
A Review of the Current Deficiencies in Personnel Beta Dosimetry, With Recommendations

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I. INTRODUCTION

Although papers have been appearing periodically in the professional health physics literature for a number of years describing the inadequacies of current dosimetry practices (Be66a, Be66b, Ha68, Zi68), many health physics practitioners ignore the problems, do not understand them, or are unfamiliar with the relevant literature and so are unaware of the existence of any problems. Most of these practitioners are responsible for radiation safety programs in hospitals, universities, and nuclear power facilities. Few of them encountered any unusual or baffling radiological situations in the course of their daily routines that may have alerted them to the possibility that there was anything amiss. In any case, there was little that one could do to solve the problems even if one were aware of them, because the technology until very recently had not produced solutions that were readily applicable for routine personnel monitoring.

One unfortunate characteristic of the field of applied personnel dosimetry is that it is not self-correcting. In most endeavors, there is a more or less direct connection between action taken and effect observed, and the correlation between the two is generally obvious. For example, if an engineer produces a faulty bridge design, the bridge will collapse; if a chemist adds the wrong reagent, the desired reaction will not occur. No such relationship exists in routine personnel dosimetry; that is, for the practitioner the dosimeter readings do not normally bear any observable correlation with a biological effect, except in cases

of severe accidental overexposure. This is so because in most cases an effect fortunately never occurs, but even in those rare instances in which an effect does occur, it is usually displaced from the cause by a long period of time, and its manifestations are identical to those observed in the general population. Furthermore, it is almost never possible to establish the cause and effect relationship on an individual basis; such relationships are detected only through epidemiological studies. This discussion may appear trivial, even naive, to those versed in radiation biology, but it is worth repeating since, as a result of the above considerations, the dosimeter readings often degenerate into mere columns of numbers with the label "dose" attached to them. The numbers serve to satisfy administrative and regulatory record keeping requirements, but there is usually little incentive to speculate on what they really mean. Even if such an incentive were present, the task is usually very complex and beyond the technical capability of many of those normally entrusted with it. Such a state of affairs is easy to perpetuate since few expect the numbers to correlate to any observable physical effects, except in severe accident situations. The primary concern becomes that of keeping the readings below the applicable regulatory or administrative limits. Some semblance of accountability and standardization is attempted through periodic test irradiations, but these are usually performed under ideal conditions that often bear little resemblance to the actual conditions under which the dosimeters are used. Even under these

ideal conditions, many processors are unable to meet the minimum requirements of accuracy and precision (Be66a, P180a, P180b). Ironically, dosimetry records provide the basic data for epidemiological studies of the effects of low levels of radiation, and for this reason, if for nothing else, every effort must be made to keep the data as accurate as possible.

Research and development in the area of dosimetry systems and concepts has been going on for years in many laboratories, but such work was often regarded as esoteric, and the field of applied personnel dosimetry lay dormant. The major impetus for reform came in the wake of the accident at Three Mile Island. Personnel dosimetry equipment and practice at that power plant before the accident were more or less on a par with most others in the nuclear power industry, possibly somewhat better than many. Following the accident and several entries into highly contaminated areas of the plant, the dosimetry supervisors found that their dosimeters were giving unexpectedly high readings. Outside technical assistance was enlisted to help evaluate these readings and to estimate the proper doses to be assigned. It was soon discovered that the dosimeters were not responding in a manner consistent with established algorithms for dose calculation from dosimeter readings. This led to further experimental investigations of the response characteristics of the dosimeters and survey instruments then in use, and also to a search for systems more suited for use under the conditions existing in the damaged unit at TMI (Ri81). Much has been learned as a result of

these investigations, and this report is a review of the important findings and a discussion of recommendations based on those findings.

II. DEFICIENCIES OF THE TWO-ELEMENT DOSIMETER

The discussion of the two-element dosimeter will be introduced through consideration of a specific case, namely that of the personnel dosimetry practice as observed at TMI. Although such an approach may appear too limited or specific, it is in fact quite typical, and the points raised apply to the industry as a whole, with some notable exceptions.

The personnel dosimeter in use at TMI at the time of the accident was the Harshaw (G-7) two-chip TL dosimeter. This is also the dosimeter used by a large number of organizations involved with ionizing radiation, and was until recently considered a kind of industry standard. The dosimeter consists of a rugged plastic casing containing within it a so-called TLD card. The card is a rectangular sheet of aluminum designed to hold two TLD chips in fixed positions within the plastic casing. The chips do not actually come in contact with the aluminum but are sealed between two sheets of Teflon, each about 0.06 mm thick. The aluminum acts as a frame to which the Teflon sheets are glued. The chips are TLD-700 LiF, each $1/8 \times 1/8 \times 0.035$ inch and, at a nominal density of 2.6 gm/cm^3 , have a mass thickness of about 240 mg/cm^2 each. The TLD card and the two chips sealed between the teflon sheets form an inseparable unit. The card is positioned inside the badge in such a way so as to align each chip with a circular opening in the badge. One of these openings is covered on the outside by an adhesive paper label and the other is

covered by an aluminum filter in addition to the paper. The first chip is referred to as the open window, or shallow, element and the other as the deep element. The total filtration over the shallow element, including the teflon and paper, is about 35 mg/cm². The filtration over the deep element is approximately 250 mg/cm².

The quantity obtained upon reading an exposed badge is the integrated current, in nanocoulombs, from the entire heating cycle. No provisions are made for any other forms of heat treatment, such as preheat or postheat. The badging period is normally monthly, and no adjustments are made for fading during that period; indeed, there is currently no acceptable method for making such an adjustment. The omission of complete heat treatment at the end of each read cycle could lead to readings of uncertain accuracy, especially in situations involving long badging cycles. Many installations using dosimeter designs that permit handling of individual chips employ oven heat treatment, using some sequence such as the Cameron cycle (At66). But oven heat treatment is not possible with the badge design used at TMI because the chips are sealed in teflon, which softens and eventually burns if heated appreciably above 300° C. The reader is normally adjusted so that a nanocoulomb of output corresponds to what is believed to be a millirad of absorbed dose in tissue. Such an adjustment is not technically necessary but is often found convenient. Calibration is performed by exposing a number of badges in a Cs-137 gamma field. The dose delivered is

obtained from exposure measurements using a secondary standard, most often a condenser R-meter. The badge irradiations and the exposure measurements are usually performed free in air, although lead bricks placed immediately behind the dosimeters to act as a shield have been observed.

After calibration of the reader, the doses are calculated from the readings as follows:

$$\begin{aligned}D_d &= C_d \\D_s &= f_2(C_s - f_1 C_d)\end{aligned}$$

where, D_d = deep dose, millirads
 D_s = shallow dose, millirads
 C_d = deep chip reading, nanocoulombs
 C_s = shallow chip reading, nanocoulombs
 f_1 = factor designed to adjust C_d to equal C_s when the badge is exposed in a pure gamma field, usually Cs-137
 f_2 = a factor to convert the net shallow reading to a shallow dose. It is often referred to as the beta factor.

The value of f_1 is typically about 1.15 and of f_2 is 4. Both values are supplied by the dosimeter manufacturer. f_1 is an experimentally determined quantity and is simply equal to the ratio C_s/C_d when the badge is exposed to a gamma field, usually Cs-137. Periodic checks by processors seldom yield 1.15 for this ratio, which is hardly surprising in view of the fact that a value of 1.15 implies a precision on the order of about 0.5%, which is difficult to achieve in most installations. The uncertainty in the value of the factor 1.15 is rarely, if ever, known by the processor, nor are the uncertainties in any of the other quantities involved in dose calculations. This situation illustrates one of the shortcomings of current personnel dosimetry

practice, namely the complete absence of any kind of analysis of the uncertainties involved in dose measurements. Dosimeter readings are invariably treated as though they were error-free quantities when in many cases the errors may be so large as to render these readings quite meaningless as dose estimates.

The value of 4 for the beta factor f_2 is based on contact exposures of the badges to a slab of natural uranium. The accepted dose rate from such a slab under 7 mg/cm² absorber, as measured by an extrapolation chamber, is 229-233 mrad/hour (RH70, PL79) and this is used to calculate f_2 . The origin of this practice of using uranium as the beta reference source for personnel dosimetry and survey instrument calibration is obscure, but presumably it was believed that the beta spectrum from such a slab is representative of the beta radiation most likely to be encountered in fuel cycle facilities.

As far as could be determined, the design of the badge was based on the following reasoning. 10CFR Part 20, section 20.101, requires that the dose to the whole body, blood forming organs, lens of the eye, or gonads not exceed a lifetime average of 5 rem/year. Since the lens of the eye has the least inherent shielding of the organs mentioned, it is the limiting organ. The lens begins at a depth of about 250 mg/cm² (Ch75) and hence the filtration on the deep chip was made to be approximately equal to that value. The extremities are subject to different dose limits and are generally monitored separately. Extremity considerations thus do not normally influence the design of dosimeters intended

for whole body monitoring. Finally, the skin of the whole body is limited to 7 1/2 rem/quarter. The shallow chip was designed to monitor that part of the dose that was contributed by nonpenetrating radiation, normally beta particles. The dose to the skin of the whole body should be measured at a depth of 7 mg/cm² or less (NRC Form 5). The filtration of 32 mg/cm² on the shallow chip is presumably the smallest that was obtainable by current technology that is consistent with the requirements for mechanical ruggedness and a tamperproof and lightproof design. As for the chip thickness used in the badge, LiF is commercially available in two thicknesses: 100 mg/cm² and 240 mg/cm². The thinner chips show a higher breakage rate and greater nonuniformity of response from chip to chip than the thicker chips, hence the use of the thick chips in the badge. The thick chips also put out more light per unit of exposure, thus giving a higher sensitivity and lowering the demands on operating precision, particularly at low doses.

The practice of calibrating dosimetry systems using free-air exposures probably arose out of a combination of circumstances. Part 20, paragraph 20.4(d), specifies that the dosimeters are to measure "air dose" at or near the body surface. Although this appears to imply use of a phantom in calibrating the dosimeters, this is not explicitly stated. The term "air dose" is quite vague and does not give the processor an operational definition that he can use to design a suitable calibration procedure. Furthermore, the secondary reference instruments, usually conden-

ser R-meters, used to measure the exposure are calibrated by NBS free-in-air and the calibration would not be applicable for exposure measurements at the surface of a phantom. As a result of this somewhat vague state of affairs, most processors defaulted to free-in-air calibrations. Many do not even have a phantom of any kind in their calibration facilities. In any case, most processors operate at a level of precision that does not enable them to observe any differences in response between free-air irradiations and phantom irradiations. Until such a situation is improved it is irrelevant and futile to worry about the use of a phantom. Since Part 20 specifies that the roentgen and the rad may be considered to be equivalent, the general practice has been to use the condenser R-chamber reading as the delivered dose on which to base the calibration of the reader. Unfortunately, Part 20 also refers to the roentgen as a dose, a usage that is contrary to accepted practice.

As mentioned in the introduction, the first indications of trouble with the badges at TMI came following entries into highly contaminated areas after the accident. It had been the experience of most dosimetry supervisors that the net shallow readings of the dosimeters were almost always either close to zero or much lower than the deep element reading; in other words, the deep dose was limiting. Then they were faced with the reverse situation, namely, that the shallow chip reading was much higher than that from the deep chip, implying that the skin dose was limiting. The situation was made even more confusing when at-

tempts were made to compare the dosimeter readings with the results of pre-entry surveys recorded on radiation work permits. The readings in many cases were found to be very different. Extensive investigations were undertaken and the findings identified a number of serious problems. A mapping of the radiation levels in the areas of concern in the plant showed very rapidly varying fields of nonpenetrating radiation (herein to be called beta radiation). The dosimeter readings were thus critically dependent not only on the locations of the dosimeters on the body, but also on such factors as the amount of protective clothing covering the dosimeter, the orientation and location of the body in the room, and even on the posture of the worker while performing the work, that is, whether he was standing erect or bending forward, or kneeling. This is not a new problem, and it has been discussed in the literature (Cr65, Wh66, C172). Some of the results in these studies indicated that the beta/gamma dose ratios from surfaces contaminated with fission products can, under certain circumstances, reach values as high as 600. Nevertheless, the situation at TMI caught everyone concerned by surprise. A partial solution to this problem adopted at TMI was to equip personnel entering contaminated areas with multiple dosimeters distributed over the trunk, head, and extremities. Although this expedient appeared to solve the problem of spatially variable fields, it introduced a new set of problems related to interpretation of the readings of the dosimeters. Such multiple readings must be interpreted with care to ensure

that the doses to the critical organs are properly evaluated, particularly since most conversion and calibration factors are specified with the implicit assumption that the dosimeter is placed in the chest area. For example, a frontal exposure of 1R of 200 keV gamma radiation results in a dose of about 1.3 rads to the testes; an equivalent exposure from the back delivers a testes dose of about 0.4 rad (Jo66). There is also the problem of averaging the skin dose; currently accepted practice recommends that skin dose from external exposure should be averaged over a skin area of 100 cm² (ICRP65), but application of this recommendation to the dose readings from multiple dosimeters is not easy. A regulatory position regarding the placement of multiple dosimeters and the interpretation of the results would be very helpful in minimizing inaccuracies and inconsistencies in the dosimetry records.

Further investigations at TMI revealed that neither the survey instruments nor the dosimeters were responding in the radiation fields in the manner they were expected to respond. (The survey instrument problem will be considered in a later section.) The TL dosimeters showed two major shortcomings: penetration of the "non-penetrating" radiation into the deep chip, and a beta factor that was not constant and of value 4, but rather that varied over a wide range of from around 2 all the way to 20, and probably much higher values. These conclusions were initially reached by way of a theoretical analysis of the dosimeter design. Beta depth-dose models indicated that high

energy beta radiation could easily penetrate the shield covering the deep chip and contribute a significant dose to that chip. The analysis also indicated that the average beta dose over the chip thickness is substantially lower than the dose close to the entrance surface of the chip. This difference is expected to be greater for lower energy beta radiation. These theoretical predictions were later substantiated by experimental measurements on the dosimeters.

As it turned out, the fission products found in areas of the plant where the primary coolant had breached the barrier contained substantial amounts of $\text{Sr}^{90}/\text{Y}^{90}$. Sr^{90} emits a relatively low energy beta ($E_{\text{max}} 0.55 \text{ MeV}$) but Y^{90} emits a beta with a maximum energy of 2.27 MeV, with a range of approximately 1100 mg/cm². Since the filter on the deep chip is about 250 mg/cm² thick, it is clear that a fairly large fraction of the betas will penetrate to the deep chip. It was found by experiment that when exposed to a highly filtered $\text{Sr}^{90}/\text{Y}^{90}$ field with perpendicular incidence, the deep chip registered a reading about 30% that of the shallow chip. The readings were checked for bremsstrahlung contribution by adding low atomic number filters in front of the source (Lucite) to attenuate the beta radiation. This contribution was found to be small compared with that from the beta radiation.

Penetration of the betas to the deep chip leads to two errors: the deep chip reading will be too high because of the beta contribution, and the net shallow chip reading will be too

low because of overcorrection resulting from subtraction of the erroneously high deep chip reading.

The significance of the penetration of high-energy beta radiation to the deep chip must be examined in terms of the concept of the significant volume for dose specification in an organ. Although NCRP recommends that this volume be of the order of one cubic centimeter (NCRP71), current practice appears to follow the recommendation that the significant volume is that of the entire organ or tissue under consideration (ICRP65, ICRP77). This concept is not currently applicable to the skin, but the other organs are sufficiently deep and sufficiently large so that even if some beta radiation does penetrate to these organs, averaging the beta dose over the organ volume will reduce the dose to insignificant levels in comparison with that contributed by penetrating radiation. The lens of the eye is an exception, however; the inherent shielding on the lens is of the order of 250 - 300 mg/cm² and the thickness of the sensitive part is about 100 mg/cm² (Ch75, ICRP75). These dimensions suggest that the lens could receive a substantial dose even from moderately energetic beta radiations since the dimensions are of the same order as, or smaller than, the ranges of such radiations. The deep chip on the Harshaw badge is well suited to measure such a dose, even though it would underestimate the beta dose somewhat because the chip is 240 mg/cm² thick rather than 100 mg/cm². A 100 mg/cm² chip would be ideal, and would give the total lens dose directly, without the need for any correction factors. Increas-

ing the filtration over the chip to around 1000 mg/cm^2 , as is often suggested, would destroy the ability of the badge to measure eye dose, and would make the eye dose virtually impossible to measure with any degree of accuracy. Such an expedient would be justifiable only if the badged personnel wore sufficient eye protection. But most personnel required to wear dosimetry do not wear eye protection, even at nuclear power facilities. In those cases it would appear that one would have to either provide dosimeters with medium filtration, "eye-dose" elements, or make the assumption that personnel not required to wear eye protection will not be exposed to beta radiation of any appreciable penetrating ability. If such an assumption is made, then the Harshaw two-chip badge would be an acceptable dosimeter, not, interestingly enough, because it has a moderately filtered element, but because there would be no penetrating betas to interfere with that element's ability to measure deep dose. The presence of penetrating beta radiation makes it necessary for the dosimeter to have an element with sufficient filtration to stop this radiation; this element would be used to estimate the dose to the deep organs.

The second problem with the two-chip badge, as mentioned above, is the use of a constant beta factor of 4. Measurements and calculations in the literature and made by the author indicate that the beta factor is a sensitive function of the shape of the beta spectrum reaching the chip (Ma71, Ho80). One factor that might cause a change in the incident beta spectrum is ob-

viously the mix of isotopes giving rise to the beta field. But measurements also appear to suggest that the amount of absorbing material between the source and the chip also has an effect. This implies that the beta spectrum degrades with attenuation, contrary to that implied by the exponential attenuation model (Cu31, Fi67, Ka52). Experimental measurements and recent theoretical treatments of the problem, however, indicate that the exponential model is only approximate, particularly for relatively small absorber thicknesses (Be74, Br52). Further work is needed to explain the observed dependence of the beta factor on absorber thickness. For instance, the beta factor for a 100 mg/cm² chip exposed to an unfiltered Tl-204 source (end-point 0.77 MeV) with a 10 mg/cm² filter was measured to be about 2.2. Addition of about 140 mg/cm² of absorber to simulate protective clothing raised the beta factor to about 5.9. The beta factor for the same chip with no added absorber and a Pm-147 source (end-point 0.22 MeV) was found to be over 200. It is clear that the appropriate value of the beta factor for the badge can only be determined from a detailed knowledge of the irradiation geometry and beta spectrum incident on the chip. Such data is almost never available in practice, but even if it were available, the calculations would be very complex and cannot be performed for each dosimeter used in everyday operations.

Two-element Tl dosimeters are in use at many nuclear fuel cycle facilities and at others using radiation, such as hospitals, research laboratories, universities, etc. Most of

these dosimeters suffer, in principle, from the shortcomings discussed above. The qualification "in principle" serves to point out the fact that some of these shortcomings may be irrelevant in certain situations. For example, although the dosimeters may be poor for use in beta fields, this would not be a factor in facilities using x-ray machines or sealed gamma sources in which the beta radiation is absorbed in the source encapsulation. The adequacy of any two-element dosimeter must therefore be evaluated in light of the intended use.

For those facilities in which unshielded beta sources may be encountered, most two-element dosimeters in current use are not adequate, as discussed above. However, some measure may be possible that would improve the accuracy of such dosimeters, at least on a temporary basis until better dosimeters are acquired. One such measure is to ensure that the filter in front of the deep element is thick enough to stop the beta component of the field. In most cases this is simply accomplished by adding a piece of aluminum of suitable shape, and of 200-500 mg/cm² thickness, over the shield already in place. A recalibration of the reader may be necessary after such a change. The addition of extra shielding may not be easy in some dosimeter designs because of space limitations, particularly since it is most desirable to add the shielding on the inside of the dosimeter casing. In such cases the extra shielding would have to be added on the outer surface of the dosimeter. This is technically sound but may cause some functional or esthetic objections. The above

modifications should be undertaken cautiously, especially in situations requiring monitoring of eye dose. Increasing the shielding over the deep element may make accurate estimation of this dose virtually impossible when nonpenetrating radiation is present.

The problem of determining the appropriate beta factor for each exposure cannot be resolved because two-element dosimeters do not generally yield sufficient information to enable estimation of a beta factor. As an interim measure, the value of the beta factor in use may be re-examined to determine whether it is appropriate. A review of the fields to which workers of the facility are normally exposed may indicate the desirability of changing the beta reference source used to determine the beta factor. It may also be possible to make measurements in each radiation area that would help in estimating a beta factor for use in each of these areas. Such measurements can be made using light-shielded surface barrier detectors or diffused junction detectors connected to a portable multichannel analyzer. The energy distributions of the beta fields obtained in this way may then be compared to that of the beta calibration source in use at the facility. The comparisons may be made either qualitatively or quantitatively, and the objective would be to determine whether the observed beta fields are more or less energetic than that from the calibration source. Adjustments to the beta factor would be made accordingly.

A much less expensive method of measurement, and one much

easier to implement though yielding less information, is to use a pair of modified two-element dosimeters. One of these would be equipped with relatively thick shields over the chips and would be used to measure the gamma field at a given location. The other dosimeter would be modified to have two shallow elements, one behind a shield of 20-30 mg/cm² thickness and the other behind 60-70 mg/cm². The two dosimeters would be placed adjacent to one another and the "gamma" dosimeter would be used to correct the readings of the "beta" dosimeter for gamma contributions. The net readings of the two beta chips may then be used to estimate the effective energy of the beta field, or to estimate a value for the beta factor appropriate for the unmodified two-element dosimeter in the radiation area in question. Pairs of the modified dosimeters may be placed in all the radiation areas and may be left there for the duration of the badging period. In this case they would yield mean values for the period. Of course, using the modified dosimeters in this way implies that the badged personnel always work in the same area, or at least receive the major part of their exposure in one area. Estimating the beta factors from the readings of the modified dosimeters would be accomplished using an algorithm developed for that purpose.

The above procedure is cumbersome and somewhat inaccurate, but it would probably represent a significant increase in accuracy over the practice of using a constant beta factor. Furthermore, the above measurements would have to be repeated

only infrequently for fields that do not change significantly in quality over relatively long time periods, even though the fields may change rapidly in intensity. The above approach probably represents the best that can be achieved using the current generation of two-element dosimeters.

Two alternatives have been investigated in an attempt to correct this situation: either make the dosimeter beta-energy independent, in which case the beta factor would be constant and equal to one; or somehow extract sufficient information from the badge readings to enable a determination of the appropriate beta factor for each exposure. The second approach has not been achieved using two-element dosimeters, but successful trials have been made using multi-element dosimeters (Ge79, Sa78). A great deal of work has also been done toward achieving an energy-independent dosimeter (Ma71, Ig77, Ch78a, Ch80, La80, Uc80, He82). Energy independence in this context means that the dosimeter dose response to beta radiation as a function of energy parallels that of the absorbed dose in the skin at the desired depth. The approach taken to achieve an energy-independent dosimeter is always the same, namely to make the beta-sensitive element as thin as possible. This has not been easy to accomplish because making the element thin reduces the TL output and the precision of the readings, thus increasing the lower limit of detection; it also causes the elements to become very fragile and difficult to handle and read. For these reasons the process of reducing the element thickness cannot go on indefinitely, and the

current generation of thin dosimeters are only approximately energy independent. An ultra-thin TL dosimeter is currently under development in a number of laboratories that is based on the idea of forming the beta-sensitive element as a surface layer in a thick TLD chip (La77, Ch80). The surface layer is formed by diffusing boron into LiF to the desired depth; the diffused layer produces a distinct glow peak that is separate from the curve produced by the main body of the chip. Although this concept appears promising, the problem of low sensitivity remains to be solved.

Whichever of the approaches described above is adopted, there is a price to be paid. Great care must be taken in the operation and maintenance of the TLD system to avoid rapidly degrading the precision of the measured beta dose, particularly at low dose values and in the presence of gamma radiation. In the case of the thin dosimeters, this is caused by a reduction in the quantity of light output for a given dose level. The multi-element dosimeters also suffer from the same effect to some extent, because it is desirable to have thin elements in this design too; in addition, there is a further degradation in the precision of these dosimeters caused by the numerous arithmetic manipulations that must be performed on the dosimeter readouts to calculate the beta dose (Ge79, Sh82). Such arithmetic manipulations on measured quantities result in a propagation of errors that causes an increasing degradation of precision as the manipulations become more extensive. In view of these considerations

it should be stressed that personnel beta dosimetry involves more than simply acquiring a suitable dosimeter; it also requires careful control of the entire operation to maintain a consistently high level of precision, much higher in fact than most processors are currently routinely achieving. A minimum amount of statistical analysis will also be needed to determine the limits outside of which the dosimeter cannot yield a meaningful beta dose, even though it may appear to do so.

It should be explained at this point that much of the difficulty associated with applied beta dosimetry stems from the regulatory requirement that the beta dose be measured at a depth of 7 mg/cm^2 in the skin. The depth dose function for beta radiation drops rapidly with depth of penetration into the medium of interest, in this case the skin. In order for a dosimeter to give a good indication of the dose at a given location in any medium, the dimensions of the dosimeter should be small compared with the range of the radiation in the dosimeter material. This means that the radiation being measured should not suffer significant attenuation in traversing the dosimeter. This condition is usually easy to achieve in the case of gamma radiation, but most dosimeters are quite thick compared to the range of most beta radiation. Many dosimeters are thicker than the maximum range of that radiation. In this case the dosimeter yields the average beta dose over the dosimeter thickness. But the dose to skin should be measured at the basal layer of the epidermis, which occurs at an average depth of 7 mg/cm^2 for the

skin of the whole body and about 40 mg/cm^2 for the skin of the extremities (Wh73, ICRP77). This requirement that the skin dose be measured at a depth of 7 mg/cm^2 places two severe constraints on the design of a good beta dosimeter: the sensitive element must be very thin so as to give the dose at a specified depth and not an average over a specified thickness, and also the thickness of material covering the sensitive element must not exceed 7 mg/cm^2 , to simulate the thickness of the epidermis. If either of these two requirements is violated it becomes necessary to multiply the dosimeter reading by a correction factor. This factor corrects for attenuation if the shield over the element is thicker than 7 mg/cm^2 , or corrects for dose averaging if the element is not sufficiently thin, or both. Most dosimeter designs do not meet either of the above conditions, and this is the cause of the difficulties and inaccuracies discussed above.

The requirement that skin dose be measured at a depth of 7 mg/cm^2 is believed by many workers in the field to be rather arbitrary and not based on a substantial body of data. In fact, many experiments appear to suggest that the radiosensitive part of the skin does not lie at the basal layer but at greater depths into the dermis, and around the hair follicles (Gl63, Al67, He69, Bu70). There is ample evidence indicating that basal cell carcinoma is the most common type of skin cancer, particularly following relatively low exposures (Mo72, Ve72, BE80), but there is controversy as to the origin of the cells producing this type of skin cancer. Some believe that these cells arise in the basal

layer (Sa68), but others disagree and argue that such cells do not arise in the epidermis but in layers as much as 300 mg/cm² below the surface of the skin (Ri66, Bu70, Ve72). Practically all of the experimental data comes from animal experiments and it is still unclear how such data may be extrapolated to humans, if at all. Nevertheless, the data is at least suggestive, and it is important to reexamine the requirement of measuring skin dose at 7 mg/cm² since it is this factor more than any other that is causing great difficulties in applied dosimetry. These difficulties have led to the accumulation of skin dosimetry records that contain errors of indeterminate magnitude. Some believe that these errors are probably so large as to make the records useless in any future quantitative use, such as in epidemiological studies.

There are other examples in the regulatory literature that have contributed toward making the practice of personnel dosimetry less accurate and less consistent than it might have been. For example, 10 CFR Part 20 specifies that the monitoring of individuals is to be carried out by measuring the "air dose" using a suitably calibrated dosimeter. However, the dosimeter cannot be properly calibrated unless the quantity it is to measure, presumably the air dose, is clearly defined. Thus the dosimetry processor is left without an operational definition of the quantity to which his dosimeters must be calibrated. Part 20 also requires monitoring the dose to the blood forming organs and the gonads as well as that to the whole body, but it is not

made clear how one is to monitor gonadal and blood forming organ doses, nor how one might interpret such doses as distinct from whole body dose. Can a person receive a whole body dose without exposing the blood-forming organs as well? If so, how? If not then including blood forming organs with the whole body is a confusing redundancy from an operational point of view. Of course, answers to the above questions are scattered throughout the professional literature, but many are controversial and not generally accepted, and most involve very technical and sometimes convoluted discussions. One cannot expect the typical processor either to understand these discussions or adjudicate the unsettled questions.

The point being made here is that there are two aspects to the field of personnel dosimetry: conceptual or theoretical, and operational. The conceptual aspect forms the basis of the discipline but is generally complex and requires a great deal of knowledge and training to understand, and usually involves many open questions. The operational part represents the detailed specifications of the methods to be used to measure certain quantities, such as dose, and the acceptable interpretation of the results of certain types of measurements. In the past these two aspects of the field have tended to be intertwined, and this has led to confusion. One example to illustrate this point is NRC Form 5. This form requires that the whole body dose "should include dose delivered through a tissue equivalent absorber having a thickness of 300 mg/cm^2 or less ---When the lenses of

the eye are protected ---whole body dose should include the dose delivered through a thickness of 1000 mg/cm² or less". These specifications appear to bridge the gap between the organ dose equivalent and the dosimeter reading. But the statements regarding the 1000 mg/cm² absorber and the 300 mg/cm² absorber lead to a false sense of comprehension. It has been our experience that this statement is almost universally interpreted by the dosimetry processors to mean that the dosimeter should have a filter over the deep element of 1000 mg/cm², and that if this condition is satisfied then he is in a position to measure the required dose. This is in fact not the case since the thickness of the filter is not directly relevant to the measurement of deep dose to a given organ. The dosimeters used in personnel monitoring are not absolute instruments and the reading of an instrument such as a TLD reader is quite arbitrary in the sense that almost any setting that is within the linear operating range of the instrument may be used. The important criterion which the dosimeter should satisfy is that its response per unit exposure as a function of energy should parallel the absorbed dose per unit exposure in the organ of concern. The filter thickness must be determined on the basis of other considerations, mainly the penetrating ability of non-penetrating radiation. The filter thickness needed to fulfill this requirement may turn out to be close to 1000 mg/cm², but use of such a filter would stop the beta radiation without simulating the deep organ in question. Requirements for achieving charged particle equilibrium for the

gamma radiation commonly encountered in nuclear plant operations are generally satisfied with a substantially thinner filter than is needed to stop penetrating beta radiation.

It is being suggested here, in the interest of accuracy and consistency, that regulatory guides be formatted in two sections: an abstract section giving the theoretical and philosophical bases for the regulations, and an operational section giving a detailed discussion of the methods recommended for implementing the regulations. The operational section would not be in terms of specific steps, which would be too narrow and restrictive, but certainly in terms of directly executable concepts. Such a format would first of all allow those who do not fully understand the theoretical aspects of the subject (most practitioners) to nevertheless carry out their work accurately and consistently. Second, and probably equally important, this format will at least discourage regulatory agencies from putting out obscure regulatory requirements or requirements that are next to impossible to execute in everyday practice. The idea here is that if one does not clearly understand a concept, or if the concept cannot be practically implemented, one will not be able to give its operational definition.

III. PERFORMANCE TESTING STANDARD

The Draft Performance Testing Standard (TS80) illustrates the point raised in the last few paragraphs above. In the Standard, the deep dose is defined as the dose at a depth of 1.0 cm in soft tissue. This is a conceptual definition which cannot be implemented directly in practice, since dosimeters are worn and calibrated on the surface of the body or of a phantom. The Standard then provides the equivalent of an operational definition in the form of tabulated values of Cx, the rad/R conversion factors. Unfortunately, it fails to define the precise meaning of the Cx values supplied, this meaning being only implied in the text.

Briefly, the Draft Standard calls for the testing of Processors, or suppliers of personnel dosimetry services. To complete a test, the processor provides 15 randomly selected dosimeters to an independent testing laboratory. The laboratory irradiates the dosimeters using a specified source, or combination of sources, to a dose within specified limits. The irradiated dosimeters are sent back to the processor where they are read and the shallow and deep doses or dose equivalents are calculated. The results are then reported to the testing laboratory. Finally, the testing laboratory calculates the following quantities from the reported results:

(I) The Performance Quotient P_i for each badge, defined as

$$P_i = (H_i' - H_i)/H_i$$

where H_i' = reported dose or dose equivalent, as appropriate.

H_i = delivered dose or dose equivalent

(II) The Bias, B for the group of badges being tested, defined as

$$B = (1/n) \sum_{i=1}^n P_i$$

(III) The Standard deviation for the distribution of P_i ,

$$S = \left[\frac{\sum_{i=1}^n (P_i - \bar{P})^2}{n-1} \right]^{1/2}$$

where, $\bar{P} = \frac{\sum P_i}{n}$

A processor would be considered as having passed a test if the results satisfy the following inequality

$$|B| + S \leq L$$

where $L = 0.3$ in the accident range tests

$L = 0.5$ in the protection range tests

The tests that a processor can elect to take include nine categories: two in the accident range (one for low-energy photons and one for high-energy photons), and seven in the protection dose range. The seven protection categories include low-energy photons, high energy photons, a mixture of these two, beta radiation, mixed beta and high energy photons, and two mixed neutron and high energy photons. The accident range test results

are to be reported in dose units, whereas the protection category results are to be reported in terms of dose equivalents. All protection categories include both deep and shallow dose equivalent results, whereas the accident categories include only deep doses.

Concerning the Standard in general, there are serious deficiencies that make it, in our opinion, unsatisfactory. Consider for example the parameter in terms of which the test results are to be expressed, namely the bias. The use of the term bias is an unfortunate choice of terminology because the word means a tendency for the reading to be on one side or the other of the proper value, which is zero. A positive bias may then be interpreted by the processor being tested to mean that his system reads too high, and conversely for a negative bias. However, since the phenomenon under test is statistical in nature, the sum of the deviations does not become a bias until it is shown to be statistically significant. Otherwise, positive and negative sums of deviations mean nothing more than the expected random variations around the mean. This point may seem trivial, but one must not forget that the average processor is statistically unsophisticated, and in any case, deciding whether a given observed deviation from zero is statistically significant requires the application of suitable statistical tests, which are not included in the standard. This brings up the related matter of the pass fail criterion for the test results, namely that $|B| + S < L$, where B is the bias and S is the standard deviation of the

so called performance quotients; the performance quotient is the relative deviation of the measured dose equivalent from the delivered dose equivalent. This criterion has the advantage of simplicity because it expresses the test in a simple formula. However, this simplicity is gained at the cost of an excessive sacrifice of useful information. A processor can fail a test either because his calibration is off (excessive bias), or because the scatter of the data is too high (large standard deviation), or both. But the results of the test do not indicate clearly to the processor which of the two factors deviated significantly from its proper range, or possibly that both factors deviated significantly. Furthermore, the two factors in the test equation, namely B and S, are not independent since S is the standard deviation of the distribution for which B is an estimate for the mean. An operator working with a large S value must expect his estimate of the mean of the distribution, B, to show large deviations from the true mean; in other words, large values of S will tend to be associated with large values of B even though there may not be any significant bias in the processor's results. This is true because a large value of the standard deviation implies a broad distribution of measurements around the mean value. In other words the data in such cases shows a relatively wide scatter. Since the mean of the distribution is generally unknown and is determined from the measurements, a large scatter in the data will mean a large uncertainty in the location of the true mean. But the test statistic is $|B| + S$, and,

as explained above, the calculated value of B must be expected to fall within broader limits around the true mean. Therefore, the sum $|B| + S$ will show a wider range of scatter with increasing S , both because of the increase in S itself and also because of the increased scatter in B , even though the true mean μ_B may have remained unchanged. Under these conditions, understanding the true significance of the test results will need the application of suitable statistical tests not included in the Standard.

It is realized that the use of the concept of bias may have been suggested by the fact that each dosimeter in any given test may be irradiated to a different dose, but the objections given above are nevertheless felt to be such as to detract seriously from the usefulness of the test. Other statistical methods might be used that would overcome these objections; for example a linear regression analysis with weighting of the data may be used. Such an analysis, admittedly more complicated from a computational point of view, can easily be programmed and would test not only the processor's calibration and scatter, but offers other possibilities, such as a linearity check. The results can also be presented both as parameter values and also graphically. Since the processor will not be performing the data analysis, the main requirement as far as he is concerned is that the results are presented to him in a format that is unambiguous and easy to understand. The data analysis can be designed to extract as much information from the test as possible. Since computers are now universally accessible, the whole analysis, as well as the prep-

aration of the reports and any graphical presentations, can be automated.

An interesting point that should be mentioned in passing is the matter of setting lower limits for the delivered doses used in the tests. The Standard specifies these lower limits to be 30 mrem for photons, 150 mrem for beta radiation, and 200 mrem for mixed beta and high energy gammas. The reason given for establishing the limits is that testing below these dose values would result in unacceptably large errors. But much of the official dosimetry record is made up of readings below the cutoff levels; one may ask what the implications are of establishing the lower limits. If the testing authorities consider the errors below the limits too large to even consider testing at such levels, then what is the use of recording dosimeter readings in this range? Would such records be of any legal or epidemiological value? We believe processors should be tested down to the dose levels at which they are required to start keeping a legal record. Furthermore, there are studies suggesting that processors unable to attain a reasonable precision below 30 mrem gamma will probably not be able to do much accurate beta dosimetry using the new multi-element dosimeters (Ge79, Sh82). The reason for this is that the readings from such dosimeters must be subjected to a number of arithmetic manipulations to calculate the required doses. Such manipulations cause whatever uncertainty present in the measured quantity (in this case the dosimeter readings) to be compounded with each step. The final results

will contain an uncertainty much larger than that in the original data. Therefore, to keep the uncertainty in the calculated doses within acceptable limits, the uncertainty in the dosimeter readings must be made quite small.

A look at the overall structure of the Standard reveals some points worthy of comment. The most important of these is that the Standard does not appear to have resolved the question of whether it is testing the processor or the dosimeter. The forward to the Standard, as well as NRC documents referring to the Standard, make it clear that the intent is to test the processor. In this case, it would be pointless to test the angular dependence of the dosimeter because there is nothing the processor can do about it no matter what the results come out to be, other than discard the dosimeter. There would also be little value in testing the processor in the beta radiation and mixed beta/gamma categories since such tests do little more than check the processor's ability to do simple arithmetic. This is because the beta dose is obtained by applying a predetermined algorithm to the readings of the elements. That algorithm is a function of badge design and is not an operational variable. In fact, the only factors over which the processor has any control on a day to day operational basis are selection of TLD's for uniformity of response and calibration, and maintenance of the dosimetry system. All these can be adequately tested using a single photon category, such as for example Cs-137. The other categories need not be used, once an appropriate category has been selected,

without any loss of testing accuracy. In that case the number of dosimeters used per test might be increased from 15 to 20 or even 30. The net result would be a simpler testing procedure, a less expensive and time consuming one, and also more useful test results because of the improved statistics gained through the use of more dosimeters per test.

The above comments are not meant to imply in any way that angular response and beta response are not important, but these and other characteristics not addressed by the Standard are dosimeter characteristics determined largely by the dosimeter design and hence are not suitable for inclusion in the periodic testing of a processor's operation. The Standard should therefore be split into two parts, one for testing processors and one for testing dosimeters. The latter would include such things as angular response at various energies, beta response, and variation of photon response as a function of photon energy, as well as other tests such as fade characteristics, etc. Passing this part may be made a requirement for dosimeters to be used in licensed facilities, and badges that pass such a battery of tests would be considered "certified" in their appropriate categories. Such a test would be required only once for each badge design, to be repeated only if the design is modified. Such a testing program would put the burden of dosimeter design and evaluation on the manufacturer, where it belongs, instead of leaving it up to the processor to figure out how, or whether, the dosimeter can be used to perform a given function, a task for which the

processor is generally ill prepared. The Standard in its present form falls far short of this objective, and hence is neither a good standard for testing processors nor is it a good one for testing dosimeters. It falls short of the latter objective for a number of reasons, one of which is the beta standard. The proposed beta standard, which is a filtered Sr⁹⁰/Y⁹⁰ source, is neither representative of the beta spectra to which most workers are likely to be exposed, nor does it test the dosimeter's beta dose capabilities. In fact, the Standard has continued the old practice of using a single source to calibrate and check all dosimeters and has merely substituted Sr⁹⁰/Y⁹⁰ for uranium. One might even argue that the old method was better since uranium probably has a more representative beta spectrum than Sr⁹⁰/Y⁹⁰.

The key factor in a dosimeter's ability to measure beta dose is either its energy independence if it is a thin dosimeter design, or its ability to yield a suitable beta factor from the readouts if it is of the multi-element design. The use of a single beta source in a standardized configuration, especially a high-energy source such as filtered Sr⁹⁰/Y⁹⁰, is probably the worst possible choice for beta performance evaluation. Such a test ignores, or sidesteps, the most important problem in beta personnel dosimetry and one that has been at the root of most of the problems in the past, namely how to account for the variation of dosimeter response with variations in incident beta spectra; or stated another way, how to get away from the practice of using a constant beta factor to obtain the beta dose from the dosimeter

readings. All that is needed to pass the proposed test is to determine the constant beta factor for the dosimeter when exposed to $\text{Sr}^{90}/\text{Y}^{90}$. In view of this, one may well ask what purpose such a test is supposed to serve. A proper beta response evaluation requires the use of several beta sources, both separately and in combination, as well as degraded beta spectra obtained by passing the source spectra through absorbers of different thicknesses.

In an analogous manner, the use of a single photon source, such as Cs-137, does not accomplish any useful purpose as far as testing the dosimeter's response is concerned. Rather, one must measure the dosimeter's response as a function of photon energy from the highest expected down to perhaps 20 keV. Furthermore, unless the dosimeter is to be used as an energy spectrometer, the relative response as a function of energy should match the relative values of the appropriate Cx function (Vi82). This is important since radiation workers probably receive a large part of their photon exposures from a continuum of scattered radiation rather than from a few well defined energies.

The above are merely rough suggestions. Much thought will have to be devoted to developing a good dosimeter test. Such a test would undoubtedly be time consuming and expensive to conduct, but since it would be required only once or very infrequently, and the results would be used to justify many years of dosimeter use by many processors, the effort and expense seem justified. Acceptance of the proposed Standard in its current format would, in our opinion, be very unfortunate. It could lull

many into believing that they are able to perform beta dosimetry and that they are measuring up to the highest standards of their trade when in fact they would not be doing so at all.

It should be pointed out before closing this section that the proposed Testing Standard includes many excellent features that should be preserved in any future modifications of the Standard. These features were not specifically mentioned because the purpose of the text above has been to point out the weaknesses which, in our opinion, indicate the need for extensive revisions.

IV. SURVEY INSTRUMENTS

The problems encountered using beta survey instruments are of the same general nature as those discussed in connection with personnel dosimeters, and for the same basic reason, the rapid attenuation of beta radiation as it traverses matter. A beta dose rate is obtained from most survey instruments in much the same way as it is from TL dosimeters: two readings are taken, one with the instrument window open (the gross reading) and one with the window closed (the gamma reading). The net reading is the gross minus the gamma reading, and the beta dose rate is obtained by multiplying the net reading by a beta factor. The beta factor used with many common survey instruments is close to 4 and is determined by using a natural uranium slab. The survey instrument is normally placed with its window in contact with the face of the slab and a reading is taken. Dividing this reading into the known contact dose rate gives the beta factor.

A number of problems are inherent in the above procedure. One is that the uranium beta radiation may not be, and usually is not, representative of the field to be surveyed. The beta factor is a sensitive function of the shape of the incident spectrum and should ideally be determined for each survey. However, no survey instrument now in use can do that, and the only alternative is to use a constant factor. In this case the beta dose rate obtained in any survey will be in error, and the magnitude of the error will be largely unknown.

In addition to the uncertainty resulting from the use of a

constant beta factor, a second source of error arises from the way the uranium slab is used. As mentioned above, the survey instrument is usually placed with its window in contact with the surface of the slab. It has been shown that although the beta dose rate is approximately constant up to a few millimeters above the surface, it falls off rapidly thereafter and reaches about 4% of its surface value at 10 cm from the slab (Ro75). Therefore, unless the sensitive volume of the detector is only a millimeter or so deep, the radiation field in that volume will be quite nonuniform. Also, most detectors have sensitive volumes far thicker than a few millimeters. Some reach 5 cm, 10 cm or more. In such cases the average dose rate in the sensitive volume would be much lower than the dose rate at the surface of the slab. The beta factor calculated using the surface dose rate is supposed to compensate for this effect, but the problem is that not only does the detector perturb the beta field substantially, but the field itself is highly nonuniform within linear dimensions equal to those of the detector. Calibrations under such unfavorable conditions would not be applicable to any other geometry or for any other source. The errors involved in field use of an instrument calibrated in this manner are probably very large.

Additional problems are introduced into the situation by the fact that the uranium slab emits gamma radiation as well as beta radiation. This gamma contribution amounts to about 10% of the beta dose rate at the surface, rising to about 20% at 10 cm (Ro75). Because this photon contribution is nonuniform over the

detector volume it is difficult to make an accurate adjustment for its effect, and in most cases none is made. For all the above reasons, the uncertainties involved in current beta dose rate survey practices and equipment are of such magnitude that the results of the surveys should not be considered as giving more than a qualitative idea of the magnitude of the beta dose rate in the area surveyed.

Health physics practitioners have traditionally tended to underestimate the hazards that may be associated with unshielded beta sources. Many were surprised when in some cases survey instruments went offscale while surveying contaminated areas at TMI that showed only moderate gamma dose rates upon making gamma field surveys. But beta sources can rapidly build up impressive fields; for example a 1 mCi/cm² planar source of Sr⁹⁰/Y⁹⁰ gives a contact skin dose of 16 krad/hour (We81), falling to maybe 4 krad/hr at 10 cm from the source. Such dose rates are far beyond the ranges of operation of currently available survey instruments. High range beta survey instruments are needed for these situations. Measurements in such fields can be easily performed by properly clad personnel. The results of such measurements are usually required to determine the amount of protective clothing to be worn by workers entering these areas for repair work or other duties.

Survey instruments that allow for on-the-spot determination of the appropriate beta factor in each survey situation are not

available and, as far as we know, no research is being conducted towards this end. Rather, all efforts are directed towards making the dose rate readings of the survey instruments independent of the shape and energy of the incident beta spectrum. This is achieved in most cases by making use of the fact that electrons of a given energy lose nearly equal fractions of their energies as they traverse thin layers of different materials, the layers being of equal mass-thickness (At66). This means that electrons will deposit the same amount of energy in, say, 20 mg/cm² of tissue as in 20 mg/cm² of plastic. Furthermore, since the energy lost by electrons in a thin layer of any substance is given by the stopping power for the electrons, and since the stopping power is practically constant for electrons above about 300 keV (We58, At66, Pa72), electrons above 300 keV transfer nearly equal amounts of energy to the material regardless of their energy. Survey instruments are now being developed along these lines in the form of ionization chambers (Ha79, Bo81), thin scintillators (Bi80), and solid state diffused junction (We81) and surface barrier detectors (He79). None of these instruments has been adopted for general use in the nuclear industry, and more development and testing will be needed before this happens.

One feature that would be very helpful in such instruments would be the ability to insert calibrated absorbers reproducibly in front of the detector window. Technicians conducting beta surveys could in this case insert a total absorber thickness

equal to that of their protective clothing to observe the degree of protection such clothing is providing. Conversely, the absorbers could be used to determine the amount of protective clothing needed to reduce the dose rate to acceptable levels. Before such instruments are adopted for general use, some problems remain to be investigated. These include the expected energy dependence for electrons below 300 keV, and the problem of interference from photon radiation.

Due to the low penetrating power of beta radiation, most survey instruments are designed with thin windows through which the radiation reaches the sensitive element of the detector. Such windows introduce an angular dependence in the detector response that follows more or less a cosine law; that is, a maximum response for radiation incident normally on the window, dropping to zero at 90° to this direction. Much effort appears to have been expended in eliminating or at least reducing this angular dependence. This objective may not be desirable because, in the case of nonpenetrating radiation, the dose absorbed by the skin at a specified depth also depends on the angle of incidence. This angular dependence may turn out to closely follow a similar cosine law. For normally incident radiation, a survey instrument with an isotropic response will correctly estimate the dose rate. If the radiation is isotropic, however, such an instrument will substantially overestimate the dose rate. Careful consideration should be given to this

problem and to the related question of dose averaging over prescribed areas of the skin of the whole body.

V. BETA DOSIMETRY

Analytical beta dosimetry is concerned mainly with the problem of calculating the beta dose at any point in a medium arising from any given source geometry. Attempts to solve this problem have proceeded along two different lines of approach: empirical and theoretical. In this context, "empirical" means relying on experimental measurements without investigation of the underlying theory. "Theoretical" is the opposite situation, namely, using theoretical considerations to derive a model to describe the behaviour of the system. "Analytical" is used here to refer to the use of mathematical models and calculations to arrive at the desired quantity, say a dose rate, as opposed to "experimental", in which case the quantity is measured using appropriate instruments. The theoretical approach makes use of current theory on the interaction of electrons with matter to establish a theoretical model that would give the dose profile. Solutions of such mathematical models are frequently prohibitively difficult and simplifying assumptions are often necessary. Experimental data are used only to check the accuracy of the solutions. In both the theoretical and analytical approaches the results are generally expressed as depth-dose functions. The functions are in the form of equations or numerical tabulations.

One of the first attempts along the empirical route was probably that of Parker in 1943 (Pa43). In this work the

scattering of electrons in the medium is assumed to be self-replacing; that is, on the average, each electron scattered out of the beam is replaced by an equivalent electron scattered into the beam. Thus, only inverse square attenuation is considered and the dose is calculated from the particle fluence using appropriate stopping powers for the electrons in the medium. Exponential attenuation is mentioned, and the opinion is expressed that exponential attenuation probably affects the electron transport only during the first mean free path; the idea is not fully developed, however. The results of some measurements that were made using a thin-walled cylindrical ionization chamber and an extrapolation chamber are also presented in the paper. Comparisons between the results of these measurements and predictions of the empirical model show poor agreement.

In 1950 Loevinger used experimental data he obtained from a planar P-32 source to derive a point-source depth-dose function (Lo50). He does this by establishing a simple point source function based on stopping power, and then integrates that function over the planar source. The integral is compared with the experimental data to obtain a suitable functional form for the relationship between dose and depth. The result for the point source shows inverse square attenuation over the first mean free path, then exponential and inverse first power attenuation thereafter.

In the same year in which Loevinger published the work described above, Rossi and Ellis also published a paper in which

they make the assumption that beta radiation is absorbed exponentially in addition to the inverse square effects (Ro50). This assumption is used as a basis to derive depth-dose distributions around slabs and spheres. In a later paper, the derivations are extended to other geometries (Ro52). Comparisons they make of the predictions of their model with some available data show reasonable agreement. They also show that, based on available experimental results, the effective attenuation coefficient is related to the beta end-point energy by a simple exponential function.

In the meantime, experimental measurements were being made in a number of laboratories (So53, So54, Cl55), most of them of the distribution of energy absorption around point sources in air. In 1956 Loevinger used the accumulated data to derive an empirical point-source kernel directly, rather than through the use of measurements on planar sources as he had done earlier (Lo54, Lo56). The result is the now famous Loevinger equation, which gives the dose around point sources, but can also be integrated analytically for many other geometries (Hi56). The functional form of the equation is such that it gives nonzero dose values at very large distances. This form was found to be necessary in order to simplify the mathematics considerably. It is not believed to be a serious drawback since the equation accounts reasonably well for about 95% of all the energy deposited. Loevinger also presents expressions for calculating the

effective attenuation coefficients to be used in the equation, and shows that the depth dose equation can be used for media other than air if suitable parameters for the media are used. The equation has been widely used in beta dosimetry work, and revisions of some of the values of the parameters appearing in the equation have been published recently based on the latest experimental data (Mu73).

One of the first attempts at a theoretical derivation of the depth dose function for beta radiation was probably the work of Roesch, published in 1954. Using neutrons as a model, Roesch applied age diffusion theory, which had been developed in connection with neutron transport, to the problem of beta transport (Ro54). Age diffusion theory makes the assumption that the successive collisions whereby electrons lose their energy can be approximated by a continuous energy loss model. The age of the particle is a quantity that is indirectly related to the energy of the particle at any point during its movement through the absorbing medium. The results were found to be in good agreement with experimental data for distances greater than a mean free path or so from the sources, but not at closer distances for point sources and thin planar sources. Several other attempts have been made to derive theoretical beta depth-dose functions. Most involve considerable simplifying assumptions that diminish the applicability of the results. The most extensive work in this area, and the one involving the fewest assumptions, was published in 1955 by Spencer (Sp55). Most theoretical results

in current use are based on this work. Some simplifying assumptions were found necessary, the main one being the assumption of continuous slowing down of the electrons. The angular deflection of electrons was treated using the Mott scattering cross section. The energy loss was treated using Bethe's stopping power theory (Ev55). The depth dose distribution was obtained by numerical solution of the steady state transport equation applied to monoenergetic electrons. Tables were produced giving the absorbed dose distributions for point and planar sources in various media. The results were shown to be in good agreement with available data. Berger used these results to produce tabulations of the distribution of absorbed dose around point sources in a homogeneous water medium for monoenergetic electrons and for 75 beta emitters (Be71). The beta distributions were obtained from Spencer's results by weighting the data with the beta energy spectra of the isotopes under consideration, the spectra having been computer generated in connection with another work (Di69). The data thus generated for water can be used for any low atomic number medium by suitable adjustments to the water values.

In 1969 Cross published the results of an extensive series of measurements of the dose distributions around point beta emitters in air, argon, ethane, and polystyrene (Cr67). His results showed that the doses calculated using Spencer's data agree with measured values to within about $\pm 4\%$ for maximum beta energies between 0.16 and 3.58 MeV and for a variety of spectral

shapes, except for dose at the end of the electron range. Disagreement at the end of the range is expected because of the effects of straggling which, in Spencer's treatment, were neglected when continuous slowing down was assumed. Straggling is the variation in the ranges of electrons of the same initial energy. The phenomenon results from the fact that electrons lose their energy in discrete amounts and not continuously along their paths. The discrete energy losses are not equal but vary within a fairly wide range. Cross also showed that distributions in different media differ only by a constant scaling factor on distance in mg/cm^2 that is the same $\pm 1\%$ for all beta energies except at short distances from the source. These latter findings were also presented by Cross in a later paper based on calculations using Spencer's results (Cr68).

Two main choices are currently available for beta dose calculations: Loevinger's equation and its integrations over a variety of geometrical shapes, and Berger's point source tabulations. Loevinger's equations are by far the easier of the two approaches to use because the equations are in relatively simple analytical forms. Berger's results are in the form of numerical tabulations for point sources, and as is usually the case with numerical data, use of these results for geometries other than a point source presents major difficulties for the average practitioner. A computer is normally required, together with a suitable program to integrate the point source data numerically over the required geometrical configuration. For this

reason, although Berger's tabulations lead to more accurate dose predictions than Loevinger's equation, the latter is used most often in health physics applications. Papers are beginning to appear in the literature describing methods for integrating Berger's data over simple geometrical shapes, as well as tabulations of the results obtained using these methods (Va74, Sh82a).

Although the above discussion may have given the impression that the beta depth-dose problem is essentially solved, this is not the case. A major assumption that was made in all the works described above, except the age diffusion theory, is that the source is embedded in an infinite homogeneous medium. Most applied problems, on the other hand, involve beta sources in nonhomogeneous media and beta radiation passing through a number of different media. A typical example is contamination on the outside of a worker's protective clothing. The contaminant, which may be approximated by a thin planar or point source, is located at the interface between air and protective clothing material. The beta radiation will pass through this material, then probably through some cotton or other underwear, and finally through the epidermis before reaching the basal layer. The question that must be asked is, of course, does the theory for infinite homogeneous media apply to such situations. Some preliminary work appears to give a negative answer to this question, implying that some modifications to the theory are necessary (Os69, Ra72). Other work suggests that, at least for sources at

the interface between two homogeneous media, the deviations are relatively small, amounting to a maximum of around 10% in some cases but usually much less than that (Ob74). The problem remains unsolved, and in the meantime the results derived from infinite homogeneous media are being used for nonhomogeneous media in practical applications based on the tentative assumption that the errors involved in such usage are probably sufficiently small to allow reasonable approximations to be obtained.

VI. A DISCUSSION OF THE TMI SITUATION

The response of the TMI staff to the dosimetry problems after the 1979 accident was, we believe, sound and commendable. When it became clear to them that they were faced with a difficult problem, they requested expert assistance. The problem started with the entry of workers into a highly contaminated area of the plant. Their TLD dosimeters showed unexpectedly high readings following the entry. At this point, the main questions were: are the doses registered by the dosimeters accurate, and if not, what dose should be assigned to the workers? Also, if the dosimeters were not responding as expected, why were they responding unusually, and what can be done to correct the problem? The answer to the second question was the subject of this review. Having decided that the dosimeters were not responding properly, the next step was to use all available data to calculate the doses to be assigned to the workers. Pre-entry survey results and self-reading dosimeter readings were used. TLD trees were placed in the contaminated area in an attempt to estimate the spatial distribution of the field. Reactor coolant isotopic analyses were used to determine the source of the field in the contaminated area. A mockup of the important piping in the work area was constructed. The mockup was used to go through a reconstruction of the movements of each worker during the entry, including a time and motion reenactment with the workers fully dressed in anti-C and respirators. The thicknesses of the dif-

ferent layers of clothing worn by each worker were measured and depth-dose models were used to attenuate the beta fields through this clothing.

The primary coolant that caused the high beta personnel exposures was plated out on a large plaque in order to make an appropriate calibration source. This plaque was taken to the National Bureau of Standards for calibration with their extrapolation chamber.

As a result of these studies, what are believed to be reasonably accurate doses were assigned to each of the workers, including whole body, extremity, eye, gonadal and skin doses.

VII. BETA DOSIMETRY PROBLEMS WITHIN THE U.S. INDUSTRY

It is important at this point to view the problems at TMI within the perspective of conditions in the industry in general. A survey conducted in 1978 on personnel dosimetry practices in the USA provides some revealing facts (Ch78). The survey included 1000 health physicists, 200 of whom responded. Of those responding, about 40% used TLD personnel dosimetry at their facilities. About 85% of these TLD users monitored for both gamma and beta radiation. The calibration sources used by most TLD users were either Cs-137 or Co-60 for gamma exposures, and either U-238 or Sr-90 for beta exposures. Many of the respondents did not know any of the radiologically significant characteristics of their dosimeters, such as TL element thickness and shielding over the shallow and deep elements. Of those who did know, most indicated that the shielding over the deep element was around 300 mg/cm^2 . The shielding over the shallow element varied between $10\text{-}100 \text{ mg/cm}^2$, but most were in the range of $20\text{-}30 \text{ mg/cm}^2$. Eighty-five percent of the respondents did not use phantoms during dosimeter irradiations. The methods used to evaluate skin dose from the dosimeter readings were not uniform. Some considered the skin dose to be equal to the rem equivalent of the shallow element reading. Others corrected the net shallow element reading by adding various fractions of the deep element response.

Based on the results of the survey, the dosimetry hardware

at TMI at the time of the accident in 1979 was typical of national practice. The dosimetry operation must be considered to have been at least above average. The personnel in charge were familiar with at least the approximate specifications of their system; what was believed to be an appropriate beta factor was used to correct shallow element readings; and a quality control program was in effect to monitor reader output and individual chip sensitivity.

The dosimetry equipment and dosimeters in use at TMI in 1979 were considered by most health physicists to be close to state of the art for commercially available systems, at least from the radiological point of view. A journal article published in 1982 (Du82) evaluated the commercially available dosimetry systems worldwide. The article lists five major systems, one of which was the Harshaw 2271 system in use at TMI in 1979. The article discusses beta dosimetry problems briefly but comes to the conclusion that "---accurate measurement of soft beta radiation is of limited importance in practical personnel monitoring situations, due to the fact that such radiation very rarely occurs---". The article goes on to discuss some problems encountered in using the 2271 system, but the problems are mostly mechanical in nature. Although some may vehemently disagree with the above quote, we believe most health physicists still hold this view concerning beta dosimetry. Considering that this attitude prevails even with the advantage of post-TMI hindsight, one cannot fault the dosimetry personnel at TMI in 1979 for being compla-

cent, or for believing that their system was at least radiologically adequate for their purposes. This is not to imply that their operation at that time was perfect. There were problems, but these were mostly administrative in nature.

Following the 1979 accident at TMI, the inadequacies of their station's dosimetry system quickly became evident. But it would be grossly misleading to think of this as a TMI problem. The location in this case is fortuitous and the problem is industry-wide. Today, more than three years after the TMI accident, the deficiencies encountered at TMI remain unchanged at most facilities, with the significant exception of TMI and a few other facilities.

The shortcomings in the dosimetry system that eventually led to the problems at TMI, as well as the behavior of the system in the post-accident environment, were entirely predictable. The question, of course, is why were these problems not anticipated and appropriate solutions adopted. We believe that the task of anticipating significant problems involving complex operating systems lies mainly with the experts in the field. Commercial dosimetry operations are usually in the charge of people trained in basic health physics and usually competent in running the operation. But competence in this sense refers to the ability to keep the operation running smoothly on a day-to-day basis and solving minor operational problems that inevitably arise in large volume processing. It does not usually extend to considerations

of system design and the significance of design features in relation to basic dosimetric concepts. Such competence lies in the domain of the dosimetry experts, and such experts are almost never to be found working in commercial facilities involved in routine dosimetry processing. They are to be found mainly in universities and other research-oriented facilities such as the national laboratories, in industrial research and development facilities, and in regulatory and standard-setting agencies. They would have little to do at an established commercial dosimetry processing facility, and would be involved with such facilities only in situations where exceptionally difficult problems were encountered. But since no such problems were perceived at pre-accident TMI, the experts were not called in.

Ever since the development of TLD dosimeters, papers have been appearing regularly in the professional literature describing the difficulties and uncertainties involved in personnel TLD dosimetry. Suggestions for improvement were also made. But much of this work was never translated into a requirement for the commercial processor to institute change. The organizations most in a position to start and maintain a movement toward such a change are the ICRP and the NRC. Both commissions have been slow in developing operationally useful solutions, even interim solutions, to most of the outstanding problems in personnel dosimetry. Such problems include the relationship between the quantity measured by a dosimeter, the resultant organ dose and the method of calibration; the problem of the effectiveness of using a

single dosimeter to measure whole body dose, and the problem of the acceptable accuracy (not precision) in dosimetry results, among others. Even such a seemingly trivial matter as the reasons for keeping dosimetry records is still being debated. It is also important not to lose sight of the closely related question of the state of the art and its expected rate of development. Interim operational requirements and recommendations must be made with a view of what is possible on a routine commercial basis. The state of the art in personnel dosimetry has been slow to develop, possibly because of the absence of a sufficient financial incentive, or possibly because the problems are very difficult to solve. Whatever the reason, there is currently probably only one dosimetry system that represents an improvement over the system in use at TMI at the time of the accident. But the response of this system has yet to be fully studied by the manufacturer. It is therefore not clear whether adoption of this system would represent a significant improvement as some believe. This is particularly true in view of the many other unresolved problems that are not related to the dosimetry system.

Three years after the accident at TMI, there has been no change in regulatory requirements that would prevent a repetition of the TMI dosimetry experience. The Proposed Dosimetry Testing Standard, which is supposed to improve this situation, will not do so. The dosimetry system at TMI in 1979 could have easily passed the proposed tests if the dosimeter had been slightly

modified. This is not to say that a testing standard is not desirable. It is, but the standard addresses the simplest problem in the whole operation, namely the accuracy of the system under controlled conditions. The other problems remain largely open.

VIII. SUMMARY AND RECOMMENDATIONS

The discussions presented in the previous sections contain implicit recommendations for improving the state of personnel dosimetry, particularly beta dosimetry. At the risk of some repetition, these recommendations are presented in this section in a more explicit format.

Personnel dosimetry processors, as well as facility radiation safety officers, may be divided into two broad groups with respect to their views as to the purpose served by the practice of personnel dosimetry. One group is of the opinion that the practice should be only semi-quantitative, serving the purpose of monitoring the ALARA procedures and practices at the facility and ensuring that there is no breakdown of these practices at any time. The second group believes that personnel dosimetry should be as quantitative and as accurate as state-of-the-art technology allows. The two-fold purpose served in this case is to monitor the safety of operations, and to establish an accurate dose record which, over the years, may be used for a variety of studies. The care and effort expended in the everyday practice of dosimetry is inevitably affected by the view held by the supervisor of each operation. Differences are clearly evident even from a casual observation of the operations of various dosimetry processors. In the interest of uniformity, and also in the interest of maintaining an accurate dosimetry record if such a record is deemed worthwhile, the NRC should make a clear policy

statement on the matter and also set appropriate boundaries on the uncertainties it deems acceptable in everyday practice.

The first requirement in making any kind of measurement is to have a very clear idea, or definition, of the quantity being measured. The definition must be in terms of directly measurable physical quantities. This rule applies to dosimetry as much as it does to any of the physical sciences. Unfortunately many of the dosimetric quantities, though often relatively easy to understand conceptually, are very difficult to measure even under ideal laboratory conditions. The problem is compounded by difficulties such as the question of averaging over the volume or surface area of the organ in question, particularly if the radiation field is nonuniform. In view of these considerations it is evident that requiring the radiation user to monitor such quantities using a single dosimeter placed on the chest is asking the user to perform a virtually impossible feat. Yet the relevant regulations do just that when they require users to measure doses to the whole body, blood forming organs, etc. without supplying additional guidance and qualifications. To correct this situation, we recommend that regulations be supplemented with regulatory guides that elaborate on the theory behind the regulations as well as giving acceptable procedures for making the required measurements in everyday field work. Such procedures would not be in terms of any specific instrument, but would be generic. Some effort would be required on the part of the processor to translate the generic procedures to procedures specific to his

operation, but such a step would be fairly easy to perform by a competent processor. A discussion of implementation procedures necessarily involves a discussion of calibration procedures since the interpretation of the readings of a non-absolute instrument is inseparable from a clear understanding of the calibration of that instrument. Therefore the regulatory guides would also have to consider the problem of calibration.

The question of measuring the dose to the basal layer of the skin, at a depth of 7 mg/cm², was discussed in the text above. This monitoring requirement is very difficult to satisfy in everyday practice. The difficulties are caused by the small depth at which the dose must be measured as well as by the fact that no dose averaging over a depth of skin is permitted. In an effort to reduce some of these problems and therefore improve the reliability of personnel beta dosimetry, we recommend that the question of the radiosensitivity of the skin be critically re-examined. The aim of such an effort would be to demonstrate that the dose selected for measurement is expected to give a true indication of the risk of skin carcinogenesis, and also to make sure that the problem of skin dose measurement is not being made unnecessarily difficult by a requirement that does not in fact reflect the proper dose-effect relationship.

Related to the above are the problems of dose averaging over a given area of skin and of the angular "response" of the skin when exposed to nonpenetrating radiation. We recommend that

clear regulatory positions be expressed regarding both of these questions, since they have a direct bearing on the design of dosimeters and survey instruments. The problem of dose averaging in the case of external beams is practically intractable and is totally ignored in practice. Even in the relatively easy case of skin contamination, difficulties still plague the efforts of health physics personnel attempting to estimate the skin dose resulting from such contamination. In these cases, the survey instrument used to estimate the activity on the skin, as well as the geometry in which such an instrument is used, will result in an implicit averaging over some area of the skin. Some attempts are often made to estimate this area, but the geometry and the instrument response are both usually poorly defined. Such attempts can therefore be considered as only semi-quantitative. Efforts should be directed toward developing a survey instrument and a procedure for use in such situations. The problem of the penetration of the contaminant into the skin should also be addressed since such penetration is known to occur in many, if not most, cases of skin contamination, and the assumptions made in this regard can substantially affect both the measurement of activity and the dose estimates for a given activity. Finally, a resolution of the problem of contamination "hot spots" should be provided. Such hot spots are high activity skin contaminants of essentially zero area. Many practitioners feel that averaging the dose from such hot spots over an area even as small as 1 cm^2 would lead to a substantial underestimation of the effective skin

beta dose regardless of the characteristics of the specific source giving rise to the field. Therefore, to test such a dosimeter, it would only be necessary to expose the dosimeter to a number of beta fields of different energies, even though the exact energies or spectral shapes may not be known. The dose rates at the dosimeter location must, of course, be known, and these would be measured by means of the extrapolation chamber. It is important not to confuse the requirements placed on sources to be used for testing with those to be used for research. Requirements for the latter are generally much more stringent because the results are often expressed in the form of dosimeter output as a function of one or more source characteristics. Some thought on the matter of the shape of such sources may avoid future problems in the use of the sources in applications other than dosimeter testing, such as for example in testing survey instruments.

The recommendations have thus far addressed problems relating to equipment and procedures, but it is also necessary to devote some attention to the personnel who will use the equipment and apply the procedures. We therefore recommend that the training of dosimetry personnel, particularly those in charge of facility dosimetry operations, be upgraded to ensure that they understand the basic concepts of dosimetry and general health physics, as well as specific procedures and guidelines. Such training should be quite rigorous and of sufficient depth, and

should be followed by an examination. The examinations should be repeated biennially to ensure that the material is not forgotten. Such examinations can be regarded to be in the nature of recertification for a facility dosimetry operation.

Many specific recommendations can probably be made if one wishes to do so, but the above are believed to cover those areas of personnel dosimetry that require the most urgent attention. One possible addition to the list is a recommendation to speed up the development of suitable survey instruments for use in beta survey work. After the main problems have been corrected and experience is gained in the new mode of operation, many refinements will probably be needed to fine tune the system and also to correct problems that will inevitably be generated by the adoption of new procedures. It is hoped that such problems will be easy to correct and that by that time the field will have reached a high level of professionalism. Further improvements would then be limited by the rate of technological and scientific developments pertaining to the field.

dose.

Situations in which workers must enter areas in which the radiation fields show very large variations from point to point present exceptionally difficult personnel dosimetry problems. One solution that has often been adopted is to use many dosimeters distributed over different parts of the body. The practice in such cases is to use the highest reading dosimeter as the indicator of the dose to be assigned to the wearer. A regulatory position is needed either to sanction such a practice or, preferably, to give guidelines on the placement of multiple dosimeters and the method to be used in assigning doses based on the readings of these dosimeters.

Based on the discussions presented in the text above, we recommend that the proposed dosimetry testing standard not be adopted. We recommend that a new standard be developed and that this new standard contain two sections, one for testing processors and one for testing dosimeters. The processor testing section should restrict itself to testing the processor's operation in a manner that is as independent of dosimeter design considerations as possible. The test would be administered frequently. The processor would also be required to demonstrate that the dosimeter in use in his operation is able to satisfy minimum operational requirements. He would accomplish this by passing the dosimeter testing part of the standard. This latter test would be required only once for each processor, or for each

dosimeter design, and would be quite elaborate and exhaustive, testing such factors as energy response to photons, beta radiation and neutrons, angular response, variation of precision with absorbed dose, etc. Minimum performance criteria would be established for each category. The criteria would automatically place a lower limit on the acceptable overall performance of dosimetry systems to be used in the industry. The criteria would be reviewed periodically and made more restrictive to reflect advances in technology. Specific recommendations regarding the facility that would administer such a test cannot be given at this point, but logical choices must include the National Bureau of Standards and the Dosimetry Section at the Idaho Falls Engineering Laboratories. Funding to cover the cost of administering the tests as well as of any necessary auxiliary equipment such as jigs and fixtures to hold specific dosimeter designs in place would be covered by the manufacturer of the dosimeter being tested. Much discussion has centered around the matter of selecting an appropriate beta reference source, but these discussions probably over emphasize the importance of this topic, partly because no single beta source can be adequate, and also because the primary standard is not the source but rather the extrapolation chamber. Practically any set of beta sources would serve the purpose provided they satisfy the requirements of adequate half-life, field uniformity at the dosimeter location, and a sufficiently broad range of beta end-point energies. This is so because an adequate beta dosimeter must give an estimate of the

IX. SUMMARY OF PROBLEMS ENCOUNTERED IN PERSONNEL BETA DOSIMETRY, WITH RECOMMENDATIONS

1. The personnel dosimeter shows an excessive beta energy dependence. The filtration over the beta element should be examined to ensure it is as close to 7 mg/cm^2 as practicable. The thickness of the TL element will affect the extent of energy dependence. The possibility of using thinner phosphors should be investigated.
2. Inappropriate beta correction factor. This factor is normally treated as a constant, but in fact it is not. The optimum solution is either to acquire a dosimeter with an energy independent response, or one that enables calculation of a beta factor for each exposure. Lacking such solutions, an effort should be made to determine a "compromise" factor, that is, one that will overestimate some exposures and underestimate others such that the total will average to an approximately correct dose assignment for a given period, such as a badging period.
3. Dosimeter not properly positioned in relation to the skin. It should be remembered that any material between the beta source and the target will alter the beta dose to the target. The target is normally the skin and the dosimeter is to measure skin dose. Therefore, the dosimeter must have the same amount of absorbing material over it as the skin does in any radiation field. Putting the dosimeter on the outside of clothing will violate this condition and result

in overestimating the skin dose. It should be remembered that one effect of clothing over the dosimeter will probably be to change the beta factor.

4. Difficulty in estimating skin contamination activity. The current recommendation from ICRP is to use the average activity over a 1 cm^2 area of skin. This affects the detection geometry to be used in estimating the activity on the skin. The geometry selected automatically imposes an averaging process over a specified area. Therefore, if a 1 cm^2 average is to be used, the detector window area and geometry should be such that averaging over this area is achieved. It should also be remembered that the response of many of the detectors used in such situations is very dependent on the isotopes in the contaminant, and also on the extent of penetration of these isotopes into the epidermis, as well as the thickness of the contaminant layer.
5. Difficulty in calculating the skin dose resulting from skin contamination. The main difficulty here is that the models commonly used to calculate the beta dose to the basal layer assume that the beta source is immersed in an infinite homogeneous medium. Since the contaminant on the skin is not in such a configuration, the models may give erroneous results. There is not much a practitioner can do at this point, except to be aware of this fact. Research work is needed to investigate the applicability of current models and to develop a more appropriate one if necessary.

6. Survey Instruments show a high beta energy dependence.

Most of the survey instruments in general use are not suitable for surveying beta fields. Their responses show marked dependence on the energy and direction of the beta field. Better instruments are being developed but are not generally available yet. In the meantime, the results of beta surveys should be viewed as semi-quantitative and should be used only as indicators of the presence of a field and its order of magnitude. Some consideration may also be given to the method of beta calibration with the view of making these methods duplicate the expected beta fields as much as possible.

7. The proposed dosimetry standard does not accomplish the purpose it appears to accomplish. The standard calls for testing dosimeters for beta response by exposure to a filtered Sr⁹⁰ source. A facility can ensure passing this test by providing sufficient filtration over the gamma element to prevent penetration of the Y⁹⁰ beta radiation (about 900 mg/cm²). The dosimeter should then be exposed to a filtered Sr⁹⁰/Y⁹⁰ source to a known dose and the beta factor calculated from the dosimeter readout. This beta factor is then used to interpret the test results. The facility should keep in mind, however, that passing this test does not mean that adequate beta dosimetry capability has been achieved. This is due to two important considerations. First, the beta

factor used with the test results is generally not appropriate for use in fields existing at most facilities. A different beta factor will usually be necessary for interpreting the results of field exposures in the facility. Second, as was discussed in #3 above, the beta factor is generally not a constant except for a dosimeter with an energy independent response. Use of a constant beta factor must therefore be viewed as a crude approximation employed with most dosimeters for lack of a better method.

8. Difficulty in interpreting the test results in the proposed dosimetry testing standard. One of the quantities used in characterizing the results of test irradiations is the bias. This is the mean of the deviations of the test results from the delivered doses. Since both the irradiation and the readout processes are statistical in nature, the bias will rarely be zero, even for a perfectly calibrated TLD system. It should therefore be remembered that a non-zero bias may not mean anything more than normal statistical variations. To determine whether a real bias does exist, a suitable statistical test must be applied to the results. Please refer to the text in this report for details of this and related considerations.
9. The present requirement to measure the skin dose at 7 mg/cm^2 may not be appropriate. This requirement places severe constraints on the design of a good beta dosimeter. Also, it may not represent the depth of the radiosensitive layer of

the skin. To measure this dose without the need for correction factors requires a thin filter over the beta element as well as a very thin beta TL element. But thin filters and thin elements usually make the dosimeter fragile and difficult to read automatically, and also makes attainment of good accuracy at low dose levels difficult. An NRC request to organizations such as NCRP and ICRP to study the problem of the radiosensitivity of different parts of the skin is recommended.

10. Beta calibration sources are not generally available and accessible to dosimetry processors and users. A sufficiently wide range of beta sources are needed in any measurements to check the beta energy response of personnel dosimeters and survey instruments. Such sources must be of suitable construction and must be calibrated using a well-designed and controlled extrapolation chamber system. One solution to this situation is for the user to purchase such a set of sources and have them calibrated by the National Bureau of Standards. Since this is a fairly expensive undertaking, sharing such sources with a number of facilities with similar needs may be more efficient.
11. Quantities to be measured are not defined operationally in many cases. It is important to clearly understand the intended meanings of the dosimetric quantities and then translate these into a series of steps which, if properly exe-

cuted, will yield the desired quantity. An example of such a situation is the need to measure dose to an organ or to the whole body. Such a dose cannot be measured directly in ordinary situations. There is therefore a need to devise a series of operational steps that start with a calibration source, such as Cs¹³⁷, then a secondary reference instrument such as a condenser R-meter to give delivered exposure, a phantom to irradiate the dosimeters, and finally a function to relate the measured exposure to the dosimeter readings to give the desired dose. Each of these steps must be carefully controlled and its function in the overall process clearly understood. It is recommended that all applied dosimetric quantities be defined by the various agencies both conceptually as well as operationally. Such operational definitions would make implementations of regulatory requirements more accurate and consistent between different users than is currently the case.

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