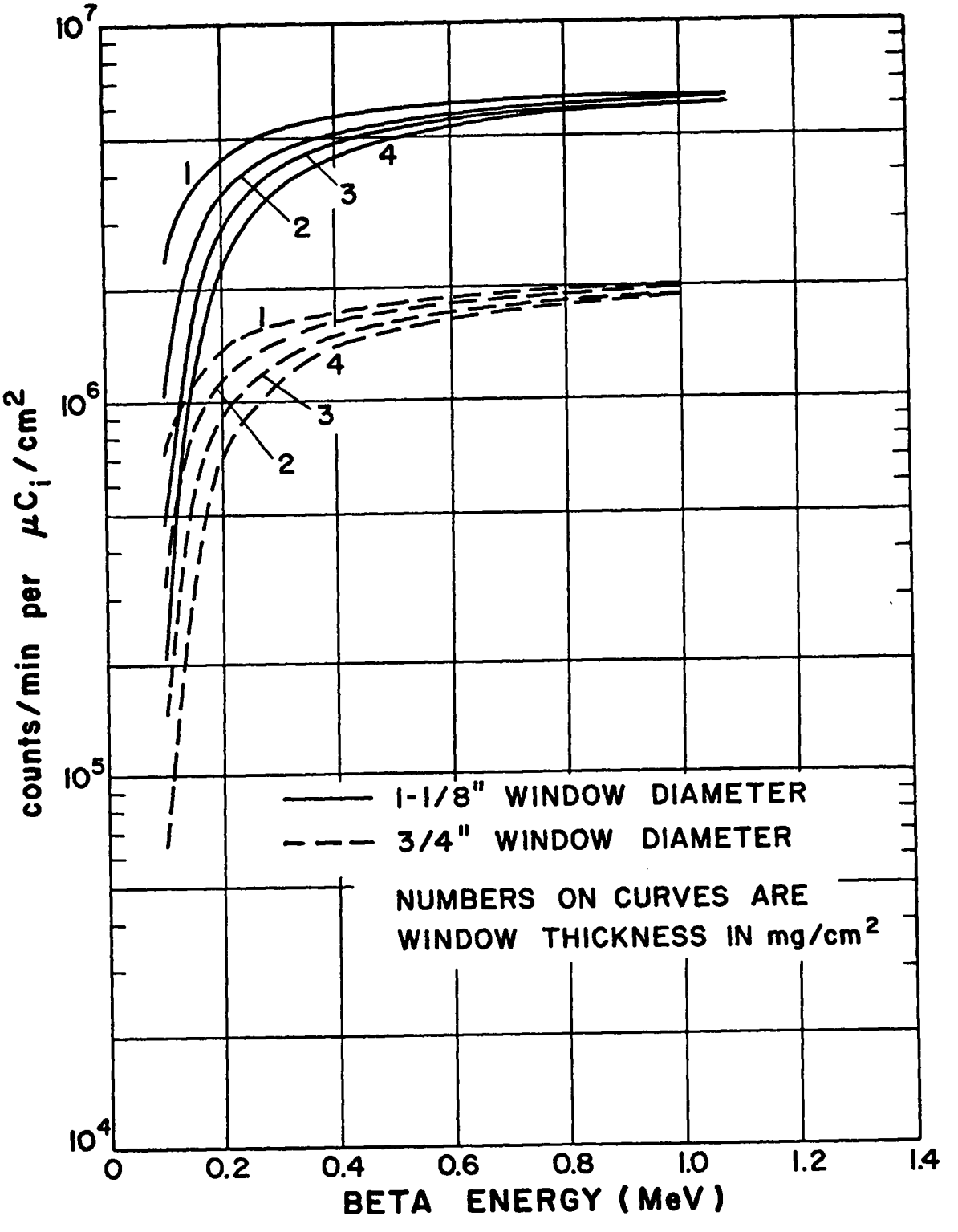

Fig. 9. End window counter calibration.

One other correction which has not been considered at this time is that for self-absorption. This would be of interest primarily for the lower energies although a comparison between the dose rate through 7 mg/cm^2 from a thin deposit and for material uniformly distributed through several thicknesses of material (Fig. 1) indicates some reduction at all energies. It is suggested that, until better corrections are formulated, the ratio of the dose values taken from Fig. 1 be used as an approximate correction factor in those cases where it is known that self-absorption is of importance.

C. Gamma Emitters-Portable GM Counter

Data upon which to base a calibration for those isotopes that emit only electromagnetic radiation is not available. An approximation of the response was obtained by calculating the exposure rate at the approximate center of the tube for disk sources of several sizes and by using the measurements of Krohn et al.[33] to correct for the energy dependence of the instrument.

The GM tube is approximately 3/4 in. in diameter and 2 in. long with the surface of the tube about 1/4 in. from the outer surface of the probe. Thus, the center of the tube is about 1/2 in. from the surface when the probe is in contact. The exposure rate at a distance above a source of 1 μCi/cm^2 with a radius Z is given by

$$D = 1.07\ \mu_a\ \bar{E}\left[E_i(\mu s) - E_i\left(\mu s\sqrt{1+\left(\frac{a}{z}\right)^2}\right)\right] \quad R/h \quad , \tag{34}$$

where μ_a is the energy absorption coefficient, $\bar{E}$ is the average energy of the gamma radiation, $E_i(x)$ is the exponential integral,[12] μ is the total absorption coefficient, and s is the shielding thickness between the point of measurement and the source. Because the tube is calibrated for gamma radiation from ^{60}Co, only the thickness of the air was considered.

For small values of E_i ($<0.01 = \mu s$), tabulated values are not available. However, when μs is small, the exponential term approaches zero and the integral reduces to $\int_z^{0.01} \frac{dz}{z}$ or $\frac{\ln 0.01}{z}$. Thus, for $\mu s < 0.01$ the integral reduces to

$$E_i(z) = 4.0379 + \ln\frac{0.01}{z} \quad . \tag{35}$$

Substituting in the above equation for exposure rate, one obtains

$$D = 1.07\ \mu_a\ \bar{E}\ \ln\sqrt{1+\left(\frac{a}{z}\right)^2} \quad . \tag{36}$$

This equation was used to obtain the exposure rate above sources of 2.5 cm radius (about twice the length of the counter), 5 cm radius, and 10 cm radius. The results were corrected for the energy response as measured in Ref. 33 and are given in Fig. 10.

These values can only be considered as orders of magnitude because of the change in dose rate across the source and the variation at various places in the counter tube. The correction for energy response affects only the values below 0.5 MeV. It should be noted that these have been applied to the average energy. This is not strictly correct since an emitter that has 10% of a 1-MeV gamma will have an average energy of 0.1 MeV but the response of the instrument is that of the 1-MeV gamma.

D. Alpha Emitters

The instrument used for the measurement of alpha emitters is the air proportional counter that has a window area of 60 cm^2 and is covered with a Mylar window (polyethylene terephthlate) about 1 mg/cm^2 thick. The instrument is adjusted by comparison with a source without self-absorption so that the indication on the meter is equal to half the number of disintegrations occurring in the source when the probe is placed in contact with the source.

The readings on this instrument should be adequate for measurement purposes when the alpha emitter is spread thinly over a nonabsorbent surface. In many cases, however, the measurement is made with the alpha emitter on an absorbent surface or in a situation where the emitter is mixed with slight quantities of other materials, such as oil or water, so that the source has significant self-absorption. Since the range of alpha particles from radioactive materials is only on the order of a few milligrams per square centimeter, even a slight addition of absorbing material will seriously affect the reading. Corrections can be made for such absorption if the thickness of the film and the distribution of the alpha emitter through the film is known, but this case is an exception rather than the rule.

A method for calculating the self-absorption when the distribution of the material in the source is known has been given by Finney and Evans.[34] For a thin source they give

$$n_a'' = \frac{N''}{4}\left[\frac{2(R'-\delta-\sigma) - \frac{m}{\omega A \rho_m}}{R' - \delta}\right] , \qquad (37)$$

where n_a'' is the counting rate per gram of source, N" is the number of disintegrations per unit time per gram of the source material, R' is the range of the alpha particle in air under standard conditions, σ is the thickness of any absorber between the source and the sensitive volume of the counter in air cm, δ is the path length in the counter required to produce a measurable event, m is the total mass

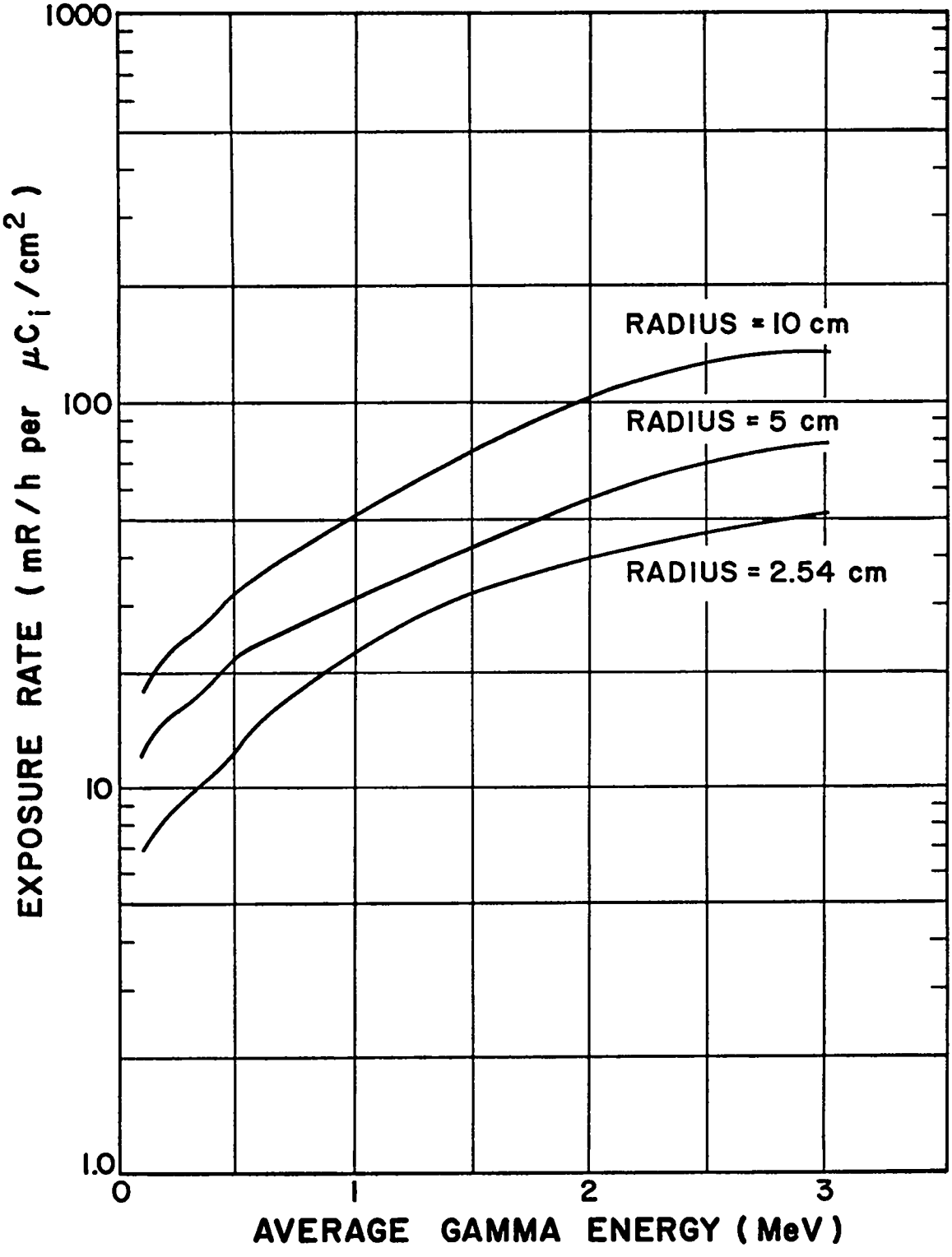

Fig. 10. Calibration of portable counter for gamma emitters.

of the source with an area A, ρ_m is the density of the source material, and ω is the ratio of the range of the alpha particle in the material of the source to the range in air. (This is the reciprocal of the linear stopping power.) For ease of handling and for clarity we have expressed the source mass in thickness per unit area that rro-provides the counting rate as the rate per square centimeter (n_a'). In addition, we have substituted the mass stopping power for the linear stopping power by using the expression

$$S_m = \frac{\rho_a}{\rho_m} \cdot \frac{r_a}{r_m} = \frac{\rho_a}{\rho_m} \cdot \frac{1}{\omega} \quad , \tag{38}$$

where ρ_a is the density of air under standard conditions, ρ_m is the density of the source, and S_m is the mass stopping power of the medium. This gives

$$\frac{n_a'}{N''} = \frac{m}{4A} \left[\frac{2(R-\delta-\sigma) - \frac{m}{A}\frac{S_m}{\rho_a}}{R - \delta} \right] \quad . \tag{39}$$

Note that $\frac{mN''}{A}$ is the total disintegration rate per square centimeter.

For a thick source, the counting rate is contributed only by the material that lies within a distance from the surface such that the particle emerging perpendicular to the surface will just cause a count. Any added source below this will not increase the counting rate. In other words, once this thickness is exceeded, the counting rate will be constant and will be a function only of the activity per unit weight of the source material. In the above equations, this thickness is equal to $(R-\delta-\sigma)$ and the mass of the source per square centimeter required is

$$\frac{m}{A} = \frac{(R-\delta-\sigma)}{S_m} \rho_a \quad . \tag{40}$$

Substituting this value in the thin source equation, one obtains for the thick source

$$\frac{n_a'}{N''} = \frac{\rho_a}{4S_m} \left[\frac{(R-\delta-\sigma)^2}{R-\delta} \right] \frac{\text{counts/min per cm}^2}{\text{dis/min per g}} \quad . \tag{41}$$

In evaluating these equations, the value of S_m must be known. This is evaluated by empirical measurements because of the uncertainty of the theoretical expressions for ionization losses for alpha particles at low energies. Values for tissue ranging from 1.01 to 1.21 are found and comparing the ranges given by Lea[35] with the range in air from Etherington's Handbook,[36] values up to 1.29 can be obtained. The value of S_m will vary somewhat with the energy of the

particle, being somewhat lower for low energies, but in this approach, the total range of the particles is used so that an overall stopping power for the full energy can be used. The stopping power will also vary with the atomic number of the medium or absorber being higher for the lower-number absorbers. Finney and Evans[34] use the relation depending upon the square root of the effective atomic weight while Fitzgerald et al.[9] recommend a variation with the cube root of the effective atomic weight. For our purposes, the mass stopping power of the source material and Mylar window (which serves as the absorber σ) was taken as unity. This could introduce an error of 10 to 20% in consideration of the self-absorption for tissue or clothing, but this was considered to be negligible in comparison with the other unknowns. Note that application of this relation to other materials such as soils or metals requires that the mass stopping power of the medium be considered.

The value of δ, the path length in the sensitive volume required to trigger a pulse, was arbitrarily taken as 2 mm which will release about 0.2 to 0.3 MeV or produce about 10^4 primary ionizations. Although the result is not too sensitive to the choice of this parameter, a change from 0.2 to 0.5 mm can result in a 10 to 15% change in the thick-source counting rate for a 4-MeV alpha emitter. Perhaps of more interest is the question of whether the adjustment made on the instrument to bring it into calibration with a thin source has any major effect on the value. If so, it is possible that significant changes in the response to the spectrum from a thick source may occur from instrument to instrument.

One other variable worth mentioning is the geometry. The following evaluations were made for a 2-π geometry and neglecting edge effects. Again, the effect of these variables on the overall response should be small in comparison to the uncertainties of the basic problem as it is encountered in the field.

The effect of self-absorption on the response of the counter assuming a source with radioactive material uniformly distributed through the source material has been evaluated from these equations and is presented in Fig. 11. The ordinate presents the number of counts per unit time expected per square centimeter for alpha emitters of the given energy distributed through a source thickness as given. The total disintegration rate in the source is taken as the total rate throughout the full thickness of the source. The critical thickness points are marked on the curve. For thicknesses below this, the counting rate will increase as the source thickness increases. Above this point, the counting rate will remain constant and the loss of efficiency is due to the addition of radioactive material without a corresponding increase in counting rate.

It must be remembered that this curve is based on a uniform distribution of activity in the source materials. A distribution of radioactive material which differs from this will give a different counting rate that could be evaluated by these methods if the distribution were known. Since the distribution is seldom known in the

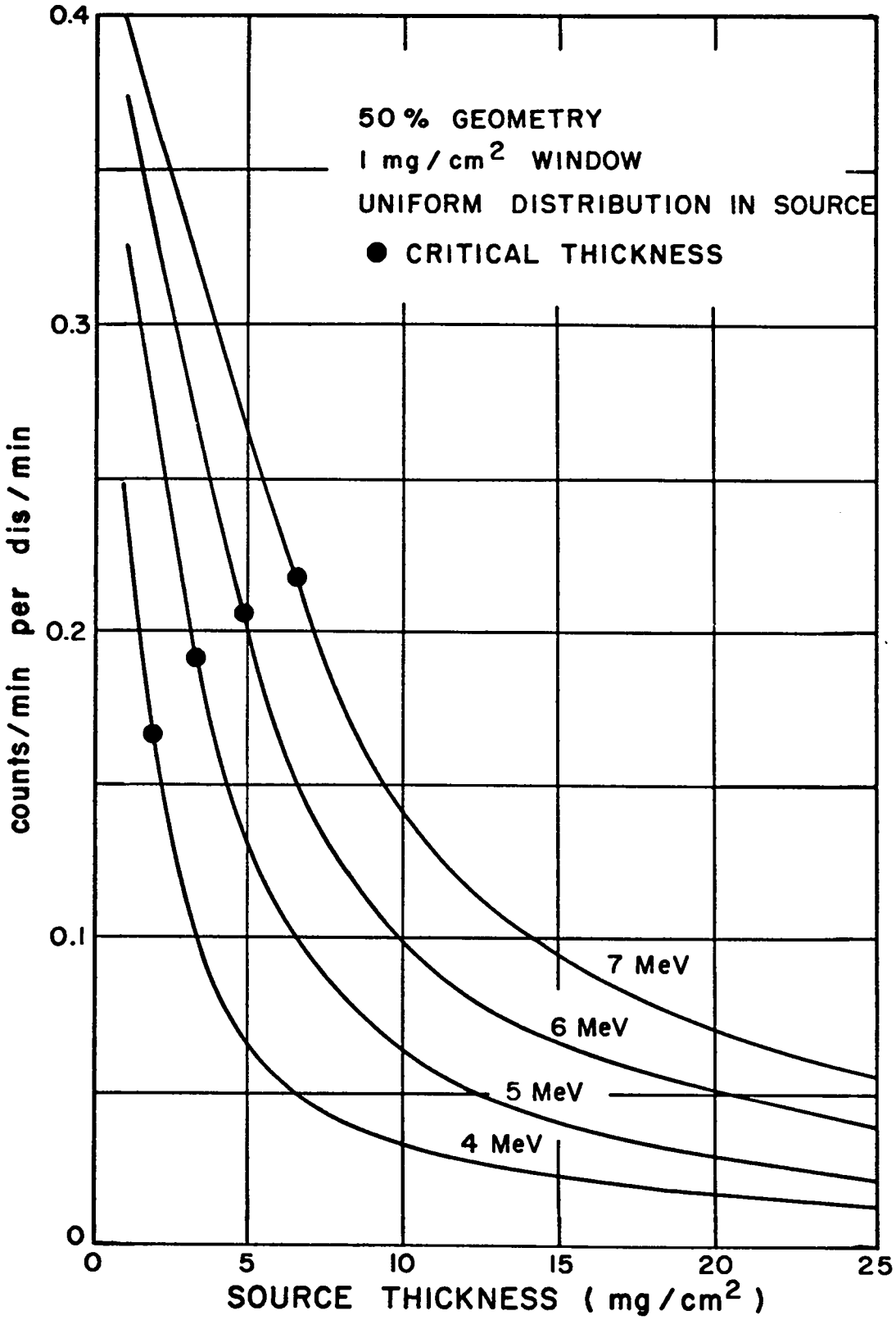

Fig. 11. Response curves - alpha counter.

field, the curve given here is intended to provide some feeling for the importance of the self-absorption factor.

E. Application of Factors

The rough instrument calibrations have been applied to the decision levels derived earlier, with the results given in Table D-IV of Appendix D. Where the decision level was expressed as μCi per day, such as for skin absorption or the transfer levels, an area of 10,000 cm^2 was used to provide a "warning level" for the instrument. Only the levels for workers were considered with the instrument readings estimated for the most limiting effect of a given category. Thus, for skin contamination the reading is based on the lowest level from the dose due to material on the skin, from absorption through the skin, or from direct inhalation or ingestion. For clothing, the effect is based on skin dose from contaminated clothing or from direct ingestion or inhalation. The two most limiting values for the transfer are given to enable comparison and the use of judgment as to the possibility of a given effect under the particular circumstances. Presumably the skin and clothing values would apply to the individual at work whereas the transfer values would apply to his leaving the work area to a clean area. However, the worker decision levels are based on an exposure time of 2000 h/yr and any contamination left on his body when he leaves work will produce exposure for a time greater than this. If he is considered to carry this contamination full time, then the values should be reduced by a factor of 0.25.

It must be remembered that the levels were derived to give the full permissible dose under the conditions assumed and any reduction to account for exposure from other sources must be included.

For the beta emitters, the values in Table D-IV include only the beta response of the instrument as read from Figs 4 and 8. Where a gamma component is significant and the beta is of low energy or frequency, the gamma could provide additional response. For example, with ^{22}Na having a 0.545-MeV beta and a 2.2-MeV gamma, the response of a portable GM counter from a 10-cm-radius source could be about 25% greater than that given. The estimated readings on a portable GM counter are given for the higher energy beta emitters and on the mica window counter for the lower energies. For the intermediate energies, the response of both instruments is estimated. The gamma response of the portable GM is based on a source radius of 10 cm and for both the beta and gamma readings some isotopes have energies below the calibration curves. In these cases, no value is given. The response for the alpha air proportional counter is based on a 60-cm^2 area with a 2-π geometry and no correction for self-absorption. It should therefore be regarded as a maximum value.

If a smear test is used to determine a "loose" component, one must consider the effectiveness of the test in removing the contamination in comparison to the assumptions made in calculating the spread or intake of the material as well as the efficiency of the the instrument for measuring contamination concentrated over a

smaller area. From Table IV, the response of the portable GM to $^{90}Sr + ^{90}Y$ is about 40 "mR/h per μCi for small sources of 0.75 to 4 cm diam and is reasonably uniform. If the smear is taken over an area of 100 cm^2 and has a removal efficiency for loose contamination of "eff" then the response in comparison to the 1500 "mR" for a large area source is

$$\frac{40 \times 100}{1500} \text{ eff} = 2.7 \text{ eff} \quad .$$

In other words, the reading given in the table would correspond to a smear over 100 cm^2 that removed the contamination with an efficiency of about 38%.

For the end window counter, similar presumptions can be made. The values given in the table were corrected for a source 2.5 in. in diameter or with an area of about 32 cm^2. A smear over 100 cm^2 would, therefore, cover about three times the area used in the counter calibration. Depending upon the technique used in obtaining the sample, the source, as measured, could be small or large. For a 1-in.-diam smear, the spread source correction factor is about 0.8 rather than the value of 0.25 used for the 2.5 in. source so that the counting rate for a given amount of activity would be about three times greater. Depending, then, upon the size of the smear source, the efficiency of removal to give the numbers listed would be 10 to 30%. It should be noted that the isotopes measured with the end window counter emit low-energy betas and self-absorption in either the surface or the smear could be significant. For ^{35}S, for example, a source thickness of 4 mg/cm^2 could reduce the reading by 50%.[32] This phenomenon is not taken into account in Table IV.

VI. DISCUSSION

The foregoing derivations are an attempt to obtain surface contamination levels based upon a number of possible defined mechanisms that have not been considered seriously in the past and to incorporate a philosophy that such levels should consider all of the controls on radioactive materials that are normally imposed. Firm data for an objective derivation are missing in many cases and it has been necessary to substitute a considerable degree of subjective reasoning. Obviously there will be varying degrees of belief or disbelief as to the various numerical factors derived by this means and there will undoubtedly be major changes when more complete data are available. In particular, the use of the same constant for all isotopes for such mechanisms as absorption through the skin, direct ingestion, direct inhalation, or the various transfer and retention coefficients provides a possible serious source of uncertainty and the values should be used with any available information that would further define these factors. However, it is believed that the decision levels given will be useful in comparing restrictions on various isotopes, as a framework to indicate where additional information is needed in a field situation, and hopefully, to provide a better

understanding of the relative importance of these possible mechanisms of exposure. Further, they can be used along with local information to indicate the sensitivity of routine monitoring procedures and instruments to give adequate assurance of contamination control.

A brief word on the subject of "fixed" and "loose" contamination is in order since we have not distinguished between these except in brief discussions. Obviously, for some effects, such as the dose to the skin from contamination on the skin or clothing, it is the total contamination per unit area that is important. For others, such as direct inhalation or the transfer levels, only the "loose" contamination is applicable. However, here the problem of defining "loose", particularly in terms of an operational test, become inportant. For example, a smear test of a piece of clothing may show nothing and yet the movement of the fibers while the individual is wearing the clothing could dislodge a significant number of particles that could then become airborne. A piece of equipment or scrap could have the contamination "fixed" on or in the surface and yet be subjected to forces far beyond those of the standard swipe test (such as welding, grinding, hammering, etc., during use or repair). Such actions could convert the previously "fixed" contamination to a transferable form. Decisions as to "fixed" or "loose" require an input as to past history and probable future use before a reasonably definitive level can be derived. For this reason, separate levels have not been given and it is suggested that consideration be given to these factors, as well as those used in deriving the levels, before making a final decision.

In approaching this problem by deriving levels based on a number of different exposure mechanisms,it must be recognized that the inherent uncertainties and, therefore, the accuracy of the level based on each mechanism, will vary widely. The dose rate to the skin from beta emitters on the skin can be evaluated with reasonable accuracy. The dose rate from contamination on the clothing depends, to some extent, on the type of clothing and the distribution of radioactive material in the cloth, but the values are probably reasonable. In these cases, it may also be noted that the dose rate to the skin underlying the contaminated area is dependent upon the contamination per unit area so that the total dose is a function of the time that a particular area is contaminated. The direct inhalation level is less certain since it is based upon only a few studies with one contaminant but is probably better than the direct ingestion level which is almost arbitrary. The level based on absorption through the skin uses data from only a few chemical forms of a few isotopes and generalizes these rates of transfer to all isotopes and chemical forms. There is no doubt that the assumption is conservative for many materials, but data reviewed in the text indicate also the possibility that the values may underestimate the potential uptake by this mechanism for, at least, a few isotopes in some chemical form. The transfer levels are uncertain because of the complexity of the environments into which such transfers are possible. It may be noted that, while many of the transfer parameters used are undoubtedly conservative, the situations chosen are the probable ones rather than the most conservative. For example, transfer to an

automobile or a smaller residence, such as a trailer, could result in lower values if the same parameters were used. Probably the most uncertain are the estimated instrument readings because they include the above uncertainties plus those inherent in the calculation of the instrument calibrations. In this connection, it should be noted that the instruments chosen for this work were picked because they are in common use and there is no intent to imply that these particular types of instruments are in any way optimum for this use.

An interesting conclusion of this study is that, under the assumptions used, the contamination levels of concern for many isotopes can be based on radiation dose considerations. Further, the application of a single value for all emitters of a particular type of radiation can be overconservative or underconservative from a strictly radiation protection point of view. There are, however, other considerations, such as the contamination of raw materials or of measuring instruments, which may override the radiation dose for the less hazardous materials.

As a final word of warning, the tables in Appendix D list values of the decision levels for about 180 isotopes with more than 3000 individual values, each comprising a separate calculation. Since the emphasis in this study is primarily on the concepts, the individual calculations have not been repeated to permit a check on each value. The author would appreciate having any errors or discrepancies called to his attention.

APPENDIX A

THE SKIN

The skin is of particular interest since its surface can be contaminated resulting in a radiation dose to the underlying tissue, and there is always the possibility of absorption through the large surface area presented by the skin. A brief discussion of the skin and its structure is given to provide a basis for the radiation dose calculations. An even briefer review of data on absorption of materials through the skin is provided to permit some appreciation of the assumptions upon which the calculations are based. This appendix is not intended to be a complete and exhaustive review of knowledge on these subjects, but, rather, a discussion of some of the more pertinent factors as obtained from a brief review of the literature.

A. Skin Structure

Most authors consider the skin as two or three distinct layers.[37] Starting from the outer surface, these are the epidermis, the dermis, and the subcutaneous tissues and subcutaneous fat. Our main concern is with the epidermis since it provides the chief target for radiation and the main barrier to absorption. The dermis contains the nerves and the blood vessels and supports such structures as the

hair follicles and the sweat and sebaceous glands. The blood vessels in the dermis have a large surface area and material absorbed through the skin must penetrate to this region if it is to be taken up by the blood and moved to other regions of the body.[7]

Figure A-1 gives a rough schematic diagram of the skin.[37] The epidermis overlies the dermis with a definite membrane at the junction to cement the two together. The bottom layer of epidermal cells is the basal layer (stratum germinativium). This is a single layer of cells which is the source of all other cells in the epidermis. These cells continuously undergo division to produce daughter cells that migrate upward as the prickle cell layer (stratum spinosum) and, later, as the horny layer (stratum corneum). In this fashion the epidermis is continually renewed. Tregear[7] indicates that in man, most, but not all, cell divisions take place in the basal layer. There are some divisions in the prickle cell layer. He also notes that in hairy mamals the epidermis is much thinner than in man and, in this case, it is likely that all cell divisions are in the basal layer. The basal layer is normally chosen as the critical organ or target organ for calculations of radiation dose presumably because of the rapid cell division. It is of interest to note, however, that Albert et al.[38] by using rats and monoenergetic electrons with different penetrations have noted that tumor incidence correlates with the dose delivered at a depth of 0.27 mm and not with the dose calculated for depths somewhat greater and somewhat smaller. This "critical depth" is greater than the thickness of the epidermis and they indicate it to be close to the bottom of the resting hair follicle.

As the cells produced by the basal layer move toward the surface, they become larger and accumulate granules to form the granular layer. The horny layer is the outer dead layer consisting of a layer of cells without nuclei and with the cytoplasm replaced by keratin. The granular layer appears to play an important role in the keratinization of the cells before they enter the horny layer. The cells of the horny layer are thin, flat, approximately hexagonal plates about 25 μm across and 0.5 μm thickness in man. The edges of the plates overlap and connect so that layers can be lifted off on adhesive tape.

The outer horny layer of the skin is continually renewed by cells originating in the divisions in the basal layer and migrating outward. There is a signal mechanism of some nature between the basal layer and the horny layer because damage to the horny layer resulting in a removal of a portion of the cells causes a stimulation of cell division in the basal layer to replace the lost protective layer. The total turnover time ascribed to Rothberg by Baker et al.[39] as measured by injection of glycine ^{14}C and measuring serial scrapings is 28 days. Rothberg estimated a theoretical turnover time from data on the mitotic rate of the basal layer as 27 days. Baker et al.[39] also quote Weinstein and Van Scott as indicating the turnover time of the horny layer to be about 16 days. Allen[40] indicates the renewal time for the Malpigian layer (epidermis exclusive of the horny layer and the granular layer) to be about 13 to 18 days.

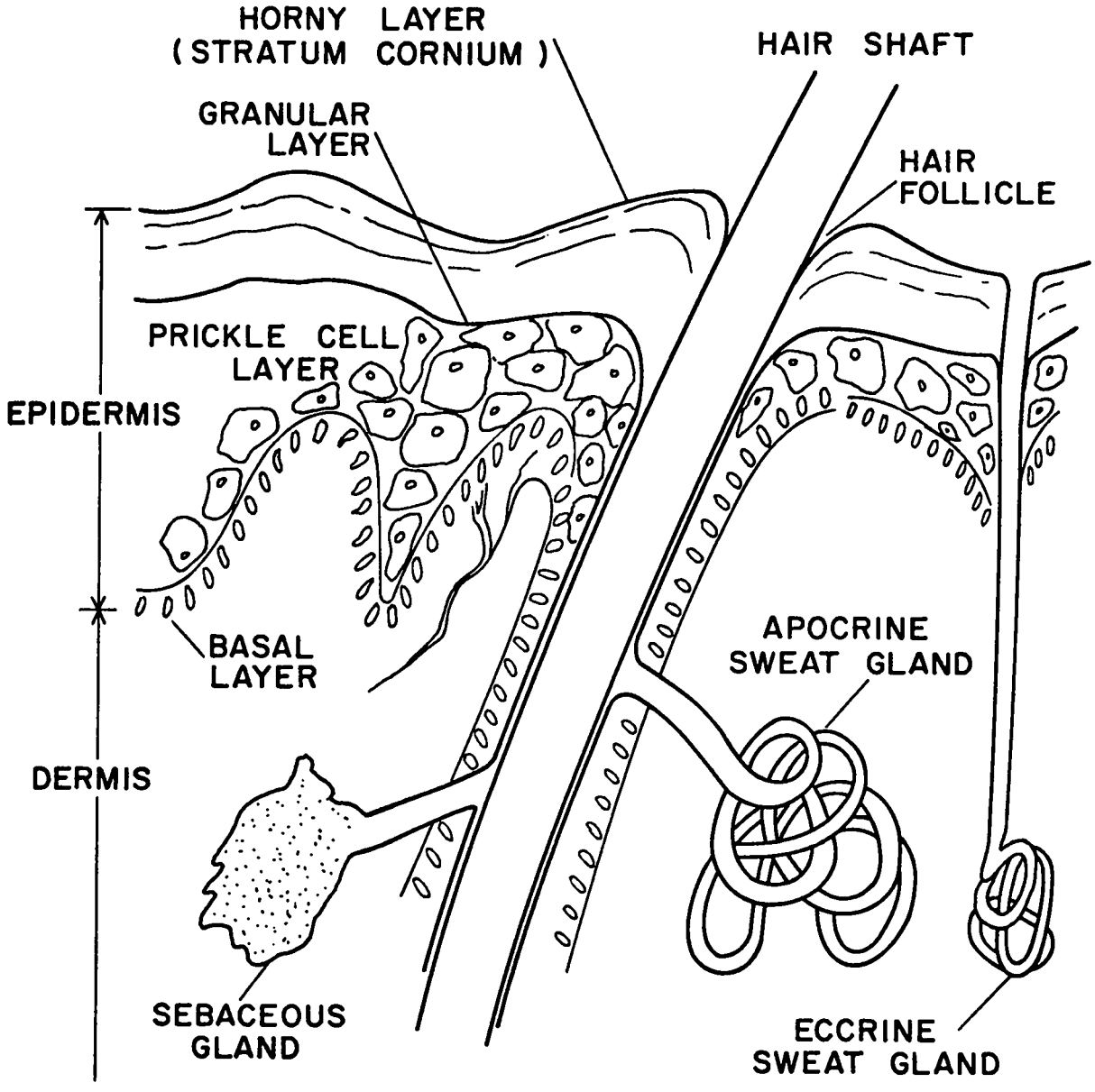

Fig. A-1. Schematic diagram of skin.

Baker and Kligman[39] measured the turnover time of the horny layer by using a fluorescent dye, which stained the dead cells, and by noting the time for the fluorescence to disappear. The site was occluded under clear plastic which they indicated did not influence the turnover time. Their conclusions are given in Table A-I.

TABLE A-I

TURNOVER TIME OF HORNY LAYER

Region	Number People	Average Turnover Time (days)
Back	14	15.3 ± 5.6
Forearm	9	13.3 ± 1.5
Back of hand	6	20.8 ± 2.3
Forehead	7	6.3 ± 1.4
Shin	5	19.6 ± 2.5
Abdomen	9	9.6 ± 2.9
Scalp	5	9.6 ± 1.0

For the back, eight people were in the range of 13 to 17 days, 13 in the range of 10 to 19 days, and one had a turnover time of 34 days. In a further test, they measured the number of layers of cells at each site by swelling them in NaOH to make them visible and calculated the turnover time for each site relative to the turnover time for the number of layers found in the back (Table A-II).

TABLE A-II

CORRECTED TURNOVER RELATIVE TO THAT OF BACK

Region	Number Cell Layers	Corrected Turnover Time (days)
Back	15-17	15.3
Forearm	15-17	13.3
Back of Hand	25-30	12.1
Forehead	13-15	7.2
Abdomen	14-16	10.2

They also tested the effect of exposure to erythemogenic light and found that the treated skin had a turnover time of 5 to 9 days as compared to 12 to 16 days for skin on the other arm which was not treated. In a similar test, the treated area was immersed in a 5% aqueous solution of sodium lauryl sulphate at 40°C for 1 h while a similar area on the other arm was immersed in water. The turnover time on the detergent area was 7 to 8 days while the control areas was 14 to 15 days. They judged that the effect was not due to leaching by the nature of the fluorescence.

It would appear that for normal skin the turnover time from cell division to sloughing is about 28 days with about one-half of the time required to move to the horny layer and the other half in

the horny layer. It is noted that the skin on the forehead appears to have a lower turnover time in the horny layer than other regions of the body.

B. Skin Appendages

The hair grows from a follicle which is rooted deep in the dermis (3 to 5 mm beneath the surface). The follicle is formed of epithelial cells that represent a downward extension of the epidermis[41] although data on the thickness of this epidermal layer are not immediately available. Inside the epidermis of the follicle are two sheaths around the hair formed from hair matrix cells. There are 40 to 70 hairs per square centimeter on the skin of the trunk and limbs of man, whereas densely haired rodents may have up to 4000 hairs per square centimeter.[7] Tregear[7] gives measurements from 2 to 4 animals indicating the approximate dimensions for several species (Table A-III).

TABLE III

HAIR FOLLICLE DIMENSIONS

	Number per cm^2	Length (mm)	Width (μm)
Man, forearm	60	0.1	50
Pig, flank	40	0.3	120
Horse, belly	800	0.3	100
Rabbit, flank	(700	0.15	50
	(3000	0.15	20

The sebaceous glands open into the hair follicles and excrete a fatty material which exudes from the hair follicle to cover the skin. It is estimated that this layer is 0.4 to 4 μm thick in man.[7] The glands are lined with epithelial cells in their opening into the hair follicles and with sebaceous cells deeper in the gland. It is estimated that there are 400 to 900 such glands per square centimeter on the forehead and about 100 per square centimeter elsewhere on the body.[40] There are no sebaceous glands on the palms, soles, and dorsum of the foot.[37]

The apocrine sweat glands also open into the hair follicle and are found on limited areas of the body: the ear canal axillae, nipples and anogential regions.[37] The eccrine sweat glands are found on the whole surface of the body and are most numerous on the palms, soles, and forehead. They secrete a weak solution of sodium chloride, urea, and lactic acid with heat as the prime stimulus. Evaporation of this sweat is a principal means of heat loss when body temperature increases.[37] In mammals other than primates, sweat glands open into or just adjacent to the hair follicles except on the pads and snout.[7]

C. Dimensions[37,40]

The surface area of the skin is about 0.25 m^2 in the newborne, about 1.85 m^2 for an average man and about 1.6 m^2 for an average woman. An empirical formula relating body weight and height to surface area is

$$cm^2 = (kg)^{0.425} \times (cm)^{0.725} \times 71.84 \quad .$$

The distribution of area is given by Laylee as:

Head and neck	9%
Upper limbs (9% each)	18%
Lower limbs (18% each	36%
Trunk	36%
Gentials	1%

The outstretched palm and fingers is 1% of the total area of the body.

The specific gravity of skin is quoted as about 1.1 by Laylee and about 1.25 by Allen. The mass of skin in an average adult is given as 4 kg with the epidermis as 225 g. (This would be an average of 12.2 mg/cm^2 for the 1.85 m^2 adult.) The volume of the skin of an average adult is given by Laylee as 3600 cm^3 and by Allen as about 2400 cm^3.

The thickness of the skin ranges from 0.5 mm (55 mg/cm^2) on the eyelid to 3 to 6 mm (330 to 660 mg/cm^2) on the palms and soles of the feet. The epidermis ranges from 0.06 to 0.09 mm (7 to 10 mg/cm^2) on the eyelid to 0.5 to 0.8 mm (55 to 88 mg/cm^2) on the palm or sole. The above mass thicknesses were obtained by using a density of 1.1 g/cm^3. The granular layer is only one to three or four layers of cells thick. The horny layer on the forehead and cheeks averages 0.02 to 0.4 mm (2 to 4 mg/cm^2) and on the palm or sole 0.4 to 0.7 mm (40 to 80 mg/cm^2).

For radiological calculations, the thickness of the epidermis to the target cells at the basal layer is usually taken as 7 mg/cm^2. As can be seen from the above numbers, this is conservative for many areas of the body. Of the full thickness of the epidermis in the thinner areas, about one-half is in the horny layer and about one-half is in the prickle cell layer to the uppermost extension of the folded basal cell layer. Thus, a radiological model of the skin would have a flat layer of inert material 3.5 mg/cm^2 thick with a second layer of the same thickness before the target cells. Even with this model, only a fraction of the target cells would lie at the quoted depth because of the folding of the basal layer.

D. Absorption through Skin

Although the intact skin is an effective barrier for minimizing the entry of most materials into the body, many solutes and solvents

will penetrate to some degree. Such penetration occurs by a passive mechanism for most materials. That is, there is no cellular energy involved and the barrier appears to consist of a membrane with high resistance. It is possible, for example, to use incised skin as a membrane to study the passage of materials with the same results as if the skin were still on the animal.[7] There are many variables depending upon the exact nature of the penetrant and its solute. Allen states:[40] "Each penetrant substance encounters different barriers in accordance with its own chemical and physical properties and its interactions with tissue as it penetrates the epidermis. Even the absorption capacity of the skin components provides protection against penetration." This is about as succinct a statement of present knowledge and the problems of predicting absorption as seems to appear in the literature.

Tregear[7] has reviewed much of the physical chemistry data and biological data concerning the mechanisms of absorption through the skin and the reader is referred to the first chapter of his book for additional details. Here we will cover some of the mechanisms briefly before referring to specific data on several radioactive materials.

Tregear points out that the movement of materials through the skin often, but not always, follows Fick's law of diffusion. That is, the rate of movement through the skin is proportional to the driving force which, in turn, is the concentration difference across the skin. This can be further defined for a particular substance by the permeability constant which is the ratio of the rate of passage through a given area of the skin to the concentration applied. This assumes that the concentration below the skin is held to zero by the constant removal of the material by the blood capillaries. This proportionality will break down when high concentrations of penetrant are applied to the skin, presumably due to interactions between penetrant and skin, such as with mercury, or to changes in the chemical activity of the material. The units of the permeability are those of velocity, such as centimeters per second. It should be noted that in such a diffusion process there is a transient phase when the material is first applied to the skin where the penetration changes slowly from zero to the constant rate defined by the steady-state permeability constant. Tregear defines a time t_d which is equal to the extrapolation of the straight line portion of a plot of the penetration rate against the time as a characteristic of this transient phase. Note that the equilibrium rate is not attained even in this time because of the extrapolation of the curve. This time is attributed to the capacity of the barrier layer for holding the penetrant. Values of t_d as given by Tregear for several materials are given in Table A-IV. Tregear lists permeabilities as measured for a number of substances in various animals with the conclusion that the overall range of permeabilities to different substances is very large (0.004 to 660 μcm/min). However, most of the aqueous solutes lie in the range of 3 to 60 μcm/min and most of the nonaqueous materials lie in the range of 0.2 to 10 μcm/min. He further indicates that a material whose penetration had not been measured might be expected to lie within these ranges if it were of small molecular weight.

TABLE A-IV

TRANSIENT TIME, t_d

Material	t_d (min)	Permeability (cm/min × 10^6)
Tri-n-butyl phosphate		
Rabbit	15	2.2
Pig	80	0.34
Tri-n-propyl phosphate		
man	10	0.4-4
Tri-ethyl phosphate in aqueous solution		
man	5	30
Paraoxon		
cat	10	0.2
Na + ions from 0.9% NaCl		
man	55	

The permeability of the skin of various animal species to the same penetrant varies in a reproducible manner. Rabbit skin is consistently more permeable than that of other rodents, pigs, or men. Human skin is usually the least permeable and is particularly impermeable to sodium and other common ions. From Tregear's data for five different penetrants, the average penetration of human skin is about 1/3, the pig about 1/2, the guinea pig about 1/2, and the rat about 70% of the rabbit. This relation will vary with the specific penetrant, but these differences must be borne in mind while interpreting experimental data.

Measurements on the penetrability of rat skin at various ages were made using a 5% solution of triethyl phosphate. These data show that the barrier layer appears during the late stages of fetal development with a rapid decrease in permeability immediately before birth. After birth there is a less rapid decrease in permeability over the first 5 to 10 days followed by a very gradual decrease up to 90 days.

There are variations in the permeability of the skin from one region to the next in the body. As measured by the insensible water loss, the palm and the sole appear to be the most permeable, followed by the forehead, check and back of the hand, and then other surfaces. However, iodine has been shown to penetrate the palm at about one-third the rate of forearm skin and tri-butyl phosphate also penetrates more slowly than in other regions. Baker and Kligman[39] used tests designed to show the penetration through the horny layer of the skin. With thurfyl nicotinate, six people developed an erythema after application to the forehead in 2.7 min while the same test on the back took 6.6 min. Tests with tetrachlorsalicyclanilide

in dimethyl sulfoxide indicated penetration times of 0.68 min on the forehead and 4 min on the back. They also quote studies of steroid penetration which indicate that the skin of the face has greatly increased penetration as compared to the skin of the trunk.

There is a temperature dependence of the permeability for many substances. Measurements on human skin with sarin, tricresyl phosphate, and ethanol indicate an increase in permeability of a factor of 2 to 3 with each 10°C increase in temperature of the skin. Although the body heat regulation mechanisms tend to keep the skin temperature relatively constant, the diffusion barrier is in the outer 0.1 mm or so of the skin and the temperature of this portion can vary widely in sparsely haired animals. Thus, in cold temperatures, the absorption may be considerably lower than at higher temperatures. With temperatures above normal, the permeability may be increased, but with many materials the chief effect may well be the increased perspiration rate which could tend to wash the contaminant or to serve as a solubilizing medium to permit greater availability.

The penetration rate of a solute can vary widely with the solvent. Water often, but not always, seems to enhance skin penetration. A solvent is not essential for skin penetration, however, since solids dried onto the skin from a volatile solvent penetrate long after the solvent has evaporated. There seems to be a coarse relationship between molecular size and penetration rate. However, there is no definitive relationship since other factors appear to be of more importance. There is some evidence that particles of significant size will pass through the skin slowly. For example, colloidal or powdered sulfur has been reported to pass across rabbit skin and metallic mercury is known to absorb through human skin.[7] The rates are low and cannot be defined in numerical terms. The solubility characteristics of a material related to its penetration of skin are not well defined. There are some relations between the ether-water partition of an aqueous solute and its permeability but Tregear points out that ions in aqueous solution will penetrate skin while such ions are barely soluble in ether. Also some organic liquids and solutes contained in them penetrate skin more rapidly than would be expected from their water solubility.

It is well established that the chief barrier in the skin is in the outer horny layer. The permeability of the skin can be increased by stripping this layer with adhesive tape. Each stripping increases the permeability with the effect increasing greatly as the last few layers are removed. There is some indication that the lower part of the horny layer is less permeable than the upper layers. Some authors have postulated a critical membrane at the base of this layer. Tregear, however, points out that if such a layer existed, one would expect a more critical change of permeability with stripping and a more definite relation of solubility to penetrability since the barrier would be provided by activation energy and not bulk diffusion resistance. After stripping of the horny layer, the barrier regenerates as the horny layer regenerates.

Although the evidence is not clear, it appears that entry through the skin structure is by diffusion through the horny layer and not by entry into sweat glands or hair follicles. Penetration of various materials into hair follicles and sebaceous glands has been demonstrated but considerations of relative epidermal area and rate of penetration would indicate that, for most substances, the diffusion through the horny layer provides the main barrier. The effect of the sebum excreted to the skin from the sebaceous glands is considered to be slight.

While the permeability constants for a maintained concentration on one side of the skin are useful in defining relative permeability and possible movement into the body under some situations, in dealing with radioactive contamination the material is usually on the skin surface with the only liquids available to maintain it in solution from the excretions of the skin itself. We have noted earlier that continued penetration can occur from depositions left from volatile solvents dried on the skin. To fill the holes in the skin with liquid, requires a film of about 1 mg/cm^2 with any excess above this amount forming a definite pool on the surface. Above this amount, penetration rate is independent of the mass applied and the use of the permeability constant is appropriate. Below this amount, there is no liquid on the surface and the penetration rate is dependent linearly on the mass of the penetrant applied. Under these latter conditions, Tregear points out that the appropriate parameter in assessing the penetration is the fraction of the material which penetrates per unit time. He presents data on the penetration of tri-n-butyl phosphate through the excised pig skin which shows such a linear relation with the fraction absorbed about 2×10^{-3} %/min.

Data are immediately available under these conditions for only a few radioactive materials (excluding tritium oxide as a special case). A summary of the absorption rates for plutonium as measured in the Hanford work with rats [15-19] is given in Table V.

It should be noted that the application of 10 N HNO_3, even in the small quantities used here, produced significant skin damage. In one experiment in which only 10 µl were applied the authors stated: "Histologic examination of skin specimens showed that coagulation occurred through the entire thickness of the skin and the underlying skeletal muscle within 15 minutes after the application of the acid. The epidermis surrounding the exposed area gradually undermined the coagulated tissue ... , forming a slough which separated between the 15 and 30th day. The final scar at the site of exposure consisted of fibrous tissue covered by regenerated epithelium with a complete loss of dermal appendages and the coagulated skeletal muscle ... ."

Several other points are of interest in these data. In the cases where the plutonium was in the 0.1 or 2 N acid, the retention at the site of administration after 5 days was in the range of 8 to 12% of that applied, whereas in the 10-N acid cases the retention on the skin after this time was in the range of 50 to 60%. One could conclude from these data that the damage from the higher normality acid permitted the plutonium to penetrate into and be held by the

TABLE A-V

PLUTONIUM ABSORPTION RATES-Pu^{+4}

Time of Absorption	Acid Normality (HNO_3) 0.1	2	10
15 min	30[a]		130
1 h	5[a]		180
5 h	7[a]		
6 h			14
24 h	23		8
	7[a]		43
5 day	10[c]	6	31[b]
	7.5[c]	7	17[b]
	2.5[c]	3	25[b]
	1.8[c]		39[b]
			43[b]
			22
			10
			8
			18
15 day			14
30 day			5

Applied in TBP and CCl_4 with traces of HNO_3

15 min	270 (Decontaminated at 15 min. Animal sacrificed at 5 day.)
24 h	28
6 day	8

---

[a]PuF dissolved in HNO_3 of unspecified normality.

[b]Total quantity varied from 1.6×10^7 to 1.9×10^3 dis/min.

[c]Corrected for average amount on skin for 5 days (1.5 day $T_{1/2}$).

skin more tenaciously than the material which apparently did not penetrate the undamaged skin. It is also of passing interest to note that the data presented in Ref. 18 included tests on plutonium injected subcutaneously and on absorption through the skin containing a subcutaneous cut and a dermal cut as well as tests with intact skin. In each case of the previously damaged skin the fraction of the plutonium absorbed which deposited in the liver was in the range of 10 to 30% while the material absorbed through intact skin deposited only to the extent of about 1 to 3% in the liver.

There are three cases of human data which are of interest. Langham[26] measured the absorption of plutonium in 0.4 N HNO_3 through the palm as less than 0.0002%/h (<7 × 10^{-6}%/min). Wilson[42] describes an exposure in which a hand was immersed for several minutes in a CCl_4-TBP solution containing 2 to 3 Ci of plutonium per liter. Total deposition on the hand was estimated as about 5 mCi with about 10 μCi remaining after 1 wk. Total absorption into the body as estimated from urinalysis was on the order of 10^{-3} μCi. Since the quantity of plutonium present varied by a factor of 1000 for the week and the hand was actually immersed in the solution for a short time, it is difficult to arrive at an absorption rate, but it was undoubtedly less than 10^{-6}%/min. Lister[43] describes a case of contamination on the middle finger in which the contamination was not discovered for about 1-1/2 h. The contaminating material was strongly acid and the contamination level was about 2 μCi. From urine analysis results he estimates that a penetration factor was on the order of 10^{-4}. Again, it is difficult to convert such a number to a rate, but the maximum, assuming that all absorption occurred during the 1-1/2 h before discovery would be on the order of 10^{-4}%/min. He also notes that EDTA was present in the contaminating solution and this may have had an accelerating effect on the penetration.

Data on the uptake of ^{131}I applied as a solution and a gas are given for human skin by Harrison[23] and for pig skin by Murray.[24] A summary of these experiments and calculated uptake rates is given in Table A-VI.

Additional data were presented for the absorption of the deposited vapor from human skin using increased amounts of carrier up to 5 mg of stable iodine. With 3 and 5 mg of carrier, there was obvious damage to the skin and the fraction absorbed was increased. With 2 mg of carrier, no tenderness developed although the fraction absorbed was greater than in the one piece of data presented in the table where the amount of carrier was 0.8 mg.

The series of values given for the gas exposure of swine skin were from a single exposure where the quantity on the skin and in the thyroid were measured for 6 days. The skin contamination fell off duing this time with a half-life of about 1.5 days. The absorption rates were calculated on the basis of the average amount of iodine on the skin for the time in question.

If measurements of the permeability of the skin by the method of sustaining a concentration on the surface were available for these materials, a scaling factor for other materials that have had their permeabilities measured could be obtained by assuming the rate of penetration to be proportional to the permeability. Such data have not been found. Tregear lists the permeability of bromide from a 1 1.6% solution of sodium bromide in a section of excised human skin as 0.3 to 0.7 μcm/min. The permeability of potassium from a 1.2% solution of KCl in intact human skin is listed as 1.1 μcm/min. By contrast he listed 0.02 to 0.12 for aluminum from $AlCl(OH)_2$; and 20 for laurate ion from sodium laurate. In the guinea pig, the mercuric ion is given as 15 to 45 and the chromate ion as 20 to 30 μcm/min.

TABLE A-VI

UPTAKE OF ^{131}I

Material	Time of Exposure	% Remaining after Washing		Absorption (%/min)
Human				
KI-Aqueous	2 h	9-14		1.6×10^{-3}
				1.1×10^{-3}
				1.3×10^{-3}
I_2-Aqueous	2 h	2-5		4.8×10^{-3}
				1×10^{-3}
I_2-Gas	2 h	20		1×10^{-3}[a]
				4×10^{-3}[a]
Swine[b]				
85%-I_2; 15%-KI				
Aqueous	2 h	4		5×10^{-3}
I_2-Gas	-	not washed	1 day	5×10^{-4}
			2 day	3×10^{-4}
			3 day	3×10^{-4}
			4 day	3×10^{-4}
			5 day	3×10^{-4}
			6 day	5×10^{-4}

[a]Higher value calculated on 2-h exposure of amount deposited. Lower value on average skin contamination over 24 h.

[b]Thyroid uptake given in paper. This was assumed to be 30% of the total absorbed.

E. Penetration into Skin

Even if a material does not penetrate through the skin and enter the body with great ease, the question of penetration into the horny layer is of interest in assessing possible radiation dose to the skin from contamination by alpha emitters. In making calculations of such dose, no problem exists if the material is concentrated on the surface of the horny layer because the thickness is great enough to absorb the alpha particles. If penetration occurs to a depth such that the alpha particle does come within range of the basal layer, however, sizable and possibly significant doses can be delivered.

No information has been found on the resulting distribution of contaminant through the skin, although Newberry[5] indicates that Chamberlain has experimental evidence that, at least in one case, a concentration of alpha emitter (presumably plutonium) of 1% of the concentration at the surface was found at a depth of 2 mm.

From the knowledge of the skin as a barrier one can speculate as to the possible configurations of distributions of contaminant in

the epidermis. It seems likely that those materials that penetrate the skin most easily will have higher overall concentrations in the lower parts of the epidermis. Even this must be viewed with some caution, however, because the exact nature of the barrier process is not known in all cases. For example, if the horny layer has a very high absorptive capacity for the contaminant with little absorptive capacity in the granular layer or the dermis, the horny layer may, upon continued exposure, build up an essentially uniform concentration with little passing through.

If the horny layer is the chief barrier, as most authorities seem to feel, then the distribution through the tissue can be predicted by the nature of the barrier and the physical and chemical nature of the contaminant and its carrier. For example, if the horny layer is considered as a uniform layer with each thickness of material of uniform permeability, then the equilibrium distribution through the barrier after some time of passage is essentially exponential. Further, if the material is immediately removed from the bottom of the barrier by rapid diffusion to the blood, the concentration on the bottom will be essentially zero. If, however, the permeability decreases as one passes through the barrier, the concentration gradient will be steeper than an exponential with more material absorbed toward the bottom than in the simpler case. In either case, under transient conditions before the equilibrium flow is established, the quantity at the bottom of the barrier will be smaller than the exponential would predict.

Many contaminants may react with the keratin of the horny layer or the protein of underlying tissue to become essentially fixed at a given position in the skin. Under these conditions, the amount present can build up in almost any portion of the skin depending upon the specific reactions. As long as this occurs in the epidermis, nature has provided a method of eventual elimination through the constant migration of new cells upward to form the horny layer which is essentially sloughed.

As a pragmatic viewpoint, one could consider the possibility of contamination through the epidermis to be in some way related to the ease with which a particular contaminant is removed. For example, most plutonium contamination can be removed from the surface of the skin with relative ease indicating that it has not fixed in the horny layer, at least in a depth equivalent to the range of the particles. However, in gross contamination cases, particularly those involving solutions, the contamination may be very difficult to remove and may persist for days or weeks. In the former case, it is probably not of concern. In the latter case, the penetration may have been significant and the basal layer may well be exposed. Note that such contamination usually occurs by accident and the question is not how to limit contamination but rather, how to minimize damage. It is doubtful that any recommendation would be made to excise the skin to prevent the dose to the basal layer. However, it may be advisable to make a record of such occurrences for inclusion in the individuals exposure record in the event that difficulty should develop in the exposed area in the future.

APPENDIX B

BETA DOSE TO THE SKIN

The skin dose from beta rays was estimated from the formulations of Loevinger.[8,9] These derive from his empirical fit to measured dose distributions around a point source with extension to other configurations by integration over the area. The solutions to these equations contain constants that vary with energy and atomic number and the purpose of this appendix is to document the actual values used in the calculations.

For the contamination cases, the two equations of interest are those for a thin, infinite plane source with no self-absorption, but with absorbing material between the source and the receptor and for an infinite plane source of finite thickness again with absorbing material between the source and the receptor. The first is used to describe the dose rate from a thin layer of radioactive material on the skin surface or on the surface of clothing. The second is used to describe the dose rate from a layer of clothing uniformly contaminated through its thickness. These two equations are

<u>Thin plane source with no self-absorption</u>

$$D(x) = 1.066\ \upsilon\bar{E}\beta\ \alpha \left\{\left[c\left(1+\ln\frac{c}{\upsilon x} - e^{-\left(1-\frac{\upsilon x}{c}\right)}\right)\right] + e^{(1-\upsilon x)}\right\} , \qquad \text{(B-1)}$$

and

<u>Thick plane source with self-absorption</u>

$$D(x,h) = \frac{1.066\ \bar{E}\ \alpha}{h}\left\{c^2\left[3-e^{\left(1-\frac{\upsilon x}{c}\right)} - \frac{2\upsilon x}{c} - \frac{\upsilon x}{c}\ln\frac{c}{\upsilon x}\right] + e^{(1-\upsilon x)}\right.$$

$$- c^2\left[3 - e^{\left\{1-\frac{\upsilon}{c}(x+h)\right\}} - \frac{\upsilon(x+h)}{c}\left\{2 = \ln\frac{c}{\upsilon(x+h)}\right\}\right]$$

$$\left. - e^{\{1-\upsilon(x+h)\}}\right\} . \qquad \text{(B-2)}$$

In these equations, D(x) is the dose rate in rads/h through a thickness of x g/cm^2 for a deposit of 1 μCi/cm^2 and D(x,h) is the dose rate in rads/h from a source of h g/cm^2 thickness and through

a shielding of x g/cm^2. The terms in the square brackets [ ] are taken as zero when $(\upsilon x)/c \geq 1$ in Eq. (B-1) and the first term in (B-2) and when c/υ is between x and (x+h) in the third term of (B-2). The other terms are described below along with a discussion of the values used.

υ is a mass absorption coefficient in cm^2/g given for tissue by the expression

$$\upsilon = \frac{18.6}{\left(E_{max} - 0.036\right)^{1.37}} \left[2 - \frac{\bar{E}_\beta}{\bar{E}_\beta^*}\right] \quad . \qquad \text{(B-3)}$$

E_{max} is the maximum energy of the beta spectrum in MeV, $\bar{E}_\beta$ is the true average energy of the beta spectrum whether allowed or forbidden, and $\bar{E}_\beta^*$ applies only to those isotopes that decay by a forbidden transition. $\bar{E}_\beta^*$ is the average energy for an allowed spectrum having the maximum energy of E_{max}. For isotopes decaying by allowed transitions, the term in square brackets in Eq. (B-3) reduces to 1. For these calculations, the forbidden transitions were ignored and all isotopes were calculated as allowed transitions.

c is a constant that arises in the normalization of the point source formula to permit accounting for all of the energy emitted by absorption in the tissue. Loevinger suggests the following values for c for tissue.

$0.17 \leq E_{max}$	<0.5 MeV	c = 2
$0.5 \leq E_{max}$	<1.5 MeV	c = 1.5
$1.5 \leq E_{max}$	<3.0 MeV	c = 1

The use of these values introduces a discontinuity in the curve of dose rate vs energy that is within the range of accuracy of the estimates. However, to eliminate these discontinuities, the value of c was read from a plot that used the above values at the midpoint of the energy range given. The value of c was extrapolated to energies as low as 0.1 MeV from this plot.

α is a function of c and, again, arises from the normalization of the energy emitted to the energy absorbed. It is given by

$$\alpha = [3\,c^2 - (c^2-1)\,e]^{-1} \quad . \qquad \text{(B-4)}$$

$\bar{E}_\beta$ is the average energy of the beta-ray spectrum that varies with both maximum energy of the beta spectrum and the atomic number. The ICRP[2] lists an equation which they indicate to be accurate to within about 5% for most beta emitters.

$$\frac{\bar{E}\beta}{E_{max}} = 0.33\ E_m \left(1 - \frac{Z^{\frac{1}{2}}}{50}\right)\left(1 + \frac{E_{max}^{\frac{1}{2}}}{4}\right) \quad , \qquad \text{(B-5)}$$

where Z is the atomic number of the emitter. Comparison of this equation with curves given by Loevinger[8] indicates reasonable agreement at high energies with some divergence of the ratio at low energies. For an atomic number of 10, for example, the equation is about 10% higher than Loevinger's curves at 0.2 MeV. In general, the ratio of the average to the maximum energy is higher for positron emitters than for electron emitters. However, in view of the other uncertainties inherent in the overall estimates, the ratio of the average energy calculated from Eq. (B-5) for an atomic number of 10 was applied to all isotopes. This predicts a higher average energy for electron emitters with a Z above 10, but will underestimate the average energy for positron emitters.

APPENDIX C

RESUSPENSION

The resuspension of radioactive materials from surfaces has been expressed as a "resuspension factor" or the ratio of the air concentration to the surface contamination levels. The units of such a ratio are those of length^{-1}. In a review of resuspension factors from a literature search, Mishima[44] has tabulated measurements that range from about 10^{-3} m^{-1} to about 10^{-8} m^{-1} for several materials under different conditions both indoors and outdoors with various degrees of activity over the contaminated surface. He also notes values of 10^{-13} to 6×10^{-10} m^{-1} for the resuspension of plutonium resulting from the Plumbob test. Stewart[45] concludes that a representative value for the resuspension factor outdoors under quiescent conditions is about 10^{-6} m^{-1} and, under conditions of moderate activity is about ten times greater. Indoors, under quiescent conditions, he tentatively suggests the same factor of 10^{-6} m^{-1} while under "operational" conditions a value of 10^{-5} or even 10^{-4} m^{-1} is suggested as a "guide". Dunster[6] in deriving limits for surface contamination in occupational situations indicates: "For controlled areas the lower figure of 2×10^{-6} m^{-1} ... is certainly safe for long-term use." Later, in a discussion of the area over which the surface contamination may be averaged, he indicates that no difficulties arise if averaging is permitted over areas of 300 cm^2 for inanimate surfaces and 1000 cm^2 for surfaces such as floors, walls, and ceilings. He then states that: "Averaging over much larger areas might require a reappraisal of the value adopted for the dispersion constant" thereby implying that such an area might be critical in determining the resuspension and subsequent air concentration.

While the resuspension factor or "constant" is a simple concept and one that can be easily applied, the conditions of application and

measurement must be rigidly defined because the concept is not completely applicable to all situations. If we consider, for example, an outdoor situation with the contaminated area upwind and no contamination in the immediate area of the air sampler, any resuspension of the upwind deposition will result in a positive air sample in the area in question, although the ground deposition is zero, and a resuspension coefficient of infinity would result. Conversely, measurements in the center of a small contaminated area could result in a resuspension factor of zero if the resuspended material were carried off by the winds before reaching the sampling height. In this situation, the resuspension factor could increase as the area contaminated upwind increased until the area is large enough so that an equilibrium is reached between the processes of resuspension and the natural processes of removal of material from the air under the particular micrometeorological conditions existent at the time. Thus, experimental values are dependent upon the size of the contaminated area or the size of the contaminated area which is disturbed by movement in the area. The measured value is also representative of an average deposition upwind, with the average at various distances weighted by the efficiency of removal processes to the point where the resuspension occurs. Since both the resuspension and deposition mechanisms are believed to depend upon the particle size, this will result in a distortion of the particle size spectrum of the material. Thus, measurements of deposition in the vicinity of the sampling point could be misleading if used as a basis for calculating the resuspension factor unless a large area is reasonably uniformly contaminated. One can conclude that care should be used in extrapolating such coefficients very far beyond the conditions existent at the time of the measurement.

Indoors, the air concentration results from a balance between the rate at which the radioactive material is added to the air by the forces resulting in resuspension and the rate at which the material is removed by redeposition or dilution and elimination by air changes in the room. For most measurements of the resuspension constant, the conditions are typical of industrial conditions although some experimental values have been obtained in unventilated areas. Redeposition is expected to be smaller than would occur outdoors because of the decreased turbulence but could be of considerable importance in limiting air concentrations when ventilation of the room is small. It can also serve as an effective mechanism for spreading contamination to all surfaces in the room.

A rough idea of the comparative importance of ventilation and redeposition for very large particles can be obtained by consideration of the settling rate of spheres suspended in the air. If A is the area of the room, V_g is the settling rate of the spheres, and χ is the concentration in the air, then the total quantity settling per unit time is $\chi V_g A$, whereas the total quantity present in the air is χV where V is the volume of the room. V is also equal to hA where A is the floor area. The fraction settling per unit time is then given by the ratio of the quantity settling to the quantity present or V_d/h. For a room 2.5 m high, this corresponds to a rate of 0.058/h for 1-μm particles and 10/h for 10-μm particles of unit density. For

a density of 10, the rates become 0.58/h for 1-μm particles and 100/h for 10-μm particles. Even in a reasonably tight building with low wind speeds, the air changes are one per hour, or greater, indicating that the ventilation probably predominates for particles in the size of most concern for inhalation. This crude calculation also indicates that where ventilation is not great, a fractionation mechanism in favor of the smaller particle sizes exists. It should be noted that the above calculation will minimize the redeposition factor since it is known that deposition will occur through mechanisms other than gravitational settling such as impaction, electrostatic attraction, etc. These mechanisms will be of importance for other than upward facing horizontal surfaces and studies with vapors or small particulates have indicated that these mechanisms can be of more importance in determining the deposition rate than the gravitational settling.

Because of the strong influence of the ventilation rate on the concentration, the resuspension constant measured in a room with good ventilation may be misleading when applied to another room with lower ventilation rates. It is true that the rate of resuspension in a room without movement (quiescent condition) may be somewhat higher with higher ventilation, but this is believed to be a second-order effect when compared to the dilution. The times of most concern are probably when there is movement in the room. For this reason, we have chosen to evaluate the problem in terms of the fraction resuspended per unit time evaluating the air concentration in terms of the number of air changes and considering the removal by redeposition to be negligible. This approach is, again, too simple and probably conservative. In a large room, other air movement patterns will have strong influence on the concentration at a given point. The calculation also assumes that the material which is resuspended is reasonably uniformly distributed throughout the volume of the room before dilution occurs. In either case, application of the data available to conditions other than those for which it was obtained introduces many uncertainties.

One other variable is of interest. The resuspension coefficient is based upon the contamination per unit area in the room. In most cases where measurements are available, the contamination is reasonably uniform and an average level is used as the basis. In the ideal case, where resuspension forces are uniform throughout the room, one would, however, expect that the air concentration would be related to the total amount of contamination in the room rather than the amount on any one limited area. This is of importance in the problem at hand because the distribution of material, once it reaches the environs, is completely unknown and basing limits on the highest area may be too conservative. This concept again requires an assumption of complete mixing throughout the room and a lack of relation between the quantity present and the degree of fixation to the surface. In the actual case, an additional effect of nonuniformity can occur if the resuspension forces are nonuniform over the area. The most obvious situation would be one where disturbance of the surface is nonuniform from traffic in the area due to the placement of furniture or doors in the room. It is also probable that this area of

highest traffic may coincide with the areas of highest deposition since these are the most likely places for a contaminated individual to transfer the contamination to his surroundings.

The nature of the surface and of the contaminant also play an important part in the possibility of resuspension. Most studies have been made for surfaces found in the laboratory or in industrial environs and with contaminants in particulate form. It is to be expected that the quantity resuspended from a floor covered with carpeting or from material deposited on furniture covered with fabric would be different than that from a linoleum floor and would presumably be smaller. On the other hand, a linoleum floor is usually cleaned by water or mopping whereas the carpeting may be cleaned by a vacuum cleaner which may not have a highly efficient filter for the inhalable sizes of particles. For materials that are somewhat volatile, the mechanism of resuspension may be completely different from those which have been studied. Information on these factors is extremely meager.

The availability of the material for resuspension and the degree of fixation to the surface should depend upon many of the same factors, such as the amount of traffic over the surface to wear it into the upper layers and the methods and frequency of cleaning. It can be presumed that the availability of any quantity brought into the home, for example, will decrease with time although the rate of decrease in a typical situation is not known.

Resuspension and removal of the contamination by ventilation implies a finite lifetime of the contamination in a room. Stewart[45] points out that the half-life of material in the room is expressed as

$$T_{\frac{1}{2}} = \frac{0.693A}{KnV} \quad ,$$

where $T_{\frac{1}{2}}$ is the half-life in hours, A is the area of the room contaminated from which resuspension occurs, K is the resuspension factor in m^{-1}, V is the volume of the room in m^3, and n is the number of air changes per hour. For a room of 500 m^3 volume with a contaminated floor area of 100 m^2, a resuspension factor of 10^{-3} m^{-1} and eight air changes per hour would result in a half-life of 17 h or about 4%/h resuspended. The fraction resuspended is related to these variables by

$$\chi = \frac{f\ A\ \Omega}{Vn} \quad ,$$

where χ is the air concentration, f is the fraction resuspended per unit time, V is the volume of the room, n is the rate of air change, A is the contaminated area, and Ω is the surface contamination. Note

that χ/Ω is the resuspension factor K. If only the floor is contaminated, then V=Ah where h is the height of the room, and

$$\chi = \frac{f\Omega}{hn} \quad .$$

Spangler and Willis[46] quote a "characteristic value" for the fraction resuspended per time of 10^{-4} h^{-1} with reference to a study of a uranium diffusion plant by Schultz and Becher.[47] However, they do not indicate how this value was obtained from the data given in the reference.

Fish et al.[48] describe tests with ZnS and CuO particles of 3.1 and 2.0 μ MMD, respectively, in an 8 by 8 by 12 ft room of painted wallboard and an asphalt tile floor. The room was contaminated by blowing a suspension of the particles into the room and allowing them to settle for 2 days. Individuals then entered the room and performed given tasks while air concentrations and amounts retained in the filter of a respirator were measured. Air concentrations were given in terms of the fraction of the concentration before initial settling. These values should represent the fraction of the material that has settled on the floor which becomes airborne during the experiment. (It is noted, however, that the resuspension factor calculated on this assumption is higher than the resuspension factor given by the authors and it is assumed that they must have had additonal information which is not quoted.) Since the room was not ventilated, the equations given above for the resuspension are not appropriate. However, if one assumes that there was no loss of material from the room and the redeposition rate was small enough to be negligible, the quantity present in the air must represent the fraction of the total that was resuspended over the time of the experiment. With these assumptions, the resuspension rates were

1.	ZnS-10 min of vigorous work including sweeping	6×10^{-3} h^{-1}
2.	ZnS-20 min of vigorous walking	2×10^{-3} h^{-1}
3.	ZnS-40 min of collecting contaminated samples	1×10^{-3} h^{-1}
4.	CuO-90 min total. 20 min of light sweeping. Remainder of time sample collecting. Four fans directed at an angle upward to promote air circulation	7×10^{-3} h^{-1}

In the last test with CuO, measurements were also made of the deposition of material on various surfaces of the body by using double-faced adhesive tape to trap the particles. The average rate of transfer in terms of the concentration of particles on the tape as compared with the concentration on the floor was 22%/h. This ranged

from about 50% on the feet to 10%/h on the hands, 20%/h on the head, and 3%/h on the chest.

Brunskill[27] reports experiments carried out in a change room with an 8-1/2-ft ceiling, granolithic concrete floors, and with a ventilation rate of 9 air changes per hour. Low-level contamination of the floor area had occurred through its normal use. During the experimental period, 4 to 6 people walked around the room in a random pattern wearing clean socks. The average resuspension factor measured was 1.2×10^{-4} m^{-1}. Brunskill also reports that smear tests removed only about 1 to 3% of the contamination. A water wash removed 50%. Use of the ventilation rate and ceiling height leads to an estimate for the rate of resuspension of about 3×10^{-3} h^{-1}. This, however, is based on the total measured contamination on the floor. If only the smearable fraction is considered to contribute, the value would be higher by a factor of 30 to 100. In a second experiment, he used a small room 10 ft high adjacent to the main change room with the floor covered by wax paper. The contamination was introduced by changing coveralls in the room. There was no forced ventilation but there was a free flow of air from the larger adjacent ventilated area. Here, the experimental staff moved around the area in clean clothing. The resuspension factor in this experiment was measured as 3.8×10^{-3} m^{-1}. The fraction resuspended per hour was, then, 1×10^{-2} n. If, as seems reasonable, n is between 2 and 5, the fraction suspended per hour becomes 0.02 to 0.05.

Jones and Pond[49] describe experiments in which various floor coverings were contaminated with PuO_2 and plutonium nitrate and the resuspension factors measured under several conditions of activity. The room used had a floor area of 15.7 m^2, a height of 3.15 m, and a ventilation rate of 540 m^3/h (n = 10.9). The PuO_2 was dispensed in water solution by dropping from a pipette as uniformly as possible over the area. The plutonium nitrate was dispensed, again as uniformly as possible, by a dropping bottle. The area contaminated in each case was about 10 sq m. The area was allowed to dry for 16 h and measurements were made of the air concentration under the following conditions: (1) no movement; (2) detailed survey of the area over a period of about 60 min with every probe area measured (about 14 steps/min during this period); (3) spot survey of the area for about 60 min (about 36 steps/min during this period); and (4) two operators walking over the floor with a hair drier directed toward the floor for about 45 min (about 100 steps/min during this period). In addition to samplers arranged to permit measurement of the average concentration of the room air, samples were obtained of the exhaust air and from personnel samplers. The average ratio between the exhaust air and the room air was about 1/3 for both the nitrate and the oxide. The personnel sampler with the oxide experiment showed average concentrations about 1/5 of the room air, whereas in the nitrate experiment the personnel sampler showed about 1/2 of the room air sampler. There was wide variation in the ratios. Smear samples indicated about 0.1 to 0.2% removable by this technique for the nitrate on paper, 6% for the nitrate on waxed and polished linoleum, 10 to 20% for the oxide on polyvinyl chloride, 20 to 30% for oxide on unwaxed linoleum or nitrate on polyvinyl chloride, and 50 to 60% for the oxide on waxed and polished linoleum.

Resuspension coefficients were calculated as based on the room air and the monitoring results on the floor. In general, the monitoring results agreed well with the estimates based upon the amount dispensed with the exception of the nitrate on the paper where the monitoring results showed slightly more than 50% of the amount dispersed. These resuspension factors have been converted to the fraction resuspended per hour and are given for the various surface and conditions in Table C-I

TABLE C-I

FRACTION RESUSPENDED PER HOUR

	Condition			
	1	2	3	4
Surface	Quiet	14 st/min	36 st/min	100 st/min
Oxide				
Paper	2×10^{-7}	3×10^{-4}	2×10^{-3}	-
	8×10^{-6}	6×10^{-4}	3×10^{-3}	-
PVC	0	2×10^{-4}	2×10^{-3}	-
	5×10^{-7}	4×10^{-4}	1×10^{-3}	-
	1×10^{-7}	3×10^{-5}	1×10^{-3}	-
Lino-waxed	5×10^{-7}	4×10^{-4}	2×10^{-3}	2×10^{-3}
Lino-unwaxed	0	1×10^{-3}	1×10^{-2}	8×10^{-3}
Nitrate				
Paper	3×10^{-6}	7×10^{-5}	1×10^{-4}	-
	2×10^{-6}	2×10^{-5}	5×10^{-5}	-
PVC	0	2×10^{-5}	2×10^{-4}	-
	5×10^{-7}	7×10^{-5}	9×10^{-4}	-
	5×10^{-7}	5×10^{-5}	2×10^{-4}	-
Lino-waxed	3×10^{-6}	2×10^{-5}	8×10^{-5}	4×10^{-4}

The authors also noted that the resuspension under maximum conditions was not significantly different from that under the spot survey conditions and speculated that walking on the surface during the less active experiments had tended to make the material on the floor less susceptible to resuspension.

APPENDIX D

NUMERICAL VALUES FOR DECISION LEVELS

The numerical values for the decision levels for individual isotopes are grouped in the tables in this appendix to avoid numerous

and confusing tables through the text. Four tables are given: Important characteristics of the isotopes plus the direct levels based upon radiation exposure to the contaminated worker; direct levels for an individual in the general public; levels based upon transfer of the contamination to another location (primarily the home); and readings on several selected instruments that correspond to the limiting decision levels from the proceeding tables. Although a brief description of the entries and the basis for their derivation is included at the end of each table, the user is urged to be familiar with the derivations given in the text and the many assumptions used so that he may revise the numbers as necessary for application to his particular situation.

Only isotopes with half-lives greater than 1 day are included and tritium is specifically excluded because of its low radiation energy and the special considerations necessary for its behavior in various chemical forms.

Each of the tables is divided into three main groupings of the isotopes according to their mode of decay. Within these sections, the isotopes are arranged in ascending order of atomic number.

The decision levels have been based on estimated doses equal to the limits for workers or individuals in the public as recommended by the NCRP. That is, no reduction factor to allow for radiation exposure from other sources has been included.

It should be noted that the decision levels are given in two units: nCi/cm^2 when the radiation dose depends upon the quantity of radioactive material per unit area and μCi when the dose depends upon the total quantity of radioactive material. In the latter case, a decision level reasonably conservative for most conditions can be obtained by considering the area contaminated to be 10,000 cm^2 (∿1/2 of the body area). The decision level in nCi/cm^2 is then obtained by dividing the tablulated value in μCi by 10.

TABLE D-I

DIRECT LEVELS-WORKERS

(1) Isotope	(2) E_β MeV	(3) $\bar{E}_\gamma$ MeV	(4) $T_{1/2}$	(5) Skin Dose	(6) Clothing Dose	(7) Direct Inhal	(8) Direct Inges	(9) Skin Abs
					nCi/cm^2			µCi
Beta Emitters								
^{14}C	0.156		5730 y	5	50	5000	3000	5000
^{22}Na	0.545	2.2	2.62 y	0.9	2	10	1000	200
^{32}P	1.710		14.28 d	0.8	0.8	90	70	90
^{35}S	0.167		87.9 d	5	50	400	300	500
^{36}Cl	0.714		3.08×10^5 y	0.9	2	20	300	500
^{45}Ca	0.252		165 d	2	9	40	40	40
^{47}Ca	18%-1.98 82%-0.67	1.0	4.535d	0.9	1	200	100	100
^{46}Sc	0.357	2.0	83.9 d	1	3	20	100	100
^{47}Sc	0.600	0.12	3.43 d	0.9	2	600	400	2000
^{48}Sc	0.65	3.8	1.83 d	0.8	1	100	100	1000
^{48}V	49%-0.7	2.9	16.0 d	1	2	700	100	100
^{52}Mn	36%-0.58	3.2	5.60 d	2	3	100		200
^{59}Fe	0.475	1.2	45.6 d	1	2	60	300	90
^{58}Co	15%-0.47	0.98	71.3 d	5	10	60	400	700
^{60}Co	0.314	2.5	5.263y	1	3	10	100	300
^{63}Ni	0.063		92 y			70	100	50
^{65}Ni	2.13	0.57	2.564h	0.8	1	600	400	7000
^{74}As	29%-1 32%-1.36	0.75	17.9 d	1	2	100	300	500
^{76}As	2.97	0.38	26.4 h	0.9	1	100	80	3000
^{77}As	0.68	0.09	38.7 h	0.9	2	500	300	10,000
^{82}Br	0.444	2.6	35.34 h	1	2	200	100	2000
^{86}Rb	1.78	0.09	18.66 d	0.8	1	90	100	500
^{87}Rb	0.274		4.8×10^{10} y	2	8	90	400	700
^{89}Sr	1.46		52.7 d	0.8	1	40	40	20
^{90}Sr	0.546		27.7 y	1	2	1	1	0.7

(1) Isotope	(2) MeV	(3) MeV	(4) $T_{1/2}$	(5) Skin Dose	(6) Clothing Dose	(7) Direct Inhal	(8) Direct Inges	(9) Skin Abs µCi
					Ci/cm^2			
Beta Emitters (Cont.)								
^{90}Y	2.27		64.0 h	0.8	1	100	80	200
^{91}Y	1.55	0.004	58.8 d	0.8	1	40	100	20
^{93}Zr	0.06		1.5×10^6 y			400	3000	70
^{95}Zr	0.4	0.73	65.5 d	1	3	40	300	70
^{95}Nb	0.16	0.77	35.0 d	4	20	100	400	200
^{99}Mo	1.23	0.26	66.7 h	0.8	1	200	100	900
^{99}Tc	0.292		2.12×10^5 y	2	6	70	700	2000
^{103}Ru	0.21	0.47	39.5 d	3	10	100	300	500
^{106}Ru	0.039	0.20	368 d	0.8	1	8	40	70
	1.1							
^{105}Rh	0.568	0.08	35.88 h	0.9	2	600	40	400
^{110m}Ag	31%-0.53	2.5	255 d	2	4	10	100	500
^{111}Ag	1.05	0.023	7.5 d	0.8	1	200	100	2000
^{115m}Cd	1.62	0.031	43 d	0.8	1	50	100	20
^{115}Cd	1.11	0.36	53.5 h	0.8	1	200	100	300
^{114m}In	95%-1.99	0.08	50.0 d	0.9	1	20	70	50
^{115}In	0.48		6×10^{14} y	1	2	40	400	100
^{125}Sn	2.34	0.09	9.4 d	0.8	1	100	70	200
^{122}Sb	1.97	0.41	2.80 d	0.8	1	100	100	30
^{124}Sb	2.31	2.1	60.4 d	0.8	1	20	100	100
^{125}Sb	0.61	0.42	2.71 y	0.9	2	40	400	300
^{127m}Te	0.70		109 d	0.9	2	50	300	100
^{129m}Te	36%-1.6	0.10	34.1 d	0.8	1	40	80	60
	64%-1.45							
^{131m}Te	82%-2.46	1.2	30 h	1	1	200	100	600
	18%-2.14							
^{132}Te	0.22	2.6	77.7 h	0.6	0.9	100	80	300
	2.12							
^{126}I	45%-1.25	0.35	12.8 d	2	3	10	3	6
^{129}I	0.150	0.004	1.7×10^7 y	3	20	3	0.7	1

^{131}I	0.606	0.37	8.05 d	0.9	2	10	4	7
^{134}Cs	0.662	0.018	2.04 y	1	2	10	40	70
^{135}Cs	0.21		3.0×10^6 y	3	10	100	400	700
^{136}Cs	0.341	2.2	13.7 d	1	3	200	300	500
^{137}Cs	0.514	0.56	30.0 y	1	2	10	50	90
^{140}Ba	1.02	0.24	12.80 d	0.8	1	50	100	70
^{140}La	20%-1.7	2.4	40.22 h	0.8	1	100	100	1000
	80%-1.36							
^{141}Ce	0.581	0.07	32.5 d	0.9	2	200	400	200
^{143}Ce	1.39	0.28	33 h	0.8	1	200	100	1000
^{144}Ce	0.31	0.05	284 d	0.6	0.9	8	40	5
	2.99							
^{143}Pr	0.933		13.59 d	0.8	1	200	100	200
^{147}Nd	0.81	0.12	11.06 d	0.9	1	200	300	200
^{147}Pm	0.224		2.62 y	2	10	70	800	20
^{149}Pm	1.07	0.002	53.1 h	0.8	1	200	100	2000
^{151}Sm	0.076	0.001	87 y			80	1000	50
^{153}Sm	0.80	0.036	46.8 h	0.9	1	500	300	2000
^{152}Eu	28%-1.48	1.0	12.7 y	3	3	10	300	7
^{154}Eu	0.87	1.2	16 y	0.8	1	5	80	2
^{155}Eu	0.25	0.05	1.81 y	4	8	90	800	50
^{160}Tb	0.86	0.95	72.1 d	0.8	1	40	100	50
^{166}Dy	0.40	0.014	81.5 h	2	3	200	100	200
^{166}Ho	1.84	0.022	26.9 h	0.8	1	200	100	900
^{169}Er	0.34		9.6 d	1	5	500	400	700
^{170}Tm	0.97	0.003	134 d	0.8	1	40	100	20
^{171}Tm	0.097	0.067	1.92 y	100	400	100	1000	70
^{175}Yb	0.47	0.036	101 h	1	3	800	400	1000
^{177}Lu	0.5	0.016	6.74 d	1	2	700	400	700
^{181}Hf	0.41	0.50	42.5 d	1	3	50	300	20
^{182}Ta	0.522	>1.1	115.1 d	1	2	20	100	20
^{185}W	0.429		75 d	1	3	100	400	7000
^{186}Re	95%-1.07	0.012	88.9 h	0.9	1	200	100	600
^{187}Re	0.003		4.3×10^{10} y			700	6000	5000
^{191}Os	0.14	0.031	15.0 d	8		500	700	2000
^{193}Os	1.13	0.05	31.5 h	0.8	1	400	300	2000
^{192}Ir	96%-0.67	0.78	74.2 d	0.9	2	40	100	90

(1) Isotope	(2) E_β MeV	(3) $\bar{E}_\gamma$ MeV	(4) $T_{1/2}$	(5) Skin Dose	(6) Clothing Dose	(7) Direct Inhal	(8) Direct Inges	(9) Skin Abs
					nCi/cm^2			μCi
^{196}Au	6%-0.26	0.45	6.18 d	20	40	700	500	2000
^{198}Au	0.962	0.40	2.697d	0.8	1	200	100	2000
^{199}Au	0.30	0.075	3.15 d	2	6	1000	500	5000
^{203}Hg	0.214	0.21	46.9 d	4	10	90	70	90
^{204}Tl	0.766		3.81 y	0.9	1	40	300	600
^{210}Pb	0.061	0.002	20.4 y			0.1	0.5	0.07
^{210}Bi	1.160		5.013d	0.8	1	8	100	5
^{228}Ra	0.05	0.47	6.7 y	0.8	1	0.05	0.1	0.05
	2.11							
^{227}Ac	0.046		21.6 y			0.003	8	0.001
^{234}Th	0.191	0.014	24.10 d	0.7	1	40	70	2000
	2.29							
^{230}Pa	10%-0.41	0.82	17.7 d	20	30	1	1000	0.2
^{239}Np	0.44	0.10	2.346d	1	3	900	500	2000
^{241}Pa	0.021		13.2 y			0.1	1000	5
^{249}Bk	0.125	0.18	314 d	10	70	1	3000	0.5
^{253}Cf	0.27		17.6 d	2	8	1	500	0.4
^{254m}Es	25%-1.13	0.26	39.3 h	1	2	7	70	3
	75%-0.43							
	K X Ray keV							

Electron Capture and Internal Transition Decay

^{7}Be			53.6 d			1000	7000	3000
^{51}Cr	5	0.03	27.8 d	100		2000	7000	700
^{54}Mn	6	0.84	303 d	20		50	400	200
^{55}Fe	6		2.60 y	100		1000	3000	500
^{57}Co	6	0.12	270 d	70		200	1000	5000
^{59}Ni	7	0.3	8 $\times 10^4$ y	50		600	800	400
^{65}Zn	9	0.56	245 d	30		70	400	70
^{71}Ge	9		11.4 d	100		7000	7000	20,000

^{73}As	10	0.005	80.3	d	100	500	1000	1000
^{75}Se	11	0.38	120.4	d	40	100	1000	7000
^{85}Sr	14	0.51	64.0	d	30	100	400	200
^{93m}Nb	17		13.6	y		100	1000	70
^{96}Tc	19	2.5	4.35	d	9	200	100	2000
^{97m}Tc	19		91	d		200	700	3000
^{97}Tc	19		2.6×10^4	y	100	400	3000	10,000
^{97}Ru	19	0.22	2.88	d	60	2000	1000	3000
^{103}Pd	21		17.0	d	100	900	1000	900
^{105}Ag	22	0.38	40	d	40	100	400	1000
^{109}Cd	23	0.09	453	d	80	90	700	30
^{113}Sn	25	0.25	115	d	60	60	300	200
^{125m}Te	28	0.003	58	d		100	400	300
^{131}Cs	30		9.70	d	100	4000	4000	20,000
^{131}Ba	32	0.41	12.0	d	40	500	700	1000
^{153}Gd	44	0.056	242	d	100	100	800	100
^{181}W	60		140	d	200	100	1000	10,000
^{183}Re	61		71	d	200	200	1000	2000
^{185}Os	63	0.64	93.4	d	30	60	300	900
^{190}Ir	65	1.3	11	d	20	500	700	900
^{191}Pt	67	0.15	3.00	d	100	700	400	900
^{193m}Pt	67		4.3	d		6000	4000	7000
^{193}Pt	67		>500	d	200	400	4000	700
^{197}Hg	71	0.02	65	h	200	1000	1000	2000
^{200}Tl	73	3.2	26.1	h	8	1000	1000	8000
^{201}Tl	73	0.016	74	h	200	1000	700	4000
^{202}Tl	73	0.42	12.0	d	50	200	300	1000
^{203}Pb	75	0.25	52.1	h	80	2000	1000	2000
^{206}Bi	77	3.2	6.234	d	8	100	100	90
^{207}Bi	77	1.5	30.2	y	20	10	300	90
Alpha Emitters								
^{144}Nd			2.4×10^{15}	y		0.1	300	0.05
^{147}Sm			1.05×10^{11}	y		0.09	300	0.05
^{210}Po			138.40	d		0.2	3	0.3
^{223}Ra		*	11.43	d		0.2	3	1

(1) Isotope	(2) K X Ray keV	(3) $\bar{E}_\gamma$ MeV	(4) $T_{1/2}$	(5) Skin Dose	(6) Clothing Dose	(7) Direct Inhal	(8) Direct Inges	(9) Skin Abs
				nCi/cm²				µCi
^{224}Ra		*	3.64 d			0.9	10	0.5
^{226}Ra		*	1602 y			0.04	0.06	0.03
^{227}Th		*	18.2 d			0.2	70	20
^{228}Th		*	1.910y			0.008	30	0.5
^{230}Th		*	8.0×10^4 y			0.003	7	0.1
^{232}Th			1.41×10^{10}7			0.003	7	0.1
Th-nat						0.003	4	0.07
^{231}Pa		*	3.25×10^4 y			0.001	4	0.0007
^{230}U			20.8 d			0.1	10	3
^{232}U			72 y			0.04	3	0.05
^{233}U			1.62×10^5 y			0.1	10	0.2
^{234}U			2.47×10^5 y			0.1	10	0.2
^{235}U			7.1×10^8 y			0.1	10	0.2
^{236}U			2.39×10^7 y			0.1	10	0.2
^{238}U			4.51×10^9 y			0.09	3	0.2
U-nat						0.08	3	0.1
^{237}Np		*	2.14×10^6 y			0.005	10	0.002
^{238}Pu			86.4 y			0.003	10	0.07
^{239}Pu			24,390 y			0.003	10	0.07
^{240}Pu			6580 y			0.003	10	0.07
^{242}Pu			3.79×10^5 y			0.003	10	0.07
^{244}Pu			7.6×10^7 y			0.003	10	0.07
^{241}Am			458 y			0.008	10	0.002
^{243}Am		*	7950 y			0.008	10	0.002
^{242}Cm			162.5 d			0.1	100	0.07
^{243}Cm		*	32 y			0.008	10	0.002
^{244}Cm			17.6 y			0.01	30	0.005
^{245}Cm		*	9300 y			0.006	10	0.002
^{246}Cm			5500 y			0.006	10	0.002
^{247}Cm			1.6×10^7 y			0.006	10	0.002
^{248}Cm		*	4.7×10^5 y			0.0007	1	0.0002
^{249}Cf		*	360 y			0.002	10	0.0007

^{250}Cf		13.2	y	0.006	50	0.003
^{251}Cf	*	800	y	0.002	10	0.0007
^{252}Cf	*	2.646	y	0.007	30	0.003
^{254}Cf		60.5	d	0.006	0.6	0.003
^{253}Es		20.47	d	0.7	100	0.4
^{254}Es	*	276	d	0.03	50	0.007

This table includes the basic decay data used in the calculations and the numerical decision levels for workers as based upon exposure or potential exposure to the contaminated individual.

Column 1: The isotope.

Column 2: For beta emitters, the maximum energy of the spectrum for the predominant group (or groups) of particles.

For orbital electron capture or internal transition decays, the energy of the k-electron shell.

Column 3: The average gamma energy per disintegration ignoring lines below 0.1 MeV.

Column 4: The radioactive half-life of the isotope.

Column 5: The contamination level on the skin to deliver 15 rems/yr to the basal layer if maintained 40 h/wk and 50 wk/yr. Levels twice as high on the forearms and five times as high on the hands will deliver doses at the maximum for the current NCRP recommendations.

For a single event during the year and with exposure continuous over the following period of time, the annual dose limit will be delivered by a contamination level which is $4[1 + (15/T_{\frac{1}{2}})]$ times as great as the continuously maintained level. ($T_{\frac{1}{2}}$ is the radioactive half-life in days).

Column 6: The contamination level distributed through a clothing thickness of 23 mg/cm^2 that will deliver an annual dose of 15 rems to the basal layer of the skin if the clothing is worn 40 h/wk and 50 wk/yr.

Column 7: The contamination level on clothing (and skin) which could result in inhalation of a quantity of radioactive material equivalent to that in air at the MPC_a for workers. Normally this would refer to "loose" contamination although an operational definition of the concept of "loose" is not possible with present data.

Column 8: The contamination level on clothing and skin that could result in the ingestion of a quantity of radioactive material equivalent to that of ingesting water at the MPC_w for workers over the work day. (See discussion of "loose" contamination under Column 7.)

Column 9: The total quantity of radioactive material maintained on the skin for each work day that could result in the absorption of a quantity of radioactive material equal to that which would be absorbed from the GI tract if water at the MPC_w for workers as based on soluble isotopes were ingested during the work week.

For a single contamination event during the year where the contamination is not (or cannot) be removed before leaving work, the appropriate decision level could be four times the continuously maintained level given.

TABLE D-II

DIRECT LEVELS-PUBLIC

(1) Isotope	(2) Skin Dose	(3) Clothing Dose	(4) Direct Inhal	(5) Direct Inges	(6) Skin Abs
	nCi/cm²				μCi
Beta Emitters					
^{14}C	0.04	0.4	30	20	40
^{22}Na	0.007	0.01	0.08	0.09	6
^{32}P	0.007	0.007	0.6	0.6	0.8
^{35}S	0.04	0.4	2	5	9
^{36}Cl	0.007	0.01	0.2	2	10
^{45}Ca	0.02	0.07	0.3	0.3	0.3
^{47}Ca	0.007	0.01	2	0.9	2
^{46}Sc	0.009	0.02	0.2	1	1
^{47}Sc	0.008	0.01	6	3	30
^{48}Sc	0.007	0.01	1	0.9	10
^{48}V	0.01	0.02	0.6	0.9	1
^{52}Mn	0.02	0.02	1	0.9	2
^{59}Fe	0.008	0.01	0.6	2	0.5
^{58}Co	0.04	0.08	0.6	3	20
^{60}Co	0.01	0.03	0.08	0.9	5
^{63}Ni			0.6	0.9	0.5
^{65}Ni	0.007	0.008	6	3	60
^{74}As	0.01	0.01	1	2	8
^{76}As	0.007	0.009	0.8	0.6	30
^{77}As	0.007	0.01	3	2	100
^{82}Br	0.008	0.02	2	1	50
^{86}Rb	0.007	0.009	0.6	0.6	4
^{87}Rb	0.01	0.06	0.6	3	5
^{89}Sr	0.007	0.009	0.3	0.3	0.2
^{90}Sr	0.008	0.02	0.01	0.01	0.006
^{90}Y	0.007	0.009	0.8	0.6	2
^{91}Y	0.007	0.009	0.3	0.9	0.2
^{93}Zr			1	20	0.5
^{95}Zr	0.009	0.02	0.3	2	1
^{95}Nb	0.03	0.2	0.8	0.04	3
^{99}Mo	0.007	0.009	2	1	8
^{99}Tc	0.01	0.05	0.6	6	20
^{103}Ru	0.02	0.1	0.8	2	5
^{106}Ru	0.007	0.01	0.06	0.3	0.6
^{105}Rh	0.008	0.02	6	3	3
^{110m}Ag	0.02	0.30	0.08	0.9	3
^{111}Ag	0.007	0.01	2	1	10
^{115m}Cd	0.007	0.009	0.3	0.9	0.1
^{115}Cd	0.007	0.01	2	0.9	3

(1) Isotope	(2) Skin Dose	(3) Clothing Dose	(4) Direct Inhal	(5) Direct Inges	(6) Skin Abs
	nCi/cm²				μCi
^{114m}In	0.007	0.009	2	0.6	0.4
^{115}In	0.008	0.02	0.3	3	1
^{125}Sn	0.007	0.009	0.8	0.6	2
^{122}Sb	0.007	0.008	1	0.9	30
^{124}Sb	0.006	0.008	0.2	0.6	1
^{125}Sb	0.007	0.01	0.2	3	2
^{127m}Te	0.007	0.01	0.3	2	0.8
^{129m}Te	0.007	0.01	0.3	0.6	0.5
^{131m}Te	0.008	0.008	2	1	6
^{132}Te	0.005	0.007	1	0.6	3
^{126}I	0.01	0.02	0.04	0.03	0.05
^{129}I	0.02	0.1	0.008	0.006	0.01
^{131}I	0.007	0.01	0.04	0.03	0.05
^{134}Cs	0.008	0.02	0.1	0.02	0.5
^{135}Cs	0.02	0.1	0.8	3	5
^{136}Cs	0.01	0.03	2	2	10
^{137}Cs	0.008	0.02	0.1	0.6	1
^{140}Ba	0.007	0.01	0.3	0.6	0.5
^{140}La	0.006	0.01	1	0.6	10
^{141}Ce	0.008	0.02	1	3	2
^{143}Ce	0.006	0.009	2	1	10
^{144}Ce	0.004	0.007	0.06	0.3	0.04
^{143}Pr	0.007	0.01	2	2	2
^{147}Nd	0.007	0.01	2	2	2
^{147}Pm	0.02	0.1	0.6	6	0.3
^{149}Pm	0.007	0.01	2	1	10
^{151}Sm			0.6	10	0.3
^{153}Sm	0.007	0.01	3	2	20
^{152}Eu	0.02	0.03	0.1	2	0.05
^{154}Eu	0.006	0.01	0.03	0.6	0.02
^{155}Eu	0.03	0.07	0.8	6	0.4
^{160}Tb	0.007	0.01	0.3	1	0.4
^{166}Dy	0.02	0.03	2	1	2
^{166}Ho	0.007	0.009	2	0.9	5
^{169}Er	0.01	0.04	3	3	5
^{170}Tm	0.007	0.01	0.3	2	0.2
^{171}Tm	0.9	3	1	20	0.5
^{174}Yb	0.008	0.02	6	3	10
^{177}Lu	0.008	0.02	6	3	5
^{181}Hf	0.009	0.02	0.3	2	0.2
^{182}Ta	0.008	0.02	0.2	1	0.2
^{185}W	0.009	0.02	1	3	50
^{186}Re	0.007	0.01	2	2	6
^{187}Re			6	60	40
^{191}Os	0.6		3	6	20

(1) Isotope	(2) Skin Dose	(3) Clothing Dose	(4) Direct Inhal	(5) Direct Inges	(6) Skin Abs
	nCi/cm²				μCi
^{193}Os	0.007	0.01	2	2	20
^{192}Ir	0.007	0.01	0.2	1	0.5
^{196}Au	0.2	0.3	6	3	20
^{198}Au	0.007	0.01	2	2	10
^{199}Au	0.01	0.05	8	6	40
^{203}Hg	0.03	0.1	0.6	0.6	0.8
^{204}Tl	0.007	0.01	0.2	2	5
^{210}Pb			0.001	0.003	0.0004
^{210}Bi	0.007	0.01	0.06	1	0.03
^{228}Ra	0.007	0.008	0.0003	0.0009	0.0005
^{227}Ac			2×10^{-5}	0.06	1×10^{-5}
^{234}Th	0.006	0.008	0.2	0.6	30
^{230}Pa	0.2	0.2	0.008	6	0.005
^{239}Np	0.009	0.02	6	3	20
^{241}Pu			0.0008	6	0.03
^{249}Bk	0.09	0.6	1	20	0.003
^{253}Cf	0.01	0.06	0.008	3	0.003
^{254m}Es	0.008	0.02	0.06	0.6	0.02
Electron Capture and Internal Transition Decay					
^{7}Be			10	60	30
^{51}Cr	1		20	60	10
^{54}Mn	0.2		0.3	3	2
^{55}Fe	1		8	20	4
^{57}Co	0.6		2	10	100
^{59}Ni	0.4		6	6	1
^{65}Zn	0.2		0.6	5	0.5
^{71}Ge	0.9		60	60	200
^{73}As	0.9		3	20	20
^{75}Se	0.3		1	10	10
^{85}Sr	0.3		1	6	3
^{93m}Nb			1	10	0.5
^{96}Tc	0.07		2	2	30
^{97m}Tc			1	6	30
^{97}Tc	1		3	20	100
^{97}Ru	0.5		20	9	20
^{103}Pd	1		8	9	7
^{105}Ag	0.4		0.8	3	10
^{109}Cd	0.7		0.8	6	0.3
^{113}Sn	0.5		0.6	2	2
^{125m}Te			1	3	3
^{131}Cs	1		30	30	200
^{131}Ba	0.4		3	6	10
^{153}Gd	1		0.8	6	1
^{181}W	2		1	9	100

(1) Isotope	(2) Skin Dose	(3) Clothing Dose	(4) Direct Inhal	(5) Direct Inges	(6) Skin Abs
	nCi/cm²				μCi
^{183}Re	2		1	9	40
^{185}Os	0.3		0.6	2	5
^{190}Ir	0.1		3	6	10
^{191}Pt	0.9		6	9	5
^{193m}Pt			60	30	50
^{193}Pt	2		3	30	5
^{197}Hg	2		10	9	10
^{200}Tl	0.06		10	6	70
^{201}Tl	2		8	6	50
^{202}Tl	0.4		2	2	7
^{203}Pb	0.6		20	10	20
^{206}Bi	0.06		1	1	1
^{207}Bi	0.1		0.1	2	1
Alpha Emitters					
^{144}Nd			8×10^{-4}	2	4×10^{-4}
^{147}Sm			6×10^{-4}	2	3×10^{-4}
^{210}Po			2×10^{-3}	0.02	2×10^{-3}
^{223}Ra			2×10^{-3}	0.02	0.01
^{224}Ra			6×10^{-3}	0.06	0.03
^{226}Ra			3×10^{-4}	3×10^{-4}	2×10^{-4}
^{227}Th			2×10^{-3}	0.6	0.2
^{228}Th			6×10^{-5}	0.2	4×10^{-3}
^{230}Th			2×10^{-5}	0.06	1×10^{-3}
^{232}Th			2×10^{-5}	0.06	1×10^{-3}
Th-nat			2×10^{-5}	0.03	5×10^{-4}
^{231}Pa			1×10^{-5}	0.03	5×10^{-6}
^{230}U			1×10^{-3}	0.06	2×10^{-3}
^{232}U			2×10^{-4}	0.02	4×10^{-4}
^{233}U			6×10^{-3}	0.1	2×10^{-3}
^{234}U			1×10^{-3}	0.1	2×10^{-3}
^{235}U			1×10^{-3}	0.1	2×10^{-3}
^{236}U			1×10^{-3}	0.2	3×10^{-3}
^{238}U			8×10^{-4}	0.02	3×10^{-3}
U-nat			6×10^{-4}	0.02	1×10^{-3}
^{237}Np			3×10^{-5}	0.09	2×10^{-5}
^{238}Pu			2×10^{-5}	0.2	8×10^{-4}
^{239}Pu			2×10^{-5}	0.2	8×10^{-4}
^{240}Pu			2×10^{-5}	0.2	8×10^{-4}
^{242}Pu			2×10^{-5}	0.2	8×10^{-4}
^{244}Pu			2×10^{-5}	0.1	6×10^{-4}
^{241}Am			6×10^{-5}	0.1	2×10^{-5}
^{243}Am			6×10^{-5}	0.1	2×10^{-5}
^{242}Cm			1×10^{-3}	0.6	5×10^{-4}

(1) Isotope	(2) Skin Dose	(3) Clothing Dose	(4) Direct Dose	(5) Direct Dose	(6) Skin Abs
	nCi/cm²				μCi
^{243}Cm			6×10^{-5}	0.2	3×10^{-5}
^{244}Cm			8×10^{-5}	0.2	4×10^{-5}
^{245}Cm			6×10^{-5}	0.1	2×10^{-5}
^{246}Cm			6×10^{-5}	0.1	2×10^{-5}
^{247}Cm			6×10^{-5}	0.1	2×10^{-5}
^{248}Cm			6×10^{-6}	0.01	2×10^{-6}
^{249}Cf			1×10^{-5}	0.1	6×10^{-6}
^{250}Cf			6×10^{-5}	0.3	2×10^{-5}
^{251}Cf			2×10^{-5}	0.1	6×10^{-6}
^{252}Cf			6×10^{-5}	0.2	3×10^{-5}
^{254}Cf			6×10^{-5}	0.003	2×10^{-5}
^{253}Es			6×10^{-3}	0.6	3×10^{-3}
^{254}Es			2×10^{-4}	0.3	8×10^{-5}

Column 1: The isotope.

Column 2: The contamination level maintained on the skin for 24 h/day to deliver 0.5 rem/yr to the basal layer.

For a single event during the year, the inital level required to deliver 0.5 rems in the following year can be higher by a factor of 17 $[1 + (15/T_{\frac{1}{2}})]$ where $T_{\frac{1}{2}}$ is the radioactive half-life of the isotope in days.

Column 3: The contamination distributed through a clothing thickness of 23 mg/cm² to deliver an annual dose of 0.5 rems to the basal layer of the skin if the clothing is worn continuously.

Column 4: The contamination level on clothing and skin that could result in inhalation of air at the MPC_a for the public. (See note on "loose" contamination in the description of Table D-I, Column 7.)

Column 5: The contamination level on skin or clothing that could result in ingestion of a quantity of radioactive material equivalent to the ingestion of water at the MPC_w for an individual in the public. (See note on "loose" contamination under the description of Table D-I, Column 7.)

Column 6: The total quantity of radioactive material maintained on the skin for 24 h/day that could result in absorption of a quantity equal to that which would be absorbed from the GI tract if water at the MPC_w for "soluble" isotopes for an individual in the public were ingested.

For a single contamination event during the year, the initial contamination could be 20 times the value given for a continuously maintained level.

TABLE D-III

TRANSFER LEVELS

(1) Isotope	(2) Gamma Dose	(3) Beta Dose	(4) Resus	(5) Skin Dose	(6) Direct Inhal	(7) Direct Inges	(8) Skin Abs
				μCi/day			
Beta Emitters							
^{14}C			20,000	30	20,000	20,000	2000
^{22}Na	9		50	5	60	600	200
^{32}P		4	500	6	500	600	40
^{35}S			2000	30	2000	4000	400
^{36}Cl		20	100	5	100	1000	500
^{45}Ca			200	10	200	200	10
^{47}Ca	100	40	2000	10	3000	2000	100
^{46}Sc	10		100	7	200	900	40
^{47}Sc	2000	200	10,000	20	10,000	6000	3000
^{48}Sc	90	300	4000	20	4000	3000	2000
^{48}V	20	90	500	10	500	900	50
^{52}Mn	40		2000	20	2000	1000	200
^{59}Fe	30		400	6	400	1000	20
^{58}Co	30		300	30	400	2000	700
^{60}Co	8		50	7	60	600	200
^{63}Ni			300		400	600	20
^{65}Ni	9000	400	200,000	300	200,000	100,000	100,000
^{74}As	70	40	900	10	1000	1000	400
^{76}As	1000	20	3000	30	4000	3000	8000
^{77}As	4000	300	8000	30	10,000	9000	20,000
^{82}Br	200		5000	30	6000	5000	10,000
^{86}Rb	500	3	400	6	500	600	200
^{87}Rb			300	10	400	2000	200
^{89}Sr		2	200	5	600	200	6
^{90}Sr			6	5	7	8	0.2
^{90}Y		20	2000	20	2000	1000	300
^{91}Y	7000	2	200	5	200	700	6

^{93}Zr			600		700	20,000	20
^{95}Zr	40		200	7	200	1000	40
^{95}Nb	50		600	30	700	2000	100
^{99}Mo	900	100	4000	20	5000	3000	1000
^{99}Tc			300	9	400	4000	800
^{103}Ru	70		600	20	700	2000	200
^{106}Ru	100	9	30	4	40	200	20
^{105}Rh	5000		20,000	30	20,000	10,000	600
^{110m}Ag	8		50	10	60	600	100
^{111}Ag	4000	40	2000	9	3000	2000	700
^{115m}Cd	1000	2	200	5	200	700	5
^{115}Cd	800	100	4000	20	5000	3000	400
^{114}In	400	2	100	5	1000	400	20
^{115}In			200	6	200	2000	40
^{125}Sn	900	6	800	8	1000	700	100
^{122}Sb	500	20	3000	20	3000	2000	4000
^{124}Sb	10	2	100	5	100	500	50
^{125}Sb	200	20	100	5	200	2000	60
^{127m}Te		20	200	5	200	1000	20
^{129m}Te	400	2	200	5	200	500	20
^{131m}Te	400	30	6000	30	7000	5000	2000
^{132}Te	80	10	2000	10	2000	1000	300
^{126}I	200	60	40	10	40	30	3
^{129}I	5000		5	20	6	4	0.4
^{131}I	200	80	40	20	50	40	3
^{134}Cs	1000	20	60	5	70	20,000	20
^{135}Cs			500	10	600	2000	200
^{136}Cs	30		1000	10	2000	2000	600
^{137}Cs	30		80	5	90	400	40
^{140}Ba	300	30	200	7	300	600	30
^{140}La	100	80	3000	20	4000	2000	2000
^{141}Ce	500		1000	6	1000	2000	70
^{143}Ce	2000	200	7000	30	8000	5000	2000
^{144}Ce	400	0.7	30	3	40	200	2
^{143}Pr		30	1000	7	2000	2000	100
^{147}Nd	600	30	2000	8	2000	2000	90
^{147}Pm			300	10	400	4000	10

(1) Isotope	(2) Gamma Dose	(3) Beta Dose	(4) Resus	(5) Skin Dose	(6) Direct Inhal	(7) Direct Inges	(8) Skin Abs
				μCi/day			
^{149}Pm	100,000	100	5000	20	6000	3000	2000
^{151}Sm	20,000		300		400	8000	9
^{153}Sm	9000	100	7000	20	8000	7000	3000
^{152}Eu	20	4	60	10	70	2000	2
^{154}Eu	20	8	30	4	20	400	0.6
^{155}Eu	400		500	20	600	4000	10
^{160}Tb	30	10	200	5	200	900	20
^{166}Dy	10,000		3000	30	4000	2000	200
^{166}Ho	20,000	40	7000	30	8000	4000	1000
^{169}Er			3000	10	3000	3000	300
^{170}Tm	8000	10	200	5	200	1000	6
^{171}Tm	300		600	600	700	10,000	20
^{175}Yb	4000		8000	10	10,000	5000	1000
^{177}Lu	6000		6000	10	8000	4000	400
^{181}Hf	60		200	7	200	2000	7
^{182}Ta	20		100	5	100	900	6
^{185}W			700	7	800	2000	2000
^{186}Re	10,000	80	4000	10	4000	3000	700
^{187}Re			3000		4000	40,000	1000
^{191}Os	2000		2000	60	3000	6000	1000
^{193}Os	9000	200	9000	30	10,000	6000	5000
^{192}Ir	30	20	200	5	200	900	20
^{196}Au	200		7000	200	8000	4000	1000
^{198}Au	600	100	5000	20	5000	4000	1000
^{199}Au	3000		20,000	30	20,000	10,000	4000
^{203}Hg	100		400	20	400	500	30
^{204}Tl		20	100	5	200	1000	200
^{210}Pb			0.6		0.7	2	0.02
^{210}Bi		60	80	10	90	2000	2
^{228}Ra	40	1	0.2	4	0.2	0.6	0.02
^{227}Ac			0.1		0.02	40	4×10^{-4}
^{234}Th	3000	3	200	5	200	500	1000

^{230}Pa	60		7		8	6000	0.3
^{239}Np	3000		10,000	20	10,000	8000	2000
^{241}Pu			0.5		0.6	4000	1
^{249}Bk	100		600	60	800	10,000	0.1
^{253}Cf			6	10	8	3000	0.2
^{254m}Es	1000	600	200	30	200	2000	3

Electron Capture and Internal Transition Decay

^{7}Be			7000		8000	50,000	1000
^{51}Cr	1000		20,000	1000	20,000	50,000	500
^{54}Mn	20		200	100	200	2000	80
^{55}Fe			5000	800	6000	20,000	100
^{57}Co	200		1000	400	1000	8000	5000
^{59}Ni	60		3000	300	4000	4000	40
^{65}Zn	40		300	200	400	3000	20
^{71}Ge			50,000	900	60,000	70,000	10,000
^{73}As	5000		2000	600	2000	10,000	600
^{75}Se	60		700	200	800	10,000	500
^{85}Sr	50		700	200	800	5000	100
^{93m}Nb			600		700	8000	20
^{96}Tc	60		30,000	100	4000	3000	2000
^{97m}Tc			900		1000	4000	1000
^{97}Tc			2000	700	2000	20,000	4000
^{97}Ru	1000		30,000	1000	40,000	20,000	2000
^{103}Pd			7000	900	8000	9000	400
^{105}Ag	90		600	300	700	2000	400
^{109}Cd	200		300	500	600	4000	9
^{113}Sn	90		300	300	400	2000	60
^{125m}Te	10,000		700		800	2000	100
^{131}Cs			30,000	1000	30,000	30,000	10,000
^{131}Ba	200		3000	400	3000	6000	700
^{153}Gd	400		500	700	600	400	40
^{181}W			700	1000	800	6000	4000
^{183}Re			900	1000	1000	7000	2000
^{185}Os	40		300	200	400	2000	200
^{190}Ir	50		3000	200	3000	7000	600

Isotope	Gamma Dose	Beta Dose	Resus	Skin Dose	Direct Inhal	Direct Inges	Skin Abs
				μCi/day			
^{191}Pt	1000		10,000	2000	10,000	20,000	600
^{193m}Pt			80,000		100,000	50,000	5000
^{193}Pt			2000	1000	2000	20,000	200
^{197}Hg	10,000		20,000	5000	30,000	20,000	1000
^{200}Tl	200		50,000	300	50,000	30,000	20,000
^{201}Tl	10,000		20,000	4000	20,000	10,000	5000
^{202}Tl	200		2000	400	2000	2000	400
^{203}Pb	1000		40,000	2000	50,000	30,000	3000
^{206}Bi	30		2000	90	2000	2000	80
^{207}Bi	10		80	80	90	1000	40
Alpha Emitters							
^{144}Nd			0.5		0.6	1000	0.01
^{147}Sm			0.3		0.4	1000	0.01
^{210}Po			1		1	10	0.08
^{223}Ra			2		2	20	0.6
^{224}Ra			9		10	100	3
^{226}Ra			0.2		0.2	0.2	0.006
^{227}Th			1		2	600	8
^{228}Th			0.03		0.04	100	0.1
^{230}Th			0.01		0.01	40	0.04
^{232}Th			0.01		0.01	40	0.04
Th-nat			0.01		0.01	20	0.02
^{231}Pa			0.006		0.007	20	0.0002
^{230}U			0.8		1	50	0.05
^{232}U			0.1		0.2	20	0.01
^{233}U			0.6		4	80	0.07
^{234}U			0.6		0.7	80	0.07
^{235}U			0.6		0.7	80	0.07
^{236}U			0.6		0.7	80	0.09
^{238}U			0.5		0.6	10	0.09
U-nat			0.3		0.4	10	0.04

^{237}Np	0.02	0.02	60	0.0006
^{238}Pu	0.01	0.01	100	0.03
^{239}Pu	0.01	0.01	100	0.03
^{240}Pu	0.01	0.01	100	0.03
^{242}Pu	0.01	0.01	100	0.03
^{244}Pu	0.01	0.01	100	0.03
^{241}Am	0.03	0.04	80	0.0001
^{243}Am	0.03	0.04	80	0.0001
^{242}Cm	0.7	0.8	400	0.02
^{243}Cm	0.03	0.04	100	0.0009
^{244}Cm	0.05	0.06	100	0.001
^{245}Cm	0.03	0.04	80	0.0007
^{246}Cm	0.03	0.04	80	0.0007
^{247}Cm	0.03	0.04	80	0.0007
^{248}Cm	0.03	0.004	8	7×10^{-5}
^{249}Cf	0.008	0.009	80	0.0002
^{250}Cf	0.03	0.04	200	0.0006
^{251}Cf	0.01	0.01	80	0.0002
^{252}Cf	0.03	0.04	100	0.001
^{254}Cf	0.04	0.04	2	0.0006
^{253}Es	4	5	500	0.1
^{254}Es	0.7	0.1	200	0.003

These values are based upon the estimated radiation dose that could result to the occupants of a home if the given quantity of radioactive materials were transferred to the home per day.

Column 1: The isotope.

Column 2: The amount transferred per day that could result in an annual external exposure to the occupants of 0.5 R.

For a single event during a year, the quantity transferred could be 100 times as great.

Column 3: The amount transferred per day that could result in an annual external beta dose of 0.5 rads.

For a single event during a year, the quantity transferred could be 100 times as great.

Column 4: The amount transferred per day that could result in air concentrations due to resuspension in a medium-sized home averaging at the MPC_a for an individual in the public.

For a single event during a year, the quantity transferred could be 200 times as great.

Column 5: The amount transferred per day that could result in annual skin dose due to skin contamination of 0.5 rems.

For a single event during the year, the quantity transferred could be 200 times as great.

Column 6: The amount transferred per day that could result in clothing or skin contamination sufficient so that the air concentration from direction inhalation could equal the MPC_a for an individual in the public.

For a single event during a year, the quantity transferred could be 200 times as great.

Column 7: The amount transferred per day that could result in contamination of clothing or skin of the occupant such that direct ingestion could exceed the amount of radioactive material ingested in water at the MPC_w for an individual in the public.

For a single event during the year, the quantity transferred could be 100 times as great.

Column 8: The amount transferred per day that could result in skin contamination such that the amount absorbed would equal the amount absorbed through the GI tract for individuals ingesting water at the MPC_w for soluble isotopes for an individual in the public.

For a single event during the year, the quantity transferred could be 100 times as great.

TABLE D-IV

INSTRUMENT READINGS

(1) Isotope	(2) Worker Skin GM "mR/h"	(2) Worker Skin MW Cntr counts/min	(3) Worker Clothing GM "mR/h"	(3) Worker Clothing MW Cntr counts/min	(4) Transfers GM "mR/h"	(4) Transfers MW Cntr counts/min	(4) Transfers GM "mR/h"	(4) Transfers MW Cntr counts/min
Beta Emitters								
^{14}C		10,000S		100,000C		6000S		400,000A
^{22}Na	0.3 S	4000S	0.8C	8000C	0.2 S	2000S	0.3 γ	4000γ
^{32}P	2 S		2 C		0.9 β		1 S	
^{35}S		10,000S		100,000C		6000S		80,000A
^{36}Cl	0.6 S		1 C		0.4 S		1 β	
^{45}Ca		6000S		30,000C		3000A		3000S
^{47}Ca	0.8 S		0.9C		0.9 S		4 β	
^{46}Sc	0.09S	3000S	0.3C	10,000C	0.06 S	2000S	0.09γ	4000γ
^{47}Sc	0.4 S		1 C		1 S		10 β	
^{48}Sc	0.5 S		0.6C		1 S		5 γ	
^{48}V	0.3 S		0.7C		0.3 S		0.7 γ	
^{52}Mn	0.3 S		0.5C		0.3 S		0.6 γ	
^{59}Fe	0.2 S	4000S	0.5C	8000C	0.2 S	2000S	0.5 A	8000A
^{58}Co	0.2 S	3000S	0.4C	6000C	0.1 γ	2000γ	0.1 S	2000S
^{60}Co	0.05S	3000S	0.2C	10,000C	0.04 S	2000S	0.04γ	3000γ
^{63}Ni								
^{65}Ni	2 S		2 C		70 S		100 β	
^{74}As	0.9 S		2 C		0.9 S		4 β	
^{76}As	3 S		3 C		6 β		9 S	
^{77}As	0.6 S		1 C		2 S		20 β	
^{82}Br	0.2 S	4000S	0.4C	8000C	0.6 S	10,000S	4 γ	60,000γ
^{86}Rb	2 S		2 C		0.7 β		1 S	
^{87}Rb		6000S		20,000C		3000S		60,000A
^{89}Sr	1 S		2 C		0.4 β		0.9 S	
^{90}Sr	0.03A	300A	0.4H	4000H	0.01 A	80A	0.2 S	2000S
^{90}Y	2 S		3 C		5 S		5 β	
^{91}Y	2 S		2 C		0.4 β		1 S	

(1) Isotope	(2) Worker Skin GM "mR/h"	(2) Worker Skin MW Cntr counts/min	(3) Worker Clothing GM "mR/h"	(3) Worker Clothing MW Cntr counts/min	(4) Transfers GM "mR/h"	(4) Transfers MW Cntr counts/min	(4) Transfers GM "mR/h"	(4) Transfers MW Cntr counts/min
^{93}Zr								
^{95}Zr	0.2 S	4000S	0.5C	10,000C	0.1 S	3000S	0.6 A	10,000A
^{95}Nb		8000S		40,000C		6000S		10,000γ
^{99}Mo	1 S		2 C		3 S		20 β	
^{99}Tc	0.1 S	6000S	0.3C	20,000C	0.5 S	3000S	1 R	100,000R
^{103}Ru		8000S		30,000C		5000S		20,000γ
^{106}Ru	1 S		1 C		0.6 S		1 β	
^{105}Rh	0.3 S		0.8C		1 S		20 A	
^{110m}Ag	0.2 S	2000S	0.4C	5000C	0.09γ	1000γ	0.1 S	1000S
^{111}Ag	1 S		1 C		1 S		5 β	
^{115m}Cd	2 S		2 C		0.4 β		1 S	
^{115}Cd	1 S		1 C		3 S		10 β	
^{114m}In	2 S		2 C		0.4 β		1 S	
^{115}In	0.3 S		0.5C		0.2 S		1 A	
^{125}Sn	2 S		3 C		2 β		2 S	
^{122}Sb	2 S		2 C		5 S		5 β	
^{124}Sb	2 S		3 C		0.5 β		1 S	
^{125}Sb	0.5 S		1 C		0.2 S		1 β	
^{127m}Te	0.6 S		1 C		0.3 S		1 A	
^{129m}Te	2 S		2 C		0.4 β		1 S	
^{131m}Te	3 S		3 C		8 β		8 S	
^{132}Te	1 S		2 C		2 S		2 β	
^{126}I	0.4 A		2 C		0.2 A		0.7 S	
^{129}I		200A		1000H		80A		800E
^{131}I	0.3 A		1 C		0.1 A		1 S	
^{134}Cs	0.6 S		1 C		0.3 S		1 A	
^{135}Cs		8000S		30,000C		3000S		50,000A
^{136}Cs	0.08S	3000S	0.2C	8000C	0.08S	3000S	0.2 γ	8000γ
^{137}Cs	0.3 S		0.6C		0.2 C		0.9 γ	
^{140}Ba	1 S		1 C		0.9 S		4 A	
^{140}La	1 S		2 C		4 S		10 β	
^{141}Ce	0.4 S		0.9C		0.3 S		3 A	

^{143}Ce	1	S		2	C		5	S		40	β	
^{144}Ce	1	A		3	C		0.2	β		0.6	S	
^{143}Pr	0.9	S		1	C		0.8	S		3	β	
^{147}Nd	0.8	S		0.9	C		0.7	S		3	β	
^{147}Pm			5000S			30,000C			3000A			3000S
^{149}Pm	1	S		1	C		3	S		10	β	
^{151}Sm												
^{153}Sm	0.8	S		0.9	C		2	S		9	β	
^{152}Eu	0.4	A		2	C		0.1	A		0.2	β	
^{154}Eu	0.2	A		1	C		0.06	A		0.4	S	
^{155}Eu			10,000S			20,000C			3000A			6000A
^{160}Tb	0.8	S		1	C		0.5	S		1	β	
^{166}Dy	0.3	S	7000S	0.9	C	10,000C	0.5	S		3	A	
^{166}Ho	2	S		2	C		7	S		9	β	
^{169}Er	0.08	S	3000S	0.4	C	20,000C	0.08	S	3000S	2	A	
^{170}Tm	0.9	S		1	C		0.6	S		0.7	A	
^{171}Tm												
^{175}Yb	0.2	S	4000S	0.7	C	10,000C	0.2	S	4000S	20	A	
^{177}Lu	0.3	S	4000S	0.6	C	8000C	0.3	S	4000S	10	A	
^{181}Hf	0.2	S	4000S	0.5	C	10,000C	0.1	A	3000A	0.1	S	3000S
^{182}Ta	0.3	S		0.7	C		0.2	S		0.2	A	
^{185}W	0.2	S	4000S	0.6	C	10,000C	0.1	S	2000S	3	R	
^{186}Re	1	S		1	C		1	S		10	β	
^{187}Re												
^{191}Os			10,000S						10,000S			200,000A
^{193}Os	1	S		1	C		4	S		30	β	
^{192}Ir	0.5	S		1	C		0.3	S		1	A	
^{196}Au			4000S			7000C			4000γ			4000S
^{198}Au	0.9	S		1	C		2	S		10	β	
^{199}Au			6000S			20,000C			6000S			30,000β
^{203}Hg			10,000A			30,000C			5000S			8000A
^{204}Tl	0.7	S		0.8	C		0.4	S		2	β	
^{210}Pb												
^{210}Bi	0.7	S		1	C		0.3	A		1	S	
^{228}Ra	0.01	A	20A	0.1	H	200H	0.002	A	10A	0.02	R	90R
^{227}Ac												
^{234}Th	2	S		3	C		0.8	β		1	S	

(1) Isotope	(2) Worker Skin GM "mR/h"	(2) Worker Skin MW Cntr counts/min	(3) Worker Clothing GM "mR/h"	(3) Worker Clothing MW Cntr counts/min	(4) Transfers GM "mR/h"	(4) Transfers MW Cntr counts/min	(4) Transfers GM "mR/h"	(4) Transfers MW Cntr counts/min
^{230}Pa	7 A		400 H		10 A		300 R	
^{239}Np	0.2 S	4000S	0.6C	10,000C	0.4 S		40 A	
^{241}Pu								
^{249}Bk		70A		1000H		10A		8000S
^{253}Cf		100A		3000H		60A		2000R
^{254m}Es	0.2 A		1 C		0.2 A		2 S	
Electron Capture and Internal Transition Decay (Portable GM)								
^{7}Be								
^{51}Cr								
^{54}Mn	0.9 S		2 H		0.09γ		0.4 A	
^{55}Fe								
^{57}Co	1 S		4 H		0.4 γ		0.8 S	
^{59}Ni	1 A		10 H		0.1 A		0.2 γ	
^{65}Zn	0.2 A		2 H		0.07A		0.1 γ	
^{71}Ge								
^{73}As								
^{75}Se	1 S		3 H		0.2 γ		0.6 S	
^{85}Sr	0.7 A		3 H		0.1 γ		0.3 A	
^{93m}Nb								
^{96}Tc	1 S		10 H		0.8 γ		1 S	
^{97m}Tc								
^{97}Tc								
^{97}Ru	1 S		20 E		2 γ		2 S	
^{103}Pd								
^{105}Ag	1 S		3 H		0.3 γ		0.8 S	
^{109}Cd	0.05A		2 H		0.02A		0.3 γ	
^{113}Sn	0.5 A		1 H		0.1 A		0.2 γ	
^{125m}Te								
^{131}Cs								
^{131}Ba	1 S		10 H		0.6 γ		1 S	
^{153}Gd								

^{181}W				
^{182}Re				
^{185}Os	1 S	2 H	0.2 γ	0.7 A
^{190}Ir	1 S	30 H	0.3 γ	1 S
^{191}Pt	2 A	8 E	1 A	2 γ
^{193m}Pt				
^{193}Pt				
^{197}Hg				
^{200}Tl	1 S	100 H	3 γ	4 S
^{201}Tl				
^{202}Tl	1 S	6 H	0.6 γ	1 A
^{203}Pb	2 S	20 E	2 γ	5 S
^{206}Bi	1 S	10 H	0.4 γ	1 A
^{207}Bi	0.7 A	0.8H	0.08γ	0.3 A

Alpha Emitters-Air Proportional Counter

	Dis/min	dis/min	dis/min	dis/min
^{144}Nd	700A	10,000H	100A	7000R
^{147}Sm	700A	10,000H	100A	4000R
^{210}Po	3000H	3000H	1000A	10,000R
^{223}Ra	3000H	3000H	8000A	30,000R
^{224}Ra	700A	10,000H	40,000A	100,000R
^{226}Ra	400A	500H	80A	3000R
^{227}Th	3000H	3000H	10,000R	30,000H
^{228}Th	100H	100H	400R	500H
^{230}Th	40H	40H	100R	100H
^{232}Th	40H	40H	100R	100H
Th-nat	80H	80H	300R	300H
^{231}Pa	9A	10H	3A	9R
^{230}U	1000H	1000H	700A	10,000H
^{232}U	500H	500H	100A	1000R
^{233}U	1000H	1000H	900A	8000R
^{234}U	1000H	1000H	900A	8000R
^{235}U	1000H	1000H	900A	8000R
^{236}U	1000H	1000H	1000A	8000R
^{238}U	1000H	1000H	1000A	7000R

(1) Isotope	(2) Worker Skin dis/min	(3) Worker Clothing dis/min	(4) Transfers dis/min		dis/min
U-nat	2000H	2000H	500	A	8000R
^{237}Np	30A	70H	8	A	300R
^{238}Pu	40H	40H	100	R	100H
^{239}Pu	40H	40H	100	R	100H
^{240}Pu	40H	40H	100	R	100H
^{242}Pu	40H	40H	100	R	100H
^{244}Pu	40H	40H	100	R	100H
^{241}Am	30A	100H	1	A	400R
^{243}Am	30A	100H	1	A	400R
^{242}Cm	900A	1000H	300	A	200R
^{243}Cm	30A	100H	10	A	400R
^{244}Cm	70A	100H	10	A	700R
^{245}Cm	30A	80H	9	A	400R
^{246}Cm	30A	80H	9	A	400R
^{247}Cm	30A	80H	9	A	400R
^{248}Cm	3A	9H	0.9	A	50H
^{249}Cf	9A	30H	3	A	100R
^{250}Cf	40A	80H	8A	A	400R
^{251}Cf	9A	30H	3	A	100R
^{252}Cf	40A	90H	10	A	400R
^{254}Cf	40A	80H	8	A	500R
^{253}Es	5000A	9000H	1000	A	50,000R
^{254}Es	90A	400H	40	A	1000H

The estimated readings on several instruments commonly used for measuring contamination are given for the lowest decision level for direct exposure of the worker from skin and clothing and the lowest two transfer levels. Where the decision level is given in Tables D-I through D-III in μCi or μCi/day, a contaminated area of 10,000 cm^2 was assumed.

The entries are marked as to the mechanism giving the lowest value according to the following code:

S - Dose to skin from skin contamination
C - Dose to skin from clothing contamination
A - Skin absorption
H - Inhalation from clothing or skin
E - Ingestion from skin or clothing
γ - External gamma dose
β - External beta dose
R - Resuspension.

For beta emitters, the estimated reading corresponding to the decision level is given for a portable Geiger counter (GM) with a 30 mg/cm^2 GM tube. Where the beta energy is too low to permit an adequate reading on this instrument, the estimated counting rate on a mica window counter (MW Cntr) 1 in. in diameter with a 2 mg/cm^2 window is given. For orbital electron capture isotopes and those decaying by internal transition, the estimated reading on the portable GM tube from the gamma radiation is given. In a number of cases, the energy of the radiation is below 0.1 MeV, the lower value used for the calculations of the efficiencies, and no entry is made. For alpha emitters, the disintegrations per minute for a 60 cm^2 probe area are given. In no case is allowance made for self-absorption in the source.

Column 1: The isotope.

Column 2: The decision level for skin contamination of workers based upon the lowest value for dose to the skin, direct inhalation, direct ingestion, or absorption through the skin.

Column 3: Decision level for clothing contamination of the worker based upon the lowest value of dose to the skin from clothing, direct inhalation, or direct ingestion.

Column 4: Decision level for transfer to the home based on an area of contamination of 10,000 cm^2. The two lowest transfer levels from Table D-III are included.

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