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UNITED STATES
ATOMIC ENERGY COMMISSION
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TENNESSEE

HEALTH-PHYSICS, INSTRUMENTATION, AND RADIATION PROTECTION

by

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Date of Manuscript: Unknown

Document Declassified: March 25, 1947

This document consists of 59 pages.

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I. SCOPE OF HEALTH PHYSICS

Introduction

Shortly after the discovery of X-rays and radium, the damaging properties of penetrating radiation were observed. The earliest injuries affected the surface of the body, notably the fingers and hands, and steps were taken to adjust the exposure of the individual in such a manner that these injuries would not arise in future cases. It was some time before more insidious forms of damage, frequently not accompained by easily recognized early signs of injury, were observed. This period was one in which many people exposed to radiation were subsequently afflicted with anemia. Throughout the history of the use of penetrating radiation, steps have been taken to organize the work program in such a manner that observed injuries would not be reproduced in the future. In practically all cases, protection has been a corrective procedure following a series of misadventures, and in some cases there was a situation approximating a public scandal before suitable remedial measures were established. Only within the last few years has there been attention to prophylactic action against new hazards before injury experience was developed. In a general sense, Health-Physics has existed for fifty years, of which the last twenty-five have seen steady improvement in the techniques involved. The particular title, Health-Physics, was a product of the wartime organization within the Plutonium Project. There has been no absolute definition of the scope of the proposed new subject of Health-Physics, but in general it is concerned with the physics and bio-physics involved in the interaction of radiation with the human body, with special emphasis on the protection of radiation workers against the potential hazards of their occupation. Health-Physics is, thus, a restricted aspect of Medical Physics in which the basic intention can be seen from a study of proposed alternative titles.

Nomenclature

While Health-Physics was used as the descriptive title at the Metallurgical Laboratory in Chicago and at the Clinton Laboratories in Oak Ridge, the equivalent organization at Hanford Engineer Works was called the "Health Instrument Section," (commonly abbreviated H. I.) for security reasons. The title "Radiation Hazard Control" has also been proposed, and this is probably the closest short description of the scope of the program. A less ambitious title, "Hazards Evaluation," has recently been introduced at the Argonne National Laboratory. The intention here is similar except that a measurement or evaluation of the hazards without any promise of effective control is implied.

The pre-war title "Radiation Protection," which is understood to mean the protection of workers against radiation, is certainly not out of place, and would be more directly in line with previous experience outside the Manhattan District Project. Perhaps the only justification for regarding Health-Physics as a new subject is that the recent large-scale expansion in the use of radiation and radioactive materials has apparently established the need for a group of men engaged full-time in the considerations of radiation protection. In previous experience, medical physicists were required to give only part-time attention to the problems involved in their occupation. Whether Health-Physics will become a permanent branch of Medical-Physics of sufficient magnitude to justify separate definition is a matter for debate; it is entirely conceivable that the subject approximates its maximum status at the present time. Despite the fact that utilization of nuclear machines and other uses involving radiation and radioactive materials will undoubtedly expand during the next few decades, it is to be expected that the methods of hazard control will become sufficiently stabilized that specialists may no longer be required to regulate safety aspects, with the exception of the consultant services of a small group of qualified experts. This would restore the relative importance of the subject to its pre-war status.

Nature of Advances

Regardless of nomenclature, fundamental advances in the protection aspects of Medical-Physics have been few or nonexistent. This by no means belittles the advances that have been made. It does imply that they are not of fundamental research character, but fall more into the development field or are practical problems of group organization and protection policy. This chapter will describe these phases, and will at the same time specify indirectly what is meant to be included in the expected proper field of Health-Physics.

Health-Physics is a borderline subject surrounded by Industrial Medicine, Radiobiology, Industrial Safety, Public Health, Physics, Engineering, and Chemistry. The area between these boundaries is ill-defined. Whether any area at all is to remain will be largely determined by the experience of laboratories and industrial organizations with the present Health-Physics groups. The immediate prospect appears to be that such groups have thoroughly demonstrated their value and adequacy in the case of industry, whereas laboratory groups may cover the same territory by suitable extensions of the various surrounding subjects.

II. PAST EXPERIENCE IN PROTECTION

Luminous Paint Industry

Of the various modes in which radioactive materials have been used in the past, that concerned with the handling of radioactive luminous compounds has received the most careful consideration. Acceptable standards for the handling of such materials have been published in the National Bureau of Standards Handbook H-27 (1941). The known hazards in the order of their importance are, (1) ingestion or inhalation of solid radioactive luminous compounds; (2) inhalation of radon liberated from compound into the air; and (3) exposure of the whole body to gamma radiation from compound.

Radium Poisoning

Accumulation of small quantities of radium in the body may result in eventual damage to the blood-forming organs, or to the bone-forming cells, with malignant change as the end-result. Such injuries have been known to result fatally when the fixed radium content of the body was approximately 1 μg (Evans, R. D., 1943). The accepted limit for radium deposition in the body is 0.1 μg. The inhalation of radium dust is more hazardous than its ingestion. Approximately 100 μg administered orally, or 20 μg intravenously or by inhalation results in the deposition of 1 μg of "fixed" radium. (Rajewsky, B., 1939). In the past there has been inadequate attention to the possible concentration of radium dust in the air, whereas ingestion which now must come largely from transfer from the fingers is rather easily and routinely controlled. Emphasis on the ingestion hazard is possibly a legacy from the early catastrophe in the widely-known New Jersey poisoning case in which the material was primarily ingested by the pointing of brushes at the lips. In current plant practice, the greatest body radium content frequently is found not in dial painters, but in inspectors and assembly workers who remove small chips of the dried compounds in the course of their work. The protection of radium-dial painters against the accumulation of radium in the body depends largely on good-housekeeping, which includes the provision and maintenance of a clean work location, and of suitable protective clothing. Power ventilation is used to remove radium dust as well as escaping radon. Routine breath radon analyses are used as the most sensitive index of radium accumulation. A radon concentration of 1 $\mu\mu$c/ liter air is said to correspond to a body content of about 0.1 μg Ra. However, there is no general agreement that the approximately 50% escape of radon represented by this figure always occurs. For radium of long fixation, emission as low as 7% has been quoted (Jones, J. C., Day, M. J., 1945). Despite the precautions taken, substantially all dial painters, inspectors, and assemblers ingest or inhale a sizeable fraction of the tolerance amount of radium, and about 15% exceed the tolerable amount (Evans, R. D., 1943). In another report, 30% of workers of less than one year's standing and 60% of all others showed breath samples above tolerance (Morse, K. M. and Kronenberg, M. H., 1943). The worker removed from radium exposure usually excretes enough radium to restore the content to less than the tolerance amount. Experience of overexposure is reported from locations in which considerable care is taken to offer proper working conditions to employees. It represents the results of a philosophy in which temporary excursions above the tolerable amounts are considered proper. The efficacy of this approach depends on the frequency of the breath tests, the numerical accuracy of the results, and the extent to which temporary overexposures are harmless. In one published series, a maximum of 850% of the tolerance amount was observed. With breath analyses, every four to six months, a substantial portion of the radium in in the body at the time of test may be permanently fixed, and accumulations of this order of magnitude would not readily be excreted down to the tolerance level (Hoecker, F. E., 1944). Conservative practice should lead to a work system in which the deposited amount at no time exceeds the stated tolerance value. Routine measurements of active dust concentration in the air seem to be uncommon, despite the ease with which they could be made and the stimulus they might give to the maintenance of improved conditions.

Radon Exposure

Evidence on the exposure of humans to radon in the atmosphere is less definite than that arising from deposits of radium in the body, but it is generally accepted that a tolerance value of 10 $\mu\mu$c Rn/ liter is safe. In European practice, 100 $\mu\mu$c Rn/ liter has been frequently used as an acceptable standard (Russ, S., 1943) (Jones, J. C. and Day, M. J., 1945). Maintenance of an acceptable air concentration in factories has been achieved by suitable design of a ventilating system. An intake-rate of about 50 cubic feet minute per hood is the customary standard. The accepted standards of ventilation appear to insure that the room air content does not exceed 30% of the tolerable concentration. However, in a survey of 10 plants, Evans showed about 15% of the samples above tolerance. These values occurred mainly in storage or packing rooms and in offices not provided with suitable ventilation. Morse and Kronenberg reported excessive concentrations in 60% of the tests. Wartime experience in England has shown normal concentrations in luminizing rooms and radium labboratories, in the range of 20 to 100 $\mu\mu$c per liter, with some values as high as 8000 $\mu\mu$c per liter. There has been no apparent ill effect up to the present time, but the experience should ultimately be of interest in determining whether the American standards are unnecessarily stringent.

Gamma Radiation

The third hazard, namely that arising from the external irradiation by the gamma rays from radium, and its decay products, is no longer a serious consequence in any location in which a legitimate attempt is made to meet the recommended standards of protection. Control is achieved by limitation of the working amount of compound and by housekeeping to reduce general irradiation in a room. The normal exposure appears to be about 20 mr per day.

General Policy

The provision of the necessary protective mechanisms in this industry is expensive, and its continued proper operation requires careful examination. In modern plants it appears that the proper safeguards lead to conditions close to the supposed tolerance standards, an acceptable condition if those standards have been written with a reasonable margin of safety. However, there is not equal diligence in all parts of the country in maintaining such standards. Relocation of luminous paint industry in regions which have not previously had occasion to regulate such operations may lead to a relaxation of standards. Education of radium workers in the hazards of their occupation is one of the best mechanisms for promoting the preservation of good conditions. The trained worker can assist the conscientious employer in the preservation of safety and can suitably guide himself in other cases.

X-Radiation in Hospitals

X-ray protection has received detailed consideration, especially by the Advisory

Committee on X-ray and Radium Protection, which has published and revised at suitable intervals a unified set of safety recommendations (National Bureau of Standards Handbooks HB15 and HB20). Valuable additional details have been published by many authors (Braestrup, C. B., 1938 and 1942; Taylor, L. S., 1944; Glasser, O., Quimby, E. H., Taylor L. S., and Weatherwax, J. L., 1944). For protection considerations, the field of X-rays is subdivided into five classifications: (1) diagnostic, (2) superficial therapy, (3) deep therapy, (4) super-voltage therapy, and (5) multimillion-volt therapy. In each case, there are two primary types of possible protection failure; the one being accidental exposure to a single damaging dose or excessive dosage in a short series, and the other the eventual damage arising from prolonged exposure to low intensity radiation. Accidental exposures to physicians and technicians arise primarily from carelessness in entering the radiation beam, while accidents to patients come from omission of the proper filter, treatment at the wrong distance, treatment for an excessive period, or by an outright electrical defect in the equipment. Few, if any, of these occurrences fall outside the category of negligence on the part of physicians or technicians; their occurrence in modern usage is rare, and many are beyond the scope of Health-Physics. The hazard of principal concern is that arising from the small exposures which occur daily, and in this field there is a rather sharp differentiation between the diagnostic and therapy cases.

Fluoroscopy

In fluoroscopy, the physician must necessarily observe the fluorescent screen. The screen itself has to be backed by glass of sufficient thickness to reduce the transmission of radiation to a safe level and be surrounded by wings of protective material of adequate thickness. Protective aprons and gloves may be required by the physician or technician where the equivalent protection cannot be built into the equipment itself. The requirements are well known, but not always well respected. Possibly the greatest hazard in fluoroscopy arises in those cases where the physician is required to introduce his hands into the direct beam for palpation. This can be done safely when lead rubber gloves are worn. In the practice of some institutions, however, these examinations are made without protective gloves, the exposure received being held to a minimum by selection of the smallest possible irradiated field and by fast operation. There is no unanimity of opinion on the permissible daily dose to the fingers under such conditions. The Mayo Clinic group has made careful attempts to measure the exposure which in their experience had proved to be safe (Cilley, E. I. L., Kirklin, B. R., and Leddy, E. T., 1934, 1935 a and b). This was about 250 mr per day and as much as 700 mr per day to the finger tips. On the other hand, it has been suggested that radium exposures as low as 4 r per week have been known to produce injury (Parker, H. M., 1943). It seems evident that the restriction to 100 mr per day as required for whole body radiation is unnecessarily severe for this particular case, but whether 200, 500, or 1000 mr per day should be substituted has not been established. The continued widespread occurrence of finger damage among fluoroscopists should be sufficient to encourage the maintenance of a conservative standard. The risk of injury in fluoroscopy is greatest among those whose utilization of the equipment is sporadic. Orthopedic surgeons and veterinarians are particularly vulnerable in this sense, and reminders of the hazard (Harding, D. B., 1945) are much in order.

Photofluorography

The recent extension of photofluorography introduces additional hazards for both patient and operator in comparison with the previous routine chest film technique. The average entrance dose in photofluorography is about 1 r (Birnkrant, M. I., and Henshaw, P. S., 1945), and as high as 2.5 r in some cases (Gamertsfelder, C. C., 1943). This exposure is approximately twenty times that required by direct radiography. It is preferable that radiation workers be given the advantage of the low exposure method. Repetition of a photofluorographic exposure, which appears to be required with significant frequency in some clinics, is especially out of place for a radiation worker. The increased exposure results in a corresponding twenty-fold increase in the room scatter and may also lead to overexposure of the operator, if suitable restrictions on permitted approach to the patient are not maintained.

Radiography

Properly conducted radiography has none of the hazards peculiar to fluoroscopy. It can be conducted like superficial therapy. That the fingers of dentists and their assistants continue to show damage as a result of holding films in position is directly ascribable to inadequate training. The customary practice of having the patient hold his own films is presumably sound, but in one community of radiation workers a simple wooden device has been used to avoid this unnecessary exposure, and it is surprising that the same method is not universally employed.*

Therapy

In the various branches of therapy, it is the exception to find injuries to physicians or technicians working under modern conditions of shielding with up-to-date equipment. The protection of the room in which the tube is housed is usually such that the normal work conditions give negligible exposure to persons outside the treatment room. The increasing use of electrical interlocks and similar safety devices helps to prevent such errors as operation of the tube with the lead protective doors open. Training of the operator to keep all except the patient outside the therapy room during treatment also seems to be successful. In one series of film tests (Clark, L. H., and Jones, D. E. A., '943), 84% of the films from a hospital read less than 100 mr per day, and 56% from a hospital where some diagnostic work was done. Two other locations, doing mainly diagnostic work showed 99% less that 100 mr per day. It should be noted that 200 mr was the accepted daily dose, and 93% of all cases came within this limit.

Protection of super-voltage therapy equipment has been for the most part at an acceptable standard, although greater possibility has existed in these cases for casual overexposure. This has sometimes arisen from the combination of the therapy tube with facilities for physical measurements, and is therefore not properly chargeable to X-ray therapy.

Multi-Million-Volt Therapy, which is intended to cover the range from approximately 10 million volts up to perhaps 300 million volts, has not yet been extensively developed, but in this case an attempt is being made to establish proper safety standards before the equipment is used (Failla, G., 1945).

Radium in Hospitals

The protection of workers against exposure to radium, particularly in the applications

*In the same location, the "avoidance of unnecessary exposure" principle has led to a critical attitude toward the use of radiation in shoe stores, etc.

to hospital practices, has been formulated by the Advisory Committee on Radium and Radium Protection, and published as National Bureau of Standards Handbook H-23 (which superseded the earlier H-18). Protection is required against (1) local overexposure to radiation, especially upon the hands, and (2) overexposure of the entire body. Frequently overlooked in the manipulation of radium sources is the possibility of leakage which may permit the emission of radon and its accumulation in dangerous quantities in confined spaces, such as radium safes (Read, J. and Mottram, J. C., 1939). In the past, there has been a record of injury produced by rather short-time exposure to gamma radiation from radium, particularly at the time when the so-called radium bombs were first developed. In present practice, the hazards are essentially confined to those which arise from long-continued exposure at low radiation intensities. The planned application of radium to patients for therapeutic reasons can easily result in damage to the patient; this is the physician's responsibility. However, it is possible for the patient to be unnecessarily injured by the introduction of leaking radium needles, or by the superficial application of radium sources with improper filtration. These in part would be considered Health-Physics probelms, and methods of avoiding such injuries should logically be included in the general rules for radium protection. More generally, the injuries from hospital handling of radium occur to (a) technicians assigned to the preparation of treating units, (b) therapists and nursing staff in the operating theatre, and (c) nurses when patients are hospitalized in wards.

Hand Exposure of Technicians

It is especially prevalent to find that technicians tolerate a fairly close approach of the hands to radium during manipulations. In the past, there has been no specific attempt to maintain the hand exposure at the limiting value for general exposure. In fact, as recently as 1934, 5 r per day was described as the permissible exposure for the fingers. (Handbook H-18). At the present time, by far the greatest amount of injury to radium technicians occurs on the hands, and there are certainly cases in which hand exposure of closer to 5 r per week than 5 r per day have resulted in skin changes which may later assume a dangerous character. The conception that a certain degree of skin injury can be tolerated and that the technician may terminate his handling of radium sources at such a stage without the expectation of subsequent deterioration in his condition has been widely sponsored (Failla, G., 1932, Nuttall, J. R., 1943). Although true as applied to the primary injury, it appears that radiation effects skin changes in such a way that subsequent trauma, inconsequential in a normal hand, may lead to breakdown in the irradiated skin up to several years after the termination of significant exposure. Even the professional worker finds it difficult to avoid the minor trauma that is sufficient to initiate degeneration. Precise measurements of the actual exposure of fingers of radium technicians have been infrequent. The contribution due to gamma radiation is fairly well known, both by measurement with thimble chambers and by calculation from time and distance of exposure, but the additions due to beta radiation are quite variable. Where sources with a minimum filtration of 0.5 mm Pt. are employed, it is rare for the secondary beta-ray dose to exceed 25% of the gamma-ray dose. With other sources, especially glass capillary tubing containing radon, the beta-ray contribution may be extremely high.

General Exposure of Therapists

Whereas the risk of overexposure to the radium technician may be greatest with respect to the fingers, it appears that radium therapists should consider the general body radiation as the determining factor. Such men will usually receive more radiation to the hands than to the rest of the body. It is therefore tacitly assumed that the limiting tolerance is higher for the hands. It has been by no means uncommon in the past decade for therapists to retire from active radium work as a result of a progressive change in the blood count, used as an index of the welfare of the individual. It has been shown (Paterson, R., 1943) that the average worker in the Holt Radium Institute, Manchester, shows a permanent reduction in white-cell count in comparison with other persons with similar general surroundings without radium exposure. The stage at which white-cell changes can be considered harmful is not yet known, and modern tendency has been to regulate the exposure in such a way that the average white-cell count more closely approximates the normal value. It is of interest that the best evidence for a sustained and possibly non-injurious fall and reduction in the white-cell count comes from this Institute, where considerable attention has been given to proper protection (Nuttall, J. R., 1939). This Institute has operated with 200 mr per day as the tolerable exposure, and has in fact condoned exposures closely approximating 100 mr per day. Common practice in radium institutions has permitted daily general body exposure of about 70% of the tolerance value adopted. Experience in a typical teleradium installation has shown average daily exposures between 130 and 250 mr (Wilson, C. W., 1940). This experience is extremely useful in its applications here by providing a body of evidence of exposure at the supposed present-day tolerance limit. It is not known to what extent additional exposure was tolerated in England during the war period when staff reduction was necessary.

Industrial Preparation of Radium Sources

Preparation of radium sources may be considered to begin with the mining and refining of uranium ore. The health conditions under which this has been done have not been clearly defined except in the experience of the Canadian Great Bear Lakes deposits. (McClelland, W. R., 1933, Leitch, J. D., 1935). The methods of protection in the purification stages are similar to the requirements in the luminous compound industry, with the exception that as the matter is further purified the hazard is increasingly that of general body exposure to gamma radiation. The further stage of subdivision of the radium into capsules for hospital use has not been governed by general regulations of the type applied to the luminous paint problem. Such work is performed by relatively few companies, and the standards of protection accepted by them appear to be variable, and in some cases less desirable than the standards proposed by the Advisory Committee on X-ray and Radium Protection. The average radon concentration in the general laboratory of one of the most reputable companies has been quoted as 2200 $\mu\mu$c per liter (Read, J. and Mottram, J. C., 1939). The operation of radon plants either commercially or in hospitals can be one of the most hazardous modes of handling active materials, since it may lead to radon contamination of the air as well as hand exposure to beta radiation and general body exposure. Such installations as that designed and built by J. E. Rose in the U. S. Marine Hospital, Baltimore, Maryland, however, demonstrate many of the best protection practices. In general, a radon plant should be located in a separate building to localize contamination.

Industrial Radiography

Radiography has had to be guided by the recommendations of the Bureau of Standards that were specifically made for hospital application. The wartime publication of rules by the American Standards Association (1945) has been a valuable advance. More could be achieved by future closer liaison between all organizations using radiation methods. Industry has developed considerable experience with supervoltage X-radiation, and the use of betatrons at 20 MV and even up to 100 MV may be common practice within a year or two. Radium experience, especially in naval ordnance has also been extensive. The wholesale production of fission products has opened up the portentous possibility that sources of 100 or 1000 curies may be used in the future for radiography where sources of small dimensions are required.

Transportation of Radioactive Sources

The shipment of radium, radon, or similar radioactive substances through the mails has been prohibited by postal regulations in the United States. Shipment of radium up to 100 milligrams in a single shipment is permitted by Railway Express under a well-established code of protection (Curtiss, L. F., 1941). These regulations were designed to prevent damage to photographic films, an immediate effect subject to damage claims. Possible damage to individuals by the transportation of radioactive sources may not become evident for a considerable length of time, and the possibility of claim and subsequent correction of malpractice becomes poor. In this instance, the public has been protected against exposure hazards by the greater sensitivity of film than of the individual. Shipment of larger quantities of radium has been performed either by special license or in some instances by courier in which case persons in the vicinity of the source have not always been satisfactorily protected. Indifferent procedure in the event of loss in transit has marred the carriers' performance. Too frequently, the criterion of search expenditure has been the insurance value, not the potentially much greater health hazard. The existing regulations have been rendered inadequate by the recent increase in shipment of active materials and by unexpected changes in their character. The establishment of revised regulations is one of the most important functions of any organization concerned with radiation protection. These will have to include special consideration of neutron sources, active materials with parent-daughter relationships, where the hazard increases during shipment, liquid samples, and alpha-emitters where the hazard is not detectable by such simple means as Geiger counters.

Universities and Similar Institutions

With the development of atomic and nuclear physics, particle accelerating equipment—such as high voltage X-ray machines, positive ion tubes, cyclotrons, and linear accelerators—have become familiar features of the average university laboratory.

Pioneer work has been done with this equipment, and it is unreasonable to expect the highest standards of protection at all times. The radiation physicist was required to protect himself against neutron irradiation before the neutron beam could be used to irradiate patients or even animals. The radio-chemist prepared new radio-isotopes before the biochemist could determine their metabolism. That very few men have been permanently disabled by radiations from these machines and their by-products is much to the credit of the scientists responsible for these installations. Nevertheless, when the pioneer stage has been passed, there has been some reluctance to install safeguards comparable with industrial safety practice.

Radiochemical Manipulation Hazards

At the low level of activation produced by exposure to most nuclear machines, no particular damage has in general occurred as a result of sample manipulation. This has been helped too by the fact that much of the handling has been done by graduate students not assigned to such work for prolonged periods. This has fostered the belief on the part of many of the leading radio-chemists in the country that the hazards from hand exposure in the range of 200 mr per day to 2 r per day have been greatly exaggerated by the health physicists. At the present time, this is one of the major potential weaknesses in radiation protection in the country. Even when an attempt is made to maintain safe levels, the measurement of contact exposure with an instrument suitable only for remote measurements frequently gives results low by one or two orders of magnitude.

Future experience will be with sources which produce activated materials of greatly higher intensity. A change in work habit as a result of increase in source strength is one of the more difficult developments for the scientists to make, since the chemical and other associated properties remain unchanged, while only the relatively intangible radiation levels go up. The advantages of proper shielding and remote handling in future radio-chemical operations cannot be too widely publicized (Levy, H. A.,1946).

General Radiation Injuries

In addition to the hazards of radio-chemical manipulation of laboratory materials, the generating sources themselves are a potent source of injury, and it is recognized that they have in many cases been operated under conditions which depart from the ideal. Again, the number of eventual injuries which may arise from long-continued exposure at low intensity is not known. and is probably held to a minimum by the frequent turn-over of personnel under university laboratory conditions. Attempts have been made to specify proper protection against new types of radiation (Aebersold, P. C.,1941, Warren, S.L.,1941). In the more immediate field of visible radiation injury occurring either in a single accident or as a fairly rapid result of overexposure, more can be stated about the customary standards achieved. There appears to be no comprehensive survey of the frequency rate of such palpable injuries in radiation laboratories, but a private survey led the writer to propose the figure of one palpable injury per thirty man-years of active employment in radiation work. Subsequent discussion has indicated that many health physicists would accept a higher rate, such as one injury per twenty man-years as a representative value. Whether the rate is one to 20 or one to 50 years, it compares very unfavorably with a record such as that at the Hanford Engineer Works, where over 3,000 man-years of active exposure have been compiled without a single palpable radiation injury. Original research work carried on in laboratories is of such a character that safety in handling cannot be expected to equal that in a well-regulated, established industry; however, the differences are sometimes overemphasized, and in the particular example cited, the first operation of Power Piles and the wholesale production of plutonium can hardly be described as well-established industries. The postwar interest in all the major radiation laboratories in maintaining radiation safety comparable with Project standards may be a deciding factor in the permanent establishment of Health-Physics.

MANHATTAN PROJECT EXPERIENCE - Development of the Health Division

The anticipated scale of the radiation quantities involved in those parts of the Manhattan Project which were to be concerned with the development of chain-reacting units led to a fairly early recognition of the need for the establishment of an extensive Medico-Physical organization for the protection of workers against deleterious effects of radiation. The

Health Division under the direction of Dr. R. S. Stone worked along three major lines:

"(1) Adoption of pre-employment physical examinations and frequent re-examinations, particularly of those exposed to radiation.

"(2) Setting of tolerance standards for radiation doses and development of instruments measuring exposure of personnel; giving advice on shielding, etc.; continually measuring radiation intensities at various locations in the plants; measuring contamination of clothes, laboratory desks, waste water, the atmosphere, etc.

"(3) Carrying out research on the effects of direct exposure of persons and animals to various types of radiation, and on the effects of ingestion and inhalation of the various radioactive or toxic materials,such as fission products, plutonium,and uranium." (From Smyth, H. D., 1945).

Paragraph (2) comes close to a definition of the Health-Physics activities on the Project. The purely medical activity of paragraph (1) developed more and more along normal industrial lines, as the incidence of significant radiological findings proved to be essentially zero. Radiobiological research as in Paragraph (3) provided invaluable data for the progressive improvement of tolerance dose data, and in some cases there was a satisfactory integration between Radiobiology and Health-Physics.

The early work in the Metallurgical Laboratory differed neither in principle nor in magnitude from that previously practiced in several university laboratories. Since it developed from the putting together of the work of several such groups, the initial attention to radiation protection followed the standards of the parent institutions. In this period, also, the available staff for improvement in the hazard control and the necessary instrumentation for this purpose were both in short supply. However, after the successful operation of the first chain-reacting unit in December 1942, there was, throughout the Project, a steadily increasing interest in radiation hazards. The introduction of industrial organizations of the regular kind helped to stimulate the extension of protection rules and their more rigid observation. Those branches of the Project under such industrial control rather naturally became leaders in the establishment of functioning Health-Physics service organizations. The parent organization in the Metallurgical Laboratory continued to make valuable contributions, especially in the design and fabrication of new instruments.

TYPICAL EXPOSURE PROBLEMS - Shielding

In principle, the Project program posed no new problems with regard to the irradiation of personnel by penetrating radiation. The required shielding of Pile units and of the chemical equipment involved in the Separations Process was deduced by a logical extension of existing mode of calculations of the absorption of radiation in such materials as concrete, steel,and lead. Uncertainties in the calculation of the transmission through unusually large thicknesses* of these materials did not exceed a factor of perhaps three, and if an entire structure was designed for an intended safety factor of 10, no great harm would have been done by finding a residual safety factor of 3 or 30. For Pile units themselves, the calculations of neutron absorption in the proposed shields represented a greater extrapolation

*Greater than 3 feet of concrete or equivalent. The maximum thickness in standard tables was 10 cm Pb, or 54 cm concrete (Taylor, L. S., 1940).

from previous information. The early work of the theoretical and experimental physicists in this field was substantiated when the Pile structures were actually in operation. One interesting factor of the protective measures required in the new designs was the necessity for protection of workers from "sky-shine," i.e., radiation scattered by free air from a primary beam which itself would not irradiate the observer. This had not been of practical consequence in earlier experience unless one considers a limited case such as the exposure of an observer standing just outside a primary X-ray beam. No new phenomenon was involved in the sky-shine calculations, which were essentially an exercise in the application of the Klein-Nishina formula. As a corrollary to shielding, the development of remote-control handling, both for laboratory tools and on the grand scale, became a fine art. Although steered by health physics, credit for this phase belonged to design engineers.

Beta Radiation

The effects of beta-ray exposure had to be closely considered, although in fact this experience was no different from that intrinsically available in the earlier radium knowledge, when the use of beta-ray sources was a common practice. Reliable dosage calculations of these cases proved to be so infrequent that the subject was essentially a new one. These beta-ray exposures were expected to arise primarily on the hand, forearm, and face; and typical sources of the activity were the natural uranium itself, materials activated in Piles, and the fission products. It was late in the project history before biological data on controlled beta exposures were available (Life, 1947).

Metabolism

The metabolism of the anticipated fission products, and of uranium and plutonium, became of prime importance in the consideration of how much of each particular element could be allowed to come in contact with the individual by such methods as skin absorption, injestion, inhalation, and introduction through open wounds. With the exception of uranium, this metabolism had to be evaluated by animal experience with meagre amounts of the active materials, prior to the time that the operating Piles made them available in quantity. It was obviously desirable to have at least provisional answers on the toxicity of all these materials before this stage of plentiful supply was reached. The work of the biological organizations at the Metallurgical Laboratory and later at Clinton Laboratories (together with the invaluable contributions of many associated laboratories, notably the Radiation Laboratory, University of California, at Berkeley, and the University of Rochester, Rochester, New York) cannot be evaluated too highly in the final assessment of the merit of the health protection of the Plutonium Project. Despite these efforts, the development of precise information on toxicity of radioactive materials at low levels over long periods of time could not be expedited by accelerated experiments, nor could the findings in animals be translated into the human case in terms of numerical tolerable dose. Fortunately, the relative deposition of active material within the animal was a good index of the corresponding deposition in the human case, and where the toxicity was a function of the radiation effect, the health physicist could calculate the limiting intake of the noxious material to produce a specified dose in the organ most affected. This was the mode of approach to the establishment of tolerable dosage for the various fission products before any extensive body of exposure information had been accumulated.

Waste Disposal of Fluids

As indicated in the Smyth Report, the operation of the facilities at Clinton Laboratories involved the emission of active gases, particularly radio-xenon and radio-iodine, into the atmosphere. It was the responsibility of the Clinton Laboratories to determine conditions of of operation under which such emission would cause no hazard, not only to the operating personnel in the laboratories but to the large public area over which these gases might have been disseminated (Parker, H. M., 1944). This was successfully accomplished, and the method of approach established a satisfactory standard for the consideration of allied problems at future locations faced with the problem of large-scale disposal of active gas. The second problem was the related one of disposal of active liquid wastes. This was solved by the retention in underground storage of all very active wastes and the dilution of other materials to such an extent that no possible interference with the safety of public water supplies was effected. The required standards for waste disposal of this type constitute one of the most pressing problems for future Health-Physics considerations. This is particularly true in connection with the operation of radio-chemical laboratories in urban areas, where the disposal of certain types of waste to the sewer is complicated by the precipitation or absorption of the active material in the sewer pipe or its soil contents; under unfavorable conditions this could produce a hazard at a much later date to unsuspecting persons repairing or otherwise handling such pipes. In large bodies of water, the concentration of activity in algae or in colloidal materials with its possible utilization by fish, later used for food, presents a chain of events of great consequence to the public health. Up to the present time, these problems have been by-passed by ultra-conservative policy in waste disposal, but future pressure for economical disposal facilities greatly point the need for extensive research on these problems.

Waste Disposal of Solids

All future radiation organizations will be faced with the disposal of solid contaminated items which may range from collections of waste paper used to clean contaminated equipment to large pieces of equipment which are so contaminated that their restoration to service would be more expensive than their replacement. As regards its basic nature, this problem is no new one, since it is well known that the photographic industry has had to institute routine tests for activity of the paper used to package photographic film, as a result of the uncontrolled return for reprocessing of paper contaminated in luminous compound operations. If this source is enough to contaminate the paper stock of the country, it is easy to visualize the condition set up by the indiscriminate use of similar pieces of paper from operations which dwarf the activity of the entire radium industry. Obvious means of preventing the return of such material to the public domain are storage in special vaults, burial in underground pits, or dumping in the sea, which are currently employed. The implications of contamination of the stocks of pure metal, for example, which might occur by careless release of contaminated materials or scientific equipment require careful consideration by some Advisory Board of high caliber.

Protective Clothing and Decontamination

Although special clothing is provided in such industries as luminous compound operations, the requirements of the Manhattan Project for decontamination of clothing, equipment, and personnel, constituted almost a new subject. There appears to be no absolute guide to the preferred method of decontamination, but information of general interest is that fission products can be most suitably removed from clothing by laundering in dilute acetic acid, and that whenever the condition of the equipment warrants its use, nitric acid is a preferred cleanser for practically any radioactive material. For the removal of radioactive contamination from the hands or other parts of the body, a titanium dioxide paste has been found effective against fission products, while an application of potassium-permanganate solution, followed by sodium-bisulfite, is effective against plutonium contamination. The use of nitric acid and hydrochloric acid on the hands has been condoned under carefully regulated conditions.

Safety Performanance

The overall safety record of the Project enterprise has been remarkable. At the Hanford Engineer Works, the largest organization concerned with virtually all the forms of activity of practical interest, the exposure record for 1946 shows, for example, that no single individual received as much as 200 mr in any one day; that only four individuals received more than 100 mr in any one day; and that the average daily exposure of all radiation workers was less than 5 mr per day. There has been no known instance of the ingestion, inhalation, or other mode of introduction of a damaging amount of radioactive material into any individual. This standard was achieved with a working force of less than 3% of the total payroll. The financial considerations involved have therefore not been out of proportion, although it has been suggested (Bale, W. F., 1946) that industrial economies might lead to a reduction in the present coverage. It is felt, rather, that in the future expansion of radiation work, the laboratories and similar institutions might be the ones which would apply somewhat less than the present rate of 3% to the protection program. It is just these institutions which most need to maintain a technical force engaged in hazard control, because of the variable nature of the basic hazards encountered in a research program. In the industrial field, it is evident that stabilization of a given operation, additions to the protective equipment, and the provision of improved instrumentation, especially in the field of automatic recording, will lead to a logical and safe reduction in the full-time protection force. However, the foreseeable change is not such as to reduce the percentage representation appreciably below 2%.

III. EXPOSURE STANDARDS

Dose Units

Discussion of tolerance dose has been obscured in some cases by ambiguity or misinterpretation of the meaning of "dose" as applied to radiation exposure. "Dose," as intended in radiobiology, is a measure of the energy absorption of radiation per unit volume or mass of tissue. In practical usage, dose is measured in terms of the energy absorption in air which closely parallels the absorption in tissue for the particular range of X-radiation and gamma radiation for which the principles of dosimetry were established (Gray, L. H., 1937 a and b). The practical unit of dose, the "roentgen," corresponds to the absorption of 83 ergs per gram of air. This is usually considered equivalent to the absorption of 83 ergs per gram or per cc of tissue.* It is convenient to use subsidiary dose units based on the energy absorption per cc of tissue. That "dose" of any ionizing radiation which produces energy absorption of 83 ergs per cc of tissue is defined as 1 rep. This is an abbreviation of "Roentgen Equivalent Physical," an expression which replaces such other titles as tissue roentgen, roentgen equivalent, or equivalent roentgen, which have become familiar in the literature. This unit may now be applied to X-radiation, gamma radiation, alpha, beta, proton, or neutron irradiation. It is well known that equal energy absorption arising from exposure to these various radiations will not produce the same biological effects. When the additivity of different types of radiation is to be considered, an additional unit — the "rem" — is introduced. One rem is that dose of any radiation which produces a biological effect equal to that produced by one roentgen of high-voltage X-radiation. The title "rem" is derived by abbreviation of "Roentgen Equivalent Man" or, optionally, mammal. It was selected in preference to the more obvious "roentgen equivalent biological" to avoid the confusion between "rep" and "reb" in speech. It is obvious that biological equivalence may depend on treatment conditions, protraction, fractionation, tissue exposed, and so on; in some cases, there can be no true equivalence since one type of radiation may produce damage of a character never observed with other modes of exposure. Moreover, the mere introduction of the unit "rem" does not solve the problem of writing down the numerical value of the equivalence, which remains a complex problem in experimental biology. Despite these disadvantages, the use of the expressions "rep" and "rem" has been found to simplify discussions of exposure to radiations other than X- or gamma-radiation, and especially to the mixed radiations that have been common in the experience of the Plutonium Project. For tolerance purposes, only the relative values of "rep" and "rem" for long-continued exposure to low intensity radiation need be considered. An accepted scale of relation is as follows:

X-rays and gamma rays	1 r = 1 rep = 1 rem
Beta rays	1 rep = 1 rem
Protons and fast neutrons	1 rep = 4 rem
Slow neutrons	1 rep = 4 rem
Alpha particles	1 rep = 10 rem

*The actual energy absorption per cc of tissue varies between 42 and 89 ergs/cc/r in fat, and between 87 and 95 ergs/cc/r in muscle in the energy range 12 KEV to 830 KEV. (Spiers, F. W., 1946).

Tolerance Dose

For the present purposes, tolerance dose or permissible exposure will be assumed to be that dose to which the body can be subjected without the production of harmful effects. When the exposure considered is given on a single occasion, the tolerance dose or permissible exposure is clearly defined. Health-Physics is commonly concerned with the case in which repeated small exposures occur, and it is not entirely clear whether dose in this connection should refer to the total dose or to the element of dose in a given time. A suitable convention follows the latter view, with the given time as one day.

Tolerance Dosage-Rate

"Tolerance dosage-rate" has to be interpreted as that dosage-rate which is continuously tolerable. It will be maintained that the daily tolerance dose is 100 mr (in the general case). If one writes that the tolerance dose is 100 mr/day, it is argued that this is dimensionally a dosage-rate, and that one should write "tolerance dosage-rate is 100 mr/day." This statement has an entirely different meaning, and implies the existence of a maximum permissible rate of about 3×10^{-6} r/sec.

Tolerance Dose Versus Tolerance Dosage-Rate

The question of interpretation between "dose" and "dosage-rate" as applied to the tolerance problem is fundamental in the consideration of the permissible exposure of the body. The tolerance dosage-rate of 10^{-5} r/sec was apparently introduced by Wintz and Rump (1931), who very clearly were equally content to quote a weekly or monthly total dose. The same election of convenient choice between tolerable exposure of 0.2 r per day or 1 r per week and tolerance dosage-rate of 10^{-5} r/sec is contained in the current International Recommendations. It is entirely erroneous to suppose that these sources intended a rate in excess of 10^{-5} r/sec to be considered hazardous. The utility of the rate was restricted to survey measurements around fixed installations, which would be safe if all readings fell below this limit.

The practical background on permissible exposure has, of course, come from exposures at much higher rates, viz.

Occupation	Approximate Dosage-Rate of Exposure r/sec
Fluoroscopists : Hands	10^{-2} - 10^{-1}
Body	10^{-4} - 10^{-3}
X-ray Therapy Technicians:	10^{-4}
X-ray Patients: Scattered radiation	10^{-2}
Radium Therapists and Technicians	10^{-4} - 10^{-3}

The main body of experience has been in the range 10^{-4} to 10^{-3} r/sec, and the rate of 10^{-5} r/sec should receive no special significance. On the other hand there is no sound information relative to high rates, except for erythema and therapeutic doses (McWhirter, R., 1935) where no significant rate dependence exists. In the tolerance field, daily short exposures at high rates may be more damaging than equal doses at normal rates. Simple control policy makes it impractical to condone receipt of a daily quota of 100 mr in less than 30 secs. This is a rate of 3×10^{-3} r/sec, only a factor of 10 from the ordinary case, and significant changes in this range are unlikely. For a single major exposure, of course, the damage produced appears to be a rapid function of the rate. Most, if not all, of the variation is due to the necessary change in total exposure time (protraction) in this single shot case.

The proposed restriction to a daily tolerance dose of 100 mr is arbitrary and occasionally unnecessary. One cannot prove (without a long animal experiment) that 200 mr and zero on alternate days or 300 mr followed by two clear days are unacceptable. For control purposes only the restriction to 100 mr per day is proper in almost all cases. Deliberate exposure of 100 N mr balanced by a radiation-free period of (N - 1) work days is foolhardy if N exceeds 10, and unwise if N exceeds 3.

Foundations of Tolerance Experience

The development of any extensive experience of tolerance is restricted to exposure to X-radiation and gamma radiation. The following account is included primarily to emphasize the scanty and inadequate data on which tolerance figures have had to be based even in these cases. Inadequate dose measurement and statistically insignificant groups have been common.

Although the first case of X-radiation injury was described in July 1896, the first published tolerance dose appears to be due to Rollins in 1902. His photographic plate fogging limit was perhaps 10 r/day. Early radiation injuries were primarily confined to the skin, but the demonstrations of the radio-sensitivity of the blood-forming organs (1904-1905) and of the reproductive organs of animals (1903-1904) carried fair warning that more dangerous damage than dermatitis could be anticipated. It is important and instructive, however, to note that the first organized step to insure protection from X-radiation was taken in 1915 (Russ, S.). It has been pointed out by Henshaw (1941) that the war activity at that time resulted in delay on protective measures, and undoubtedly contributed to the large group of radiation injuries, especially aplastic anemia, manifest in 1919-1921. The American Roentgen Ray Society formed a Committee in 1920 to recommend protection measures, which were formulated and published in 1922. The British X-ray and Radium Protection Committee presented its first recommendation in 1921. The two sets of recommendations were similar and dealt largely with protective materials recommended for use in building X-ray and radium laboratories and apparatus.

At the second International Radiological Congress, 1928, protection proposals were carefully considered, and subsequently an International Committee on X-ray and Radium Protection was formed. The recommendations of this Committee contained no specific reference to a tolerance dose until the reports of 1934 and 1937, which described the tolerance dose as being 0.2 roentgen per day.

Mutscheller (1925) had published a tolerance figure of 0.01 of the erythema dose per month, based on measurements in several installations in which no apparent injury to the operators was being occasioned. This figure was later substantiated (Mutscheller 1928) and subsequently extended (Mutscheller 1934) for rays of higher penetration. Erythema dose for this quality was 340 r and the tolerance dose therefore 3.4 r per month, or about

150 mr per work day. The German Committee on X-ray and Radiation Protection (Glocker, R. and Kaupp, E., 1935) accepted the same figure. Laboratory and hospital measurements by Sievert (1925) led to the same statement of safe dose. Typical of the necessity to extrapolate from insufficient data was the publication by Barclay and Cox (1928) of a safe daily exposure of 0.00028 of an erythema dose* on the basis of determinations on two individuals. This permissible exposure, equivalent to about 170 mr per day, was believed at that time to include a safety factor of 25 fold. A reconsideration of the early data (Kaye, G.W.C., 1928) led to a proposal of 0.001 of an erythema dose in 5 days, closely equivalent to 100 mr per day. The first comprehensive report on tolerance exposure to gamma radiation (Failla, G., 1932) led to a value of 0.001 of a threshold erythema dose (radium) per month, or of the order of 60 mr per work day.

An important step in the improvement of protective practice in the United States was the formation of an Advisory Committee on X-ray and Radium Protection,which published proposals in 1931 in the Bureau of Standards Handbook H-15. This and subsequent handbooks have been models of sound approach to radiation hazard control. This first handbook recommended a tolerance dose of 200 mr per day, but the revised handbook (#20, 1936) quoted a value of 100 mr per day with no specific explanation of the reduction. In an independent publication, the chairman of the Advisory Committee referred to the safety value as 20 mr per day (Taylor, L.S., 1941). A League of Nations publication (Wintz and Rump 1931) reviewed the various statements of tolerance dose, and concluded that the permissible exposure is 10^{-5} r per second, assuming a 7-hour working day, and 300 working days per year. This is equivalent to 250 mr/day. The exposure was qualified for persons "remaining in proximity to sources of radiation giving off rays without intermission," (i.e., radioactive preparations) by reducing it by a factor of 3 or in round figures to 100 mr per day. The limit of 100 mr per day has been widely established in American practice for both X-radiation and gamma radiation although the higher value of 200 mr per day still remains in the International Recommendations.

Recent Considerations

Recently proposed changes in tolerable exposure for X or gamma radiation are a fairly general desire on the part of health physicists to establish a lower rate for multi-million-volt radiation (Failla, G., 1945), as a precautionary measure until more is known about this field, and a suggestion that the exposure of women employees should be less than that of men (Lorenz, E., 1946), in consideration of the possible irreversible effects on the reproductive organs. In both cases, provisional values of 20 mr per day have been suggested.

The stimulus of the Manhattan Project has initiated much valuable experimental work

*The translation of any early result expressed in terms of erythema dose to the equivalent roentgen dose is by no means clear-cut, but the following table includes representative values:

Quality	To Produce Erythema
Grenz rays	100 r
100 kv	350 r
200 kv	600 r
1000 kv	1000 r
γ rays (radium)	1500 r (threshold erythema ~1000 r)

in animals exposed over long periods of time to low intensity radiations. Not much is known of the results of these experiments beyond the fact that there is a general tendency to feel that the present limit of 100 mr per day is well chosen, although the safety factor involved is by no means as large as the earlier observers intended.

Biological Aspects of Tolerance Dose

For completeness in developing the current approach of Health-Physics to the tolerance problem, some consideration of the biological effects of radiation on the body is required; this is not the place for an extensive description or discussion of these effects. Radiosensitivity of tissues and its dependence on differentiation, rate of growth, and cellular environment are of basic importance in the study of the effects of radiation on the tissues. Also paramount is the distinction between threshold and non-threshold effects (Henshaw, P. S., 1944). Fortunately, the majority of radiation effects are thought to be of threshold type, which simplifies the practical problems of protection at the expense of introducing many variables into the manner in which radiation exposure can be legitmately received. The reversibility of radiation effects is of particular consequence in occupational exposure. This depends upon the reparative properties of the tissue, and where recovery is large the total radiation dose can be materially increased. When the potential damage in question is reversible, the protraction and fractionation of the given dose are major determinants of the end-result. Repeated exposure initially followed by repair may eventually exhaust the regenerative reserve and result in permanent damage. Exhaustion of bone marrow reserve is typical. The dramatic decline in the welfare of the individual following a long period of apparent normalcy is one of the most disturbing problems for the physician and health physicist to face in the investigation of permissible exposure to any type of radiation. The damaging effects of protracted exposure are customarily divided up as follows:

General Body Effects

The early toxic signs in man resulting from external irradiation of essentially the whole body are (a) lassitude and fatigue (Nuttall 1943), and (b) demonstrable effects upon the leukocytes of the blood (Goodfellow, D. R.,1935, Paterson, R.,1943, and many other references).

Either diminution in the total number of white cells or an altered ratio of neutrophils to lymphocytes are considered as possible indexes of early radiation effects, although it is well known that either may be caused by many other agents. Significant changes in the red blood cell picture are said to be late effects of continued overexposure. The coagulogram has been reported to be another critical index (Kaufmann, J., 1946). The concensus is that regular blood counts, carefully done, serve as an adequate early index of overexposure. Technicians can arrive independently at the same answer on a blood count within 10% (Cantril, S. T., 1943). The observation of the Manchester group (Paterson, R., 1943) that the normal white cell count of radiation workers is maintained at a level statistically demonstrated to be significantly lower than the general norm is of prime importance. If this can be accepted, then the white count index is certainly sufficiently sensitive, provided that the subjects of the Manchester experience are found not to suffer any eventually ill effects. Unfortunately, if shortening of life is one of the residual effects, then even the large Manchester group is too small to establish this difference, nor would the results be available soon enough to be of interest to the present generation of medical physicists.

Internal Emitters

General body effects arising from internal radiation have been extensively studied in the special cases arising from the ingestion or inhalation of radium, mesothorium, and their decay products. The effect on the blood-producing organs has been correlated with the level of radioactivity of the expired air (McClelland, W. R., 1933; Schlundt, H., McGarock, W., and Brown, M., 1931).

Widely discussed too is the effect of radon inhalation in the lungs and its possible contribution to lung cancer in the Schneeberg miners (Peller, S., 1939; Dohnert, H. R., 1938). If lung cancer in man is essentially carcinoma of the bronchus, it can be shown that the expected daily dose to the bronchus for men in these mines is 300 mrep per day, approximately 20 times that derived as an average dose throughout the lung. Since the exposure is almost entirely due to alpha radiation, the equivalent daily dose would be 3 rem. By the same calculation, the tolerable concentration of radon in the air would be 10^{-13} curie per cc to produce a bronchial irradiation of the permitted 100 mrem per day. It is of interest that this is the concentration considered tolerable in the British and Continental philosophy, and 10 times higher than the recommended value in the United States. Specific damage to the lung or bronchus is perhaps not properly included as a general body effect, but the inhalation of radioactive gases or dust has become a prominent hazard in recent experience, and whether the effect is limited to lung damage or becomes a general body effect is determined only by the rate of absorption of the toxic material through the lung surfaces. The general effects produced by the ingestion of radioactive material are only too well known, specifically with reference to radium (Martland, H. S., 1931). Careful studies by Evans and Rajewsky and their respective co-workers have shown that damage to the individual can occur as the result of the permanent deposition of approximately 1 μg Ra in the body, and the accepted safety limit is invariably taken as 0.1 μg Ra. This represents a daily irradiation of the average bone of about 16 mrep per day, or 160 mrem per day.*

SKIN EFFECTS - Erythema and the Layer of Passive Absorption

The characteristic effect of large doses of X-rays and γ-rays upon the skin is the production of an erythema, the result of dilation of the fine capillaries, venules, and arterioles supplying the skin. The outermost layer of the epidermis, the stratum corneum, consists of dead, hornified, flattened cells. The thickness of this outer layer may be 0.4 mm on the palm, 0.8 mm on the sole, and approximately 0.05 - 0.1 mm elsewhere. This layer of passive absorption (Wilhemy, E., 1936) may be considered as an inert filter which serves to protect the sensitive levels of the skin from injury by alpha-particles, low-energy beta radiation, and extremely soft X-radiation. Prolonged exposure of the skin to natural alpha radiation therefore produces no erythema and probably no significant change in the skin condition.** On the other hand, skin injury can occur with accelerated alpha-particles where the

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* The average daily dose of the bone when the whole body receives the tolerable X-ray dose is:

500 mrep at 100 KEV	(150-200 KV therapy)
250 mrep at 150 KEV	(200-300 KV therapy)

** Presumably alpha emitters applied to skin could be absorbed and so penetrate the natural filter.

rays can penetrate the horny layer (Larkin, J. C., 1941). In the average case, beta radiation is well able to penetrate the passive layer and to produce severe skin injury. In very special cases, the additional thickness of the horny layer is of value in reducing the effective beta-ray exposure. This might be the case, for example, if the palm only were involved. In laboratory manipulation of beta sources, the exposure of the dorsal surface of the fingers usually exceeds that of the palmar surface, and here the passive layer is relatively thin.

Late Skin Damage

The more insidious forms of damage to the skin occur in occupational exposure when the administered dose extends over one or more years. There may be at no time an erythema, and the first injury sign may be ridge changes on the finger tips, epilation, polishing around the nail beds, fissuring or ridging of the nails, and skin dryness. Later evidence of injury includes telangiectasis, pigmentation, atrophy, and thickening with the apperance of wart-like growths. Ulceration may follow minor abrasions, which heal reluctantly. This may progress to cancer of the skin which in some 25% of the cases (Colwell, H. A., and Russ, S., 1934) may spread beyond the hands. The widespread occurrence of skin injury has led to a diligent search for improved methods of early recognition. Dental compound impressions of the skin ridges of the finger tips have been used in one case, and have shown promising results where the picture is not obscured by ridge flattening due to other causes. Another promising approach has been the microscopic study of the capillaries of the nail bed region (Nickson, Margaret, and Nickson, J. J., 1946). As indicated already, uncertainties as to the permissible skin dose exist. A limit of 200 mrep per day on the surface of the skin would be generally considered acceptable.

Effects on Reproductive Organs

This most dreaded hazard in the lay mind is usually considered subordinate to the effects on skin or on the blood-forming organs (Nuttall, 1943). Formal attempts to estimate fertility reduction in terms of the family-size of radiation workers have been obscured by the influence of other social conditions on this factor; there is no clear-cut evidence of such a reduction, and there is, in fact, some suggestion of an anxiety-stimulated overcompensation. For accidental short-term overexposure, permanent sterilization is produced by 400—600 r to the ovary, or 800—1000 r to the testes. There is a threshold dose which must be exceeded before any effect becomes evident. Early experiments in rats (Russ, S., and Scott, G. M., 1937, 1939) show that continued exposure to gamma radiation at 2 r/day led to a reduction in fertility. Extensive work at the National Cancer Institute, stimulated by the potentialities of the Manhattan Project, showed damage to the ovaries of mice at levels not far above 100 mr per day. The effect on the female mouse is significantly different from that on the male, as it proves to be an irreversible change, and therefore a function of the total dose and not the manner in which it is distributed in time (Lorenz, E., 1946). This has formed the basis for the recommendation of reduced radiation exposure of female workers.

Radiogenetic Effects

An excellent discussion of the potentialities of the genetic effect in its relation to radiation protection has been given by Henshaw, P. S., (1941). Extensive experimental work has been restricted to exposure of the fruit-fly in which it has been shown that the genetic effect has no threshold and exposure is not only cumulative in the individual but in succeeding generations. On this basis, there would be no true tolerance dose, but rather an acceptable injury-limit. Similar considerations led to doubt concerning the safety of repeated fluoroscopic exposures of children (Buschke, F., and Parker, H. M., 1942). Fortunately, several factors indicate that fear of the genetic effect may have been over-emphasized. In the fruit-fly, single exposure of 30—40 r doubles the low natural mutation rate, whereas doses of 500 r are required to produce recognizable mutations in the mouse. Dose-effect in the human case is entirely unknown. Speculations have been made regarding the contribution of cosmic radiation to such mutations; present information appears to exclude this possibility. It is also clear that the transmission of recessive characteristics would require the irradiation of substantial portions of the population, which is not anticipated. Of fundamental importance is a recent suggestion that the genetic effect in the fruit-fly when examined closely at low dosage is not truly of the non-threshold type. If this were substantiated, and applied also in the human case, there might be no fear whatever of genetic injury arising from prolonged exposure at very low intensity, which is a necessary corollary of radiation work. This has far-reaching consequences in the present communities of exposed persons, where, for the first time, there is a significant percentage of intermarriage of exposed persons.

DEPENDENCE OF TOLERANCE DOSE ON NATURE OF THE RADIATION - Specific Ionization

Although the mechanism of the interaction of radiation with living matter may not be fully understood, it is certain that one determining factor is the specific ionization of the radiation in the irradiated material [(Zirkle, R. E., (1940); Gray, L. H., and Read, J. (1943)]. This has led to the acceptance on the Project of the ratio of 1 rep = 4 rem for neutron radiation, and the arbitrary extrapolation of 1 rep = 10 rem for alpha-particle ionization.

X-rays

The original choice of the general tolerance dose was, of course, founded on experience with low energy radiation with an effective wavelength of the order of 0.3 Å. For 100 mr measured at the body surface (without backscatter), the tissue dose can be taken as 150 mr at 1 cm deep, and 50 mr at 10 cm deep. 400 KV radiation at the present time is as common as was 150 KV radiation when the tolerance was first established. The comparable depth doses with this radiation are 120 mr at 1 cm and 50 mr at 10 cm. The systemic effect on the body is surprisingly constant over this range, assuming biological equality of the radiation. This is only true when the defining dose of 100 mr is measured "in air."

Little has been written about the damaging effects of radiation generated between 400 and 2000 KV. In this range the increase in percentage depth dose is not very large. It is reasonable to suppose that the tolerance dose established for 150 KV radiation with a margin of safety of five or better would still be entirely safe for X-radiation up to 2000 KV. Experience with teleradium sources should also be applicable in this case.

Multi-million-volt X-rays show no striking increase in tissue ionization, because the increased penetration is offset by the fact that an increasing portion of the body falls in the transitional layer where equilibrium with the secondary radiation has not been established (Koch, H. W., Kerst, D. W., Morrison, P., 1943). The relative integral dose at different radiation energies is plotted in Figure 1, where the incident dose is supposed to be measured in a Bragg-Gray air-walled cavity. Concern has been expressed over the excessive ionization in bone at high voltage, due to the pair-production effect in calcium and phosphorus. The figure shows that up to 100 MEV at least, the energy absorption in bone, is comparable with that at 150 KEV. At lower energies (e.g., normal 200 KV therapy), the bone dose caused by photoelectric absorption exceeds any corresponding increase due to pair-production at high energies. The calculations are made with allowance for absorption in tissue and with a simplified picture of the body distribution of bone. On this basis, it appears that a reduction of tolerance dose with deference to bone ionization is unnecessary. Preliminary biological experience at 200 MV shows no striking difference from 200 KV experience (Quastler, H., and Clark, R. K., 1945).

Gamma Rays

Adequate experience with gamma radiation prior to the Project was largely confined to the use of radium and its products. It has been accepted that the danger of gamma radiation in practice exceeds that of "traditional" X-radiation for two reasons:

(1) X-ray equipment can be de-energized when not in use;

(2) Gamma-ray penetration is higher.

On the basis of 98 mr at 1 cm, and 67 mr at 10 cm, one might have a factor of 2 or 3 fold to represent the additional total body ionization, compared with the X-ray case. The expression of tolerance dose in terms of total body ionization rather than in terms of the incident dose has recently gained favor (Clarkson, J. R., 1945). The unit employed for this purpose is the gramme-roentgen. It is worthy of note that the total body ionization changes much more rapidly as a result of the position of the exposed person relative to the source than as a result of quality change from soft X-radiation to radium-gamma rays.

	Relative Total Body Ionization *
Soft X-rays from large distance	1
Gamma-rays from large distance	2.5
Gamma-rays from point source at 100 cm	1.9
Gamma-rays from point source at 10 cm	0.6

Although the integral dose point of view may have significance in measuring the relative potential injury for different qualities of radiation and different geometrical depositions, it can hardly supplant the existing method of limiting the incident daily dose. This would be especially true if the damaging dose were not significantly different for blood changes, skin damage, or effects on the reproductive organs. If the existing tolerance dose does not have a large safety margin for the second and third of these effects, little is gained by an elaboration of the gramme-roentgen aspect of exposure.

Recent experience in the administration of radio-isotopes for therapeutic purposes has introduced the problems of permissible exposure from this source. When the distribution of the material is known, the effective dose can be readily calculated; in general, it is overshadowed by the contribution of the accompanying beta radiation.

*Clarkson quotes a ratio of 5 in integral dose for exposure to stray radiation from deep therapy and diagnostic irradiations.

Beta-Rays

There is no extensive body of evidence on the permissible exposure of the body to beta radiation despite the extensive use of potent beta-ray sources in the past, and related sources such as cathode ray tubes and Lenard tubes. With such installations, it is easy to maintain adequate shielding at all times, and the damage from their use has been essentially restricted to short exposure to the direct beams, with insufficient knowledge of the dose received.* It is assumed for the present that for equal ionization in tissue, beta radiation will produce the same effect as X-radiation of average energy. The tolerable exposure to beta radiation has, therefore, been taken as 100 mrep per day. This should be conservative since the damaging effects of external beta radiation must be confined to the skin or to tissue within a few millimeters of that surface. The protection of the horny layer is introduced to set a limit to the lower energy of the beta radiation that need be included in measurements of the skin exposure. Alternatively, one can conveniently elect to use beta-ray chambers with wall thickness equivalent to that of the layer of passive absorption (approximately 7 mg/cm^2).

NEUTRONS - Fast Neutrons

The effects of prolonged exposure of the body to low intensity beams of fast neutrons are unknown. At higher intensity, there have been many comparisons of the radiation effects on biological materials when irradiated respectively by neutrons and X-or gamma-radiation. The neutron dose has been frequently stated in "n" units, representing the scale deflection of a Victoreen Condenser R Chamber, which is unsuited to fast neutron dosimetry. In more recent practice, attemps have been made either to measure or to calculate the ionizing effect of the radiation in a "tissue" chamber (Gray, L. H. and Read, J., 1939). For cyclotron neutrons, it is considered that 1 n is equal to 2.5 rep. Biological effectiveness ratios between 5 and 9 in terms of roentgen to "n" unit are quite common, and led to the proposed tolerance value of 0.01 n per day. This is the basis of the currently accepted relation 1 rep = 4 rem for fast neutrons.

A more refined study would make allowance for biological effectiveness dependence on energy of the incident neutrons. The reliable evidence of neutron exposure in humans rests on the erythema observations by R. S. Stone and J. C. Larkin (1942) mainly with neutrons from the 60" cyclotron. Erythema dose was 110 n for conditions approximately comparable with a 675 r erythema dose for 200 KV X-radiation or about 850 r of 400 KV radiation, the proposed standard for rep comparisons.** The biological equivalence ratio is, therefore, 1 rep = 3.4 rem. Gray's specific ionization calculations would give:

37" cyclotron neutrons	1 rep = 5.5 rem***
d-d neutrons	1 rep = 8.7 rem

For deeper effects, the neutrons will be slowed down in tissue with a consequent increase in biological effectiveness. On this basis, the usual value 1 rep - 4 rem is far from conservative. Moreover, there is a possibility that the effectiveness ratio may increase

*This applied also in a recent accidental exposure to scattered beta rays.

**Lower voltage radiation introduces a photoelectric contribution at the sensitive depth in skin. Appreciably higher voltage radiation has a surface transitional layer thicker than the layer of passive absorption.

***Stone and Larkin observed 90 n as the erythema dose on a short series. This makes 1 rep = 4.2 rem. Their instrumentation was admittedly somewhat open to question.

sharply under the extended low intensity bombardment of interest in tolerance.

Slow Neutrons

The present estimate of tolerance to fast neutrons has been deduced from some experimental evidence, but at the beginning of the Manhattan Project there was no experimental foundation for a slow neutron tolerance exposure. Three factors were considered:

(1) Production of gamma rays in the body by the interaction of neutrons with hydrogen-nuclei,

(2) Production of fast protons by the neutron reaction on some constituent atoms; and

(3) Production of new atomic nuclei.

Although it seemed at first that the exposures would be primarily controlled by the first effect (in which case one would have 1 rep = 1 rem), it appeared later both by revised calculations of the nuclear reactions and by animal experimentation, that the reaction $N^{14}(n,p)$ C^{14} played a considerable part in the total effect. This led to a provisional effectiveness ratio of 1 rep = 4 rem. In numerical value, the ratio must be a function of the size of the irradiated body, because the production of fast protons is a purely local phenomenon, whereas the conversion to gamma radiation will be larger in the larger animal. Further refinement is hardly necessary until there is a greater body of biological observation of the slow neutron damage. The actual slow neutron flux that will produce the daily tolerable exposure of 100 mrem is said to be 1500 n/cm^2 sec. This is probably a lower limit of a value which may be as much as three times higher.* The precise value depends on measurements of body ionization arising from slow neutron incidence, which have not been satisfactorily performed. Slow neutron fluxes around nuclear machines appear to be low in comparison with other hazards, and there has been no critical urgency to perform detailed physical experiments required to specify the tolerable flux in greater detail. The data on epi-thermal neutrons, those in an energy range between that required to produce proton tracks and the approximately thermal energy significant for the $N^{14}(n,p)$ C^{14} reaction, is incomplete. There may be some molecular disturbance in the tissue by such neutron bombardment. For measurement purposes, the epi-thermal flux is indicated qualitatively by surrounding slow neutron counters with hydrogenous moderators. Large counts under these conditions are corrected by alterations on the primary shielding.

Alpha Rays

As stated before, there is no danger from the external radiation by natural alpha-particles under normal conditions. The tolerance to accelerated particles is based on the tissue ionization with the biological effectiveness ratio of 1 rep = 10 rem. The ratio is the best guess of alpha-ray exposure in small organisms (Zirkle, R. E., 1946). Inside the body, the same tolerance is allowed; the practical problems are confined to the calculation of energy absorption arising from a given amount of the alpha emitter in the tissue or organ of interest.

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*J. S. Mitchell (1947) has recently published a value of 1250 n/cm^2 sec.

Protons and Other Particles

Bombardment of the body by fast neutrons results in a fast proton effect in the body. Consequently, for a primary fast proton bombardment, the same biological ratio of 1 rep to 4 rem is assumed to apply. Radiological use of fast protons is anticipated when new machines yielding 125 MEV protons or better are completed (Wilson, R. R., 1946). More detailed consideration of proton effects may then be required.

Combined Radiations

In the absence of evidence to the contrary, it is assumed that small contributions of different types of radiation produce additive effects when measured in the biological equivalence units of rem.* There is a wide field of biological experiment in the examination of this proposition. From the physical point of view, the heavy weighting of neutron, proton, and alpha-particle bombardment in terms of biological damage makes it important to apportion the total ionization as accurately as possible to the respective causative agents. In particular, measuring devices which record mixed radiations in terms of rem are to be avoided. The rep/rem ratios are provisional, and such devices exclude the possibility of back-correction of data.

GEOMETRICAL CONSIDERATIONS - Conditions of measurement of tolerance dose

In the field of therapeutic irradiation, there is one school which normally quotes all surface dose in terms of the measurement in an air chamber without the presence of the human body as a scattering medium; and another school which quotes the alleged skin dose which includes the air measurement supplemented by whatever scattered radiation would arrive at the surface from the patient's body. With the exception of the recent industrial regulations (American Standards Association, 1945), there has been no clear definition of the method intended in the tolerance literature. If one supposes that the European and international systems of 200 mr per day exposure include all scattered radiation, while the American system of 100 mr per day specifically excludes it, there would be fairly close agreement for low energy X-radiation on which the tolerance was originally founded. At higher energy, the American system becomes relatively more conservative. In this system, the readings of suitably designed monitoring instruments in exposure-areas would apply directly in tolerance considerations. On the other hand, an ionization chamber worn on the body would give a reading greater than that involved in the tolerance calculation. This difference is rarely taken into account, but it can amount to as much as 40 or 50%.

Directional and Narrow Beam Irradiation

Other principal factors which make the estimation of the dose received by the body in terms of a pocket-meter reading unreliable are: (1) directional radiation, and (2) limited or subdivided beams. With X-radiation of normal penetration, the error can be by a factor of about 10 if the meter is worn on the chest and the irradiation incident on the back. This extreme case would be evidence of considerable stupidity on the part of those responsible for protection, but similar cases of lesser degree necessarily occur. Under item (2), one has the familiar overexposure of hands and head while assembling radium sources behind a lead shield. Another aspect arises in the shielding of equipment which requires controls

*Although the definition of rem does not necessarily imply such additivity, the concept would be virtually useless without it.

to be brought to the outside, and again in the use of shielding boxes or vessels with removable lids or plugs. Proper design of such boxes calls for the elimination of intense narrow beams. Much attention has been given to this in the protection of X-ray treatment rooms. It was an important consideration in Pile design where a regular pattern of holes through the principal shield was required. Although it is recognized that a considerably higher dose can be given safely to a small field than to a large one, the difference is hardly great enough to justify change in tolerance dose. Also, if the exposure is measured on the person rather than by monitoring equipment, the recording pocket-meter may happen to spend much of its time in a shielded zone while parts of the body are in fact being irradiated. For these reasons, it is considered good policy to restrict the permissible dosage-rate of emergent beams to a necessarily safe level.

IV. ORGANIZATION AND FUNCTIONS OF A TYPICAL HEALTH-PHYSICS GROUP

General

A general account of the responsibilities and functions of a Health-Physics organization has been given by R. S. Stone (1946) and K. Z. Morgan, (1946a); these references should be consulted. Activities are divided into two parts: (1) Operational or Service, and (2) Control and Development.

Operational Division

By convention, the Operational Division has been further subdivided into (a) Personnel Monitoring, and (b) Area Monitoring or Survey.

Personnel Monitoring

Personnel Monitoring has included routine records of the daily gamma-ray exposure of each individual as recorded by pocket ionization chambers. Early equipment for this purpose was unsatisfactory; the policy of wearing two meters to decrease the percentage of readings totally lost by instrument defects was adopted and maintained. Mass observation of pocket-meter readings has shown that well prepared meters do not give the same reading when uniformly exposed to 100 mr (say). The readings fall on a probability curve of standard deviation corresponding to 6 mr. The chance of reading a tolerance exposure as 80 mr or less is therefore about 1 in 1000. In large well-protected plants this might occur about once in four years. For weekly totals, the random daily fluctuations become inconsequential. Mass preparation of data essentially accurate to within 25 mr per week is practicable. Pocket-meter readings have been supplemented by the observation of the blackening of special dental films arranged to record beta and gamma radiation separately. Fast neutron exposures were recorded by the measurement of proton recoil tracks produced in the Eastman Kodak special fine grain particle film. Slow neutron exposures have been observed by means of boron-lined pocket meters. Exposures of special parts of the body, notably the fingers, have been made either by micro-ionization chambers or by small film packs contained in special rings. These operations have been conducted on a scale approximately 100 times that of similar pre-Project experience, and the records probably constitute the best available collection of personnel exposure data of reasonable technical accuracy.

Area Monitoring

The responsibility of area monitoring has been discharged by (a) fixed instruments with recorder charts, (b) technical graduates trained in the measurement and interpretation of radiation data, and (c) technicians trained in radiation measurement. Contrary to some reports, this area monitoring was entirely similar to pre-war practice. Differences were in degree only and included greater frequency, more varied instrumentation, and improved reporting. For the latter, various room or area maps have been used for data plotting. While suitable for special locations, these lack the three-dimensional feature frequently required, and well planned tabulations have proved more adaptable. Exposure standards for all radiation types were established. Special interpretation was needed for surface contamination. For alpha emitters, the hazard was confined to possible transfer to the body. Beta contamination required consideration both in this manner and as a direct contact hazard. Hazard limits in either case came close to the minimum conveniently detectable contamination. With the area monitoring was combined a written control system for access to a potentially hazardous area. The cooperation between operating, maintenance, technical and health groups prior to and throughout any maneuver involving radiation utilized the monitor results to best advantage.

The wartime use of technical graduates for survey, when scientific talent was at a premium, was indicative that the task was more involved than would appear at first sight. Qualifications for area monitoring are given on page 30.

As available instruments were steadily improved and made more suitable for specific applications, and as many phases of laboratory and industrial operations became stereotyped, the amount of monitoring executed competently by specially trained technicians increased. It is anticipated this procedure will be further extended in the future, but successful elimination of the graduate surveyor is improbable.

Control and Development Division

In the Control and Development Division is included such control items as measurement of activity on protective clothing and radio-analysis of samples of many kinds submitted by the separate monitoring groups, or collected over a wide area to maintain surveillance of the contamination conditions of air, ground, or water, at all relevant locations. Bio-assay of the amount of activity excreted or exhaled by laboratory personnel is another control function. One vital responsibility is the calibration of all instruments, which, experience has taught, requires to be done with great frequency. The development field is subdivided into groups whose function is to improve methods of solution of such exposure problems as the body content of radiotoxic materials, absorption through skin, etc. Although the Health-Physics departments have been provided with instruments through the very successful efforts of general instrument departments, it has been found essential that they should themselves continue research and development into specific forms of instrumentation. The special bio-physical requirements of radiation measurement instruments have not been well known to those most familiar with the general instrument field, and it has required a particular combination of the skills of both groups to achieve adequate results. In some cases, required radio-biological investigations have been profitably integrated with the Health-Physics activities, and form a natural part of the responsibility for the improvement in health hazards control.

FACTORS CONTRIBUTING TO A SUCCESSFUL HEALTH-PHYSICS ORGANIZATION - The Objective

The primary difference between radiation protection is general and that offered where this is an established Health-Physics organization rests in the completeness of control. The luminous compound industry has no unsolved protection problem, yet violations of safe practice are commonplace (U.S. Dept. of Labor, 1942). In the hospital field, one clinic alone saw 80 cases of possible radio-dermatitis in physicians between 1934 and 1939 (Leddy, E. T., and Rigos, F. J., 1941). Another clinic saw 70 radiation injuries in 3 years (Uhlmann, E., 1942); 30 injuries followed treatment, and the remainder occurred in diagnostic or technical work. In a survey of 45 leading radiation hospitals, hand exposures over 20 r per occasion were noted, and skin changes in one-quarter of the radiologists observed (Cowie, D. B., and Schelle, L. A., 1941). Four physicians died in 1946, as a result of X-ray accidents or complications (Editor, J. Am. Med.Assn., 1947). The Plutonium Project locations,* entering new levels of potential exposure for the first time, have a record of no radiation injury. What factors have permitted this advance, and can it be perpetuated in future laboratory and industrial practice? It is essential to appreciate that the success of a protection program comes only in part from the health-physics unit. Some of the factors which influence the overall program are described below:

Attitude of Laboratory or Plant Personnel

Management support is a prerequisite for success in any safety program of which radiation safety is one component. Also, full cooperation of each and every employee in protecting himself and his colleagues is required. It is common to find a junior scientist who believes he has reasonable regard for the safety of co-workers, but is willing to take chances, or if a senior man "calculated risks," in his own exposure. Industrial experience has shown that this fails as a safety policy; the radiation problem is no exception. Reaction of senior staff personnel to the protection program frequently conditions the standards for a whole laboratory. Where there is passive acceptance of the program, or even covert resistance, the probability of effecting detailed safety control is low. Radiation accidents befall men who know how to conduct themselves and feel that rules are for the uninitiated.

Aptitude of the Health Division Leadership

In the control of a radiation project scaled up by orders of magnitude beyond previous experience, it is generally conceded that the primary health responsibility is preferably divided between a competent radiotherapist and a medical physicist. In normal laboratory or industrial practice, the special clinical skills of the radiotherapist are not required. The protection program is then largely in the hands of medical physicists, supplemented by very necessary industrial-medical examination of the health of the personnel.

Aptitude of the Health-Physics Force

The key members of the organization are the H. I. engineers, health-physics surveyors, or radiological monitors, on whom rests the day-to-day contact between protector and protected. Requirements for a successful engineer or surveyor are:

(a) Personality and Diplomacy:

The engineer must be able to "sell" the employee on the advantages of close hazard control. Law enforcement or policeman tactics impede the program.

(b) Technical Skill:

He must have a sound, not necessarily profound, knowledge of the health hazards, with a knowledge of tolerance and protective policies. He needs some electronics background to standardize instruments, and critically examine their field of performances. He must also have a general knowledge of laboratory or industrial processes involved. Where the program includes research or development, he must be competent to appreciate the objectives. He need not be, and in fact should not be, a research-type himself.

*Metallurgical Laboratory, Argonne National Laboratory, Clinton Laboratories, and Hanford Engineer Works.

(c) Appreciation of his Responsibilities:

The engineer's occupation has a negative character, the prevention of over-exposure, and he has nothing tangible to show for his day's effort. Unless he learns to appreciate the confidence that other employees develop in his recommendations, he will fail to realize the contribution that he has made. Whenever this happens, his morale and that of his contacts will suffer.

(d) Training Ability:

The engineer is required to advise diverse members of the force — research physicists and chemists, electricians, pipe fitters, chemical operators, etc. — on how to execute their work safely. Special ability to indicate the necessary maneuvers simply, under these conditions, is required.

Training Programs

Health-Physics organizations have trained all their engineers and technicians because there was no available pool with prior experience. The large industrial units have set as their objective the training of all other senior employees in Health-Physics. This is accomplished either by formal training of personnel already assigned to other duties, or by apprenticeship to the Health-Physics organization. Whenever circumstances permit, assignment to health instrumentation for a period between 6 months and 1 year has proved profitable.

Liaison with Operating or Technical Groups

A system of written instructions for the execution of all hazardous jobs has been formulated, and has become an important feature of radiation hazard control. At the Hanford Engineer Works, for example, a Special Work Permit is completed by all the organizations involved in a proposed job prior to its inception. This method of control was developed not by the Health-Physics group but by a general committee representing all groups. Such agreement on method of approach ensures a high standard of cooperation in the planning of each specific hazardous operation. Where the nature of the work is technical, and especially as it borders on original research, the operation of similar formal work permits is considered less applicable. However, this difference has been over-rated, and considerable success achieved in some cases with the application of permits to technical work.

Instrumentation

Particular stress has to be laid on the use of instruments in good condition and on their frequent calibration. The manner in which instrument readings are permanently recorded can also greatly affect the overall response. For health instrumentation, printing registers are frequently superior to rate meters, although the technical reliability may be identical.

Tolerance Limits

With the exception of the nationally accepted value of permissible dose of X-or gamma-radiation, there may be legitimate debate on other exposure limits. A competent Health-Physics Section must keep in touch with the main biological developments that could lead to a better understanding of such limits. Flexibility of interpretation has to be maintained, and there should be no reluctance to change exposure standards. Conservatism is essential when dealing with incompletely evaluated hazards. If X μg is the tolerable deposition of a toxic element deduced from early animal experimentation, and it later turns out that X/10 μg is the limit, then the health-physicist who has a number of colleagues with a body content of this element between X/10 and X μg occupies an infelicitous position. Final exposure limits have generally been lower than those originally proposed, and there can be little criticism of the physicist who elects to preserve an additional safety factor (up to 10) in permissible exposures. A corollary to the proper statement of standards is the necessity to measure the exposures competently. Where this hinges on a bio-assay, as it does for many problems of internal deposition, the measurement of the eliminated amounts may prove to be an extremely difficult technical procedure. It is imperative that health groups establish the highest possible technical standards in these cases.

New Protection Services

There is danger that the protection policy becomes stereotypes, perhaps with good control of general body radiation (especially gamma). Method development must be continued in order to put protection against other radiations, and especially against various forms of body exposure such as inhalation of active gases, inhalation or ingestion of alpha-emitting dusts, beta-emitting dusts, exposures to neutrons, etc., on a routine basis as soon as proper procedures can be established.

Reports and Records

Good records are required to make long-range studies of small exposures. To correct any condition which may be substandard, and for legitimate protection against fraudulent claims of overexposure, the primary record should be as complete as possible. Any instance of apparent overexposure should be thoroughly investigated to ascertain its cause and prevent its repetition. Wide publicity of incidents involving imperfect control, regardless of actual exposure, is desirable.

Detailed Control

In the last analysis, hazard control, especially where surface contamination is the issue, depends upon attention to minute details — invariable wearing of gloves, covering of work surfaces with paper, segregation of clean from contaminated tools, etc. Success in this field depends largely on the personal attitude of the individual concerned. In laboratories, in particular, it may represent the determining feature between good and fair hazard control.

Triple Safeguard Philosophy

Misadventures occur when several things go wrong in sequence. All important steps should, therefore, be protected by three safety devices so that all would have to fail before exposure occurred. The general policy is applicable to all phases of radiation-handling from the operation of a major Power Pile down to laboratory manipulation of active solutions. Safeguards should not be substituted for vigilance — the chemist careless while wearing gloves, and the driver reckless because he has good brakes have much in common.

Consistency of Rules and Enforcement

Protection rules must be consistent, and should observe the unities of time and place. Housekeeping rules, including contamination clean-up, respirator and glove wearing, eating and smoking are particularly vulnerable in this respect. Hazard control which allows smoking in laboratories on some days, and forbids it on others, is incompatible with the best practice. Rules should never be enforced by a Health-Physics organization. An advisory capacity is the objective, and the degree to which advice is accepted is a measure of the group's success.

Design

Radiation protection is relatively simple in any building initially provided with properly planned hazard control facilities. This includes suitable shielding of fixed apparatus, portable shielding for temporary sources; test stations for hands, shoes, and clothing; facilities for the provision of protective clothing, and change-house facilities were needed. When the basis of operation has been properly prepared, there is a saving of time in any subsequent operation performed. Economically, this partially offsets the initial higher cost of protection planning.

V. INSTRUMENTS

Status

One surprising feature of Health-Physics experience since 1942 has been the realization, prior to that time, equipment needed for radiation monitoring at the levels of interest in protection was generally unreliable, improperly calibrated, or not available at all. There has been no extensive release of information on the improvements effected during the war years. From some publications (K. Z. Morgan, 1946a; W. P. Jesse, 1946a), it can be deduced that considerable effort was devoted to this subject. Also, certain specific instruments have been released for general use. Brief accounts of such are included.

Calibration and Maintenance

No quicker way of destroying confidence in protective schemes exists than the use of instruments which do not appear to be functioning perfectly. This applies sometimes to devices such as counting rate meters which show a proper statistical fluctuation but are not as convincing to the average observer as a scaler and register that gives a definite count in the same time. More important is the elimination of loose connections, sticking needles, poor switches, tired batteries, defective tubes, and like defects that arise in sensitive electronic equipment subjected to fairly rough treatment. Preventive maintenance, which could be practiced more extensively in laboratories and institutions, is required. Calibration of health instruments should be done at least once a week. This includes a direct test of the instrument response to known amounts of radiation at different scale deflections and for all ranges. Whenever possible, calibration at more than one radiation energy is advocated. Standardization, which by custom means a spot check of response at one scale-position on each range, should be practiced every time a portable instrument is to be used. The provision of safe portable test sources for high intensity taxes the physicist's ingenuity. For such instruments as pocket-meters, it is generally conceded that daily standardization is unnecessary, and monthly calibration adequate.

Basic Health Instrumentation

The primary specialty that differentiates health instrumentation from process or control instrumentation is the behavior of the radiation receptor. This has to be made to give a response related in the simplest possible manner to the pertinent biological exposure. In the simplest case one designs an ion chamber to read in roentgens; this is done empirically over the required range of wavelength and is an exercise in the construction of an electrically conducting shell with an insulated electrode, the whole having an effective atomic number equal to that of air. For more refined measurements, tissue-wall vessels with "tissue-gas" are required. As applied to fast neutron irradiation, the close imitation of the hydrogen content of tissue is indicated; for slow neutron irradiation the precise amount of all elements present has to be regulated to govern the activation. More frequently, secondary methods have to be utilized, such as the physical measurement of slow neutron flux, and its theoretical conversion to tissue dose.

The physicist is normally interested in the number of particles or photons emitted by a source, or crossing unit surface. The health-physicist searches for the energy absorption in tissue-like materials. Typical of the consequences are the difficulties of interpretation of G.M. Counter readings, especially for gamma-ray counting. Very few health-physicists will accept portable counters as more than qualitative tools to locate areas of activity or contamination. Quantitative survey results come almost exclusively from ionization readings. In control work, counters, especially for alpha-particles, are invaluable and have been brought to standards of refinement normally unnecessary in analytical work.

FIXED INSTRUMENTS - Area Monitors

Beta-gamma monitoring of selected work locations is accomplished by custom-built combinations of ion chambers with commercial micro-microammeters and recorders. Where there is no size restriction, any desired sensitivity may be reached by using large chambers filled with air at atmospheric pressure. These are normally more reliable than pressure vessels and a suitable "air-wall" more easily provided. Sensitivity is approximately $1 \mu\mu \text{amp} = \frac{10}{V}$ mrep/hr, where V = chamber volume (liters). It is optional whether the circuit be made to indicate the instantaneous dosage-rate or to integrate the exposure over a work period. The ideal monitor accomplishes both. Alarm systems may be coupled in, actuated either by high rate or high integrated dose.

PERSONNEL MONITORS - Alpha Hand Counters

The detection of alpha-particle contamination on the hands is accomplished by adaptations of the standard pulse-type counters or of proportional counters with counting surface as large as the hand. A convenient modification is the two-fold counter which has flat multiwire proportional counters arranged to make contact with both sides of the hand. The collecting electrode system consists of a series of fine tungsten wires, to which approximately 2500 volts are applied, producing proportional counter-action in the flat air-filled chamber. The electronic circuit consists of an a-c amplifier, pulse leveler, integrating circuit, and vacuum tube voltmeter. Registration in this case is by counting rate meter with a useful range from 200 to 10,000 dis/min. None of these devices records the presence of alpha-particle contamination on the medial and lateral surfaces of the fingers. Where some contamination on the hands is found, sound policy calls for a detailed inspection with a small proportional counter probe. The objective in this type of counting is to determine the total amount of toxic material present. Its local concentration is unimportant except as an aid to localized removal treatment.

BETA-GAMMA - Hand Counters

Combinations of thin-walled counter tubes are normally disposed for this purpose to cover adequately all four principal hand surfaces simultaneously. As the objective is to locate contamination and remove it immediately, there is no need for quantitative measurements. The calibration of these instruments is made on the basis that contamination is spread over 3 sq in of the hand, to give a surface dosage-rate of 4 mrep/hr. Where the contamination can be limited to a small spot, the local surface dose may be quite high. Only if this occurred repeatedly on the same skin area would hazard arise. Protection against this is maintained by special checks for small spots. Preferred operation of the counter tubes is through a scaler and register system, with a permanent record of the results. In some cases, spot checks can be taken more conveniently on a system using four counting rate meters.

Foot Counters

Groups of counters in parallel can be arranged to check for contamination on the soles of the shoes, the early detection of which reduces the tracking of active material from one location to another. These units may be coupled to the hand counters for simultaneous registration.

Thyroid Counters

Typical of a check depending on the metabolism of a specific active material is the use of gamma counters for the measurement of radio-iodine in the thyroid in laboratories or other areas where this could be present. The method has been widely used in therapy with radio-iodine. For Health-Physics, a suitable calibration is obtained by putting a standardized radio-iodine solution in a glass model thyroid in a neck phantom. Practical sensitivity limit is about 4% of the tolerable value.

EQUIPMENT, ATMOSPHERIC, AND MISCELLANEOUS MONITORING - Standard Alpha Counter

The standard parallel plate chamber is used for the precision-measurement of the alpha-particle emission of samples of low mass, such as come from the evaporation of water samples, scrapings from contaminated surfaces, ashed tissue, etc. With reasonable care, the background may be reduced to 1 dis/min, and the useful range is then from 1 dis/min to about 40,000 dis/min. Resolution of alpha-particles occurs in the presence of up to 10^5 beta counts per min.

Simpson Proportional Counter

The Simpson proportional counter (Simpson, J. A., 1946) avoids the microphonic and electric disturbances of the standard type; it permits very fast counting (up to 5×10^5 dis/min), in the presence of strong beta counts (up to 5×10^9 dis/min). It is occasionally of value in health-physics work, but the limitation on sample size to 2 cm diameter, and the difficulty of decontamination, make it troublesome unless the high speed and resolution are essential.

Low Background Counter

Of special interest is the low background counter designed to expedite the detection of minimal amounts of alpha-emitters in the urine, tissue, etc. If the daily elimination of "fixed" radium were 0.001% of the body content, as little as 0.025 μg Ra in the skeleton could be detected with ease. The background of these counters is easily maintained at 6 counts/hr, although values as low as 0.1 count/hr have been claimed. With normally pure metals for the electrodes, the natural emission would amount to 3 counts/hr (Rajewsky, B., 1939). Surfaces of electrolytically pure metal could eliminate most of this. Then radon and thoron and their products would introduce 0.5 counts/hr, unless inactive gas (e.g., old air) were used to sweep out the counting enclosure. Radon concentration can also be appreciably reduced in a perfectly air-conditioned room.

BETA-GAMMA COUNTERS - General

Innumerable variations on the mounting of single or multiple G.M. tubes to facilitate the contamination test of laboratory glassware, tools,and other items can be postulated. Other obvious applications are:

Gas Counters

Representative gas samples are collected in prepared evacuated cans, and then introduced into a previously evacuated vessel containing a counter. In some cases, introduction into an ion chamber is preferred, as in radon breath sampling. In either case, subsequent contamination of the equipment may be troublesome.

Water Counters

Counters immersed in vessels of active water may be used to measure the activity, especially if readings in different sized vessels are obtained. In all such applications, contamination of the parts, and the peculiar wavelength response of some counters makes quantitative work difficult.

Dust Monitors

The collection of active dust from the air on filter paper surrounding a counter tube permits the evaluation of the air contamination in terms of the rate of increase of deposited activity. A natural limit of sensitivity is set by the simultaneous deposition of decay products of radon and thoron.

Special Instruments

Extrapolation chambers (Failla, G., 1937) are invaluable for the determination of contact dosage-rates of active sheets. Especially useful is an inverted type to measure surface activity of a liquid. The customary equipment is not portable, and the source has to be brought to it. Where this is impracticable, subsidiary standard sheets are calibrated and taken to the field. Extrapolation chambers require the best available electrometers. Both the project-improved Lindemann electrometers and the Vibrating Reed electrometer appear to have features superior to the traditional FP54 electrometer circuit. Triple coincidence counters in the standard arrangements are a valuable asset in the health instrumentation list.

PORTABLE SURVEY INSTRUMENTS AREA MONITORING ALPHA TYPES - Poppy

For the rapid detection of alpha-particle contamination, a proportional counter system is preferred. The typical probe operates with about 2500 volts on a fine tungsten wire collector. Its output operates an a-c amplifier, integrating circuit and vacuum tube voltmeter indicating circuit. An audio-oscillator triggered by each pulse makes the audible "pops" responsible for the popular name "Poppy." The Poppy is sensitive to mechanical and electrical disturbances, and is affected by moisture. The "geometry" is also sensitive to the operating conditions and should be tested frequently during operation. Inasmuch as the primary function of the equipment is to locate contamination that has to be removed, these variable features cause little concern. Sensitivity down to 200 dis/min over the probe face is the usual limit.

Zeuto

The Zeuto (Jesse, W. P., 1946b), is a convenient unit including an ion chamber with thin screen window transparent to alpha-particles, and a circuit employing a balanced pair of miniature tubes for amplifying the ion current with a microammeter in a bridge circuit for measurement. A third tube controls positive feedback, which reduces the time constant sufficiently to permit use of a 10^{12} ohm input resistor. The instrument is sensitive to about 200 dis/min, and high readings can be accommodated by scale changing. As applied to large flat surfaces, Zeuto is at least competitive with Poppy. The latter is effective where curved surfaces and narrow strips are concerned.

BETA-GAMMA TYPES - Zeus

Many successful beta-gamma monitors have been constructed, but apparently few are available for description. One such is the Zeus (Jesse, W. P., 1946c), a survey meter for alpha, beta, or gamma work, but rather insensitive and non-uniform for alpha-quantification. Built-in alpha and beta shields provide a convenient method for estimating the relative intensity of beta and gamma components, and indicating the presence of alpha contamination. Zero stability is good and the time constant short. The useful range of the Zeus is from 1 to 2500 mrep/hr in three ranges, viz., 1 to 25, 5 to 100, and 100 to 2500. Separate calibration of each range is needed. Ion chamber current is amplified by a balanced pair of miniature triodes and measured by a microammeter in a bridge circuit. The range is selected by changing the value of the input resistor, which, at maximum sensitivity is 10^{11} ohms. The wire chamber screen and metal chamber wall on some instruments will cause energy dependence with soft gamma radiation.

Lauritsen Electroscope

The Lauritsen electroscope (Lauritsen, C. C. and Lauritsen, T., 1937), modified by the provision of a thin window with screens to eliminate alpha-particles or alpha and beta at will, is an excellent tool for the small laboratory. It has to be calibrated over a wide range, because there is a peculiar intensity response due to the inadequate collection field around the fine quartz fiber system. Limiting factors in the use of the instrument are energy dependence for gamma radiation, fixed sensitivity, and the inconvenience of obtaining measurements with the aid of a microscope while timing the observation with a stopwatch. Reliable determinations of dosage-rate can be made in the range from 0.1 mr/hr to 1 r/hr, provided sufficient time is available for low intensity measurements. The instrument is unsurpassed for reproducibility.

LANDSVERCK - Wollan Electrometer

Improvements on the Lauritsen electroscope have been incorporated in the Landsverck-Wollan electrometer. The new device is superior in linearity and sensitivity. A condenser-resistor circuit is used to flash a neon lamp at the beginning and end of one of two predetermined time periods, permitting the fiber to be observed at those instants, effectively making it a dual-range instrument. The timing system eliminates the need for a stopwatch to time fiber drift, when high precision is not required. The useful ranges of the instrument are 0 to 200 mr/hr, and 0 to 2 r/hr.

Victoreen Radiation Meter

The Victoreen Radiation Meter* was primarily designed for measurements of stray radiation from X-ray installations, but can be put to wider use in the protection field. Obvious circuit changes could make the meter suitable for higher ranges, by a combination of chamber size and resistor variation. The cautious observer would wish to mount the chamber on the end of an extension rod for high level operation. It is advantageous to prepare special scales calibrated over the whole range, and to standardize frequently.

Betty Snoop

The Betty Snoop is a lightweight portable meter for measuring high intensity radiation fields. Its probe contains a small plastic ion chamber, range switch, input resistors,and the electrometer tube. An extension cable permits using the probe at some distance from the meter circuit. Four sensitivities of nominal maxima, 0.2, 2, 20, and 200 rep/hr are provided. The calibration curve for the three lower ranges is nearly linear, but the high range curves with a negative slope. The circuit employs a balanced pair of triodes and a microammeter in a bridge circuit, with a third tube providing positive feedback to permit use of a 10^{12} ohm input resistor on the most sensitive range. A long time constant results on the lower ranges, and attempts to reduce it by increased feedback may cause oscillation. The chamber has an easily removable cap, which permits optional gamma or beta registration. As the chamber is only 3 cm diameter, it is well suited to measurements in narrow beams or close to small sources.

Condenser Chambers

Detachable condenser chambers of all sizes can be used as portable monitors where only an integrated dose is required. The method is cheap, reliable,and versatile. Ideal construction is still similar to the Sievert chambers (1932). A series of such chambers with different wall composition can be used to calculate energy absorption in tissue. Ranges from 0.04 mr to 1000 r are easily obtained on a versatile recorder such as a Lindemann electrometer. The familiar Victoreen Condenser-R-Meter is one suitable rugged commercial application of the principle. All such meters require calibration with the specific types of radiation to be used.

Portable G. M. Tube Sets

Since the first portable G. M. tube circuits were made, they have been used for the detection of lost radium and for health measurements. Low voltage counters (Chalmers, T. A., 1934) were particularly suited for systems weighing less than two pounds (Pallister, P. R., 1937). Innumerable circuit modifications have been used by commercial manufacturers and by private laboratories including registration by audio-signal, neon tube flashes, or integrating circuits. For health instrumentation, utility is restricted to qualitative detection rather than measurement. Good design features are therefore stability, lightweight, and freedom from unsuspected blocking. Modern circuits use mainly self-quenching tubes, but these exhibit a temperature coefficient (Korff, S. A., Spatz, W., and Hilberry, N., 1942), which can lead to racing counts in cold locations and no response in hot places. In survey applications, one uses a special filling of low temperature coefficient or restircts the

*Victoreen Instrument Co., Cleveland, Ohio.

operation to a certain temperature range.

Sigmion

A useful Project innovation was the Sigmion, a simple chamber and d-c . amplifier set to integrate up to 20 mr and then reset. The total exposure is tallied on a register. Successful operation depends on balancing the normal reverse leak by a subsidiary active source.

Victoreen Proteximeter

Somewhat similar in general design and function is the Victoreen Proteximeter. Dose up to 200 mr is indicated on the instrument meter. These instruments are convenient for location close to a technician. When the instrument is found to be fully discharged, there is no reset mechanism and no record of the total dose as provided by the Sigmion.

NEUTRON METERS - Differential Chambers

Quantitative measurements of fast neutron exposures are made in differential ion chambers, one of which is made sensitive to neutrons by the use of a hydrogenous gas or paraffin-lined wall, while the other provides a gamma-ray balance by ionization in argon. For high sensitivity, pressure vessels are required and the final equipment is cumbersome. Where rates above 50 n/cm^2 sec are involved, truly portable systems can be used. In all cases, special precautions are needed to compensate for asymmetrical gamma fields. Radium-beryllium sources are widely used for calibration.

BF_3 Counters

Slow neutrons are counted in conventional BF_3 Counters, or in boron-lined counters or ion chambers. All such slow neutron counters can be made into convenient detectors of fast neutrons by surrounding them with a 4" thick sleeve of paraffin, to moderate incident fast neutrons. Calibration is effected by comparison with the twin chamber apparatus, and is valid only for similar neutron spectra.

Portable Dust Monitors

Sampling for radioactive dust is easily accomplished by filtration or electrostatic precipitation. Standard formulae allow for the elimination of the Ra-Th contributions after two subsequent measurements. A convenient monogram for the elimination of thoron decay product counts when alpha contamination is to be measured,is shown. It is customary to delay the initial count until 4 hours (or better, 6) after the sample collection to reduce the radon decay product contribution to a negligible value.

PERSONNEL METERS BETA-GAMMA - Film Badges

A permanent record of integrated weekly dose is given by film badges. A typical badge contains two pieces of dental film in a silver or cadmium holder 1 mm thick, with a window to admit beta radiation. Blackening is measured on scales separately calibrated for beta and gamma radiation. One piece of film is the sensitive industrial radiography type, for the normal exposure, while the other is chosen with a range up to 40 rep to cover a possible gross exposure. The metal filter approximately compensates for wavelength dependence of film above the K limit of silver. However, soft quantum radiation on the window produces intense blackening which masks beta contributions.

Pocket Meters

Pocket ionization chambers in the general form of "pencils" have been used in many forms. Typical of the commercial species is that produced by the Victoreen Instrument Co., Cleveland, Ohio, and used in conjunction with a simple string electrometer—the Minometer. Such pocket meters should be rugged, wavelength-independent, free from insulator leaks, and unaffected by humidity. Currently available meters fall short of these ideals. With good maintenance, reliable service can be effected, and the use of duplicate meters reduces "lost" readings to an insignificant score. Technical improvements of the meters, especially protection against dust and moisture, and simplified manufacturing methods require study. Pocket meters with thin walls for beta registration can be used, or small models can be worn on the finger.

Neutron Meters

Slow neutrons can be recorded in boron-lined chambers (Landsverck, O. G., 1947). Slow neutron doses up to 200 mrem can be read on the standard model with only 1% interferency by an incident gamma tolerance dose. Neutron-sensitive film can be worn for fast neutron checks. A cadmium filter over regular film is an alternate meter for slow neutrons.

VI. SOME ELEMENTARY FORMULAE AND CALCULATION METHODS

General

Refined calculations of shielding, maximum permissible exposure, etc., are subjects for detailed treatises on the Health-Physics specialty. Much can be done by simplified methods to indicate the order of magnitude of exposure and some typical examples are given.

Shielding

X-ray shielding can be calculated from standard absorption data. It is customary to quote tables for lead absorption and to refer to other materials by their "lead equivalent" (Taylor, L. S., 1944; Glasser, Quimby, Taylor, and Weatherwax, 1944). The Graphic Calculator (Failla, G., 1945) is a convenient chart for protection calculations. Similar methods serve for the laboratory manipulation of radioactive sources. One convenient tabulation of the required shielding is shown in Table 1.* The addition of three quantities, with due regard to sign, and multiplication by one factor permit calculation of shield thickness for all normal values of source strength, quantum energy, handling distance, daily exposure time, and customary shield material. Interpolation is unnecessary because precision in temporary shielding need not be high.

Emission from Complex Sources

The emission of primary gamma radiation from a large radiating mass, in which the space variation of activity follows a simple power law, and which is covered by a uniform filter or shield, is formally identical with the radiation problems considered by E. Gold (1909). The intensity can be expressed as a series of integrals of the form

$$\int_0^{\pi/2} e^{-\chi \sec\theta} \sin\theta \, . \cos^{(n-2)}\theta \, . \, d\theta$$

which transforms to $\displaystyle\int_1^{\infty} \frac{e^{-\chi v}}{v^n} du$

Tables of this function have been published. Approximations to the radiation from large nuclear machines, tanks of active materials, reservoirs of waste material, etc., can be made on this basis. Where neutron radiation is involved, applications of diffusion theory may be needed. Many simpler cases, such as the gamma radiation from thin active discs or plates are familiar in the literature (e.g., Mayneord, W. V., 1932). Special cases of interest are the emission from active sheets or blocks and the emission inside extended masses of active material.

Emission from Sheets or Blocks

Consider a sheet emitting n particles per cc per sec, each of range R cm in the material. The emergent integrated flux is

*Prepared by C. C. Gamertsfelder, 1943.

$$\int_0^R \frac{2\pi n r^2\, dr}{4\pi r^2} = \frac{nR}{2} \text{ particles per cm}^2\text{sec.}$$

If k = number of ion pairs per cm air produced by each particle, the surface dosage-rate is: n R k $4.8 \times 10^{-10} \times 3600$ rep/hr = 8.7×10^{-7} n R k rep/hr

Radiation	k	R
α	~ 50,000	From tables: allow for relative stopping power
β	~ 75 for fast particles* ~100 for average particles	$\frac{\text{Range for maximum energy (E)}}{3}$
γ	$\frac{\sigma E}{W} = \frac{3.5 \times 10^{-5} \times E \times 10^6 \text{ approx}}{32}$ = 1.1 E E = energy per disinteg. in MEV	Reciprocal of linear absorption coefficient in medium

Examples:

1. A uranium sheet emits 1.27×10^4 alpha particles per sec per gram from U^{238} or 2.38×10^5 per sec per cc. There will be an equal number from the isotopic U^{234}. $\therefore$ $n_\alpha = 4.76 \times 10^5$. Average range = 3 cm air = 6×10^4 cm U.

   $\therefore$ alpha contact dosage-rate = 12.6 rep/hr

   Only the UX_2 beta rays will be worth consideration. $n_\beta = 2.38 \times 10^5$

   Range for average energy $2.32/_3$ is 0.25 gm Al/cm^2 = 0.34 gm U/cm^2 = 0.018 cm U beta dosage-rate = 280 mrep/hr

   Gamma ray energy is 0.8 MEV, R = 0.4 cm U
   Gamma dosage-rate = 7.2 mr/hr

2. A thick plastic sheet, s.g. 1.2 contains 1 mc P^{32} per cc. Range for average energy $1.7/_3$ is 0.14 gm Al/cm^2 = 0.12 cm in the sheet.

   Contact dosage-rate = $8.7 \times 10^{-7} \times 3.7 \times 10^7 \times 100 \times 0.12$ = 385 rep/hr

* k = 45, in the physicist's measure, follows the electron on its tortuous path. Our measure is a 1 cm translation.

Such calculated values can be relied upon to about ± 30%. For very thin sheets, an approximate value is obtained by inserting thickness t cm instead of R in the formula.

Emission inside Large Active Masses

The energy absorption per cc of the mass is evidently equal to the energy emission. When the energy absorption in the mass can be simply related to the energy absorption per cc of air, water, or tissue, the exposure in the mass can be written down immediately.
If C = concentration in μ c/liter and
E = (gamma energy + average beta energy) in MEV per disintegration* the following formulae result:

In air,	dosage-rate D.R.	=	2000 CE mrep/hr
In water,	dosage-rate	=	2.6 CE mrep/hr
or in any medium, density ρ,	dosage-rate	=	$2.6\ \frac{CE}{\rho}$ mrep/hr

Persons exposed in such masses may usually be supposed to receive the beta component from one hemisphere only. Also, on the ground for an active air case and at the surface of a water mass, the gamma rate is usually taken as one-half the above. Tolerable concentrations can readily be established on this basis. Formally, the surface case is identical with the already considered thick sheet problem, when transitional equilibrium effects are negligible.

Examples:

1. An air mass containing 1 μc Xe^{133}/liter contacts the ground.

   Average beta energy = $\frac{0.33}{3}$ MEV. Gamma energy = 0.084 MEV. (Siegel, J. M., 1946)

   A man in an airplane receives 2000 (0.055 + 0.084) = 280 mrep/hr

   On the ground he receives 2000 (0.055 + 0.042) = ~ 200 mrep/hr

   Tolerance concentration = (24 hr daily) is: 0.021 μc/liter

2. A river contains 0.02 μc Na^{24}/liter. Average beta energy = $\frac{1.39}{3}$, (Siegbahn, K., 1946)

   Gamma energy = (2.76 + 1.38). A small organism in the river receives 2.6 (0.46 + 4.14) x 0.02 = 0.24 mrep/hr.

   A man in a boat receives 1.3 x 4.14 x 0.02 = 0.11 mr/hr.

   Immersion tolerance concentration (man, 8 hr/day) = 1.1 μc/liter

TOLERANCE FOR INTERNAL EMITTERS - Simple Case

In almost all cases, the local energy absorption is governed by the particle radiation, alpha or beta. Even a small organ is then an effective large mass and the relation D. R. = $2.6\ \frac{CE}{\rho}$ mrep/hr holds. This has been more frequently used in the form D. R. = $62\ \frac{EQ}{W}$ rep/day where E = av. en. in MEV Q = μ c deposited W = grams of tissue containing the

*Usual application is to beta-gamma emitters. Same formula applies for alpha emission (e.g., in bone).

Q μc (Cohn, W. E., 1946). Let f be the fraction of the administered dose Qa deposited in the relevant tissue. Then for a single short exposure Q = f Qa; for prolonged exposure, $Q = f \frac{Qa}{\lambda}$ where Qa = daily dose and λ = decay constant in $days^{-1}$. Where the deposition is eliminated, this is assumed to be exponential with a biological decay constant λb. The effective decay constant is then $(\lambda + \lambda b)$. It is also necessary to distinguish between cases of prolonged exposure to a continuously maintained concentration (the main interest in tolerance dose), and to a decaying concentration, such as might follow accidental dispersal or the Bikini tests.

Other Variables

Recognized formulae of radioactive transformation can be applied to the case where one active material is taken in and produces a damaging daughter. Typical of the manipulation of such formulae and their application to tolerance are the data by K. Z. Morgan (1946b); some provisional tolerance values are listed in Table 2. These depend on the values of f. This is usually a composite, e.g.,for ingestion, f = fraction absorbed from gut into blood x fraction deposited from blood into tissue. For inhalation, one considers (1) lung retention from air, (2) absorption from lung to blood, and (3) deposition from blood. These factors vary for each radioactive material, its valence state, and some features of the physical and chemical form. Determination of these variables rests on prolonged radiobiological and biochemical studies, initially in animals, but in part on humans (especially for inhalation). For this reason there will continue to be discrepancies in the published tolerance values. With the termination of the war effort and the consequent restoration of channels of scientific information, the current multiplicity of values can be screened by a national committee to stabilize the best values.

Standard Man

Computers of tolerance concentrations have used a wide range of values for body organ weights, respiratory rate, water intake, etc. Uncertainties in the metabolism of isotopes and ultimately the idiosyncrasies of each exposed person will always exceed the range of variation introduced in this manner. Consequently, the continued publication of tolerance values founded on irregular basic values only further confuses the issue. Agreement on uniform figures should be possible as a first step toward complete standardization. The following values adjusted from those proposed by R. S. Stone form a logical basis for this:

Total body weight	70 kg
Muscle	30 kg
Skeleton	10 kg
Blood	4500 gm
Heart	300 gm
Liver	1500 gm
Lungs (pair)	1000 gm
Bone marrow (active)	1500 gm
G. I. tract (empty)	1500 gm

Kidneys (pair)	300 gm
Pancreas	65 gm
Spleen	160 gm
Testes (pair)	40 gm
Thyroid	25 gm
Respiratory rate	1 cubic meter/hr
Water intake	3 liters/day
Primary lung retention of small particles	25%

Table I

Shield Thickness for Laboratory Sources

Select column for energy required (use next higher if exact value is not given). Entry gives thickness in cm. Pb for different source strengths at 1 m. for 8 hrs. per day to give 100 mr. Add algebraically, correction terms for other working ranges or times, and multiply by factor for shield material.

E. G., 500 mc of 1.8 Mev sources at 50 cm. for 4 hr./day = (7.21 + 2 77 - 1.39) X 1.43 cm. Fe = 12.3 cm. Fe

Activity	0.2 Mev	0.5 Mev	0.8 Mev	1.0 Mev	1.5 Mev	2.0 Mev	2.5 Mev	3.0 Mev	4.0 Mev
10 mc	- .20	- .71	- .95	- .98	- .83	- .61	- .33	- .11	+ .19
20 mc	- .14	- .36	- .27	- .11	+ .37	+ .77	+1.15	+1.40	+1.70
50 mc	- .07	+ .11	+ .63	+1.03	+1.95	+ 2.61	+3.10	+3.39	+3.69
100 mc	- .01	+ .46	+1.31	+1.90	+3.14	+ 3.99	+4.57	+4.90	+5.20
200 mc	+ .04	+ .82	+1.99	+2.77	+4.34	+ 5.38	+6.05	+6.40	+6.70
500 mc	+ .12	+1.28	+2.89	+3.91	+5.92	+ 7.21	+7.99	+8.40	+8.69
1 c	+ .17	+1.64	+3.57	+4.78	+7.11	+ 8.60	+9.47	+9.90	+10.20
2 c	+ .23	+1.99	+4.25	+5.64	+8.31	+ 9.98	+10.94	+11.41	+11.71
5 c	+ .30	+2.46	+5.14	+6.79	+9.89	+11.82	+12.89	+13.40	+13.70
10 c	+ .36	+2.81	+5.82	+7.66	+11.08	+13.20	+14.37	+14.91	+15.21
20 c	+ .41	+3.17	+6.50	+8.52	+12.28	+14.59	+15.84	+16.42	+16.71
50 c	+ .49	+3.63	+7.40	+9.67	+13.86	+16.42	+17.79	+18.41	+18.71
100 c	+ .54	+3.99	+8.08	+10.53	+15.05	+17.81	+19.27	+19.91	+20.21
Danger Range	plus	plus	plus	plus	plus	plus	plus	plus	plus
20 cm	+ .26	+1.64	+3.16	+4.02	+5.55	+6.44	+6.85	+ 7.00	+ 7.00
50 cm	+ .11	+ .71	+1.36	+1.73	+2.39	+2.77	+2.95	+ 3.01	+ 3.01
1 m	.00	.00	.00	.00	.00	.00	.00	.00	.00
2 m	- .11	- .71	-1.36	-1.73	-2.39	-2.77	-2.95	- 3.01	- 3.01
5 m	- .26	-1.64	-3.16	-4.02	-5.55	-6.44	-6.85	- 7.00	- 7.00
10 m	- .37	-2.35	-4.52	-5.76	-7.94	-9.21	-9.80	-10.01	-10.01
Working Time	plus	plus	plus	plus	plus	plus	plus	plus	plus
1 hr.day	- .17	-1.06	-2.04	-2.60	-3.59	-4.16	-4.42	-4.52	-4.52
2	- .11	- .71	-1.36	-1.73	-2.39	-2.77	-2.95	-3.01	-3.01
4	- .06	- .35	- .68	- .87	-1.20	-1.39	-1.47	-1.51	-1.51
8	.00	.00	.00	.00	.00	.00	.00	.00	.00
24	+ .09	+ .56	+1.08	+1.37	+1.89	+2.20	+2.34	+2.39	+2.39
Absorber	times	times	times	times	times	times	times	times	times
Pb	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Fe	8.80	2.88	1.96	1.74	1.49	1.43	1.47	1.48	1.59
Al*	41.67	9.80	6.18	5.33	4.83	5.00	5.28	5.68	6.39
H_2O	106.84	21.54	13.42	11.59	10.36	11.11	11.19	12.11	12.78

* Or concrete.

Note added in proof: Source activity is quoted in millicuries or curies, where one curie is that amount of radioactive material that disintegrates at the rate of 3.4×10^{10} dis/sec. The table is computed on the further (erroneous) assumption that each disintegration yields one photon of the selected energy. This leads to inaccuracies whenever the disintegration scheme is complex. More accurate calculations can be made when the disintegration scheme is known. Ignored also is the increased effective transmission of shields under wide beam irradiation. The table is a useful guide for erection of temporary laboratory shielding.

TABLE I

SHIELD THICKNESS FOR LABORATORY SOURCES

Select column for energy required (use next higher if exact value is not given). Entry gives thickness in cm Pb for different source strengths at 1 meter for 8 hr/day to give 100 mr. Add correction terms for other working ranges or times, and multiply by factor for shield material.

e.g., 500 mc of 1.8 MEV source at 50 cm for 2 hr/day = (7.08 + 2.76 - 2.70) x 1.53 cm Fe. = 10.9 cm Fe

Activity	.2 Mev	.5 Mev	.8 Mev	1 Mev	1.5 Mev	2.0 Mev	2.5 Mev	3.0 Mev	4.0 Mev	5.0 Mev
10 mc	- .50	.86	- 1.02	- 1.05	- .83	- .61	- .39	- .13	- .23	- .37
20 mc	- .36	- .44	- .33	- .14	.33	.76	1.06	1.36	1.68	1.83
50 mc	- .17	.09	.59	1.04	1.82	2.55	2.95	3.30	3.58	3.72
100 mc	- .03	.33	1.28	1.95	2.97	3.92	4.41	4.79	5.03	5.18
200 mc	- .10	.91	1.97	2.85	4.11	5.27	5.84	6.26	6.47	6.61
500 mc	.30	1.46	2.89	4.04	5.61	7.08	7.76	8.22	8.38	8.53
1 c	.42	1.86	3.57	4.94	6.75	8.43	9.19	9.69	9.82	9.96
2 c	.56	2.27	4.27	5.84	7.87	9.78	10.63	11.16	11.25	11.40
5 c	.75	2.81	5.19	7.03	9.39	11.58	12.54	13.12	13.17	13.31
10 c	.89	3.22	5.87	7.94	10.52	12.94	13.98	14.59	14.60	14.75
20 c	1.03	3.63	6.57	8.84	11.67	14.31	15.43	16.08	16.06	16.20
50 c	1.21	4.17	7.47	10.02	13.16	16.09	17.33	18.02	17.95	18.10
100 c	1.35	4.58	8.18	10.93	14.31	17.46	18.78	19.51	19.41	19.55
Danger Range	Plus	Plus	Plus	Plus	Plus	Plus	Plus	Plus	Plus	Plus
20 cm	.64	1.90	3.22	4.19	5.28	6.31	6.70	6.86	6.70	6.70
50 cm	.28	.83	1.39	1.83	2.32	2.76	2.93	3.00	2.93	2.93
1 m	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
2 m	- .28	- .83	- 1.39	- 1.83	- 2.32	- 2.76	- 2.93	- 3.00	- 2.93	- 2.93
5 m	- .64	- 1.90	- 3.22	- 4.19	- 5.28	- 6.31	- 6.70	- 6.86	- 6.70	- 6.70
10 m	- .92	- 2.71	- 4.60	- 5.98	- 7.55	- 9.08	- 9.57	- 9.80	- 9.57	- 9.57
Working Time	Plus	Plus	Plus	Plus	Plus	Plus	Plus	Plus	Plus	Plus
1 hr day	- .41	- 1.22	- 2.08	- 2.69	- 3.40	- 4.06	- 4.31	- 4.41	- 4.31	- 4.31
2	- .28	- .81	- 1.37	- 1.79	- 2.26	- 2.70	- 2.87	- 2.94	- 2.87	- 2.87
4	- .14	- .14	- .69	- .90	- 1.14	- 1.35	- 1.44	- 1.47	- 1.44	- 1.44
8	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
24	.18	.53	1.10	1.17	1.48	1.76	1.87	1.92	1.87	1.87
Absorber	Times	Times	Times	Times	Times	Times	Times	Times	Times	Times
Pb	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Fe	4.75	2.68	2.11	1.75	1.51	1.53	1.53	1.53	1.77	1.96
Al*	17.23	7.71	5.43	5.13	4.70	4.25	4.81	5.22	6.01	6.87
H_2O	35.00	17.80	12.50	11.15	9.93	10.00	11.20	12.35	14.13	16.01

* or concrete

TABLE II

REPRESENTATIVE TOLERANCE VALUES CALCULATED BY K.Z. MORGAN (1946-b)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Element	Grams per Curie	Assumed Effective Half-Life	Method of Body Intake	Organ Affected & Fraction of Amt. in Body that is in Organ	Fraction Taken into Body that Reaches Organ	μc in Organ to Produce Tolerance Rate when t = 0	μc in Organ to Produce an Av. Tolerance during Year	One Year Tolerance Concentrations Rate (μc/sec)	One Year Tolerance Concentration in Air		One Year Tolerance Concentration in Water		Effective Energy
									μc/cc	μgm/cc	μc/cc	μgm/cc	Mev
Ra^{226} pdts	1	~ 2 wk.	Breathing	Lungs (.5)	0.25	.013	.23	7.5×10^{-9}	2.0×10^{-10}	2.0×10^{-10}			14 αγ
Ra^{226} pdts	1	~ 10 yr.	Ingestion	Bone (.6)	0.05	.155	.16	5.1×10^{-9}			4.4×10^{-6}	4.4×10^{-6}	14 αγ
Pu^{239}	16	2 mo.	Breathing	Lungs (.3)	0.25	.035	.15	4.7×10^{-9}	1.3×10^{-10}	2×10^{-9}			5.16 α
Pu^{239}	16	10 yr.	Ingestion	Bone (.6)	0.0003	.42	.43	1.4×10^{-8}			2.0×10^{-3}	3.1×10^{-2}	5.16 α
Pu^{239}	16	10 yr.	Breathing	Bone (.6)	0.0375	.42	.43	1.4×10^{-8}	2.5×10^{-9}	4.0×10^{-8}			5.16 α
Natural U	1.47×10^{6}	2 mo.	Breathing	Lungs (.3)	0.25	.041	.17	5.5×10^{-9}	1.5×10^{-10}	2.1×10^{-4}			4.43 α
Enriched U	2.7×10^{4}	2 mo.	Breathing	Lungs (.3)	0.25	.039	.16	5.1×10^{-9}	1.4×10^{-10}	3.8×10^{-6}			4.7 α
U^{233}		2 mo.	Breathing	Lungs (.3)	0.25	.037	.156	5.0×10^{-9}	1.3×10^{-10}				
Po^{210}	2.24×10^{-4}	82 d.	Breathing	Kidneys (.05)	0.011	.010	.033	1.0×10^{-9}	6.4×10^{-10}	1.4×10^{-13}			5.3 α
Po^{210}	2.24×10^{-4}	82 d.	Ingestion	Kidneys (.05)	0.001	.010	.033	1.0×10^{-9}			4.5×10^{-5}	1.0×10^{-8}	5.3 α
Sr^{89}	3.7×10^{-5}	43 d.	Ingestion	Bone (.5)	0.075	32	190	6.0×10^{-6}			3.4×10^{-3}	1.3×10^{-7}	0.6 β
$Sr^{90} \rightarrow Y^{90}$	7.74×10^{-3}	Sr - 197 d. Y - 2.49 d.	Ingestion	Bone (.5)	0.075	88 (20)*	34	1.1×10^{-6}			6.2×10^{-4}	4.8×10^{-6}	.22, .8 β
C^{14}(graphite)	0.23	2 mo.	Breathing	Lungs (.3)	0.25	32	130	4.3×10^{-6}	1.2×10^{-7}	2.6×10^{-8}			.05 β
C^{14} (CO_2)	0.23	10 d.	Breathing	Total Body (1)	0.25	2260	5.7×10^{4}	1.8×10^{-3}	4.8×10^{-5}	1.1×10^{-5}			.05 β
H^{3} (water)	2.59×10^{-4}	2 d.	Breathing	Lungs (.02)	0.25	320	4×10^{4}	1.3×10^{-3}	3.5×10^{-5}	9×10^{-9}			.005 β
I^{131}	8×10^{-6}	6.3 d.	Ingestion or Breathing	Thyroid (.2)	0.20	2.0	81	2.6×10^{-6}	8.5×10^{-8}	6.8×10^{-13}	5.5×10^{-4}	4.4×10^{-9}	.2 βγ

TABLE II (continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Element	Grams per Curie	Assumed Effective Half-Life	Method of Body Intake	Organ Affected & Fraction of Amt. in Body that is in Organ	Fraction Taken into Body that Reaches Organ	μc in Organ to Produce Tolerance Rate when t=0	μc in Organ to Produce an Av. Tolerance during Year	One Year Tolerance Concentrations rate (μc/sec)	One Year Tolerance Concentration in Air		One Year Tolerance Concentration in Water		Effective Energy
									μc/cc	μgm/cc	μc/cc	μgm/cc	Mev
Na^{24}	1.13×10^{-7}	14.8 hr.	Submersion	Body					6.3×10^{-7}	7.1×10^{-14}	4.9×10^{-4}	5.5×10^{-11}	3.3 $\beta\gamma$
Na^{24}	1.13×10^{-7}	14 hr.	Ing. or Br.	Blood (.25)	0.25	2.2	960	3.0×10^{-5}	8.1×10^{-7}	9.1×10^{-14}	5.2×10^{-3}	6.0×10^{-10}	3.3 $\beta\gamma$
Na^{24}	1.13×10^{-7}	11.5 hr.	Ing. or Br.	Lungs (.037)	0.037	0.5	258	8.2×10^{-6}	1.5×10^{-6}	1.7×10^{-13}	9.5×10^{-3}	1.1×10^{-9}	3.3 $\beta\gamma$
P^{32}	3.48×10^{-6}	14.3 d.	Submersion	Body					4.2×10^{-6}	1.5×10^{-11}	3.2×10^{-3}	1.1×10^{-8}	0.5 β
P^{32}	3.48×10^{-6}	13 d.	Ing. or Br.	Bone (.9)	0.09	39	750	2.4×10^{-5}	1.8×10^{-6}	6.2×10^{-12}	.011	4.0×10^{-8}	0.5 β
$Ba^{140} \rightarrow La^{140}$	1.33×10^{-5}	Ba - 11.75 d. La - 1.51 d.	Ingestion	Bone (.6)	0.06	48	170	5.3×10^{-6}			3.8×10^{-3}	5.1×10^{-8}	.4, 2.3 $\beta\gamma$
S^{35}	2.3×10^{-5}	25 d.	Ing. & Br.	Skin (.2)	.05(.1)**	150	1500	4.7×10^{-5}	3.1×10^{-6}	7.3×10^{-11}	.041	9.4×10^{-7}	.05 β
Ca^{45}	6.15×10^{-5}	150 d.	Ing. or Br.	Bone (.99)	.15 (.4)**	190	400	1.3×10^{-5}	2.1×10^{-7}	1.3×10^{-11}	3.6×10^{-3}	2.2×10^{-7}	0.1 β

The tolerance values in columns 9, 10, 11, 12, and 13 are for continuous exposure. If the exposure is for a 40-hour week, multiply these values by 4.2.

Column 9 is the tolerance concentration rate, P, in μc/sec, to the body organ that will produce a tolerance rate of exposure after 365 days of consumption.

It should be noted that values given in column 6 depend on the chemical form and in the case of inhalation they depend upon the size particles. Until the most likely forms of these elements in a given laboratory are known, it is difficult to assign typical values of tolerance concentration in columns 10, 11, 12, and 13.

Values in column 9 can be obtained directly from equation 14 or by dividing values in column 8 by the seconds in a year.

Column 8 is the μc in the lung, bone, kidney, or blood required to irradiate the organ with 3.65 roentgens of α or 36.5 roentgens of beta-gamma in a year. It is the μc in the thyroid required to irradiate it with 365 roentgens of beta-gamma in a year.

* The Sr-Y activity reaches a maximum after 15 days. The 88 μc is required to produce tolerance exposure rate soon after Sr reaches the bone. Only 20 μc is required to produce tolerance exposure rate on the 15th day. The 34 μc produces an average yearly tolerance dose. (See Fig. 4)

** It is assumed that the fraction reaching the skin by way of the gut is 0.05 and by way of the lungs is 0.1 in the case of S^{35}. For Ca^{45} it is assumed that 0.15 reaches the bone by way of the gut and 0.4 by way of the lung.

FIGURE 1

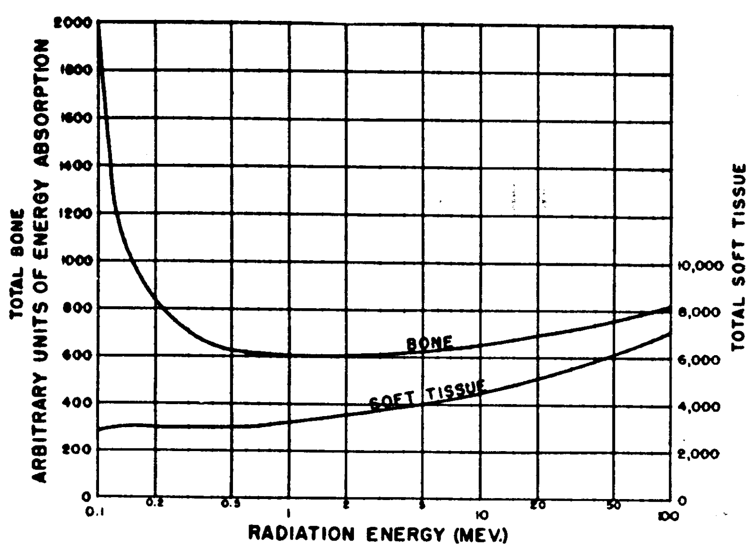
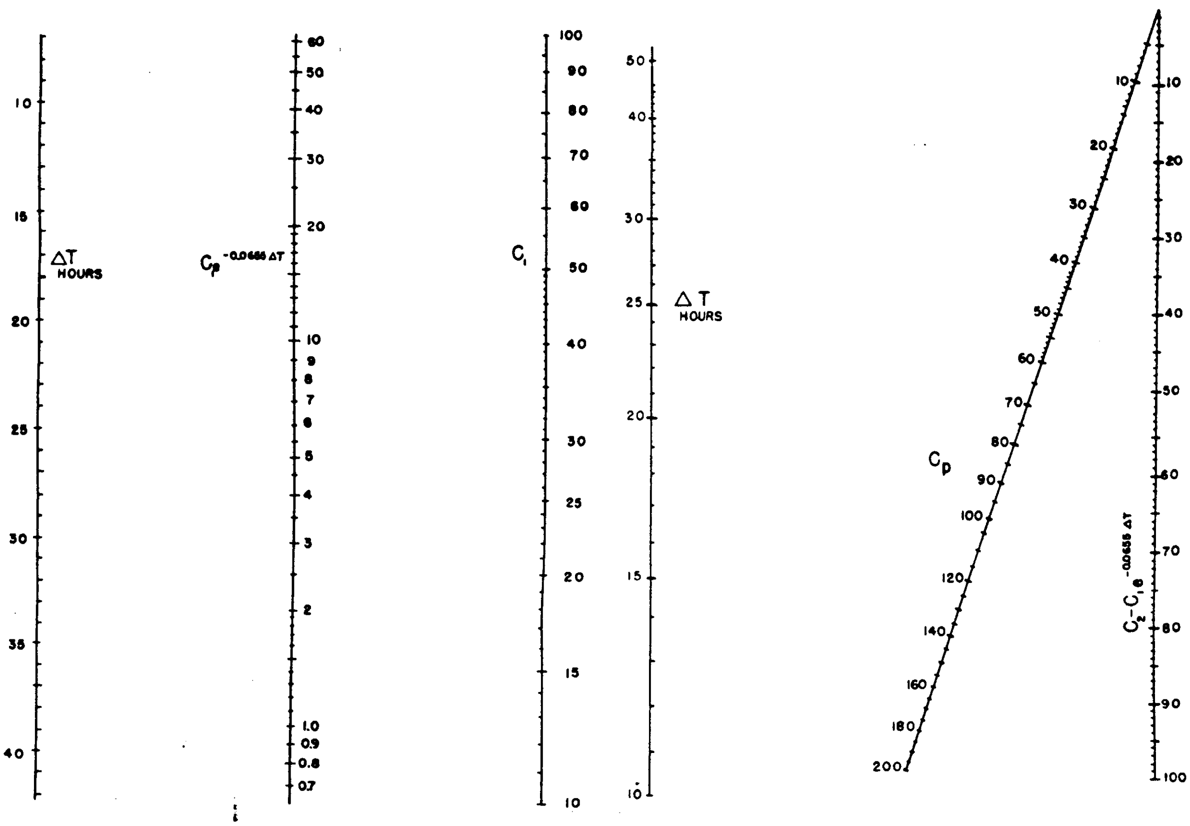


FIGURE 1



C_1 = counts/min after 4 to 6 h

C_2 = counts/min ΔT hours later.

On left-hand figure, straight edge through ΔT and C_1 defines $C_1 e^{-0.0655\ \Delta T}$ on center scale. Subtract this value from C2.

Straight edge between $C_2 - C_1 e^{-0.0655\ \Delta T}$ and ΔT on right-hand figure defines Cp on sloping scale.

Figure 2.

CALCULATION OF ALPHA COUNTING RATE Cp DUE TO CONTAMINANT IN PRESENCE OF THORON DECAY PRODUCTS.

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